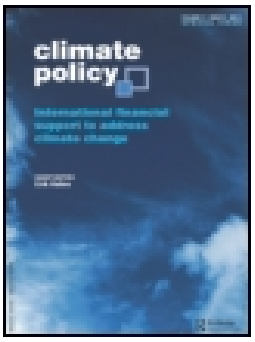

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research article

Achieving development and mitigation objectives through a decarbonization development pathway in South Africa

KATYE E. ALTIERI*, HILTON TROLLIP, TARA CAETANO, ALISON HUGHES, BRUNO MERVEN, HARALD WINKLER

Energy Research Centre, University of Cape Town, Private Bag X3, Rondebosch, Cape Town, Western Cape 7701, South Africa

Achieving the international 2 °C limit climate policy requires stringent reductions in GHG emissions by mid-century, with some countries simultaneously facing development-related challenges. South Africa is a middle-income developing country with high rates of unemployment and high levels of poverty, as well as an emissions-intensive economy. South Africa takes into account an assessment of what a fair contribution to reducing global emissions might be, and is committed to a 'peak, plateau and decline' emissions trajectory with absolute emissions specified for 2025 and 2030, while noting the need to address development imperatives. This work utilizes an economy-wide computable general equilibrium model (e-SAGE) linked to an energy-system optimization model (TIMES) to explore improving development metrics within a 14 $GtCO_2e$ cumulative energy sector carbon constraint through to 2050 for South Africa. The electricity sector decarbonizes by retiring coal-fired power plants or replacing with concentrated solar power, solar photovoltaics and wind generation. Industry and tertiary-sector growth remains strong throughout the time period, with reduced energy intensity via fuel-switching and efficiency improvements. From 2010 to 2050, the model results in the unemployment rate decreasing from 25% to 12%, and the percentage of people living below the poverty line decreasing from 49% to 18%. Total energy GHG emissions were reduced by 39% and per capita emissions decreased by 62%.

Policy relevance

Lower poverty and inequality are goals that cannot be subordinated to lower GHG emissions. Policy documents in South Africa outline objectives such as reducing poverty and inequality with a key focus on education and employment. In its climate policy and Intended Nationally Determined Contribution (INDC), South Africa is committed to a peak, plateau and decline GHG emissions trajectory. As in many developing countries, these policy goals require major transformations in the energy system while simultaneously increasing affordable access to safe and convenient energy services for those living in energy poverty. The modelled scenario in this work focuses on employment and poverty reduction under a carbon constraint, a novel combination with results that can provide information for a holistic climate and development policy framework. This study has focused on the long term, which is important in generating clear policy signals for the necessary large-scale investments.

Keywords: development pathways; economic models; employment; energy models; GHG reductions; mitigation scenarios

1. Introduction

In 2010, total GHG emissions in South Africa were 544.3 $MtCO_2e$ (excluding forestry and other land use (FOLU[1]) – with FOLU included the total is 518.2 $MtCO_2e$ (Department of Environmental Affairs, 2014). South Africa is a high emitter in per capita terms, 10.3 tCO_2 per person (t cap^{-1}), which is above the global (6.3 t cap^{-1}) and subSaharan Africa (3.2 t cap^{-1}) averages (World Resources Institute,

*Corresponding author. *E-mail*: katye.altieri@uct.ac.za

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2015). In 2009, South Africa made a voluntary commitment to reduce GHG emissions below business-as-usual (BAU) levels by 34% by 2020 and 42% by 2025. In the 2015 INDC, South Africa committed to a long-term peak, plateau and decline (PPD) trajectory in which total GHG emissions will be in a range between 398 to 614 $MtCO_2e$ in the years 2025 and 2030 (Department of Environmental Affairs, 2015), which is based on national policy outlined in the South African Climate Change White Paper (Department of Environmental Affairs, 2011). Thus, South Africa has progressed from a pledge to reduce emissions relative to BAU, to an absolute emissions range for 2025 and 2030.

The INDC states that eliminating poverty and eradicating inequality are national priorities (Department of Environmental Affairs, 2015). In 2011, the proportion of the South African population living below the nationally established upper-bound poverty level (R620 per month in 2011 prices) was 45.5% (Statistics South Africa, 2014). South Africa has a Gini coefficient of 0.69, consistently one of the highest values in the world (World Bank, 2015a). The top decile of the population earns 54% of all income, whereas the lowest 10% of earners account for 1% of all income (World Bank, 2015b). As such, the main research question addressed here focuses on the development of a South African socio-economic pathway that reduces unemployment and improves income distribution under a carbon constraint consistent with a mid-PPD GHG trajectory.

