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Modelling the costs of constraining the transition to renewable energy in South Africa

Bruno Merven, Faaiqa Hartley, Sherman Robinson and Channing Arndt

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Southern Africa –Towards Inclusive Economic Development (SA-TIED)

SA-TIED is a unique collaboration between local and international research institutes and the government of South Africa. Its primary goal is to improve the interface between research and policy by producing cutting-edge research for inclusive growth and economic transformation in the southern African region. It is hoped that the SA-TIED programme will lead to greater institutional and individual capacities, improve database management and data analysis, and provide research outputs that assist in the formulation of evidence-based economic policy.

The collaboration is between the United Nations University World Institute for Development Economics Research (UNU-WIDER), the National Treasury of South Africa, the International Food Policy Research Institute (IFPRI), the Department of Monitoring, Planning, and Evaluation, the Department of Trade and Industry, South African Revenue Services, Trade and Industrial Policy Strategies, and other universities and institutes. It is funded by the National Treasury of South Africa, the Department of Trade and Industry of South Africa, the Delegation of the European Union to South Africa, IFPRI, and UNU-WIDER through the Institute's contributions from Finland, Sweden, and the United Kingdom to its research programme.

Corresponding author: ifpri@cgiar.org

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ABSTRACT

For decades cheaper and easily available fossil fuels have underpinned the energy system of South Africa and inhibited the potential for achieving a sustainable low carbon economy. Favourable developments in renewable energy technologies and falling prices provide an opportunity for the country to reduce its emissions significantly without sacrificing economic development. This paper assesses the technical potential for expanded use of renewable technologies in electricity production and the economic impact of a transition to renewable energy in South Africa. The paper compares two possible energy pathways for the country, both of which respect South Africa's aggregate emissions commitments under the Paris Accord. In one scenario, investment in renewable technologies is constrained and, in another, it is not. Our findings show that, under the unconstrained investment scenario, renewable energy technologies would become the largest least-cost contributor to electricity generation in the country over the next two decades. At the national level the shift to renewable energy would have a net positive impact on real GDP and employment, with gains shared widely across the economy. Under both scenarios, there is a decline in coal mining that requires policy attention to mitigate the negative impacts on employment and regional incomes.

1 INTRODUCTION

The global power sector is changing rapidly as a result of rapid technological advance, particularly in renewable energy, and of current or expected policies to mitigate greenhouse gas emissions. Since 2008, the solar module price index has fallen by, roughly, a factor of about five, and the price of wind power has declined by a factor of about two. Gains in systems integration, especially the ability to accommodate variable renewable energy supplies on a system-wide basis, are not as easily quantified, but also appear to have been rapid. With these advances, the economics of power systems are changing. Global power generation investments are now about twice as large for renewables as for fossil fuels (Arndt et al, 2019).

South Africa has a coal-based energy system, which has been in the past a source of abundant and cheap energy. This coal-based system is ageing and, given climate and environmental concerns, there are good reasons for South Africa to embark on a transition to clean energy. Fortunately, South Africa is also well endowed in solar and wind energy resources (Ireland 2017). These resources, combined with recent and projected future improvements in wind and solar technology, offer South Africa a real opportunity to make the transition without compromising its other development objectives, such as poverty reduction and improved welfare. International studies (Inglesi-Lotz 2013; IRENA 2016) have shown that renewable energy and environmental conservation on the one hand and economic growth on the other are no longer mutually exclusive. There is a positive relationship between renewable energy adoption and macroeconomic indicators such as real gross domestic product (GDP), real per capita income, and employment. South Africa's energy-dependence on coal has, however, supported the coal-mining industry, which is concentrated in two provinces (Mpumalanga and Limpopo) and provides significant employment and income to people in these regions.

This paper contributes to the discussion on the energy transition in South Africa by both assessing the role of renewables in energy supply and quantifying the economy-wide impacts of changes in the energy system. The model framework hard-links two simulation models of South Africa: an engineering-based energy systems model (see Winkler et al. (2012) for an early application) and a dynamic computable general equilibrium model building on Diao and Thurlow (2012). The linked system deployed here was first described in Arndt et al (2016). Similarly to Lanz and Rausch (2011), the linking in Arndt et al related only to the electricity sector. This paper differs from other studies in that it: (1) considers the impacts of technology developments in the full energy system, not only the electricity sector; (2) assesses the economic and development impacts in an economy-wide economic simulation model that includes assessment of the impacts in specific sectors such as coal-mining; and (3) does both in a consistent modelling framework that incorporates behavioural responses to changing prices (i.e. fuel-switching, efficiency gains and volume changes) in both the energy system and economy-wide markets.

