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Quantifying the macro- and socio-economic benefits of a transition to renewable energy in South Africa

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About the project

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

The SA-TIED programme looks at ways to support policy-making for inclusive growth and economic transformation in the southern Africa region, through original research conceived and produced in collaboration between United Nations University World Institute for Development Economics Research (UNU-WIDER), National Treasury, International Food Policy Research Institute (IFPRI), and many other governmental and research organizations in South Africa and its sub-region. A key aspect of the programme is to encourage networking and discussion amongst people involved in policy processes across the participating organizations and civil society aiming to bridge the gap between research and policy-making.

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Quantifying the Macro- and Socio-Economic Benefits of a Transition to Renewable Energy in South Africa

Part 1: The Energy Landscape

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ABSTRACT

Recent technical advances in renewable energy technologies are causing the contours of the global power sector to change. There have been dramatic gains in wind generation, PV generation, storage, and system integration. In 2016, global investment in renewables was roughly twice that in fossil fuel generation. South Africa, which has an energy system that is predominantly based on coal, is facing mounting international pressure to decarbonize. However, it needs to do so without compromising its other socio-economic objectives of energy access and poverty reduction. Fortunately, South Africa is well endowed with renewable energy resources and, given technological progress, this socio-economically acceptable decarbonization should be possible. This paper lays the foundation for the analysis of the macro- and socio-economic benefits of a transition in the power sector to be made using a linked energy-economy modelling framework called SATIMGE. SATIMGE is made up of an energy systems model, SATIM (South African TIMES Model), and a general computable equilibrium model of South Africa. Two recent studies by the Council for Scientific and Industrial Research and the National Renewable Energy Laboratory have demonstrated that the least-cost pathway for the power sector in South Africa is one with a significant role for renewable energy. These studies were done using detailed temporal and spatial models of the power sector in South Africa. This paper demonstrates that, although SATIM is temporally and spatially simplified, it produces similar least-cost future technology mixes to these models, and would thus provide a suitable platform for analysis using SATIMGE. The paper also quantifies the potential impact and resulting opportunity cost of not fully embracing the recent technology developments on the electricity price by limiting new investment.

Keywords: energy systems modelling, energy policy, electricity, renewable energy, energy economics

1 INTRODUCTION

The contours of the global power sector are changing rapidly, due to ongoing technological advance, particularly in the renewable energy space. Since 2008, the solar module price index has fallen by, roughly, a factor of five. Gains in wind generation technologies have been less dramatic, but rapid by almost any standard. Gains in systems integration, notably the ability to accommodate variable renewable energy supplies on a system-wide basis, are not as easily quantified but have also been substantial. With these advances, the economics of power systems are changing. Lazard Freres, a global investment bank, lists wind as the lowest-cost generation technology (unsubsidized) for the United States in its most recent (2016) analysis of levelized cost of energy. Utility-scale photovoltaics are not far behind, at about the same cost levels (again unsubsidized) as combined-cycle natural gas, which is the cheapest conventional generation option.

Global investments in power generation have reflected these shifts. In 2014, for the first time, the amount of new renewable generation capacity surpassed that of new fossil fuel-based systems, on a global basis. This trend continued in 2015, with new renewable capacity outstripping fossil fuels by a factor of more than two. Investment volumes are correspondingly large, with the amount of money committed to renewables (excluding large hydro-electric projects) reaching USD 286 billion in 2015. In 2016, estimated investment spending on renewables declined to USD 241.6 billion; however, the volume of installed capacity in that year increased by 9% as a result of lower per-unit costs. Overall, in 2016, global investment in renewables was roughly double that in fossil fuel generation.

South Africa has a coal-based energy system, which has been a source of abundant and cheap energy. This system is ageing and, given climate and environmental concerns, there are good reasons for South Africa to embark on a clean-energy transition. Fortunately, the country is also well endowed with solar and wind energy resources (Ireland 2017). This, combined with recent and projected future improvements in wind and solar technology, offers South Africa an opportunity to make the transition without compromising its other development objectives such as poverty reduction and improved welfare. Several recent studies including (Wright et al 2017; Reber et al. 2018) used detailed power sector models to show that it is technically possible and cost-effective for South Africa to make this transition, at least in the electricity sector. However, the macro and socio-economic implications of making the transition have not been quantified. The linked energy-economic model SATIMGE, developed by the Energy Systems, Economics, and Policy group of the Energy Research Centre (ERC) at the University of Cape Town is a suitable platform to do so. SATIMGE is made up of two main components: a full sector TIMES energy model of South Africa (ERC 2015), described below, and a dynamic recursive general equilibrium model of South Africa (eSAGE), (Arndt et al. 2011). The two components are linked via critical parameters which ensure internal consistency between the two models, as described in Arndt et al. (2014) and Merven et al. (2017). SATIM is based on principles similar to those of the expansion planning feature of the Plexos and NREL models used by Wright et al. and Reber et al. However, in SATIM, spatio-temporal detail is traded-off with sectoral detail, and all energy carriers are considered. Having the economic model linked to an energy model helps to ensure that the energy supply sector and the way that different demand sectors consume energy are technically plausible. Future projections for drivers for the energy model (sectoral GDP and household income) are also then internally consistent, given that they come from the CGE model.

