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The development of a linked modelling framework for analysing the socioeconomic impacts of energy and climate policies in South Africa

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Abstract: This paper presents some methodological improvements made to the linked SATIM–eSAGE energy-economy-environment modelling framework for analysing energy and climate policy in South Africa. The improvements include the linking of the households and the other economic sectors of the eSAGE economy-wide model to the SATIM energy model. Two scenarios are used to illustrate the benefits of having the new links, which include an energy efficiency scenario and an ambitious climate mitigation scenario. The results show that there are significant socio-economic benefits in having a more energy-efficient economy. The work presented in the paper provides some solid foundations for further work on the energy-economy-environment policy arena for South Africa.

Keywords: CGE model, TIMES model, energy models, economic modelling, South Africa
JEL classification: C61, C68, Q40

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1 Introduction

Energy-economic and environment (E3) models are simplified representations of the complex energy-economic and environment systems that we are part of. These models are useful in that they help us to organize information about the system. They help decision-makers and stakeholders to better understand the system, both in terms of how different courses of action affect the system and contribute to objectives, and in terms of how the system responds to different uncertain and uncontrollable situations.

There are two widespread modelling approaches to the quantitative assessment of economic impacts induced by energy and climate policies: models focusing on the energy system and models of the broader economy. The two model classes differ mainly with respect to the emphasis placed on technological details of the energy system vis-à-vis the comprehensiveness of endogenous market adjustments (Böhringer and Rutherford 2008; Hourcade et al. 2006). In some energy policy studies, the energy sector can be appropriately viewed in isolation from the remainder of the economy. In other situations, this may be inappropriate, as there may be interdependence between energy markets and the rest of the economy (Hogan et al. 1977). At the same time, economy-wide models represent sectoral economic activities and energy through aggregate production functions, which are not well suited to capturing the temporal and discrete nature of technology choice, nor to ensuring basic energy conservation principles (Lanz and Rausch 2011).

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

1. To embed a simplified energy model within an economy-wide model, as done in Crassous et al. (2006)
2. To embed a simplified economy-wide model in an energy model, as done in Remme and Blesl (2006)
3. To keep both models as they are but link them by passing variables between them (as described below).

Initial work on using the third (iterative) approach has been undertaken at the Energy Research Centre in collaboration with UNU-WIDER, focusing on the power sector (Arndt et al. 2014), where the energy sector is represented by the existing South African TIMES Model (SATIM) (Analysis and Group 2013) and eSAGE (Arndt et al. 2011) is the economy-wide model. However, in order to more adequately analyse energy and climate policies that go beyond the power sector, it is important to also link the other sectors. Another limitation of the current approach is that changes other than in demand (e.g. labour, capital costs, and exchange rates) that occur in the economic model are not currently passed back to the energy model.

2 Objective of paper

The objective of the paper is to describe the methodology of further coupling the two models and to provide illustrative results showing the impacts of the improved methodology in relation to two questions:

- What are the socioeconomic benefits of improving the efficiency of energy utilization in the South African economy?

- What are the socioeconomic implications of committing to an ambitious CO_2 reduction target for South Africa?

3 What has been done until now?

3.1 Work done at ERC in collaboration with UNU-WIDER: the SATIMel–eSAGE linked modelling framework

The Deep Decarbonization Pathway Project (DDPP)

Altieri et al. (2016) present two scenarios focusing on employment and poverty reduction under a carbon constraint for South Africa in 2050. The cumulative GHG limit is imposed on SATIM. SATIM is used to find the overall least-cost mix of demand and supply technologies, and the resulting CO_2-eq trajectory for the power sector is imposed on SATIMel[1] in the linked model. The modelled CO_2-eq constrained power sector in the linked model results in a new trajectory for future economic activity. This is then relayed back to SATIM for a new iteration. The economic indicators of interest are then extracted from the final run of the linked model. The paper presents two scenarios where the current INDC commitments are not incompatible with some of the other development goals for South Africa—namely, improved employment and poverty alleviation.

Two main limitations of this approach are:

- The CO_2-eq constraint in SATIM affects not only the power sector but also other sectors, especially the liquid fuel supply sector. These changes outside of the power sector need to be passed to the economic model to get the full picture of the 'socioeconomic' impacts of the CO_2 constraint. This is especially crucial if more ambitious CO_2 targets than are currently envisaged are to be adopted, as they would have to rely on more mitigating measures taking place on the demand side (e.g. switching to electric vehicles).
- Having two versions of SATIM (SATIM and SATIMel) in addition to the Computable General Equilibrium (CGE) model is very cumbersome and caused several version control issues. This approach would be especially problematic if one wanted to explore a broader/larger set of scenarios.

