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Socio-economic implications of mitigation in the power sector including carbon taxes in South Africa

Working paper for CDKN project on Linking sectoral and economy-wide models

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September 2014

MAPS
Mitigation Action Plans & Scenarios

Suggested citation for this paper:

Merven, B, Moyo, A, Stone, A, Dane, A and Winkler, H. 2014. The socio-economic implications of mitigation in the power sector including carbon taxes in South Africa. Working paper for CDKN project on Linking sectoral and economy-wide models. Energy Research Centre, University of Cape Town, Cape Town.

Acknowledgement
We would like to acknowledge the contribution of Channing Arndt and James Thurlow from UNU-WIDER for the development of the linked modelling framework.

Disclaimer

This document is an output from a project funded by the UK Department for International Development (DFID) and the Netherlands Directorate-General for International Cooperation (DGIS) for the benefit of developing countries. However, the views expressed and information contained in it are not necessarily those of or endorsed by DFID or DGIS, who can accept no responsibility for such views or information or for any reliance placed on them. This publication has been prepared for general guidance on matters of interest only, and does not constitute professional advice. You should not act upon the information contained in this publication without obtaining specific professional advice. No representation or warranty (express or implied) is given as to the accuracy or completeness of the information contained in this publication, and, to the extent permitted by law, the entities managing the delivery of the Climate and Development Knowledge Network do not accept or assume any liability, responsibility or duty of care for any consequences of you or anyone else acting, or refraining to act, in reliance on the information contained in this publication or for any decision based on it. Management of the delivery of CDKN is undertaken by PricewaterhouseCoopers LLP, and an alliance of organisations including Fundación Futuro Latinoamericano, INTRAC, LEAD International, the Overseas Development Institute, and SouthSouthNorth.

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1. Introduction

South Africa has a carbon-intensive energy economy. The energy sector is responsible for most of the country's emissions, with the national greenhouse gas (GHG) inventory for 2000 indicating that 78.9% of total emissions were from energy supply and use (DEAT, 2009). These emissions have largely resulted from the extensive use of coal in the generation of electricity, as well as the conversion of coal into liquid fuels by Sasol, a petrochemicals company. The economy was historically built around the minerals-energy complex (Burton, 2011; Fine & Rustomjee, 1996), linking energy-intensive industries with coal-based energy supply.

The South African government made a voluntary commitment during the 15th Conference of Parties in 2009 to reduce emissions by 34% and 42% below 'business as usual' by 2020 and 2025 respectively, provided they receive the necessary international support (DEA, 2010). The government developed its 2010 Integrated Resource Plan (IRP) in order to meet South Africa's future electricity demand by moving towards less carbon-intensive generation. This would contribute to efforts aimed at achieving South Africa's emissions reduction targets. According to the IRP Policy adjusted scenario, renewable energy (RE) would contribute 14% to South Africa's electricity generating mix by 2030 (DOE, 2011). The Renewable Energy Independent Power Producers Programme (REIPPPP) has also been launched to help contribute to the expansion of renewable energy in South Africa .

The Long Term Mitigation Scenarios (LTMS) study found carbon taxes to have the biggest emissions reduction potential compared to various other mitigation options (Winkler, 2007). South Africa's National Treasury planned to implement a carbon tax of R120 per ton of carbon dioxide (CO_2) from 1 January 2015 (National Treasury, 2013). Implementation of the tax has however been postponed to 2016 This carbon tax would be subject to tax-free thresholds and exemptions for trade exposed sectors (National Treasury, 2013).

In a developing country like South Africa, it is important that policies and measures aimed at achieving the country's emissions reduction targets are not applied to the detriment of other national objectives. The National Development Plan put the reduction of poverty and inequality as top priorities among several, with other policies such as the New Growth Path highlighting the importance of job creation (EDD, 2010). The government is therefore likely to take a favourable view on mitigation actions that contribute positively to these priorities. There is, however, limited understanding of the socio-economic implications of mitigation actions such as the expansion of renewable energy. A number of studies have been carried out to model the potential socio-economic implications of implementing a carbon tax in South Africa (Van Heerden et al., 2006; Pauw, 2007; Devarajan et al., 2009; Alton et al., 2012). The main limitation of these studies, however, has been that analysis was conducted using only economy-wide models so that the energy sector was not detailed and the build plan did not response to changes in demand, amongst other things. We use linked energy and economy-wide models for our analysis to address some of these issues.

The structure of this paper is as follows. The first section provides a discussion of recent developments within South Africa aimed at increasing the contribution of renewable energy. The second section gives a brief description of the carbon tax that National Treasury plans to implement and also provides an overview of previous studies on the implications of a carbon tax in South Africa. The linked model that we use for our analysis is described in section 3. This is then followed in section 4 by a description of the scenarios that we modelled, with results presented in section 5. The last section presents the conclusions and recommendations for further research.

2. Mitigation actions in the South African power sector

We consider the expansion of renewable energy in South Africa's energy mix in our analysis. This section will begin by giving a background on the power sector in South Africa and will then discuss current plans to expand the contribution of renewable energy.

2.1 Background on the state of the power sector

Around 96% of South Africa's electricity is generated by the state-owned national utility Eskom (Eberhard, 2011), which operates 27 power stations with a total nominal capacity of 41.9GW, of which 85% of the capacity is coal-fired. The balance of capacity is provided by nuclear, open-cycle gas turbine, hydro and pumped-storage power plants (Eskom, 2013). This coal-intensive electricity grid emitted 230.4 million tons of CO_2 in 2010 (Eskom, 2011), just over 66% of the 346.8 million tons arising from all fuel combustion in 2010, making South Africa the 18th highest emitter worldwide of CO_2 from combustion and cement (IEA, 2012). South Africa's per capita fuel combustion CO_2 emissions of 6.94 tons/capita occupied a less prominent position at 40th in the world in 2010, especially compared to the United States and Australia which emitted over 17 tons/capita (IEA, 2012). Fuel combustion emissions of CO_2 per unit of gross domestic product (GDP) purchasing power parity (PPP), however, show South Africa to be the 12th most carbon-intensive economy in the world in 2009, emitting 0.80 kg/$ GDP PPP (2005) compared to a global average of 0.44. Other than China, Russia, and Saudi Arabia, none of the other countries above South Africa are significant emitters in absolute terms (IEA, 2012). This carbon-intensity of the economy, while having dropped around 15% since 2000, remains driven both by carbon-intensive electricity production and a predominance of energy-intensive industries consuming that production in the mining and metals sectors – the minerals-energy complex.

Given its abundant coal reserves, South Africa invested extensively in coal-fired power stations in the 1970s and 1980s (Marquard, 2006).In addition to economies of scale, price deregulation in 1986 resulted in electricity prices that were amongst the lowest in the world. The expansion assumed the continued high levels of industrial growth that characterised the first decades of the post-war period (Eberhard, 2011). In the event, demand did not grow as expected, and growing opposition to apartheid both within and without stifled demand and a situation of excess capacity prevailed until the early 2000s. Three power stations were 'mothballed', exemplifying the high cost to the economy of overinvestment.

This situation changed dramatically with reserve margins declining steadily from the 1990s. While Eskom's nominal generating capacity has increased from 36.2GW in 2005 to 41.9GW in 2013, the reserve margin of capacity relative to demand has, in stark contrast, been tight in recent years. The reasons are complex, including that government was considering power sector reform, and did not wants its utility, Eskom, to build if 30% of assets were to be sold off. Widespread 'load-shedding' was experienced in the country from November 2007 to the end of January 2008, resulting in scheduled residential blackouts and reduced industrial output – with the major mining houses shutting down operations on 24 January 2008 for safety reasons, amidst much publicity (NERSA, 2008). The electricity system has remained tight since then, with unplanned load-shedding avoided only by including demands on large customers to reduce consumption at critical times. The cost of underinvestment in the last two decades is also high.

While domestic coal prices are rising with costs and competition, with exports increasing, domestic coal prices in South Africa, on average, remain relatively cheap in global terms at around R170 or $23/ton (Eberhard, 2011), and until recently Eskom remained one of four suppliers of the cheapest industrial electricity in the world (Kiratu, 2010). This, combined with South Africa having a couple of hundreds of years' worth of coal reserves, results in coal remaining, for now, the cheapest electricity generation option in terms of levelised cost of energy, though wind is close to parity. Thus it is that for the immediate future, the key Eskom generation expansion projects are the 4 764MW Medupi and 4 800MW Kusile coal-fired stations. Several factors, however, militate against further expansion of coal-fired power, including, firstly, that South Africa has international commitments to mitigate greenhouse gas emissions; secondly, that South Africa exports a lot of its CO_2 emissions embodied in commodities, with some studies showing values of as much as 30% which is very high in global terms even compared to exporting nations like China (The Carbon Trust, 2011) – South Africa is thus particularly vulnerable to potential tariffs or border carbon adjustments imposed by its trading partners on carbon-intensive goods and commodities or on their importers (Kiratu, 2010).

Increased costs for coal transport would make coal-fired electricity more expensive. Eskom's increasing exposure to short- and medium-term road haulage coal contracts, which are more expensive than its existing long-term contracts with mines adjacent to its power stations (Eberhard, 2011).

