Climate mitigation in South Africa

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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:

Towards Inclusive Economic
Development in Southern Africa

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ABSTRACT

The Paris Agreement calls for a reduction in global emissions to limit the global temperature increase in this century to 2°C (above preindustrial levels), while pursuing the means to limit the increase to 1.5°C. This target requires commitment by both developed and developing countries to reduce national greenhouse gas emissions. However, for individual countries to commit to emission reductions, an understanding of current and future emissions without action is required, to ensure that commitments made are realistic and, equitable and sufficient at the global scale, with the lowest possible cost to the economy. This paper assesses the changes in emissions and emissions pathways in South Africa over the past decade and looks at the potential for climate mitigation and the associated economic costs. The key findings from the paper highlight that (i) over the past decade the reference pathway for emissions in South Africa has been revised downward, largely due to the increased ability to cost effectively lower emissions in the power sector; (ii) the reference case presented here indicates that by taking a least-cost approach to energy planning, South Africa can reach an emissions level well within its NDC commitment (below the mid-point thereof) and below the Climate Equity Reference Calculator 2°C fair share allocation; (iii) decreasing energy emissions beyond this has a negative impact on economic growth and employment, although this impact is small for energy emissions caps of up to 8 GT; and (iv) the negative impacts on the economy can be mitigated by increasing energy efficiency in line with government policies and measures.

Keywords: climate mitigation, economic development, welfare, South Africa

JEL classification: mitigation, energy, economic development, linked modelling, nationally determined contributions

1 INTRODUCTION

to limit the global temperature increase in this century to 2°C (above preindustrial levels), while pursuing the means to limit the increase to 1.5°C. This target requires commitment by both developed and developing countries to reduce national greenhouse gas emissions. However, for individual countries to commit to emission reductions, an understanding of current and future emissions without action is required, to ensure that commitments made are realistic and, equitable and sufficient at the global scale, with the lowest possible cost to the economy. Reference case emissions pathways must, however, be consistently updated with the most recent information and data available to ensure that they are relevant and account for changing trends.

In South Africa, the first emissions pathways analysis was completed in 2007 in the Long-Term Mitigation Scenarios (LTMS, Winkler 2007). The update to this was completed seven years later in the form of the Mitigation Potential Analysis (MPA, DEA 2014). These two studies have been the cornerstone for the emissions reduction commitment of South Africa, expressed by the peak, plateau and decline trajectory and echoed in the nationally determined contribution (NDC). Since 2014, several analyses have reassessed the state of the reference case emissions pathway in South Africa. These have been spurred by changes in input assumptions such as growth as well as in advances in technology, which have been dramatic, particularly in the electricity sector, a key source of emissions in the country. Developments, particularly in electricity technologies, have changed the dynamic when mitigation and economic development in South Africa are debated, with clean power no longer being considered a threat to economic development and employment. Instead, the discussion has shifted to ensuring a just transition, whereby those that are vulnerable to changes in the power sector are empowered to transition along with the sector.

Debate, however, exists about the level of South Africa's mitigation ambition, with Climate Action Tracker (CAT)[1] showing this to be incompatible with the 1.5◦C Paris Agreement target. The objective of this paper is therefore twofold. The first aim is to assess the changes in emissions and emissions pathways in South Africa and the drivers underlying these (Sections 2 to 4). The second is to understand the potential mitigation ambitions South Africa could shift toward and the implications these would have for economic development (Section 5 and 6). The linked energy-economic model, SATIMGE, is used in the analysis of the latter. Section 7 concludes, with a discussion.

2 EMISSIONS TRENDS IN SOUTH AFRICA

National emissions statistics show that between 2000 and 2015 gross and net emissions in South Africa increased by 23.1% and 20.2%. Emissions from the energy sector was the largest contributor to this increase. Emissions from the forestry and other land use sectors decreased, providing a carbon sink to offset cumulative emissions from other sectors by 15% (DoE 2019). Since 2012, the growth in both gross and net emissions slowed to an average annual rate of 0.4% and -0.1% respectively, from 1.7% and 1.6% in the 2000–2012 period. The slowdown in growth was primarily driven by flat emissions in the energy sector, as emissions from the power sector declined.