2 OBJECTIVE

The objective of this paper is to show, by using similar assumptions and applying a few conservative constraints on reserve and dispatch rules, that the sectorally detailed but spatially and temporally aggregate energy model SATIM can replicate the least-cost technology mix seen in two recent studies by the Council for Scientific and Industrial Research and the National Renewable Energy Laboratory (Wright et al. 2017; Reber et al. 2018), which were done using more temporally and spatially detailed models. It draws from a previous paper (Ireland 2017) for most of the assumptions, and lays the foundation for evaluating the macro- and socio-economic benefits of embracing the technological developments using the linked energy-economy modelling framework SATIMGE.

3 METHODOLOGY AND APPROACH

The approach used to construct this future South African energy system is a least-cost optimization energy model like the ones used in other studies done on South Africa (DOE 2016a; DOE 2016b; Wright et al. 2017; ERC 2013; ERC 2015), more specifically a model developed at the ERC called SATIM: South African TIMES Model. SATIM has been in development over several years and has recently been calibrated to the 2012 energy balance, with some further calibration to 2015 (ERC 2015). SATIM depicts the full energy sector, as was done in DOE IEP (2016), as opposed to only the power sector as was done in DOE IRP (2016), Wright et al. (2017) and Reber et al. (2018). The advantage of using this type of model is that it captures interactions between supply and demand. It is also an end-use type of model, where demand is specified as a 'useful' energy demand or demand for energy services (e.g. heating, lighting, passenger-km), instead of final energy. The rationale for this approach is that demand for energy services is more strongly linked to demand drivers such as economic and population growth, income, etc, than to 'final demand' (demand for electricity and oil product, etc). An end-use model gives a detailed description of how energy is used and the types of equipment (technology) that are used to meet the useful demand. It can capture structural changes in the economy, as well as technology efficiency improvements and fuel-switching. It also allows for a more accurate representation of distributed energy resources technologies within each sector, such as embedded solar PV generation and behind-the-meter battery storage, with their associated interacting demand profiles.

The existing stock of technologies (e.g. power plants, refineries, vehicle parc), and committed build to 2022 provide the first building blocks for the model. From this point onward, an optimization algorithm is used to derive the technology and fuel mix that will minimize the total discounted system costs over the planning horizon (2015–2050), subject to imposed constraints. The main constraint is that the demand for energy services across all sectors must be met. For demands that can be met using electricity, a demand profile is specified to capture seasonal diurnal fluctuations. Other constraints include CO_2 emission limits, reliability constraint limits, operational limits, new technology penetration share limits, and resource limits both cumulative (coal/gas resource) and seasonal/diurnal (wind and solar profiles). The objective function (Net Present Value), is parameterized by unit capacity costs (investment costs and fixed O&M costs – ZAR/kW) and unit variable costs (ZAR/GJ). Once a technology is 'commissioned', it is available to the system for a finite number of years, and for a finite amount of time each year, given necessary planned and unplanned maintenance or seasonal/diurnal availability of variable resources such as wind and solar.