GDP growth has averaged 1.9% since 2008, a value significantly below that targeted by the National Development Plan – 2030 (NDP; 5% per year; National Planning Commission, 2012). The growth rate of the economy has not been able to keep up with the large number of new people entering the labour market post-apartheid. Unemployment as of the first quarter of 2015 was 26%; however, if discouraged work seekers are included, the unemployment rate is 34% (Statistics South Africa, 2015). The health and education sectors make up 27% of government expenditures (National Treasury, 2015), yet the health and educational outcomes are subpar (Spaull, 2013), which does not bode well for the much-needed growth in skilled labour.

Many labour market challenges are linked to the capital- and energy-intensive mining, minerals beneficiation and heavy manufacturing core of the economy (Fine & Rustomjee, 1996). Systematic efforts to limit black education during apartheid, and unsuccessful measures to improve black education and training post-apartheid impact the options available for current industrial policy in its attempts to reduce unemployment. High-wage and high-productivity growth within the current structure of the economy has not led to reduced unemployment due to difficulties in absorbing the high levels of unskilled labour (Nattrass, 2011). An economy-wide analysis using a computable general equilibrium (CGE) model suggests that unemployment could be reduced to 12% by 2025 by reducing infrastructure gaps, easing the skills constraint and increasing foreign and domestic investment while removing the incentives that favour capital-intensive and not labour-intensive industries (Faulkner, Loewald, & Makrelov, 2013). Black (2012) suggests that unemployment could be addressed by identifying and growing sectors with higher employment potential. Nattrass (2011) also concludes that high-wage, high-productivity growth within the current structure of the economy does not lead to reduced unemployment.

South Africa's emissions are largely driven by energy-intensive industries and heavy reliance on coal, which represents 66% of the total energy supply (Department of Energy, 2010). The energy sector contributes 79% of the total GHG emissions (Department of Environmental Affairs, 2014), increasing to 84% if the emissions from production of synthetic fuels such as coal-to-liquids (CTL) and gas-to-liquids (GTL) are included. The majority (>90%) of electricity generation comes from coal, and the largest contributor to CO_2e emissions by sector is electricity generation (62.5%) (Department of Environmental Affairs, 2014).

This study utilizes recent advances in economic modelling that focus on unemployment reduction (Black, 2012; Faulkner et al., 2013; Nattrass, 2011), as well as national GHG mitigation modelling studies (Winkler, 2010). It builds upon recent work that has explored the relationship between development and climate (Winkler, Boyd, Torres Gunfaus, & Raubenheimer, 2015; Winkler & Marquard, 2011), as well as research that has focused on linked energy–economic modelling in developing countries including Chile, Colombia, Brazil, Peru and South Africa (Shukla, 2013 and references therein). In South Africa this linked modelling framework was used to explore the socio-economic impacts of a carbon tax (Merven, Moyo, Stone, Dane, & Winkler, 2014). The work presented here focuses on the technical feasibility of an illustrative decarbonization development pathway, and not the political feasibility of implementation, with the intention of initiating a discussion on additional pathways for South Africa.

2. Methods

2.1. Economic modelling

e-SAGE is a CGE model (Arndt, Davies, & Thurlow, 2011) in which the main input is the 2007 Social Accounting Matrix (SAM), a set of accounts that represents all of the productive sectors and commodities in South Africa, as well as factor markets, government, enterprises, 14 household-types based on their per capita expenditure and the 'rest of the world' (Thurlow, 2004). The SAM has 61 productive sectors (industries) and 49 commodities. Factors of production include land, labour and a distinction between energy and non-energy capital (Arndt, Davies, Makrelov, & Thurlow, 2013). Labour is disaggregated into four groups according to level of education and mapped to level of skill: individuals that have attained primary and middle-school education are considered unskilled, those that have completed secondary school are semi-skilled, and those with tertiary education are skilled. Labour closures vary by labour groups: primary and middle-school groups assume some level of unemployment, allowing endogenous labour absorption (fixed wages), whereas the secondary and tertiary educated labour groups are assumed to be fully employed and mobile with supply specified exogenously. Other closures follow those in (Thurlow, 2008).[2]

e-SAGE is a dynamic recursive model, in this case run for two time-periods, the within and between periods, from 2006 to 2050. The static part of the CGE model makes up the within period. Some variables and parameters are updated during the between period, with capital accumulation and re-allocation being determined endogenously, whereas forecasts for population growth, factor productivity and technical change in the energy sector are exogenous (Alton et al., 2014). A key feature of e-SAGE is that non-energy industries can react to energy price changes during the between period by shifting their investments to less energy-intensive capital and technologies, the ease of which is specified exogenously (Alton et al., 2014).[3] Although recent analyses suggest that the goals of the NDP (National Planning Commission, 2012) may be unrealistic (Cilliers, 2015), for policy cohesion some exogenous changes made in e-SAGE replicate NDP policy goals: a labour participation rate of 65% by 2030, an increase in South Africa's agricultural exports, increasing national savings to 25% and increasing the savings portion of absorption to 25%.