The key drivers of emissions in South Africa are GDP and population growth. Between 2010 and 2015, real GDP growth slowed to an average annual rate of 2.2%, down from 3.5% in the previous decade. The composition of growth also shifted over this period, with GDP contributions from emissions-intensive sectors such as mining, manufacturing, and utilities decreasing and contributions of less

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[1] See https://climateactiontracker.org/countries/south-africa/. CAT is an online data tool that tracks and evaluates the climate commitments and actions of 32 countries with significant annual emissions. It attempts to tackle the challenge of competing principles in different equity frameworks by combining the emission results of multiple underlying mitigation effort-sharing studies.

emissions-intensive sectors, such as trade, and finance and business services, increasing over the same period. This is also reflected in the (net) emissions intensity of growth, which decreased by 1.6% between 2012 and 2015.

Energy demand continued to grow in line with real GDP growth. Between 2000 and 2010, energy demand grew at 1.8%, and this slowed to 1.4% in the 2010–2015 period. The slowdown was driven by a decline in demand for liquid fuels and other energy sources, while the demand for electricity grew marginally faster than in the previous period. Waste and agriculture now account for 13% of gross emissions (DEA 2019), primarily due to emissions from the waste sector. Between 2000 and 2015, however, the net emissions contribution from the agriculture, forestry, and other land use (AFOLU) sector declined from 8.8% to 4.1%. This was due to an increase in the land sink. Emissions in the waste sector increased by 80% over the period.

3 DEVELOPMENTS IN REFERENCE EMISSIONS PATHWAYS FOR SOUTH AFRICA

The emissions debate in South Africa has changed dramatically over the last decade. This has been due to changes in the energy and economic landscape, but also due to changes in the international discourse as climatic changes are increasingly felt across the globe. The former has resulted in changes in projected mitigation pathways for the country, while the latter has resulted in a more distinct shift in thinking about decarbonization, specifically the need to push the limits of mitigation such that required-by-science targets are met. This section unpacks the mitigation pathway analyses conducted for South Africa over the past decade or so, and considers how emission trajectories have evolved.

In South Africa, the first emissions pathways analysis was completed in 2007 in the LTMS. The LTMS was commissioned by the Department of Environmental Affairs to help define South Africa’s position on future commitments under international treaties and inform its climate policy for the longer-term future (Winkler 2007). The update to this was completed seven years later in the form of the MPA (DEA 2014), which provided an updated outlook to reference case emissions and potential emissions pathways in South Africa and also developed marginal abatement cost curves for key sectors and sub-sectors. These two studies have been the cornerstone for the emissions reduction commitments of South Africa, which is expressed by the peak, plateau, and decline (PPD) trajectory and echoed in the NDC.

Over the past three years, government has been in the process of updating its mitigation potential analysis studies, through the “Alternative greenhouse gas emission pathways for South Africa” study (Pathways study, DEA 2018a) and the “Policies and measures report” (PAMS, DEA 2018b). Pathways developed a set of emissions pathways for South Africa, in which the characteristics (technological, behavioural, and societal changes) of the current South African economy and emissions landscape could change. DEA (2018b) assessed the emissions and economic impact of planned mitigations policies and measures and identified the level of effort needed to reduce emissions to the lower target of the PPD band, and the associated economic implications of doing so. Whilst reports for both these studies have been submitted, final studies are pending release by the Department of Environment, Forestry and Fisheries (DEFF).

In addition to these government-commissioned studies, external assessments have also been done as updates to the LTMS (see ERC (2011) and NCI (2017)); and to: a) assess the uncertainty related to the development of reference case emissions pathways (ERC 2015); b) account for changes in the energy landscape (McCall et al. 2019 and IEA 2019); and c) account for the changing requirement of climate stability (Alteri et al. 2015; Zhang 2017 and CAT 2018). Table 1 presents a summary of the mitigation pathway studies undertaken for South Africa. Sector mitigation studies have also been undertaken. These have primarily focused on the electricity sector given the dramatic change in renewable energy technology costs over the past decade. Some of these studies are presented in Table 2.

