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# Introducing carbon taxes in South Africa ☆

Theresa Alton [a], Channing Arndt [b,*], Rob Davies [a], Faaiqa Hartley [a], Konstantin Makrelov [a], James Thurlow [c], Dumebi Ubogu [a]

[a] The National Treasury, 40 Church Square, Pretoria, South Africa
[b] Department of Economics, University of Copenhagen, Øster Farimagsgade 5, Copenhagen, Denmark
[c] United Nations University, World Institute for Development Economics Research, Katajanokanlaituri 6 B, FI-00160 Helsinki, Finland

## HIGHLIGHTS

- South Africa is considering introducing a carbon tax to reduce greenhouse gas emissions.
- A phased-in tax of US$30 per ton can achieve national emissions reductions targets set for 2025.
- Ignoring all potential benefits, the tax reduces national welfare by about 1.2 percent in 2025.
- Border carbon adjustments reduce welfare losses while maintaining emissions reductions.
- The mode for recycling carbon tax revenues strongly influences distributional outcomes.

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## ABSTRACT

South Africa is considering introducing a carbon tax to reduce greenhouse gas emissions. Following a discussion of the motivations for considering a carbon tax, we evaluate potential impacts using a dynamic economywide model linked to an energy sector model including a detailed evaluation of border carbon adjustments. Results indicate that a phased-in carbon tax of US$30 per ton of $CO_2$ can achieve national emissions reductions targets set for 2025. Relative to a baseline with free disposal of $CO_2$, constant world prices and no change in trading partner behavior, the preferred tax scenario reduces national welfare and employment by about 1.2 and 0.6 percent, respectively. However, if trading partners unilaterally impose a carbon consumption tax on South African exports, then welfare/employment losses exceed those from a domestic carbon tax. South Africa can lessen welfare/employment losses by introducing its own border carbon adjustments. The mode for recycling carbon tax revenues strongly influences distributional outcomes, with tradeoffs between growth and equity.



## 1. Introduction

South Africa is amongst the world's most carbon-intensive economies. An abundance of coal resources and subsidized coal-fired electricity has led to a reliance on energy-intensive mining and heavy industry as the historical drivers of economic development. Notwithstanding this legacy, the South African government has recently targeted ambitious reductions in greenhouse gas (GHG) emissions. Emissions reductions at the scale envisioned imply a structural transformation of the South African economy. The government is considering introducing a carbon tax as one instrument to foment this transformation [1].

As with any major reform, there will be winners and losers from a carbon tax, especially during the transition period. Influential interest groups in South Africa have already expressed concerns [2]. Businesses are worried about losing competitiveness, especially in export markets for minerals and metals. Organized labor is concentrated in energy-intensive sectors and so labor unions are worried about job losses. Finally, civil society groups are concerned about the effect of higher energy prices on poor households. These concerns underpin the current broad resistance in South Africa to a carbon tax [3]. The challenge then for the South African government is not only to design and implement an effective carbon tax, but also to strike a careful balance between energy, development and environmental goals.

This article evaluates the socioeconomic consequences of introducing carbon taxes in South Africa as a Pigouvian measure designed to reduce carbon emissions. The analysis employs a recursive dynamic economywide model of South Africa that includes a detailed treatment of the energy sector calibrated to the



* Corresponding author. Tel.: +1 9706892112.
*E-mail address:* channing@wider.unu.edu (C. Arndt).

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results from an inter-temporal electricity sector investment optimizing model. The economic model's high level of disaggregation permits an assessment of not only growth implications, but also employment and distributional outcomes. The latter are major factors shaping the carbon tax debate in carbon-intensive developing countries [4]. The model contains a novel treatment of industrial energy use efficiency that accounts for changes in energy prices, as well as changes in sectoral investment and capital vintages. This better reflects the adjustment costs and investment constraints that affect industries' ability to adopt more energy efficient technology [5,6]. The paper therefore contributes to the literature on carbon taxation in developing countries and to the methods used to measure its impacts.

The article is structured as follows. Section 2 considers the motivations for considering a carbon tax in the South African context, and Section 3 reviews the existing literature focused on South Africa and highlights the knowledge gaps that this article seeks to fill. Section 4 provides an overview of energy use and $CO_2$ emissions from energy, and Section 5 describes the energy-related features of the economywide-energy model. The next three sections discuss results from the model, including the baseline, carbon tax, and revenue recycling scenarios. The final section summarizes and concludes.

## 2. Motivations for a carbon tax

Given that global climate change negotiations seem to have stalled and that there is, as a consequence, no immediate international pressure on South Africa to limit emissions, it is worthwhile to reflect on why the country would pursue mitigation policy. There are at least two reasons. First, Sokolov et al. [7] estimate that, without global mitigation and compared with the end of the 20th century, there is a 50 percent chance that global temperatures will rise by five degrees Centigrade or more by 2100. The chance of a rise of less than two degrees is nil. As Weitzman [8] notes, the consequences of such extreme global warming are deeply uncertain and may be profoundly negative. Despite this uncertainty, there is broad consensus that low income countries will be affected first. Africa is vulnerable, given its underdevelopment and location in the tropics. While South Africa is better equipped to adapt to climate change than many African countries, its neighboring states are less robust. Overall, there are strong reasons to believe that Africa's long-run interests, including those of South Africa, favor effective global mitigation.[1]

A second reason for introducing a carbon tax is that other nations, notably Australia and the European Union but also China, are taking climate change seriously. Australia, for example, currently imposes a carbon tax at a value of about US$20 per ton. Even the United States has shown some willingness to enact mitigation policies – the House of Representatives passed a "cap and trade" bill (effectively a carbon tax) in 2010, but this failed to gain approval in the Senate. It is possible that, over the coming decade, mitigation policies could be implemented in a number of leading countries. For these policies to be effective, this "coalition" of mitigating countries will have incentives to expand membership. They may find it logical and politically expedient to limit the "carbon leakage" that arises when carbon-intensive supply-chains are relocated to non-coalition countries. Border carbon adjustments (BCA) that impose taxes on the carbon content of imports (and rebate domestic exporters) are one potential instrument for achieving this objective [9].

[1] Not only would implementing a carbon tax support the emergence of global policy, but it would also serve to cement South Africa's position as a leader on the continent.

In summary, South Africa has a long-run incentive to support global mitigation. In the shorter run, South Africa cannot discount the possibility of the emergence of a coalition of mitigating countries that implements policies, such as BCAs, that would disadvantage carbon intensive economies, such as South Africa, in global markets. Implementing carbon taxes in the near term would serve to initiate the transformation to a "greener" economy and hence avoid having to rapidly reduce emissions in the future. In all cases, the economic impacts of a carbon tax on the South African economy are of considerable interest. In this article, we explore these economic impacts and consider the alternative carbon tax designs being debated in the country.

The South African government has considered various instruments to reduce carbon emissions. In the 2012 National Budget, the government outlined a phased-in emissions-based carbon tax, which, given concerns over adjustment costs, provides exemptions to highly trade-exposed and energy-intensive industries. These exemptions would delay but not stop the full imposition of carbon taxes. The government therefore appears to be committed to a *gradual* introduction of carbon taxes. That being said, while some interest groups, particularly business, view a cap-and-trade scheme as preferable, the complexity of managing such a system makes a carbon tax a more immediately viable instrument and thus the main focus of the policy debate.

The level of carbon tax needed for South Africa to achieve its emissions reduction targets remains unclear given the absence of empirical evidence. The government has also not specified how carbon tax revenues would be recycled, since it is not standard practice to earmark specific revenue sources for particular investments or social programs. Nevertheless, the policy debate is broadly characterized by civil society, who advocate subsidizing energy prices for poor households, and at the other extreme, business groups, who generally support accelerated depreciation of capital assets to allow for more energy-efficient investments. In this article we contribute to the ongoing policy debate by examining different carbon tax levels and revenue-recycling options.