2.2. Energy modelling

The South African TIMES[4] Model (SATIM) is an intertemporal bottom-up optimization energy model of South Africa built around the Markal–TIMES platform. SATIM uses linear programming to solve the least-cost planning problem of meeting projected future energy demand given assumptions, e.g. the retirement schedule of existing infrastructure, future fuel and technology costs and efficiency improvements. In full energy sector mode (SATIM-F), demand is specified as useful energy demand (e.g. demand for energy services such as cooking, lighting and heat) and final energy demand is calculated endogenously based on the optimal mix of demand technologies. The optimization results in the supply-and-demand technology mix (e.g. capacity, new investment, production and consumption) that would result in the lowest discounted system cost for meeting energy demand over the time-period, subject to all other imposed constraints.

A real discount rate of 8% was used for consistency with the South African Integrated Resource Plan (IRP) (Department of Energy, 2013). Power plant cost and performance parameters were aligned to the IRP update assumptions (Department of Energy, 2013), with some updates on the investment cost for nuclear, concentrated solar power (CSP) and solar photovoltaic (PV) derived from recent work (Merven, 2015). Population growth is based upon recently developed country-specific probabilistic projections (Raftery, Li, Ševčíková, Gerland, & Heilig, 2012).

2.3. Linked economic–energy modelling under a GHG emissions constraint

Initially, SATIM-F was run with a 14 $GtCO_2e$ cumulative energy emission constraint (2015–2050) using a reference economic growth projection from e-SAGE. It includes energy sector emissions and non-energy sector emissions such as fugitive emissions from coal and gas extraction, gas transportation and production of liquid fuels from coal. It excludes process emissions from industrial processes and other non-energy sector emissions (e.g. AFOLU and waste). SATIM-F is used to compute the least-cost configuration of the energy system to 2050 under the emissions constraint. The GHG reduction burden is allocated between sectors based on relative cost of technologies and fuels in different sectors, taking into account the existing stock of technologies and their retirement profiles, i.e. not using an allocation proportional to the base year used, for example in the IRP. The resulting CO_2e trajectory in the power sector was then imposed onto SATIM in electricity supply-only mode (SATIM-E) linked with e-SAGE. In the linked model, alternate runs of SATIM-E and e-SAGE are performed from 2006 to 2050 in five-year increments, each time period exchanging information about fuel and electricity prices, electricity demand, investment and capital growth in the power sector and electricity production by technology group. Given an initial demand for electricity, SATIM-E computes an investment plan and an electricity price projection. These are passed onto e-SAGE to determine the impact that the new price projection has on demand, which goes back to SATIM-E in the next iteration and after a few iterations convergence between the two models is reached. Given that SATIM-E has similar input assumptions to SATIM-F a similar power plant mix (and electricity price) is obtained in both versions of the model.[5]

2.4. Scenario development

A key assumption in the decarbonization scenario is that no change in the skills profile of the South African labour pool happens over the next 35 years. Meeting development and mitigation goals was explored by changing the structure of the economy to enhance low-carbon high-labour absorbing growth and by allowing the economy to increase trade openness, all within the emissions constraint. The results are presented without reference to a baseline or BAU case.

Employment effects, i.e. the direct and indirect effects on employment that result from an increase in growth in a given sector, were calculated by skill level for each sector. Carbon intensities were also analysed, with the goal of identifying sectors that had a high potential for both the employment of unskilled labour and low carbon emissions (Figure S1). The identified sectors – agriculture, furniture, glass, forestry and 'other services' – were targeted for growth in a manner consistent with government inducements to private investment in order to prioritize labour-absorbing activities and generate a flow of investment toward them. This was done by exogenously increasing capital productivity of the sector by 50% over the 35 years of the simulation as South Africa currently lags behind the technological frontier in the targeted sectors. The elasticity of substitution between capital and labour factors was decreased to simulate pro-labour policy, and finally 'trade openness' was increased by relaxing trade elasticities and increasing regional trade exports.[6] Further modelling methodology is provided in the Supplemental Information.

3. Results

3.1. Economic growth and decarbonization

The energy GHG emissions constraint is achieved as population increases by 21% and GDP per capita and total energy consumption in South Africa grow steadily. From 2010 to 2050, GDP increases more than 200% and final energy consumption increases by 92%. Decarbonization is achieved in the model through a lower carbon intensity of energy production and use, and reduced energy intensity in the economy (Figure 1).

