The Effect of the Shale Gas Boom on Greenhouse Gas Emissions:
Accounting for Coal Exports *

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Abstract

Natural gas and coal compete to provide baseline electricity generation in the United States, and low domestic natural gas prices have lead to substantial switching from coal to natural gas in the electricity sector. While natural gas is difficult to transport internationally, coal can be shipped relatively easily, and in the face of low domestic demand, the US coal market has increasingly turned to foreign consumers. This paper estimates the effect of domestic natural gas prices on US coal exports, using data from 2002 to 2013, and finds that a one-percent increase in the domestic price of natural gas results in a 2.2 percent decrease in domestic coal exports. This implies that approximately 75% of displaced US steam coal will be shipped abroad.

JEL Codes: Q41, Q54, Q56

Key Words: Coal, natural gas, carbon leakage, greenhouse gas, export elasticity

1 Introduction

Hydraulic fracturing has allowed natural gas producers the ability to access reserves of gas trapped in shale formations, dramatically increasing the supply of natural gas in the US. However, natural gas is difficult to export, requiring either pipelines or liquification infrastructure. The difficulty in transporting natural gas internationally means that increases in US natural gas supply lower domestic prices, but overseas prices are unchanged. Figure 1 shows natural gas prices at several important world markets and, while the price of natural gas in the United States fell substantially following the shale gas boom, foreign prices were largely unaffected. Since natural gas and coal compete to provide baseload electricity generation, low domestic natural gas prices have led natural gas to displace coal as a source of power generation. Between 2008 and 2012, as the wellhead price of natural gas fell from $7.97 to $2.66 per thousand cubic feet, coal’s share of electricity generation in the United States fell from 48% to 39%. This has largely been viewed with environmental optimism because natural gas is a far cleaner source of electricity than coal. Between 2008 and 2012 – while natural gas was displacing coal – CO₂ emissions from the electricity sector fell 13%.

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While natural gas must be liquified in order to be shipped internationally, coal can be transported via cargo ship at a relatively low cost. As a result, world coal markets are more integrated than natural gas markets. As Figure 2 shows, US coal prices are highly correlated with prices in other major markets. US coal producers, faced with declining domestic demand and access to robust foreign markets, have increasingly turned to the export market. Indeed, as shown in Figure 3, US steam coal exports have grown substantially in recent years, from 19 million short tons in 2008 to 51 million short tons in 2012.

Figure 2: Coal Prices in the US, Europe and Asia
The potential for increased coal exports makes the net climactic impact of the shale gas boom ambiguous. On one hand, increased production of natural gas will reduce domestic consumption of coal, lowering US greenhouse gas emissions. On the other hand, $CO_2$ is a global pollutant, and the $CO_2$ emissions associated with combusting coal do not vary internationally without technology like carbon capture, and sequestration. The net environmental impact will depend on the extent to which displaced coal is exported, rather than left in the ground. While the issue has received little academic study, policy-makers seem to be attuned to the issue; Darmstadter (2013) notes that the EPA advised that an environmental review of a proposed coal export port should consider increased coal demand in Asia as an environmental impact.

While there has been scarce academic evidence of the effect of increased coal exports on global $CO_2$ emissions, several studies have addressed the question heuristically. This work has largely focused on the type and extent to which incumbent foreign fuels will be replaced by US exports. A recent, highly publicized report by an environmentalist lobbying group argued that all of the benefits of reduced domestic coal consumption were offset by increased exports, although they naively assigned all increases in coal exports to the shale gas boom. At the other end of the spectrum, Darmstadter (2013) argues that foreign demand for coal is inelastic, and increased exports of US coal will merely displace coal from other sources. Walek (2014) suggests that relatively clean coal from the United States’ Powder River Basin (PRB) will displace dirtier coal from Australia, Indonesia, and South Africa, causing US coal exports to reduce global greenhouse gas emissions. US coal exports can indeed reduce emissions if they displace sufficiently dirty
foreign fuels; Bohnengel et al. (2014) use a life-cycle analysis and find that displacing South Korean coal with US PRB coal reduces greenhouse gas emissions on a per-megawatt-hour basis, although Gilbert (2014) criticizes this result on the grounds that it is being driven by erroneously assigning US coal-to-gas greenhouse gas reductions to export policy.