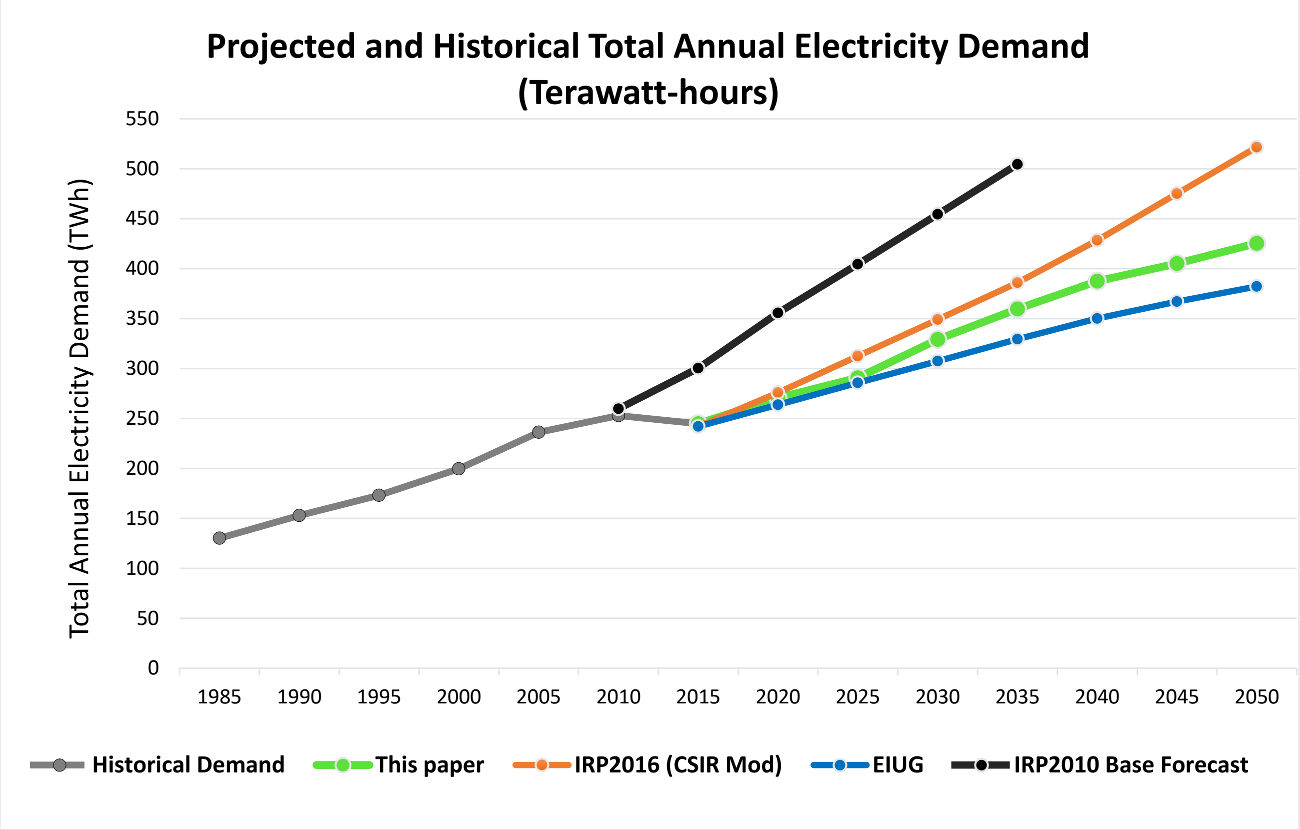
3.1 Assumptions

The version of SATIM used here is a TIMES model configured to run every five years from 2015 to 2050 (2012 is the main calibration year, with some adjustments made in 2015 based on the 2014 DOE energy balances). The global discount real discount rate is 8%. The currency unit is 2015 rands, converted in some cases from USD using a rate of ZAR 11.55 to the dollar as per DOE IRP (2016). The time resolution is quite coarse: two representative days, namely one for summer and one for winter, are modelled, using a total of eight time-slices.

3.2 Energy Demand

The starting point for this approach is a demand projection. The linked energy-economic model SATIMGE is used to generate the demand projection. Using the assumptions around growth in labour productivity, labour supply and global commodity price projections described in Ireland (2017) gives a GDP growth averaging 3.2% to 2050. The resulting electricity demand by 2050 is one that grows by around 75% relative to 2015, as shown in Figure 1. The graph shows how the projection compares to those made by other recent studies, and how the different sectors contribute to this growth. The transport sector grows faster than average as a result of the uptake of electric vehicles, and is the main contributor to the deviation from the Energy Intensive Users Group (EIUG) projection. The other sectors grow slower than GDP, due to the uptake of more efficient technologies as detailed in (ERC 2015).

Figure 1. Electricity Demand (Energy)



3.3 Existing and Committed Power Plants

Existing power plants are retired as specified in Ireland (2017) and DOE IRP (2016). Committed build includes the six units of Medupi and Kusile and the projects in the REIPPPP Bid Window 4 (expedited), as well as some peaking plants, and is summarised in Table 1.

Table 1. Technology Type and Committed Capacity of Power Plants

Technology Type	Committed Capacity (Net) [2013-2022] (MW)
Biomass/waste	10
Coal	8 660
Gas	500
Hydro	70
Oil	1 010
Pump storage	1 330
CSP	200
PV grid	4 260
Wind	4 490

3.4 New Technologies

New power generation technologies are parameterized as per DOE IRP (2016) and Ireland (2017). Some exceptions are highlighted in this section. The centralized solar PV and wind are parameterized so as to replicate the ZAR 0.62/kWh observed in the REIPPPP Bid Window (BW) 4 (expedited) from 2020 onward. The investment cost for centralized fixed tilt solar PV is assumed to continue to decrease from around USD 1.0/W in 2020 to USD 0.7/W in 2050. Given that these costs are already observed, this assumption can be considered to be conservative.

The panel costs are assumed to be the same for single axis tracking centralized PV and for distributed PV, but the balance of plant costs is assumed to vary in fix proportion, as detailed in Table 2.

Table 2. Plant Costs by PV Category

PV Category	Balance of Plant Premium (compared to fixed tilt utility)
Single axis tracking	16%
Commercial/industrial	14%
Residential	109%

Wind costs and availability are assumed to be constant from 2020 onward at USD 1.5/W and 40% respectively.

Battery costs are taken from Lazard (2017) and assumed to vary from USD 305/kWh in 2020 to USD 140/kWh in 2035 for grid-based systems, staying flat thereafter, and are adjusted by a factor of 10% for distributed systems.

3.5 Fuel Prices

Fuel prices assumed are also detailed in Ireland (2017) and are summarized in Table 3.

Table 3. Fuel Prices, 2020, 2030 and 2050

Fuel	2020	2030	2050
Coal delivered average (ZAR/GJ)	30	45	45
LNG-FOB (ZAR/GJ)	150	150	150

3.6 CO_2-eq

TIMES allows for the specification of a cumulative CO_2 constraint (as opposed to an annual limit). This allows the model to allocate the CO_2 reductions when it is optimal to do so, given retirement profiles and future technology costs. The limit is also imposed across all energy consuming and producing sectors (i.e. excludes agriculture, forestry and other land use, and waste), such that the CO_2 reduction 'burden' is optimally allocated between sectors. The assumed cumulative CO_2 constraint that is imposed is one that ensures that South Africa meets its mid-PPD CO_2 commitment by 2050, which for the whole energy sector amounts to 12.35 Gtons between 2020 and 2050 inclusive.

3.7 Other Assumptions

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, switching to and away from electricity, and distributed generation and storage installations.

Distributed PV is constrained such that it can only meet 15% of peak demand for each sector as per the NRS 097-2-3:2014 standard in South Africa, titled 'Grid interconnection of embedded generation, Part 2: Small-scale embedded generation'. This provides simplified utility connection criteria for embedded generators smaller than 1MW – one of which criteria is an allowable connection limit of 15% of the upstream medium voltage (MV) feeder's peak load before a grid impact study is needed. Compliance to this standard is not yet a national requirement and discretion is given to the owners of individual low voltage (LV) distribution networks. The standard is used as a conservative initial reference point; however, significantly higher penetrations of distributed PV are possible with negligible or small positive distribution grid stability impacts, if combined with storage, clear interconnection standards, and the appropriate maintenance and future replacements of LV networks.

