Exporting global warming? Coal trade and the shale gas boom

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Abstract. We examine the effect of the US shale gas boom on the international trade and consumption of coal and 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. Moreover, the change in total coal consumed worldwide is also small. Although a compositional change towards coal with different heat content could have significant environmental effects, we show that this is not the case either. Hence, US coal exports simply displaced other coal exports without affecting the total CO_2 and SO_2 emissions. Despite the small overall effects, several countries experience a substantial decrease in their imports of US coal and the associated emissions in the absence of the boom.

Résumé. Exporter le réchauffement mondial? Le commerce du charbon et le boom du gaz de schiste. Nous examinons l'effet du boom du gaz de schiste aux États-Unis sur le commerce de charbon, sa consommation et les émissions à l'échelle internationale. Nous estimons un modèle structurel qui lie les marchés du charbon intérieur et international et nous l'utilisons pour simuler des scénarios hypothétiques. Nos résultats démontrent que la quantité totale de charbon vendue dans le monde en l'absence du boom est essentiellement la même que la quantité réelle. En outre, la variation de la quantité totale de charbon consommée dans le monde est également petite. Même si un changement de composition vers un charbon ayant une enthalpie différente pouvait avoir des effets environnementaux significatifs, nous démontrons que cela n'est pas le cas non plus. Par conséquent, les exportations américaines de charbon ne font que remplacer d'autres exportations de charbon sans modifier les émissions totales de CO_2 et de SO_2. En dépit des minces effets globaux, plusieurs pays voient une diminution importante

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de leurs importations de charbon américain et des émissions associées en l'absence du boom.

JEL classification: F18, L13, Q53

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.
>
> Tim Dickinson, "How the U.S. Exports Global Warming"
> *Rolling Stone*
> February 3, 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 US 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, the boom) because of 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 environmental implications of the boom's effect on an international scale have not. The paper aims to fill this void by analyzing the boom's emissions leakage effect via the international coal trade.

The downward pressure on the price of US coal due to lower domestic demand by the electric power sector—which has historically accounted for more than 80% of coal consumption—made US coal an attractive option for coal-importing countries. In 2009Q1, the US 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) that made it economical for many power plants to switch away from coal and towards natural gas given the availability of ready-to-use idle gas-fired capacity (Lafrancois 2012).[1]

1 In June of 2008, the average monthly price of gas paid by US 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

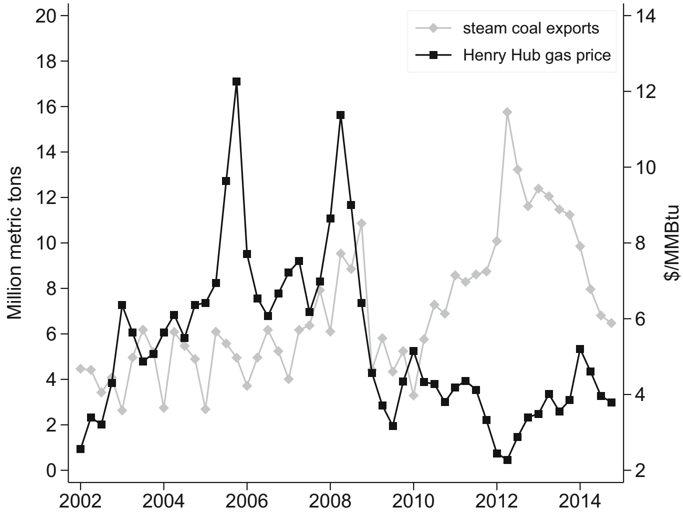

FIGURE 1 US coal exports and domestic price of natural gas
NOTES: The quarterly gas price is an average of EIA monthly prices for the Henry Hub benchmark. The quarterly exports of coal are from the EIA International Energy Statistics. For additional details, see section 2.1.

The changing landscape in the US electric power sector due to the boom, has two main effects on the trade flows of coal around the world. First, there is a decrease in the domestic demand for coal. Second, there is an increase in the export supply of US coal because domestic producers are looking for alternative markets to sell their product. Translating these domestic comparative statics to comparative statics of flows of coal around the world in order to assess the extent of emissions leakage is ultimately an empirical question. The answer depends on export supply and import demand elasticities, whose magnitude is determined by several factors. The US export supply elasticity is affected by the ability of domestic coal producers to ship coal outside the country, which depends on the country's rail and port infrastructure. The import demand elasticities for US coal in major consuming regions, such as Western Europe, China, Japan and Korea, depend on the availability of close substitutes.

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 US Energy Information Administration (EIA) has been collecting data. See `www.eia.gov/todayinenergy/detail.php?id=6990`. The widespread coal-to-gas switching throughout the industry 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 boom.

The implications of an increase in exports of US coal for emissions associated with the coal trade are ambiguous. They depend both on the aggregate level (level effect) and on the composition (composition effect) of world trade flows. For example, an increase in US coal exports may lead to a moderate or no increase in emissions elsewhere if US coal simply displaces domestically produced 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.

Our empirical assessment of the boom's implications on emissions associated with coal trade flows is based on an econometric model with an international component and a domestic component. The first component draws from the trade literature. Following Soderbery (2018), we estimate upward-sloping export supply curves, which is a notable departure 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 US coal exports. We then construct counterfactual coal trade flows in the absence of the boom, which we model as a negative shock to the US export supply. Importantly, given that the international gas markets are much less integrated compared with those for other fossil fuels because long-distance trade of gas becomes uneconomical quite quickly, the US gas prices decoupled from those in the rest of the world following the boom (Arezki et al. 2017). Such decoupling is a key component of the counterfactual exercise in the paper.

We allow export supply elasticities to exhibit heterogeneity across importers, goods, and exporters, in contrast to Feenstra (1994) and Broda and Weinstein (2006). 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 trade literature, a variety is defined by the country of supply for a particular good (Armington 1969).[2] While the Broda and Weinstein (2006) approach is better suited than the gravity models for our analysis, the 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 (US) export supply curve and then propagates to the rest of the world. We examine the implications of such heterogeneity in export supply elasticities for our counterfactual analysis in detail.

The second component of our econometric model links US coal production to the domestic price of gas. The trade model allows us to estimate import

2 For example, US bituminous coal is a different variety from Australian bituminous coal.

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 US price for gas through the US export supply curve. Using panel data, we identify and estimate this causal link and separate the boom shock from other shocks that affect all exporters simultaneously in the international coal market.

We calculate counterfactual world coal trade flows by eliminating the drop in the US price of gas caused by the boom capitalizing on the decoupling of the US price of gas from gas prices around the world. Then, using information on the heat, carbon dioxide (CO_2) and sulphur dioxide (SO_2) content of coal, we translate these trade flows into emissions to assess the environmental impact of the boom.

