**TransEnergy Global Pte Ltd**
Level 42
Suntec Tower Three
8 Temasek Boulevard
Singapore 038988

transenergy-global.com

# LEAKAGE AND MARKET DISPLACEMENT ASSESSMENT FOR COAL EXTRACTION AVOIDANCE PROJECTS

## Permanent Avoidance of Coal Extraction for a Just Energy Transition

This report forms part of the TransEnergy Global coal abatement methodology "Permanent Avoidance of Coal Extraction for a Just Energy Transition" framework and provides the technical assessment of market leakage and emissions displacement effects associated with coal supply reduction.

**Reference document for climate mitigation projects 2026, V5.0**

**Author: Alla Golub**

Final report submitted to TransEnergy Global

VERSION 5.0

March 2026

## Published by

TransEnergy Global

## Registered offices

Level 42 Suntec Tower Three
8 Temasek Boulevard
Singapore 038988

## Website

https://transenergy-global.com/contact/

## Contact

✉ duncan@transenergy-global.com
✉ brad@transenergy-global.com

## Author

**Alla A. Golub, PhD**
Lead Research Economist
Center for Global Trade Analysis
Department of Agricultural Economics
Purdue University
403 Mitch Daniels Blvd., West Lafayette, IN 47907 USA
✉ golub@purdue.edu

## Version

5.0

## Cite as

Golub, A. (2026). Leakage and Market Displacement Assessment for Coal Extraction Avoidance Projects

Retrieved from:
https://transenergy-global.com/resources/

## Independent Technical Review

**Dr. Vladimir Tyazhelnikov**
The University of Sydney
✉ vladimir.tyazhelnikov@sydney.edu.au

March 6, 2026

Dr. Vladimir Tyazhelnikov is a Senior Lecturer in Economics at the University of Sydney and holds a Ph.D. in Economics from the University of California, Davis. He specializes in international trade and quantitative economic modelling, with particular interest in structural models and their application to global production, trade flows, and policy evaluation.

# Contents

# Tables

# Figures

## Abbreviations

| | |
|---|---|
| $CO_2$ | Carbon Dioxide |
| GHG | Greenhouse gases |
| IEA | International Energy Agency |
| GTAP | Global Trade Analysis Project |
| $N_2O$ | Nitrous Oxide |
| $CH_4$ | Methane |
| WRI | World Resources Institute |

# 1. Introduction

Coal is an abundant fuel source that is relatively inexpensive to produce and convert to useful energy (U.S. EIA, 2024). It is extensively used in electric power generation and heavy industry due to its availability, low cost, and role in certain industrial processes such as steelmaking (IEA, 2025a). However, coal mining and transportation release carbon dioxide ($CO_2$) and methane ($CH_4$) gases, and the combustion of coal results in $CO_2$ and nitrous oxide ($N_2O$) emissions, as well as other gases and substances harmful to human health and the environment. The burning of coal accounts for the largest share of $CO_2$ emissions globally, primarily in the power sector. Phasing out coal power is the most important step the world can take to curb climate change (WRI, 2023).

The United States and South Africa are among the world's top seven coal-producing countries. In the United States, the share of coal in the total energy supply was 9%, and net coal exports represented 25% of coal production in 2024 (IEA, 2025a)[1]. In 2022, $CO_2$ emissions from burning coal for energy accounted for about 19% of total U.S. energy-related $CO_2$ emissions and about 55% of total $CO_2$ emissions from the electric power sector (U.S. EIA, 2024). Methane emissions from active and abandoned coal mines accounted for about 7% of total U.S. methane emissions and about 1% of total U.S. greenhouse gas (GHG) emissions in 2021 (based on global warming potential) (U.S. EIA, 2024)[2]. In South Africa, the share of coal in the total energy supply was 69.3%, net coal exports represented 35.4% of coal production, and the share of coal emissions in total $CO_2$ emissions from fuel combustion was 80% in 2023 (IEA, 2025b)[3].

The goal of this project is to evaluate the economic and GHG emissions implications of reducing coal production in South Africa and the United States. Specific objectives include quantifying the impacts on:

1) coal prices in South Africa, the United States, and globally;
2) production and use of coal around the world;
3) South Africa, the United States, and their trading partners' exports and imports of coal;
4) GHG emissions in South Africa, the United States, and globally, and an assessment of emissions leakage.

---

[1] https://www.iea.org/countries/united-states/coal

[2] https://www.eia.gov/energyexplained/coal/coal-and-the-environment.php

[3] https://www.iea.org/countries/south-africa/coal

# 2. Methods

The study employs a multi-sector, multi-region, comparative static, computable general equilibrium GTAP-E-Power model (Peters 2016a), a version of the standard Global Trade Analysis Project (GTAP) model (Corong et al. 2017; Hertel 1997)[4]. Similar to the standard GTAP, the GTAP-E-Power model assumes perfect competition and constant returns to scale. Bilateral trade is modeled using the Armington assumption, under which goods produced in different countries are imperfect substitutes for one another due to their country of origin (Armington 1969). The model estimates production, consumption, trade, and price effects of changes in policies, technologies, and other shocks. It takes into account interindustry linkages as well as impacts mediated through factor markets and trade. The model is employed together with the GTAP-Power data base (Chepeliev 2023; Peters 2016b) with reference year 2017 (the latest year available at the time of writing). The GTAP-Power data base extends the standard GTAP data base version 11c (Aguiar et al. 2023) to include a detailed representation of electric power generating technologies: transmission and distribution, coal, gas, oil, nuclear, hydroelectric, wind, solar, and other. Gas, oil, and hydroelectric power are further differentiated as base and peak load. The data base also includes information on $CO_2$ and non-$CO_2$ GHG emissions by sector and driver (Chepeliev 2024a; 2024b). The model and data are designed to analyze the energy-economy-environment-trade linkages.

The GTAP-Power data base represents the global economy with 160 countries and regions and 76 production activities[5]. To create a regional aggregation of the 160 countries and regions for the model, we analyze coal exports and imports for South Africa and the United States. About 80% of coal exports from South Africa are shipped to 10 countries shown in Figure 1, with India being the single largest destination country (37%). South Africa also imports coal, though the imports are small relative to exports (about 1% of exports). The main sources of coal imports are Australia, Eswatini, and Botswana (Figure 2). Major destinations for U.S. coal include India, Japan, Germany, and South Korea (Figure 3). The United States' imports of coal are minimal and mainly come from Colombia and Canada. The United States imports coal to meet some domestic demand. For coal-burning power plants along the Gulf Coast and the Atlantic Ocean, it is sometimes cheaper to import coal from other countries than to obtain coal from U.S. coal-producing regions (U.S. EIA 2023)[6]. Using information on the importance of each of South Africa's and the United States' trading partners as measured by the share in exports and imports (Figures 1-3), as well

---

[4] The analysis uses the GTAP-Power model code synchronized with version 7 of the standard GTAP model code (Corong 2023), and modified for this study to track changes in non-$CO_2$ and process-based $CO_2$ GHG emissions.

[5] See https://www.gtap.agecon.purdue.edu/databases/contribute/detailedsector.asp for a description of GTAP sectors and https://www.gtap.agecon.purdue.edu/databases/regions.aspx?version=10.211 for a description of GTAP regions. The single electricity sector present in the standard GTAP data base is disaggregated into 11 generation technologies and a transmission and distribution activity, resulting in 76 sectors in the GTAP-Power data base.

[6] https://www.eia.gov/energyexplained/coal/imports-and-exports.php

as the standard GTAP grouping of the regions based on the location of each country/region[7], 160 GTAP countries and regions of the GTAP database are aggregated into 48 countries and regions (Appendix A1), with South Africa, the United States, and its main trading partners and competitors in coal markets represented as separate countries.

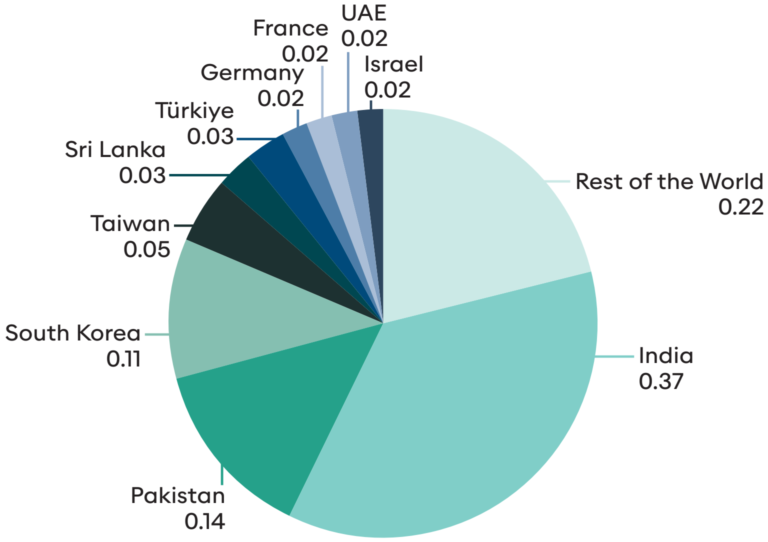

**Figure 1. Structure of South Africa's coal exports (value share)**

Source: Constructed by the author using the GTAP v.11 data base.

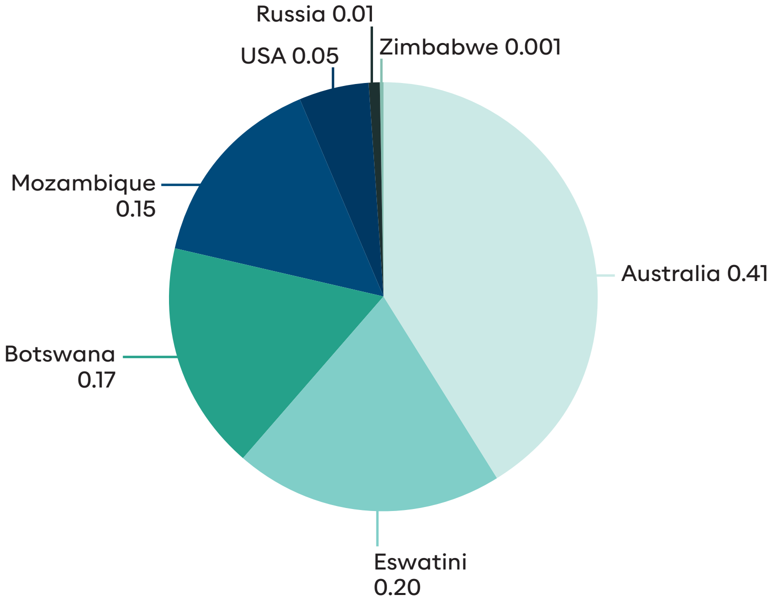

**Figure 2. Structure of South Africa's coal imports (value share)**

Source: Constructed by the author using the GTAP v.11 data base.