While the effect of coal exports depends on the type of foreign fuel that is displaced by US coal exports, the first step in the causal chain is the extent to which low natural gas prices lead coal producers to increase their exports. If low natural gas prices lead to only minor increases in coal exports, i.e. the majority of displaced coal is left in the ground, the shale gas boom will have only minor negative effects on international greenhouse gas emissions. In this vein, Newell and Raimi (2014) note that while US coal exports have grown during the period of the shale gas boom, US coal consumption has fallen at thrice the rate, suggesting that while the shale gas boom likely leads to an increase in exports, this may not outweigh the reduction in emissions associated with displacing coal in the US electricity system. One source that may help inform the coal export elasticity debate is the US EIA’s Annual Energy Outlook, which uses the NEMS general equilibrium model to project future US energy systems. The 2014 Annual Energy Outlook presents a high oil and gas resource scenario in which total recoverable reserves of natural gas are 50% higher than the baseline. The high gas resource scenario implies relatively inelastic coal exports, the model predicts a 16% increase in coal exports and a 40% reduction in natural gas prices by 2040, relative to the baseline scenario. This would suggest a cross-price export elasticity with respect to the price of natural gas of around -0.4.

This paper seeks to complement the growing literature on foreign fuel displacement by estimating the export elasticity of coal with respect to the price of natural gas. I use panel data on US coal exports from 5 major US Customs regions between 2002 and 2013 to empirically estimate the export elasticity of coal with respect to the price of natural gas. The climatic effects of these exports are assessed using simple assumptions about the amount of coal that will displaced in the US electricity sector due to a decrease in domestic natural gas prices.

The rest of this paper is laid out as follows. Sections 2 and 3 discuss the natural gas and coal markets. Section 4 presents the methodological framework. Section 5 discusses the data. Section 6 presents the results and discusses the implications for climate change. Finally Section 7 concludes the paper.
2 Natural Gas Background

Natural gas must either be transported by pipeline or by liquefying natural gas into LNG through intense cooling. Pipelines must run over land, and there is little liquification infrastructure in the United States. The only existing LNG export terminal in the United States is in Alaska, and is thus ill-suited to export shale gas produced in the contiguous states. While a number of LNG export terminals have been proposed, only four have received FERC approval and they are unlikely to begin operation for several years.

As a result of the difficulties in shipping natural gas abroad, US natural gas producers are largely separated from global markets. Although the United States currently exports approximately 6% of its total natural gas production, these exports are predominately sent via pipeline to Canada and Mexico. Natural gas that is sold to Canada and Mexico sells for about the same price as natural gas in the United States. Less than 1% of US natural gas exports are sent to Europe or Asia in the form of LNG, and these shipments receive substantial price premiums relative to the domestic market.

Due to the difficulty in inter-continental transportation of natural gas, world markets are not well integrated. Silverstovs et al. (2005) finds that while intra-continental markets are relatively co-integrated, the US market is separated from both the Asian and European markets. The shale gas boom in the United States has dramatically increased natural gas production and decreased prices, while international market prices have remained relatively high. According to the World Bank, US natural gas prices in 2013 were $3.52 per million BTUs, compared to $11.11 per million BTUs in Europe, and $15.04 per million BTUs in Japan.

3 Coal Background

Coal is a relatively cheap and abundant energy source. Coal is divided into two categories: steam coal and metallurgical coal. Steam coal, alternatively referred to as thermal coal, is primarily used for electricity and heat production. Metallurgical coal has a higher energy content than steam coal and is primarily used for industrial purposes, generally production of steel. Demand for steam coal is driven by electricity needs, while demand for steam coal is related to industrial production. Importantly, steam coal faces many substitutes in the electricity generation process, namely natural gas, nuclear, and renewables. Metallurgical coal on the other hand, has few substitutes.

Despite growing concern about the deleterious environmental impacts of coal combustion, it remains the
dominant global electricity fuel, and it is behind only petroleum in terms of total energy consumption (See IEA (2014)). Coal is a particularly important fuel in the developing world; coal provides approximately 29% of global energy supply but only 19% of energy supply within the OECD.