## 3. Existing literature and knowledge gaps

We are not the first to explore these issues in the South African context. Three recent studies use computable general equilibrium (CGE) models to evaluate the potential effects of a carbon tax [10–12]. Devarajan et al. [10] find that carbon taxes reduce national welfare but are more efficient than other tax instruments on energy use or pollution. Through detailed sensitivity analysis, the authors show that their results depend crucially on labor market rigidities and technological substitution possibilities. One limitation of the study is that the authors do not distinguish between different energy technologies or capture the long-term electricity investment plan for South Africa, which largely determines the future energy mix and includes a shift towards renewable energy. The study might therefore overstate the responsiveness of electricity production and prices to the carbon tax. In contrast, Pauw [11] distinguishes between energy technologies and bases long-term electricity investments on a partial-equilibrium energy model. Pauw finds smaller welfare reductions when a carbon tax is introduced, although less attention is paid to labor market rigidities. Van Heerden et al. [12] concentrate on revenue recycling options. They find that a "triple dividend", implying decreased $CO_2$ emissions and poverty while increasing GDP, is possible if revenues from environmental taxes are recycled such that they reduce food prices.

Perhaps the main limitation of these studies is the lack of a time dimension. They use static CGE models, which exclude changes in investment behavior in response to energy prices. Their static models also allow a costless reallocation of capital across industries and so understate adjustment costs. In a real world dynamic setting, capital typically becomes immobile after investment, implying that new investment is needed to shift production and employment towards less carbon-intensive activities. Moreover, none of the studies allow industries to invest in less energy-intensive technologies. Efficient mitigation policies are implemented over time, allowing the carbon intensive capital stock to depreciate away and providing clear signals to investors and innovators to take carbon emissions into account. For these reasons, South African emissions targets focus on 2025. Considering the path to achieving these emissions reductions forms an important part of the analysis.

To address these limitations, we develop a dynamic CGE model of South Africa. Following Pauw [11], our model contains detailed energy technologies and is calibrated to investment projections from an energy sector model. Our dynamic specification allows non-energy industries to endogenously invest in more energy-efficient technologies in response to higher energy prices. The model is calibrated to a purpose-built database that reconciles energy and economic data. We simulate various policy options, including carbon taxes; foreign and domestic BCAs; and various revenue recycling options, similar to van Heerden et al. [12]. As with Devarajan et al. [10], we conduct sensitivity analysis on labor market rigidities.

The implications of BCAs merit further mention. BCAs are the subject of a recent study by Energy Modeling Forum that is summarized in Böhringer et al. [13]. In the study, BCAs are found to reduce carbon leakage and reduce output losses associated with same level of emissions reductions. This article contributes to this emerging literature by considering BCAs in a middle income country.

## 4. Energy use and carbon emissions in South Africa

### 4.1. Sources of GHG emissions

South Africa has committed to reducing its GHG emissions by 34 percent by 2020 and 42 percent by 2025 relative to a “business-as-usual” baseline [1]. Such ambitious targets reflect South Africa’s ranking as the world’s thirteenth largest GHG emitting country in absolute terms in 2007, with per capita emissions nearly twice the global average [14].

Arndt et al. [2] compile an emissions profile for South Africa using information from national supply-use tables and energy balances. Table 1 describes the sources of carbon dioxide ($CO_2$) emissions from burning primary fossil fuels (i.e., coal, crude oil and natural gas).[2] Had South Africa burned its entire fossil fuel supply in 2005 it would have generated 523.6 million metric tons of $CO_2$ emissions. However, more than a quarter of coal is exported, implying that the $CO_2$ emissions of net domestic supply are lower at 387.8 million tons. Despite these exports, coal still accounts for 87.8 percent of net emissions, followed by crude oil at 9.7 percent.

More than three-fifths of domestic coal supply is used to generate electricity. In 2005, coal-fired power plants generated 92.9 percent of total electricity supply, followed by nuclear (4.9 percent) and hydropower (1.8 percent). This reliance on coal-fired plants explains why 53.1 percent of South Africa’s total emissions are from electricity generation. Coal is further used to produce liquid fuels, where it generates an additional 31 percent of total emissions. Natural gas is used to produce electricity and liquid fuels, although the quantities are relatively small and it contributes little to total emissions. The remaining 16.2 percent of coal and 68.4 percent of natural gas that are not transformed into electricity or liquid fuels are used directly by industries and households.

**Table 1**
Carbon dioxide emissions from fossil fuel use, 2005[a]. *Source*: [2].

| | Total | Coal | Crude oil | Natural gas |
|---|---|---|---|---|
| Domestic production ($CO_2$ mt) | 479.8 | 472.8 | 0.0 | 7.0 |
| Plus imports | 43.8 | 3.6 | 37.6 | 2.5 |
| Total supply | 523.6 | 476.4 | 37.6 | 9.5 |
| Less exports | 137.1 | 137.1 | 0.0 | 0.0 |
| Less change in stocks | −1.3 | −1.3 | 0.0 | 0.0 |
| Domestic supply | 387.8 | 340.6 | 37.6 | 9.5 |
| Direct domestic use | 387.8 | 340.6 | 37.6 | 9.5 |
| Electricity | 205.8 | 205.3 | 0.0 | 0.5 |
| Petroleum | 120.2 | 80.1 | 37.6 | 2.5 |
| Other industries | 52.0 | 45.5 | 0.0 | 6.5 |
| Households | 9.7 | 9.7 | 0.0 | 0.0 |

[a] Includes $CO_2$ emissions from burning primary fuels but excludes other GHGs.

Table 1 showed the emissions associated with the *direct* use of primary fuels. However, all industries generate emissions *indirectly* by using carbon embodied within intermediate inputs. Arndt et al. [2] estimate carbon intensities for products and find that indirect carbon use accounted for two-thirds of total emissions in 2005, of which approximately a quarter is carbon embodied within imported goods and services. Not surprisingly, energy products are found to be the most carbon intensive, with electricity and petroleum generating 3.29 and 0.66 tons of $CO_2$ per 1000 Rand (US$160) of final demand, respectively. Carbon intensity is also relatively high for the more export-intensive heavy industries, such as wood products (0.37) and metals (0.40). Carbon use tends to be lower in services, such as government (0.08) and finance (0.03). Services do, however, use carbon indirectly, especially in the form of electricity. The carbon-intensity of electricity generation therefore has economywide implications beyond the energy and heavy industrial sectors.

### 4.2. Long-term electricity investment plan

South Africa recently announced its electricity sector investment plan for 2010–2030 [15]. The plan draws on an energy sector model which estimates least-cost investment options subject to various constraints, including demand forecasts, portfolio risks, domestic production quotas, and emission targets. Fig. 1 shows results from three simulations that satisfy the same demand forecast.

The “business-as-usual” scenario is unbounded by carbon taxes or emission targets. Under this scenario, $CO_2$ emissions in the electricity sector rise from 237 million tons in 2010 to 381 million tons in 2030. The total cost of the “business-as-usual” plan (in present value terms) is estimated at R0.79 trillion (US$108 billion), which is equivalent to a third of gross domestic product (GDP) in 2010.[3]

The least carbon-intensive investment plan in DOE [15] still fails to achieve the national emission reduction targets. In the “low emissions” scenario, total $CO_2$ emissions only reach the targeted 42 percent decline from baseline by 2030 rather than 2025. Even this delayed achievement incurs a substantial financial cost to the economy, with the “low emissions” investment plan costing R1.25 trillion (US$171 billion). This implies that, given domestic production quotas and demand forecasts, meeting the national emissions targets in the electricity sector will cost the economy *at least* an additional R0.46 trillion (US$63 billion) or 19 percent of GDP in 2010. Much of this additional cost is due to greater use of renewable energy, which has lower load factors and therefore requires more installed system capacity in order to deliver the same electricity output as coal-fired and nuclear alternatives.

[2] We use standard carbon emissions factors equal to 1.93 tons of $CO_2$ per metric ton of coal, 2.33 per metric ton of crude oil, and 0.056 per gigajoule of natural gas.

[3] The present value calculation uses an eight percent discount rate for the period 2010–2030.

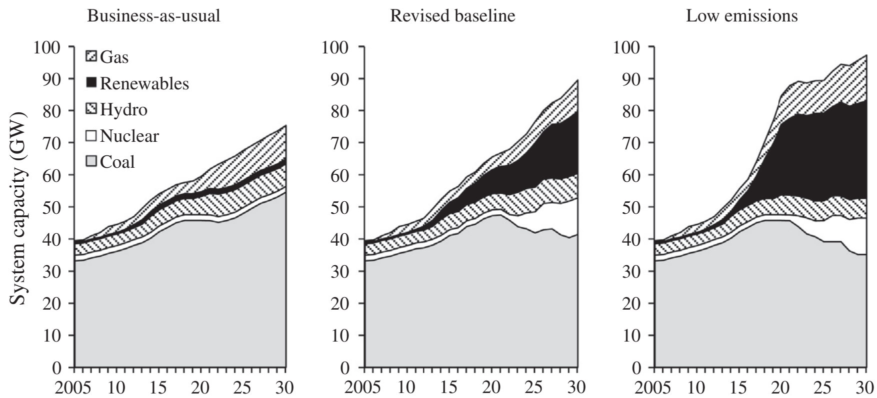


**Fig. 1.** Electricity system capacity in the energy sector model scenarios, 2005–2030. *Source*: Authors' calculations using [15]. (All three scenarios supply the same electricity demand forecast after accounting for differences in load factors.)