---

[7] These regions are East Asia, Latin America, Middle East and North Africa, North America, Oceania, South East Asia, South Asia, Sub Saharan Africa, Western Europe and Rest of the World.

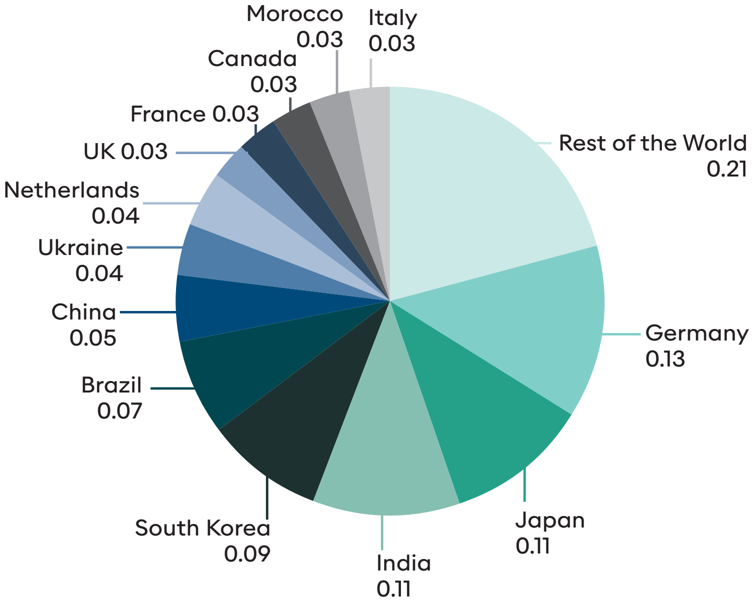

**Figure 3. Structure of U.S. coal exports (value share).**

Source: Constructed by the author using the GTAP v.11 data base.

To construct an aggregation of the 76 production activities, we analyze industrial use of coal and overall industrial energy use within South Africa and the United States. In South Africa, the largest industrial uses of coal are coal power plants and petrochemical production, representing 61% and 24% of total industrial use (Figure 4). In the United States, use of coal is even more concentrated, with coal-powered electricity generation accounting for more than 90% of total industrial use, followed by small shares used by petroleum & coke and non-metallic mineral products (Figure 5). The largest industrial users of energy from all sources (natural gas, oil, coal, petroleum products, electricity) in South Africa are coal-powered electricity generation, followed by the petrochemical sector. In the United States, the largest user of energy is the petrochemical sector, followed by coal power plants (Figures 6 and 7)

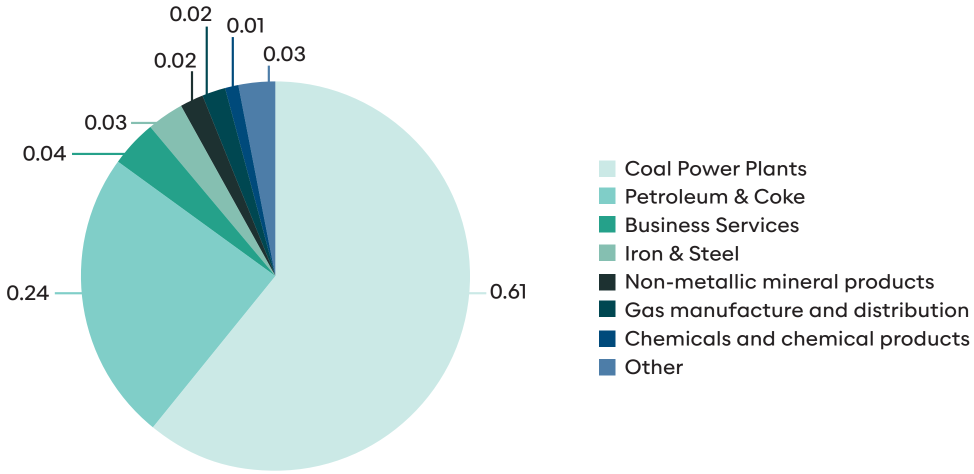

**Figure 4. Structure of industrial use of coal in South Africa (share in the sum of domestic and imported Mtoe[8]).**

Source: Constructed by the author using the GTAP v.11 data base.

---

[8] Mtoe stands for million tonnes of oil equivalent.

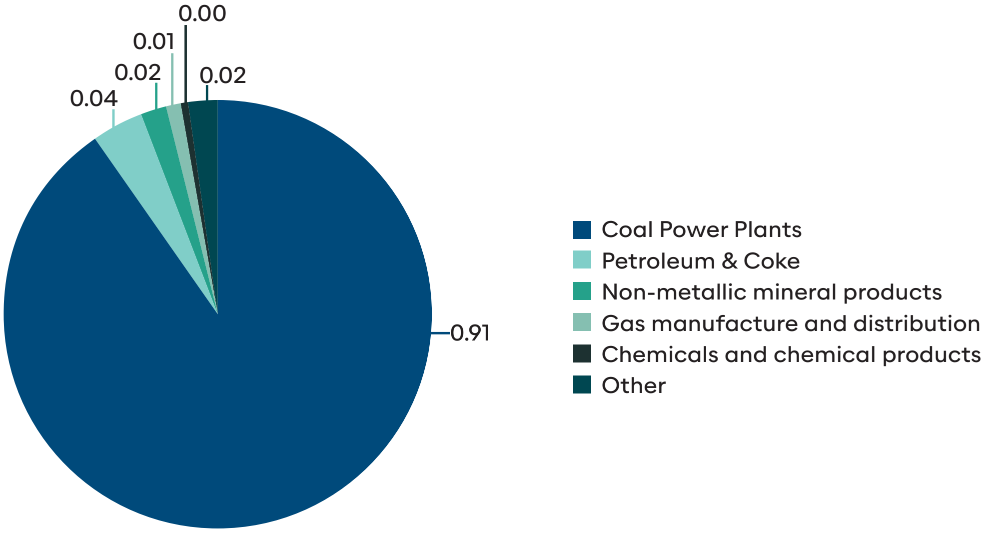

**Figure 5. Structure of industrial use of coal in the United States (share in the sum of domestic and imported Mtoe).**

Source: Constructed by the author using the GTAP v.11 data base.

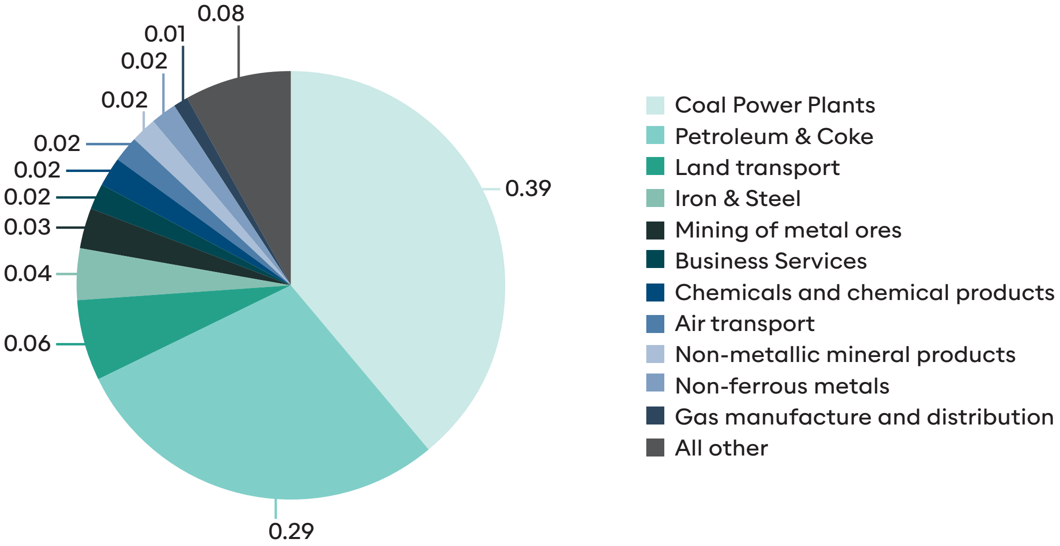

**Figure 6. Share of economic activity in total industrial energy use in South Africa (share in the sum of domestic and imported Mtoe).**

Source: Constructed by the author using the GTAP v.11 data base.

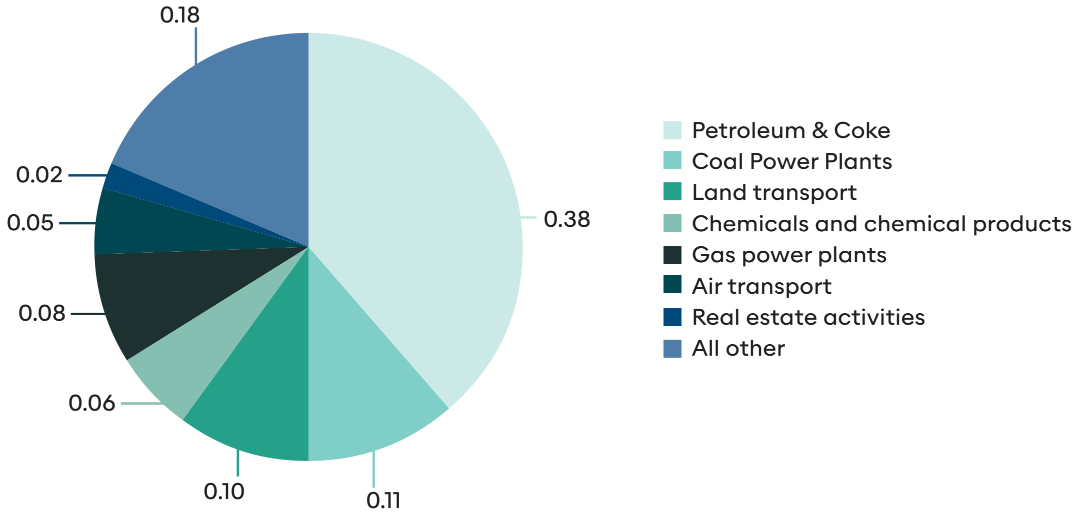

**Figure 7. Share of economic activity in total industrial energy use in the United States (share in the sum of domestic and imported Mtoe)**

Source: Constructed by the author using the GTAP v.11 data base.