2 A LINKED SYSTEM OF ENERGY AND ECONOMIC MODELS

Energy-planning and economic analysis have often been done independently or through soft linkages in which energy information derived from an energy system model is passed to an economic model to assess the effects on the economy. For example, the Times energy model includes a simplified economic model- to make benefit-cost analysis of energy projects (Loulou et al, 2005). The economics in Times neglects broader links through commodity and factor markets between the energy sector and the rest of the economy. These are important, because the general equilibrium impacts of energy transitions are large. On the economics side, there are many examples of economic simulation models that include a simplified representation of the energy sector. As shown by Lanz and Rausch (2011), these representations of the energy sector are often hardly recognizable by specialists in energy systems. For example, Lanz and Rausch (p. 1035) find that "widely used top-down representations of electricity technologies produce fuel substitution patterns that are inconsistent with bottom-up cost data."

The approach taken in this paper is to build a system of two hard-linked models, one of the energy systems and a second of the national economy. The energy model is a bottom-up integrated energy systems model called SATIM (South Africa Times Model) that includes electricity production by thermal, nuclear, solar, and wind technologies (ERC 2015). The simple benefit-cost analysis in the standard Times model is not carried over to the economic model. The economic simulation model is a dynamic recursive, economywide, multisector, computable general equilibrium (CGE) model, called eSAGE (Energy South Africa General Equilibrium model) built on the framework from Diao and Thurlow (2012). As already noted, Arndt et al. (2016) detail the linking with respect to the electricity sector. The linked system is called the SATIMGE model.

A major advantage of building a linked system of two separate models is that they can be run independently, and so be developed, tested, and validated separately by experts in the two disciplines of energy engineering and economics. By combining these detailed models of different aspects of the country, SATIMGE captures both the technical detail needed for full energy systems modelling and economic detail for assessing the impact of changes in the energy system on various sectors, markets, and agents in the economy.

The challenge in working with a modular system of independent models is to specify how they are linked. Soft linking would involve passing information in one direction—for example, from the energy model to the CGE model—with no or very limited feedback to the energy model. That approach is a viable first pass but fails to capture important feedbacks from the economic model to the energy model. Similarly to Lanz and Rausch (2011), SATIMGE runs the linked models iteratively, passing information in both directions within the annual time step of the CGE model.

The iterative process (see Figure 1) mimics South Africa's electricity sector planning process, in which energy investment and pricing decisions are taken. New energy and electricity investment are determined by the Department of Energy, with updates expected every two years (DoE 2011), while electricity prices are set by the National Energy Regulator of South Africa. Given initial sector and household income growth projections for a particular year, SATIM is used to compute the least-cost energy technology mix, resulting investment plan and electricity cost price. This information, along with information on fuel efficiency and fuel-switching, is passed to eSAGE, which is run for that year to incorporate the new energy supply and demand composition.

In addition, aggregate investment is determined in eSAGE by assuming a macro adjustment process where any changes in aggregate final demand are shared proportionally across the macro aggregates: consumption, investment, and government spending on goods and services. This process determines the pool of investable funds. Electricity investment is first allocated from this pool. Other sectors in the economy then compete for the remaining funds. This arrangement ensures that the opportunity costs of investment between sectors are captured within the modelling framework. The run of eSAGE incorporates all this information and the solution provides a new set of projections of economic variables.

These updated sector and household income growth projections are then passed back to SATIM which optimizes again based on this new information. This iterative process continues until the overall model converges such that energy utilization (and associated CO_2 emissions) in both models are aligned and internally consistent in terms of demand, price and production mix. In effect, SATIM is used to generate a rolling energy investment plan, reoptimizing annually as the eSAGE model updates economic variables.

The refining sector is treated in a similar way to the electricity sector, except that in the current formulation liquid fuel prices are not imposed, nor are capital increments. The SATIM and eSAGE models are calibrated based on the 2012 energy balance and social accounting matrix (van Seventer et al. 2016) respectively.