For our trade model, we use the nonlinear estimator in Soderbery (2018) and UN Comtrade data between 1990 and 2014 to estimate import demand and export supply elasticities, as well as shocks to the export supply curve for US coal. We then use the first-order conditions of the domestic model to link these shocks to the domestic price of gas in the US We estimate the relationship between the price of gas in the US and Europe for 1990 to 2006 and use it to construct counterfactual US gas prices for 2007 to 2014. Our assumption is that these counterfactual prices are the ones that would have prevailed in the absence of the boom (decoupling). The counterfactual US gas prices allow us to construct counterfactual shocks to the US export supply curve that translate into counterfactual coal trade flows around the world.

We report detailed results regarding our counterfactual analysis of trade flows for about 40 countries that account for more than 90% of global coal imports and exports during the period of interest. The same group of countries also accounts for more than 90% of imports of US coal. We find a small level effect—the total quantity (metric tons) of coal traded is only 0.14% lower than the actual quantity traded in the absence of the boom. The price (USD/metric ton) and total dollar value of coal increase by 0.37% and 0.24%, respectively. Moreover, after accounting for heterogeneity in the heat and sulphur content and changes in the equilibrium of the global coal market, total CO_2 and SO_2 emissions associated with coal trade flows also remain virtually the same—hence, the composition effect is also small. Therefore, and in contrast to commentary around the time of the surge in US coal exports, we show that US 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 21.3% (18.7%) in the quantity (dollar value) of US coal exports with US coal exporters losing $15.4 billion in revenue. Although the overall decrease in US coal imports is 21.3%, several major importers experience a decrease in coal quantity between 43% (Korea) and 71% (Japan). In all, most of the decrease in US exports of coal is compensated by exports from other countries, resulting in small changes to coal consumed worldwide. Our main results are qualitatively the same when we allow for substitution between domestically produced and imported coal.

The paper contributes to the scarce literature on the global environmental effects of country-level energy shocks.[3] Our work is most closely related to Wolak (2016). Wolak uses a spatial equilibrium model to assess the boom's impact on global coal market outcomes accounting for coal-to-gas switching in the electricity sector in the US and Europe, the potential for China to exercise buyer power and the impact of increasing the coal export capacity of Western US ports. Wolak's 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 only North America and Western Europe. 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. A version of our model with limited heterogeneity in export supply elasticities has material implications for our counterfactuals.

The paper also contributes to the 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 gas prices on US coal exports and finds that a 1% increase in the domestic price of gas leads to a 2.2% decrease in US coal exports. According to his findings, approximately 75% of the displaced US steam coal used in electricity generation was shipped abroad. Although an interesting exercise, Eyer's analysis does not allow for substitutability between US and other coal exports, which are important for the global balance of coal trade and the associated environmental implications. Other papers in this strand of the literature include Arezki et al. (2017) and Shapiro (2016). Arezki et al. find that the US energy-intensive manufacturing sectors benefited from the reduced gas prices due to the boom.[4] A back-of-the-envelope

3 There is a rich literature on international trade and the environment, which is recently reviewed in Cherniwchan et al. (2017). The authors emphasize a novel decomposition linking changes in emissions to changes in productive activity at the plant, firm, industry and national levels based on a Melitz-type approach. In general, the effect of trade on the environment is theoretically ambiguous. For example, the race-to-the-bottom hypothesis (negative effect) competes against the gains-from-trade hypothesis (positive effect). Frankel and Rose (2005) find that trade tends to reduce air pollution; in particular, sulphur dioxide and nitrogen dioxide emissions.

4 As discussed earlier in this section, one of the main points in the paper by Arezki et al. is that natural gas markets are much less integrated compared with markets for other fossil fuels. As a result, in the aftermath of the boom, US gas prices fell sharply and decoupled from those in the rest of the world.

calculation suggests that energy-intensive manufacturing exports increased by about \$100 billion in 2012 because of the boom. Shapiro finds that the benefits of international trade exceed environmental costs because of 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).[5]

An additional contribution of the paper is to the carbon leakage literature. We focus on only the so-called energy market channel, which is often found to be the main driver of carbon leakage overall and the most difficult to address without global carbon pricing (Cosbey et al. 2019). In its "textbook" version, the main leakage driver through the energy market channel is the reduced demand for fossil fuels in regions adopting environmental regulations that drives down the world price of fossil fuels, which in turn increases fuel consumption and carbon emissions in non-regulated parts of the world. In our case, the reduced domestic demand for US coal—and the associated increase in export supply along with the potential increase in coal consumption elsewhere—is attributed primarily to the drop in the domestic gas price despite the simultaneous development of environmental policy aiming to reduce coal use in the US electric power sector.

We also need to recognize the limitations of the paper. The paper is about the emissions leakage effect via international coal trade. It is not on the global environmental effect of the net change in coal consumption—for example, US domestic coal consumption is not considered in the analysis. Second, the paper does not analyze the boom's effects on emissions from gas and oil consumption by considering trade shifts in these fossil fuels, which might lead to a more significant non-US effect of the boom than that via the international coal market alone. Third, we abstract away from the boom's impact on the development of renewable energy and we do not speak to the concern that cheaper gas (fossil fuels in general) may slow the growth of cleaner sources of energy such as wind and solar.

The remainder of the paper is organized as follows. In section 2, we provide a background on US 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 US 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

5 Richter et al. (2018) discuss a multi-period equilibrium model of the international steam coal market to study a tax on steam coal. A unilateral export tax (levied by Australia, a major exporter, alone) has little impact on global emissions and global coal prices as other countries compensate for reduced export volumes from the taxing country. By contrast, a tax jointly levied by a coalition of major coal exporters would significantly reduce global emissions from steam coal and leave them with a net sector level welfare gains.

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 online appendix.

2. Background

2.1. US coal

Production: The US 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. According to figures from the World Energy Council for 2011, the US accounts for 28% of global recoverable coal reserves followed by Russia (18%) and China (13%). Ten countries account for more than 92% of global reserves.

Coal is an organic rock that contains 40% *to* 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. 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 to 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 to 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 to 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 to 28 MMBtu. In the US, it is extracted only in northeast Pennsylvania. Between 1994 and 2015, bituminous and sub-bituminous coal accounted for 93% of annual US production (tons), while anthracite accounted for less than 1% (EIA, Annual Coal Review).

Exports: Coal consumption by the US electric power sector from 2004 to 2008 was close to 1 billion short tons, its highest levels since 1992. By 2012, it fell to 824 million short tons. This drop in coal consumption and associated emissions has been attributed to the drop in gas prices, the slowdown of the economy due to the Great Recession, a series of regional and federal environmental regulations aiming to curb coal-related emissions and the increased penetration of renewable sources.[6] This contraction of the domestic market was accompanied by the surge in exports of US coal documented in figure 1,

6 For the role of the Great Recession, see the discussion starting on page 194 in ERP (2013). Fell and Kaffine (2018) show that gas prices and wind generation jointly account for the vast majority of the observed decline in generation and

FIGURE 2 US coal production, consumption and exports
NOTES: The production and consumption data are from the EIA monthly coal production and the EIA International Energy Statistics, respectively. We calculate exports as a percentage of production using EIA and census data. For additional details, see section 2.1.

attracting increased attention in the popular press.[7] As a result, the exports' share in production increased from 5.3% to 12.5% (figure 2).[8]

emissions. Coglianese et al. (2020) estimate that the declining price of gas relative to coal is responsible for 92% of the total decline in US coal production over the period 2008 to 2016 and that environmental regulations account for an additional 6% with other factors making small and offsetting contributions.