System adequacy is insured by imposing an overall reserve margin of 15% of firm capacity over peak demand. Thermal plants (including CSP 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. System adequacy can also be measured using probabilistic metrics such as the loss of load expectation (LOLE). These probabilistic metrics require a higher level of temporal detail than is available in the version of SATIM used in this analysis.

Coal and nuclear based technologies are given limited flexibility in that they are not permitted to vary their output during the day.

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).

Because of the low time resolution, a lower limit is imposed on the electricity production from gas. The lower limit is specified as 20% of the sum of the production from wind and PV.

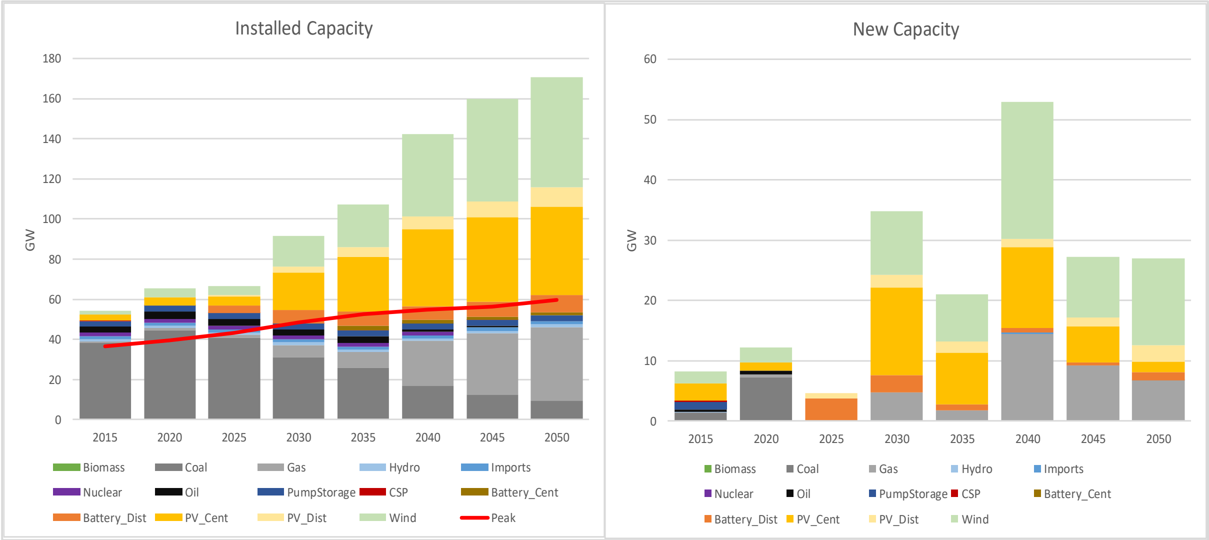
4 RESULTS

This section presents the results obtained from SATIM using the assumptions listed above.

4.1 Capacity and New Capacity in the Power Sector

Figure 2 shows the evolution of the power system's total capacity and the new capacity requirements from 2015 to 2050. The capacity mix goes from being predominantly coal based in 2015 to one dominated by PV, wind and gas plants by 2050, with only Medupi and Kusile coal plants left in the system.

Figure 2. Total Installed and New Capacity (Net)



New grid-based generation capacity requirements in the period around 2025 is nil, as the system remains with excess capacity until then, although some investments are made in distributed generation and in battery storage to accommodate the existing RE and improve the overall demand profile as seen by the grid. But investment requirements after that are considerable, peaking at around 35 GW in 2040 (4 GW per annum of new wind and 3 GW per annum of new solar). This level of investment is not totally unheard of, and has already been observed in some other parts of the world – Germany, for example, has had this level of investment in wind over the last five years and the UK had that level of investment in PV in 2015.

Figure 3 compares the total installed capacity in 2030 and 2050 with that in the studies by Wright et al (2017)[1] and Reber et al. (2018). The chart shows that the results obtained are very similar to those in Wright et al. The NREL study uses more wind and gas and less PV and storage. This could possibly be explained by slightly different input cost assumptions for wind, solar or gas (it is not clear from the paper what the assumptions are). Another possible explanation is that NREL is using a spatially more disaggregated model, although from the paper it is not clear whether they were using region-specific demand profiles (mentioned in the 'future work' section).