2.2 Expansion of renewable energy

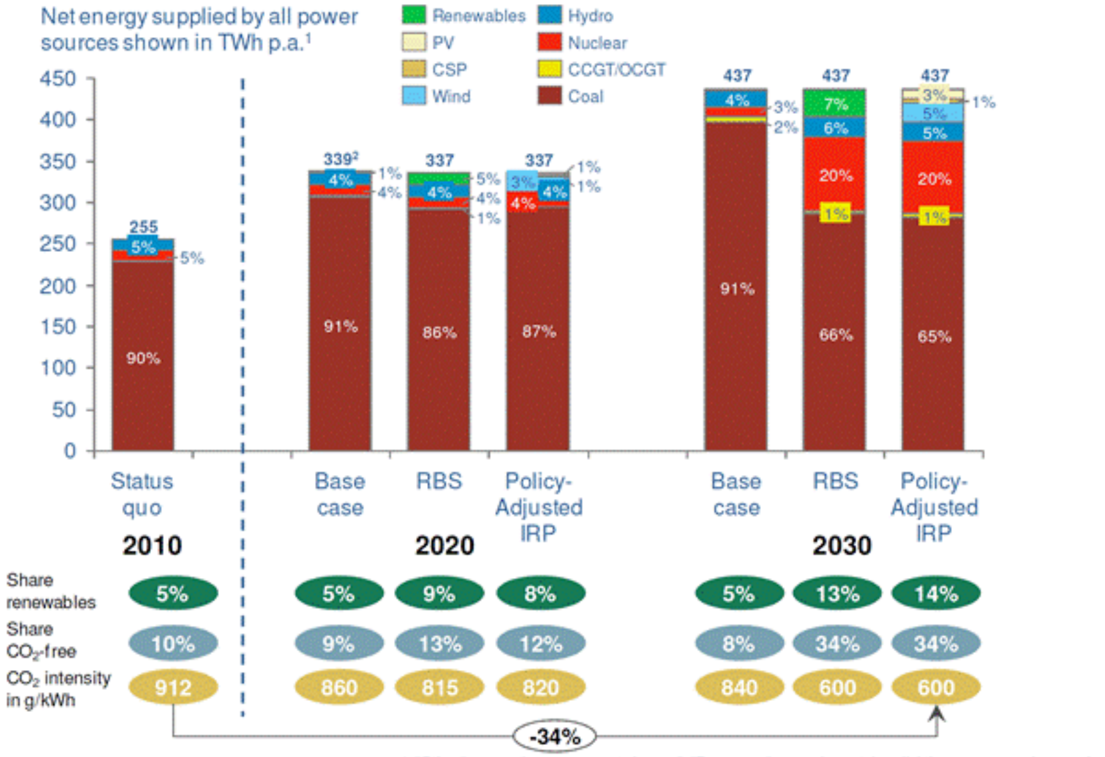
After 20 years of over-capacity and abundant cheap electricity, followed by an erosion of the reserve margin, the energy landscape in South Africa is transforming profoundly into a phase of aggressive expansion, consistently rising prices to finance a new build programme, and public and sometimes controversial debate on the optimal supply options that has mainly centered on renewable and nuclear technologies. The national Department of Energy (DoE) updated its IRP for the country, including both rigorous modelling and data-gathering processes combined with extensive stakeholder consultation that involved 479 submissions from organisations, companies and individuals, resulting in over 5000 specific comments (DOE, 2011). An update to the official IRP was published for comment in 2013, with the intent to regularly update the plan in the light of changing conditions.

The IRP's stated objectives were to balance a least-cost solution with other pressing requirements, including CO_2 mitigation, local job creation and energy security. Thus the plan for a new build fleet for the period 2010 to 2030 published after the first round of public participation in October 2010 was known as the Revised Balanced Scenario (RBS), following consideration of a range of alternative plans. The RBS included a nuclear fleet of 9.6 GW; 6.3 GW of coal; 11.4 GW of renewables; and 11.0 GW of other generation sources. The RBS imposed an emission constraint of 275 million tons of CO_2 per year after 2024 and assumed a modest energy efficiency gain on the demand side of 1617 MW through solar water heating programmes (DOE, 2011)

A second round of public participation and analysis led to what has been called the Policy-adjusted IRP, which included the following main features:

- Disaggregation of renewable energy technologies into solar photovoltaic (PV), concentrated solar power (CSP) and wind options and the inclusion of learning rates which increased the total share of these technologies from 11.4 GW to 17.8 GW in 2030.
- The bringing forward of renewables (solar PV, CSP and wind) installations in order to accelerate a local industry.
- The intention to bring the last coal-fired capacity in the plan to before 2025.
- Adjustment of investment costs for nuclear units. While this analysis indicated that anticipated demand could be met without nuclear, the commitment to the nuclear fleet of the RBS remained unchanged on the basis that, 'this should provide acceptable assurance of security of supply in the event of a peak oil-type increase in fuel prices and ensure that sufficient dispatchable base-load capacity is constructed to meet demand in peak hours each year' (DOE, 2011).

As shown below in Figure 1, the final CO_2 mitigation impact of the IRP was projected to have been a one third reduction in the CO_2 intensity of electricity production.



1. "Other" generation sources not shown 2. "Base case" scenario contains slightly more pumped energy in 2020 than RBS and Policy-Adjusted IRP and thus requires more total energy being generated

Figure 1: Projected impact of RBS and policy-adjusted IRP on net energy supply
Source: (DOE, 2011)

Critical to this reduction is the roll-out of renewable generation, which, crucially, is being awarded to independent power producers through the current REIPPPP, aiming for an initial target of 3 725 MW installed by 2015. REIPPPP is a competitive bid scheme that kick-started the process of reaching the IRP 2010 targets in relation to renewable energy, following the failure of previous policies – including an overall goal and a feed-in tariff, to result in more than a few projects at the scale of tens of megawatts. The role of an independent IPP unit, established by National Treasury and DoE, is widely considered one of the key factors in the success of the REIPPPP. Eskom is to be the buyer of the power generated by means of a Power Producer Agreement (PPA) based on a feed-in tariff that forms part of the competitive bid. The capacity awarded so far in the first two rounds is compared to the REIPPPP targets in Table 1.

Notably the CSP target has been reached in terms of bids, while no awards to the smaller technology allocations like biogas have been made as yet. The Request for Proposals (RFP) for the third round has reportedly allocated significantly increased capacity to CSP, small hydro and biomass generation capacity. The implementation of an IPP-owned renewable rollout is therefore running more or less to plan. Remaining issues relate to the cashflow pressure that the lengthy and rigorous bid process places on the bidding parties and the competition on feed-in tariffs that may drive prices to unsustainable levels for later rounds. The socio-economic benefits required of REIPPPs may find full implementation a challenge.

The IRP identified many areas that require future study, including research into the availability and cost of gas from various sources, the feasibility of imported hydro, the impact of distributed generation on demand, storage technologies for solar thermal technologies and the impact of this and geographical distribution on the variability of solar and wind generation. In order to achieve a reliable supply, these so-called variable technologies require a much greater installed capacity to guarantee the supply of a given amount of energy than a baseload technology like nuclear.

Table 1: REIPPPP Window 1 and 2 total bid awards compared to programme targets for 2015

Technology	*REIPPPP Window 1[a] (Bids awarded)*	*REIPPPP Window 2[a] (bids awarded)*	*REIPPPP Window 3[b] (bids closing)*	*Total W1 – W3*	*DOE target[c]*
PV	706.8	342.1	401.3	1450.2	1450
Small Hydro		14.3	120.7	135	75
Solar CSP – central tower			200	400	200
Solar CSP – trough	100	50			
Onshore Wind	634.1	562.5	653.6	1850.2	1850
Biomass			60	60	12.5
Biogas			12.5	12.5	12.5
Landfill gas			25	25	25
Small projects					100
Total	**1490.9**	**968.9**	**1473.1**	**3932.9**	**3725**

Notes:
a. Source: energy.org.za
b. Source: (CSP World, 2012)
c. Source: (DOE, 2012)
d: CSP – Concentrated Solar Power

CO_2 mitigation potentials per MW of installed capacity for solar CSP and wind, given the current South African grid, are therefore typically lower at 4 500 ton CO_2/MW and 2 300 ton CO_2/MW respectively (Eskom, 2013) compared to nuclear which would be around 7 800 ton CO_2/MW. The LTMS study (Hughes et al., 2007) showed the large impacts of learning rate assumptions on the assessment of technology mitigation potential, with learning rate assumptions dropping mitigation cost effectiveness for a scenario wedge of renewables from R92/ton CO_2 equivalent to R3/ton CO_2 compared to nuclear at R18/ton CO_2, given a 10% discount rate (see also Winkler et al., 2009). The more accurate assessment of the costs, reliability and mitigation potential of solar and wind technologies, given local conditions and emerging storage technologies, is therefore critical in a decision of which route to invest in.

Also critically, the IRP report noted that, ‘the lack of a socio-economic impact study was a concern, as was the exclusion of the impact of network costs on the choice of technologies’ (DOE, 2011). While the direct technology costs are generally a data exercise, the greater socio-economic impacts are less straightforward to assess and clearly critical to the sustainable mitigation potential of power generation technologies. This has largely been due to a lack of an appropriate model with which to conduct such analysis, as sectoral models are not able to provide us with information on socio-economic impacts. In this paper we used a model which links the energy sector model with an economy-wide model to conduct analysis of the socio-economic impacts. The methodology is discussed in Section 4 below.

3. Potential to reduce emissions through carbon taxes

In addition to mitigation actions in the power sector, we use the linked model to get a better understanding of the potential socio-economic implications of carbon taxes in South Africa. This section will provide an overview of the carbon tax proposed by National Treasury followed by a discussion of previous studies aimed at ascertaining the potential impacts of implementing a carbon tax in South Africa.

3.1 The national carbon tax policy

The South African government has signalled its intention to price carbon. Most recently, National Treasury published a Carbon Tax Policy Paper (CTPP) (National Treasury, 2013). The paper, an update of an earlier discussion paper on the carbon tax option (National Treasury, 2010), responds to public comments and builds on and contextualises the specific carbon tax design features discussed in the 2012 budget review. The policy paper locates the carbon tax as part of the overall response climate change and aligns with the National Climate Change Response White Paper (DEA, 2011).