Using information about the structure of industrial coal and overall energy use, we aggregate 76 sectors of the GTAP-Power data base into 31, with all energy commodities, electricity generation technologies, other coal-intensive, and overall energy-intensive sectors represented as individual sectors (Appendix A2).

This framework is used to simulate the reduction of coal output in South Africa by 3.12% and in the United States by 1%.[9] In the GTAP model, sector output variables are endogenous under the standard model closure. To implement a reduction in coal output in the model, coal output is "swapped" with an exogenous technical change variable such that the coal output variable becomes exogenous and can be reduced, while the technology variable becomes endogenous and changes to accommodate the imposed reduction in output.[10] The simulations are used to quantify the impacts of leaving coal in the ground on coal prices, production, trade, and emissions.

The reduction in coal output in the United States and South Africa will likely lead to an increase in the production and use of other sources of energy in these two countries and a reduction in

---

[9] The size of the shock for coal output in South Africa was determined in discussion with TransEnergy Global. In South Africa, the Limpopo Project site produces approximately 15 million tonnes (Mt) of coal per annum. We consider the reduction of coal output from 15 to 7.86 Mt per annum. This represents a 7.14 Mt per annum reduction, which is about a 3.12% reduction relative to South Africa's national coal output of 228.5 Mt in 2023-2024. 1% reduction in coal output in the United States is hypothetical.

[10] Except for the coal output swapped with technology, the standard GTAP model closure is used. The comparative static simulations are conducted assuming a medium-run adjustment period.

coal exports. Also, the United States and South Africa may increase imports of coal (currently relatively small), as well as imports of other energy commodities. These changes, in turn, will lead to the expanded production of coal and other energy commodities around the world. Environmental benefits from leaving coal in the ground in these two countries may result in negative environmental outcomes elsewhere. Using simulated changes in GHG emissions, we calculate GHG emission leakage from the reduction of coal output in South Africa and the United States. The supply shock simulations for South Africa and the United States are implemented independently, and the results are presented independently (i.e., only one supply reduction shock is modeled at a time).

# 3. Results

## 3.1. Impacts of reducing coal output in South Africa

A 3.12% reduction in coal output in South Africa leads to a relatively small increase in coal prices in both domestic and international markets. South Africa experiences a 1.77% increase in coal prices, while the impact on other countries remains negligible (Table 1). Globally, the coal price increased by 0.07%.

**Table 1. Impacts of a 3.12% reduction in coal output in South Africa and 1% reduction in coal output in the United States on coal prices in major coal-producing countries**

| Region | Reference value share in global coal production | Change in coal prices in the South Africa scenario, % | Change in coal prices in the USA scenario, % |
|---|---|---|---|
| China | 0.41 | 0.00 | 0.00 |
| USA | 0.12 | 0.01 | 0.79 |
| Australia | 0.11 | 0.03 | 0.03 |
| India | 0.07 | 0.02 | 0.01 |
| Indonesia | 0.06 | 0.03 | 0.02 |
| Russia | 0.06 | 0.02 | 0.03 |
| South Africa | 0.04 | 1.77 | 0.02 |
| R_Europe | 0.02 | 0.01 | 0.02 |
| Germany | 0.02 | 0.00 | 0.01 |
| Canada | 0.01 | 0.02 | 0.03 |
| Colombia | 0.01 | 0.04 | 0.07 |
| World | 1 | 0.07 | 0.11 |

Source: Author's simulations.

About two-thirds of coal produced in South Africa is used domestically, and one-third is exported to South Africa's trading partners in the coal market (Figure 1). Within the domestic economy, South African households account for 0.05 share, whereas production activities account for 0.95 share, primarily driven by coal power plants and petroleum & coke sectors (Table 2). The reduction in coal output results in about 1% reduction in domestic use of coal and 7% reduction in coal exports. Within the domestic use, all sectors that use coal experience a reduction in the use of domestic coal, with coal power plants and the petroleum & coke sector reducing domestic coal input by 0.86% and 0.62%, respectively. The largest relative reduction in coal use, 4.29%, is by South Africa's gas industry, which uses coal to produce synthetic natural gas (Table 2).

### Table 2. Reference levels and changes in domestic use of coal and related GHG emissions due to a 3.12% reduction in coal output in South Africa

| Sector | Reference | | | Change | | |
|---|---|---|---|---|---|---|
| | Use, Mtoe | Share | Emissions from use of coal, $MtCO_2eq$[11] | Use, Mtoe | Use, % | Emissions from use of coal, $MtCO_2eq$ |
| Coal power | 56.92 | 0.58 | 226.45[12] | -0.49 | -0.86 | -1.96 |
| Petroleum and coke | 22.17 | 0.23 | 57.54 | -0.14 | -0.62 | -0.36 |
| Business services | 3.36 | 0.03 | 14.17 | -0.04 | -1.18 | -0.17 |
| Iron & Steel | 2.37 | 0.02 | 9.42 | -0.03 | -1.09 | -0.10 |
| Non-metallic mineral products | 1.98 | 0.02 | 7.95 | -0.02 | -1.23 | -0.10 |
| Gas extraction, production, and distribution | 1.77 | 0.02 | 0.00 | -0.08 | -4.29 | 0.00 |
| Chemicals and chemical products | 1.27 | 0.01 | 1.76 | -0.01 | -0.93 | -0.02 |
| Metals nec | 0.89 | 0.01 | 3.68 | -0.01 | -1.18 | -0.04 |
| Other Industries | 0.54 | 0.01 | 2.11 | -0.01 | -0.97 | -0.02 |
| Agriculture | 0.47 | 0.00 | 1.98 | 0.00 | -0.82 | -0.02 |
| Energy-intensive industries | 0.44 | 0.00 | 0.61 | -0.01 | -1.21 | -0.01 |
| Land transport and transport via pipelines | 0.12 | 0.00 | 0.49 | 0.00 | -1.04 | -0.01 |
| Services | 0.09 | 0.00 | 0.38 | 0.00 | -0.98 | 0.00 |
| Paper and paper products | 0.09 | 0.00 | 0.36 | 0.00 | -0.94 | 0.00 |
| Food products nec | 0.09 | 0.00 | 0.35 | 0.00 | -0.85 | 0.00 |
| Minerals nec | 0.08 | 0.00 | 0.31 | 0.00 | -0.78 | 0.00 |
| Water transport | 0.00 | 0.00 | 0.00 | 0.00 | -0.91 | 0.00 |
| Coal | 0.00 | 0.00 | 0.00 | 0.00 | -2.22 | 0.00 |
| Households | 5.22 | 0.05 | 20.67 | -0.09 | -1.67 | -0.37 |
| Total | 97.86 | 1.00 | 348.23 | -0.92 | -0.94 | -3.17 |

Source: GTAP v.11 complementary GHG emissions data (Chepeliev 2024a; 2024b) and simulation conducted by the author.

---

[11] $MtCO_2eq$ refers to million tonnes of carbon dioxide equivalent.

[12] GHGs released when coal is combusted consist mostly of $CO_2$ with smaller amounts of $N_2O$ and CH4. Reference GHG emissions from coal power plants in South Africa consist of 225.42 Mt of $CO_2$, 0.04 $MtCO_2eq$ of CH4, and 0.99 $MtCO_2eq$ of $N_2O$. Construction of $CO_2$ emissions from fossil fuel combustion in all sectors and regions for the GTAP v.11 data base is documented in Chepeliev (2024a) and is based on the Tier 1 methodology from the 2006 IPCC Guidelines. For example, calculation of reference $CO_2$ from coal combustion by power plants in South Africa takes into account conversion coefficient 41.868 TJ/1000 toe, emission factor 25.8 tC/TJ, and conversion factor 44/12 representing molecular weight of $CO_2$ to the molecular weight of carbon.

South Africa reduced coal exports to all destinations, with the largest by absolute magnitude reduction, 1.45 Mtoe, to India, its main coal export destination (Figure 8). In relative terms, coal exports declined the most to South Korea, Taiwan, Germany, Türkiye, and India (by 8–9%), though the absolute reductions in trade flows to Taiwan, Germany, and Türkiye were modest due to the small size of reference trade flows to these destinations. South Africa imports a small amount of coal (0.32 Mtoe), and the reduction in domestic supply leads to a 4% increase in coal imports, about half of which comes from Australia (Figure 9). South Africa also expands imports of natural gas (0.72%) and petroleum & coke (0.28%).

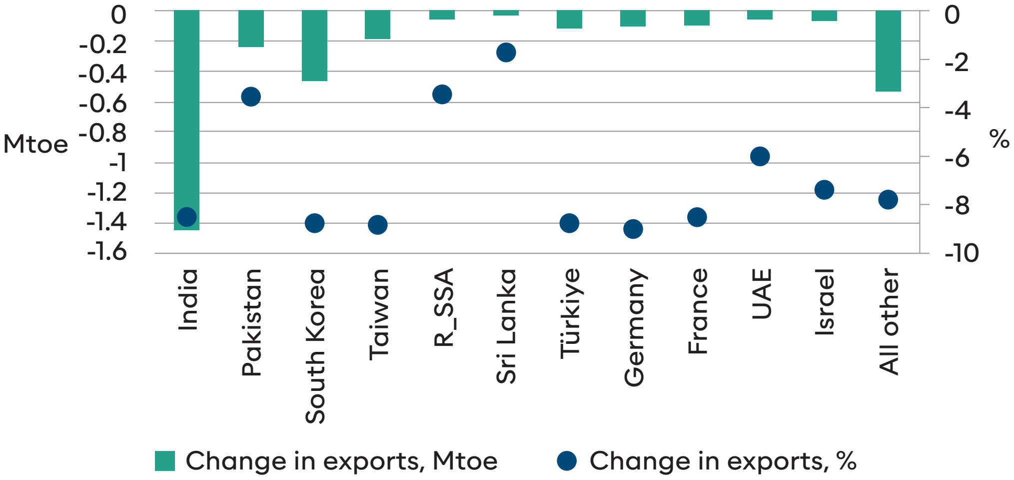

**Figure 8. Effects of a 3.12% reduction in South Africa's coal output on coal exports by destination.**

Source: Simulation conducted by the author.