An integrated approach to modelling energy policy in South Africa

Arndt et al. (2014) present the first application of the linked SATIMel–eSAGE modelling framework to assess the implications of different carbon tax levels with and without trade restrictions on electricity. The CO_2 tax is imposed in eSAGE (and on the price of fossil fuels in SATIMel). The paper shows the benefits of opening up electricity trade within the region with a CO_2 tax in South Africa, but it suffers from similar problems to the DDPP study: in the medium to long term, a CO_2 tax changes not only how SA produces electricity but also how it would produce (or procure) liquid fuels and how energy would be consumed in other productive sectors (and households). As described below, eSAGE has limited flexibility to respond to these price effects.

[1] SATIMel is a variant of SATIM where only the power sector is represented. A demand for electricity is specified and the optimization computes the least-cost mix of power-generating technologies.

3.2 Other current and past attempts to answer similar questions on South Africa

LTMS

Pauw (2007) describes analysis done on the results of the precursor to SATIM: the Long-term Mitigation Scenario (LTMS) MARKAL energy model (Winkler 2007), using a CGE model for South Africa called STAGE. Like eSAGE, STAGE is a descendant of the CGE models introduced by Dervis and Robinson (1982). The analysis looks at three possible mitigation trajectories for South Africa and makes use of the results of the energy model to characterize technical change shocks and investment shocks using a hybrid comparative static–dynamic approach. The scenario with energy efficiency results in a loss of GDP compared with the reference, which was unexpected. Possible reasons for this are the limited effort in hybridization of the energy commodities and the method used for passing investment results from the energy model to the CGE—aspects that are significantly refined in the linked SATIM–eSAGE framework.

Green growth and its implications for public policy—the case of South Africa

Schers et al. (2015) use a 'hybrid' CGE-energy modelling framework (IMACLIM-SA) to gain insights into the trade-off between South Africa's mitigation objectives and the key development challenges. It focuses on economic growth and unemployment, with discussions about inequalities and education. IMACLIM-SA represents the South African economy as a small, open economy with ten sectors (five energy, five non-energy) and five income classes. It features technological insights into electricity production—physical limitations, carbon intensity, and technical change—obtained from the SATIMel energy model. Calibrated on the 2005 SAM[2], the model produces an economic equilibrium of the economy in 2035 based on assumptions about the evolution of key parameters (notably demography, labour and capital productivity, and international prices). Equilibria in 2035 are computed both without (reference projection) and with mitigation policies, and analysed in terms of GDP growth, employment, and income distribution. In this study extensive effort is put into the hybridization of the SAM in the CGE model but, as in the case of the DDPP, the focus is on the power sector.

3.3 Other current and past attempts to answer similar questions using methodology adopted by this study but implemented in models of other countries

Imaclim-Brazil linked to Brazilan MESSAGE model

The approach by La Rovere et al. (2013) is very similar to the approach used by Schers et al. (2015) described above, except that it is applied to the Brazilian economy. The energy model is on a platform called MESSAGE, which is very similar to TIMES used by SATIM and the CGE model is IMACLIM-Brazil. The analysis looks beyond the power sector at technical change happening on the other energy supply sectors. The approach used on the demand side is different in that a static MAC curve derived from a bottom-up approach is used to characterize the energy/CO_2-related technical changes in the CGE model.

[2] SAM—Social Accounting Matrix, which includes Supply and Use Tables (SUTs) and the government (income/savings/consumption), household (income/savings/consumption), and 'rest of the world' (imports/ exports) sectors.

HYBTEP linked to Portugal TIMES model

Fortes et al. (2014) describe the development of a modelling framework linking a CGE model (HYBTEP) and an energy model (TIMES_EP) to perform analysis on various climate and energy policies for Portugal. The linking framework is very similar to the one adopted for this study. Some differences include the treatment of investment in the power sector. In the SATIMel–eSAGE framework care is taken to separate out the expenditure on new power plants, as this occurs during the construction phase, with the power sector capital stock also controlled exogenously by the energy model. In the case of HYBTEP–TIMES_EP, the focus is purely on the refinements of the production functions inside HYBTEP based on the TIMES_EP results. It is also not clear whether changes in labour and capital costs observed in HYBTEP are being passed back to TIMES_EP.

4 Description of models used in the linked modelling framework

4.1 SATIM

SATIM is an inter-temporal bottom-up optimization energy model of South Africa built around the 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.

Why are SATIM-type models good for medium- to long-term analysis?

Methods that rely on time-series data (econometric methods) are generally inadequate for long-term demand projections, as they cannot incorporate changes that are not present in historical data, and extrapolation techniques often lack the basic checks and balances that would ensure the technical feasibility of a future energy system. Thus, more theoretical models that can allow for significant departures from the current and past system configurations, as would be possible in the long term, while ensuring internal consistency, have to be used. Such models are more useful for exploring 'what if' scenarios than to forecast the future.

SATIM is such a model: demand is specified as useful energy demand or demand for energy services (e.g. cooking, lighting, and process heat) and final energy demand (e.g. demand for electricity and petrol) is calculated endogenously based on the optimal mix of demand and supply technologies. The flow of energy from extraction to energy services is governed by a set of theoretically derived relations that will ensure the technical feasibility of the scenario (e.g. energy conservation: energy produced must be greater than energy consumed; production from a facility in a particular year cannot exceed what is technically possible given available installed capacity; availability of resources must be respected, etc.).