The carbon tax is seen a tool to change behaviour through a price mechanism, and seen as complementary to regulatory measures. It aims to do so in three main ways: changing producer and consumer behaviour; contributing to mitigation and adaptation being taken into account in investment decisions (including on infrastructure); and creating incentives for low-carbon technologies (National Treasury, 2013).

The tax is to be levied on fuel inputs at a nominal rate of R120 per ton of CO_2, deliberately set low and acknowledging that the effective rate is lower but rising over time. The effective rate is the result of a number of factors: tax-free thresholds, increases in the tax rate over time, off-sets, and adjustments to reward good practice within sectors. All sectors are covered except for agriculture, forestry and land use (AFOLU) and waste. Earlier announcements had envisaged the carbon tax in the financial year 2013/14, but this was postponed to 1 January 2015 and then again to 2016. The first period is to run from 2016-2020, with revisions prior to a further 2021-2025 period. Over the first period, the tax rate will increase at 10% per year until the end of 2020, but it is unclear if this is nominal or real. The rate of increase from 2021 will be announced towards the end of the first period.

A key design feature is sector thresholds, which reduce the effective tax by applying the tax only to emissions above a percentage-based threshold of actual emissions. All sectors are exempt from tax on 60% of their emissions in the first phase. This is a ‘basic tax-free threshold’ and effectively lowers the tax rate. This is to encourage firms to reduce the carbon intensity of their products, penalise or reward firms, up to 5% additional to the threshold, in relation to a sectoral benchmark intensity – so their net tax exemption might be between 55% and 65%. Further exemptions are granted for process emissions. Energy-intensive and trade-intensive (EITI) sectors get a maximum of 10% additional reduction. Overall, there is a 90% maximum tax-free emissions allowance (except AFOLU and waste). The high initial thresholds set the effective tax rate at between R12 and R48 per ton CO_2-eq emitted.

National Treasury seeks to minimise any negative socio-economic impact of the tax. In particular the CTPP seeks to ensure that poor households and trade-exposed industries are cushioned from the impacts of a carbon tax. In this regard the paper considers exemptions and revenue recycling options such as tax shifting, tax incentives and targeted assistance to households. Treasury models various options in an attempt to design a system that minimises negative impacts, including free basic alternative energy, public transport and direct transfers. The exemptions for trade-exposed sectors mention energy intensity, but fail to operationally limit the exemptions to energy-intensive *and* trade-exposed sectors, which would be more appropriate.

The National Treasury has not yet estimated the mitigation potential associated with the carbon tax design options; a study by the University of Pretoria is expected to apply an economy-wide model to provide such an estimate, as well as another source of socio-economic results. The CTPP refers to modelling exercises conducted by the National Treasury and highlights specific attention paid to understanding the economy-wide impacts of the proposed tax. Such work has typically been based on computable general equilibrium (CGE) modelling (Alton et al., 2012; Kearney, 2008; Pauw, 2007) and the forthcoming University of Pretoria study, in some cases with an energy extension to the CGE (Arndt et al., 2011), or in energy sector models (Hughes et al., 2007; Winkler, 2007). Efforts have been initiated to link energy sector and economy-wide modelling to ensure better consistency of economic projections in energy planning, and more fully endogenise investment decisions in the energy sector in economic analysis.

3.2 Modelling the potential impacts of a carbon tax

The LTMS was the first significant study to model the impacts of mitigation actions in South Africa in terms of the mitigation costs (in R / t CO_2), the total costs expressed as a share of GDP or as a change in energy system costs, and by plotting costs against cumulative emission reductions on a mitigation cost curve (Winkler, 2010). This included a consideration of the impacts of an escalating carbon tax (starting at R100 / t CO_2 and rising to R750 in 2040-50)

(ERC, 2007). While not presented as a complete solution on its own, the escalating carbon tax was the single biggest mitigation option, with reductions of 12 287 Mt over the period 2003-2050. Combined with other economic incentives in a ‘Use the market’ package of actions, an additional 5 000 Mt reductions was projected to be achievable. These results were drawn from energy modelling using the Energy Research Centre’s Markal model (Hughes et al., 2007; Winkler, 2007), and to assess the broader socio-economic implications, the LTMS process included an assessment of the economy-wide impacts of the tax through the application of CGE models for South Africa (Pauw, 2007; Kearney, 2008). Pauw (2007) took results from the energy model into a comparative static CGE, while Kearney (2008) repeated the experiment using a dynamic recursive CGE model. The CGE modelling found that for ‘Use the market’, the key driver was the CO_2 tax, which quickly reduced coal in the electricity and synfuel sectors, and induced shifts in fuels and towards efficiency. Impact on GDP was modest (–2% in 2015) as a result of energy price increases – unless countered by fiscal policies. Recycling revenue can off-set economic impact at lower tax levels. Employment effects varied, with job increases for lower-skilled (+3% semi-skilled, 0% for unskilled in 2015), but a negative impact was indicated for higher-skilled workers (–2% for skilled and –4% for highly skilled). Impacts on poverty / welfare were negative, but could be off-set for poor households if revenue was recycled via a food subsidy.

Several other studies have been undertaken to model the broad macroeconomic impacts of a carbon tax. These include work done by the University of Pretoria (Van Heerden et al., 2006), the World Bank (Devarajan et al., 2009) and the National Treasury (Alton et al., 2012). These studies, together with the LTMS economy-wide assessments, share the broad finding that a carbon tax can bring about a considerable reduction in carbon emissions while the impact on economic output is largely neutral, provided appropriate revenue recycling measures are implemented (i.e. depending on the design of the tax). The World Bank, University of Pretoria and the University of Cape Town studies used a top-down CGE model to assess the economy-wide impacts of the carbon tax. Alton et al. (2012) suggest that a limitation of the World Bank study is that the authors do not distinguish between different energy technologies or capture South Arica’s long-term electricity investment plan, which largely determines the future energy mix and includes a shift towards renewable energy. It might therefore overstate the responsiveness of electricity production and prices to the carbon tax. The modelling of the economy-wide impacts of the tax as part of the LTMS (Pauw, 2007; Kearney, 2008) also used a CGE model. However, a distinction was made between energy technologies and long-term electricity investments were based on a partial-equilibrium energy model. This resulted in smaller welfare reductions being found in the analysis of the carbon tax. In these studies, however, results from the energy model were only run through CGE models once, without feedback. Since GDP is a key driver for energy demand, but also an output of the CGE model, a coherent story line requires linking between the models.

The main limitation in most of these studies is that they used static CGE models that excluded changes in investment behaviour in response to energy prices. The static models allow a costless reallocation of capital across industries – understating adjustment costs – and do not allow industries to invest in less energy-intensive technologies (Alton et al., 2012). Kearney (2008) did use a dynamic recursive CGE, but found results comparable to Pauw (2007). None of the studies represented both the linkages across the economy (in CGE models) and detailed specification of technology and change (in bottom-up models such as Markal or TIMES, for the energy sector).

To address some of these limitations the National Treasury, in collaboration with the United Nations University–World Institute for Development Economics Research (UNU-WIDER) (Alton et al., 2012) developed a dynamic CGE model of South Africa. Their model contains detailed energy technologies and is calibrated to investment projections from an energy sector model developed by the ERC. The South African CGE model with an energy extension (e-SAGE) is calibrated to a purpose-built database that reconciles energy and economic data but is not directly linked to an optimising energy model (energy investments are exogenous). As such, the model can produce sub-optimal energy investment decisions.

The model allows National Treasury to evaluate the socio-economic impacts of a carbon tax, as well as domestic and foreign border tax adjustments. Treasury has also examined a range of revenue recycling options, including reductions in personal or corporate income taxes, direct transfers to households or investments in cleaner, more productive sectors of the economy. Several scenarios were modelled in a study to support the CTPP. The Treasury's results suggest that the carbon tax, coupled with various revenue recycling options, will contribute to significant emission reductions and have a largely neutral impact on economic growth, employment and income inequality. These results are consistent with the results of previous studies cited above.

The model does have a number of limitations, however. Since there is no accounting for the social cost of carbon, the model 'will tend to overestimate the costs of a carbon tax and underestimate the benefits from lower levels of emissions' (National Treasury, 2013: 11). The link between South Africa's efforts on mitigation and the climate impacts is indirect – the latter depends on collective action by all countries, which would tend to be encouraged by action by a single country, but cannot be guaranteed unless other follow suit. Treasury considers South Africa to be a 'climate change taker' and therefore some underestimates of benefits may be appropriate, considering the current low level of pledged emission reductions globally. Furthermore, the model cannot evaluate recycling options that have a complex institutional setup, but may be more effective than the presented options. Most importantly, however, the model is limited by the exogenously imposed energy investment plan (based on the IRP). Supply of energy is therefore not dynamically linked to energy demand, distorting the likely changes in the economy associated with a carbon tax in the energy sector. The linking of bottom-up, technology-rich models for key GHG-emitting sectors (in South Africa's case, energy) to economy-wide models that account for indirect costs (through forward- and backward linkages) is a key challenge that this working paper seeks to address. Similar approaches by research teams in Brazil, Chile, Colombia and Peru, in the same project, have allowed comparison of approaches and results.

4. Methodology

To address these challenges, we use a 'linked model' in which the energy sector model and economy-wide model interact or are linked. This enables electricity supply for the CGE model to be endogenised. Demand for SATIM is also endogenised. Another advantage of the linked model is we can use it to assess the socio-economic implications of mitigation actions that are effected through the sectoral energy model. The sectoral model on its own would not be able to provide us with insight on the impacts of mitigation actions on employment and household income distribution.