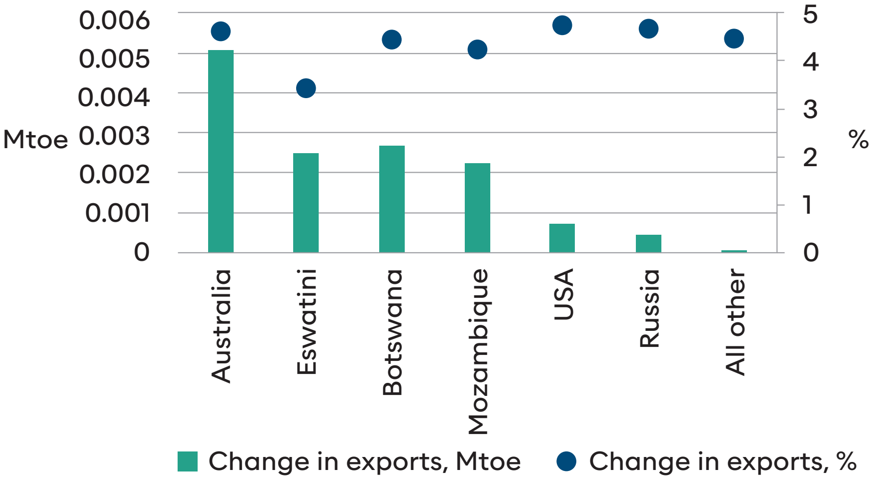

**Figure 9. Effects of a 3.12% reduction in coal output in South Africa on its coal imports by source.**

Source: Simulation conducted by the author.

The reduction in coal availability leads to contraction of coal power generation and a small expansion of nuclear and wind energy (Figure 10).

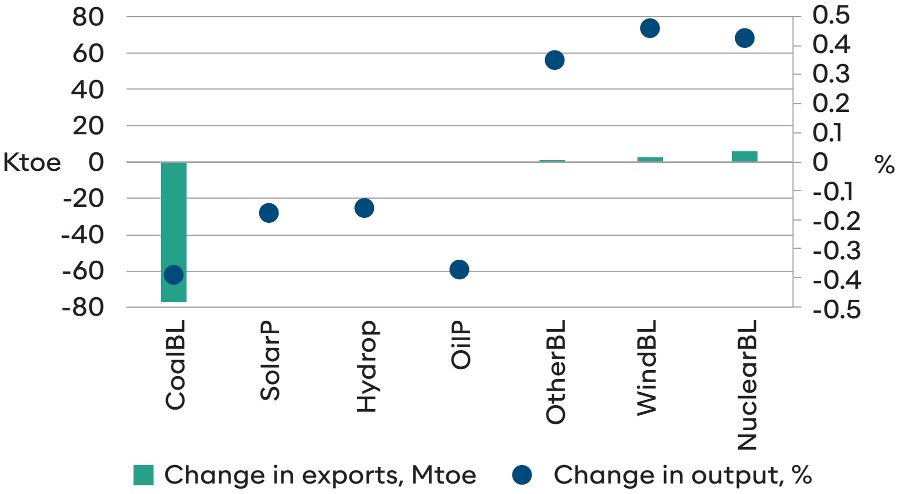

**Figure 10. Impact of a 3.12% reduction in coal output in South Africa on its electricity generation by technology.**

Source: Simulation conducted by the author.

Marginally higher coal prices encourage a small expansion of coal outside South Africa, partially offsetting the reduction of coal output in South Africa (Figure 11). In major coal-producing countries, coal output experienced a relatively small expansion, 0.01-0.23%. Small coal-producing countries that either import coal from (e.g., Pakistan) or serve as sources of imported coal for South Africa (e.g., Mozambique) experienced larger percentage increases in coal output, ranging from 0.43 to 1.8%. Globally, coal production decreased by 1.82 Mtoe (0.05%), reflecting a 4.49 Mtoe (3.12%) decline in South Africa and small increases in other countries.

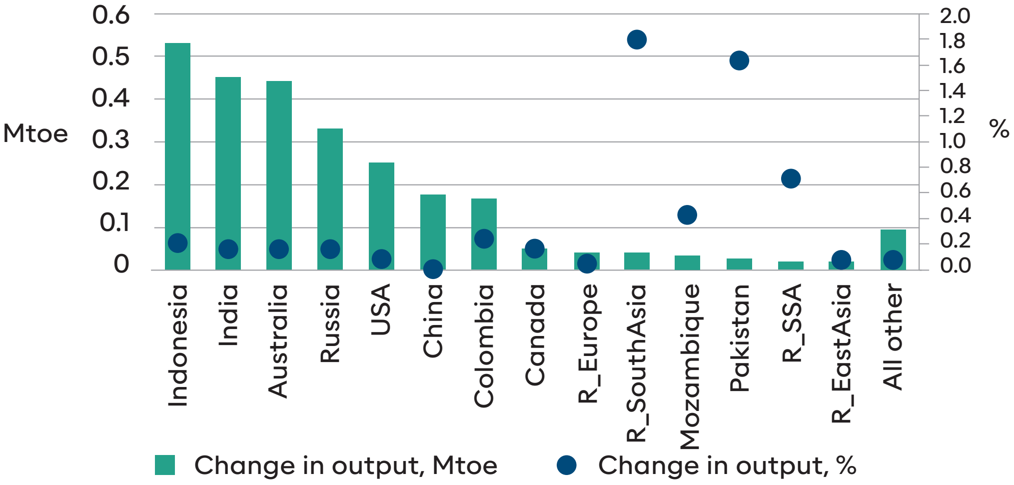

**Figure 11. Expansion of coal production in major coal-producing countries due to a 3.12% reduction in coal output in South Africa.**

Source: Simulation conducted by the author.

The reference level of coal production in South Africa is 144.13 Mtoe per year. This production activity releases 49.75 $MtCO_2eq$. A 3.12% reduction in coal output leads to a direct 1.55 $MtCO_2eq$ reduction in GHG emissions from the coal sector. Reduction in the use of domestic coal by firms and households results in direct GHG emissions reduction by 3.17 $MtCO_2eq$ (Table 2). Assuming the exported coal would have been combusted, a 3.38 Mtoe reduction in coal exports results in a direct 13.39 $MtCO_2eq$ reduction in GHG emissions. Thus, the reduction of coal output in South Africa by 3.12% will result in a direct 1.55+3.17+13.39 = 18.11 $MtCO_2eq$ reduction in GHGs.

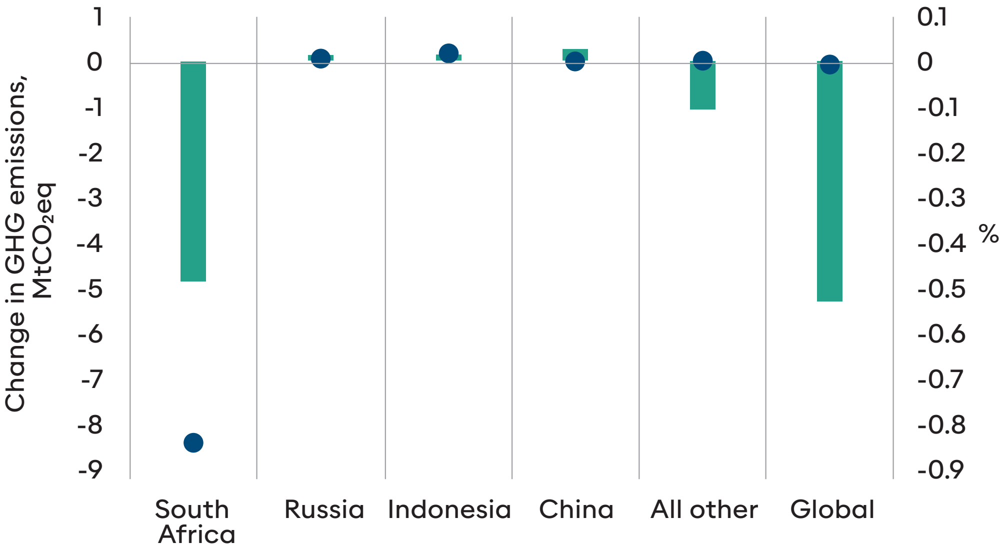

**Figure 12. Changes in GHG emissions due to a 3.12% reduction in coal output in South Africa, by selected country and globally.**

Source: Simulation conducted by the author.

Simulated 3.12% reduction of coal output in South Africa results in 5.28 $MtCO_2eq$ reduction in GHG emissions globally (Figure 12). Many countries, including South Africa, experienced a reduction in economy-wide emissions. In South Africa, economy-wide GHG emissions fell by 4.79 $MtCO_2eq$. However, major coal-producing countries – China, Indonesia, and Russia – increased their GHG emissions. The net 5.28 $MtCO_2eq$ reduction in global GHG emissions is smaller than the direct reduction of 18.11 $MtCO_2eq$ because of the leakage. The leakage rate from the reduction of coal output in South Africa by 3.12% is (18.11-5.28)/18.11 * 100 = 71%.[13]

---

[13] The GHG emissions leakage rate from reducing coal output in a country is defined as $-\frac{\Delta E_{global} - \Delta E_{direct}}{\Delta E_{direct}} 100$, where $\Delta E_{global}$ represents change in global GHG emissions, and $\Delta E_{direct}$ represents change in both direct GHG emissions from coal production in that country and direct GHG emissions from the use of domestically produced coal, both within the country and abroad through exports.

## 3.2. Impacts of reducing coal output in the United States

A 1% reduction in U.S. coal output increases the domestic coal price by 0.79% and induces smaller price increases in international markets; the global price of coal rises by 0.11% (Table 1). In the reference data, about 80% of U.S. coal output is used domestically, and 20% exported. The reduction in U.S. coal output results in 0.48% reduction in domestic use of coal. Within the domestic use, all sectors that use coal reduce their use, with the largest reductions observed in coal power plants (0.5%) and the non-metallic minerals sector (0.45%) (Table 3).