An objective function specified in terms of the unit activity and unit capacity costs of all the technologies in the model combined with the relations listed above sets the optimization problem. The result of the optimization is: the supply and demand technology mix (capacity, new investment, and production/consumption) that would result in the lowest discounted system cost for meeting the projected energy demand over the planning horizon subject to the imposed constraints.

This more detailed (bottom-up) approach allows the exploration of scenarios with trade-offs between demand and supply sectors, scenarios where structural changes (different sectors growing at different rates, household income profile changing) and process changes occur (e.g. switching from blast furnace (BOF) to electric-arc-furnace for steel production), and scenarios where fuel and mode switching (in the case of transport) and technical improvements (mainly relating to efficiency gains) occur.

Why are SATIM-type models inadequate on their own to answer the above questions?

This type of approach, unlike a forecast, does not presuppose knowledge of the main drivers of demand (economic growth, household income, 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. Given the linkages between the energy sector and the rest of the economy (industrial activity, household income, etc.), a coherent system can be very difficult to develop without the help of some form of 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 prices and GHG emissions of such policies can be estimated, it is not possible to quantify the economy-wide implications (e.g. GDP, employment, and household welfare) without the help of some form of economic model.

4.2 eSAGE

eSAGE is a recursive dynamic CGE, country-level, economy-wide model that simulates the functioning of the South African economy. This is a dynamic variant of the generic static model described in Löfgren et al. (2002). A CGE model is the SATIM-equivalent model of the economy in that it is governed by a set of theoretically founded equations, which are used to rebalance the SAM describing the economy after the SAM has been subjected to a (set of) shock(s) (e.g. CO_2 tax, increase in labour supply). The rebalancing is done by allowing prices to change and by using a variety of substitution mechanisms representing economic behaviour in response to relative price changes, while ensuring that macroeconomic constraints are maintained.

Agents optimize behaviour subject to constraints; for example, households maximize utility subject to a budget constraint, while producers maximize profits subject to a production technology constraint. Equilibrium is reached when supply equals demand in the commodity and factor markets simultaneously, given various macroeconomic constraints: aggregate demand equals aggregate supply, total investment equals total savings, government and household budgets balance (revenue or income equals expenditure plus savings or deficit), and the foreign account is also balanced (balance of payments). These equilibriums are achieved via changes in relative prices and consequent changes in the behaviour of agents.

eSAGE simulates the functioning of the South African economy and provides useful insights into the direct and indirect linkages between different groups of profit-maximizing industries and utility-maximizing households, as well as the government and the rest of the world. eSAGE provides a detailed and comprehensive representation of the economy, including multiple industries, commodities, five factors of production (capital + four labour groups), and multiple representative household groups.

eSAGE's recursive dynamic structure consists of within- and between-period components. Within each period, eSAGE is solved subject to given levels of population, productivity, and capital supply. Between periods, eSAGE is updated to reflect population growth, technical change, and capital accumulation. New capital allocation is determined endogenously based on previous-period investment levels and the relative profit rates of the different sectors. Once invested, capital becomes sector-specific.

The hybridization process

eSAGE differentiates itself from other, more standard, CGE models (e.g. SAGE) by the important extra calibration step that is undertaken on the energy commodity flows in the economy, sometimes referred to as a 'hybridization' process. This process involves the calibration of the monetary flows in the SAM that represent flows of energy commodities to be adjusted to reflect the actual physical flows. This is normally done by combining flows reported in national energy balances and energy commodity prices paid by different sectors/households. The difference is allocated to other commodity flows (e.g. services) in order to rebalance the SAM. The hybridization process followed for eSAGE is described in Arndt et al. (2011).

Why is eSAGE a good model for medium- to long-term analysis?

Like SATIM, eSAGE can be thought of as an experimental lab that can be used to explore what-if scenarios of how the economy could evolve over time given various shocks in terms of changes in policy, the supply of labour, technology, or international fuel and technology costs, while ensuring strong 'internal consistency'.

Why is eSAGE inadequate on its own?

In its current configuration, eSAGE, like other models of its type, has limited ability to endogenously capture technical change while ensuring technical feasibility for very long-term scenarios where there are large departures from baseline projections.

4.3 How SATIMel and eSAGE are currently linked[3]

Alternate runs of SATIMel and eSAGE are performed from 2006 to 2040, each time exchanging information via data links. Given an initial electricity demand, SATIMel computes the least-cost power plant mix, and the resulting investment plan. The investment (capital growth and expenditure on power plant construction), share of electricity production by technology group, and changes in average electricity generation cost are passed on to eSAGE. The change in electricity generation cost is used to calculate the change in electricity price over time in eSAGE.