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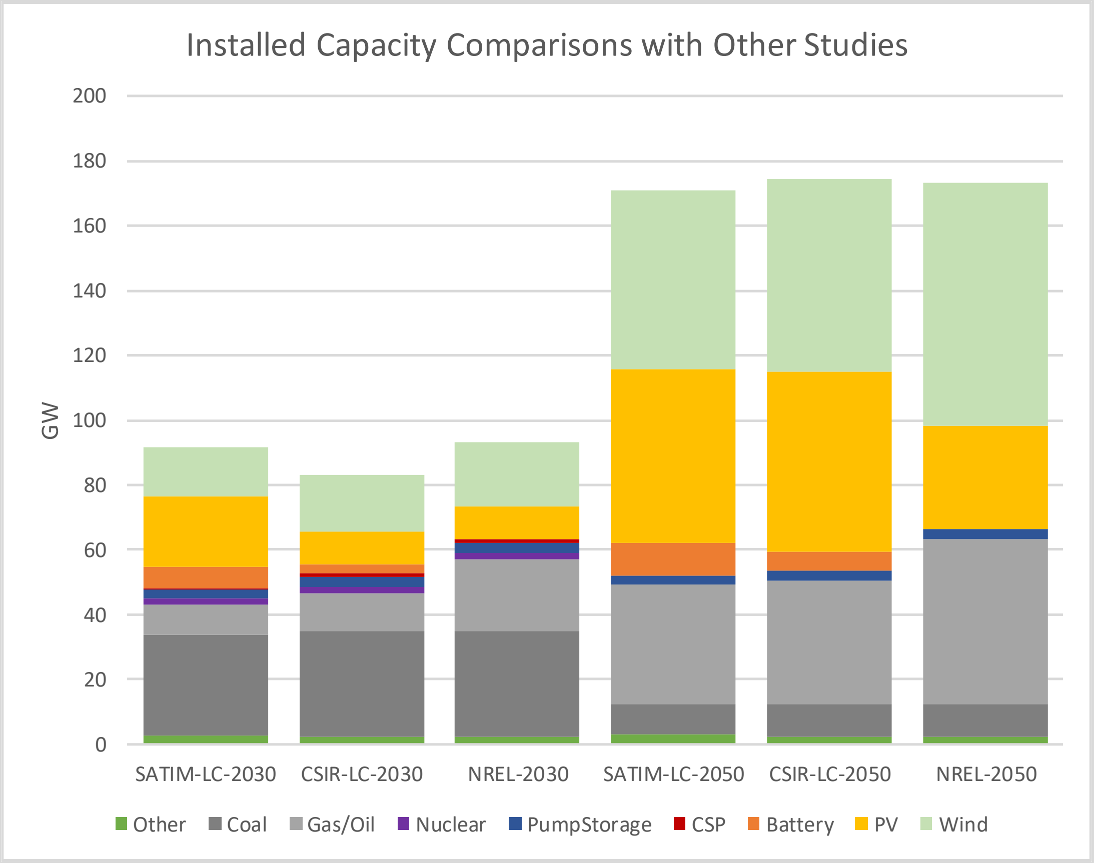
[1] More specifically the Least Cost (Low Demand) scenario, where the demand is more comparable to the one in SATIM.

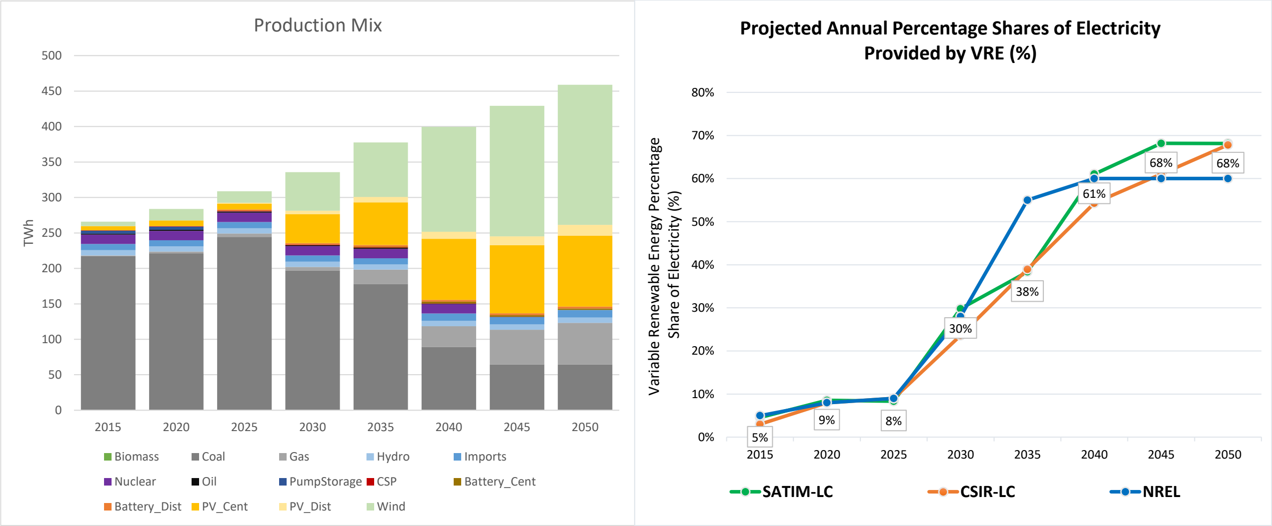
Figure 3. Comparison of Total Installed Capacity in 2030 and 2050 to other studies



4.2 Electricity Production Mix

Figure 4 shows the evolution of the production mix and the average share of variable renewable energy (VRE) contributing to total annual electricity generation to 2050. The VRE share of generation grows to around 68% in 2050. This is comparable to the results obtained in Wright et al. (2017) and slightly higher than those in Reber et al. (2018). The high VRE share from 2040 onward is made possible by the 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. Given that both studies do extensive adequacy testing at very high temporal resolution, and that the VRE share, in terms of both capacity and production, obtained here is not significantly higher, it is possible to have some confidence that the capacity expansion plan from the SATIM model would also meet system adequacy requirements.