At least some of the additional investment costs will need to be passed on to consumers through higher electricity tariffs. However, recent tariff increases suggest that any sizable pass-through will face political economy constraints [3,16]. Therefore, it is not surprising that the South African government has endorsed a more modest investment plan.[4] The total cost of this "revised baseline" scenario is well below the cost of the "low emissions" scenario. However, total $CO_2$ emissions in 2025 are only 19 percent below the baseline and so fall far short of the 42 percent target. This implies that, if future electricity production follows the revised baseline scenario, as is currently expected, then any remaining emission reductions would need to occur outside of the electricity sector. This special dispensation or "ring fencing" poses an important constraint because the electricity sector accounts for a large share of total emissions. For this reason, we initially calibrate our economywide model to replicate the revised baseline, and then use this as our reference scenario for evaluating the effects of carbon taxes on reducing the remaining emissions.

## 5. Economywide-energy model

Our CGE model is well-suited to evaluating a carbon tax. The model contains detailed information on sectors and households. It captures the functioning of a market economy in which the interactions of producers, households, government and rest of the world are mediated via prices and markets. Macroeconomic and resource constraints are respected, which is crucial for large-scale policy changes. And, the model is dynamic, which is important for policies, such as carbon taxes, that are phased in over time and meant to influence investment patterns. Overall, it provides a "simulation laboratory" for quantitatively examining how carbon taxes influence production, trade and employment patterns as well as income distributions.

The model is structured in the tradition of Dervis et al. [17]. Detailed descriptions of the modeling framework can be found in Appendix A. Here, we limit discussion to dynamics, embodied technical change in energy efficiency, and the energy subsectors in the model. Simulation design and closure rules are presented in the next section.

### 5.1. Dynamics

The model is recursive dynamic. Between periods, exogenous variables and parameters are updated based on externally-determined trends in labor supply, government consumption, foreign capital inflows, and technical change. In addition, capital stocks in period $t+1$ are augmented based on investment in period $t$ less depreciation. This new capital is allocated across productive sectors in proportion to a sector's share of current capital stocks adjusted by its own profit rate relative to the national average profit rate. Sectors with above-average profit rates receive a greater share of investible funds than their share in the existing capital stocks. Once allocated, capital remains fixed in the sector. This "putty-clay" specification implies that new capital is mobile but installed capital is sector-specific.

### 5.2. Embodied technical change in energy efficiency

The model presumes that technical change in energy efficiency must come embodied in new capital investment. Furthermore, improvements in energy efficiency must be induced through higher relative prices for energy. Our specification is motivated by a vintage capital approach to capital accumulation.[5] Specifically, between periods non-energy producers can respond to changing energy prices by investing in more or less energy-intensive capital and production technologies. This is shown below:

$$\frac{io_{jet+1}}{io_{jet}} = 1 - \left(1 - \frac{P_{st}^{-\rho_e^j}}{p_s}\right) \cdot \frac{SK_{jt} \cdot N_t}{K_{jt}}$$

where the change in the intermediate demand coefficient, *io*, in sector j for energy commodity *e* at time t depends on changes in energy market prices *P* relative to base year energy prices *p*. A sector's responsiveness to changes in energy prices depends on an elasticity of substitution, $\rho$, and the share of new investment $(SK_{jt} \cdot N_t)$ in the sector's existing capital stock *K*. This specification implies that new investment (or newer "vintage" capital) is required for a sector to adopt less energy-intensive technologies. Slower growing and less profitable sectors will find it more difficult to adjust to higher energy prices.

### 5.3. Energy subsectors

Our model includes a detailed treatment of the energy sector. As described earlier, the three primary fossil fuels, i.e., coal, crude oil and natural gas, are either transformed into electricity and petroleum or are used directly by final users, i.e., industries and households. Our model disaggregates electricity and petroleum

[4] This "policy-adjusted scenario" is an outcome of government and private sector consultations.

[5] The vintage capital approach recognizes that technological change is often embodied in new capital goods. This is also true for energy efficiency. For example, a trucking company can become more energy efficient by replacing older trucks with new trucks. The average efficiency of the trucking company is driven in large measure by the age, or vintage, of their trucks.

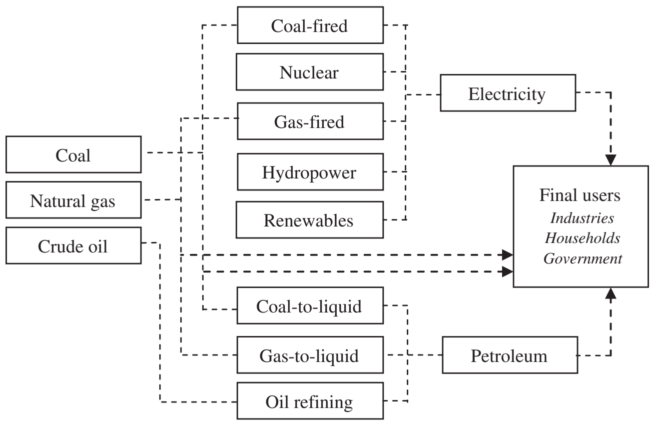


**Fig. 2.** Structure of the energy sector in the CGE model.

into subsectors, as shown in Fig. 2.

Coal and natural gas are used to produce electricity. Other sources include nuclear, hydropower (domestic and imported) and renewables (i.e., solar and wind). Each electricity subsector supplies their output to the national grid, where it is combined into a single electricity commodity. Each subsector has its own production technology, i.e., intermediate input coefficients *io* and shares in value added across factors. These technologies are based on Pauw [11] and StatsSA [18]. The coal-fired electricity subsector gradually switches to cleaner coal technology based on projections from DOE [15]. Finally, coal and natural gas are used to produce petroleum via "coal-to-liquid" (CTL) and "gas-to-liquid" (GTL) transformation processes. However, more than 80 percent of petroleum is still produced by refining imported crude oil.

## 6. Baseline scenario

We first construct a baseline scenario that excludes carbon taxes. The purpose of the baseline scenario is to provide a reasonable counterfactual with which to assess the implications of alternative carbon tax designs. In the following, we first present key assumptions in the baseline path and then consider the implications of these assumptions. Because economic growth in the CGE model is determined by labor and capital supplies and technical change, these elements are in focus. An exception is the electricity subsectors, whose production paths follow the "revised baseline" projections in Fig. 1 (using load factors to translate capacity into output). This includes employment in the electricity sector, which rises from 103,800 workers in 2005 to 174,000 workers in 2030. The productivity and employment-intensity of individual electricity subsectors are fixed over time and so total employment and technological change in the overall electricity sector is determined by the pattern of electricity supply and is the same across the baseline and carbon tax scenarios.

In labor markets, given South Africa's skills constraints, we assume that secondary and tertiary-educated labor supplies are exogenous and fully employed and grow at 2.0 and 1.5 percent per year, respectively. To reflect high unemployment amongst low-skilled workers, we assume that the supply of primary-educated and uneducated workers is determined endogenously by an upward-sloping supply curve with modest real wage-supply elasticities. We assume wage-supply elasticities of 0.1 for all labor types, which, in the baseline, generates a total employment growth to GDP growth elasticity of 0.67. This is consistent with observed national growth and employment trends in South Africa over the last two decades. Given the uncertainty about future labor market behavior, we conduct sensitivity analysis on labor market rigidities by considering lower (0.05) and upper (0.3) bound elasticities. Elasticities close to zero suggest that unemployment is primarily "structural" and that labor market adjustments occur mainly through (negotiated) movements in real wages [10]. The upper bound elasticity implies that employment levels and wages respond to changing labor demands.