Table 1: Mitigation pathway studies for or including South Africa

Reference	Name of study
Winkler (2007)	Long-term Mitigation Scenarios (LTMS)
ERC (2011)	South African Low Emissions Pathways Project (LEPS)
DEA (2014)	South Africa's greenhouse gas mitigation potential analysis (MPA)
ERC (2015)	Quantifying uncertainty in baseline projections of CO_2 emissions for South Africa
Altieri et al. (2015)	Pathways to deep decarbonization in South Africa (DDPP)
DOE (2016)	Integrated energy plan report (IEP)
Zhang (2017)	Actions towards decarbonization – Climate policy assessment and emissions modelling with case study for South Africa.
NCI (2017)	Greenhouse gas mitigation scenarios for major emitting countries. Analysis of current climate policies and mitigation pledges: 2017 update
DEA (2018a)	Alternative greenhouse gas emission pathways for South Africa (Pathways)
DEA (2018b)	Policies and measures report (PAMS)
CAT (2018)	Scaling up climate action. Key opportunities for transitioning to a zero emissions society.
IEA (2019)	Africa energy outlook 2019. World Energy Outlook Special Report
McCall et al. (2019)	Least cost integrated resource planning and cost-optimal climate change mitigation policy - Alternatives for the South African electricity system

Table 2: Power sector studies for South Africa

Year	Name of study
IRENA (2015)	Africa power sector: Planning and prospects for renewable energy
Wright et al. (2017)	Formal comments on the Integrated Resource Plan (IRP) update assumptions, base case and observations
Chartan et. al. (2017)	Preliminary findings of the South Africa power system capacity expansion and operational model study
Wright et al. (2018)	Formal comments on the Draft Integrated Resource Plan (IRP) 2018
Merven et al. (2018)	Quantifying the macro- and socio-economic benefits of a transition to renewable energy in South Africa
Oyewo et al. (2019)	Pathway towards achieving 100% renewable electricity by 2050 for South Africa.
DOE (2019)	2019 Integrated Resource Plan report
Meridian Economics (2020)	Ambitions project

Reference case emissions pathways for South Africa, presented in Figure 1, show a dramatic change over the past decade, with the reference scenarios in Winkler (2007) and DEA (2014) indicating rising trends in emissions, and more recent country-level studies showing a flatter and potentially declining trend. Winkler (2007), ERC (2011) and DEA (2014) expected emissions to continue rising over the period of study reaching, respectively, 1 448, 1 317 and 1 593 MT CO_2-eq emissions by 2050. More recent pathway studies expect emissions to peak well before this point – DEA (2018b) expects a peak in emissions in 2025 at 537 MT while McCall et al., (2019) suggests that emissions have already peaked. DEA (2018a) indicates a rising trend to 2050 like Winkler (2007), ERC (2011) and DEA (2014), although the level is lower, and the rate of increase is smaller.

Overall, between 2007 and 2019, baseline scenario expectations for emissions by 2030 and 2050 declined by 55% and 78% respectively. While some of this difference is explained by the difference in starting points, due to actual emissions data (see Section 2), the slope of emissions has become flatter than previously expected, with the more recent reference emissions pathways highlighting an increased likelihood that South Africa could comfortably achieve its NDC (indicated by the PPD green band), previously believed to be much more challenging cost-wise. This change has been driven by lower energy demand projections (because of lower GDP growth and improved energy efficiency) and rapid changes in technologies and technology prices over the past decade.