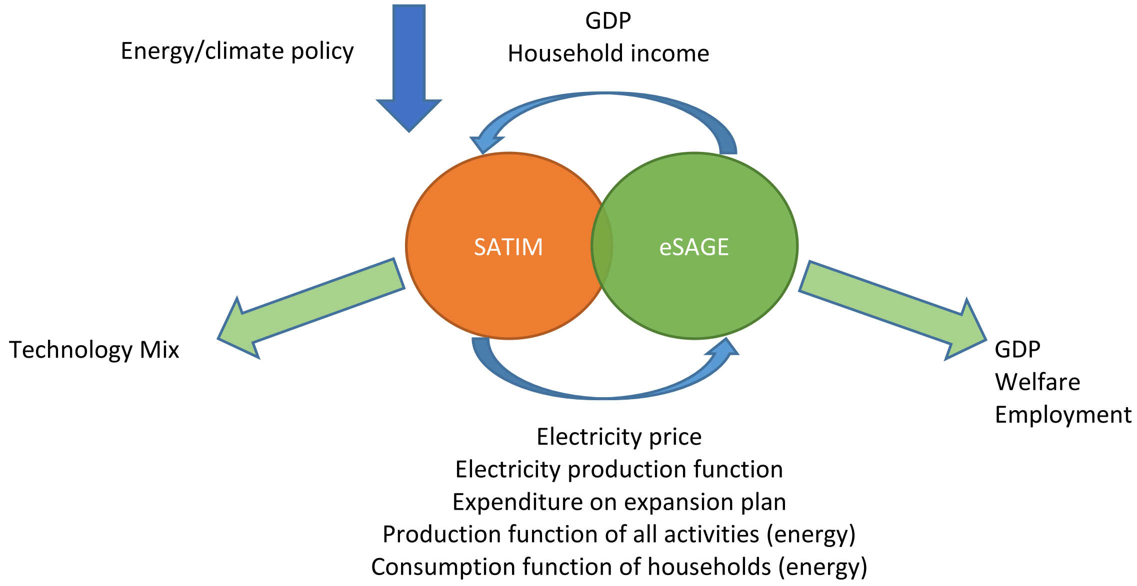


Figure 1: Iterative approach used in SATIMGE

3 SCENARIO ANALYSIS

Two scenarios are specified to assess the potential impact of renewable technology developments on the electricity system (within the larger energy system) and economy. The first scenario (CONALLRE) considers the optimal energy mix for meeting South African demand at least cost, given constraints on investment in renewable capacity as currently specified in national planning (DoE 2016). Specifically, additions to solar PV and wind capacity are respectively capped at 1 GW and 1.8G W per annum. A 15% restriction is also placed on the share of peak demand met by distributed renewable energy. The second scenario (UCONRE), assumes no constraints on investment in renewable energy capacity, freeing economically justified investment to flow into renewable energy projects. Conservative cost estimates, provided by Ireland and Burton (2018), are specified for solar PV and wind technology. In both scenarios, available technologies and costs are the same—the two scenarios differ in the constraints placed on investment in renewables. Additional scenarios using more optimistic cost projections are also run and briefly presented in the results section.

The existing stock of technologies (e.g. power plants, refineries, vehicle parc), and committed to build to 2022, are included in the SATIM model, with existing power plants retired as specified by national government energy plans (DOE IRP 2016). Technology costs are aligned to projections used in those plans (DOE IRP 2016), except for renewable energy costs, which have been updated as per Ireland (2017).

In both scenarios, energy sector CO_2 emissions are constrained to meet South Africa's mid-PPD commitment (RSA 2011), using a cumulative CO_2 constraint over the entire energy sector, leaving the least cost path determined by the model to allocate sector emissions trajectories. Demand profiles for all end-uses are assumed to be fixed over time. Fuel-switching for thermal and transportation energy services is allowed. The overall demand profile seen by the grid will vary over time because of differing growth rates by different sectors, fuel-switching to and away from electricity, and distributed generation and storage installations. System adequacy is insured by imposing an overall reserve margin of 15% of firm capacity over peak demand. Thermal plants (including concentrating solar power with storage), hydro, pump storage, and batteries are given a full capacity credit. PV is given no capacity credit. Wind is given a 15% capacity credit. PV and wind profiles are aggregated to the eight time-slices used in this model. from the profiles used in Wright et al. (2017) and Reber et al. (2018). Coal- and nuclear-based technologies are given limited flexibility in that they are not permitted to vary their output during the day.

In the baseline economic path, real GDP growth in the CGE model is targeted to follow actual growth between 2012 and 2017, whilst growth between 2018 and 2022 is calibrated to projections from the National Treasury and International Monetary Fund. Longer-term growth projections are aligned to meet the Department of Energy's planning growth rate of 3.2% to 2050. The structure of the economy does not shift dramatically, although the share of mining in gross value added (GVA) decreases, while the shares of agriculture and manufacturing increase marginally. The trend supply of labour is assumed to increase in line with population growth of ~0.56% (UNEP 2016) and, in addition, there are upward-sloping labour supply curves around this trend as a function of wages for all skill categories, so aggregate employment is affected by changes in wages.

Government spending increases by 3% per annum, essentially following GDP growth. Foreign savings increase initially at 3% per annum, with this rate decreasing over time as debt is repaid. Total factor productivity is calibrated to achieve the 2016 Draft IRP moderate growth forecast. Adjustment of macroeconomic aggregates are aligned to the stylized facts for South Africa. Aggregate investment increases with GDP, and the balance of trade is set exogenously (with a flexible exchange rate adjusting to achieve equilibrium). As noted above, investment in the electricity sector is set by the energy model, and remaining investible funds are allocated across sectors with higher shares going to more profitable sectors. Within periods, existing capital is assumed to be fully employed and activity specific. Various elasticity parameters used in the CGE model are based on the most recent published estimates for South Africa: income elasticities of demand (Burger et al. 2015); elasticities of substitution between domestically produced and trades goods or Armington trade elasticities (Saikonnen 2015); and factor substitution elasticities in production (Kreuser et al. 2015).