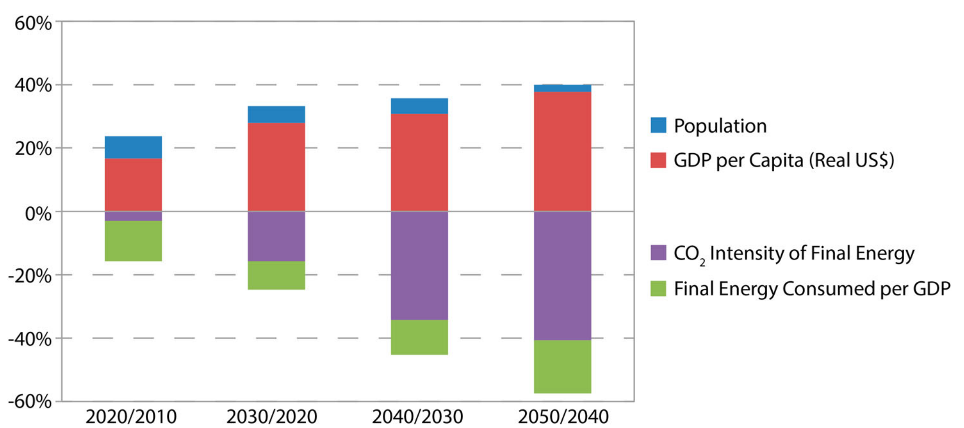

Figure 1 Energy-related CO_2e emission drivers from 2010 to 2050 expressed as the 10-year variation rate of the drivers, e.g. the ratio of 2020 to 2010

At the same time, the energy intensity of the economy as measured by final energy (indicative of sectoral energy consumption) decreases by 40%, and as measured by primary energy (indicative of the efficiency of the whole energy system including the production, transformation and end-use) decreases by 68%. Total GHG emissions per capita decrease from the currently high value of 10.3 t cap^{-1} to 3.9 t cap^{-1} from 2010 to 2050. In order to achieve a 2 °C world, the global average must approach 1.5 t cap^{-1} (UNFCCC, 2010).

The economy averages 2.8% annual GDP growth from 2010 to 2050. This is lower than the growth rate of 5.4% in the NDP and the 4–7% in the New Growth Path (NGP), both of which are targeted at these levels primarily to achieve employment growth targets. It should be noted that the NDP time horizon is through to 2030, whereas the NGP reflects growth on an even shorter term, through to 2020. GDP growth is endogenous in e-SAGE, and as such it cannot be prescribed at a certain level to match the policy projections of the NDP or NGP. This is an advantage as no *a priori* growth rate has to be assumed, and given South Africa's history of jobless growth (Banerjee, Galiani, Levinsohn, McLaren, & Woolard, 2007; Casale, Muller, & Posel, 2005), it is important to not place undue weight on annual GDP growth as a metric of development itself. The annual average GDP growth rate here is consistent with recent projections for short-term growth from the South African National Treasury, which projects South Africa to grow at ~2% for 2015 with a gradual improvement to 3% through to 2017 (World Bank, 2015a).

From 2010 to 2050, the value added by industry to GDP grows at an annual average rate of 2.7% (Figure S2), yet efficiency improvements and fuel switching lead to a 30% reduction in industrial energy intensity. Within the industrial subsectors, average annual value-added to GDP growth rates of mining, chemicals and non-metallic minerals are all over 2%, whereas growth in the iron, steel and non-ferrous metals subsectors are ~1%. Agriculture grows at an annual average rate of 4.9% as it is a low-carbon sector that can absorb low-skilled labour. GDP growth is partially driven by the increased openness to trade, allowing exports in the targeted sectors (e.g. agriculture, glass, etc.) to increase, spurring demand in the economy. This is consistent with goals stated in the NDP, which highlights the importance of growing exports in globally traded sectors in the hope of stimulating domestic spin-offs.

The electricity sector nears zero-carbon by 2050. The GHG intensity of electricity production decreases from 1065 to 35 g kWh^{-1} from 2010 to 2050. The large transition to negative growth in the GHG intensity of final energy occurs from 2030 to 2040 when construction of solar thermal, solar PV and wind capacity ramps up to replace retiring coal-fired power stations (Figures 1 and 2). From 2010 to 2030, coal decreases its capacity contribution from 90% to 63%, consistent with the IRP,[7] but then coal is completely eliminated by 2050 (Figure S3).