7 As an example, the *The New York Times* published an article by Andrew Revkin entitled, "U.S. Push to Export Dirty Fossil Fuels Parallels Past Action on Tobacco," in Februaryn2014.

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

2.2. International trade

According to the EIA international energy statistics, world coal consumption increased from around 5 billion metric tons in 1990 to more than 7.5 billion metric tons by 2012 (online appendix figure A1, panel (a)).[9] 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.[10] 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. Approximately 40 countries account for more than 90% of total exports, total imports and imports of US coal during this period (online appendix table A2). For several of these countries (e.g., Canada), there is substantial cross-hauling, a feature of coal trade that our model can accommodate.

Australia, Indonesia, the US, 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 online appendix figure A1 accounted for more than 80% of all coal exports from 1990 to 2012. Australia, Indonesia, Russia and the US accounted for about 70% of total coal exports (tons) for 1990 to 2014 (online appendix table A3). Ten countries accounted for more than two thirds of annual world coal imports from 1990 to 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 to 2014. India's share increased from less than 10% in 2010 to about 20% in 2014, while none of the remaining countries accounted for more than 5% during the same period (online appendix table A4). Canada, Japan, Brazil, Italy and Great Britain, accounted for half of the imports of US coal from 1990 to 2014 (online appendix table A5).[11]

9 We use ISO Alpha 3 country codes to identify countries in various tables and figures. See online appendix table A1.

10 Based on annual figures from the IEA Coal Information 2014 (see table 3.1).

11 There is no doubt that the carbonization of the global energy system poses a severe challenge for efforts to reduce carbon emissions. Although coal was central to the industrial revolution, it was increasingly superseded by oil and gas in 20th century. However, in recent years coal again has become the predominant source of global carbon emissions. Steckel et al. (2015) show that this trend of rapidly increasing coal-based emissions is not restricted to a few individual countries such as China. Instead, it is due to global renaissance of coal driven by poor, fast-growing countries that increasingly rely on coal to satisfy their growing energy demand. The low price of coal relative to gas and oil has played an important role in accelerating coal consumption since the end of the 1990s.

Online appendix figure A2 shows the annual time series of the quantity (million metric tons), value (billion USD) and price (USD/metric ton) based on UN Comtrade import data for the three types of coal used in estimating our international trade model: anthracite, bituminous and other coal, which includes sub-bituminous coal and lignite.[12] 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 between 2009 and 2010 because of the recession.[13]

Import prices paid for coal in China, India, Japan and Korea, are highly comparable and follow the same pattern over time, especially prior to 2005 (online appendix figure A3, panel (a)). The import prices paid in major European markets, such as Germany, Great Britain, the Netherlands and Spain, also track each other closely and are comparable to those in Asia (panel (b)). In general, the price spread between the European and Asian markets is small. Import prices for coal originating from major producing countries, such as the US, Australia, Indonesia, Russia, Colombia, Canada and South Africa, track each other closely (panels (c) and (d)).

3. Model

In what follows, we first describe our international trade model and we then link it to a model of the US domestic market for coal. In the case of the international trade model, we maintain common assumptions from the new trade theory in a model that is amenable to structural estimation. We bring the model to the data following common functional forms and the estimation strategy in Soderbery (2018). The stylized model for the US domestic production of coal allows us to establish a link between the US coal export supply shock and the domestic price of gas.

12 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 Harmonized System (HS), 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. According to the IEA (`www.iea.org/fuels-and-technologies/coal`), both sub-bituminous and lignite are used in electricity generation.

13 Online appendix section A.2 provides information regarding the primary destinations (sources) of bituminous coal for major exporters (importers).

3.1. International trade

To introduce some notation, we use I to denote the importing country, g to denote the imported good and v to denote the variety of the imported good. The total number of goods imported by country I is G^I and the total number of varieties is G_v^I. Goods are defined by their Comtrade HS6 code and their varieties are determined by their country of origin. A good is one of three types of coal: anthracite, bituminous and other. Following the Armington tradition, US bituminous coal imported in, say, Japan is a different variety from Australian bituminous coal imported in Japan because of physical characteristics, such as heat content (calorific value), sulphur content, ash content, moisture, etc.[14]

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

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

$$Q_{gt}^I \equiv \left(\sum_{v=1}^{G_{vt}^I} (b_{gv}^I)^{\frac{1}{\sigma_g^I}} (q_{gvt}^I)^{\frac{\sigma_g^I - 1}{\sigma_g^I}} \right)^{\frac{\sigma_g^I}{\sigma_g^I - 1}}, \tag{2}$$

where Q_{gt}^I is the CES aggregate consumption of imported coal varieties assuming G_{vt}^I varieties and G_t^I is the total number of goods. Additionally, $\sigma_g^I > 1$ is the elasticity of substitution across coal types and b_{gv}^I are demand shocks (shifts) that capture variety-specific tastes. For example, b_{gv}^I 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 because of its coking properties and its sulphur content, respectively. Because of the Cobb–Douglas preferences across coal types, the expenditure for coal type g accounts for α_{gt}^I of the total expenditure associated with the purchases of imported coal.

Although we model preferences similar to Shapiro (2016), our approach generally departs from his. Shapiro focuses on emissions due to trade of a wide range of goods. We focus on emissions associated with coal trade alone.

14 We use the following 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 only the US and Australia, $G^I = 3$ and $G_v^I = 6$.

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.

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 equation (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. In particular, export supply curves are variety- and exporter-specific with an (inverse) 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 US gas prices affect the world coal trade flows. The US shale gas boom (boom) serves as a positive shock to the US coal export supply curve. Given estimates of the import demand, σ^I_g, and inverse export supply, ω^I_{gv}, elasticities, we calculate the demand and supply shocks using equations (3) and (5). We then use the firms' profit-maximizing first-order conditions from the domestic model to link US gas prices to world coal trade using 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:

$$U^I_t = (Q^I_{dt})^{\alpha^I_{dt}} \prod_{g=1}^{G^I_t} (Q^I_{gt})^{\alpha^I_{gt}}. \tag{6}$$

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 domestically produced coal. In a subsequent section, we show that the qualitative conclusions of our analysis hold when we allow for substitutability between domestically produced and imported coal.