Because coal is solid, it is relatively easy to transport by ship, and there is a robust international coal market. There is broad evidence of statistical but incomplete integration between coal markets around the world (See Wårell (2006) and Zaklan et al. (2012)). There is also evidence that international coal markets are competitive. Haftendorn and Holz (2010) and Trüby and Paulus (2012) find that perfect competition fits international steam coal markets better than Cournot competition, although both studies find evidence of bottle-necks or capacity constraints. The strong international market allows producers who face waning domestic demand to easily reach alternative consumers.

While international coal markets have historically relied on multi-year contracts, increasing international competition and the development of financial hedging instruments have allowed the international spot market to gain prevalence. By 2003, 80% of the Atlantic coal market was conducted on the spot market (See Ekawan and Duchêne (2006)), and in the Pacific, the spot market was rapidly growing as well (See Ekawan and Duchêne (2006)). Li (2010) explains the relatively more prominent Atlantic spot market on the basis that long-term contracts are more necessary when coal provides baseload electricity generation. Unlike Asia, Europe has substantial hydro-electric and nuclear capacity, and coal operates along the middle of the dispatch curve.

The United States is the second largest producer of coal in the world, and has the largest coal reserves (See IEA (2014)). While coal has long been the dominant electricity source in the United States, environmental regulation and competition from natural gas has eroded its status. While coal provided over 50% of US electricity generation in 2003, by 2013 coal’s share of electricity generation had fallen to 39%, and the share of generation from natural gas had climbed from 17% to 28%. While coal consumption has been falling in the United States, international energy demand has been growing as developing nations industrialize. World coal consumption has grown substantially since 2000 and Wolfram et al. (2012) argue that world consumption will continue to grow. Domestic producers, faced with falling domestic demand, and rising international demand, are increasingly turning to the international export market. The US remains a relatively small player in the international export market, accounting for approximately 8% of world exports and 1.5% of world coal consumption. By comparison, Indonesia and Australia are responsible for 34% and 27% of world exports, respectively.
Most coal shipped from the United States leaves from ports on the east coast. Ports in Baltimore, MD, New Orleans, LA, Norfolk, LA, Mobile, AL, and Charleston, SC were responsible for over 80% of sea-borne US steam coal exports in 2012. On the west coast, Seattle, WA and Los Angeles, CA combine for an additional 11% of US exports, although there are several proposals to substantially increase the capacity of coal export facilities on the west coast. Because it is costly to ship coal over land, most coal is exported from a port relatively close to it’s destination. Table 1 shows the most common destination country for coal exports from the 5 largest US Customs Districts. As shown, the east coast ports tend to export coal to Europe, while the west coast ports tend to export coal to Asia.

Table 1: Primary Export Destinations by Port

<table>
<thead>
<tr>
<th>Port</th>
<th>1st Country</th>
<th>2nd Country</th>
<th>3rd Country</th>
<th>4th Country</th>
<th>5th Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baltimore</td>
<td>Netherlands (27%)</td>
<td>Belgium (11%)</td>
<td>Germany (10%)</td>
<td>Romania (7%)</td>
<td>Portugal (7%)</td>
</tr>
<tr>
<td>New Orleans</td>
<td>U.K. (34%)</td>
<td>Netherlands (15%)</td>
<td>Morocco (11%)</td>
<td>Germany (6%)</td>
<td>India (4%)</td>
</tr>
<tr>
<td>Norfolk/Mobile/Charleston</td>
<td>Netherlands (20%)</td>
<td>Italy (15%)</td>
<td>U.K. (13%)</td>
<td>France (13%)</td>
<td>Germany (13%)</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>Japan (62%)</td>
<td>China (25%)</td>
<td>Chile (7%)</td>
<td>Singapore (3%)</td>
<td>France (1%)</td>
</tr>
<tr>
<td>Seattle</td>
<td>South Korea (80%)</td>
<td>China (11%)</td>
<td>Australia (4%)</td>
<td>Taiwan (4%)</td>
<td>Japan (1%)</td>
</tr>
</tbody>
</table>

