The Effects 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' 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. I use 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 do increase, but this is mostly offset by reduced foreign use of oil and gas. But although foreign emissions do not change, foreign welfare does, as the restriction causes changes in trade that benefit foreign households. I also find that coal restrictions lead to increased usage of gas for electricity generation. As a result, coal reductions of more than 30 percent have almost no further impact on emissions. However, due to the very large percentage changes these restrictions impose, there is substantial uncertainty in the level of emissions under such policies.

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Disclaimer

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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 its impact on world emissions is ambiguous, depending on whether foreign production is more or less emission intensive than in the United States.[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] But although they haven't been quantified, 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, 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."

The literature on coal policies shows that these spillover 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 coal restriction, the restriction could increase exports by 47 percent, or decrease exports by 64 percent. Look at implications of an Australian coal export tax, Richter, Mendelevitch, and Jotzo find that such a policy could both reduce Australian welfare and increase world emissions.[22] 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 capture these carbon leakage and welfare spillovers.

I find that a policy that restricted U.S. coal consumption would lead to substantial changes in U.S. electricity generation, but only have small impacts on the rest of the world's emissions. While U.S. coal exports to the rest of the world would increase, the effect is small, leading to little international carbon leakage. However, substantial interfuel switching would occur in the United States, as generators replace coal with gas. This means that while all policies do reduce emissions, restrictions greater than 30 percent are more costly but do not really reduce emissions further. However, the model predicts electricity generation in the United States will be substantially different than historical norms, with far more gas than coal. Since the model's parameters' are derived from history, this means the model's predictions are less reliable in that area. Internationally, the costs of abatement are almost entirely concentrated in the United States, with the rest of the world actually benefiting from the U.S. restriction on coal consumption.

The rest of this paper is organized into 3 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 electricity generation, coal trade, emissions, and welfare. Section 4 provides concluding remarks that summarize the paper and point out avenues for future work.

[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 Methodology

2.1 Overview of the Model

To simulate the effects of reducing coal consumption I use the GTAP-E model. The GTAP model is a multi-region multi-sector comparative static computable general equilibrium model of the world economy. 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.[23]

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 2011 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 all energy commodities used (coal, oil, gas, and petroleum products) by 10 percent. As the power sector generated 95 percent of all emissions from coal combustion in the United States in 2015, [24] restricting this sector is very similar to an economy-wide restriction. 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, or 40 percent decrease in the coal input ratio (instead of 10 percent).

2.3 Constrained Cost Minimization in GTAP-E

In order to model this policy experiment in GTAP-E, a number of practical challenges must be overcome. The main problem is 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

[23] My implementation of GTAP-E was aggregated to 8 sectors and 9 regions and was solved using GEMPACK release 11.40. I use version 6-pre2 of the GTAP-E model and version IR9.2_2011_Jan2017 of the GTAP-E database.
[24] Environmental Protection Agency, "Inventory of U.S. Greenhouse Gas Emissions and Sinks Report: 1990-2015," 3–6.

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”.[25] 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.

