THE EFFECT OF RESTRICTING COAL CONSUMPTION ON COAL EXPORTS AND GREENHOUSE GAS EMISSIONS

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ABSTRACT

Reducing coal consumption is a goal of many countries' energy and environmental policies. However, policies that restrict domestic coal consumption also incentivize the export of coal to non-abating foreign countries and encourage coal consuming industries to move their production to these countries. This paper uses a modified version of the GTAP-E model to quantify these effects for a restriction on U.S. coal consumption. I find that a restriction on coal consumption in the United States has a negligible effect on foreign emissions but a substantial effect on foreign welfare. U.S. coal exports increase, but this is offset by increased U.S. demand for oil and gas, reducing the availability of these fuels in foreign countries. But although foreign emissions do not change, foreign welfare does, as the restriction causes changes in trade that benefit foreign households. While the marginal U.S. welfare cost of abatement ranges from 15 to 678 dollars per metric ton, foreign welfare increases by 15 to 19 percent of the U.S. welfare loss.

JEL: Q54; F17; Q48; C68

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1 Introduction

In 2016, 30 percent of U.S. electricity generation came from coal.[1] However, coal generation is substantially more carbon intensive than alternatives. Coal produces 2.1 to 2.2 pounds of carbon dioxide per kilowatt-hour of electricity generated, compared with 1.2 for natural gas, the other main source of U.S. electricity.[2] These coal emissions are also large in absolute magnitude. In 2015, electricity generation from coal produced 70 percent of the power sector's greenhouse gas emissions, or 21 percent of all U.S. emissions.[3]

In order to combat coal emissions, some national and local governments have enacted policies to eliminate the use of coal for electricity generation. Canada, France, and the United Kingdom have committed to phase out their remaining coal fired power plants by 2030.[4] Ontario closed its last coal power plant in 2014 and has banned the construction of any new ones.[5] Oregon has passed a law to do the same by 2035.[6] And politicians in other regions have also expressed support for phasing out coal.[7]

However, policies that restrict coal in a particular region create unintended incentives, since they do not apply to other regions. For example, reduced coal demand by the United States depresses international coal prices, increasing consumption abroad.[8] Moreover, such policies put energy-intensive sectors in the United States at a cost disadvantage compared to competitors abroad,[9] incentivizing the relocation of these industries abroad. [10] If these sectors are trade exposed, production and exports of domestic industry would decline while imports from non-regulated foreign countries would increase.[11]

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[1] Energy Information Administration, "What Is U.S. Electricity Generation by Energy Source?"

[2] Energy Information Administration, "How Much Carbon Dioxide Is Produced per Kilowatthour When Generating Electricity with Fossil Fuels?"

[3] Total U.S. greenhouse gas emissions in 2015 were 6,586.7 million MT (metric tons) of CO_2 equivalent of which 1,941.4 million was from electricity generation in general and 1,350.5 million was from coal generation in particular. Environmental Protection Agency, "Inventory of U.S. Greenhouse Gas Emissions and Sinks Report: 1990-2015," 2–10, 3–6.

[4] Lou, "Canada Speeds up Plan to Phase out Coal Power, Targets 2030"; Williams, "France Follows UK in Naming Coal Phase-out Date"; BBC News, "UK's Coal Plants to Be Phased out within 10 Years."

[5] Ontario Ministry of the Environment and Climate Change, "Ontario Permanently Bans Coal-Fired Electricity Generation."

[6] The Guardian, "Oregon Becomes First State to Pass Law to Completely Eliminate Coal-Fired Power."

[7] Cuomo, "2016 State of the State"; Kerry, "Remarks at UN's Earth to Paris Event with Mashable's Andrew Freedman."

[8] Böhringer, Lange, and Rutherford, "Optimal Emission Pricing in the Presence of International Spillovers: Decomposing Leakage and Terms-of-Trade Motives."

[9] Fischer and Fox, "Climate Policy and Fiscal Constraints: Do Tax Interactions Outweigh Carbon Leakage?"

[10] Böhringer, Carbone, and Rutherford, "Unilateral Climate Policy Design: Efficiency and Equity Implications of Alternative Instruments to Reduce Carbon Leakage."