4 Methodology

A number of empirical studies have examined the effect of domestic prices on exports, primarily in the context of agriculture (See Gardiner and Dixit (1987)). Recently, these studies tend to rely on the calculation method put forth Tweeten (1967) and Johnson (1977). Global demand for a country’s exports can be expressed based on supply and demand elasticities at the national level, as well as the degree to which prices are transmitted between countries. While the calculation method is well grounded in theory, it requires substantial assumptions about the structure of national markets. Indeed, Reimer et al. (2012) note that most studies that use the calculation method rely on educated guesses about supply and demand parameters.

In the case of coal, quality estimates of supply and demand elasticities are relatively scarce. An alternative approach is to directly estimate the quantity of exports in a reduced form setting (See Faria et al. (2009) for a recent example). Because of the requirements associated with the calculation method, I employ
the direct approach and estimate the quantity of coal exports econometrically as a function of domestic natural gas prices. Miller and Paarlberg (2001) note that the downside of the econometric estimation of exports (generally referred to as the direct method) is the potential for mis-specification. The direct method generally errs on the side of finding inelastic demand. In this case, though, an overly inelastic estimate has the useful property that it will lead to a lower-bound on increased global coal consumption.

First, I examine the national effect of natural gas prices on total coal exports. I specify the natural log of total coal exports from the United States as

\[
\ln(Q_{i,t}) = \beta_0 + \beta_1 \ln(P_{i,t}) + \beta_2 gwp_t + \tau + \eta_i + \epsilon_{i,t} \tag{1}
\]

where \(Q_{i,t}\) is the amount of coal exported in quarter \(t\) from port \(i\) and \(P_{i,t}\) is the average price of natural gas near port \(i\) at time \(t\). \(gwp_t\) is the growth rate of world gross domestic product, \(\tau\) is a set of time controls, \(\eta_i\) is a set of customs region fixed effects, and \(\epsilon_t\) is an idiosyncratic error term. \(gwp_t\) captures the effect of global business cycles, which affects international demand for steam coal. \(\tau\) is comprised of a time trend and quarterly fixed effects. The time trend captures global and domestic trends in export markets, such as decreases in international shipping costs and changes in preferences for coal relative to other fuels. The quarterly fixed effect accounts for cyclical variation in global demand for coal. For example, coal is likely to be in greater demand in the summer, when the populous northern hemisphere requires electricity for cooling, than in the winter, when the less-populous southern hemisphere is using electricity for cooling. The port-specific fixed effect \(\eta_i\) captures time-invariant port-specific characteristics, such as total export capacity or access to foreign markets.

The above specification requires that variation in the price of natural gas causes variation in coal exports. One might be concerned, however, that an increase in the foreign demand for coal would drive up the domestic price of coal, in turn increasing the price of natural gas. This is unlikely to be the case because US coal exports constitute a relatively small portion of the overall US market for coal and exports are generally viewed as a secondary market for US coal producers, as evidenced by the high variability in exports over time. Moreover, if foreign coal exports affect domestic natural gas prices, this will bias the estimate of the cross-price export elasticity toward zero. If increased exports are attributable to changes in international coal demand, then domestic coal prices and domestic natural gas prices would rise. If this sort of behavior were the dominating effect, the estimated effect of natural gas prices on coal exports should be positive. The
simple correlation between natural gas prices and coal exports, however, is negative ($\rho = -0.2$), suggesting that foreign demand shocks are not driving US natural gas prices.

Even though it is unlikely that foreign coal exports are endogenous to the domestic price of natural gas, I provide a specification which accounts for potential endogeneity. I instrument for the price of natural gas using domestic weather shocks. Weather shocks increase the demand for natural gas; abnormally cold weather result in increased demand for natural gas as a heating fuel and abnormally hot weather shocks result in increased demand for natural gas as a source of electricity. Domestic weather shocks are also plausibly unrelated to foreign demand for US coal exports, satisfying the exogeneity requirement of the instrumental variables approach.