**Table 3. Reference levels and changes in domestic use of coal and related GHG emissions due to a 1% reduction in coal output in the United States.**

| Sector | Reference | | | Change | | |
|---|---|---|---|---|---|---|
| | Use, Mtoe | Share | Emissions from use of coal, $MtCO_2eq$ | Use, Mtoe | Use, % | Emissions from use of coal, $MtCO_2eq$ |
| Coal power | 301.61 | 0.91 | 1219.61 | -1.51 | -0.50 | -6.13 |
| Petroleum and coke | 12.96 | 0.04 | 0.00 | 0.00 | -0.03 | 0.00 |
| Non-metallic mineral products | 5.08 | 0.02 | 20.32 | -0.02 | -0.45 | -0.09 |
| Other Industries | 2.00 | 0.01 | 8.06 | -0.01 | -0.39 | -0.03 |
| Gas extraction, production, and distribution | 1.92 | 0.01 | 0.00 | 0.00 | 0.02 | 0.00 |
| Chemicals and chemical products | 1.52 | 0.00 | 6.11 | -0.01 | -0.41 | -0.03 |
| Paper and paper products | 1.45 | 0.00 | 5.82 | -0.01 | -0.42 | -0.02 |
| Food products nec | 1.33 | 0.00 | 5.37 | -0.01 | -0.42 | -0.02 |
| Services | 0.65 | 0.00 | 2.70 | 0.00 | -0.38 | -0.01 |
| Iron & Steel | 0.56 | 0.00 | 2.22 | 0.00 | -0.39 | -0.01 |
| Energy-intensive industries | 0.42 | 0.00 | 1.71 | 0.00 | -0.39 | -0.01 |
| Coal | 0.12 | 0.00 | 0.48 | 0.00 | -0.36 | 0.00 |
| Metals nec | 0.05 | 0.00 | 0.21 | 0.00 | -0.37 | 0.00 |
| Business services | 0.05 | 0.00 | 0.22 | 0.00 | -0.37 | 0.00 |
| Minerals nec | 0.03 | 0.00 | 0.10 | 0.00 | -0.38 | 0.00 |
| Land transport and transport via pipelines | 0.02 | 0.00 | 0.10 | 0.00 | -0.41 | 0.00 |
| Agriculture | 0.02 | 0.00 | 0.06 | 0.00 | -0.39 | 0.00 |
| Households | 0.01 | 0.00 | 0.39 | 0.00 | -0.80 | 0.00 |
| Total | 329.90 | 1.00 | 1273.48 | -1.58 | -0.48 | -6.35 |

Source: GTAP v.11 complementary GHG emissions data (Chepeliev 2024a; 2024b) and simulation conducted by the author.

U.S. exports of coal fell by 3.53% (1.94 Mtoe), with the largest absolute declines occurring for its main trading partners in the coal market—Germany, Japan, and India (Figure 13). In relative terms, coal exports to China fell the most, though the absolute reduction is modest due to the small size of the reference trade flow. The reference amount of U.S. imports of coal is very small -- less than 1% of U.S. coal output. A 1% reduction in domestic supply results in a 1.8% increase in the quantity of imported coal, most of which comes from Colombia.

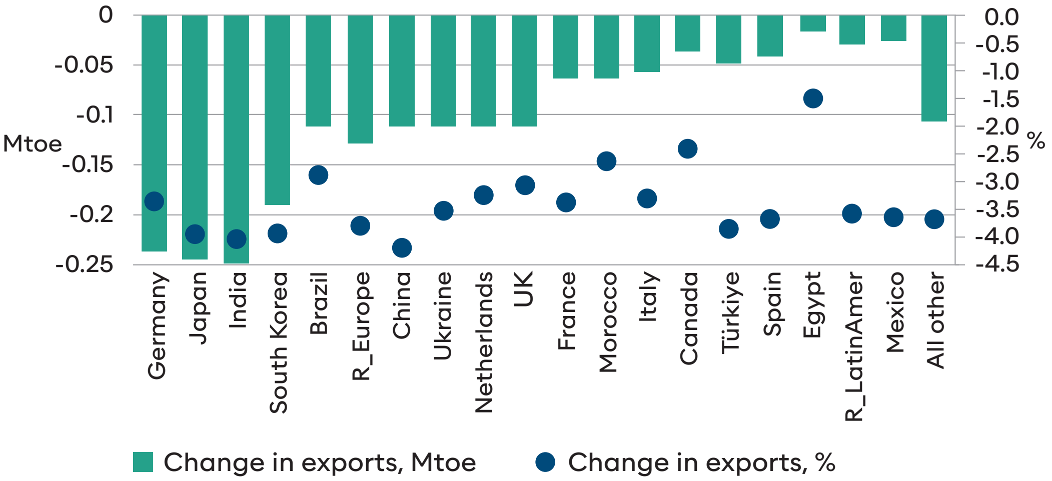

**Figure 13. Effects of a 1% reduction in U.S. coal output on coal exports by destination.**

Source: Simulation conducted by the author.

Reduction in coal availability in the United States leads to contraction of coal power generation and expansion of other baseload technologies (nuclear, gas, hydro, wind, and others) (Figure 14).

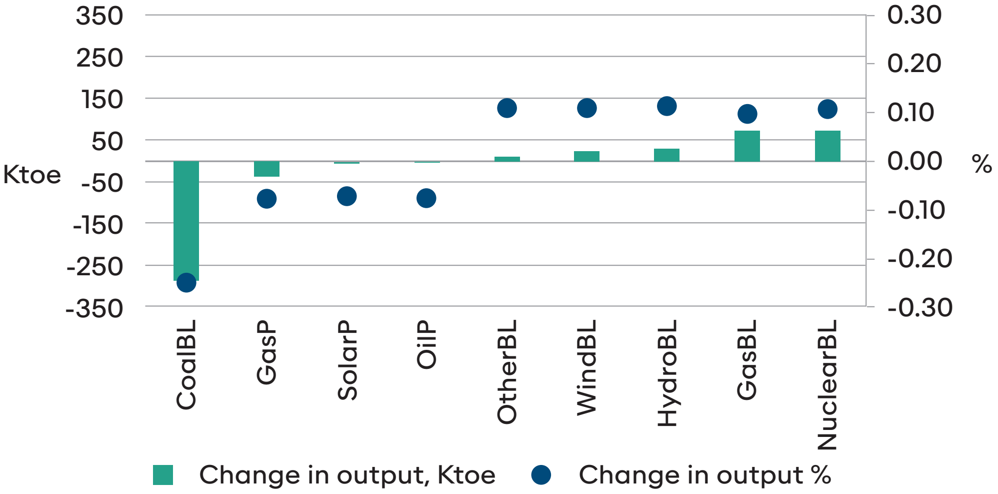

**Figure 14. Impact of a 1% reduction in U.S. coal output on electricity generation by technology.**

Source: Simulation conducted by the author.

A 0.11% rise in the global coal price prompts a small increase in coal production in coal-producing countries. Major net exporters and U.S. competitors in coal markets – Russia, Australia, Colombia, and Indonesia increase coal production by 0.1-0.4% (Figure 15). Global coal production fell by 1.45 Mtoe (0.04%), driven by a 3.85 Mtoe (1%) reduction in the United States, partly offset by small increases in other countries totaling 2.4 Mtoe.

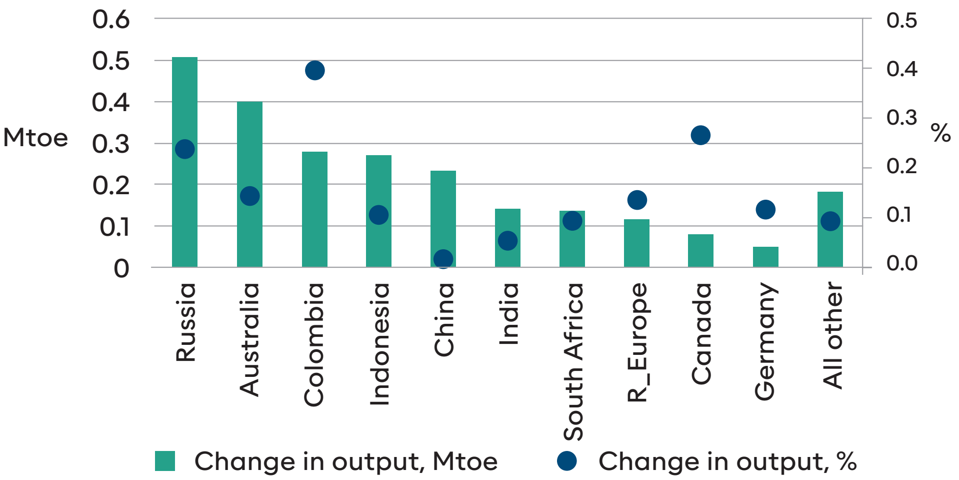

**Figure 15. Expansion of coal production in major coal-producing countries due to a 1% reduction in U.S. coal output.**

Source: Simulation conducted by the author.

The reference level of coal production in the United States is 385 Mtoe per year. This production activity releases 68.1 $MtCO_2eq$ per year[14]. A 1% reduction in coal output leads to a direct 0.66 $MtCO_2eq$ reduction in GHG emissions from the coal sector. Reductions in the use of domestic coal by firms and households result in direct GHG emissions reduction by 6.35 $MtCO_2eq$ (Table 3). Assuming the exported coal would have been combusted, a 1.94 Mtoe decline in U.S. coal exports results in a direct reduction of 7.7 $MtCO_2eq$ in GHG emissions. Thus, the reduction of coal output in the United States by 1% will result in a direct 0.66+6.35+7.7 = 14.71 $MtCO_2eq$ reduction in GHGs.

---

[14] These emissions include $CO_2$ (20.04 $MtCO_2$), methane (44.41 $MtCO_2eq$), and a small amount of $N_2O$ (0.005 $MtCO_2eq$) associated with coal output (Chepeliev 2024a), as well as 3.65 $MtCO_2eq$ from fossil fuel combustion by mining machinery (Chepeliev 2024b).