[11] Böhringer, Lange, and Rutherford, "Optimal Emission Pricing in the Presence of International Spillovers: Decomposing Leakage and Terms-of-Trade Motives."

As a result, although the policy may decrease domestic emissions, it could decrease or even increase world emissions, depending on whether foreign production is more or less emission intensive than the U.S. industries.[12] But either way, these effects promote the export of coal to non-abating foreign countries and encourage coal consuming industries to move their production to these countries. This increases the domestic welfare cost of the policy and reduces its impact on global greenhouse gas emissions.

Researchers are well aware of these spillovers and there has been extensive research on their magnitude for comprehensive carbon policies, such as cap and trade or carbon taxes. This literature has typically found that these comprehensive policies increase foreign emissions by somewhere between a few percent, and one quarter of the domestic emissions reduction.[13] And a review of the literature by Zhang and Baranzini concludes that the competitive losses and distributive impacts are generally not significant for cap and trade or carbon taxes.[14] [15]

However, compared to comprehensive policies, there is less research on spillover effects for policies that apply only to a single fuel. The most extensive work has been done on the impact of biofuel mandates and how these policies may **increase**, not **decrease**, global emissions, by changing foreign land-use.[16] Literature on the carbon leakage of other types of policies is more limited. For example, Goulder, Jacobsen, and Benthem examine how one U.S. state's automobile fuel efficiency standard can cause emissions to spillover to other states, but did not look at international effects.[17] However, authors looking at these topics have noted that these effects likely exist.[18] [19]

These spillover effects may be much larger for coal-specific policies than for comprehensive policies. In particular, by ignoring natural gas emissions, coal-focused policies incentivize domestic fuel switching to natural gas more than comprehensive carbon policies do. And while coal can be traded globally, gas is difficult to transport.[20]

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[12] Fell and Maniloff, "Beneficial Leakage : The Effect of the Regional Greenhouse Gas Initiative on Aggregate Emissions."

[13] Paltsev, "The Kyoto Protocol: Regional and Sectoral Contributions to the Carbon Leakage"; Barker et al., "Carbon Leakage from Unilateral Environmental Tax Reforms in Europe, 1995-2005"; Böhringer, Balistreri, and Rutherford, "The Role of Border Carbon Adjustment in Unilateral Climate Policy: Overview of an Energy Modeling Forum Study (EMF 29)."

[14] Zhang and Baranzini, "What Do We Know about Carbon Taxes?"

[15] See also Arlinghaus, "Impacts of Carbon Prices on Indicators of Competitiveness: Review of Empirical Findings."

[16] Searchinger et al., "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases through Emissions from Land-Use Change."

[17] Goulder, Jacobsen, and van Benthem, "Unintended Consequences from Nested State and Federal Regulations: The Case of the Pavley Greenhouse-Gas-per-Mile Limits."

[18] Yeh and Sperling, "Low Carbon Fuel Standards: Implementation Scenarios and Challenges"; Goulder and Stavins, "Challenges from State-Federal Interactions in US Climate Change Policy."

[19] Riker, "International Coal Trade and Restrictions on Coal Consumption."

[20] Barbe and Riker, "Obstacles to International Trade in Natural Gas."

These trade effects can be substantial. Riker estimates that a U.S. policy to restrict domestic coal consumption could substantially impact coal exports to foreign countries.[21] Depending on how many other countries jointly implemented the policy, the restriction could increase exports by 47 percent, or decrease exports by 64 percent. Other researchers have looked at other countries. Richter, Mendelevitch, and Jotzo look at implications of an Australian coal export tax on both international trade and world emissions.[22] They find that such a policy could both reduce Australian welfare and increase world emissions. As a result, we should not be surprised if restrictions on domestic coal consumption induce very different amounts of carbon leakage or domestic welfare costs than comprehensive policies do.

The key questions are thus: how substantial are these spillover effects? And what is the impact of coal restrictions, once these spillovers are taken into account? In order to answer these questions, I simulate the impact of U.S. coal consumption restrictions using the GTAP-E model. I utilize this model because of its detailed treatment of the two areas most relevant for this policy: electricity generation and international trade. These features allow the model to accurately capture these carbon leakage and welfare spillovers.