Natural gas is a storable commodity, though, so natural gas markets can smooth over seasonal variation in natural gas demand by increasing or decreasing the amount of natural gas in storage throughout the year. Deviations from expected temperatures, however, lead to greater than expected injections and withdrawals of natural gas from storage, leading to price variation. White (2013) found that monthly natural gas prices can be modeled as the sum of several months of weather deviations relative to the average monthly temperature. Following this approach, I estimate the price of natural gas as

$$
\ln(P_{i,t}) = \beta_0 + \beta_1 \sum_{j=0}^{3} (HDD_{t-j} - \bar{HDD}_{t-j}) + \beta_2 \sum_{j=0}^{3} (CDD_{t-j} - \bar{CDD}_{t-j}) + \tau + \eta_i + \epsilon_{i,t} \tag{2}
$$

where $HDD$ is the number of heating degree days and $CDD$ is the number of cooling degree days, $\tau$ is a time trend, $\eta_i$ is a port-specific fixed effect, and $\epsilon_{i,t}$ is an idiosyncratic error term. Heating degree days and cooling degree days are a simple relationship between ambient outdoor temperature and an indoor temperature. Heating degree days are defined as $HDD = \min(0, tAvg - 65)$ and cooling degree days are defined as $CDD = \min(0, 65 - tAvg)$ so that as the temperature increases (decreases) the number of heating (cooling) degree days increases. $\bar{HDD}$ and $\bar{CDD}$ are the average number of HDDs and CDDs in the quarter in which an observation falls. For example, if the first quarter of 2012 registered 1000 HDDs and 10 CDDs, and the average first quarter registered 800 HDDs and 100 CDDs, the deviation from average would be +200 HDDs and -90 CDDs. To reflect the fact that natural gas prices are affected by storage, weather deviations are summed over the current period and the preceding three periods.  

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1Results are robust to the number of weather lags. Between one and three quarters of cumulative weather shocks are a strong
In the second stage, coal exports from the United States are re-estimated as

\[ \ln(Q_{i,t}) = \beta_0 + \beta_1 \ln(\hat{P}_{i,t}) + \beta_2 gwp_t + \tau + \eta_i + \epsilon_{i,t} \]  

(3)

where \( \hat{P}_t \) is the fitted price of natural gas in the first stage regression presented above. The effect of natural gas prices on coal exports, then, is estimated using only the variation in natural gas prices that is induced through weather shocks.

Coal is often transported within the United States before it is exported and contracts for coal exports may not be negotiated in the same time period that coal is observed leaving the port. This could bias the export elasticity estimate because high coal exports could erroneously be assigned to a month in which natural gas prices were high, when the decision to ship the coal was made in the face of low natural gas prices in a previous month. In order to account for this effect, I estimate the effect of lagged natural gas prices on coal exports as

\[ \ln(Q_{i,t}) = \beta_0 + \beta_1 \ln(P_{i,t-1}) + \beta_2 gwp_t + \tau + \eta_i + \epsilon_{i,t} \]  

(4)

where \( P_{t-1} \) is the price of natural gas in the preceding month, and all else is the same as the baseline regression.

Finally, in the United States, electricity generators are dispatched to meet electricity needs from lowest marginal cost to highest marginal cost. While low natural gas prices allow natural gas power plants to submit lower electricity generation bids – and move early on the economic dispatch curve, variation in coal prices also affects the order of dispatch. If coal prices are low, coal may still be an economically viable electricity fuel in the United States, even when the price of natural gas is also low. To account for the effect of coal prices on domestic electricity generation decisions, I estimate monthly coal exports as

\[ \ln(Q_{i,t}) = \beta_0 + \beta_1 \ln(RP_{i,t}) + \beta_2 gwp_t + \tau + \eta_i + \epsilon_{i,t} \]  

(5)

where \( RP_t \) is the relative price of natural gas to coal, and all else is the same.

Each of the latter two functional forms are also estimated in an instrumental variables framework, using weather shocks as an instrument for fuel prices.