The problem is that if both the price and capital growth are imposed onto eSAGE for the entire model horizon, there is little room for demand to react. Demand tracks the investment (capital growth), which defeats the point of using a CGE model to estimate the demand response. To circumvent this, only the price projection and the production mix are imposed onto eSAGE for the entire model horizon, and capital growth and expenditure are only gradually imposed. In order to accommodate the fixed electricity price, the indirect sales tax on electricity is freed up. The result of this is that, by the end of the planning horizon, the demand projection is consistent with price, and can react to price changes.

On the basis of 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

[3] For further details, see Arndt et al. (2014).

or renewables programme, or how the energy sector in particular and the economy as a whole would respond to CO_2 mitigation policies.

5 Description of improvements made to the linked modelling framework in this study

The work carried out in this study builds on the foundations of the existing linked SATIMel–eSAGE modelling framework and expands the framework to increase the breadth of energy and climate policy analysis that can be performed as well as improve on the quality of the analysis. The improvements are achieved mainly by:

- Revisiting some of the hybridization steps in the SAM of eSAGE
- Adding new links between the two models:

  eSAGE > SATIM link:
    - Instead of electricity demand projections:
        - Industry sectors: activity-level changes by the various economic sectors are passed on to SATIM via a demand module that converts the activity-level changes to changes in demand for energy services in the industry sectors. The electricity demand from industry is determined endogenously by SATIM.
        - Households: income levels by the different household groups are passed on to SATIM via a demand module that converts the changes in income levels to changes in demand for energy services by households. The demand module includes a mode-switching feature for passenger transportation (mode switching is currently specified exogenously).
    - CGE results to feed into SATIM cost parameters: changes in labour costs, cost of capital goods (including changes in the exchange rate) as observed in the economic model used to adjust the investment and running costs of technologies in SATIM.

  SATIM > eSAGE links:
    - Adjustments to the production coefficients in the CGE on the basis of the results of SATIM for the use of energy in other economic activities (other than just electricity)
    - Adjustment of household energy consumption (including for transportation) based on the results of SATIM.[4]

As mentioned above, eSAGE is a recursive (myopic) dynamic model, where the SAM is rebalanced in each time period (annually). The linkages from SATIM are shocks imposed in the in-between periods. This process can be described as follows:

- Iteration 1:
    - Run SATIM forward-looking model with optimization performed for the whole period (to 2050) with initial growth projection.
    - Start with balanced 2007 SAM.

[4] One of the useful aspects of the SATIM framework is that it is forward-looking and allows the specification of a cumulative CO_2 constraint. This generates a CO_2 marginal trajectory that can be imposed on the CGE as a CO_2 tax, for example.

- Implement shocks for 2008:
    - Labour supply (high skill linked to population)
    - Capital supply based on savings of previous period and putty-clay accommodation
    - Global commodity prices
    - Labour and capital productivity
  - Update production function of power sector given results of SATIM.
  - Update production function of other sectors given results of SATIM.
  - Update consumption function of households given results of SATIM.
  - Update capital stock of electricity sector based on increment observed in SATIM.
  - Deduct expenditure on power plants (from SATIM) from total savings.
  - Allocate the rest of savings for 2011.
  - Update CO_2 tax if any.
  - Balance SAM for 2009 given shocks listed above.
  - Implement shocks listed above for 2010.
  - …
  - Repeat until 2040.
- Iteration 2:
  - Take activity growth projection, and household income projections and pass them on to SATIM for a new run to get updated energy sector results.
  - Start again with balanced 2007 SAM.
- …
- Repeat above until convergence is reached (3–5 iterations).

As mentioned above, it was observed that if the capital stock for the power sector was exogenously imposed for the whole period from Iteration 1, there is not much response by the economy to changes in electricity price. So, instead, the period for which the capital stock for the power sector (as well as the deduction of expenditure on power plants from savings) is specified exogenously is gradually increased with each iteration. In parallel, the investment decisions made in the power sector are gradually frozen in the power sector for this gradually increasing period. The 'exogenous capital periods' used in the results presented in this paper are:

- Iteration 1: 2007–2010
- Iteration 2: 2007–2015
- …
- Iteration 7: 2007–2040.

Results are then reported only for the final iteration.

6 Scenario descriptions

Four scenarios are used to illustrate the new insights obtained with the new linkages:

1. Limited Link: Only the power sector is linked.
2. Full Link+EE: All sectors and households are linked, and energy efficiency improvements are specified in the energy model.
3. Limited Link+CO_2: Only the power sector is linked and a CO_2 tax trajectory for reaching a 10 GT cumulative level for the period 2015–2040 is imposed on the CGE.

4. Full Link+CO_2: Same as 'Full Link+EE' plus a CO_2 tax trajectory for reaching the 10 GT cumulative level imposed on the CGE.