The section below provides a brief overview of the two models that are linked and then proceeds to detail how the link between the models has been established and how it works.

4.1 The South African TIMES[1] Model (SATIM)

SATIM is an inter-temporal bottom-up optimisation energy model of South Africa built around the Markal-TIMES platform. SATIM uses linear or mixed integer programming to solve the least-cost planning problem of meeting projected future energy demand, given assumptions about the retirement schedule of existing infrastructure, future fuel costs, future technology costs, and constraints such as the availability of resources. SATIM can either run in 'full sector' mode (SATIM-F) or in 'supply only' mode (SATIM-S and SATIM-E for electricity supply only). In SATIM-F, demand is specified as useful energy demand (e.g. demand for energy services like cooking, lighting and process heat), and final energy demand is calculated endogenously based on the optimal mix of demand technologies. This more detailed model allows for trade-offs between demand and supply sectors, explicitly captures structural changes

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[1] TIMES is a well-established partial equilibrium optimization energy modelling platform that was developed by IEA-ETSAP (www.iea-etsap.org) and is widely used by a large number of countries for energy planning and analysis.

(different sectors growing at different rates), process changes, fuel and mode switching (in the case of transport), and technical improvements (mainly relating to efficiency gains). The result of the optimisation is both the supply and demand technology mix (capacity, new investment, and production/consumption) that would result in the lowest discounted system cost for meeting the project energy demand over the planning horizon, subject to imposed constraints. In SATIM-E, which is the one used in the analysis presented here, demand for electricity is specified exogenously, and the result of the optimisation is the optimal supply technology mix for the provision of electricity. In this mode of operation, SATIM is really only just a supply analysis model and the demand projections still need to be determined with a separate analysis or by using already existing demand studies.

4.1.1 Limitations of SATIM

For long-term demand projections, methods that rely on time-series data (econometric methods) are generally not adequate and thus scenario-based approaches have to be used. This type of approach, unlike forecasts, does not pre-suppose knowledge of the main drivers of demand (economic growth, technological improvement and choice, and energy prices). Instead, a scenario consists of a set of coherent assumptions about the future trajectories of the drivers leading to a coherent system, which can form the basis for a credible storyline for each scenario. This can be very difficult to do without the help of some form of an economic model.

SATIM can be used to analyse energy policies, for example, renewable energy targets or a nuclear programme; but, although the impact on electricity price and emissions of such policies can be estimated, it is not possible to quantify economy-wide implications, including backward and forward linkages, without the help of some form of an economic model.

4.2 Energy Extended South African General Equilibiruim (e-SAGE) Model

The economy–wide model that we link with SATIM is e-SAGE (Arndt et al., 2011). The e-SAGE model is a dynamic recursive CGE model developed by UNU-WIDER and is based on an earlier International Food Policy Research Institute (IFPRI) standard CGE model and a static model by Thurlow and van Seventer (Thurlow, 2004). CGE models are useful in that that they can provide us with useful insights on the direct and indirect impacts of policies due to the linkages between the various sectors in the economy.

The e-SAGE model simulates the functioning of the economy and uses South Africa's 2007 Social Accounting Matrix (SAM) as data input. A SAM is a set of accounts which represents all of the industries and commodities in South Africa, as well as factor markets, enterprises, households and the 'rest of the world'. The 2007 SAM has 61 industries and 49 commodities. It also has 9 factors of production, namely, land, 4 education based labour groups, and capital2 which is divided into 1 energy and 3 non-energy capital groups (Thurlow, 2013). There are sectors that represent government, households that have been dissagregated into 14 groups based on their per capita expenditure and a sector representing the 'rest of the world' (Thurlow, 2004). Rational expectations govern the behaviour of economic agents, that is industries and households, in an intertemporal optimisation model such as e-SAGE (Thurlow, 2008). In the model, industries or producers exhibit profit maximisatisation behaviour, whereas households aim to maximise their utility subject to a budget constraint. The model maintains product and factor market equilibrium. Being a dynamic recursive model, e-SAGE essentially has two time periods: that is, the within-period and the between period. The static part of the CGE model makes up the within period. The between-period is characterised by the updating of various variables and parameters with capital accumulation and re-allocation being determined endogenously and technical changes and population growth being determined exogenously (Alton et al., 2012). An important feature of the e-SAGE model is that non-energy industries can react to energy prices changes during the between-period by shifting their investments to less energy intensive capital and technologies (Alton et al., 2012). Macroeconomic closures are

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[2] There is only one capital sector in the standard IFPRI model.

important in CGE models. The closures that we use will be discussed in more detail in a later section that describes how our simulations were set up.

4.2.1 Limitations of e-SAGE

The CGE model is not designed to allocate investment and production to different electricity generating technologies, as the rational allocation requires some technical considerations such as the demand and renewable energy resource profiles, which are not normally incorporated in CGE models, and this needs to be done with the help of a model with more detailed representation of technology and demand profiles, such as SATIM.

4.3 Alternatives for addressing limitations

The alternatives for addressing the limitations of the two modelling approaches are:

- to embed a simplified energy model within an economy-wide model as done by IMACLIM (a CGE model developed by the Centre International de Recherche sur l'Environnement et le Développement);
- to embed a simplified economy-wide model in an energy model as by Markal-Macro; or
- to keep both models as they are but link them by passing variables between them, either via a hard-link or a soft-link.

For this study, we build on the previous work started through a collaboration between the ERC and UNU-WIDER on the linking of SATIM and e-SAGE models (Arndt, 2014).

We apply the third alternative identified above. The main advantage of using the linked model approach is that it preserves each model's strengths without any compromise, and builds on the track record of each of the models. A challenge is that a communication framework between the two models had to be developed to ensure that both models are representing the same system.

4.3.1 The communication framework between SATIM and e-SAGE

Alternate runs of SATIM and e-SAGE are performed from 2006 to 2040, each time exchanging information about fuel prices, demand, investment (capital growth), and electricity production by technology group and electricity price. Given an initial demand, TIMES computes an investment plan, and a resulting electricity price projection, which is passed onto e-SAGE to see the impact, if any, that this new price projection has on the demand and fuel prices, which then go back to TIMES in the next iteration. The problem is that if both the price and capital growth are imposed onto e-SAGE for the entire model horizon, there is little room for demand to react. Demand tracks almost exactly the investment (capital growth), which defeats one of the main points of using a CGE.

To circumvent this, only the price projection is imposed onto e-SAGE for the entire model horizon, and the production schedule and capital growth is only gradually imposed. This is done as follows:

A set of planning years (TT $\in$ {2006, 2010, 2014, 2018, 2022, …})[3] is defined for which there is a TIMES model run. The TIMES model is run for the entire model horizon but investment decisions are gradually imposed:

- If TI[4] $\leq$ TT then NCAP(TI)[5] is fixed
- Otherwise if TI > TT, NCAP(TI) is left to the linear programming optimization in SATIM.

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[3] This is just an example. It is possible to run more frequent TIMES run, e.g. every two years.

[4] TI: TIMES model years.

[5] NCAP(TI) incorporates all the investment decisions for new electricity generation capacity, taking into account lead times. For example, if 100 MW of new coal capacity is needed in 2013 and coal has a lead time of 4 years, then the investment is made in NCAP(2009) is 100. If TT is 2010 then this investment decision is frozen, and the 100 MW is committed for 2013.

For each set of TIMES model runs, the CGE is run for the entire model horizon (TC ϵ {2006-2040}) but in two different configurations:

- If TC $\leq$ TT: then in the CGE the following variables are fixed to the results of the TIMES run
    - capital growth;
    - production mix by technology group (e.g. coal, nuclear, solar thermal, etc);
    - electricity price.
- Otherwise if TC > TT, only the electricity price is fixed to the results of the TIMES run, the production mix is fixed to that of TC=TT, and capital growth is solved by the CGE, based on the electricity price. This results in a demand new projection for TC>TT, which can be passed back to TIMES for the next TIMES run.

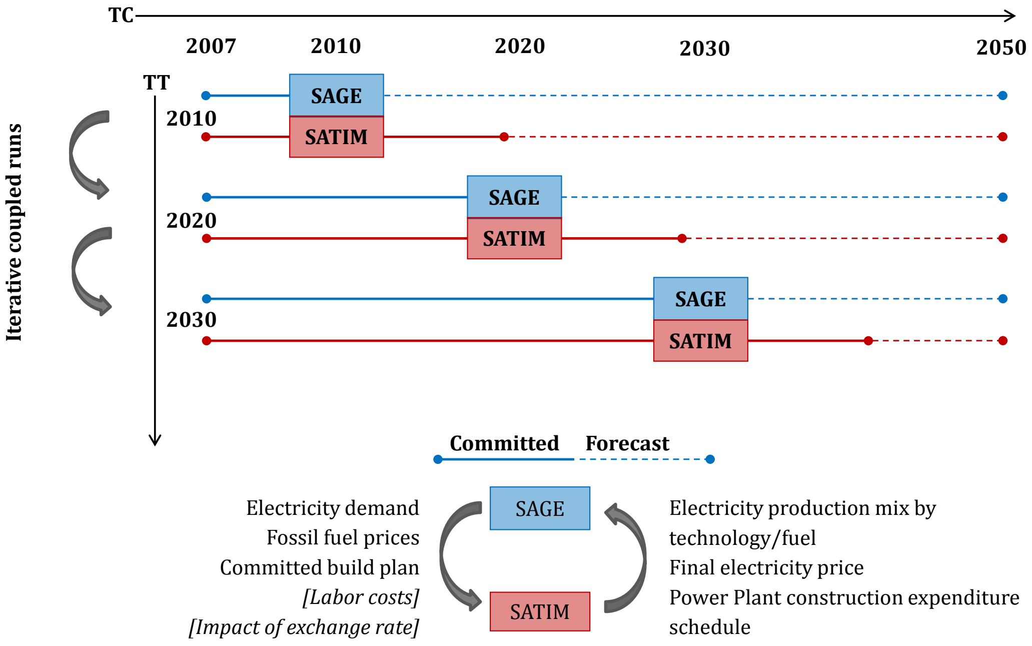

Figure 2: Interaction of SATIM and e-SAGE over time and exchange of various parameters

The result of this is that by the end of the planning horizon, we have used a demand projection that is consistent with price, and can react to price changes. Based on this consistency, we can analyse the economic impacts of the investment decisions that were made in the power sector subject to constraints defined in that sector, such as a nuclear programme or a renewables programme. The linked system also models the reaction to investment decisions in the power on the rest of the economy. For example, an economy-wide CO_2 tax is captured in the fuel price, which translates to a different electricity generation technology mix and electricity price, perhaps also a lower growth trajectory for the rest of the economy, which translates into a lower demand projection.