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instrument, and second stage results are similar.
5 Data

Steam coal export data is available at the quarterly time-step between 2002 and 2013 from the Energy Information Agency (EIA). Data is disaggregated by the customs region through which it is exported as well as the country of destination. Although Canada and Mexico are frequent destinations for US coal exports, these observations are removed from the dataset because exports to these countries because these countries are connected to the United States natural gas market. As a result, natural gas prices in Canada and Mexico are relatively low, allowing electricity producers to perform the same coal-to-gas switching that was observed in the United States. Exports are summed to the port-level for each time period, so the unit of observation is a port-quarter. Exports are not consistently observed from many ports, so analysis is limited to only the Baltimore, Los Angeles, New Orleans, Norfolk/Mobile/Charleston, and Seattle customs regions. The ports that remain in the sample capture the majority of US steam coal exports. Over the period of the sample, these customs regions were responsible for 92% of coal exports leaving the United States. The data is further limited to only observations that had non-zero amounts of coal export in a given quarter. In only 8 quarter-port observations were exports of zero observed. Seven of these observations were in Seattle between 2006 and 2008. The final observation was from New Orleans in the fourth quarter of 2005, shortly after Hurricane Katrina made landfall and limited shipping capabilities.

Monthly City Gate natural gas prices are available from the EIA at the state-level. City Gate prices reflect the price of natural gas paid by natural gas distribution companies at the point that the natural gas is physically transferred between the pipeline company and the distribution company. These prices reflect the commodity price of natural gas as well as the costs of storing the gas and transporting it to the state. These prices are computed prior to end-use taxes, although there may be variation in how taxes are assessed on intra-state natural gas pipeline transportation services. City Gate natural gas prices are expressed in dollars per thousand cubic feet and are adjusted to 2002 dollars and aggregated over months in a quarter. Census regions are assigned to natural gas prices based on the state of the census region. The Norfolk/Mobile/Charleston census region is assigned Virginia natural gas prices, because Norfolk is the largest of the three ports.

Annual average coal prices are available from the EIA Form 7A (Coal Production Report) at the national level between 2002 and 2013. Coal prices are expressed in dollars per short ton, and are adjusted to 2002 dollars. Because average coal prices are available on a relatively aggregated temporal scale, the relative
price of natural gas and coal is computed by dividing the quarterly price of natural gas by the annual price of coal.

Finally, daily weather data was obtained from the National Climactic Data Center (NCDC) between 2002 and 2013. The NCDC reports daily heating and cooling degree days at the state level, weighted by population. Heating degree days and cooling degree days are summed over days in the month and national heating and cooling degree days are calculated using a simple average across states.

6 Results

Table 2 presents estimation results from each of the models. In the baseline regression, the effect of contemporaneous natural gas prices has a statistically significant effect on coal exports. A one-percent increase in the domestic price of natural gas results in a 0.88 percent decrease in coal exports. Given the relatively small quantity of coal exports, this is actually a relatively small quantity response. The results are similar when the relative price of natural gas to coal is used to estimate coal exports, a one percent increase in the relative price of natural gas to coal results in a 1.04 percent decrease in natural gas exports. The similarity between these results is unsurprising because coal prices are more stable than natural gas prices, and data constraints required coal prices to be at a more aggregated time-scale than natural gas prices. In the naive regression, the effect of lagged prices is statistically insignificant. This is not particularly surprising because the data is at a quarterly time-step and spot coal trades can easily be negotiated within a period of several months, and there is little reason to believe that producers would make export decisions a month prior to exports leaving ports. In all cases, the effect of world gdp growth does not have a statistically significant effect on coal exports. Again, this could be driven by the annual time scale of world gdp growth, and the lack of variation throughout the sample. ²

Results from the instrumental variables regressions are presented in Table 3. The instrumental variables approach finds coal exports to be more elastic than the non-instrumented regressions, finding a cross-price export elasticity between -1.3 and -2.2. The simplest model, finds that a one percent increase in natural gas prices will cause an decrease in steam coal exports of around 1.9 percent, approximately twice as elastic as the non-instrumented version. Similarly, the instrumented relative price of natural gas to coal suggests an elasticity around -2.2, again about twice as elastic as the non-instrumented counter-part. Because the