The setup discussed so far does not allow for substitution between coal and gas, which is relevant for electricity generation, either. Wolak (2016) argues that such substitution is possible only in North America and Western Europe because of the availability of gas supplied by pipelines and the 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. US domestic market

We now sketch the stylized model for the US domestic production of coal, which allows us to establish a link between the US coal export supply shock and the domestic price of gas. In particular, we consider a representative firm that extracts coal for sale in the international (f) and domestic (d) markets at time t with (p^c_{ft}, q^c_{ft}) and (p^c_{dt}, q^c_{dt}) being the corresponding prices and quantities. The representative firm is a price taker in the foreign market but faces a downward-sloping residual demand curve in the domestic market. The domestic inverse demand for coal is a function of the domestic gas price, p^g_{dt}, and a demand shifter, w_{dt}, to account for additional factors driving the demand for coal, such as fossil-fuel generation by electric power plants. Assuming linearity, we write

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

where $\theta \equiv (\theta_0, \theta_1, \theta_2, \theta_3)'$. The motivation for the domestic inverse demand curve stems from the fact that electric power plants account for the vast majority of coal consumption and natural gas is the closest substitute for coal during the period that is relevant in our analysis.[15]

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 between the domestic and

15 In equation (7), we remain agnostic on whether p^c_{dt} pertains to spot or contract (long-term) coal prices in the US. domestic market noting that most of the coal purchases by US power plants are under long-term contracts; see, e.g., `www.eia.gov/energyexplained/coal/prices-and-outlook.php`. In general, we would expect the response of coal purchases with long-term contracts (hence, prices) to gas prices to be smaller in magnitude than those of coal spot purchases. Hence, estimating equation (7) using spot coal prices would entail coefficients that would be larger in magnitude than their counterparts using contract prices. To avoid any confusion, we should emphasize that we do not estimate equation (7). This equation is a component of the US Domestic Market model that rationalizes the reduced-form equation (21), which we estimate and which is discussed in detail in section 4.2. The dependent variable in equation (21) is the variety-specific shock to the inverse export supply estimated using our trade model and Comtrade prices paid by the importers.

foreign markets is not possible, the two markets are related through production costs:[16]

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

where $\gamma \equiv (\beta_0, \beta_1, \alpha_d, \alpha_f)'$. The parameters α_f and α_d introduce convexity assuming $\alpha_f > 1$ and $\alpha_d > 1$. The interpretation for the functional form in equation (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.[17]

Based on the assumptions above, the firm's profit-maximization problem is as follows:

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

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

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

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

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

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

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

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

16 By assuming away arbitrage, we assume either no difference between the price (including transportation costs) of US coal and the domestic price of coal in an importing country (e.g., Japan or Netherlands) or a difference that cannot be eliminated because of frictions (e.g., long-term contracts, transportation costs, port and rail capacity constraints). In the presence of long-term contracts, limited port capacity and high transportation costs, the effect of lower US gas prices on US coal exports would be smaller compared with the case in which these frictions are eliminated, all else equal.

17 In online appendix section A.4, we discuss two alternative functional forms for the cost function that allows a link between the domestic and foreign coal markets.

In the special case of $\beta_1 = 1$, which maintains 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

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

Given the nature of the profit-maximization problem, knowing the optimal level of domestic production allows us to infer production for the foreign market using equation (11), which we write as

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

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 equation (10), we establish a link between the domestic and foreign markets as follows:

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

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

$$exp(\eta^I_{gvt}) = \beta_1 \alpha_f (H(p^g_{dt}, w_{dt}; \theta, \beta_0))^{\alpha_d}. \tag{20}$$

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), our key identifying assumption 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 2SLS estimator, which uses 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 NLSUR estimator accommodates heterogeneity 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.

For our NLSUR estimation, we need only bilateral trade flows associated with country pairs for the three types of coal, which are readily available from the UN Comtrade database. From 1990 to 2014, which is the period we study, 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. The former exhibit variation by origin (exporting country) and coal type for each importing country (ω^I_{gv}). The latter exhibit variation by importing country and coal type only (σ^I_g).[18] Following the elimination of observations associated with 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.[19]

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 small countries in the same region have identical export supply technologies.[20] Although this is a restrictive assumption, it still allows for substantial heterogeneity in our estimates. Importantly, because of 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.

18 For example, although we estimate a different inverse export supply elasticity for US and Australian bituminous coal for Japan, we estimate a single import demand elasticity for bituminous coal. From 1990 to 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.

19 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.

20 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 (online appendix table A3), have the same export supply elasticities for bituminous coal because they all belong to the region we define as Asia (ASA) (see online appendix table A6). We follow an analogous approach for small importers to reduce the number of import demand elasticities (see online appendix table A7.

TABLE 1
Inverse export supply and import demand elasticities

	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

NOTES: 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. For additional details, see section 4.1.

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^I_{gv}) and import demand (σ^I_g) elasticities for the three types of coal.[21] 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, respectively.

Table 2 provides summary statistics for ω and σ for major importers in the case of bituminous coal. It also provides information about the size of the importing country in terms of GDP and its imports in both USD and tons.

21 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.

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

NOTES: 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 to 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. For additional details, see section 4.1.

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	0.768	339.881	3792.081	0.279	0.259	0.291	3.867
02-IDN	BIT	0.364	95.080	1355.568	0.225	0.272	0.166	3.678
03-RUS	BIT	0.987	88.663	955.471	1.223	0.910	1.458	1.099
04-USA	BIT	13.202	88.035	829.707	0.580	0.132	1.814	7.572
05-CAN	BIT	1.251	70.791	702.655	0.347	0.348	0.165	2.870
06-COL	BIT	0.136	43.407	607.324	0.331	0.196	0.433	5.111
07-CHN	BIT	2.668	32.391	585.872	0.316	0.275	0.094	3.634
08-ZAF	BIT	0.255	29.027	461.395	0.796	0.200	1.410	5.009
09-POL	BIT	0.339	13.477	216.958	0.150	0.118	0.060	8.447
10-KAZ	BIT	0.077	2.167	20.397	0.140	0.132	0.021	7.571

NOTES: 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 to 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. For additional details, see section 4.1.

The standard deviation of ω highlights the degree of heterogeneity in the curvature of the supply curves of the exporters serving a particular importer. Table 3 provides summary statistics for ω for major exporters along 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. For China, the median ω is much smaller compared with 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.

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 US, Kazakhstan and Poland are the least exposed to importer buyer power with median ω values in the tight range 0.12 to 0.13 (table 3). For Australia, Indonesia, Colombia and South Africa, the median ω values are 0.19 to 0.27. Both 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.

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's imports of bituminous coal are from Kazakhstan and the US, 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: US, Australia, Colombia and, to a lesser extent, Canada. Hence, there is a 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: 4.21 and 4.36, respectively. For both countries, there is also a plethora of exporters—Australia, Indonesia, China, Canada, Russia and the US—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.[22]

22 As we discuss in online appendix section A.5, our inverse export and import demand elasticity estimates are comparable to others in the literature.