3.1 Unconstrained investment scenario: the role of renewables in power generation

In a least-cost optimization scenario, in which investment in renewable energy is not constrained (UCONRE) but South Africa's commitments under the Paris accord are maintained, grid-based generation capacity shifts from being coal-dominant to renewables-dominant by 2030, with only the recently constructed Medupi and Kusile coal plants left in the system by 2050 (Figure 2). New capacity additions of wind and solar are 65 GW and 55 GW between 2025 and 2050 (some of which retire during the period) with smaller additions of 3 GW and 37 GW of batteries and gas also taking place. This new capacity requires investment of ZAR 229.9 billion over the period. While this investment is large, it is feasible and has already been observed in other parts of the world, such as Germany and the UK. Very little new investment is made before 2025, as the system remains in excess capacity.

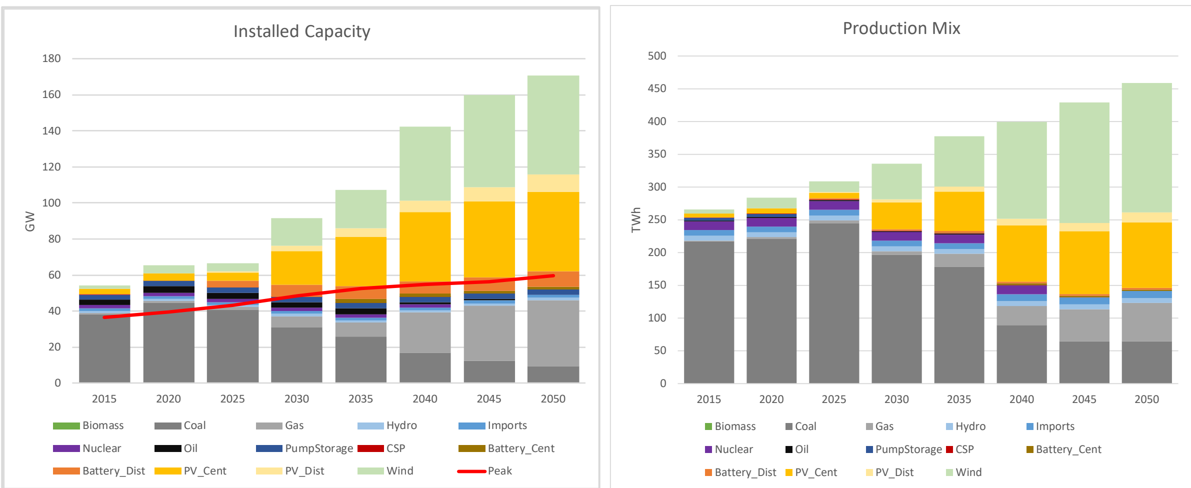


Figure 2: Total installed capacity and production in the electricity sector

The renewable energy share of generation grows to around 68% in 2050. The high renewable energy share from 2040 onward is feasible because of highly complementary solar and wind resource profiles and the use of flexible gas generators and storage technologies in hours of low wind and solar resource availability. The remaining coal and nuclear stations provide a steady supply. These results are comparable to Wright et al. (2017) [1] and Reber et al. (2018), although in the latter more wind and gas and less PV and storage capacity are used. For the electricity sector, both studies do extensive adequacy testing at very high temporal resolution. The renewable energy share, both in terms of capacity and production, obtained here is not significantly higher than in these studies, which provides confidence that the capacity expansion plan from the SATIM model would also be feasible and meet system adequacy requirements.

3.2 Unconstrained investment scenario: reduced South African CO_2 emissions

Increased renewable energy deployment decreases CO_2 emissions in the power sector from 250 Mt per annum in 2015 to less than 100 Mt in 2050 (see Figure 3), with its share in overall energy sector emissions declining from around 55% to 28%. Overall emissions in the energy system decline, indicating the advantage of investing in mitigation directly in the power sector relative to changing power demand in other sectors (e.g., transport, industry, commerce).