Investment and capital accumulation rates are determined by the level of savings. Since marginal savings rates are fixed, private savings are determined endogenously by private incomes. We assume that foreign and public savings grow at roughly the same rate as national economic growth and thus remain a fixed share of total GDP in the baseline. These assumptions imply a flexible exchange rate and public consumption growth of three percent per year (consistent with current exchange rate and public consumption growth policies). Technical change is captured by exogenous TFP growth of one percent per year in all sectors.

The above assumptions lead to average annual GDP growth of 3.9 percent during 2010–2025, which is consistent with the growth rate used to forecast electricity demand [15]. Economic growth (and hence electricity demand) grows faster than electricity supply, causing *real* electricity prices to rise initially. These prices eventually stabilize and begin declining as the growth in electricity supply accelerates. Total labor employment grows at 2.6 percent per year, implying an employment-growth elasticity of 0.67 and a gradual decline in the national unemployment rate (given annual population growth of 1.5 percent).[6] GDP growth is fairly even across sectors as a result of uniform productivity growth and mobile labor. Overall, the baseline scenario provides a reasonable economic trajectory for South Africa.

## 7. Carbon tax scenarios

We now introduce carbon taxes while maintaining all other assumptions. The resulting counterfactual simulations are compared to the baseline scenario. We simulate three carbon tax scenarios. The first simulation imposes a domestic carbon tax on the net supply of primary fossil fuels.[7] A carbon tax of US$3 (R21) per ton of $CO_2$ is introduced in 2012 and this rises gradually until it reaches US$30 per ton in 2022. We call this the "production" scenario because the tax is imposed on all domestically-produced goods. For now, all carbon tax revenues are recycled through a uniform percentage point reduction in indirect sales tax rates for all products.

The second simulation not only imposes a phased-in US$30 per ton carbon tax on fossil fuel supplies, but it also introduces an equivalent phased-in BCA that taxes imports and rebates exports based on embodied carbon. For the calculation of export rebates, we use the estimates of embodied carbon for the South African economy calculated in Arndt et al. [2] multiplied by the value of the carbon tax. For the calculation of import taxes, we should, in principle, employ estimates of embodied carbon by commodity and by bilateral trading partner. As this information is not available, we simply apply the South African estimates from Arndt et al. [2]. These coefficients would tend to overstate, on average, the actual carbon content of imports due to South Africa's overall high carbon intensity. However, other than liquid fuels, South African imports are not particularly carbon intensive. Imports from Europe, where carbon intensity would be much lower than in South Africa, are concentrated in products, such as capital goods, that have low car-

[6] The growth elasticity of employment is higher than in other emerging markets but is consistent with South Africa's experience during 2003–2008.

[7] We tax fossil fuels at their point of entry into the economy, i.e., imported fuels (crude oil) are taxed at the border, and domestic fuels (coal and natural gas) are taxed at the mine-head.

bon intensities. For example, Arndt et al. [2] estimate that the embedded carbon content in Machinery, a major import item sourced from Europe, is the lowest of any industrial sector. So, while the true coefficient on imports of European machinery is likely to be lower, the absolute magnitude of the difference is small because the coefficients themselves are small.[8] Imports from Asia, particularly China, are reasonably well estimated by the South African values as economy-wide carbon intensities are similar.

The BCA compensates domestic producers by maintaining their import and export competitiveness even though trading partners do not introduce their own carbon taxes. The BCA means that South Africa only pays carbon taxes on consumed products, regardless of whether they are produced domestically or imported. We therefore call this the "consumption" scenario. Again, we assume that all carbon tax revenues, including revenues from BCAs net of export rebates, are recycled through reduced indirect taxes.

The third simulation assumes that South Africa's trading partners introduce a carbon tax and BCA, but South Africa does not. In this scenario, import prices that South Africa pays remain essentially unchanged because the carbon tax applied in countries that export to South Africa is rebated. However, export prices that South Africa receives decline because at least some of the incidence of the carbon tax imposed in the partner country accrues to South Africa (and the revenue remains within the partner country).[9] Again, we use South African coefficients, but we set the foreign BCA at half the value of the carbon tax imposed in the second simulation. The BCA is phased-in from US$1.50 in 2012 to US$15 in 2022. This is the "foreign carbon tax" scenario.

Table 2 shows the changes in $CO_2$ emissions in the three simulations. The table uses two metrics to measure carbon emissions. The "reference" approach is based on fossil fuel supply, whereas the "sectoral" approach accounts for the carbon embodied within imports and exports. For example, the latter approach includes the carbon within imported refined petroleum, which only indirectly uses crude oil. The former approach is consistent with a production based tax (i.e., no BCAs), while the latter approach is consistent with a consumption based tax. In the Production scenario and using the reference approach, the phased-in US$30 per ton carbon tax reduces total emissions by 36.6 percent relative to the "business-as-usual" scenario. As discussed in Section 2, the revised baseline scenario in DOE [15] projects a 19 percent reduction in electricity sector emissions by 2025, which is equal to an 8.6 percent reduction in total emissions. The production-based carbon tax therefore generates an additional 28 percentage point reduction in emissions, all of which comes from reduced carbon use in the non-electricity sectors. In the consumption scenario and using the sectoral approach, total emissions decline by 41.4 percent by 2025, which is close to the national target. Both approaches result in similar total emissions reductions.[10] Hence, the choice between a production- and consumption-based carbon tax depends principally upon economic impacts and political feasibility.

Table 3 presents macroeconomic results. A production-based carbon tax reduces total absorption in 2025 by 1.2 percent below the baseline GDP level in 2025.[11] This implies a modest 0.08 percentage point reduction in the average annual absorption growth rate during 2010–2025. This deceleration is mainly due to the effect of falling national incomes and savings on investment.[12] Private consumption growth also decelerates, although this is offset by recycling carbon taxes through lower indirect taxes, principally sales taxes. Exports also decline with a production-based tax because producers' competitiveness is eroded in foreign markets. This prompts a slight depreciation of the real exchange to support exports and discourage imports.

In the production-based approach, the carbon tax puts pressure on producers of traded goods because embodied carbon on imports is not taxed and embodied carbon in exports is not rebated. In contrast, a consumption-based carbon tax rebates exports and taxes imports making the implications for traded sectors unclear *a priori*. In the event, the consumption-based tax heightens incentives to produce for foreign markets resulting in a small increase in exports. Given a fixed trade balance, imports increase as well. The consumption-based tax maintains a higher level of employment and does not push resources out of (often more productive) traded sectors. As a result, the deceleration in absorption growth is smaller under the Consumption scenario. A BCA therefore reduces the economic losses of a carbon tax and addresses concerns raised about a loss of export and import competeviness.

Labor demand declines with the introduction of a carbon tax due to slower national economic growth. This is reflected in slower employment growth for less educated workers and slower wage growth for more educated workers. Overall employment in the Production scenario is about 0.6 percent below the baseline in 2025. This implies a modest 0.04 percentage point reduction in annual employment growth. As shown in Table 4, slower job creation occurs in the more export- and carbon-intensive mining and heavy industrial sectors, such as chemicals. This is offset by new production and job opportunities in less carbon-intensive sectors, such as food, textiles and financial services. Fewer job losses occur in the Consumption scenario because exporters and import-competing producers are shielded by a BCA. The only exceptions are machinery and transport, which rely on imported carbon-intensive inputs that are now subject to the carbon tax, such as refined petroleum. Overall, the slowdown in job creation is relatively small, although more unionized industrial sectors are most affected.

We conduct sensitivity analysis on the size of the carbon tax and on labor market rigidities. The left-hand side of Fig. 3 shows the final GDP losses in 2025 at different carbon tax rates (i.e., an economywide abatement cost curve), while the right-hand side shows the sectoral sources of GDP losses. The abatement cost curve is strongly non-linear and rises rapidly for carbon tax rates above US$20 per ton. This is because the economy initially reduces emissions at relatively low cost by focusing on the more carbon-intensive sectors, such as mining. However, as carbon taxes rise, the economy's ability to further reduce emissions becomes more constrained, and eventually even less carbon-intensive sectors are affected, such as services. Importantly, the electricity sector accounts for half of total emissions and its future emissions path is fixed. This implies that any further emissions reductions have to take place in non-electricity sectors, even if economywide abatement costs are higher.

Employment losses are also more pronounced at carbon taxes above US$20 per ton. The dashed lines in Fig. 3 shows results using lower and higher labor supply elasticities (see Section 3). Not surprisingly, the estimated number of job losses is sensitive to the value of these elasticities. For example, the decline in employment by 2025 for a US$30 per ton carbon tax ranges from 0.71 to 0.32 per-

[8] For example, suppose the true coefficient on European machinery is two thirds of the South African value. This would imply, for a R210 (US$30) per ton carbon tax, a border carbon adjustment of one percent rather than 1.5 percent. These differentials have essentially no impact on the reported results.