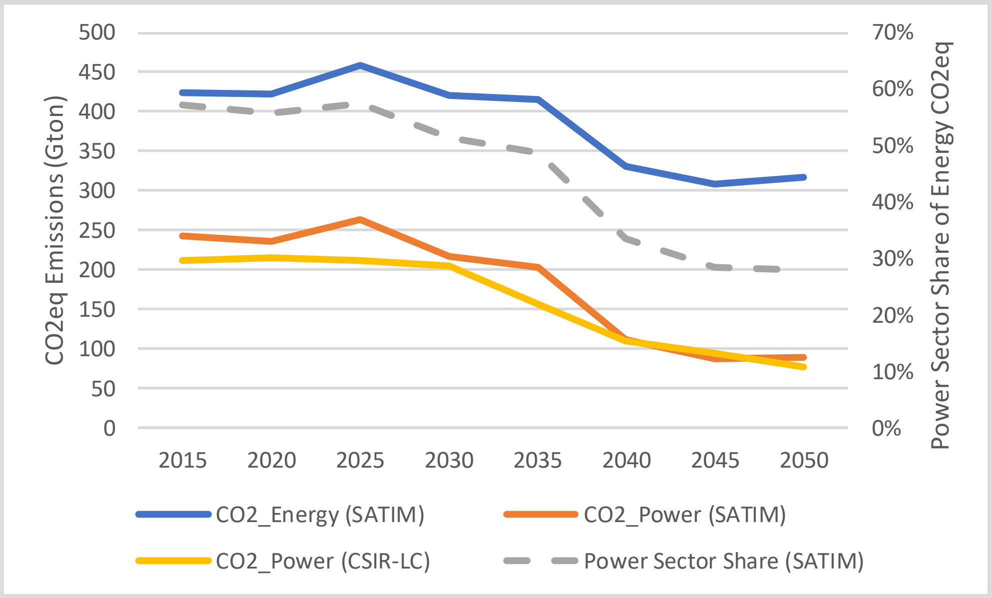
Figure 4. Production Mix and Variable Renewable Energy Share



4.3 CO_2 Emissions

Figure 5 shows the total energy system CO_2 emissions, the CO_2 emissions from the power sector, and how they compare to those in Wright et al. (2017), and how the power sector share of total emissions evolve to 2050. The emissions from the power sector declines from around 250 Mt/annum to around 100 Mt/annum, with its share declining from around 55% to 28% of energy emissions. This shows that the power sector is an attractive one for CO_2 mitigation relative to the others (transport, industry, commerce).

Figure 5. CO_2 Emissions from the Energy System and from the Power Sector

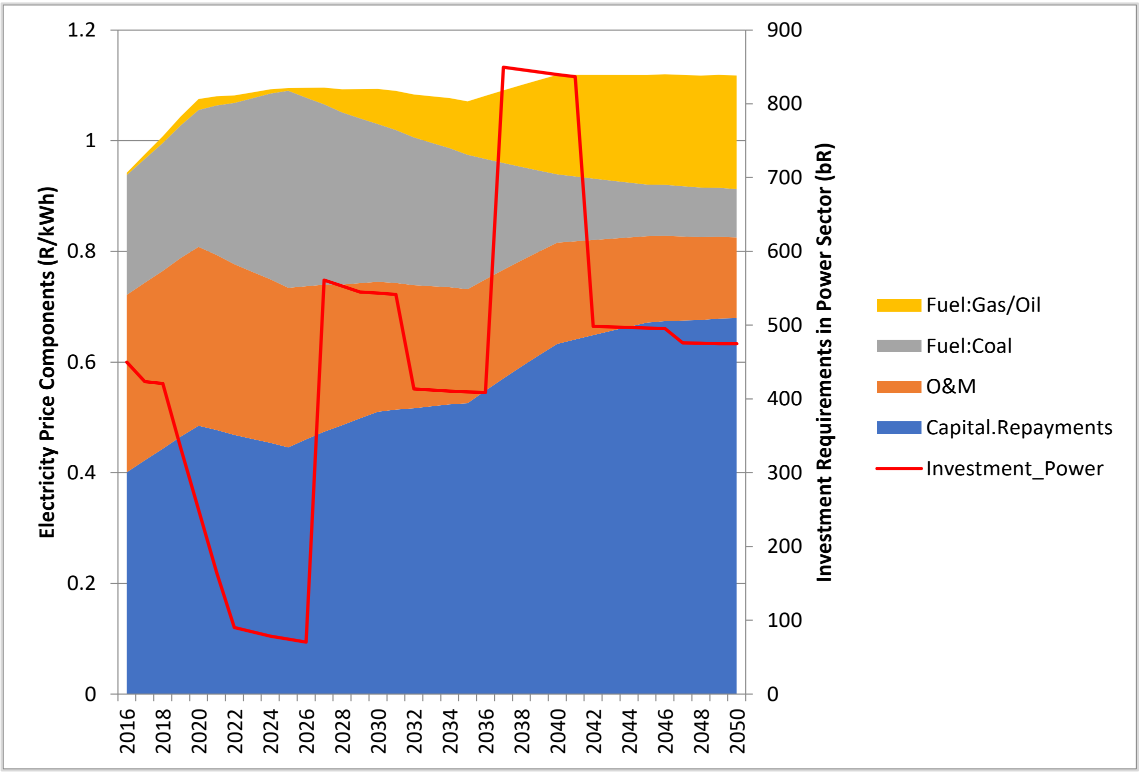


4.4 Electricity Price and Investment Requirements

Figure 6 shows the unitized electricity cost components, the sum of which can be interpreted as the average electricity price. After the completion of Medupi and Kusile, which drives up the unit price, a stabilization in price of around ZAR 1.1 per kWh is seen. In terms of the electricity price components, the increase can be seen to be primarily driven by the increasing capital repayments due to the high capital requirements of the installed wind and solar. The expenditure on coal is partly replaced by expenditure on natural gas.