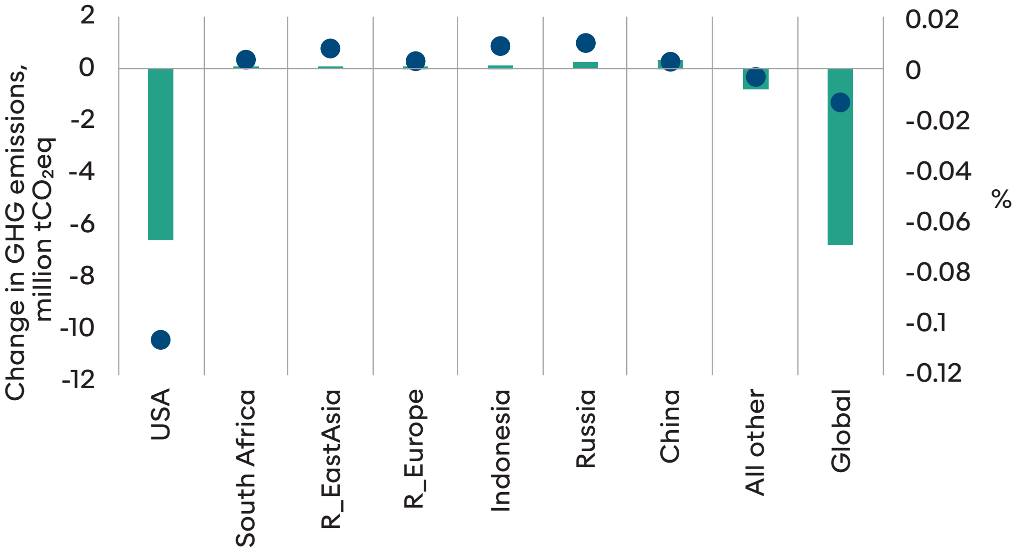

**Figure 16. Changes in GHG emissions due to a 1% reduction in U.S. coal output, by selected country and globally.**

Simulated 1% reduction of coal output in the United States results in 6.91 $MtCO_2eq$ reduction in GHG emissions globally (Figure 16). Emissions fell in the United States and many other countries. In the United States, economy-wide GHG emissions fell by 6.8 $MtCO_2eq$. However, major coal-producing countries – China, Russia, Indonesia, and South Africa – increased their GHG emissions. The net 6.91 $MtCO_2eq$ reduction in global GHG emissions is smaller than the direct reduction of 14.71 $MtCO_2eq$ because of the leakage. The leakage rate from the reduction of coal output in the United States by 1% is (14.71-6.91)/14.71 * 100 = 53%.

# 4. Sensitivity analysis

As with all structural models, CGE policy simulation results depend on key model parameters and assumptions. Using discrete scenarios, we explore the sensitivity of the carbon leakage results with respect to supply elasticities of fossil fuels, trade elasticities, and substitution between electricity-generating technologies.

## 4.1. Supply elasticity of fossil fuels

Reductions in coal output in South Africa and the United States increase the price of coal in international markets (Table 1). Although the simulation results presented above show that these changes are small, the responses of coal producers worldwide to these changes are an important determinant of carbon leakage. In addition, the increase in coal price results in higher demand for and prices of other fossil fuels. A responsiveness of fossil fuel producers to changes in fossil fuel prices is summarized by supply elasticities. For example, if fossil fuel supply were completely price inelastic, the leakage rate in coal output reduction experiments would be zero. In the model, supply elasticities of coal, oil, and gas depend on the elasticities of substitution in value added-energy composite in the production structure of these sectors. For the same cost structure, a larger elasticity of substitution results in a more elastic supply. In the GTAP-Power model, the elasticities of substitution in value added-energy composite in the fossil fuel extraction sectors are calibrated to supply elasticities of 10, 1, and 4 for coal, oil, and gas, respectively. These default magnitudes of the GTAP-Power model parameters are taken from the GTAP-E model (Burniaux and Truong 2002). The alternative set of fossil fuel supply elasticities for use with the GTAP-E model is provided by Beckman et al. (2011). The authors conducted a literature review and adopted substantially lower supply elasticities -- 1, 0.25, and 0.6 for coal, oil, and gas, respectively. Daubanes et al. (2017) suggest that the price elasticity of fossil fuels' supply is usually low, even in the long run. Based on their literature review, the authors report a range of 0.9-1.4 for the long-run supply elasticities of natural gas. For coal, however, they report a much wider range from 0.1 to 7.9.

How sensitive is the magnitude of carbon leakage in our experiments to the supply elasticities of fossil fuels? To answer this question, coal output reductions in South Africa and the United States are simulated with the GTAP-Power model recalibrated to fossil fuel supply elasticities reported in Beckman et al. (2011). In the case of 3.12% reduction in coal output in South Africa, the direct GHG emissions reduction is 18.16 $MtCO_2eq$, very similar to the 18.11 $MtCO_2eq$ reduction obtained with the default parameters. The similarity in the direct reduction is expected because these changes are mostly determined by the size of the imposed reduction in coal output. Global emission reduction, however, is much larger, at 8.34 $MtCO_2eq$. As a result, emission leakage is substantially lower: (18.16-8.34)/18.11 * 100 = 54%, compared with 71% under the default assumption of a more price-elastic fossil fuel supply (Figure 17). In the case of 1% reduction in coal output in the United States, the direct GHG emissions reduction is 14.77 $MtCO_2eq$, while the global emission reduction is 9.73 $MtCO_2eq$, and emission leakage (14.77 – 9.73)/14.77 * 100 = 34% vs. 53% under the default assumption of a more price-elastic fossil fuel supply (Figure 17). In these alternative scenarios, the lower carbon leakage outcomes in both South Africa and the United States are expected, as a lower supply elasticity of fossil fuels leads to smaller carbon leakage.

## 4.2. Trade elasticities

The extent to which a reduction in coal output originating in one country propagates to coal markets in other countries depends on the elasticity of substitution among imports from different sources, or trade elasticity. We consider how sensitive our carbon leakage estimates are with respect to the trade elasticities. Our “central” carbon leakage estimates reported in the Results section are obtained with default commodity-specific GTAP trade elasticities (Hertel et al. 2007). In the two sensitivity runs, we increase and decrease the magnitudes of these elasticities by 50%. Relative to the central results, higher trade elasticities are expected to lead to greater carbon leakage, while lower elasticities are expected to reduce leakage. The sensitivity runs for South Africa experiments yield 79% and 53% carbon leakage rates with higher and lower elasticities, respectively. For the United States, experiments with alternative sets of trade elasticities result in 66% and 31% for higher and lower parameters, respectively. In addition, we conducted experiments with trade elasticities increased by 80%.[15] These experiments yield leakage rates of 82% in South Africa and 71% in the United States, demonstrating that even under the assumption of very high substitutability among imports, there is still some net global GHG emission reduction, and, after a certain level, further increase in trade elasticities has little effect on the leakage rate (Figure 17).

---

[15] In Hertel et al. (2007), almost all of the estimates of the trade elasticities (Armington parameters) at the disaggregated GTAP commodity level are statistically significant, with many exhibiting relatively small standard errors. For most of the commodities, the +/-80% range of values is much larger than two standard deviations reported in Hertel et al. (2007). The solution with trade elasticities reduced by 80% is not accurate and results are not reported.

## 4.3. Substitution between electricity-generating technologies

Electricity generation is one of the most significant uses of coal, and substitution between electricity-generating technologies affects the leakage rate. In the model, the electricity good purchased by firms and households consists of transmission and distribution service demanded in a fixed proportion with a virtual generation good. A virtual generation good, in turn, consists of virtual base load and virtual peak load goods, also demanded in a fixed proportion. The leakage rates reported above are obtained under the GTAP-Power model's default assumption that different generation technologies are not perfect substitutes, and a system operator—acting on behalf of firms and households—responds to changes in relative prices by adjusting the generation mix. That is, within base-load generation, the operator can substitute among nuclear, coal, gas, oil, hydro, wind, and other base-load technologies, while within peak-load generation, substitution is allowed among gas, oil, hydro, and solar. The substitution is governed by parameters calibrated on the data for the United States (Peters and Hertel 2017) and applied to all regions in the model. Noting that the specification of the electric power substitution "is not validated in a robust manner" (Peters 2016a), we consider two alternative specifications. The first alternative specification models the situation when electricity produced by different technologies are perfect substitutes within peak and base load goods. Under this assumption, coal exports are affected very little, and most of the adjustment happens within the country that cuts coal output. The adjustment consists of reducing coal-based power and expanding cleaner power-generating technologies. In this case, leakage rates are very small, 0.4% in South Africa and 3% in the United States. We emphasize that these plausible outcomes are conditional on the ability of South Africa and the United States to expand cleaner power generation technologies. The second alternative specification assumes that compositions of peak load and base load are fixed and not responsive to changes in relative prices. Under this assumption, in both South Africa and the United States relative reduction in coal exports is larger and relative reduction in the use of domestic coal is smaller than under default specification, and leakage rates are 75% and 64%, respectively (Figure 17).

Overall, the results show that carbon leakage estimates are highly sensitive to assumptions about the ability to substitute away from coal-based power, as well as the responsiveness of fossil fuel supply and trade substitution.