[9] For a discussion of the terms of trade implications for developing countries of BCAs implemented in developed countries, see [19].

[10] The difference in percentage reduction is the result of differences in the denominator. Because South Africa is a major net exporter of embodied carbon, the production approach yields a larger denominator than the consumption approach.

[11] Absorption is an aggregate welfare measure equal to the sum of private and public consumption and investment.

[12] This is partly a result of our savings-driven investment macroeconomic closure, which is justified by empirical evidence showing that changes in gross fixed capital formation in South Africa are caused by changes in the level of national savings, rather than vice versa – see [20].

**Table 2**
GHG emissions results, 2010–2025[a]. *Source*: CGE model results.

| | Business-as-usual, 2010 | Deviation from "business-as-usual" scenario, 2025 (%) | | | |
|---|---|---|---|---|---|
| | | Revised baseline | Production carbon tax | Consumption carbon tax | Foreign carbon tax |
| Total $CO_2$ emissions (mil mt) using the reference approach | 447.5 | −8.6 | −36.6 | −36.2 | −19.6 |
| Electricity generation | 237.0 | −19.0 | −19.0 | −19.0 | −19.0 |
| Other sectors/households | 210.5 | 0.0 | −51.3 | −50.5 | −20.1 |
| Total $CO_2$ emissions (mil mt) using the sectoral approach | 397.4 | −8.6 | −40.4 | −41.4 | −21.0 |

[a] Includes $CO_2$ emissions from burning primary fuels but excludes other GHGs. "Sectoral approach" includes the carbon embodied within imports and excludes carbon within exports. We assume that exported fossil fuels are exempt in the production carbon tax scenario but imported fossil fuels are not.

**Table 3**
Macroeconomic results, 2010–2025. *Source*: CGE model results.

| | Initial value, 2010 | Baseline growth rate (%) | Deviation from baseline value, 2025 (%) | | |
|---|---|---|---|---|---|
| | | | Production carbon tax | Consumption carbon tax | Foreign carbon tax |
| GDP at market prices (%) | 100.0 | 3.91 | −1.23 | −1.07 | −1.00 |
| Absorption | 100.1 | 3.93 | −1.20 | −1.04 | −1.74 |
| Household consumption | 63.0 | 4.15 | −0.63 | −0.56 | −2.06 |
| Percentile 0–50 | 11.3 | 2.56 | −0.78 | −0.79 | −1.74 |
| Percentile 50–90 | 25.1 | 2.67 | −0.67 | −0.62 | −2.07 |
| Percentile 90–100 | 26.6 | 2.59 | −0.52 | −0.40 | −2.17 |
| Government consumption | 19.2 | 3.00 | 0.00 | 0.00 | 0.00 |
| Investment demand | 17.9 | 4.38 | −4.06 | −3.48 | −2.15 |
| Exports | 24.6 | 4.11 | −0.88 | 0.24 | −0.42 |
| Imports | −26.6 | 4.19 | −0.81 | 0.22 | −3.19 |
| Employment (1000s) | 12,244 | 2.63 | −0.56 | −0.50 | −0.83 |
| High-educated workers[a] | 5148 | 1.83 | 0.00 | 0.00 | 0.00 |
| Low-educated workers | 7096 | 3.16 | −0.90 | −0.80 | −1.32 |
| Average wages (R per year) | 74,303 | 2.72 | −1.37 | −1.20 | −1.90 |
| High-educated workers[a] | 116,709 | 4.11 | −1.97 | −1.73 | −3.11 |
| Low-educated workers | 43,538 | 0.89 | −0.92 | −0.80 | −0.39 |

[a] High-educated labor includes workers with completed secondary or tertiary educations.

**Table 4**
Sectoral employment results, 2010–2025. *Source*: CGE model results; carbon intensity measures from [2].

| | Employment share, 2010 (%) | Carbon intensity measure, 2005[a] | Deviation from baseline value, 2025 (%) | | |
|---|---|---|---|---|---|
| | | | Production carbon tax | Consumption carbon tax | Foreign carbon tax |
| All sectors | 100.0 | 0.265 | −0.56 | −0.50 | −0.83 |
| Agriculture | 3.7 | 0.138 | 1.54 | 0.21 | 0.47 |
| Mining | 7.4 | 1.661 | −5.43 | −3.74 | −2.03 |
| Manufacturing | 15.4 | 0.201 | 0.05 | −0.13 | −0.42 |
| Food | 2.7 | 0.154 | 1.05 | 0.41 | −0.89 |
| Textiles | 1.0 | 0.115 | 1.84 | 0.19 | 0.42 |
| Wood products | 2.2 | 0.372 | −0.83 | −0.63 | −0.79 |
| Chemicals | 2.0 | 0.422 | −0.61 | 0.05 | −0.83 |
| Non-metals | 0.8 | 0.312 | −1.09 | −1.02 | −1.13 |
| Metals | 2.3 | 0.396 | −0.22 | 0.95 | −0.25 |
| Machinery | 1.8 | 0.092 | −1.34 | −1.84 | −0.51 |
| Vehicles | 1.6 | 0.115 | 1.38 | −0.08 | 0.74 |
| Other | 0.9 | 0.145 | 1.79 | 0.65 | 0.65 |
| Other industry | 4.9 | 0.513 | −2.43 | −2.08 | −1.51 |
| Services | 68.6 | 0.162 | −0.12 | −0.13 | −0.80 |
| Trade | 17.4 | 0.194 | −0.30 | −0.21 | −1.04 |
| Transport | 6.5 | 0.171 | −0.60 | −0.89 | −0.48 |
| Finance | 6.1 | 0.031 | 0.19 | 0.10 | −0.63 |
| Business | 5.0 | 0.142 | 0.10 | 0.07 | −1.06 |
| Government | 20.6 | 0.080 | 0.19 | 0.17 | −0.43 |
| Other | 12.9 | 0.137 | −0.31 | −0.30 | −1.19 |

[a] 'Carbon intensity' is tons $CO_2$ per R1000 (US$160) final demand in 2005 prices.

cent under more or less elastic supply, respectively. Estimates of GDP losses are far more robust – ranging from 1.04 to 1.07 percent for a US$30 per ton carbon tax.

The above discussion has focused on the impacts of *domestic* carbon taxes. Should other countries unilaterally impose a carbon tax on South African exports, in the absence of a domestic carbon tax, it also causes South African emissions to decline (see Table 2).

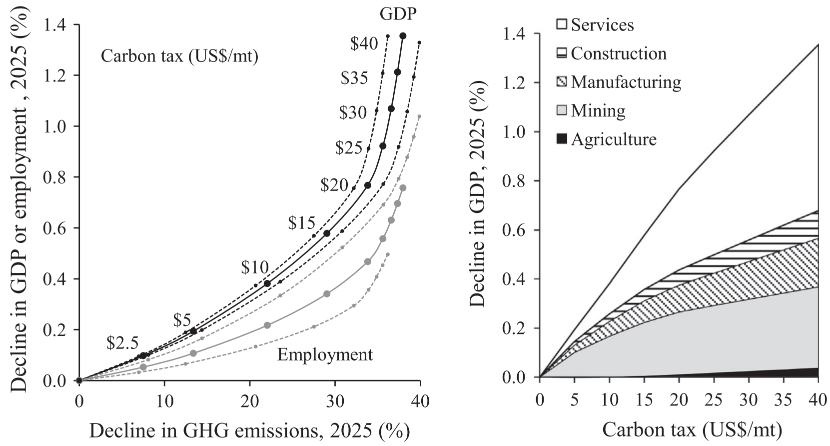


**Fig. 3.** Economywide abatement costs and their sectoral sources, 2010–2025. *Source*: CGE model results. (The left hand side of the figure shows reductions in GDP, employment and total emissions at different carbon tax levels (measured in US$ per ton of $CO_2$). The right hand side of the figure shows in which sectors the decline in GDP occurs. Emissions reductions are in addition to the 8.9 percent in the revised baseline scenario. The carbon tax is in 2005 prices and includes a BCA. Black dashed lines are GDP results using lower (top) and upper (bottom) bound labor supply elasticities. Grey dashed lines are employment results for upper (top) and lower (bottom) bound elasticities.)