4.2. US domestic market

The domestic model provides the equation that relates the estimated export supply shock, $exp(\widehat{\eta}^{I}_{gvt})$, to the US price of gas in equation (20). In a fully structural model, the functional form for $H(\cdot)$ in equation (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 US coal producers as we discussed in section 3.2. For the purpose of our counterfactuals, and aiming to allow some flexibility in this important relationship, we estimate via OLS the following model:

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

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, $h(\cdot)$ is the logarithmic transformation of $H(\cdot)$ and u_{gvt} is the econometric error. Furthermore, μ_{Igv} is an importer-exporter-by-coal-type fixed effect, μ_t is a year fixed effect, p_t is the US 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. The annual frequency is due to the Comtrade data used to obtain $\widehat{\eta}^{I}_{gvt}$. The domestic gas price directly affects only the US export supply curves. Furthermore, we expect positive slope coefficients, such that an increase in the US price of gas shifts the US export supply curve to the left.[23]

According to table 4, the slope coefficients in equation (21) have the proper signs. The gas price is estimated to have a positive effect on the US coal export shocks in the case of bituminous coal. The effect is significant at 1% level. The coefficients for anthracite and other coal are not statistically significant at conventional (less than or equal to 10%) levels. These findings are consistent with the fact that bituminous coal is a closer substitute

23 A potential concern about the model in equation (21) is that we do not control for US environmental policy in the electric power sector, which is correlated with the US price of gas and is part of w_{dt} in equation (20). The correlation should be fairly strong because the electric power sector has accounted for 25% of the annual US 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 US price of gas and US environmental policy because lower gas prices allow more aggressive policies, such as stricter emission standards for coal-fired plants. The dependent variable in equation (21) is the intercept of a constant elasticity inverse export supply curve, which is expected to be negatively correlated with the US 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.

TABLE 4

Regression of export supply shocks on US natural gas prices

Variable	
US gas price × BIT	0.0695***
	(0.0215)
US gas price × ANT	−0.0701
	(0.2111)
US gas price × OTH	0.0108
	(0.0327)
R-squared	0.9632
Observations	11,966

NOTES: We report the results from the regression in equation (21) of 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 equation (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%. For additional details, see section 4.2.

for gas. With these estimates in hand, we now proceed to the counterfactual analysis.[24]

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 US price of gas due to the shale gas boom (boom). We assess the implications of the decrease in the price of gas by comparing actual and counterfactual values of economic variables of interest, such as prices, quantities, dollar sales and consumer welfare. In addition, we compare the actual and counterfactual carbon dioxide (CO_2) and sulphur 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 US is higher. Second, the counterfactual demand for gas in the US electric power sector is lower than the actual demand. Due to substitutability between coal and gas, there is an

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

increase in the US domestic demand for coal that is served by the domestic supply and plays the role of a negative shock to the US coal export supply curve.[25] Importantly, our trade model allows for US 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 US price of gas (p^g_{dt}) in section 4.2, we compute counterfactual export supply shocks and simulate the counterfactual trade flows using equation (20) and the counterfactual US price of gas, $p^g_{dt,CF}$. In particular, using p^g_{dt} and p^g_{et} to denote the US Henry Hub and the Europe import border gas prices from the World Bank Pink Sheets for 1990 to 2006, we calculate counterfactual prices using the following equation based on the well-documented evidence on the post-boom decoupling of the US gas price from gas prices elsewhere in the world (Arezki et al. 2017):

$$p^g_{dt,CF} = \begin{cases} p^g_{dt}, & t = 1990, \ldots 2006 \\ \widehat{\lambda_0} + \widehat{\lambda_1} p^g_{et}, & t = 2007, \ldots 2014, \end{cases} \tag{22}$$

where $\widehat{\lambda_0}$ and $\widehat{\lambda_1}$ are the OLS estimates from the following regression:

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

Figure 3 shows that the difference between the actual and counterfactual US gas prices is most notable in 2011 and 2012 with the counterfactual prices being almost three times as high as the actual prices. Overall, in the absence of the boom, the average price from 2007 to 2014 is 136% higher. As a side note, assuming that European gas prices would have been higher in the absence of the boom because of less-intense competition from US coal exports, then our estimated counterfactual gas prices are biased downward and we underestimate the difference between actual and counterfactual prices.[26]

To calculate the counterfactual global coal trade equilibrium, we first need to calculate the changes in US exports to every importing country and then calculate how competing exporters respond to changes in the prices and quantities of US coal exports. The trade model from section 3.1, provides

25 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.

26 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 nine-fold increase) than the ones reported here.