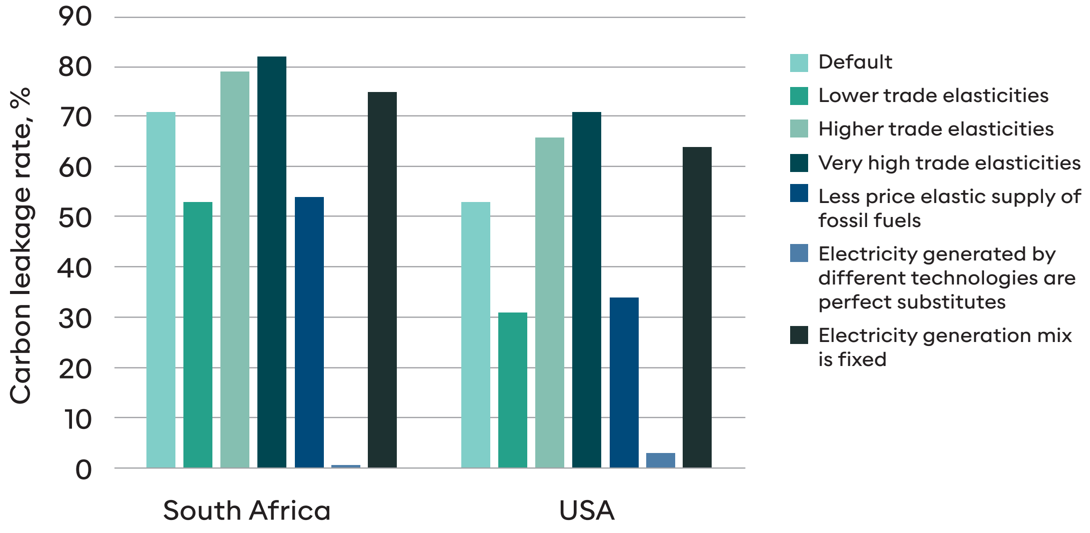

**Figure 17. Carbon leakage due to a 3.12% reduction in South Africa coal output and 1% reduction in U.S. coal output under alternative GTAP-E-Power model parameters and assumptions, %.**

## Limitations

The analysis presented in this report has several limitations, which can be grouped into those specific to this study and those inherent to CGE analysis in general. Starting from the former, first, in the real world, there are different types of coal that differ in energy content, $CO_2$ emissions per unit of energy, economic values, trade patterns, and end uses. In the GTAP-Power data base used in this analysis, however, there is only one aggregated coal sector producing a single commodity, which may lead to misestimation of the leakage. Second, in the model, a 'national' importer aggregates bilateral imports from all sources to 'produce' an aggregate import bundle, and each agent in the economy (firms, households, government, and investment) accesses this common import bundle (Corong et al. 2017). Thus, the framework does not allow tracing the end use of imports. For this reason, to calculate the leakage rate, we assumed that all coal exported from South Africa and the United States was combusted in the destination economies, and a reduction in coal exports resulted in a corresponding reduction in emissions from combustion of coal. Third, the simulations are based on a 2017 benchmark dataset. Structural changes in energy production and consumption—most notably the expansion of renewable generation in the United States over the past decade—may influence the quantitative magnitude of the results. Accordingly, the findings should be interpreted as conditional on the benchmark year. Fourth, as already mentioned in section 4.3, the substitution among electricity-generating technologies is governed by parameters calibrated on the United States data and then applied to all regions in the model.

This approach does not capture differences in energy systems among countries. Finally, the analysis considers relatively small reductions in coal output (3.12% and 1%). The leakage rate results may be quantitatively different under larger reductions in coal output.

CGE modeling is a powerful tool for numerical analysis of future policy interventions for which econometric estimation would be impossible. The models, however, have their limitations. Here, we adopt the discussion of limitations of the GTAP model and CGE models more generally from Hertel et al. (2007). First, "... CGE simulations are not unconditional predictions but rather thought experiments about what the world would be like if the policy change had been operative in the assumed circumstances and year. The real world will doubtless have changed by the time we get there" (Hertel et al. 2007). Second, like with other CGE models, GTAP results are difficult to test against historical experience, though several studies undertook the GTAP model validation exercise (Gehlhar 1996; Valenzuela et al. 2007; Beckman et al. 2011; Liu et al. 2004). Other limitations are related to the granularity of the CGE data base, availability of econometric estimates of model parameters, and sensitivity analysis. While many sectors are represented in the GTAP data base, many of them are aggregates of a large number of smaller sectors. Some of the model parameters are econometrically estimated (e.g. Armington parameters), others are based on a literature review. Sensitivity analysis is relatively easy to perform for behavioral parameters, but much less so for the data, because changing one part of the base data requires corresponding adjustments elsewhere to keep the national accounts and social accounting matrix balanced (Hertel et al. 2007). Many of these criticisms also apply to other forms of economic modeling; thus, despite their imperfections, CGE models remain the preferred tool for analyzing policies affecting the global economy.

## Summary

Coal is a cheap and abundant energy source, but it is also the largest contributor to global $CO_2$ emissions, particularly from electricity generation. This project aims to assess how leaving coal “in the ground” affects coal prices, production, trade, and GHG emissions. The analysis is based on the GTAP-E-Power CGE model with a GTAP-Power data base describing bilateral trade patterns, production, consumption, and intermediate use, and electric power generating technologies. Using this framework, we simulate a 3.12% reduction in coal output in South Africa and a 1% reduction in the United States. The two scenarios are modeled independently.

Results show that reducing coal output slightly increases coal prices domestically and globally, and reduces domestic coal use and coal exports from both countries. However, higher coal prices encourage increased coal production in other countries, partially offsetting the original reductions. In South Africa, a 3.12% cut in production of coal results in a direct emissions reduction of 18.11 $MtCO_2eq$ but only a 5.28 $MtCO_2eq$ net global reduction, implying a high leakage rate of 71%. In the United States, a 1% cut in production of coal leads to a direct reduction of 14.71 $MtCO_2eq$ and a global net reduction of 6.91 $MtCO_2eq$, corresponding to a leakage rate of 53%. In both cases, major coal producers such as China, Russia, and Indonesia expand coal output and increase GHG emissions.

Sensitivity analysis shows that leakage rates are strongly influenced by key model assumptions. Lower trade elasticities and lower fossil fuel supply elasticities significantly reduce leakage. Assumptions about the expansion of cleaner technologies and substitution among electricity-generating technologies are especially important: if cleaner power technologies can easily replace coal, leakage becomes minimal, whereas rigid power generation structures result in high leakage.

We find that reducing coal production in South Africa and the United States reduces global GHG emissions, but a substantial share of these benefits may be offset by market-mediated responses. The magnitude of these responses depends on model parameters and assumptions. Future studies should aim to narrow the range of potential carbon leakage resulting from leaving coal in the ground.

## Acknowledgements

The author thanks Vladimir Tyazhelnikov for the helpful comments and suggestions.

# References

Aguiar, A., M. Chepeliev, E. Corong, and D. van der Mensbrugghe. 2023. “The Global Trade Analysis Project (GTAP) Data Base: Version 11.” Journal of Global Economic Analysis 7 (2): 2. https://doi.org/10.21642/JGEA.070201AF.

Armington, P.S. 1969. “A Theory of Demand for Products Distinguished by Place of Production.” Staff Papers (International Monetary Fund) 16 (1): 159–78. https://doi.org/10.2307/3866403.

Beckman, J., T.W. Hertel, and W.E. Tyner. 2011. “Validating Energy-Oriented CGE Models.” Energy Economics 33: 799–806.

Burniaux, J.-M., and T. Truong. 2002. “GTAP-E: An Energy-Environmental Version of the GTAP Model.” GTAP Technical Paper No. 16, GTAP Technical Paper No. 16. http://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=923.

Chepeliev, M. 2023. “GTAP-Power Data Base: Version 11.” Journal of Global Economic Analysis 8 (2): 2. https://doi.org/10.21642/JGEA.080203AF.

Chepeliev, M. 2024a. “Chapter 13A: $CO_2$ Emissions from Fossil Fuels Combustion.” Center for Global Trade Analysis, Center for Global Trade Analysis. http://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=7130.

Chepeliev, M. 2024b. “Chapter 13B: Complementary Greenhouse Gas Emissions Database.” Center for Global Trade Analysis, Center for Global Trade Analysis. http://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=7131.

Corong, E. 2023. “GTAP Energy and Power Version 7 (GTAPv7-Ep) Model Files.” https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=7116.

Corong, E.L., T.W. Hertel, R. McDougall, M.E. Tsigas, and D. van der Mensbrugghe. 2017. “The Standard GTAP Model, Version 7.” Journal of Global Economic Analysis 2 (1): 1–119. https://doi.org/10.21642/JGEA.020101AF.

Daubanes, J.X., F. Henriet, and K. Schubert. 2017. More Gas, Less Coal, and Less $CO_2$? Unilateral $CO_2$ Reduction Policy with More than One Carbon Energy Source. MET CEEPR Working Paper Series.

Gehlhar, M. 1996. “Historical Analysis of Growth and Trade Patterns in the Pacific Rim: An Evaluation of the GTAP Framework.” In Global Trade Analysis: Modeling and Applications, edited by Thomas W. Hertel. Cambridge University Press. https://doi.org/10.1017/CBO9781139174688.015.

Hertel, T.W. 1997. Global Trade Analysis: Modeling and Applications. Cambridge University Press.

Hertel, T.W., R. Keeney, M. Ivanic, and L.A. Winters. 2007. “Distributional Effects of WTO Agricultural Reforms in Rich and Poor Countries.” Economic Policy 22 (50): 289–337.

Liu, J., C. Arndt, and T.W. Hertel. 2004. “Parameter Estimation and Measures of Fit in A Global, General Equilibrium Model.” The Journal of Economic Integration 19 (3): 626–49.

Peters, J.C. 2016a. “GTAP-E-Power: An Electricity-Detailed Economy-Wide Model.” Journal of Global Economic Analysis 1 (2): 2. https://doi.org/10.21642/JGEA.010204AF.

Peters, J.C. 2016b. “The GTAP-Power Data Base: Disaggregating the Electricity Sector in the GTAP Data Base.” Journal of Global Economic Analysis 1 (1): 209–50.

Peters, J.C., and T.W. Hertel. 2017. “Achieving the Clean Power Plan 2030 $CO_2$ Target with the New Normal in Natural Gas Prices.” The Energy Journal 38 (5): 39–66. https://doi.org/10.5547/01956574.38.5.jpet.

Valenzuela, E., T.W. Hertel, R. Keeney, and J.J. Reimer. 2007. “Assessing Global Computable General Equilibrium Model Validity Using Agricultural Price Volatility.” American Journal of Agricultural Economics 89 (2): 383–97. https://doi.org/10.1111/j.1467-8276.2007.00977.x.