These are examples of measures which are investigated in more detail in the rest of the paper.

5. Specification of the baseline and the mitigation action scenarios

As a demonstration of the linked models for the purpose of evaluating mitigation actions, the following scenarios are run:

1. A set of TIMES runs without the CGE model, but assuming the same demand as the Reference linked model run for all scenarios:
   a. A Reference case of the power sector without any mitigations actions (Reference).
   b. A CO_2 tax runs starting at $5 (R48)/ ton CO_2) in 2016, increasing to $12(R120)/ton CO_2 in 2025. These tax levels are chosen to approximate Treasury's proposed carbon tax; note the tax rates are lower than assumed in the 'escalating CO_2 tax' modeled in LTMS and related studies. (NT CO_2 tax)
   c. Two renewable energy programme scenarios, that is, aiming to reach
      - 20% share of centralised generation by 2030 and 30% in 2040 (RE Prog 1); and
      - 30% share of centralised generation by 2030 and 40% in 2040[6] (RE Prog 2).
2. The same set of runs as above but this time with the linked CGE and TIMES models.
3. Three additional levels of CO_2 taxes, again starting from 0 in 2014 and ramping up to $10, $20 and $50 per ton of CO_2 by 2025.

5.1 Assumptions for all scenarios

Overall assumptions
A real discount rate of 8% as per IRP 2010.

Investment costs and other parameters for power plants
All the cost and performance parameters for power plants were aligned to the IRP update assumptions (DoE, 2013). For the renewable technologies, two scenarios are considered for projections of annual cost reductions due to technology learning:

- A 'conservative' scenario, where annual cost reductions for renewable technologies assumed in the IRP update are halved.
- An 'optimistic' scenario (RE Opt). In this scenario, projected investment cost reductions for renewable technologies are aligned to the IRP 2010 (and the IRP update).

Socio-economic parameters for e-SAGE
These are as follows:

- The total factor productivity across all sectors are tuned to follow historical growths from 2007 to 2014, and then set at 0.92%, decreasing by 0.01% annually from that point onward.
- The adopted closures for all the runs of the e-SAGE model are as follows:
  - Savings-invest: Previous studies have found that the savings-driven investment closure is more appropriate for South Africa
  - Government: We allow for uniform sales tax rate point changes for selected commodities, while government savings remain fixed.
  - Foreign: Exchange rates in South Africa are flexible, hence the current account closure for the model adheres to that and fixes foreign savings.
  - Labour: Low skilled labour is assumed to have upward-sloping supply curves which implies that there is unemployment, with low real wage-supply elasticities for these workers indicating that their unemployment is structural. Skilled labour is assumed to be fully employed and mobile, growing at 1.5% annually for secondary school educated and at 1% annually for the tertiary level educated.
  - Capital: Fully employed and activity- or sector-specific.

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[6] RE includes: centralised solar PV, solar thermal, wind, domestic and imported hydro, and biomass.

- Land: Fully employed and mobile; that is, it can be used for different purposes.

Electricity demand and historical prices
The electricity demand projection used in the TIMES model (without the link to the CGE model) assumes the same growth rates post 2012 as the IRP2010 SO Moderate case with energy efficiency. The electricity price is fixed from 2007 to 2013 according to the actual recent regulator imposed tariff increases as shown in Table 2 in nominal rands and 2007 rands.

Table 2: Nominal and real growth rates of electricity tariffs, 2006-2013

	Standard price nominal[a] (c/kWh)	*Growth nominal (%)*	*GDP deflator[b] (%)*	*Growth real (%)*
2006	0.180		6.53	
2007	0.190	5.6	8.08	-2.3
2008	0.25	31.6	8.30	21.5
2009	0.331	32.6	7.65	23.1
2010	0.416	25.4	7.20	17.0
2011	0.523	25.8	6.04	18.6
2012	0.607	16.0	5.46	10.0
2013	0.655	8.0	5.46	2.4

Notes:
a. From Nersa (2009).
b. From World Bank (2013).

6. Results

We consider the differences in results between using only SATIM and using the linked models, in terms of generation capacity, electricity production and prices. We also consider what the impact of various scenarios would be on GHG emissions, overall and sectoral GDP, new jobs created, as well per capita consumption of poor- to high-income households.

6.1 TIMES RUNS without link to e-SAGE

Figure 3 shows the total installed capacity and Figure 4 the total production over the planning horizon for the four above-mentioned scenarios.

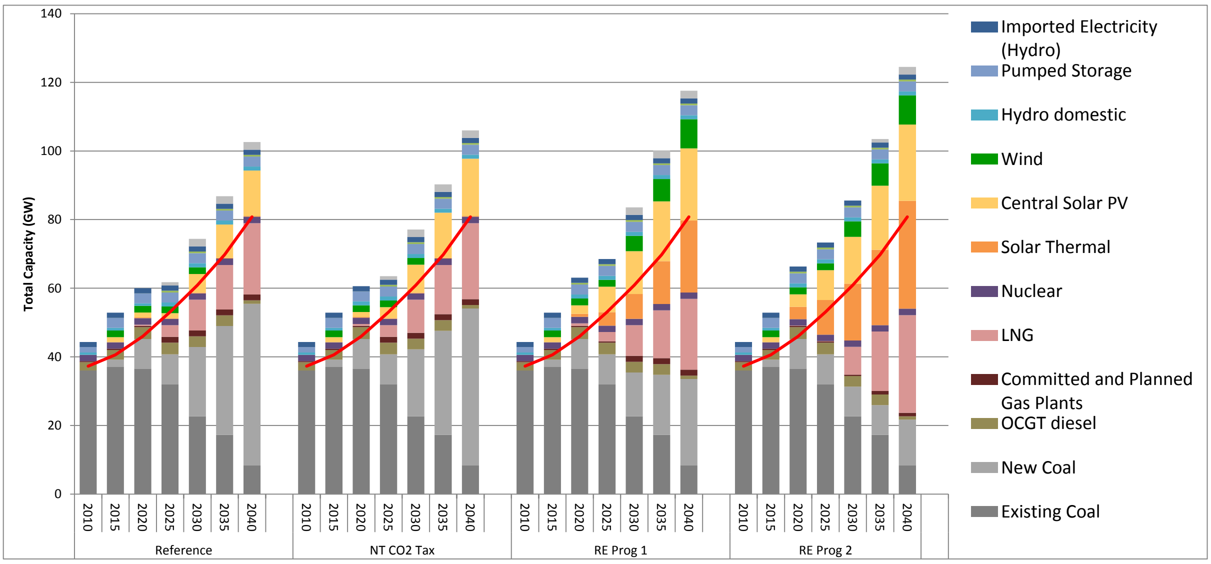

Figure 3: Total installed capacity for TIMES only runs

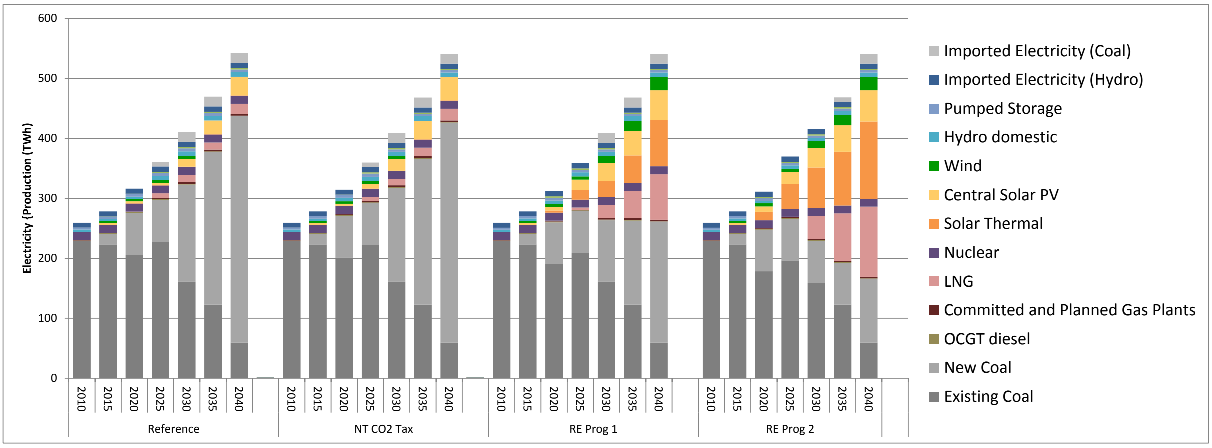

Figure 4: Electricity production for the TIMES scenarios

The reference scenario

Total capacity of the TIMES reference case reaches 103 GW in 2040, still dominated by coal with 55GW (54%). Coal also dominates production, maintaining the current share of around 81% through to 2040. Gas (open cycle gas turbines and combined cycle gas turbines) capacity reaches 23GW (23%) for peaking and mid-merit loads. The remainder is made up of solar PV (13%), hydro and pump storage (4%) and nuclear and imports (6%).