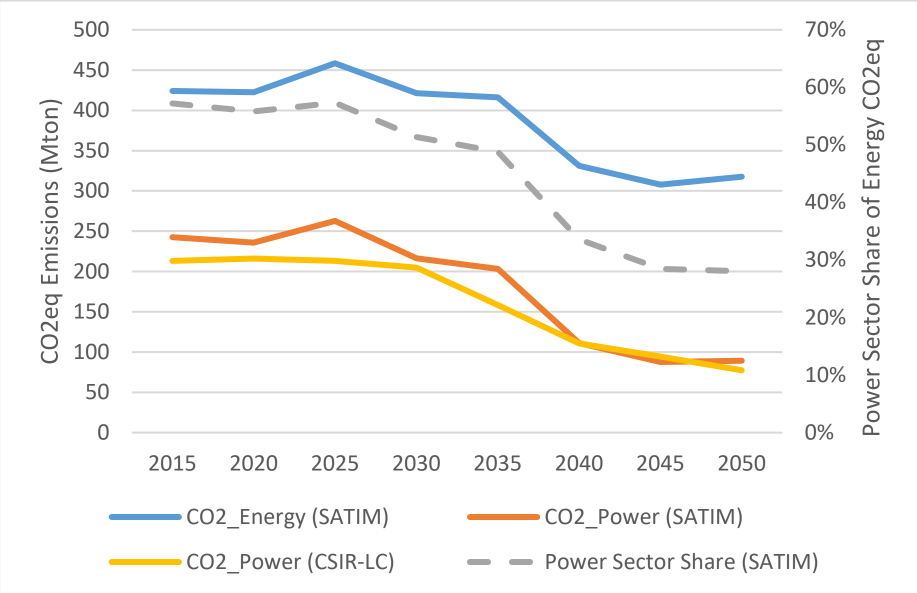


Figure 3: CO_2 Emissions from the energy system and power sector

3.3 Constrained investment scenario: increased costs of power generation

Imposing annual build constraints on solar PV and wind capacity, following government planning objectives, decreases solar PV and wind capacity included in the energy system by 50% (Figure 4), with the gap in capacity covered by 800 MW of solar CSP and 6 GW of nuclear, to help meet the CO_2 constraint; and an additional 10 GW of coal to replace gas. This investment programme results in a higher electricity price (14% higher in 2050) and a lower demand for electricity. Nuclear and coal plants run at a higher capacity in this scenario, which explains why total installed capacity is less, despite using the same demand drivers.

[1] More specifically the Least cost (Low demand) scenario, where demand is more comparable to that in SATIM.

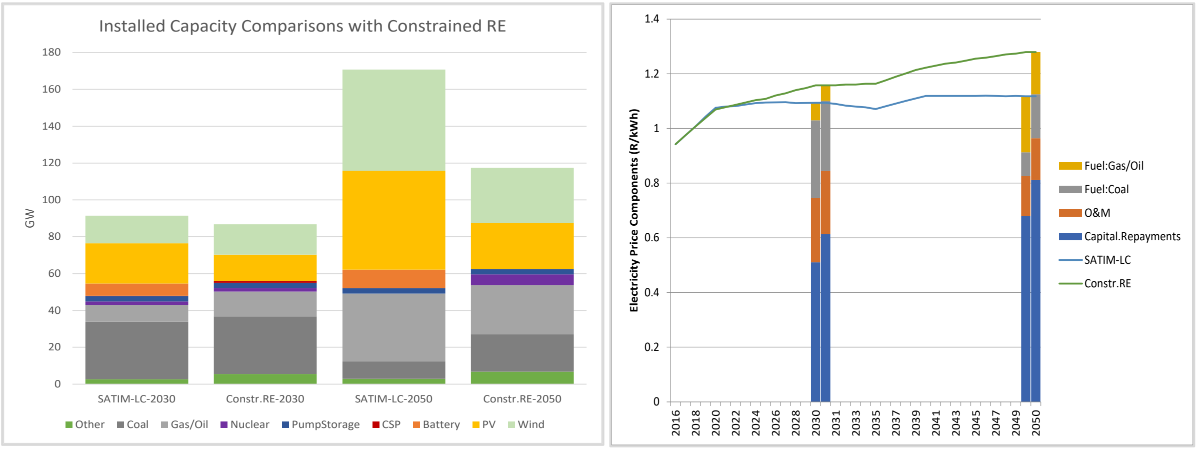


Figure 4: Comparison of total installed capacity and electricity price components

3.4 Unconstrained investment scenario: real GDP and employment are higher

On aggregate, the increased deployment of renewable energy in the unconstrained scenario results in higher levels of real GDP and employment compared to the constrained scenario (Figure 5). The increase in real GDP is driven by the lower overall level of investment in energy capacity required over the period—cumulative investment in energy capacity is 9.2% lower in the unconstrained case—and the lower electricity price.

Given that in eSAGE aggregate investment in the economy is fixed as a share of total absorption, the lower level of investment in energy capacity required in the unconstrained scenario means that more investment funds are available for the expansion of other sectors in the economy.

The lower electricity price has spillover effects, supporting economic growth in other sectors as it decreases production costs and increases profitability. By 2030 and 2050, the electricity price is respectively 6% and 20% lower in the unconstrained scenario. Lower electricity prices also increase household disposable incomes, resulting in increased real incomes of consumers and increased consumer demand for goods and services.