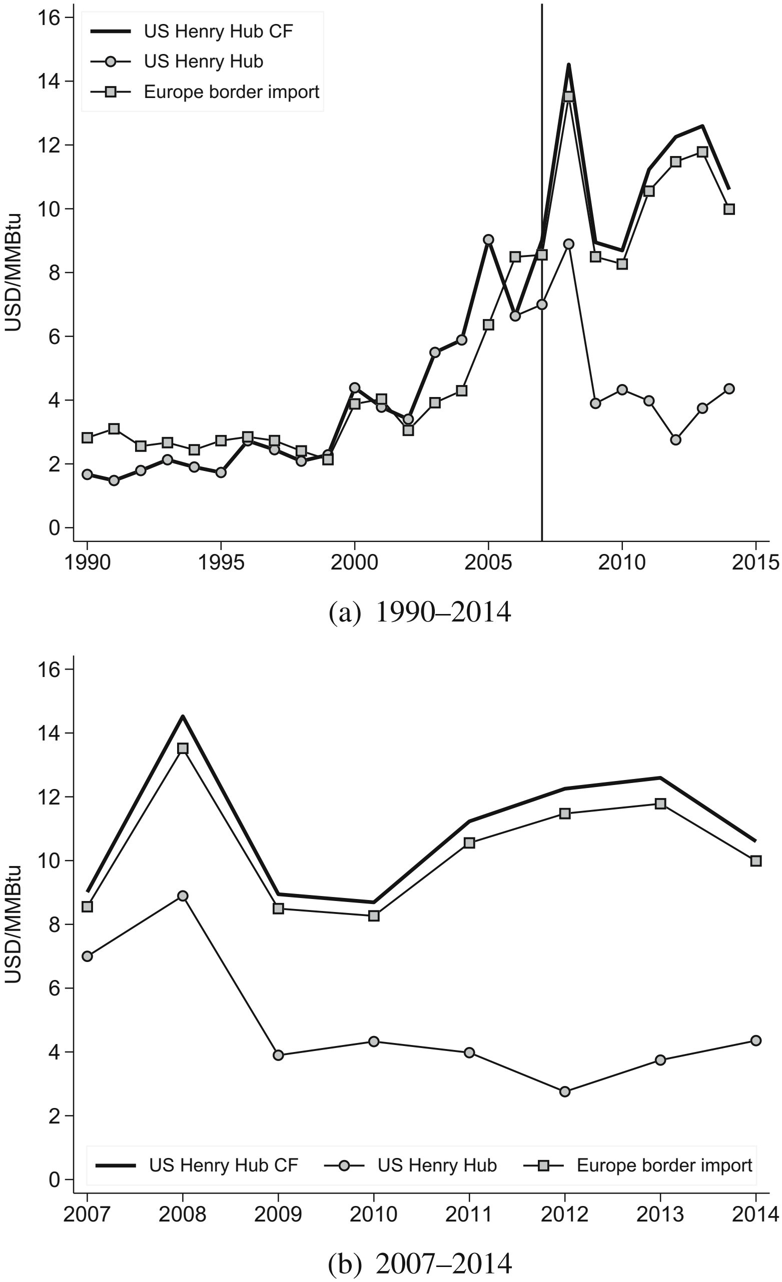

FIGURE 3 Counterfactual analysis: US gas prices
NOTES: In panel (a), the annual average of the US Henry Hub, the Europe border import and the Japan LNG gas prices are from the World Bank Pink Sheets. The counterfactual Henry Hub gas prices are constructed following the approach in section 5.1. Panel (b) shows the three prices during the period that is relevant for our counterfactual analysis (2007–2014).

estimates of the import demand (σ_g^I) and inverse export supply (ω_{gv}^I) elasticities. Given our estimates, prices and quantities 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 CES price index $\mathcal{P}_{gt}^I$ in equation (3).[27]

The first economic variable of interest is the change in the price index for coal imports implied by the change in the US 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 US 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:

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

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

where $\Delta\eta_{gvt}^I \equiv \eta_{gvt,CF}^I - \eta_{gvt}^I$. Non-US exports are affected only by changes in the price index in each importing country because $\Delta\eta_{gvt}^I = 0$ for non-US coal exports. US exports 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—not accounting for emissions—using standard expressions for the Cobb−Douglas family of utility functions given the functional form in equation (1). The equivalent variation (EV) is 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) is 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.

27 Online appendix table A8 provides summary statistics for the exponentiated actual and counterfactual supply shocks for major importers of US 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 US exports are smaller than the actual US exports at all price levels.

5.2. Economic outcomes

The first message of our counterfactual analysis is that the increase in US coal exports because of the boom displaced other coal exports, with the global coal trade remaining essentially unchanged. A second message of our counterfactual analysis is the large decrease in the imports of US coal in several Asian and Western European countries.

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. The comparison of actual and counterfactual outcomes is limited to the period 2007 to 2014, and the difference is due to the increase in the US domestic price of gas in the absence of the boom. We also aggregate across the three types of coal and we calculate differences as counterfactual minus actual values.

Our counterfactual results are based on an export shock in bituminous coal only. This is because anthracite and other coal do not appear to respond to changes in the US price of natural gas (table 4), which is consistent with bituminous being the type of coal that is a closer substitute for 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.[28]

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 online appendix figure A4 show the differences between actual and counterfactual quantities and prices by year. Hence, and contrary to commentary at the time of their peak during the boom, US coal exports simply displaced other coal exports, with the global coal trade in terms of tons and dollars remaining essentially the same.

More specifically, the counterfactual quantity of non-US coal is 1.66% higher, while that of US coal is 21.34% lower. The prices of US coal increase by 3.4%, while those of non-US coal increase by 0.63%. The pattern of the increase in the exports of countries other than the US 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 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 are 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

28 Online appendix table A18 shows that the results discussed here remain essentially the same if we exclude anthracite, which is not used for electricity generation, from our calculations.

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

NOTES: 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 US shale gas boom. For additional details, see section 5.2.

counterfactual outcomes, 4.38% and 5.09%, respectively (online appendix table A9). 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.

Focusing on imports of US coal, as discussed earlier, there is a decrease of 21.3% in quantity and 18% in value across all importers in the absence of the boom. There is also an increase in price of 3.4%. We see the largest percentage decrease in quantity for Japan (almost 71%), followed by China, Korea, the Netherlands and Italy, which all experience a decrease in the 43%-49% range in the absence of the boom (online appendix table A10). For Germany, Great Britain, Russia and Brazil, the change in prices and quantities of US 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 US. Australia and Indonesia are the dominant exporters accounting for 80% of Japan's imports. The US accounts for just 2% of Japan's imports. In the absence of the boom, 90% of US 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 US, South Africa and Russia, with the four countries accounting for 85% of the country's imports, and the US enjoying a share of 18%. Close to 60% of the 16 million metric tons of US 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 US coal.[29]

We conclude our discussion in this section by describing the welfare effects of the boom associated with the consumption of imported coal using equivalent and compensating variation. We summarize these welfare effects in online appendix table A13, where positive entries imply that consumers in the importing countries are worse off in the absence of the boom noting that we do not account for emissions.[30] Across all importers, the equivalent variation (EV) is \$19.1 billion, while the compensating variation (CV), as expected

29 Online appendix table A12 provides a breakdown of the change in economic outcomes for non-US coal by major importer. In the absence of the boom, Italy and the Netherlands experience the 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.

30 The rightmost column in online appendix table A13 shows the percentage change in the constant-elasticity-of substitution (CES) price index, $100 \times \Delta ln(\mathcal{P}^{I}_{gt})$, in the absence of the boom that is calculated using equation (24). We report a weighted average of the index for each of the major importers. As a reminder, the index exhibits variation by importer, type of coal

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.

5.3. Environmental outcomes

Even a small aggregate effect of the boom in terms of coal quantities may have a significant impact on emissions. This would be the case if, say, Australian or Indonesian coal displaces US 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 sulphur dioxide (SO_2) content of the coal trade flows, we need the heat and sulphur content—henceforth, specifications—of the various types of coal traded around the world.

Ideally, we would like to know the specifications of anthracite, bituminous and other coal for each of the exporting countries for 2007 to 2014, which is a rather demanding task. Online appendix section A.3 outlines our approach to collect information from three different sources regarding coal specifications 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 lb of CO_2 per MMBtu of coal. The calculation of SO_2 in lb per MMBtu of coal is also straightforward once the sulphur content is known.[31]

We first assume a constant heat and SO_2 content independently of the coal's country of origin: 21 MMBtu per metric ton and 1.3 lb/MMBtu. 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 provides a detailed breakdown by exporter. 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 (Interagency Working Group 2013), 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. Similarly, using 1.3 lb 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.

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and year. Online appendix figure A5, 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 from 2011 to 2013.

31 For example, assuming a heat content of 12,000 Btu/lb and a sulphur content of 3%, the SO_2 content of coal is $(0.03 \times 2)/0.012 = 5.0$ lb/MMBtu. Note that 2 is the atomic mass of sulphur dioxide divided by the atomic mass of sulphur. The denominator is due to the fact that there are 10^6 Btu in a MMBtu.