The rest of this paper is organized into 4 sections. Section 2 gives an overview of my methodology. It describes the GTAP model, the coal restriction, how the GTAP model has to be modified in order to implement the coal restriction, how welfare is calculated, and how the model is verified to be accurate. Section 3 gives the results of the simulations: the effect of the coal restrictions on emissions, coal exports, and welfare. Section 4 provides concluding remarks that summarize the paper and point out some key limitations of the analysis.

2 Methodology

2.1 Overview of the Model

To simulate the effects of reducing coal consumption, I utilize version 6-pre2 of the GTAP-E model and version 8.0 of the GTAP database. The GTAP model is a multi-region multi-sector comparative static computable general equilibrium model of the world economy. Its database describes the world economy in 2007. GTAP-E is a modification of the main GTAP model that adds additional detail to the energy sector of the economy. For example, it allows for inter-fuel substitution and adds changes in carbon emissions as an outcome variable. My implementation of GTAP-E was aggregated to 8 sectors and 9 regions and was run using RunGTAP 3.61 and GEMPACK 11.4.003.

[21] Riker, "International Coal Trade and Restrictions on Coal Consumption."
[22] Richter, Mendelevitch, and Jotzo, "Market Power Rents and Climate Change Mitigation : A Rationale for Coal Taxes ?"

2.2 Description of the Coal Restriction

I calculate the impact of restricting coal consumption by comparing a baseline scenario to one where coal consumption is restricted. The baseline is the business-as-usual scenario of the world economy in 2007 as described in the GTAP database. In the coal restriction scenario, the U.S. electricity generation sector is required to decrease its ratio of the quantity of coal inputs used to the quantity of electricity generated by 10 percent below the baseline level. As the power sector generated 95 percent of all emissions from coal combustion in the United States in 2015, restricting this sector is very similar to an economy-wide restriction on coal combustion.[23] The effects of the coal restriction are expressed as the change of various economic outcomes under the restricted coal scenario relative to the baseline scenario. I also examine alternative versions of the coal restriction with a 20, 30, 40, or 50 percent decrease in the coal input ratio (instead of 10 percent).

2.3 Constrained Cost Minimization in GTAP-E

Modeling this policy experiment in GTAP-E presents a number of practical challenges that must be overcome. The main issue concerns the firm cost function in the standard GTAP-E model. When coal consumption is restricted, a binding constraint is added to the firm's cost minimization problem. As a result, the representative firm will no longer be using the input mix that unconditionally minimizes costs. However, this is not possible to implement in the standard GTAP-E model: the form of the GTAP-E equation that relates input prices to output costs implicitly assumes that the firm's cost minimization problem is an unconstrained optimization.

I resolve this issue by revising the GTAP-E firm cost equation to allow for constrained optimization. This necessitates changes in a number of related equations. I insert slack variables into the firm demand for each input, which will represent the additional shadow price of that input when quantity restraints for that input are binding. I also modify the firm cost function so that costs depend on these shadow prices as well as nominal prices. However, other than allowing constrained optimization, I do not change the properties of the GTAP-E cost function: the nesting structure of inputs remains the same and the modified nests remain constant elasticity of substitution with the same elasticity values.

In order to better understand my implementation of constrained optimization, I will walk through the original and revised equations related to one commodify, "ncoal".[24] Ncoal is the aggregate commodity containing non-coal energy products (crude oil, gas, and petroleum products). Analogous changes are made to the equations of other commodities.

[23] Environmental Protection Agency, "Inventory of U.S. Greenhouse Gas Emissions and Sinks Report: 1990-2015," 3–6.

[24] This is not an exhaustive list of the changes to the model. A number of other equations need to be altered in order to calculate pf_so or to get RunGTAP to report additional variables in the simulation results.