Figure 6 also shows the annual investment requirements to support the capacity additions shown in Figure 3. Here a decline in investment after Medupi and Kusile can be seen, before it picks up to a similar level in the late 2020s, followed by another more intensive period of investment in the mid-to-late 2030s, as many retiring existing coal plants need to be replaced and increasing demand met.

Figure 6. Electricity Price Components and Investment Requirements for the Power Sector



4.5 The Opportunity Cost of Constraining Renewable Energy in the Power Sector

As stated in Ireland (2017), the draft IRP 2016 (DOE 2016b) appears to be quite stringent on annual new-build for solar PV and wind, limiting the rate, with little justification, to 1000MW and 1800MW respectively, and remaining constant at that level for the full planning horizon. Figure 7 shows the result of an expansion plan where these limits are imposed, as well as a limit on storage, when using the same demand drivers and other input assumptions. It shows that by 2050 roughly half the PV and wind capacity is installed, compared to the scenario described above (SATIM-LC). Instead, 800 MW of CSP and about 6 GW of nuclear is installed in order to help meet the CO_2 constraint, and an additional 10 GW of coal replaces the same capacity of gas plants. The higher price results in a slightly lower demand (6%) for electricity. This, combined with the fact that the nuclear and coal plants run at a higher capacity factor, explains why the total installed capacity is so much less, despite using the same demand drivers.

Figure 7. Comparison of Total Installed Capacity in 2030 and 2050 to the Constrained RE Case

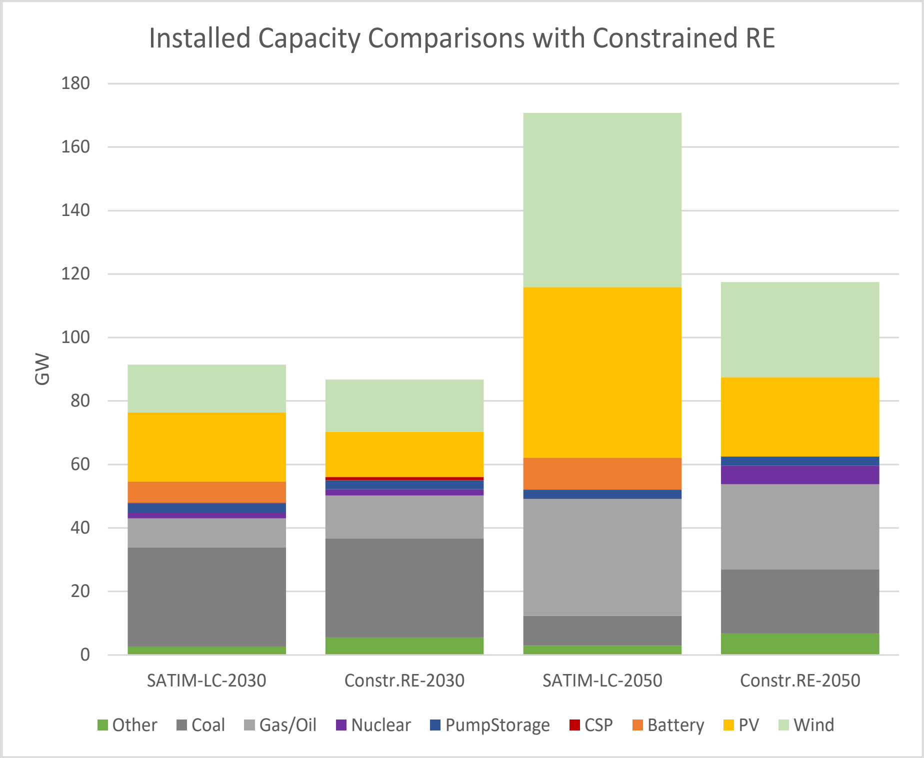
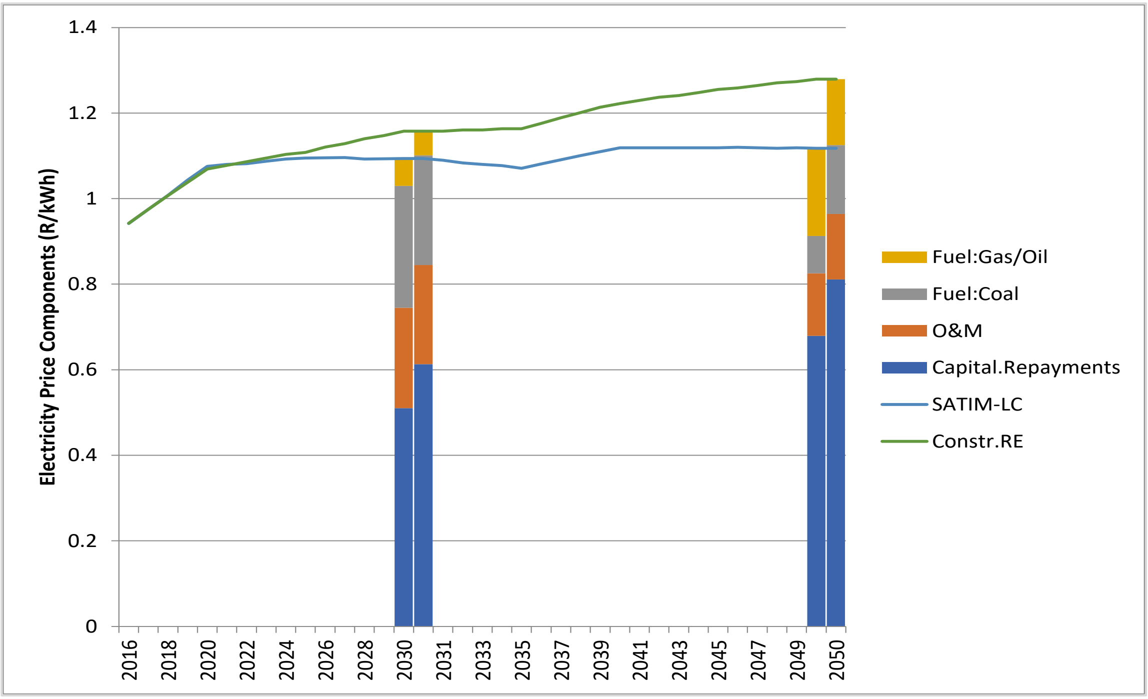