The CO_2 tax scenario

The currently proposed CO_2 tax level has a small impact on the system in this scenario. Total capacity is slightly higher at 106GW in 2040, due to increased share of gas and solar PV that run at a lower capacity factor than coal. The coal share of capacity drops to 51% and production to 79%, whereas gas remains at around 23% of total capacity. The coal production is mainly replaced by solar PV, increasing its share of production from 6% to 7%.

The renewable energy (RE) programs 1 and 2

To reach a share of production of 30% in 2040 in program 1 and 40% in program 2, the RE share of capacity reaches 43% and 50% by 2040. The high share of low-capacity technologies means that total capacity goes up to 120 GW and 126GW, respectively. The RE program pushes the coal share of capacity further down to 30%, and 19% for the two programs, respectively. The gas share of capacity reaches 18% and 23%.

Figure 5 shows the CO_2 emissions for the power sector over the planning horizon. The CO_2 emissions from the power sector of the reference scenario grows to almost double the 2010 levels reaching 430 Mton/annum in 2040. In the CO_2 tax scenario, the annual CO_2 drops by 3% relative to reference case, showing that for the given assumptions about technology costs and fuel prices that the specified CO_2 tax level is not high enough to allow for much penetration of low emission technologies into the system. However, when using the more optimistic RE costs, a 20% reduction is observed. When penetration of low emission technologies is imposed directly with the RE programs, the CO_2 emissions drop more radically by 33% and 50% respectively by 2040.

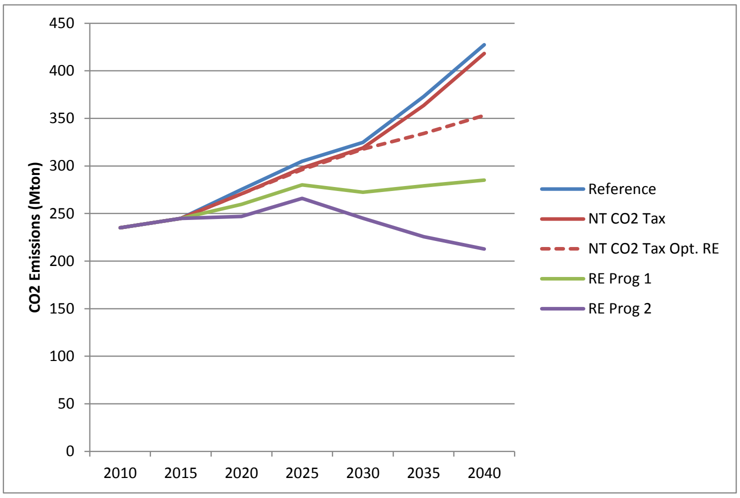

Figure 5: CO_2 emissions from power sector

Figure 6 shows the electricity price (at generation level) projection for the four scenarios. The electricity price is calculated as follows:

$$P_{elc}\,(c\ per\ kWh) = \frac{(C_{fuel} + C_{O\&M} + C_{capital})(mR) \times 100,}{Total\ Secondary\ Demand\ (TWh)}$$

where C_{fuel} and $C_{O\&M}$ are the annual fuel and maintenance costs summed across all generation technologies, $C_{Capital}$ is the annualised capital cost.[7] The electricity price with the RE programmes increases by 10% and 17% relative to the reference case in 2040. When the more optimistic RE costs are assumed, the electricity price increase relative to the reference is a bit lower at 6% and 11%, respectively. The impact of the CO_2 tax on the electricity price is significant at 14% in 2040 without any revenue recycling, but only goes up 0.5% if all the revenues were recycled to the power sector.

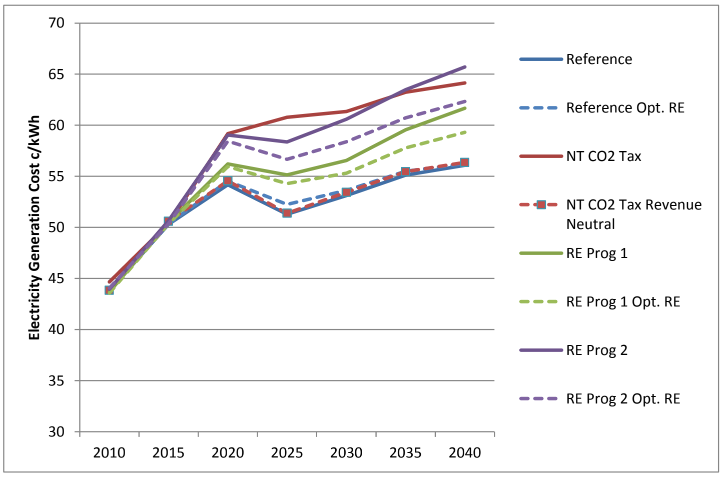

Figure 6: Electricity price for TIMES scenarios

6.2 Linked model runs

Figure 7 shows the total installed capacity by technology group comparing the TIMES runs and the CGE-linked runs for the reference case and the CO_2 tax case. The reference cases are identical, given that they have the same demand, and fuel prices. In the CO_2 tax scenario though, we see a slight drop of the peak demand in the CGE-linked run, showing some demand

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[7] Annualised over the life of each plant at 8% for new plants and 3% for existing plants assuming a life of 50 years. The 3% is a calibration parameter that gets the calculated electricity price to match the regulator price for 2012, 2013.

response from the CGE to the higher electricity price. Figure 8 shows a similar pattern when total capacity and demand for linked model runs and straight TIMES runs for the two RE programs are compared

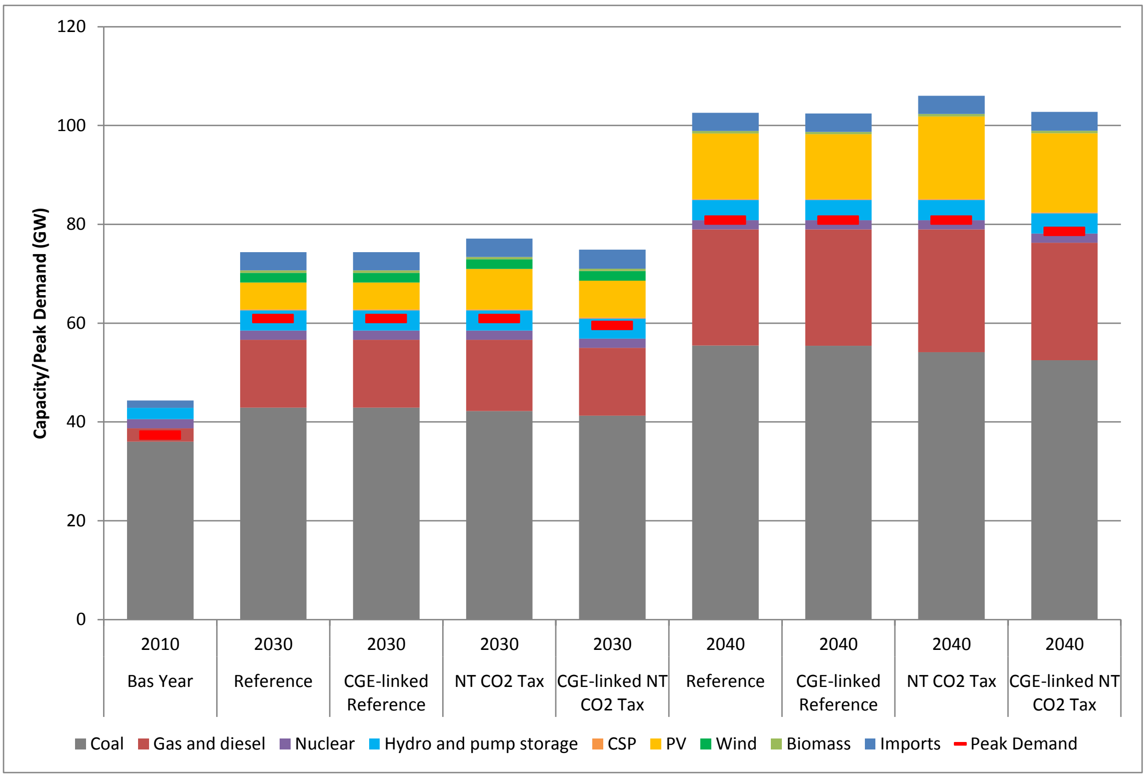

Figure 7: Comparisons of total capacity and demand for linked model runs and straight TIMES runs for the reference and CO_2 tax scenarios