In the original GTAP-E model, the cost of producing non-coal energy to industry j in region r is calculated using the following GEMPACK 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)];
```

[25] 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.

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 –40 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).[26] These variables are calculated using two different methods that are normally equivalent. EV_ALT(r) is calculated

[26] 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.

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.[27] 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 input ratio is reduced by 1 additional percent, for a total reduction of 11, 21, 31, or 41 percent. So, for example, the marginal U.S. welfare cost of abatement in the 20 percent simulation is 151 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) in all simulations except for the 40 percent emissions reduction, where it was 0.000001.

However, the above 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.

[27] 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."

3 Results

A policy that restricted coal consumption would lead to substantial changes in U.S. electricity generation, but only have small impacts on the rest of the world's emissions. While U.S. coal exports to the rest of the world would increase, the effect is small, leading to little international carbon leakage. However, substantial interfuel switching would occur in the United States, as generators replace coal with gas. This means that while all policies do reduce emissions, restrictions greater than 30 percent increase costs but do not really reduce emissions further. However, the substantial transformation of generation that is predicted under those policies means the model's predictions are less reliable in that area. Turning to international markets, the costs of abatement are almost entirely concentrated in the United States, with the rest of the world actually benefiting from the U.S. restriction on coal consumption.

3.1 Effects on Electricity Generation

A policy that restricted coal consumption would lead to substantial changes in the mix of fuels used for electricity generation in the United States (see Table 1). The model indicates that the policy would reduce electricity use in the United States, decrease coal demand, and increase gas demand. These effects greatly increase in magnitude as the restriction becomes more severe: demand for gas for electricity generation increases by 13 percent under a 10 percent coal reduction policy but by 135 percent under a 40 percent policy.

Table 1: Effects of Restricting Coal Consumption on U.S. Electricity Generation

	Coal Intensity Reduction Policy			
Change in Economic Variable (Percent)	**10**	**20**	**30**	**40**
Electricity Generation	0	-2	-7	-22
Demand for Gas for Generation	13	32	64	135
Demand for Coal for Generation	-11	-23	-39	-62
Generation use of Coal / All Energy Commodities	-10	-20	-30	-40
Generation use of Gas / Non-coal Energy Commodities	14	38	89	276

However, the size of some of the increases are so large, they may be outside the valid predictive range of the GTAP-E model. GTAP-E draws its parameter values from historical observations, which means these values may not hold for scenarios that are far from anything ever observed historical. For example, the true sector-wide elasticity of substitution between coal and gas may take one value when the two are roughly equal fractions of electricity generation (as in 2011) but may take a very different value if gas provides the vast majority of electricity (as in the 40 percent reduction policy).

As a result, while we can confidently say that coal restrictions of 30 percent or higher will lead to large changes in U.S. electricity generation, some of our specific predictions in these scenarios become uncertain. This caveat applies to some key findings of this paper: the amount of coal to gas fuel switching, the emissions reductions of the policy, and the marginal welfare cost of the emission reduction. However, findings related to other variables which did not change so drastically are much less likely to have these problems. For example, this problem is less likely to impact findings on the lack of international carbon leakage, the effects on the rest of the world, or U.S. industries outside of generation, since even in the 40 percent scenario, these variables are not too far from their historical values.

3.2 Effects on Coal Trade

Restricting U.S. coal consumption leads to increased U.S. coal exports (see Table 2). The effect increases with the stringency of the coal restriction: for a 10 percent restriction, coal exports only increase by 3 percent. But for a 40 percent restriction, they increase by 29 percent. This leads to reduced foreign coal production, decreasing total world coal production.

Table 2: Effects of Restricting Coal Consumption on Coal Trade

	Coal Intensity Reduction Policy			
Change in Economic Variable (Percent)	**10**	**20**	**30**	**40**
U.S. Production	-8	-17	-28	-44
U.S. Imports	-5	-10	-17	-26
U.S. Exports	3	7	14	29
World Production	-1	-3	-5	-9

3.3 Effects on Emissions

The coal restriction decreases U.S. coal consumption, but increases foreign consumption of coal and U.S. consumption of oil and gas (see Table 3). 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 larger than the increase in emissions from these other mechanisms, so despite carbon leakage, the policy does reduce global emissions. And while fuel switching is substantial, international carbon leakage is very small.

Table 3: Effects of Restricting Coal Consumption on Emissions

	Coal Intensity Reduction Policy			
	10	**20**	**30**	**40**
Cumulative Change in Emissions by Source (million MT)				
U.S. Total	-117	-236	-344	-364
U.S. Coal	-181	-396	-667	-1,061
U.S. Oil	0	0	0	0
U.S. Gas	60	148	298	634
Non-U.S. Total	-1	-3	-6	-13
World Total	-119	-239	-350	-377
Change in Total U.S. Emissions (percent)	-2	-5	-7	-7

However, policies that reduce coal intensity have substantially diminishing returns. The coal restriction does reduce total U.S. emissions and emissions from coal specifically fall by up to 1,061 million metric tons (MT) of CO2 equivalent per year. But energy consumers substitute to gas, increasing its emissions by up to 634 million MT. This substitution increases disproportionately with the stringency of the coal restriction: it offsets 33 percent of the reduction in coal emissions when coal is restricted by 10 percent, but offsets 60 percent of the coal reduction when coal is restricted by 40 percent. As a result, policies beyond 30 percent have almost no further impact on emissions. Although note that as discussed in section 3.1, these may be “out of sample” predictions for GTAP-E.

In all scenarios, there is almost no change in emissions in the rest of the world. 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 negligible net reduction in foreign emissions.

3.4 Costs of Emissions Reductions

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 2.8 to 146 billion dollars per year (see Table 4). Expressed in terms of the change in world emissions, the U.S. welfare cost ranges from $51 to $1,597 per MT CO2 equivalent, with marginal costs increasing as the magnitude of the coal restriction increases.

Table 4: Welfare Costs of Restricting Coal Consumption

	Coal Intensity Reduction Policy			
	10	**20**	**30**	**40**
Change in Welfare (million USD)				
U.S.	-2,801	-13,419	-43,221	-146,342
Non-U.S.	895	3,891	12,033	39,745
Total World	-1,906	-9,528	-31,188	-106,597
Ratio of Change in Welfare, Non-U.S. / U.S.	-0.32	-0.29	-0.28	-0.27
Marginal U.S. Welfare Cost (USD per MT)	51	151	571	-1,597

The U.S. restriction causes changes in trade that benefit foreign households. Aggregate foreign welfare increases and the largest foreign beneficiaries are the European Union, energy exporting countries, and some small developed countries. Foreign welfare increases range from 27 to 32 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.

However, note that restricting coal consumption has two distinct effects on welfare. It increases welfare by reducing air pollution and greenhouse gas emissions, leading to improved health and reduced climate change. It also affects welfare through more purely economic mechanisms, such as allocative efficiency and terms of trade. However, the GTAP-E model can only quantify the economic impacts of the coal restriction, not their environmental or health benefits. So while focusing on the costs of the policy, we should not conflate the welfare costs of the policy with the policy's net impact on welfare, if the environmental and health benefits were included.

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 results in substantial domestic fuel switching. The effect of fuel switching increases with the stringency of the coal restriction. As a result, restrictions beyond

30 percent have almost no further impact on emissions. However, the transformation of the U.S. energy industry predicted under this scenario is so different from the historical norm, that it may be outside the bounds for which the model's parameters are credible. Internationally, although foreign countries do not substantially change their emissions, changes in terms of trade benefit foreign households by approximately 30 percent of the U.S. welfare costs.

This research has two areas for improvement that provide a natural opportunity for future work. First, further improvements could be made to the GTAP-E model itself. For example, Beckman, Hertel, and Tyner have critiqued the default GTAP-E parameters and Peters developed a GTAP model with more detailed information on electricity generation.[28]

However, I believe that the best approach is to use a partial equilibrium model that focuses on the specific technologies available to electricity generators. This paper has found that severe coal restrictions would lead to substantial changes in how electricity is generated, and this is exactly where a partial equilibrium model excels. Conversely, this paper shows that the disadvantages of a partial equilibrium model are unimportant, as the policy has only small effects on other sectors of the U.S. economy, or the world at large. Thus, the results of this analysis indicate that a detailed partial equilibrium model is the best path for future analysis of restrictions on coal consumption.

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