In the original GTAP-E model, the cost of producing non-coal energy to industry j in region r is calculated using the following TABLO code:

```
Equation NCOALFPRICE # price of non-coal energy #
(all,j,PROD_COMM)(all,r,REG)
   pf("ncoal",j,r) = sum(k,NCOAL_FCOMM, FSHNCOAL(k,j,r) * [pf(k,j,r) - af(k,j,r)]);
```

where k indexes the inputs into producing non-coal energy, FSHNCOAL(k,j,r) is the share of input k in total costs of producing ncoal, pf is the firm's price of that input, and af is input k augmenting technological change. However, note that this formulation does not allow for binding quantity constraints. To see this, compare the left and right hand sides of the equation. Imposing a binding quantity constraint on its inputs should (but does not) increase the cost of producing ncoal, the left hand side variable, even if there was no change in technology or the price of inputs, and thus the right hand side was unchanged.

In order to allow for unconstrained optimization, I amended this equation to instead be:

```
pf("ncoal",j,r) = sum(k,NCOAL_FCOMM, FSHNCOAL(k,j,r) * [qf(k,j,r) + pf(k,j,r)]) -
          qf("ncoal",j,r);
```

where qf is the quantity of input k used by industry j.

Analogous changes need to be made to the equation defining the input quantity. The original demand for inputs to make non-coal energy is calculated by:

```
Equation NCOALFDEMAND
# demand for inputs into non-coal energy subproduction #
(all,i,NCOAL_FCOMM)(all,j,PROD_COMM)(all,r,REG)
   qf(i,j,r) = -af(i,j,r) + qf("ncoal",j,r) - ELFNCOAL(j,r) * [pf(i,j,r) - af(i,j,r) - pf("ncoal",j,r)];
```

where ELFNCOAL(j,r) is the elasticity of substitution between the inputs used to produce ncoal for industry j in region r. Note that in this formulation, quantity demanded depends only on nominal prices, not shadow prices.

I modify the input demand equation to be:

```
qf(i,j,r) = -af(i,j,r) + qf("ncoal",j,r) - ELFNCOAL(j,r) * [pf_s(i,j,r) - af(i,j,r) -
pf_so("ncoal",j,r)];
```

where pf_s(i,j,r) is the shadow price of input i and pf_so("ncoal",j,r) is the price of ncoal calculated using the shadow prices of inputs, instead of their nominal prices.

Now that the existing GTAP-E equations have been revised to allow for binding constraints, the last step is introducing the new equations. These equations involve the consumption intensity variable to be shocked and the shadow price of inputs. The shadow price of an input is defined as

Equation pf_sBINDING
 # relates the shadow and real price of commodities i for use by j in r #
(**all**,i,FIRM_COMM)(**all**,j,PROD_COMM)(**all**,r,REG)
pf_s(i,j,r) = pf(i,j,r) + pf_slack(i,j,r);

where pf_slack(i,j,r) is a slack variable that describes whether there is a binding constraint on the use of input i by industry j in region r. Finally, the input to output ratio (which is shocked by –10 to –50 percent in the scenarios) is defined as

Equation NCOALFINTENS
 # demand for inputs into non-coal energy subproduction divided by output#
(**all**,i,NCOAL_FCOMM)(**all**,j,PROD_COMM)(**all**,r,REG)
intf(i,j,r) = qf(i,j,r) - qf(*"ncoal"*,j,r);

In the initial state, pf_slack(i,j,r) is exogenous and intf(i,j,r) is endogenous. A binding constraint can be imposed on the firm cost function by swapping the slack variable pf_slack(i,j,r) with intf(i,j,r) and then shocking intf(i,j,r) in order to achieve the desired change in the ratio.

2.4 Welfare

With these modifications, special care must be taken in the model's welfare calculation. GTAP-E calculates welfare using two different variables, EV(r) and EV_ALT(r).[25] These variables are normally equivalent but are calculated using two different methods. In particular, EV_ALT(r) is calculated directly from the prices of goods, while EV(r) is calculated from consumption expenditures. Unfortunately, the modifications I made to input prices and quantities in order to allow binding constraints also break the EV_ALT(r) calculation. As a result, all welfare calculations discussed in this paper are calculated using EV(r) instead.