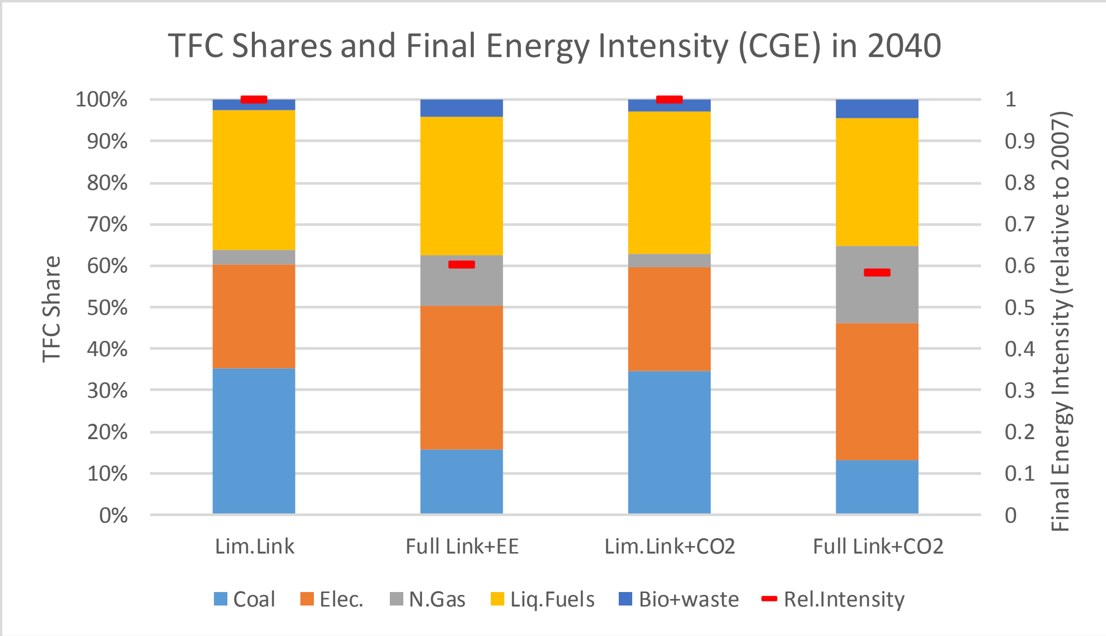
Other assumptions common to all scenarios:

- eSAGE (for further details see Arndt et al. (2011)):
  - 2007 SAM with hybridization using 2006 and 2007 energy balances
  - CO_2 tax revenues recirculated via reductions in sales tax on all goods
  - Upward sloping labour supply curves for less-educated workers
  - Putty-clay capital and endogenous capital accumulation
  - Fixed current account with flexible real exchange rate
  - Savings-driven investment
  - TFP annual growth adjusted homogenously across all sectors to 'shape' GDP growth to match historical GDP growth from 2007 to 2014, then ramped up to reach 0.9 per cent annual growth in 2017, with a decline to 0.67 in 2040.
- SATIM (for further details see ERC (2014)):
  - 2006 calibrated
  - Real discount rate: 8 per cent
  - Power sector technology costs, domestic coal prices, and global commodity prices follow the median trajectory in MAPS/UNEP (2016).
  - Electricity import options include those considered in DOE (2013) up to a maximum of 8 GW (of which 5 GW are hydro).
  - Cheap shale gas is not available.
  - Transport sector is modelled as per ERC (2014).
  - The Iron & Steel, Pulp & Paper, and Non-metallic Minerals sectors are modelled as per ERC (2014).
  - Biofuels are excluded as an option for the transport sector.
  - Energy efficiency improvements:
    - Households can adopt more efficient appliances if they are cost-effective.
    - The commercial sector adopts current and projected building codes for South Africa.
    - Passenger vehicle efficiencies improve by 1 per cent annually (as per SANEDI (2016)).
    - Freight vehicle efficiency improves by 0.5 per cent annually (as per SANEDI (2016)).
    - Modal splits and vehicle occupancies are assumed to be constant over time
    - The Iron & Steel, Pulp & Paper, Non-metallic Minerals sectors are modelled as per NAPP (2014).
    - Other industrial sectors adopt current industry standards as per ERC (2014).

7 Results

Figure 1 shows the 2040 shares of total final energy consumption and the final energy intensity relative to 2007 for the four scenarios considered. The figure shows that without the Full Link, the final energy intensity stays at the 2007 level, but that it drops by around 40 per cent in the Full Link cases. A switch away from coal to electricity and natural gas is observed.