²In a supplementary regression estimating monthly national coal exports, the effect of a one-point increase in world-gdp growth is around 2%, although this data does not disaggregate steam and metallurgical coal.
<table>
<thead>
<tr>
<th>Dependent Variable: Log Coal Exports</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Log NG Price</td>
<td>-0.879** (0.418)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Log Lagged NG Price</td>
<td></td>
<td>-0.365 (0.404)</td>
<td></td>
</tr>
<tr>
<td>Log Relative Price</td>
<td></td>
<td></td>
<td>-1.045** (0.440)</td>
</tr>
<tr>
<td>World GDP Growth</td>
<td>0.041 (0.070)</td>
<td>0.044 (0.068)</td>
<td>0.060 (0.071)</td>
</tr>
<tr>
<td>Time Trend</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Quarterly Fixed Effects</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Port Fixed Effects</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Adjusted R-Squared</td>
<td>0.6278</td>
<td>0.6447</td>
<td>0.6298</td>
</tr>
<tr>
<td>Observations</td>
<td>238</td>
<td>238</td>
<td>238</td>
</tr>
</tbody>
</table>

Instrumented versions are more elastic than their non-instrumented counterpart, there is statistical significance on the effect of lagged price in the instrumental specification. A one-percent increase in lagged price will lead to around a 1.3 percent decrease in steam coal exports. As mentioned previously, it is not surprising that the instrumented results find exports to be more elastic than the non-instrumented regressions, because endogenous foreign demand would work in the opposite direction of natural gas leading to low domestic coal demand.

Table 4 presents the results of the first stage regression. Three quarters of cumulative weather shocks are found to be strong instruments, both for the price of natural gas as well as for the relative price of natural gas and coal, and a Wald test finds no evidence of weak instruments. The F-test statistics are 11.9 and 13.6, respectively. The first stage models were also estimated in a mixed instrumental variables framework, in which price is estimated at the monthly level and then aggregated to the quarter. Neither the first nor second stage results changed substantially.
Table 3: **Instrumental Variables Regression Results**

<table>
<thead>
<tr>
<th>Dependent Variable: Log Coal Exports</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Log NG Price</td>
<td>-1.914***</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.492)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Log Lagged NG Price</td>
<td>-1.340***</td>
<td></td>
<td>-2.238***</td>
</tr>
<tr>
<td></td>
<td>(0.473)</td>
<td></td>
<td>(0.555)</td>
</tr>
<tr>
<td>Log Relative Price</td>
<td>0.065</td>
<td>0.056</td>
<td>0.097</td>
</tr>
<tr>
<td></td>
<td>(0.094)</td>
<td>(0.095)</td>
<td>(0.069)</td>
</tr>
<tr>
<td>World GDP Growth</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Time Trend</td>
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<tr>
<td>Quarterly Fixed Effects</td>
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</tr>
<tr>
<td>Port Fixed Effects</td>
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<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Adjusted R-Squared</td>
<td>0.6448</td>
<td>0.6633</td>
<td>0.6492</td>
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<tr>
<td>Observations</td>
<td>238</td>
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Table 4: **First Stage IV Results**

<table>
<thead>
<tr>
<th>Natural Gas Price</th>
<th>Relative Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Quarter CDD Shock</td>
<td>7.979<em>10^-6</em>**</td>
</tr>
<tr>
<td></td>
<td>(2.769*10^-6)</td>
</tr>
<tr>
<td>3 Quarter HDD Shock</td>
<td>5.702<em>10^-6</em>**</td>
</tr>
<tr>
<td></td>
<td>(1.133*10^-6)</td>
</tr>
<tr>
<td>Time Trend</td>
<td>X</td>
</tr>
<tr>
<td>Port Fixed Effects</td>
<td>X</td>
</tr>
<tr>
<td>F-Statistic</td>
<td>11.9</td>
</tr>
<tr>
<td>Adjusted R-Squared</td>
<td>0.7888</td>
</tr>
<tr>
<td>Observations</td>
<td>238</td>
</tr>
</tbody>
</table>

To put these results in context, in 2013 a total of 40 million tons of steam coal were exported from the five major ports. A one-percent decrease in the contemporaneous price of natural gas will result in between 350,000 and 770,000 additional tons of steam coal exports. A similar decrease in the relative price of natural gas to coal will cause an increase in steam coal exports between 420,000 and 890,000 tons. The
instrumented results find that a one-percent decrease in the lagged price of natural gas will increase coal exports by 540,000 tons.