The assumptions for technology costs and cost reductions over time due to technology learning[8] (Merven, 2015) impact the exact technology mix, and should they deviate, the mix of low-carbon technology would change, however, this would not affect the CO_2e trajectory. There is no new investment in nuclear power in the model, therefore when the Koeberg nuclear power plant retires in 2044 nuclear no longer contributes to electricity generation. Small amounts of natural gas contribute to the final generation mix, but natural gas does not become a significant electricity source as CSP is cheaper than LNG-fuelled electricity generation; although natural gas is less CO_2-intensive than coal, it does produce GHG emissions. Carbon, capture and storage (CCS) is not considered feasible for South Africa as the coal mines are located far from potential storage sites and the current and forecasted

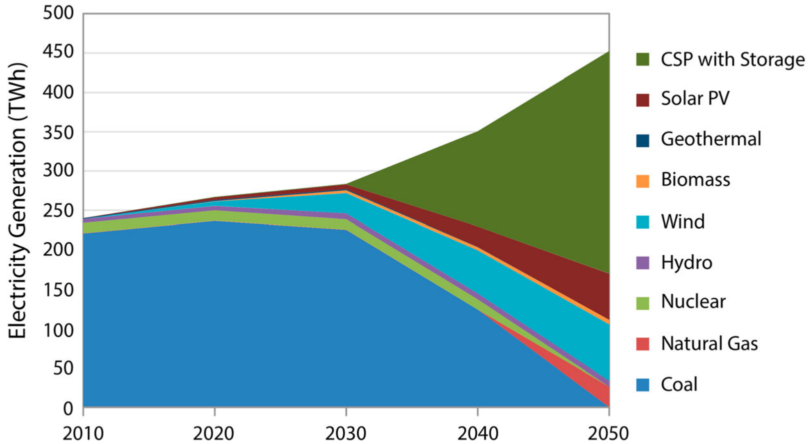

Figure 2 The total amount of electricity produced over time by technology

costs are high, much greater even than nuclear costs (>US$ 8000 kW^{-1}). PV and wind start to contribute more to electricity generation by 2020 with wind increasing significantly by 2030, whereas solar CSP does not make a large contribution until 2035 (Figure 2). Solar CSP with storage and PV dominate the electricity supply, representing 75% of electricity production (Figure 2) and 66% of installed capacity by 2050 (Figure S3). This is plausible for South Africa given the large solar resource, as well as recent data from solar installations that show capacity factors for PV plants of 27%, much higher than was originally expected.

The decarbonization of electricity, as well as reduced emissions in the liquid-fuel supply sector, results in significant declines in GHG emissions over time (Figure 3). The decarbonization of electricity also allows other sectors to fuel-switch towards electricity as a low-carbon energy. Liquid-fuel supply emissions decline due to the reduction in CTL by 46% by 2050 and the elimination of GTL by 2030. This is accomplished as both CTL and GTL plants are retired at the end of their lifetimes and subsequent demand is met through imports, whereas industry fuel-switching to electricity reduces overall liquids demand. Energy CO_2e emissions decrease by 39% from 398 $MtCO_2e$ in 2010 to 241 $MtCO_2e$ in 2050. With the application of the cumulative energy emissions constraint, total energy related CO_2e emissions do indeed follow a trajectory similar to PPD, peaking in 2030 at 449 $MtCO_2e$ before steadily declining until 2050.

This is at the low end of the South African PPD trajectory range as specified in national policy (Department of Environmental Affairs, 2011), which in 2050 has a range of 212 to 428 $MtCO_2e$ for total GHG emissions. Although the PPD policy is for total GHG emissions, in the 2010 national GHG inventory energy emissions accounted for 78.7% of all GHG emissions, hence the focus in this work on decarbonization in the energy sector. It is important to note that given higher GDP growth and increases in income, GHG reductions would be required in other sectors in addition to electricity to meet the PPD policy target. This is particularly true for transport, which only sees a 15% reduction in the CO_2e intensity of final energy consumption in this work. By 2050, electricity and hydrogen only contribute 7% to total transport energy, whereas fossil fuels remain the dominant source of liquid fuels at 77%, leaving further opportunities for GHG emissions reductions.

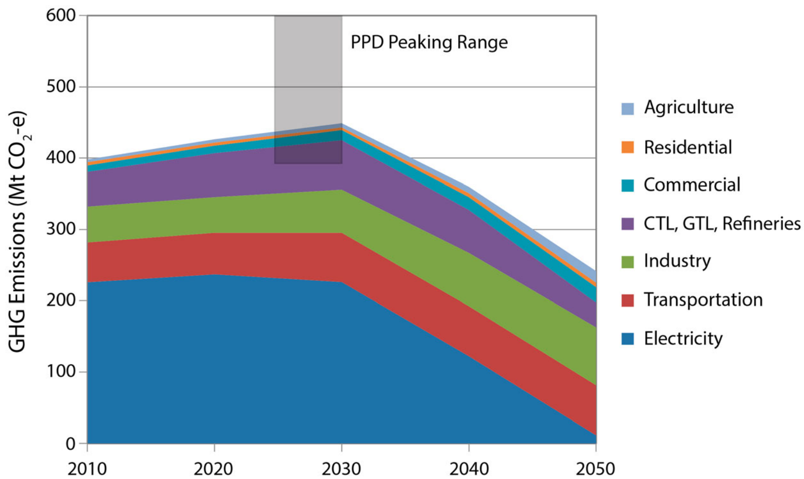

Figure 3 Energy-related CO_2e emissions by sector. The values for the PPD range from 2025 to 2030 are shaded gray. Note: All electricity related emissions are included in the 'Electricity' sector and therefore emissions for the other sectors are non-electricity CO_2e emissions, i.e. from other fuels or energy carriers.