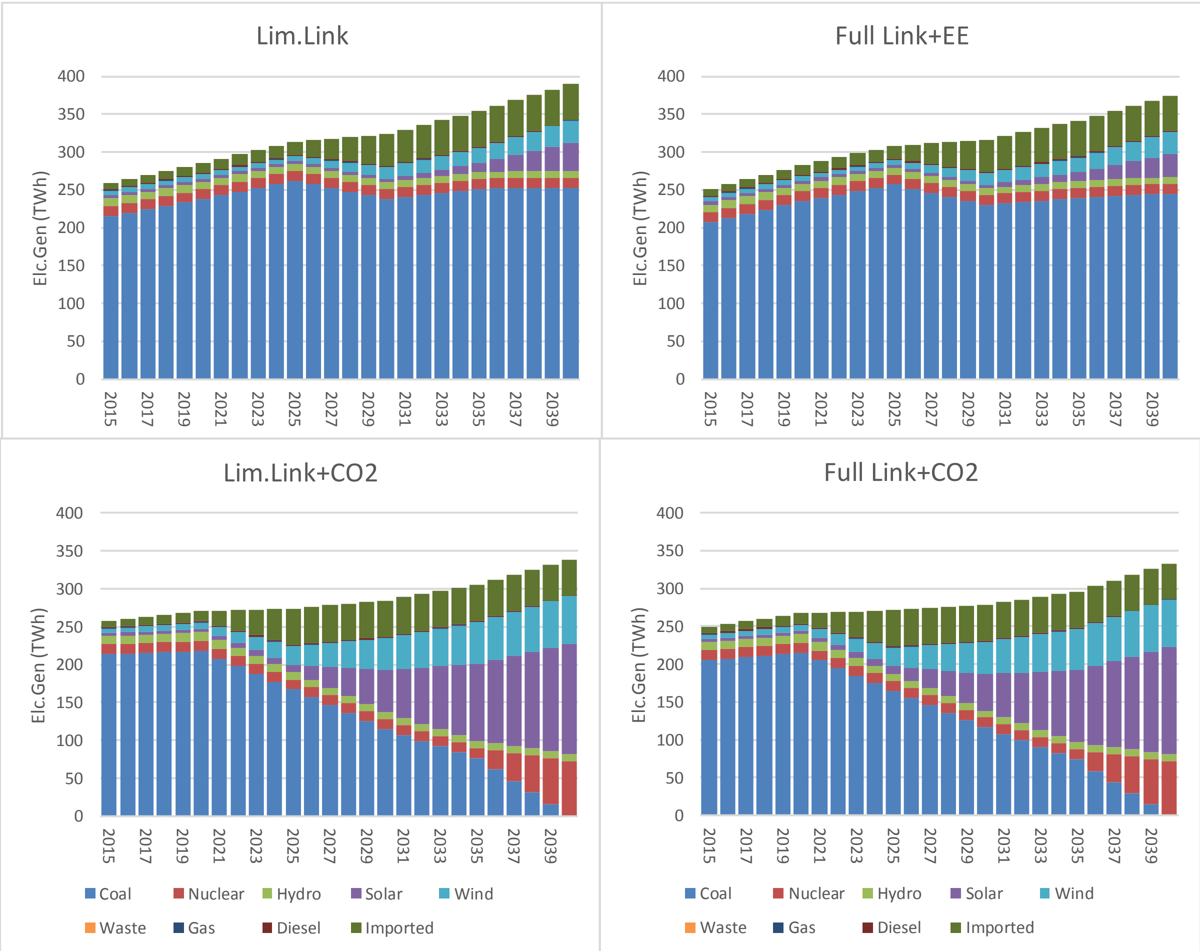
Figure 1: Total final energy consumption for the four scenarios in 2040



Source: Authors.

Figure 2 shows the power generation mix for the four scenarios considered. It shows that the shares are the same with and without the Full Link, as expected—given that the power sector is linked—but that the total production is lower in the Full Link cases, given the lower electricity demand resulting from the energy efficiency improvements. The CO_2-constrained cases show a shift away from coal to renewables and nuclear, with a complete phase-out of coal by 2040.