Some back of the envelope calculations allow for consideration of greenhouse gas effects of these exports. A one-percent decrease in the ratio of natural gas prices to coal prices will result in a 0.17 percent decrease in the ratio of coal generation to natural gas generation (See EIA (2012)). Based on the 2013 electricity generation mix, a one-percent decrease in the relative price of natural gas to coal would imply a decrease in coal consumption of approximately 2.5 megawatt hours. This amount of generation would require around 1.35 million tons of coal, suggesting that between 580,000 and 1,000,000 tons of displaced coal would not be exported. The average carbon intensity of natural gas generation in the United States is about half of the average carbon intensity of coal generation, so domestic \( CO_2 \) emissions would fall by approximately 1.5 million tons. The coal consumed abroad would add an additional 970,000 to 1.7 million tons of \( CO_2 \), for a net environmental effect that ranges between a 500,000 ton reduction in \( CO_2 \) for the naive regression to a 200,000 ton increase in \( CO_2 \) when weather is used as an instrument for the domestic price of natural gas.

7 Conclusion

While the shale gas boom has been met with environmental optimism as US coal consumption has fallen, the net environmental implications of the shale gas boom depend on global emissions as well as domestic emissions. Coal producers – faced with access to a cheap competitor – have turned to international markets. While some attention has been dedicated to the type of foreign fuels that will be displaced by US coal, little formal attention has been placed in estimating the extent to which coal exports increase as domestic natural gas prices fall.

Using panel data from coal exports from five major US ports between 2002 and 2013, I estimate the cross price elasticity of coal exports with respect to the domestic price of natural gas. Estimates range from around unit elasticity to fairly elastic under the preferred specification that uses weather as an instrument for natural gas price. This suggests that a one percent decrease in domestic natural gas prices – such as a price decrease caused by increased exploitation of shale gas – will result in around 500,000 additional tons of steam coal being exported.

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\( ^3 \)Assuming 0.00054 tons per MWh, as reported by the EIA
Based on these estimates, the net environmental impact of lower natural gas prices is uncertain. However, to the extent that reduced form estimates of export elasticity tend to err toward inelasticity, the estimates should be viewed as a lower bound, suggesting that the sum of US natural gas emissions and emissions from US-produced coal will rise. Moreover, the back of the envelope results presented in the preceding section treat coal exports as if they occur in the United States, that is they ignore the significant greenhouse gas emissions associated with transporting coal to foreign markets. Finally, US plants are far more likely to employ controls to mitigate carbon emissions than foreign countries. Proposed EPA regulations on new coal fired power plants will virtually ensure that any new coal plants utilize carbon capture and sequestration technology. If it is cleaner to burn coal within the United States than it is to burn it abroad, this will further exacerbate the effect of exported coal on greenhouse gas emissions.

Proposals to increase capacity for natural gas exports are unlikely to change the response of coal producers to low domestic natural gas prices. They will, however, reduce the extent to which increased production of natural gas reduces domestic prices, because excess natural gas supply can be exported internationally. In the event that new natural gas export facilities are constructed, they will limit the magnitude of coal exports from a given level of natural gas production, but only through the mechanism of raising domestic prices.

Will the US shale boom reduce global greenhouse gas emissions? While the shale gas boom will certainly reduce greenhouse gas emissions from the United States, the global picture is less clear. Environmental activists who hope to see all the US coal displaced by natural gas remain in the ground will be disappointed. The sum of emissions from US produced coal and US produced natural gas are certain to rise. However, global emissions may yet decline if foreign demand for coal is inelastic, and US coal displaces more carbon intensive energy sources. Further empirical research is needed on the extent to which US coal exports will displace dirty foreign fuels. While production of shale gas produces substantial economic and local environmental benefits, extraction of shale gas is unlikely to be justified on the basis of reduced global greenhouse gas emissions.
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