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

NOTES: 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 US shale gas boom. For additional details, see section 5.3.

In the case of coal exports from the US, 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 associated with the US coal exports as we move from actual to counterfactual outcomes; from 7.2 to 5.7 million metric tons. The difference between these actual and counterfactual emissions are useful to calculate the environmental benefits for US consumers associated with US coal shipped elsewhere during the boom for a rather pessimistic scenario. In a nutshell, the US coal shipped elsewhere would have been used by US electric power plants that substituted away from coal and towards gas. 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 and local pollutants such as NO_x and particulate matter. We should also highlight the fact that importers of US coal experience a decrease in both CO_2 and SO_2 emissions of 21.3% based on the decrease in coal quantity discussed earlier.

In figure 4, aiming to capture the composition effect of the boom on emissions, we refine our calculations of both CO_2 and SO_2 emissions using the heterogeneity in heat and sulphur content reported in online appendix tables A14 and A15. 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

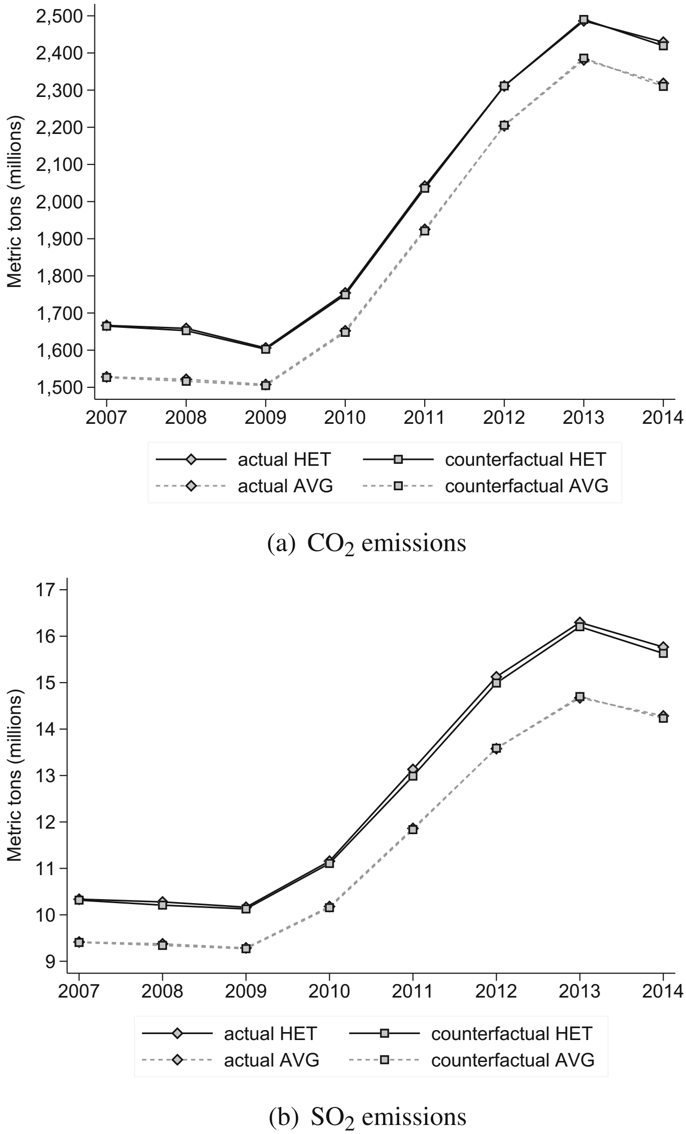

FIGURE 4 Counterfactual analysis: environmental outcomes, 2007–2014
NOTES: Panel (a) shows CO_2 emissions using an average heat content of 21 MMBtu per metric ton of coal (AVG) as opposed to the heterogeneous heat content (HET) in online appendix tables A14 and A15. Panel (b) shows SO_2 emissions using an average SO_2 content of 1.3 lb 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 in online appendix tables A14 and A15. For additional details, see section 5.3.

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.

6. Additional discussion, extensions and checks

6.1. Armington assumption and coal varieties

Based on the Armington assumption underlying our import demand and export supply estimates, coal varieties are defined as type (anthracite, bituminous and other) and country-of-origin combinations. One may raise two issues with the way we define coal varieties that may have implications for the estimated elasticities and, hence, our counterfactuals. First, our model does not account for the fact that there is substantial heterogeneity in the heat and sulphur content of the same coal type produced in the same country; for example, we do not distinguish between, say, low- and high-sulphur US bituminous coal. Second, non-US coal of a particular type (e.g., Australian bituminous coal) is not a perfect substitute for US coal of the same type with the same heat and sulphur content.

Regarding the first of the two points about our definition of coal varieties and its implications for our estimated substitution patterns, it is infeasible to link "within-country" heterogeneity in the heat and sulphur content of coal in a credible way to the publicly available Comtrade data used for estimating the import demand and export supply elasticities. In other words, we cannot account for, say, high-sulphur US bituminous coal produced in the Northern Appalachia from low-sulphur US bituminous coal produced in the Central Appalachia in the Comtrade data.[32] For the second point, our estimated elasticities should capture coal varieties that are close substitutes, as it would

32 We are not implicitly assuming all varieties within a country are perfect substitutes. Rather, we are assuming they all follow the same CES substitution patterns. If this implicit assumption holds, then introducing varieties accommodating the within-country heterogeneity discussed here would have no effect on our analysis. If this assumption is too strong, another perspective, which is our preferred given the data and model, is that we are estimating the substitution between bundles (Armington-type CES aggregates of the within-country varieties) across countries. Assuming that the composition of these bundles is stable over time, our analysis is qualitatively the same as the one in which we would be able to estimate demand elasticities for every variety in every country. Importantly, even if the most granular (HS10 level) coal trade data were available in the Comtrade database for all countries in our sample, these data would not accommodate the within-country heterogeneity discussed here.

be the case for US and Australian bituminous coal with the same heat and sulphur content.[33]

In general, it is difficult to know a priori the implications for our NLSUR estimates of import demand and export supply elasticities and counterfactuals of a different dataset that would capture the heterogeneity discussed above. Recall that Soderbery's NLSUR estimation employed in this paper is based on a *system* of demand and supply equations (equations (5), (6), (8) and (9) in Soderbery 2018) that deliver estimates of both demand and supply elasticities.[34]

As for the implications of a different dataset for our counterfactuals, it is important to track its implication for the various components of our calculations. The first component is the variety-specific shock to the inverse export supply curve in equation (21). This shock depends on the inverse export supply elasticity ω^I_{gv}, which depends on how we define coal varieties and, hence, the underlying data. We then move to equation (24), where we calculate the change in the CES price index for coal imports $\Delta ln(\mathcal{P}^I_{gt})$, which is importer-specific. If there are no imports of US coal, there is no change in the price index. Therefore, there are no changes in the counterfactual prices and quantities in equations (25) and (26) given that the difference between the actual and counterfactual variety-specific shocks to the inverse export supply curves is zero. The change in the CES price index is the only source of changes in counterfactual prices and quantities. The calculation of the CES price index contains actual quantity-weighted harmonic means of the inverse export supply elasticities and shocks. Hence, the change in the CES price index is small if imports of US coal account for a small fraction of all imports.