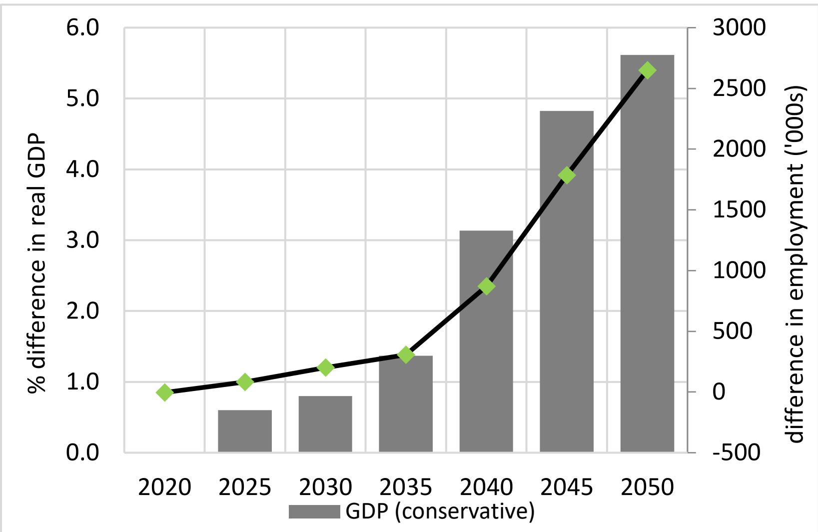


Figure 5: Real GDP and employment impacts (five-year intervals)

The expansion in activity in the economy increases labour demand, raises wages, and increases employment. Net employment increases by 0.8% and 5.5% by 2030 and 2050 respectively. This result, however, assumes that the labour supply can expand to meet demand, which is a reasonable assumption for South Africa, which is characterized by under-employment. The constrained scenario generates slower labour demand growth, as higher electricity investment requirements crowd out expansion in other sectors of the economy. The increase in employment in the unconstrained scenario is largest for the secondary (Grades 10-12) and tertiary (post Grade-12) educated labour groups, although employment opportunities are also created for lower-educated workers, i.e. primary and middle school educated labour (< Grade 10) (Figure 5).

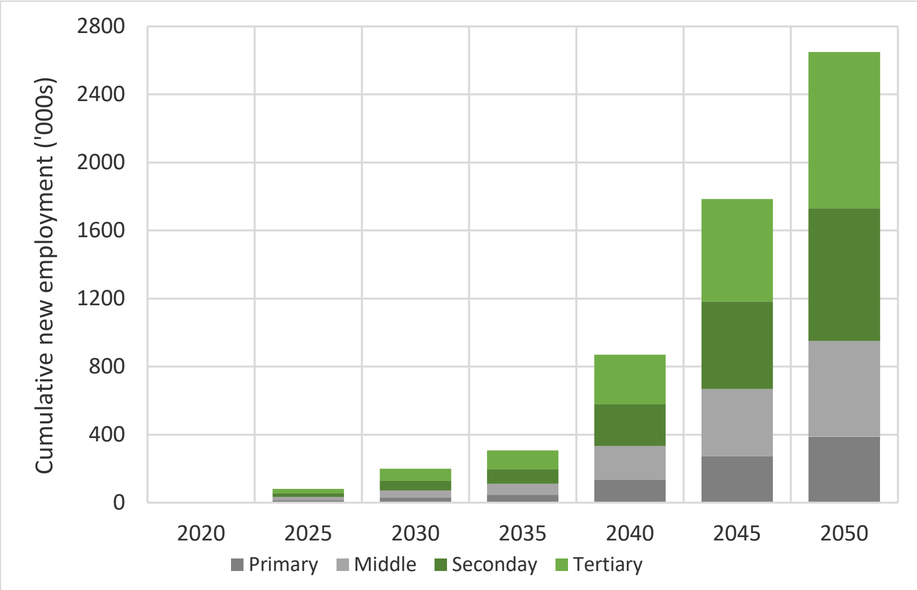


Figure 6: Employment impacts by skill level (five-year intervals), unconstrained scenario

Household welfare, measured by real household consumption, is also larger in the unconstrained scenario. By 2050, real household consumption is 6% higher, with similar increases experienced by poor and non-poor household groups. The increase in welfare is driven by increased income from labour and capital as well as from lower electricity prices. Welfare increases for both poor and non-poor households (slightly higher for the non-poor).[2]

3.5 Broad economic benefits (unconstrained scenario), coal-mining decreases (both scenarios)

Figure 8 presents the sectoral GDP and employment impacts of an increase in renewable energy investment. As shown, economic activity increases widely, including the total mining sector, despite declines in coal-mining. Coal-mining production decreases in both scenarios, with export demand declining (to ~40 MT in 2050 from a peak of 92MT in 2030) as global demand for coal decreases because power production shifts away from fossil fuels toward cleaner energy technologies, and as rail infrastructure limits export capacity (Transnet 2017). The decline in coal production is also driven by a decline in domestic power sector demand. In the unconstrained scenario, coal demand from the power sector falls from 120 MT in 2012 to 72 MT in 2030 and 24 MT in 2050 (constrained scenario: 101 MT (2030); 48 MT (2050)). Demand for high quality coal used by other sectors, especially industry, increases due to increased demand for process heat (Figure 7).