3.2. Energy poverty, income distribution and unemployment

Energy poverty takes three main forms in South Africa. First, there is an inadequate quantity of energy services for basic needs (e.g. cooking, lighting, refrigeration and heating), resulting in a low quality of life as well as social and economic exclusion. Second, there are severe health and safety issues associated with indoor air pollution from using coal and wood for cooking and heating (Bruce, Perez-Padilla, & Albalak, 2000). Third, the high cost of energy services renders them a large component of already meagre low-income household budgets. Overall, there is a need for affordable access to modern and safe energy services.

Increasing household income helps to alleviate energy poverty. In achieving decarbonization and meeting the GHG emissions constraint, the number of people living below the poverty line was reduced from 49% in 2010 to 18% in 2050 (Figure 4). There is a marked reduction in the percentage of the population classified as low income (<R19 200 per household per year, R_{2007}) and a distinct increase in the number of middle income (R19 200 to R76 800) and high income (>R76 800) households. As a result, demand-side energy poverty is decreased as households move into the middle-income category. On the supply side, 99% of households have electricity connections by 2050.

Although energy service delivery to households increases over time in the model, it is assumed that there are improvements in lighting and appliance efficiency and household thermal performance that offset the increased energy consumption. As a result, household electricity consumption increases from 0.18 EJ in 2010 to 0.21 EJ in 2030, but then declines to 0.17 EJ in 2050. The rebound effect is not considered significant as its magnitude is quite small, both at the household and macro-economic levels (Gillingham, Kotchen, Rapson, & Wagner, 2013). In the context of marked improvements in safe and reliable energy service delivery to South African residents, household electricity consumption decreases from 24% of total electricity in 2010 to 11% in 2050, and residential GHG emissions increase

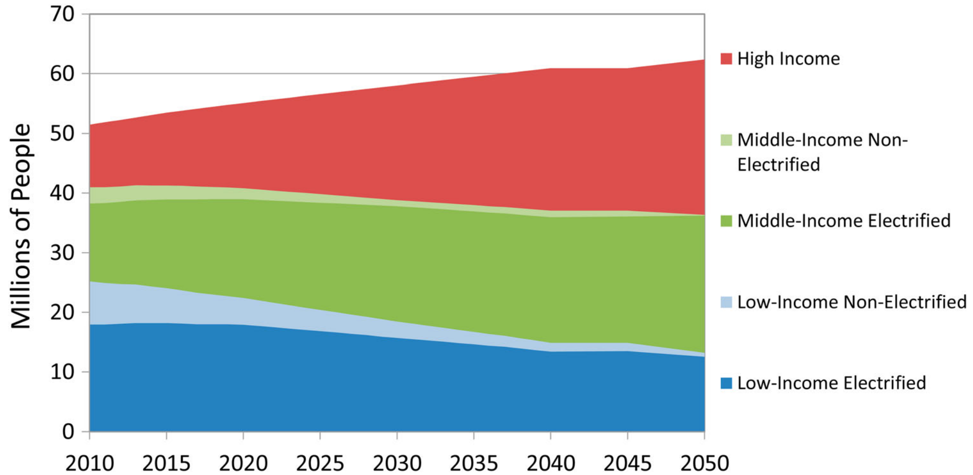

Figure 4 Household income groups and electricity access over time. These income brackets are chosen to represent the key changes in end-use technology choice and energy consumption that occur with changes in income (Energy Research Centre, 2013).

only slightly from 1.1% of the total in 2010 to 2.6% in 2050. In contrast, industry electricity consumption increases steadily over time from 0.42 EJ in 2010 to 0.79 EJ in 2050 and from 12.7% of total GHG emissions in 2010 to 33.7% in 2050.