33 We have only 7 elasticities of substitution (σ^I_g) that are not different from unity at 5% level. Four of them pertain to importers of anthracite, one to an importer of bituminous coal and 2 to importers of other coal for both panels of table 1. The summary statistics in the two panels of the table are based on 46 and 36 elasticities, respectively. Hence, for the majority of importers, varieties are not close substitutes as σ^I_g exceeds unity and changes in variety do not have a large effect on the exact price index (see section V.A. on the Feenstra price index in Broda and Weinstein 2006).

34 Blonigen and Soderbery (2010), who analyze the benefits of greater product variety for automobiles augmenting standard trade (import) data at the HS-10 level with more detailed (market) ones, discuss two opposing biases from the import-based goods (mis)classifications. One one hand, the Armington assumption on varieties hides significant churning of varieties. Hence, it misses a significant amount of net new variety change and biases toward finding lower gains from new imported varieties. On the other hand, to the extent that import goods classifications deviate from (true) market-based classifications, elasticities of substitution are biased downward, which bias toward finding a greater effect of net imported variety change on prices and welfare in the import data.

6.2. Alternative elasticity estimates

In this section, we compare 2SLS elasticity estimates with their NLSUR counterparts. 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 2SLS ω estimates: Australia (0.55), Indonesia (0.17), US (0.36), South Africa (0.47) and Colombia (0.46). Using the same 2SLS regressions for only bituminous coal, we obtained the following ω estimates: Australia (1.31), Indonesia (0.39), US (0.58), South Africa (0.64) and 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 a separate 2SLS regression for each type of coal.

The main message of this exercise is that our NLSUR elasticity estimates in tables 2 and 3 are comparable not only to other elasticity estimates in the literature discussed in online appendix section A.5 but also to linear 2SLS estimates obtained using the same data. Moreover, online appendix section A.6 shows that our counterfactual analysis is robust to elasticity estimates obtained limiting the estimation sample to the pre-boom period of 1990 to 2006.

6.3. 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. Because of 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.

Online appendix figure A7 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 0.27 for the elasticities implied by Soderbery's estimator. In the case of σ, the distribution of the BW estimates is less skewed compared with 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 (online appendix table A16). 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 US coal exports and an increase in US 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 the global coal trade.[35]

6.4. Consumption of domestic coal in importing countries

Our main results do not account for domestically produced (domestic) 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

35 An anonymous referee raised the possibility that the boom created new markets for the US coal that would have not been exploited in the absence of the boom. As a result, he/she suggested to us to try disentangle the role of substitution among existing ("intensive margin") vs new ("extensive margin") coal varieties for our counterfactual analyses. We performed two analyses showing that the intensive-margin implications are the most important ones. In the first of these analyses, our review of the UN Comtrade data showed that China (CHN), Ukraine (UKR), Chile (CHL) and India (IND) had almost zero imports of US coal before the boom and experienced a substantial increase in imports following the boom. We re-estimated our model and performed the counterfactual analysis excluding the 4 countries and the conclusions of our analysis remain essentially intact. In the second of the analyses, we calculated the λ ratios in the expression that speaks to the relationship between the conventional price index and the exact price index that incorporates changes in variety (see proposition 1 in Broda and Weinstein 2006 based on Feenstra 1994). We did so for major importers in our sample by coal type and period. For each of the three types of coal considered in our analysis, the summary statistics make it very clear that there is very low variety turnover as the ratios are essentially equal to 1 whether we consider the entire (1990–2014), the pre-boom (1990–2006) or the post-boom (2007–2014) periods. Hence, variety entry and exit are not a salient feature of the data pointing to limited extensive-margin implications.

countries are identical. We also assume that domestic coal is bituminous, which accounts for more than 70% of the coal trade in the 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 because 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 online appendix table A1. 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.

Online appendix figure A8 shows the kernel density plots 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 (0.27). 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 from 2007 to 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 in the importing countries (online appendix table A16), which is essentially identical to the change in coal quantity in our main results. We also see a decrease in the value of coal traded 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. 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 US coal and an increase in US 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 US coal exports, the qualitative nature of our main results holds.[36]

36 Our findings echo the results in Steckel et al. (2015), who show that in the increasingly integrated global coal market the availability of a domestic coal resource does not have a statistically significant impact on the use of coal and

6.5. Substitution between coal and natural gas

Substitution between coal and natural gas in our trade model is not possible. Such substitution is possible in electricity generation in the US 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 towards zero. However, 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 online appendix table A1. 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 US coal exports do not significantly contribute to an increase in global CO_2 emissions.

6.6. US gas prices and bituminous coal

In our counterfactual analysis, we shift the US coal export supply curves using the estimates from table 4. The relationship between the US natural gas price and the US 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 US coal export supply curves to the US price of natural gas 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 online appendix table A17.[37] As the table shows, the total impact of the boom

related emissions. As Steckel et al. emphasize, these findings have important implications for climate change mitigation if future economic growth is fuelled mainly by coal.

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

on the international coal market is always small for the range of sensitivities we considered.

Therefore, our main findings would continue to hold even if the shock to the US export supply curves were higher or lower than the one that we estimate using equation (21). In other words, independently of the magnitude of the shift in US coal exports, a large fraction of it would just crowd out coal exports from other countries.

7. Conclusion

The paper analyzes the impact of the US shale gas boom on global carbon emissions associated with international coal trade flows. In particular, we analyze whether the increase in US 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 (leakage).

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 US domestic coal market allows us to link the domestic natural gas (gas) prices and shocks to the US inverse export supply curve. We construct counterfactual US gas prices for 2007 to 2014 using a simple linear regression that links the gas price in the US to the gas price in Europe using data for 1990 to 2006 and capitalizing on the well-documented decoupling of the two prices in the aftermath of the boom.

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 sulphur dioxide (SO_2) emissions. We present detailed results for counterfactuals for a set of 40 countries that account for 90% of global coal imports and exports during the period of interest. In the absence of the boom, the total 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 increase by less than 1%. Hence, and in contrast to commentary around the time of the surge in US coal exports, US 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 US coal exports with US coal exporters losing $15.4 billion. Major importers of US coal experience substantial changes in quantities and associated emissions in the range of 43% to 71%.

Supporting information

Supplementary material accompanies the online version of this article. The data and code that support the findings of this study are available in the Canadian Journal of Economics Dataverse at doi.org/10.5683/SP3/SQLXCV.

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