# Appendix A1 The mapping from disaggregated 160 GTAP regions to aggregated 48 regions

| No. | Model region | Description | GTAP data base regions mapped to the model region |
|---|---|---|---|
| 1 | SouthAfrica | South Africa | zfa |
| 2 | USA | United States of America | usa |
| 3 | Germany | Germany | deu |
| 4 | Japan | Japan | jpn |
| 5 | India | India | ind |
| 6 | Pakistan | Pakistan | pak |
| 7 | SouthKorea | South Korea | kor |
| 8 | Brazil | Brazil | bra |
| 9 | China | China | chn |
| 10 | Ukraine | Ukraine | ukr |
| 11 | Netherlands | Netherlands | nld |
| 12 | UK | United Kingdom | gbr |
| 13 | France | France | fra |
| 14 | Canada | Canada | can |
| 15 | Morocco | Morocco | mar |
| 16 | Italy | Italy | ita |
| 17 | Türkiye | Türkiye | tur |
| 18 | Spain | Spain | esp |
| 19 | Egypt | Egypt | egy |
| 20 | Mexico | Mexico | mex |
| 21 | Hungary | Hungary | hun |
| 22 | Belgium | Belgium | bel |
| 23 | Taiwan | Taiwan | twn |
| 24 | Colombia | Colombia | col |
| 25 | Indonesia | Indonesia | idn |
| 26 | Malaysia | Malaysia | mys |

| No. | Model region | Description | GTAP data base regions mapped to the model region |
|---|---|---|---|
| 27 | Philippines | Philippines | phl |
| 28 | Thailand | Thailand | tha |
| 29 | Vietnam | Vietnam | vnm |
| 30 | SriLanka | Sri Lanka | lka |
| 31 | UAE | United Arab Emirates | are |
| 32 | Israel | Israel | isr |
| 33 | Madagascar | Madagascar | mdg |
| 34 | Mauritius | Mauritius | mus |
| 35 | Australia | Australia | aus |
| 36 | Eswatini | Eswatini | swa |
| 37 | Botswana | Botswana | bwa |
| 38 | Mozambique | Mozambique | moz |
| 39 | Russia | Russia | rus |
| 40 | R_Oceania | Rest of Oceania | nzl, xoc |
| 41 | R_EastAsia | Rest of East Asia | hkg, mng, xea, brn |
| 42 | R_SEAsia | Rest of South East Asia | khm, lao, sgp, xse |
| 43 | R_SouthAsia | Rest of South Asia | afg, bgd, npl, xsa |
| 44 | R_LatinAmer | Rest of Latin America | arg, bol, chl, ecu, pry, per, ury, ven, xsm, cri, gtm, hnd, nic, pan, slv, xca, dom, hti, jam, pri, tto, xcb |
| 45 | R_Europe | Rest of Europe | xna, aut, bgr, hrv, cyp, cze, dnk, est, fin, grc, irl, lva, ltu, lux, mlt, pol, prt, rou, svk, svn, swe, che, nor, xef |
| 46 | R_MENA | Rest of Middle East | bhr, irn, irq, jor, kwt, lbn, omn, pse, qat, sau, syr, xws, dza, tun, xnf |
| 47 | R_SSA | Rest of Sub Saharan Africa | ben, bfa, cmr, civ, gha, gin, mli, ner, nga, sen, tgo, xwf, caf, tcd, cog, cod, gnq, gab, xac, com, eth, ken, mwi, rwa, sdn, tza, uga, zmb, zwe, xec, nam, xsc |
| 48 | RestofWorld | Rest of the World | alb, srb, blr, xee, xer, kaz, kgz, tjk, uzb, xsu, arm, aze, geo, xtw |

# Appendix A2 The mapping from disaggregated 76 GTAP-Power sectors to aggregated 31 sectors

| No. | Model sector | Description | GTAP data base regions mapped to the model region |
|---|---|---|---|
| 1 | agr | agriculture | pdr, wht, gro, v_f, osd, c_b, pfb, ocr, ctl, oap, rmk, wol, frs, fsh |
| 2 | coal | coal | coal |
| 3 | oil | oil | oil |
| 4 | gas | gas extraction, production, and distribution | gas, gdt |
| 5 | Oil_pcts | petroleum and coke | p_c |
| 6 | TnD | electricity transmission and distribution | tnd |
| 7 | Nuclear | nuclear power | NuclearBL |
| 8 | CoalBL | coal power | CoalBL |
| 9 | Wind | wind power | WindBL |
| 10 | GasBL | gas power base load | GasBL |
| 11 | HydroBL | hydro power base load | HydroBL |
| 12 | OilBL | oil power base load | OilBL |
| 13 | OtherBL | other power base load | OtherBL |
| 14 | GasP | gas power peak load | GasP |
| 15 | HydroP | hydro power peak load | HydroP |
| 16 | OilP | oil power peak load | OilP |
| 17 | Solar | solar power | SolarP |
| 18 | nmm | mineral products nec | nmm |
| 19 | chm | chemicals and chemical products | chm |
| 20 | i_s | iron and steel | i_s |
| 21 | oxt | minerals nec | oxt |
| 22 | nfm | metals nec | nfm |
| 23 | En_int_ind | energy-intensive industries | bph, rpp |
| 24 | ppp | paper products and publishing | ppp |
| 25 | ofd | food products nec | ofd |
| 26 | Oth_ind | other industries | cmt, omt, vol, mil, pcr, sgr, b_t, tex, wap, lea, lum, fmp, ele, eeq, ome, mvh, otn, omf |
| 27 | otp | land transport and transport via pipelines | otp |
| 28 | atp | air transport | atp |
| 29 | wtp | water transport | wtp |
| 30 | obs | business services nec | obs |
| 31 | Services | other services | wtr, cns, trd, afs, whs, cmn, ofi, ins, rsa, ros, osg, edu, hht, dwe |

# Independent Technical Review

Modelling Leakage for Permanent Avoidance of Coal Projects TransEnergy Global (2026)

**Dr. Vladimir Tyazhelnikov**
The University of Sydney
vladimir.tyazhelnikov@sydney.edu.au
March 6, 2026

## Scope

This review assesses the analytical framework and conclusions of the report examining reductions in coal production in the United States and South Africa and the associated carbon leakage effects. This review focuses on the conceptual framework, parameterization, and reported implementation of the model as described in the report. It does not independently replicate or re-run the GTAP simulations. Within this scope, no material technical inconsistencies were identified.

The report evaluates the impact of decreases in coal output on domestic and international coal prices, production and consumption adjustments across regions, and the resulting trade reallocation. Because carbon leakage operates through international price and trade channels, it is inherently a general equilibrium phenomenon. The use of a multi-region computable general equilibrium (CGE) model, specifically GTAP-E-Power, is therefore methodologically appropriate and technically justified.

## Analytical Framework

The report relies on the GTAP-E-Power model, a well-established multi-country, multi-sector CGE framework.

Key features of the modeling approach include:

- A global structure covering 160 countries and 76 production sectors, aggregated to 48 regions and 31 sectors for tractability.
- Explicit input–output linkages across sectors.
- A detailed energy structure capturing substitution between fuel types and electricity generation technologies.
- Bilateral trade modeling using the Armington assumption.
- Endogenous price and quantity adjustments under general equilibrium conditions.

The model choice is suitable for analyzing market-mediated leakage effects and is consistent with standard GTAP methodology. As with all CGE-based analyses, quantitative outcomes are conditional on macroeconomic closure assumptions, including the specification of the trade balance and assumptions regarding market structure.

## Leakage Measurement and Interpretation

The report considers two counterfactual scenarios:

- A 3.12% reduction in coal output in South Africa;
- A 1% reduction in coal output in the United States.

The definition of leakage index in the report is

$$\text{Leakage} = -\frac{\Delta E_{\text{global}} - \Delta E_{\text{direct}}}{\Delta E_{\text{direct}}} \times 100\%,$$

where $\Delta E_{\text{global}}$ represents changes in global emissions and domestic emissions and $\Delta E_{\text{direct}}$ corresponds to changes in total emissions from coal produced in South Africa or the United States.

The benchmark reported price responses and leakage rates are economically plausible and consistent with theoretical expectations. The resulting leakage rates 71% for South Africa and 53% for the United States are within the range typically observed in CGE-based climate policy analyses. Overall, the interpretation of the results is internally consistent and economically coherent.

## Sensitivity Analysis

The report conducts sensitivity analysis with respect to three key parameters that govern the magnitude of carbon leakage: the supply elasticity of coal, trade (Armington) elasticities, and the elasticity of substitution across alternative energy sources.

With respect to coal supply elasticity, the results remain quantitatively robust when the elasticity is reduced from 10 to 1. Although leakage declines under the lower elasticity assumption, the qualitative conclusions remain unchanged. This suggests that the central findings do not hinge critically on a high supply responsiveness of coal producers.

The report also varies trade elasticities by ±50%, with the corresponding leakage rates ranging between 53% and 79% for South Africa and between 31% and 66% for the United States. This range is economically plausible and directionally consistent with theory: higher trade elasticities facilitate reallocation of production across countries and therefore increase leakage.

Finally, under the assumption that different energy sources are perfect substitutes, the model generates very low leakage rates. This outcome is consistent with economic intuition: if alternative energy technologies can fully substitute for coal, domestic reductions in coal production are largely offset by substitution toward other domestic energy sources rather than increased foreign coal production. While perfect substitutability across energy sources is unlikely in the medium run, this scenario provides a useful consistency check of the medhodological approach and highlights the central role of energy substitution in driving leakage dynamics.

## Limitations

The analysis is subject to a few limitations inherent to the modeling framework.

First, the simulations rely on a 2017 benchmark dataset. Structural changes in energy production and consumption, particularly the expansion of renewable generation in the United States over the past decade, may affect the quantitative magnitude of the results. The findings therefore should be interpreted as conditional on the benchmark year.

Second, substitution parameters estimated for one economy are applied to others. In particular, elasticities governing substitution across energy sources are calibrated using U.S. based estimates and then applied to South Africa. While such parameter selection is common in CGE modeling, cross-country differences in energy systems may influence the quantitative results.

Third, the reported leakage rates are derived for specific policy shocks (3.12% and 1% reductions in coal output) and should be interpreted as elasticities evaluated at those magnitudes. These estimates are not scale-invariant: substantially different shocks may generate quantitatively different responses, and would require re-solving the model. The findings presented in this review are therefore most relevant for shocks of close or similar magnitude to those analyzed.

## Conclusion

The analysis in this report provides a technically sound and economically coherent assessment of carbon leakage resulting from reductions in coal production in South Africa and the United States. The chosen modeling framework is appropriate for the research question, and the reported results are internally consistent and supported by sensitivity analysis addressing key structural parameters.

Within the scope of this review, no material technical concerns were identified.

Photo: Satellite view of eMalahleni (Witbank) coal operations and urban blocks in South Africa.
Taken from Copernicus Platform by optical methods, Jan 2026

**TransEnergy Global Pte Ltd**

**transenergy-global.com**

Level 42 Suntec Tower Three
8 Temasek Boulevard, Singapore 038988