The levelized cost of electricity generation doubles from 2010 to 2050 (from 0.056 $\$kWh^{-1}$ to 0.11 $\$kWh^{-1}$). However, the majority of this increase is inevitable given South Africa's need to build new generation capacity to meet industrial energy demand and replace the retiring coal fleet. The impact of the increase in electricity price on households in the lower income bracket can be mitigated. For example, generation costs account for less than half of household retail tariffs (Trollip & Tyler, 2011) and households that consume less electricity pay lower tariffs. One of the most successful post-apartheid policies in South Africa is the requirement that basic services are extended to all citizens. This has increased the percentage of households connected to electricity from 35% in 1994 to 87% today (Marquard, Bekker, Eberhard, & Gaunt, 2007). The free basic electricity policy provides 50 kWh of electricity per month to all eligible households. In addition, there is a progressive tariff structure whereby low-income households pay subsidized electricity tariffs whereas high-income households pay a tariff that is significantly more than the cost of electricity supply (Trollip, Walsh, Mahomed, & Jones, 2012). The much smaller proportion of households below the poverty line in 2050, 18% as opposed to 49% in 2010, will improve the sustainability of these existing policies by reducing the percentage of the population reliant upon cross-subsidies for basic electricity needs.

The structural shifts in the economy induced by growing low-carbon and high-labour absorbing sectors result in an increased uptake of labour into the economy by 2050 (Figure 5). The unemployment rate increases until it peaks in 2030 at 30%, and then declines rapidly from 2030 through to 2050. This initial increase in unemployment is driven by the youth wage bulge joining the labour force (Figure 5) and the lack of new jobs to support the increase in the size of the working population.

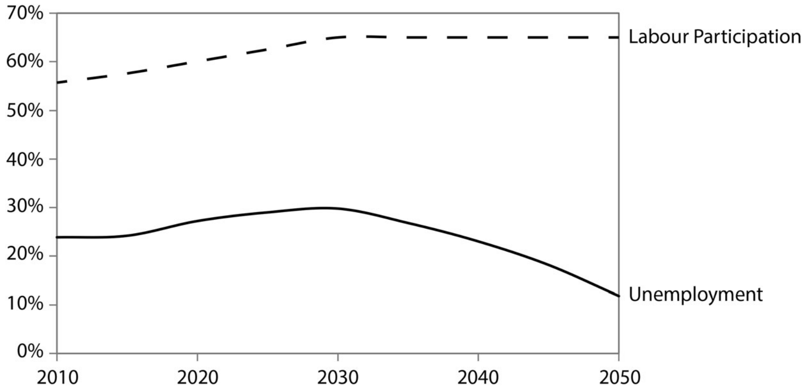

Figure 5 Labour force participation rate and unemployment rate over time as calculated from the quantity of labour demanded in the e-SAGE CGE model.

In addition, the increased saving assumption has a temporary and negative effect on consumption. Once the savings matures, it has a positive impact on unemployment. Unemployment is a key development indicator; however, if the unemployment rate falls to zero by paying everyone a wage well below the poverty line, it is not a successful development outcome. For unskilled labour, wages increase by 45% from 2010 to 2050, and for low-skilled labour they increase by 160%. In 2010, there were 5.7 million employed unskilled labourers, and this category is largely where employment is gained; the number of unskilled labourers employed increases by 170% from 2010 to 2050. In contrast, the number of semi-skilled and skilled labourers employed increases by 29% and 24%, respectively.

Overall, the reduction in unemployment in this work is much smaller than the goals of the NGP and NDP, which is similar to other modelling results (Cilliers, 2015). The NGP plans to incentivize labour absorbing industries such as agriculture, light manufacturing and services and aims to reduce unemployment to 15% by 2020. The NDP is even more aggressive with the goal to reduce unemployment to 14% by 2020 and 6% by 2030. Though unemployment is reduced from 25% to 12% in this scenario, there is a short term period of increased unemployment and the 2050 values do not bring South Africa within the averages of other middle-income countries (5-7%) (Black, 2012).

4. Discussion

The reduction of unemployment in the model relies heavily on agriculture absorbing unskilled labour. Currently, agriculture is dominated by large-scale commercial farming. There are two mechanisms to absorb unskilled labour in agriculture via increases in (1) small-holder farming practices, and (2) state funding to incentivize increases in labour demand via tax breaks or labour subsidies as agricultural practices advance. Agricultural growth is driven by increased competitiveness of South African agricultural products on the global market, which could be accomplished through domestic subsidies, a relaxing of other countries' subsidies, or an increase in the size of receiving markets. This is consistent with the Industrial Policy Action Plan (IPAP) (Department of Trade and Industry, 2014), which includes a focus on the primary productive sectors of the economy such as agriculture, though the IPAP suggests agro-processing as a means to increased agricultural productivity. Job growth in the agricultural sector has different impacts on society than job growth in industry. Agricultural jobs tend to be spread out across the country, which impacts urbanization, as well as rural development, all areas for further research. Given that South Africa is a water scarce country, the assumption that water does not constrain agricultural growth may not hold without additional investment in more advanced irrigation infrastructure.