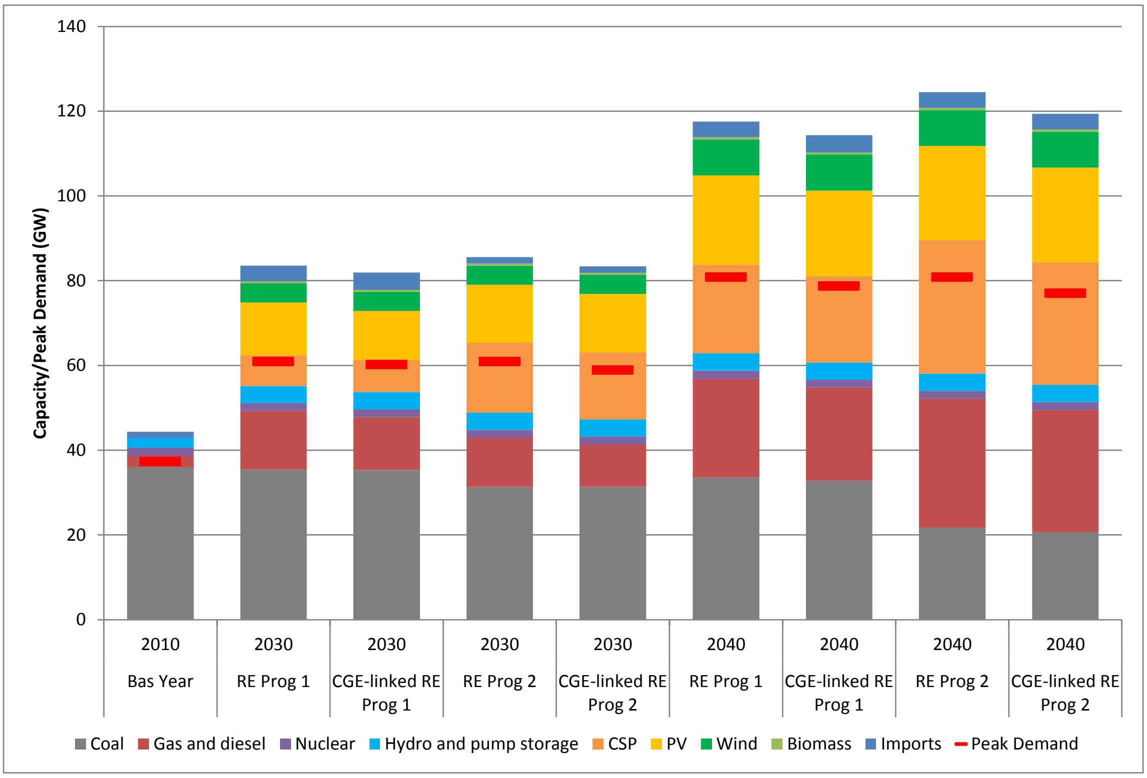

Figure 8: Comparisons of total capacity and demand for linked model runs and straight TIMES runs for the two RE programs

6.3 Impact on emissions

As there is less demand with the linked model runs for the carbon tax and the two renewable energy scenarios, CO_2 emissions from the power sector are also lower than in the TIMES only runs, as illustrated in Figure 9.

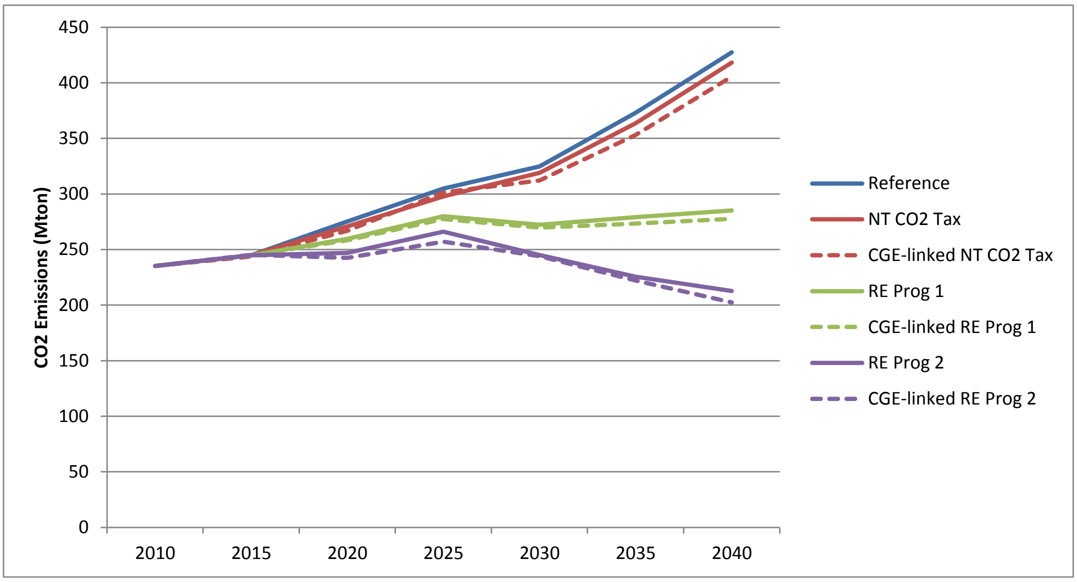

Figure 9: Power sector CO_2 emissions for the 3 mitigation scenarios with and without the CGE link

All the runs are with conservative learning curves. Figure 9 only shows changes in emissions for the power sector. Results from the modelling indicate that the NT CO_2 tax scenario emissions in the power sector would be 5% less than the reference case in 2040.

Coal would continue to be the dominant source of energy as the carbon tax would be too low to change behaviour and shift demand away from its use. Reductions in emissions would have to be much higher if South Africa were to achieve its voluntary target of reduce emissions by 34% by 2020 and 42% by 2025 relative to the reference case. The two RE program scenarios would have more emissions reductions in the power sector, with those from RE program 1 being 35% less than the reference case in 2040 and RE program 2 being 53 % less.

The changes in emissions described above are only for the power sector. The emissions from the rest of the sector, not shown here, would be over-estimated in this version of the model. This is because without the link to TIMES the other sectors, are unable to switch fuels in response to the CO_2 tax.

6.4 Socio-economic implications

Having examined the impact of mitigation scenarios on GHG emissions, we turn to the socio-economic implications using the linked modelling framework. Table 3 reports the change in economic growth, disaggregated for various sectors, due to the CO_2 tax and the two RE programmes. The results are shown with conservative learning rates for renewable energy technologies.

Table 3: Impacts on growth by sector

	2010 share of GDP	*Reference Scenario average annual growth (%)*	*Change in 2040 GDP relative to Reference (%)*		
			NT CO_2 tax	*RE Program 1*	*RE Program 2*
Total GDP		**3.08**	**-0.72**	**-1.46**	**-1.85**
Agriculture	**3.11**	**3.28**	**0.25**	**-0.68**	**-0.35**
Industry	**30.77**	**3.07**	**-1.19**	**-0.98**	**-1.12**
Mining	*8.83*	*3.61*	*-1.48*	*-4.82*	*-6.58*
Manufacturing	*16.83*	*2.76*	*-1.16*	*-1.84*	*-2.57*
Food	3.18	2.64	0.25	-1.19	-1.39
Textiles and clothing	0.61	3.02	0.11	-1.45	-1.85
Wood products	1.59	2.98	-0.55	-1.36	-1.70
Petroleum products	1.15	2.32	-1.50	-1.88	-2.50
Chemicals	2.82	2.69	-1.60	-2.34	-3.29
Non-metals	0.66	3.41	0.05	-1.33	-1.31
Metals	2.95	2.30	-4.87	-3.56	-6.01
Machinery	1.50	3.04	-0.44	-0.96	-1.08
Vehicles	1.42	3.16	-0.11	-1.52	-1.94
Other manufacturing	0.96	3.00	-0.24	-1.58	-2.00
Other industry	*5.11*	*3.01*	*-0.65*	*9.79*	*14.98*
Electricity	1.81	2.86	0.12	36.07	54.52
Water distribution	0.59	3.04	-1.73	-2.73	-3.85
Construction	2.70	3.09	-0.86	-2.75	-3.90
Services	**66.12**	**3.07**	**-0.56**	**-1.72**	**-2.27**

As shown in Table 3, all the policy scenarios would result in slight GDP loss in 2040 relative to the reference case. In all the policy scenarios, the mining and metals sectors are the most negatively affected, mainly because of the electricity price increase, and the switch away from coal for some of the electricity production. The electricity sector, however, grows quite significantly relative to the base with more investment taking place in this sector. The electricity sector's increased contribution to GDP is, however, not enough to avoid a net negative impact on GDP for the NT carbon tax and the renewable energy scenarios.

Table 4: Total number of new jobs created, 2010-2040 (1000)

		Difference in new jobs created by 2040 (%)		
	New jobs created in Reference (2010)	*NT CO_2 tax*	*RE Program 1*	*RE Program 2*
Labour	7 418	-2.60	-2.47	-3.87
Unskilled labour*	4 324	-4.47	-4.24	-6.65
Primary	1 431	-4.49	-4.02	-6.22
Middle	2 893	-4.45	-4.35	-6.86

* Skilled labour growth specified exogenously as stated in assumptions in the earlier section.

Results presented in Table 4 show a slight drop in new jobs created between 2010-2040 in all three scenarios, compared to the reference, with RE program 2 having the biggest drop.This is consistent with what is observed in the impact on GDP in Table 3. There are no new jobs for skilled labour as full employment is assumed. The reduction is driven by a) lower direct jobs in solar and wind, compared to coal, and b) higher investment costs of RE, which lead to higher electricity prices and higher GDP losses – so any jobs created in electricity generation from RE are outweighed by losses in the other sectors.

Table 5: Per capita consumption, 2010-2040

			Difference in per capita consumption in 2040 (%)		
	Initial value (2010)	*Average annual growth rate in Reference*	*NT CO_2 tax*	*RE Program 1*	*RE Program 2*
All	27 392	1.43	-0.86	-2.57	-3.62
Poor (0-50)	9 288	1.45	-0.99	-2.57	-3.69
Non-poor (50-100)	45 498	1.43	-0.84	-2.57	-3.61
Middle (50-90)	27 234	1.38	-0.88	-2.54	-3.59
Top (90-100)	118 602	1.47	-0.80	-2.59	-3.62

Consistent with GDP figures above, the average annual per capita consumption rates (of economic goods) relative to the reference scenario in Table 5, show a slight drop in per capita consumption across all income groups. Comparison of poor and richer households seems to show that there would be no re-distributional effect with any of the policy scenarios, even with the recycling of carbon tax revenues through the reduction of sales or value added tax. The negative impact on household welfare with optimistic learning rates would also be less than with conservative rates.