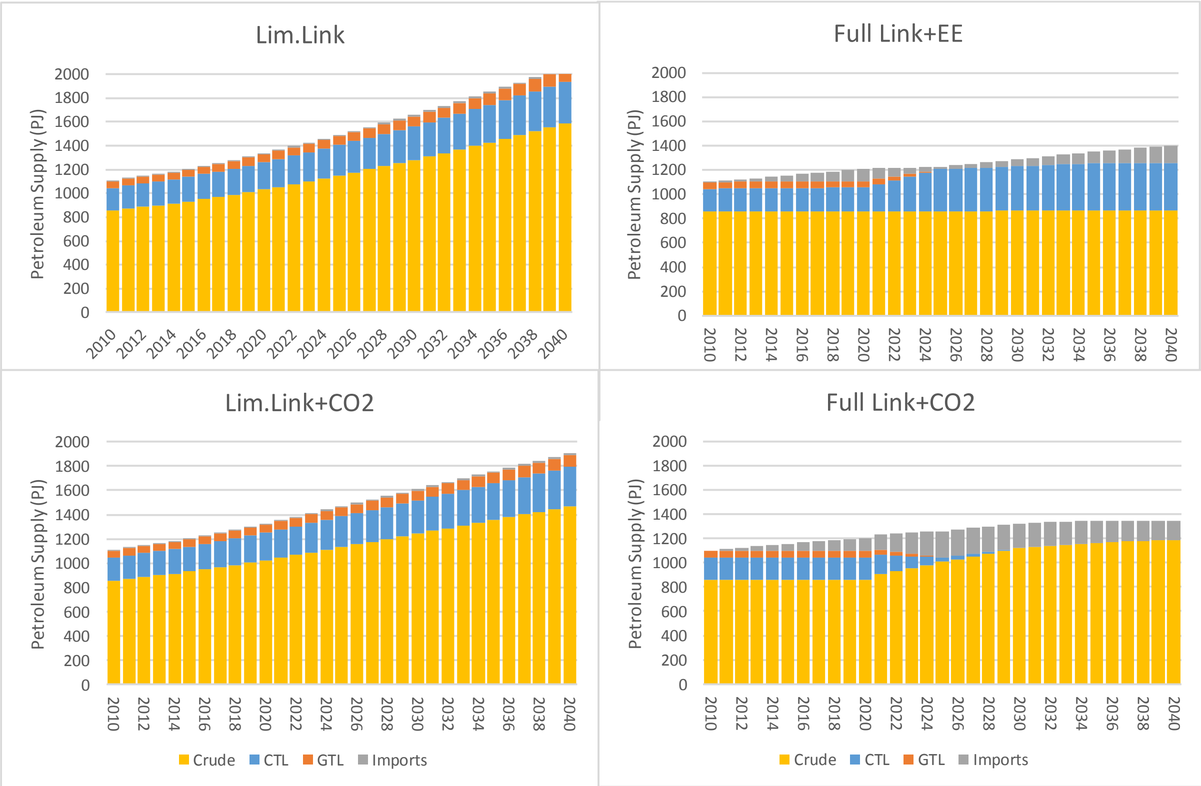
Figure 2: Electricity generation mix for the four scenarios considered



Source: Authors.

Figure 3 shows the supply of petroleum products for the four scenarios considered. The petroleum sector is not linked to the energy model in the Limited Link scenarios. The result is that, regardless of the CO_2 price, the sector keeps the base year structure. In the Full Link+EE scenario, we see an increase in the share of CTL production and a phase-out of GTL as the gas resource of PetroSA is depleted. We also see that the demand for petroleum products is significantly lower in 2040. In the Full Link+CO_2, we see a phase-out of CTL, as it is much more CO_2-intensive.

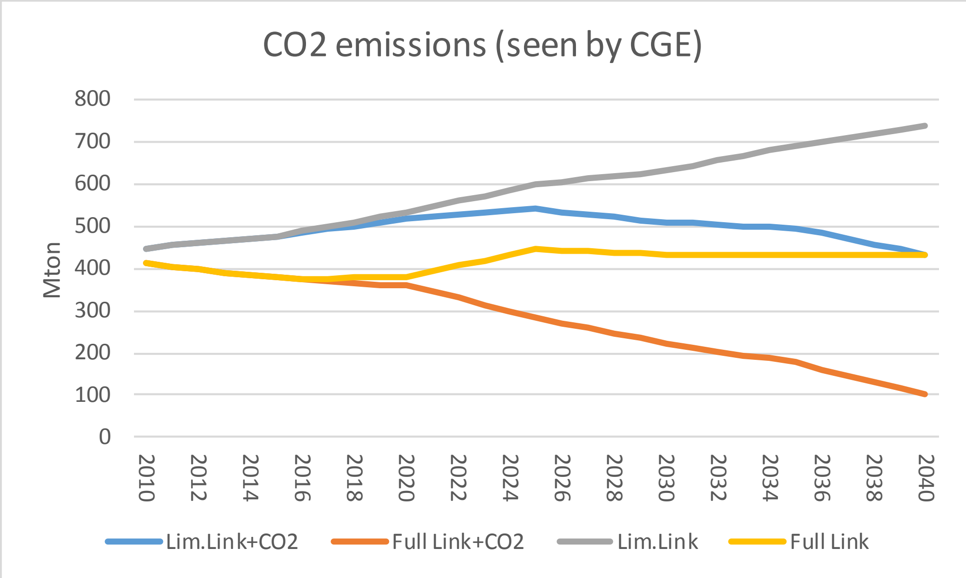
Figure 3: Petroleum products supply for the four scenarios considered



Source: Authors.

Figure 4 shows the CO_2 emission trajectories as seen by the eSAGE for the four scenarios considered. Without a CO_2 constraint and without the Full Link to SATIM, the CO_2 emissions rise to around 750 Mton/yr by 2040. When the CO_2 tax trajectory for the 10 GT cumulative cap is imposed on the CGE, with only the power sector linked, the CO_2 emissions peak around 2025 and then come back down to around 2010 levels in 2040, so completely overshooting the 10 GT cumulative target. The emissions of the Full Link scenario slowly drift down due to slow growth and energy efficiency improvements, then go up as the new coal power plants (Medupi and Kusile) come online, as well as the new CTL refinery, before stabilizing again around the 450 Mton level. In the Full Link+CO_2 scenario, emissions decline to around 100 Mton/yr by 2040. This is below the level seen in 2040 by the energy model (175 Mton/yr), showing that there are still some outstanding calibration issues between the two models.