The marginal welfare cost of abatement is a standard summary statistic used for analyzing the cost of emission abatement.[26] However, it is not normally calculated by GTAP-E. Calculating the marginal U.S. welfare cost of abatement requires calculating two things: the marginal change in welfare and the marginal change in world emissions, and then dividing the former by the latter. This is accomplished by running additional simulations where the coal

[25] GTAP measures welfare using equivalent variation. The equivalent variation of the coal restriction is the reduction in baseline household income under the original prices that would give them the same utility as under the coal restriction.

[26] For a discussion of why welfare costs should not be measured indirectly through carbon prices, see Morris, Paltsev, and Reilly, "Marginal Abatement Costs and Marginal Welfare Costs for Greenhouse Gas Emissions Reductions: Results from the EPPA Model."

input ratio is reduced by 1 additional percent, for a total reduction of 11, 21, 31, 41, or 51 percent. So, for example, the marginal U.S. welfare cost of abatement in the 20 percent simulation is 35 dollars per metric ton. This is equal to the change in U.S. welfare between the 20 and 21 percent simulation divided by the change in world emissions between the 20 and 21 percent simulation.

2.5 Model Verification

I took two steps in order to verify that the model's code accurately implemented the conceptual changes described above. First, I utilized Walras' Law. In general equilibrium, if all markets in the economy but one are in equilibrium, the last market must also be in equilibrium. This means that the system of equations describing the economy has one redundant equation. In this equation, the left-hand side is guaranteed to equal the right-hand side, if all the other equations were solved correctly. As a result, this last equation provides a useful check that the other equations in the system are solved correctly. In the GTAP model, the difference between the right and left hand sides is defined by the variable "walraslack." In my model, this variable was 0 to the computational precision typically used to display results (6 decimal places).

However, this method only checks whether the solution is an equilibrium. It does not check that the economy described is credible, or that the policy shock imposed is the one that I meant to impose. In order to check for these types of errors, I utilized a second check. I ran my model with policy "shocks" that should have no effect: no constraint on coal consumption and a non-binding constraint. In both cases, my model correctly indicated that the "shocks" had no effect.

3 Results

The coal restriction decreases U.S. coal consumption, but increases U.S. consumption of oil and gas and foreign consumption of coal (see Table 1). So the reduction in U.S. coal emissions is indeed partially offset by domestic fuel switching and increased U.S. exports of coal. However, the reduction in U.S. emissions from coal is much larger than the increase in emissions from these other mechanisms. As a result there is still a net reduction in emissions, and it is similar in magnitude to the reduction in coal emissions alone.

The coal restriction reduces U.S. emissions. Emissions from coal in the United States decrease by 204 to 1,294 million metric tons (MT) of CO2 equivalent per year, or 3 to 17 percent of total U.S. emissions. However, energy consumers substitute to oil and gas and so U.S. emissions from these fuels increase by 31 to 368 million MT. This substitution increases with the stringency of the coal restriction: it offsets 15 percent of the reduction in coal emissions when coal is restricted by 10 percent, but offsets 28 percent of the coal reduction when coal is restricted by 50 percent.

Table 1: Change in Carbon Emissions and Coal Exports from Restricting Coal Consumption

Coal Intensity Reduction (percent)	10	20	30	40	50
Change in U.S. Coal Emissions (million MT)	-204	-427	-676	-958	-1,294
Change in U.S. Oil and Gas Emissions (million MT)	31	72	127	212	368
Change in Rest of World Emissions (million MT)	-1	-2	-2	-3	-4
Change in Total World Emissions (million MT)	-173	-357	-551	-750	-930
Change in U.S. Coal Exports (percent)	3.3	7.7	13.9	23.2	39.4
Ratio of Change in Emissions, U.S. Oil and Gas / U.S. Coal	-0.15	-0.17	-0.19	-0.22	-0.28
Ratio of Change in Emissions, Rest of World / U.S. Coal	0.004	0.004	0.004	0.004	0.005
Ratio of Change in Emissions, Total World / U.S. Coal	0.85	0.84	0.81	0.78	0.72
Change in Total U.S. Emissions (percent)	-3	-6	-10	-13	-17

Restricting U.S. coal consumption leads to increased U.S. coal exports. Once again, the effect increases with the stringency of the coal restriction. For a 10 percent restriction, coal exports increase by 3.3 percent. For a 50 percent restriction, they increase by 39.4 percent.