2 Poor households are defined as those in income deciles 1 to 4 and non-poor households are defined as those in income deciles 5 to 10.

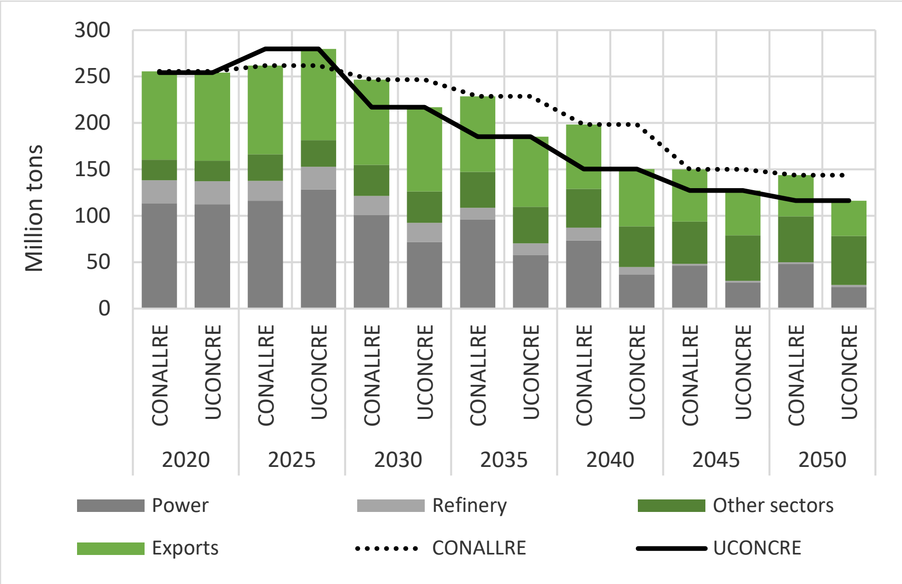
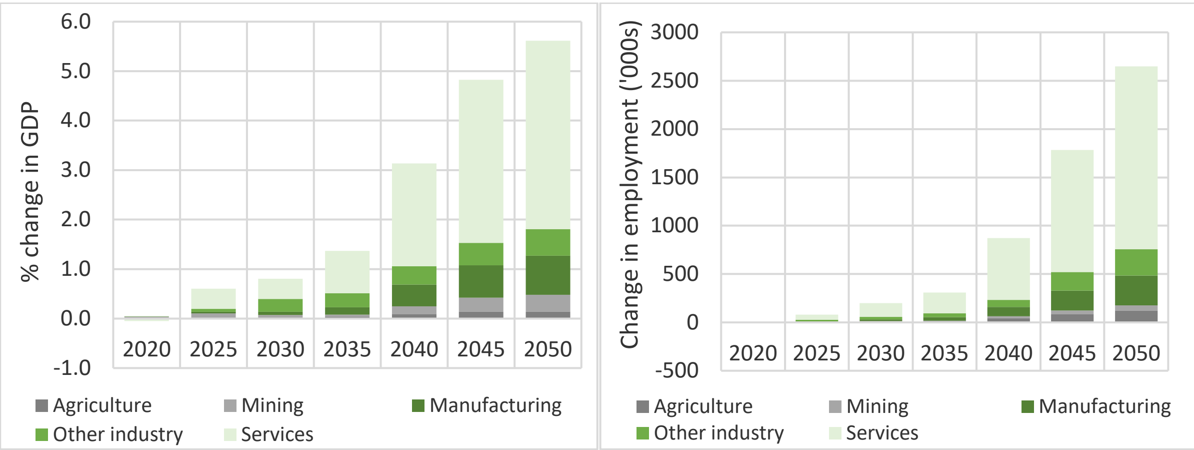


Figure 7: Coal demand (excluding residential, five-year intervals)

Figure 8 shows sectoral contributions to changes in GDP. Growth is highest in the services and electricity sectors. In the service sector, growth is driven by financial and business services, and transport and communication. Real GVA (gross value added) in the electricity sector increases due to increased demand: by 2050 electricity demand is 3.3% higher in the unconstrained scenario. Employment is largely driven by increased jobs in the services sector. The manufacturing sector creates the second largest number of jobs followed by the electricity sector. Job creation in the electricity sector is partly driven by the higher employment intensity of solar PV and wind generation per GWh relative to coal.