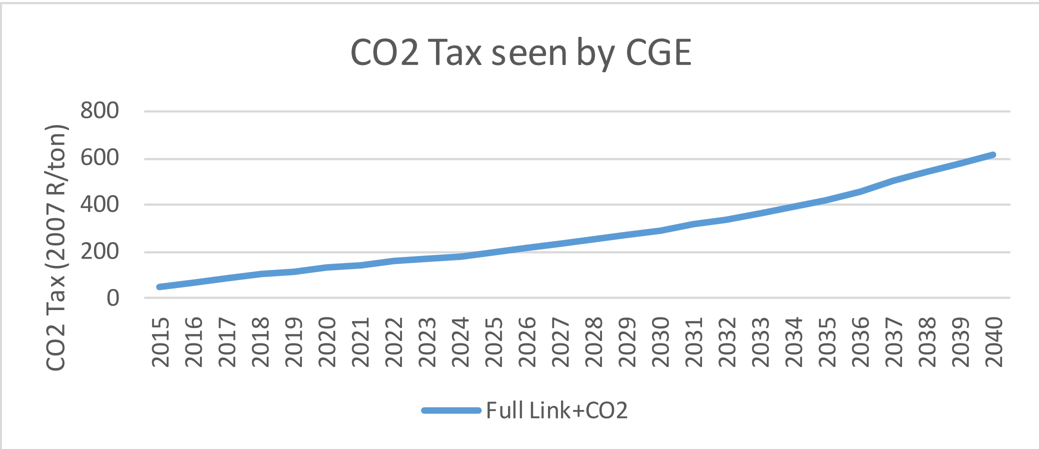
Figure 4: CO_2 emissions with Limited Link vs Full Link with EE and EE+CO_2



Source: Authors.

Figure 5 shows the CO_2 marginal trajectory that is obtained from SATIM when a 10 GT cumulative limit is specified for the period 2015–2050. The CO_2 marginal goes up over time as the model runs out of the lower cost mitigation options (in power and petroleum products), and requires more onerous fuel-switching in the other sectors (industry, transport, commerce, and residential).

Figure 5: CO_2 marginal given the 10 GT CO_2 cap 2015–2050



Source: Authors.

Figure 6 shows projected average GDP growths, GDP growths for aggregate sectors, overall household welfare, and welfare growth for different household income groups for the four scenarios considered. The results show that there is a 0.2 per cent annual average growth benefit for having better energy efficiency as modelled in SATIM, compared with an economy that uses energy to 2040 as it did in 2007. It also shows that when a CO_2 price is imposed without taking into account the possibility of higher energy efficiency and fuel-switching, that growth would be 0.19 per cent slower on average than the no energy efficiency (EE) case, and 0.39 per cent slower than the EE case without a CO_2 price. When EE and fuel-switching are considered across all sectors, meeting the ambitious 10 GT target does not actually cost anything relative to not having

EE in place, and costs 0.16 per cent average growth compared with having EE and no CO_2 taxes. This is assuming that revenues from taxes are recycled through reductions in sales taxes.

Similar observations are made on household welfare, but with slightly larger impacts, namely a 0.43 per cent improvement in welfare growth when EE is included. This welfare impact is higher in the poor income percentiles (0–50) and in the top income percentiles (90–100).

Figure 6: Socio-economic impacts

Source: Authors.

8 Conclusions and further work

This paper describes the methodology used to couple a CGE model of South Africa (eSAGE) and an energy model of South Africa (SATIM) across all sectors consuming energy. The coupling approach starts from previous work, where only the power sector was linked. The results show that the additional links between the two models do significantly improve the insights that can be obtained from analysing ambitious energy efficiency and mitigation policies for South Africa.

Further work includes:

- Update of the base year from 2007 to the latest available SAM for South Africa, namely, 2012
- Refinement of the hybridization process, perhaps with better alignment of the disaggregation of the economic sectors and households in both models
- Detailed analysis of a wider range of mitigation targets to get a better understanding of the possible trade-offs
- Other scenarios including other technologies that could lower the CO_2 marginals of meeting ambitious targets such as biofuels and electric cars, modal switching in transport, and other storage options
- Better characterization of solar and wind resources
- Increased sensitivity around the gas price (e.g. with availability of shale) and other technology costs
- Better characterization of the households in eSAGE and SATIM.

On the economic side more analysis can be done to identify the winners and losers for different levels of ambition as well as different CO_2 taxation and tax-recycling strategies; and sensitivities around assumed TFP growth projections, border tax adjustments, etc.

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