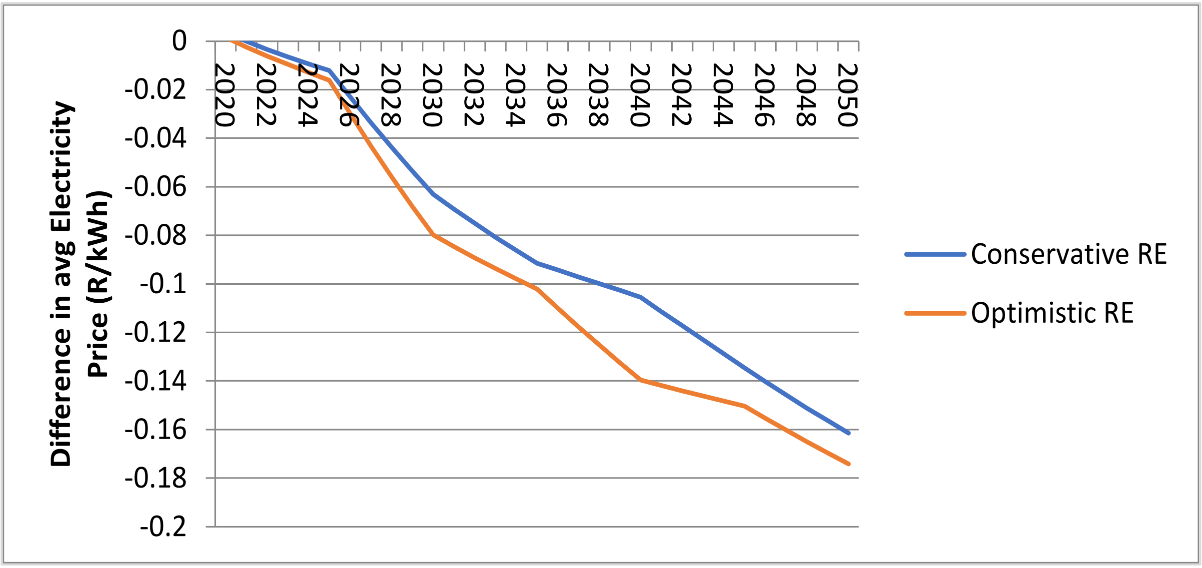
Figure 8 shows how the projected electricity price for the constrained RE case compares to the SATIM-LC case. The increase in 2030 is driven mainly by an increase in capital repayments, explained by earlier investment in RE and investment in more expensive low-CO_2 technologies (CSP and nuclear). The increase in 2050 is also driven by higher capital repayments on more expensive nuclear power plants. Reductions in gas costs are matched closely by higher coal costs.

Figure 8. Comparison of Electricity Price Components to the Constrained RE Case



Assumptions for PV and wind costs could be considered conservative. Another scenario was modelled using more optimistic costs for PV and improvements in wind capacity factors, namely, that PV costs drop to USD 0.4/W by 2050 instead of the USD 0.7/W used above, and that wind capacity factor of new installations would increase from 40% to 55% by 2050.[2] Given that the benefits of learning impact both the constrained and unconstrained scenarios, the opportunity costs are of a similar order, as shown in Figure 9.

Figure 9. Difference in Electricity Price between Least Cost and Constrained RE with conservative and optimistic technology costs for onshore wind and solar PV.



5 DISCUSSION AND 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 what the least-cost power system of South Africa could look like by 2050. This was done by applying a few conservative assumptions on reserve and dispatch rules. The paper also provides some initial insights on the opportunity cost of over-constraining renewable technologies in the system from an average generation cost point of view. The impact of constraining RE could be as high as ZAR 0.16/kWh by 2050, using conservative assumptions on RE and ZAR 0.18/kWh, using more optimistic RE costs. The version of SATIM used in this paper can be linked to eSAGE, a general computable equilibrium model of South Africa (Thurlow 2012). Continuing from the work presented in this paper, the linked modelling framework could be used to quantify the macro- and socio-economic benefits of embracing the technological developments for South Africa. This is something that has not previously been comprehensively done.

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[2] 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 projections are based on 'Scenario 3' of Fraunhofer (2015), and wind costs and capacity factor improvement assumptions are based on Weber et al & IEA (2016).

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