Note: Electricity sector included in Other industry

Figure 8: Sector contributions to the change in GDP and employment (five-year intervals)

3.6 Sensitivity analysis: optimistic trends in solar PV and wind costs

The assumptions included for PV and wind costs used in the two scenarios could be considered conservative (Ireland and Burton, 2018). Another set of scenarios were modelled using more optimistic cost estimates for PV (costs drop to USD 0.4/W by 2050 instead of USD 0.7/W) and improvements in wind capacity factors (the wind capacity factor of new installations increases from 40% to 55% by

2050).[3] Under these assumptions, the investment gap between a constrained and unconstrained investment scenarios is larger (i.e. ZAR 27.5 bn versus ZAR 23.2 bn). The deviation in the electricity price is also larger, being almost ZAR 0.18/kWh lower in the optimistic unconstrained scenario versus ZAR 0.16/kWh in the conservative unconstrained scenario. Under these conditions, the impact on real GDP and employment are also larger (real GDP: 6.4% versus 6.0%; employment: 6.1% versus 5.9%).

4 CONCLUSION

This paper shows that the sectorally detailed but temporally and spatially aggregated energy systems model (SATIM) can replicate the results obtained by two recent studies using more temporally and spatially detailed models of least-cost power systems for South Africa, while fleshing out broader economic implications. The paper explores the opportunity cost of constraining investment in renewable technologies, reflecting current policy. The impact of constraining renewable energy could be as high as 16c/kWh (in ZAR) by 2050, using conservative assumptions on renewable energy and 18c/kWh, using more optimistic renewable energy costs.

The study also highlights that a shift to increased renewable energy generation will have a positive impact on real GDP, employment, and real household income in South Africa. These gains are substantial, in the range of 5-6%, when comparing the unconstrained scenario with the constrained one. The net positive gains from unconstrained investment in renewable energy capacity are experienced broadly across sectors in the economy, with the electricity and services sectors gaining the most.

These increases in GDP, employment and real household income are principally the result of a lower electricity investment requirement, which expands investment in other sectors and lowers electricity prices. More optimistic renewable energy cost trends, which are certainly possible and may be likely, are shown to have an even larger positive impact on real GDP, employment and welfare.

These positive impacts depend, however, on the availability of labour resources required for the transition—primarily workers with at least a Grade 12 level of education. Lack of a supply response to increased labour demand over the next 30 years would reduce the positive impact of increased renewable energy deployment as sectors compete for labour, resulting in rising production cost structures and prices, which would lower demand.

Coal-mining declines in both scenarios, but the decline is larger in the (more macroeconomically favourable) unconstrained scenario. A shift in production to high quality coal for increased industry demand provides some support to the sector. The negative impact on the coal-mining sector, which is highly likely regardless of investment in renewable energy (given rail capacity constraints, lower expected global coal prices, and lower global coal demand), should be managed and mitigated as far as possible, particularly in areas where coal-mining is the primary employer and source of income. The impact of expected changes in the coal-mining sector at the provincial and community levels requires further research. The economic modelling framework in this study assumes a limited ability to switch from low- to high-quality coal-mining without incurring any additional costs. Further research is required in this area, including research on the cost structures of low- versus high-quality coal.

While a decline in coal-mining production and employment is probable, other opportunities may be on the horizon for the South African mining sector. The global increase in demand for electric vehicles. and hence for batteries, has increased the demand for metals such as cobalt, copper and nickel. While these are currently not large mining sub-sectors in South Africa, the potential (including natural resource availability) does exist for these sub-sectors to be expanded. Further research is required on

[3] Note that the SATIM uses "vintaging" of technologies, in that a wind plant built in 2020 would will retain the 2020 capacity factor throughout its life. A CF of 55% would be for plant built in 2050, not the average for all wind turbines built by then. Solar PV costs projection are based on "Scenario 3" of (Fraunhofer ISE, 2015) and wind costs and capacity factor improvement assumptions are based on (Weber et al & IEA, 2016).

the prospects of higher global demand for these metals and the impact on the South African mining sector.

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About the authors

Bruno Merven and Faaiqa Hartley are researchers at the Energy Research Center, Cape Town University, South Africa. Sherman Robinson and Channing Arndt are researchers at the International Food Policy Research Institute in Washington D.C., where Channing is the Director of the Environment and Production Technology Division.

INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE
A world free of hunger and malnutrition
1201 Eye Street, NW | Washington, DC 20005-3915 USA
T: +1.202.862.5600 | F: +1.202.862.5606
Email: ifpri@cgiar.org | www.ifpri.org