**Table 5**
Alternative revenue recycling results, 2010–2025. *Source*: CGE model results.

| | Deviation from baseline, 2025 (%) | | |
|---|---|---|---|
| | Sales taxes | Corporate taxes | Social transfers |
| Total $CO_2$ emissions[a] | −41.40 | −41.52 | −41.57 |
| Total GDP | −1.07 | −0.59 | −1.65 |
| Absorption | −1.04 | −0.58 | −1.61 |
| Total employment | −0.50 | −0.82 | −1.27 |
| Average wages | −1.20 | −1.97 | −3.48 |
| Per capita consumption | −0.56 | −0.62 | −0.87 |
| Percentile 0–50 | −0.79 | −1.61 | 3.06 |
| Percentile 50–100 | −0.51 | −0.41 | −1.71 |

[a] $CO_2$ emissions are relative to "business-as-usual" and measured using the sectoral approach. A consumption carbon tax is applied.

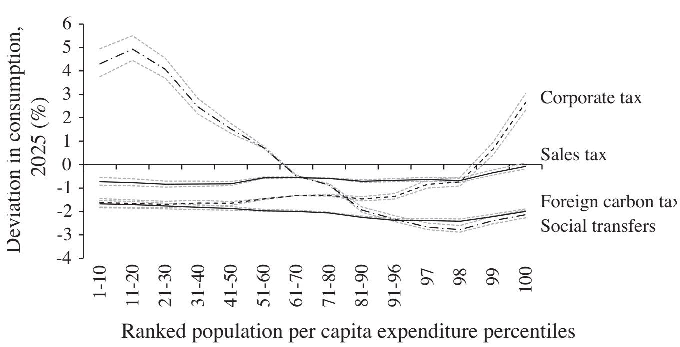


**Fig. 4.** Per capita consumption changes under retaliatory taxes and revenue recycling schemes. *Source*: CGE model results (Relative to a "no carbon tax" baseline. Revenues scenarios include a BCA. Feint dashed lines are results using lower or upper bound labor supply elasticities.).

This is primarily due to a contraction of carbon-intensive exports and slower economic growth (see Table 3). As discussed above, foreign BCAs reduce export prices for many of South Africa's larger export sectors, causing the terms-of-trade to deteriorate significantly. Although the resulting real exchange rate depreciation encourages less carbon-intensive exports, it also raises the cost of import-intensive investment, which slows absorption growth. More importantly, South Africa does not collect revenues from foreign taxes. This means that falling private consumption is not offset by recycled revenues. As a result, employment losses are larger because private consumption is an important source of demand for labor-intensive products. Ultimately, as modeled, the total absorption (welfare) losses from the foreign carbon tax imposed outweigh those of a domestic carbon tax. This supports concerns that international action to cope with global warming may reduce South African competitiveness on global markets and supports early action by South Africa to reduce its GHG emissions.

## 8. Distributional effects and revenue recycling scenarios

The choice between alternative revenue recycling options profoundly influences the distributional impacts of domestic carbon taxes and can alter, though less dramatically, growth and employment outcomes. The simulations reported above assume that revenues are recycled through a uniform reduction in indirect sales tax rates. This is compared to two other options. First, we reduce the corporate taxes imposed on the capital earnings of domestic enterprises. Secondly, we scale up existing social transfer programs. In reality there are many alternative recycling options, including targeted "green" investments in sectors that are heavily affected by the carbon tax; or targeted energy subsidies for poor households to offset higher energy prices. Although far from exhaustive, our stylized scenarios are indicative of the range of recycling options being proposed by business and civil society groups in South Africa. In each scenario, we impose the same carbon tax (gradually increasing to US$30 per ton) with a BCA. Table 5 summarizes macroeconomic results for the recycling scenarios. Note that the Sales Tax scenario replicates the earlier Consumption scenario.

Each scenario generates emissions reductions that are broadly consistent with the national target of a 42 percent reduction from "business-as-usual". Reducing corporate taxes leads to the smallest reduction in total GDP and absorption. This is because enterprises are a major source of domestic savings in South Africa and so reducing corporate taxes offsets the decline in investment. As discussed in Section 3, the rate of capital accumulation determines not only the growth rate but also the rapidity of the shift in production towards less carbon-intensive sectors or energy-saving technologies. Higher investment therefore accelerates both growth and the adjustment process, which reduces absorption losses relative to the Sales Tax scenario.

Fig. 4 reports changes in per capita consumption for different household income groups. Lowering sales taxes is almost distributional-neutral, as reflected by the nearly horizontal consumption growth incidence curve (lower income households are slightly disadvantaged as can be confirmed in Table 3). In contrast, households in the highest income percentiles are the main beneficiaries of corporate tax reductions, because a larger share of their income comes from capital earnings. This also generates larger employment losses than in the Sales Tax scenario, because high-income households consume more import- and capital-intensive products. All household groups outside the top five percentiles are worse off. Therefore, using all carbon tax revenues to reduce corporate taxes dampens the decline in investment and economic growth, but results in a more regressive welfare outcome.

Using carbon tax revenues to expand social transfers (based on current allocations) leads to strongly progressive welfare outcomes. This is shown in Fig. 4, where households in the bottom five deciles benefit from the carbon tax, whereas consumption falls for higher income households. However, household savings rates in South Africa are low, especially amongst low-income households. Directing revenues towards these households consequently leads to lower levels of aggregate savings and investment (see Table 5). Analogous to the Corporate Tax scenario, lower investment slows the adjustment process and worsens the deceleration of GDP and absorption growth. Therefore, while carbon tax revenues can be used to benefit low-income households, this comes at the cost of lower GDP, absorption (welfare) and employment.

## 9. Discussion and conclusions

South Africa is considering using carbon taxes to reduce its high levels of greenhouse gas emissions. There are concerns that this will impose substantial adjustment costs on the economy, including reduced export competitiveness, job losses and higher energy prices. In this paper, we evaluate the socioeconomic consequences of carbon taxes, including implications for economic growth, employment and the distribution of household incomes. We extend previous impact assessments for South Africa by constructing a dynamic economywide model that is linked to projections from an energy sector model. Unlike previous studies, this study is dynamic; incorporates South Africa's long-term electricity investment plan; captures rigidities in capital and labor markets; and allows industries to invest in energy-saving technology.

A carbon tax of about US$3 per ton in 2012 rising linearly to US$30 per ton by 2022 reduces emissions to targeted levels. In considering the welfare impacts of the tax, one challenge is to identify an appropriate baseline scenario (counterfactual) that captures what would occur if South Africa decided against the introduction of carbon taxes. If the baseline scenario is characterized by free disposal of emissions, constant world prices, and no behavior change on the part of South Africa's trading partners, then simulation results indicate that domestic carbon taxes reduce national income and employment, although losses are smaller than previous estimates.

However, these assumptions about the baseline may be inappropriate. Most obviously, this welfare analysis considers in detail the economic costs of a carbon tax but ignores all benefits from reduced emissions. Less obviously, we find that if South Africa's trading partners were to unilaterally impose carbon taxes with BCAs resulting in a decline in South African terms of trade, the resulting welfare losses could plausibly be as large as or larger than those resulting from the imposition of a domestic carbon tax. Under this baseline, a domestic carbon tax may increase national welfare.

Across all scenarios, economic costs are small at low levels of carbon taxes but increase though time as the level of the tax increases. Economic costs are very mild in initial years but become more pronounced at tax levels greater than about the US$20 per ton level. The phased introduction of the tax over a ten year period thus provides a window to implement, evaluate and adjust. Notably, we find that BCAs that rebate exports and tax imports based on carbon content reduce economic losses while delivering essentially the same emissions reductions.

Growth and, in particular, distributional impacts are also found to depend on how carbon tax revenues are recycled. In our principal scenario, revenues from carbon taxes are used to reduce indirect sales taxes. This scenario is essentially distribution-neutral. We compare reductions in indirect taxes with two additional options and discovered trade-offs. Reducing corporate taxes favors economic growth and higher-income households, but the welfare of most of the population deteriorates. Expanding social transfers improves the welfare of low-income households but leads to larger declines in national income. In addition, we test the robustness of our findings to assumptions about labor market rigidities and technology substitution possibilities. This sensitivity analysis shows that estimated employment losses depend on labor market assumptions, but estimated national income and welfare losses are more robust.