However, there is almost no change in emissions in the rest of the world (see Rest of the World / U.S. Coal in Table 1). This is because although foreign coal emissions increase, increased U.S. demand for oil and gas reduces foreign demand and emissions from these fuels (foreign fuel switching). These two effects approximately cancel out, leading to a net reduction in foreign emissions equal to 0.4 to 0.5 percent of the reduction in U.S. coal emissions.

When all these effects are taken into account, the effect of the U.S. restricting coal consumption is to reduce world emissions. World emissions fall by 173 million MT for a 10 percent coal intensity reduction and by 930 million MT for a 50 percent coal intensity reduction. As the coal becomes more restricted, the effects of foreign interfuel substitution and increased foreign coal consumption continue to cancel each other out. But the effect of U.S. fuel substitution offsets more and more and more of the U.S. coal emissions reduction.

The welfare costs of the coal restriction are concentrated in the United States, but not to the same extent as the emissions changes. Welfare costs increase with the stringency of the coal restriction, ranging from 1.3 to 89.9 billion dollars per year (see Table 2). Expressed in terms of the change in world emissions, the U.S. welfare cost ranges from $15 to $678 per MT CO_2 equivalent, with marginal costs increasing as the magnitude of the coal restriction increases.

Table 2: Change in Welfare from Restricting Coal Consumption

Coal Intensity Reduction (percent)	10	20	30	40	50
Change in U.S. Welfare (billion USD)	-1.3	-5.6	-15.3	-36.6	-89.9
Change in Rest of World Welfare (billion USD)	0.2	0.9	2.4	5.7	13.8
Change in Total World Welfare (billion USD)	-1.1	-4.7	-12.9	-30.9	-76.1
Ratio of Changes in Welfare, Rest of World / United States	-0.19	-0.17	-0.16	-0.16	-0.15
Marginal U.S. Welfare Cost (USD per MT CO_2)	15	35	73	166	678

The U.S. restriction causes changes in trade that benefit foreign households. Aggregate foreign welfare increases and the largest foreign beneficiaries are Eastern European countries, energy exporting countries, and some small developed countries. Foreign welfare increases range from 15 to 19 percent of the U.S. domestic reduction. As the coal reduction becomes more stringent, the dollar value of the foreign welfare gain increases, but its share of the total welfare change falls. This means that as the restriction increases in strength, the welfare cost to the United States increases faster than the gains to foreign countries do.

4 Conclusions

Reducing coal consumption is a goal of many countries' energy and environmental policies. However, policies that restrict domestic coal consumption also incentivize the export of coal to non-abating foreign countries and encourage coal consuming industries to move their production to these countries. This paper uses a modified version of the GTAP-E model to quantify these effects for a U.S. restriction on coal consumption.

I find that a restriction on coal consumption in the United States has a negligible effect on foreign emissions but a substantial effect on foreign welfare. U.S. coal exports increase, but this is offset by increased U.S. demand for oil and gas, reducing the availability of these fuels in foreign countries. Although foreign carbon leakage is minimal, domestic fuel switching is not: it reduces the total domestic emission reduction by 15 to 28 percent.

But although foreign emissions do not change, foreign welfare does, as the restriction causes changes in trade that benefit foreign households. While the marginal U.S. welfare cost of abatement ranges from 15 to 678 dollars per metric ton, foreign welfare increases by 15 to 19 percent of the U.S. welfare loss.

This research has two areas for improvement that provide a natural opportunity for future work. The database used for this simulation is from 2007. Since then, the energy sector has changed substantially due to increased energy demand by developing countries, the adoption of hydraulic fracturing, and falling renewable costs. As a result, updating the database could have a substantial impact. Improvements could also be made to the GTAP-E model itself, as Beckman, Hertel, and Tyner have critiqued the default GTAP-E parameters and Peters developed a GTAP model with more detailed information on electricity generation.[27]

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