An important result of the linked modelling is that GDP growth in key areas of industry and commerce remains strong. The IPAP promotes labour-absorbing industries with a particular emphasis on tradable labour-intensive goods and services. Interestingly, output and job growth in industry, particularly manufacturing and mining, has been static or declining in South Africa in recent years (World Bank, 2015a). This is in spite of clearly outlined industrial policies such as the Beneficiation Strategy (Department of Mineral Resources, 2011), the IPAP (Department of Trade and Industry, 2014) and the Mineral and Petroleum Resources Development Act (Department of Mineral Resources, 2002). Despite a policy focus on the importance of increasing labour absorption and trade openness, a disconnect remains between policy goals and de facto policy implementation. In addition, many aspects of these policies are clearly not in line with South Africa's GHG mitigation policy targets, resulting in strategic uncertainty across sectors (Trollip & Tyler, 2011).Thus, our results suggest that a change in policy is not necessarily required to improve development outcomes, but that further research is required to identify the barriers preventing policy implementation, coherence and effectiveness.

Our results show that maintaining a feasible energy supply system to meet the growing needs of industrial, commercial and residential sectors while meeting an energy emissions constraint requires significant decarbonization in the electricity sector. The widespread use of PV on commercial and residential properties, as well as additional CSP capacity, are plausible given South Africa's vast solar radiation resources (Fluri, 2009). A 100 MW CSP plant came online in South Africa in 2015, with an additional 1000 MW in the development and planning phase and 3300 MW allocated under the IRP update. The third phase of the Renewable Energy Independent Power Producer Programme (REIPPP) saw CSP tariffs decrease by 50% from the first phase, bringing projects in line with traditional fossil-fuel generation tariffs. As a result, solar technologies are poised to make a large contribution to the decarbonization of electricity supply in South Africa given the technical feasibility, commitment in stated policy and currently competitive tariffs. In addition, on-shore wind has seen increased uptake in South Africa over the past three years as a result of the REIPPP. The actual capacity factor of wind farms in South Africa is exceeding expectations and has been as high as 38%.

It is important to note that the current cost trade-offs between wind, solar and nuclear technologies are small. This study has implemented one fuel mix for electricity generation, but other combinations of low-carbon electricity are possible and deserve further study. The exact composition of this transition to a decarbonized electricity supply system will influence the associated grid expansion and changes in end-use technology. The decarbonization of the electricity system encourages other sectors to increase reliance on electricity as energy demands can be met without resulting in increased GHG emissions. This, alongside the increased mobility of a wealthier population, provides an opportunity for a large-scale switch to alternative transport fuels and the use of electric, hybrid and hydrogen vehicles, which could lead to additional reductions in GHG emissions from the transport sector that should be investigated in future work.

The model results suggest that improvements in development metrics can be achieved over time while following the PPD GHG emissions trajectory range (Department of Environmental Affairs, 2015). This work highlights the key interactions among economic, development and climate policies that must be explored when attempting to achieve multiple climate and development goals.

Acknowledgements

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Notes

1. The 544.3 Mt CO_2e includes agriculture, hence only FOLU is denoted separately and for consistency with the South African National Greenhouse Gas Inventory, 2000–2010.
2. Capital accumulation is determined endogenously based on the previous period investment levels. New capital is allocated to sectors based on their relative profit rates. Once invested, capital becomes sector-specific. At the macro-economic level, nominal private and public consumption and investment spending are assumed to be fixed proportions of the total absorption and the real exchange rate adjusts to maintain an exogenously determined current account balance.
3. Energy is considered to be an intermediate input and the interaction between intermediates and factors is governed by a Leontief production function. To decrease the rigidity of using a Leontief production function, there is 'response elasticity' that governs the amount sectors that are able change their energy inputs by per unit of output, based on energy prices.
4. TIMES is a well-established partial equilibrium optimization energy modelling platform that was developed by IEA-ETSAP (http://www.iea-etsap.org) and is widely used by a large number of countries for energy planning and analysis.
5. Ideally a single version of SATIM (-F) would be used together with e-SAGE to ensure consistency between the two models across the whole energy sector, but this version of the linked model is still under development.
6. See Department of Agriculture, Forestry and Fisheries figures for export in agricultural, forestry and fishery products from 1996 to 2014, http://www.daff.gov.za/daffweb3/Branches/Economic-Development-Trade-Marketing/International-Trade.
7. The IRP analysis only extends through to 2030 (Department of Energy, 2013).
8. The learning is a result of global installed capacity, assuming that South Africa is a price taker for the power generation technologies. It is possible that with large share of localization in the manufacture of power plant equipment that further learning would be observed as installed capacity increases.

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