The agenda for future research is large. We consider only six areas. First, the appropriate baseline or counterfactual is important and merits further scrutiny. For example, in the absence of global climate policy, future fossil fuel prices are expected to be higher and more volatile. The baseline could incorporate the risks from continued dependence on fossil fuels. Second, as mentioned, we use estimates for BCA rates from Arndt et al. [2] which are generated using South Africa's supply-use tables. These estimates should be refined based on the country-specific energy and industrial technologies of trading partners. Third, more detailed analysis is needed to identify the optimal combination of revenue recycling options, including a political economy assessment. Furthermore, other recycling options were not considered, such as accelerated depreciation allowances, public-funded research into cleaner energy-saving technologies, and targeted energy subsidies for low-income households. Fifth, although we allowed industries to adopt energy-saving technologies, the analysis would benefit from firm- and sector-level estimates of marginal abatement costs.

Finally, and perhaps most importantly, the emissions reductions in South Africa's electricity investment plan may be inconsistent with national emissions targets. Our analysis shows that preferential treatment for the electricity sector places considerable pressure on the non-electricity sectors to reduce their emissions. The current investment plan is based on estimated abatement costs within the electricity sector. However, further work is needed to determine whether the investment plan would change if *economywide* abatement costs are considered. Moreover, taking greater advantage of regional energy options, such as hydropower, might reduce South Africa's abatement costs. It might also reduce the need for large carbon taxes and assist South Africa in transitioning to a low-carbon development path.

## Appendix A

### A.1. Consumer and producer behaviour

The model disaggregates households into 14 representative groups based on their per capita incomes. Each representative consumer maximizes utility subject to a budget constraint using a linear expenditure system (LES) of demand:

$$P_j \cdot H_{jh} = P_j \cdot \gamma_{jh} + \beta_{jh} \cdot \left( (1 - s_h - td_h) \cdot Y_h - \sum_{j'} P_{j'} \cdot \gamma_{j'h} \right) \tag{A1}$$

where $H$ is consumption of good $j$ by household $h$, $\gamma$ is a minimum subsistence level, $\beta$ is the marginal budget share, $P$ is the market price of each good, $Y$ is total household income, and $s$ and $td$ are marginal savings and direct tax rates. The LES functions allow income elasticities to vary across household groups based on estimates from [21].

Similarly, producers maximize profits subject to input and output prices. A constant elasticity of substitution (CES) function determines output quantity $A$ from sector $j$:

$$A_j = \alpha_j \cdot \left(\delta_j \cdot L_j^{-\rho_j} + (1 - \delta_j) \cdot \bar{K}_j^{-\rho_j}\right)^{-1/\rho_j} \tag{A2}$$

where $\alpha$ reflects total factor productivity (TFP), $L$ and $K$ are labor and capital demands, and $\delta$ and $\rho$ are share and substitution parameters. Maximizing profits subject to Eq. (A2)gives the factor demand equations:

$$\frac{L_j}{\bar{K}_j} = \left( \frac{r \cdot Z_j}{W} \cdot \frac{1 - \delta_j}{\delta_j} \right)^{1/(1+\rho_j)} \tag{A3}$$

where $W$ is the labor wage and $r$ is a fixed economywide capital rental rate adjusted by a sector-specific distortion term $Z$. The factor substitution elasticity is a transformation of $\rho$. Higher elasticities mean that producers can more readily substitute between labor and capital when relative prices change. Although not shown, the South African model differentiates between four education-based labor categories.

Leontief technology determines intermediate demand. Fixed input–output coefficients $io_{jj'}$ reflect the quantity of good $j'$ used to produce one unit of good $j$. These technical coefficients are drawn from [2] and [22]. The producer price $PA$ is the sum of factor and intermediate payments per unit of output

$$PA_j \cdot A_j = W \cdot L_j + r \cdot Z_j \cdot \bar{K}_j + \sum_{j'} P_j io_{jj'} \tag{A4}$$

### A.2. International trade and carbon taxes

Imperfect substitution exists between domestic goods and goods supplied to and from foreign markets. A constant elasticity of transformation (CET) function determines the relationship between the quantity of domestically supplied goods $D$ and exported goods $E$:

$$A_j = \pi_j \cdot \left(\sigma_j \cdot D_j^{\mu j} + (1 + \sigma_j) \cdot E_j^{\mu j}\right)^{1/\mu j} \tag{A5}$$

$$PA_j \cdot A_j = PD_j \cdot D_j + PE_j \cdot E_j \tag{A6}$$

where $PD$ and $PE$ are domestic and export prices. Similarly, a CES function defines the relationship between domestically produced goods $D$ and imported goods $M$:

$$Q_j = \tau_j \cdot \left(\varphi_j \cdot D_j^{-\lambda_j} + (1 + \varphi_j) \cdot M_j^{-\lambda_j}\right)^{-1/\epsilon_j} \tag{A7}$$

$$(1 - ts_j) \cdot P_j \cdot Q_j - tc \cdot cd_j = PD_j \cdot D_j + PM_j \cdot M_j \tag{A8}$$

where $Q$ is the composite supply good, $PM$ is the import price, and $ts$ is the sales tax rate. The parameter $tc$ is the carbon tax value that is multiplied by the quantity of carbon $cd$ embodied within primary fossil fuels, i.e., $cd$ is a direct measure and so is only non-zero for coal, crude oil and natural gas. By imposing carbon taxes on the composite good $Q$, we assume that exported fossil fuels are exempt but imports are not. Import substitution and export transformation elasticities are from [23].

Minimizing $PA_jA_j - PD_jD_j - PE_jE_j$ and maximizing $PQ_jQ_j - PD_jD_j - PM_jM_j$ subject to Eqs. (A5) and (A7), respectively, gives the ratios of $D$, $E$ and $M$ in Eqs. (A9) and (A10):

$$\frac{D_j}{E_j} = \left( \frac{\sigma_j}{1 - \sigma_j} \cdot \frac{PD_j}{PE_j} \right)^{1/(\mu_j - 1)} \tag{A9}$$

$$\frac{D_j}{M_j} = \left( \frac{\varphi_j}{1 - \varphi_j} \cdot \frac{PM_j}{PD_j} \right)^{1/(1+\lambda_j)} \tag{A10}$$

Import prices $PM$ and export prices $PE$ are determined by world prices $pwm$ and $pwe$ and by the exchange rate $X$. World import prices are adjusted for import tariffs $tm$. Although not shown, the South African model also includes transaction costs on imported, exported and domestically supplied products. Transaction costs generate demand for trade and transport services and are subject to carbon taxes.

$$PM_j = (1 + tm_j) \cdot pwm_j \cdot X + tb \cdot ci_j \tag{A11}$$

$$PE_j = (pwe_j - tr \cdot (cd_j + ci_j)) \cdot X - tb \cdot ci_j \tag{A12}$$

Domestic BTAs $tb$ are based on indirect carbon measures, i.e., on the carbon within the intermediate inputs used to produce the final product. A domestic BTA causes import prices to rise depending on their carbon content, which is calculated assuming that domestic and import technologies are similar (see [2]). A domestic BTA also causes export prices to rise through rebates. When trading partners introduce their own carbon tax with a BTA equal to $tr$, then South Africa's import prices remain unchanged but export prices fall (i.e., foreign exporters receive rebates but domestic exporters are taxed in foreign markets). Foreign BTAs affect all exported products based on their direct and indirect carbon content (i.e., $cd + ci$).

The current account balance is the difference between total export earnings and import payments and, while not shown, net foreign factor payments and transfers. Our macroeconomic closure allows the exchange rate $X$ to adjust to maintain a fixed level of foreign savings $F$ (i.e., foreign capital inflows).

$$\sum_j pwe_j \cdot E_j + \bar{F} = \sum_j pwe_j \cdot M_j \tag{A13}$$

### A.3. Government and investment demand

Assuming all factors are owned by households, total income $Y$ is given by

$$Y_h = \sum_j (\omega \cdot W \cdot L_j + \theta \cdot r \cdot Z_j \bar{K}_j) + st_h \tag{A14}$$

where $st$ are social transfers from the government, and coefficients $\omega$ and $\theta$ determine the distribution of factor earnings to individual households. The South African model also includes enterprises that earn the returns to capital and use these profits to pay corporate taxes, save and pay dividends to households.