We also considered in our analysis the impact of more optimistic learning rates for investment in RE technologies.

Table 6 shows that the higher electricity price impact on economic output as well as jobs and consumption in the two RE programs is slightly reduced when the more optimistic cost reductions in RE are assumed. However, this is not the case for the tax scenario.

Table 6: Change of selected indicators when more optimistic cost reductions in RE are assumed

	*Change of selected indicators when more optimistic cost reductions in RE are assumed (%)**		
	NT CO_2 tax	*RE Prog 1*	*RE Prog 2*
Overall GDP in 2040	-1.25	-0.01	0.42
Metals gross value added (GVA) in 2040	-0.53	0.83	1.63
Electricity GVA in 2040	6.19	-2.68	-2.28
New jobs by 2040	-0.69	0.24	0.50
Per capita consumption in 2040	-1.39	0.06	0.47

* A positive value here signifies an improvement relative the cases where more conservative cost reductions in RE technologies are assumed.

7. Analysis of different carbon tax levels

As alluded to in the earlier discussion of carbon taxes in South Africa, different rates will have varying impacts on the economy. We compare results of using carbon tax levels of \$10, \$20 and \$50 per ton of CO_2. These not only enable comparison with studies by other research teams in this project, but also provide information on tax rates more likely to be effective in meeting South Africa's mitigation goals. For all the following carbon tax simulations, revenues are recycled to households through reductions in sales taxes.

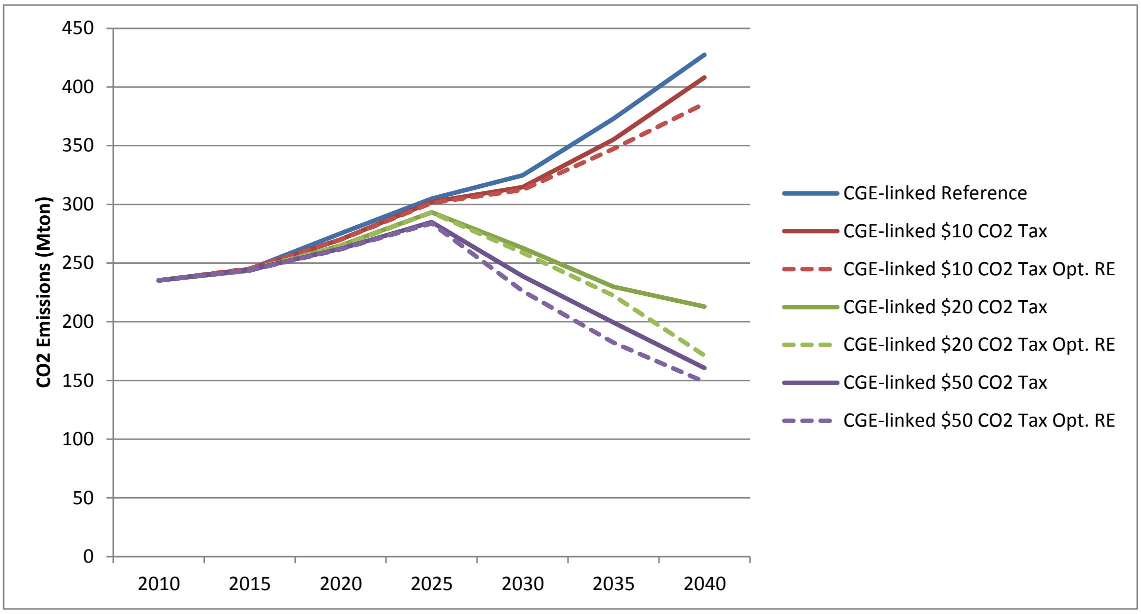

Figure 10: Power sector CO_2 emissions

Results in Figure 10 show the effect of carbon taxes set at \$10, \$20 and \$50 per ton CO_2 with conservative and optimistic cost reductions for RE technologies. Emissions reductions in the power sector would be 4.5% relative to the reference case in 2040 with a carbon tax of \$10, 50% with tax of \$20 and 62% with a \$50 tax, with conservative learning rates for RE. This indicates that there is a tipping point somewhere between \$10 and \$20.

Table 7: Change in 2040 GDP relative to Reference

	\$10	*\$20*	*\$50*
Total GDP	**-0.67**	**-3.23**	**-6.12**
Agriculture	**0.05**	**-1.17**	**-2.67**
Industry	**-1.02**	**-4.02**	**-7.53**
Mining	*-1.31*	*-9.18*	*-14.99*
Manufacturing	*-1.00*	*-3.15*	*-6.52*
Food	0.09	-1.09	-2.04
Textiles and clothing	-0.03	-1.31	-2.53
Wood products	-0.55	-2.51	-5.21
Petroleum products	-1.29	-3.88	-8.16
Chemicals	-1.35	-3.85	-7.63
Non-metals	-0.16	-2.50	-5.37
Metals	-3.78	-7.97	-17.01
Machinery	-0.46	-1.78	-3.86
Vehicles	-0.22	-1.66	-3.28
Other manufacturing	-0.31	-2.13	-4.43
Other industry	*-0.43*	*4.22*	*5.11*
Electricity	0.59	21.84	32.42
Water distribution	-1.49	-5.56	-10.78
Construction	-0.79	-3.88	-7.29
Services	**-0.54**	**-2.97**	**-5.64**

As can be seen in Table 7 above, higher carbon taxes would result in higher reductions in the GDP growth rate relative to the reference by 2040. The sub-sectors that would be affected negatively the most are again the mining, and metals sectors. The electricity sector's contribution would increase with higher tax levels, as was seen before.

Table 8: Total number of new jobs created, 2010-2040 (1000)

	Difference in new jobs created by 2040 (%) from Reference		
	$10	*$20*	*$50*
Labour	-2.18	-5.77	-11.44
Unskilled labour*	-3.73	-9.90	-19.62
Primary	-3.75	-9.92	-19.67
Middle	-3.72	-9.89	-19.59
* Skilled labour growth specified exogenously as stated in assumptions in the earlier section.			

The higher the carbon tax level, the lower the number of new jobs created, as shown in Table 8. This could be a consequence of the slowing down of the economy shown in Table 7, which would result in decreasing job opportunities and lower employment.

Table 9: Average annual per capita consumption growth rate, 2010-2040

	Difference in per capita consumption in 2040 (%) from Reference		
	$10	*$20*	*$50*
All	-0.79	-3.66	-6.93
Poor (0-50)	-0.89	-3.65	-6.88
Non-poor (50-100)	-0.77	-3.66	-6.94
Middle (50-90)	-0.80	-3.62	-6.89
Top (90-100)	-0.74	-3.69	-6.99

Table 9 above shows that higher carbon taxes lead to lower per capita consumption. The impact across the different households shows that there will be no redistributional impact in all the carbon tax scenarios through the recycling of revenues by reducing sales taxes. This is because recycling through sales tax reductions would benefit all the consumers in the economy.

8. Conclusions and recommendations for future work

In this paper we used the linked model to analyse the socio-economic implications of implementing an escalating $5 or NT carbon tax and two renewable energy programs. We considered conservative and optimistic learning rates of investment costs in renewables in all the scenarios. The NT carbon tax scenario was constructed to resemble the carbon tax level and design being proposed by National Treasury. As we currently cannot model sectoral exemptions and allowances in e-SAGE, only the 60% tax-free threshold was factored in constructing the NT carbon tax scenario. Results showed that the NT carbon tax would have very little impact on emissions reductions in the power sector (about 5% less than the reference case in 2040), using our reference assumptions for fuel and technology costs. The two renewable energy programs would have a larger impact on reducing emissions in the power sector, with RE programs 1 and 2 resulting in 35% and 53% reductions in 2040 respectively, relative to the reference case. The NT carbon tax scenario would also lead to about 0,7% less GDP in 2040 relative to the reference case, whereas the RE program 1 and 2 with conservative learning rates showed drops of 1.46% and 1.85%, respectively. The NT carbon tax, RE programs 1 and 2, would also create 2.60%, 2.47% and 3.87% fewer new jobs respectively and household consumption in all the scenarios would be less than the reference in 2040. The impact on economic output, jobs and welfare for the two RE programs is lower when optimistic learning rate for investment in RE are assumed.

Three additional tax levels of \$10, \$20 and \$50 per ton of CO_2 were examined and a tipping point was identified between tax levels of \$10 and \$20 per ton of CO_2, in terms of CO_2 emissions. At \$10 emissions reductions are very low at around 5% by 2040, relative to the reference case. At \$20 there is a 50% drop, and increasing up to \$50 only reduces the emissions by another 12%. Economic output (GDP) would also be less than in the reference for all the carbon tax scenarios, with the \$50 carbon tax resulting in a drop of 6.1% compared to a tax of \$10 which had a drop of 0.7% in 2040. The higher drop in GDP with the \$50 carbon tax would lead to the creation of fewer jobs and lower household welfare compared to the \$10 and \$20 carbon taxes. There would also be no re-distributional effect from recycling revenues through the reduction of sales taxes in any of the scenarios.

In our analysis we only considered centralised renewable energy. In future we could include distributed renewable energy. We could also explore the sensitivity of these socio-economic impacts to higher coal prices. Future coal supply security in South Africa will depend on likely significant coal price increases..The current linkages in our model are between the economy-wide model and the electricity sector in SATIM. Future work could also include integration of other sectors to allow fuel switching and better appreciation of energy efficiency. We could also consider the recycling of carbon tax revenues through transfers to households.

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