The government is treated as a separate institution. Total revenue is the sum of direct and indirect taxes, including carbon taxes and BTAs, as shown on the left-hand side of Eq. (A15):

$$\sum_h td_h \cdot Y_h + \sum_j ts_j \cdot P_j \cdot Q_j + \sum_j tc \cdot cd_j \cdot Q_j + \sum_j tb \cdot ci_j \cdot (M_j - E_j) = \sum_j P_j \cdot \bar{G} \cdot g_j + \sum_h st_h + B \tag{A15}$$

Revenues are used to purchase goods $G$ and make social transfers $st$. Any remaining funds are (dis)saved, as shown on the right-hand side of Eq. (A15). Our macroeconomic closure for the government assumes that consumption spending is equal to base-year quantities $g$ multiplied by an exogenous adjustment factor $G$. The recurrent fiscal balance $B$ adjusts to equalize total revenues and expenditures.

Our savings-driven investment closure implies that total investment adjusts to the level of total savings. This is shown below:

$$\sum_h s_h \cdot Y - h + B + \bar{F} \cdot X = \sum_j P_j \cdot I \cdot i_j \tag{A16}$$

where $i$ is fixed base-year investment quantities multiplied by an endogenous adjustment factor $I$.

*A.4. Factor and product market equilibrium*

Total labor supply $LS$ is determined by upward-sloping supply curves that depend on the prevailing wage $W$, the base-year wage $w$, base-year labor supply $ls$, and a wage-supply elasticity $\varepsilon$. In equilibrium, total labor supply $LS$ must equal the sum of all sector labor demands $L$:

$$LS = ls \cdot \left(\frac{W}{w}\right)^{s} = \sum_j L_j \tag{A17}$$

Unlike labor, which is mobile across industries, capital is sector-specific. Both factor demand $K$ and the rental rate $r$ are fixed (see Eq. (A3)) and the distortion term $Z$ adjusts to equate capital demand and supply in each sector.

Finally, product market equilibrium requires that the composite supply of each good $Q$ equals private and public consumption and investment demand. Market prices $P$ adjust to maintain equilibrium. Producers' abilities to pass-through carbon taxes to consumer prices are moderated by demand's response to higher prices.

$$Q_j = \sum_h H_{jh} + \bar{G} \cdot g_j + I \cdot i_j \tag{A18}$$

Together, the above 18 sets of equations simultaneously solve for the values of 18 sets of endogenous variables (i.e., $A$, $PA$, $L$, $W$, $Z$, $D$, $PD$, $E$, $PE$, $M$, $PM$, $Q$, $P$, $X$, $Y$, $I$, $H$ and $B$). The consumer price index (CPI) is our numéraire.

*A.5. Investment and capital accumulation*

Our recursive dynamic model has distinct within- and between-period components. The above equations specify the within-period component. Between-periods, exogenous variables and parameters are updated based on externally determined trends (i.e., labor supply $LS$, government consumption $G$, foreign capital inflows $F$, and technical change $\alpha$) and on previous period results (i.e., capital accumulation $K$).

While not shown in Eqs. (A1)–(A18), each variable has a time subscript $t$. Sector-level capital stocks $K$ are determined endogenously based on previous period investment. As shown below, the quantity of new capital $N$ is based on the value of investment and the capital price $PK$ (i.e., market prices $P$ weighted by investment shares $i$). New capital is allocated to sectors after applying a depreciation rate $\upsilon$ and according to a capital allocation factor $SK$ ($0 < SK < 1$; $\sum SK = 1$).

$$N_t = \sum_j (P_{jt} \cdot I_t \cdot i_t) \cdot PK_t^{-1}$$

$$\bar{K}_{jt+1} = \bar{K}_{jt} \cdot (1 - \upsilon) + SK_{jt} \cdot N_t$$

$$SK_{jt} = SP_{jt} + SP_{jt} \cdot \left(\frac{SR_{jt} - AR_t}{AR_t}\right)$$

where $SP$ is a sector's current share in total capital stocks, $SR$ is a sector's profit rate (i.e., $r{\cdot}Z_j$), and $AR$ is the average profit rate. New capital is allocated in proportion to a sector's share of current capital stocks adjusted by its own profit rate relative to the national profit rate. Sectors with above-average profit rates receive a greater share of investible funds than their share in the existing capital stocks. This 'putty-clay' specification implies that new capital is mobile but installed capital is sector-specific.

## References


[1] Republic of South Africa (RSA). Reducing greenhouse gas emissions: the carbon tax option. South Africa: National Treasury, Government of the Republic of South Africa; 2010.
[2] Arndt C, Davies R, Makrelov K, Thurlow J. Measuring the carbon intensity of the South African Economy. S Afr J Econom 2013;81(3):393–415.
[3] Resnick D, Tarp F, Thurlow J. The political economy of green growth: cases from Southern Africa. Public Admin Develop 2012;32(3):215–28.
[4] Liang Q-M, Wei Y-M. Distributional impacts of taxing carbon in China: results from the CEEPA model. Appl Energy 2012;92:545–51.
[5] Herring H. Does energy efficiency save energy? The debate and its consequences. Appl Energy 1999;63(3):209–26.
[6] Liu X, Niu D, Bao C, Suk S, Sudo K. Affordability of energy cost increases for companies due to market-based climate policies: a survey in Taicang, China. Appl Energy 2013;102:1464–76.
[7] Sokolov AP, Stone PH, Forest CE, Prinn R, Sarofim MC, Webster M, et al. Probabilistic forecast for twenty-first-century climate based on uncertainties in emissions (without policy) and climate parameters. J Clim 2009;22:5175–204.
[8] Weitzman ML. Fat-tailed uncertainty in the economics of catastrophic climate change. Rev Environ Econom Policy 2011;5(2):275–92.
[9] Zhang Yue-Jun, Wei Yi-Ming. An overview of current research on EU ETS: evidence from its operating mechanism and economic effect. Appl Energy 2010;87:1804–14.
[10] Devarajan S, Go DS, Robinson S, Thierfelder K. Tax policy to reduce carbon emissions in a distorted economy: illustrations from a South Africa CGE model. BE J Econom Anal Policy 2011;11(1):1–22.
[11] Pauw K. Economy-wide modeling: an input into the long term mitigation scenarios process. Long-term mitigation scenarios input, report 4. University of Cape Town, South Africa: Energy Research Centre; 2007.
[12] Van Heerden J, Gerlagh R, Blignaut J, Horridge M, Hess S, Mabugu R, et al. Searching for triple dividends in South Africa: fighting $CO_2$ pollution and poverty while promoting growth. Energy J 2006;27(2):113–41.
[13] Böhringer C, Balistreri EJ, Rutherford TF. The role of border carbon adjustment in unilateral climate policy: overview of an energy modeling forum study (EMF 29). Energy Econom 2012;34:S97–S110.
[14] World Bank. World development indicators online database. Washington (DC): World Bank; 2012 [accessed 31.01.12].
[15] DOE (Department of Energy). Integrated resource plan for electricity: 2010–2030. Revision 2. Final report, Pretoria, South Africa; 2011.
[16] Büscher B. Connecting political economies of energy in South Africa. Energy Policy 2009;37(10):3951–8.
[17] Dervis K, de Melo J, Robinson S. General equilibrium models for development policy. New York: Cambridge University Press; 1982.
[18] StatsSA. Environmental economic accounts: energy accounts for South Africa, 2002–2006. Pretoria (South Africa): Statistics South Africa; 2009.
[19] Böhringer C, Rutherford T. Who should pay and how much? Compensation for international spillovers from carbon abatement policies to developing countries – a global CGE assessment. Comput Econ 2004;23(1):71–103.
[20] Nell K. Long-run exogeneity between saving and investment: evidence from South Africa. Working paper 2-2003. Johannesburg (South Africa): Trade and Industrial Policy Strategies; 2003.
[21] Case A. Income distribution and expenditure patterns in South Africa. Unpublished mimeo. Princeton (NJ): Princeton University; 2000.
[22] StatsSA. Final supply-use tables for South Africa 2005. South Africa: Statistics South Africa; 2010.
[23] Dimaranan B, editor. Global trade, assistance, and production: the GTAP 6 database. West Lafayette (IN): Center for Global Trade Analysis, Purdue University; 2006.


## Glossary

*Absorption:* Economywide spending for consumption, investment, and government. Absorption is also equal to gross domestic product (GDP) plus imports minus exports.

*Border carbon adjustments:* A tax on imports and a rebate exports based on embodied carbon.