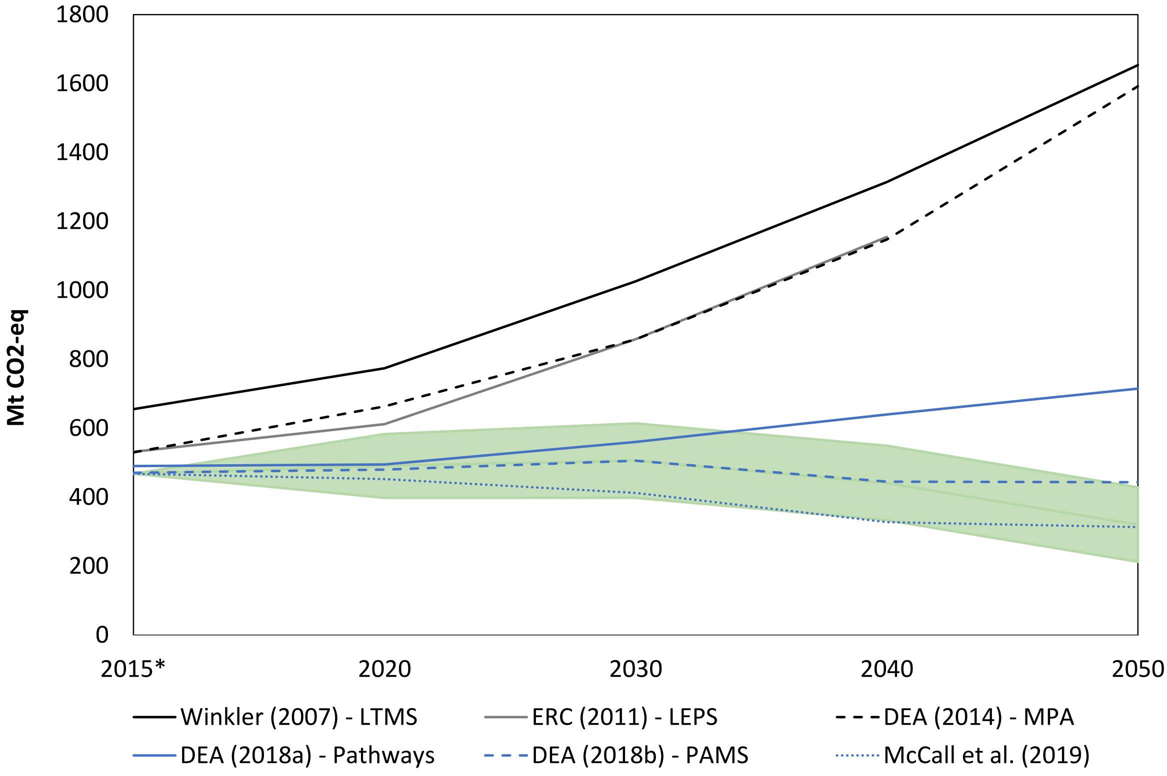

Figure 1: Estimated reference case emissions for South Africa

Much of the change in projections has been driven by changes and anticipated changes in power production technologies. Between 2007 and 2019, projections for power sector emissions by 2030 and 2050 decreased by 52% and 92% respectively. In Winkler (2007), electricity sector emissions were projected to increase from 248 MtCO$_2$-eq in 2012 to 364 MtCO$_2$-eq by 2030 and 541 MtCO$_2$-eq by 2050. DEA (2014) projected a similar trend in emissions, although the levels were higher at 395 and 810 MtCO$_2$-eq, due to larger expected increases in demand. The continued increase in power sector emissions in these scenarios is due to increased electricity demand but also to the technologies used to produce power – which continued to be coal, with very little renewable energy capacity being built and even less contributing to actual production.

More recent projections expect a change in trend for emissions from the power sector as the contribution of renewable energy increases and that of coal decreases. The 2018 IRP (DoE 2019) scenarios estimate that wind and solar PV will account for 40–60% of total power production by 2050, resulting in emissions well below the imposed 45% PPD share assigned to the power sector (see Figure 2). Least-cost optimization planning outside of government have reported optimal rates of 70% and higher (Wright et al. 2017; Wright et al. 2018; Chartan et al. 2017; Merven et al. 2018; DEA 2018 and ERC & CSIR 2019). The 2017 NREL study (Chartan et al. 2017) highlights that this share of renewable energy is possible without any significant changes needed to the current energy system. Furthermore, studies (see Hartley et al. 2019; ERC&CSIR 2019) show no economic cost to increased renewable energy inclusion. This shift has been driven by the decreases in renewable energy costs, which are now competitive with new coal (see Arndt et al. 2019).

The decline in power sector emissions is also attributed to lower expected demand. Between 2010 and 2015 electricity demand decreased by 3.2%, because of slower economic growth but also higher electricity prices (over the past ten years electricity prices in South Africa increased by over 300%). Demand has also been lower because of unmet demand and load-shedding and voluntary declines in electricity usage to keep the power system stable. Slower economic growth and efficiency gains have resulted in the projections for energy demand also being revised downward. Between 2010 (i.e. IRP 2010) and 2016 (i.e. IRP 2016 - Low CSIR scenario) projections for electricity demand by 2030 have decreased from 454 TWh/year to 297 TWh/year, with projections for 2050 also coming in below 400 TWh/year – compared to over 500 TWh/year in the IRP 2016 (i.e. IRP 2016 - High low intensity) (see Figure 4).

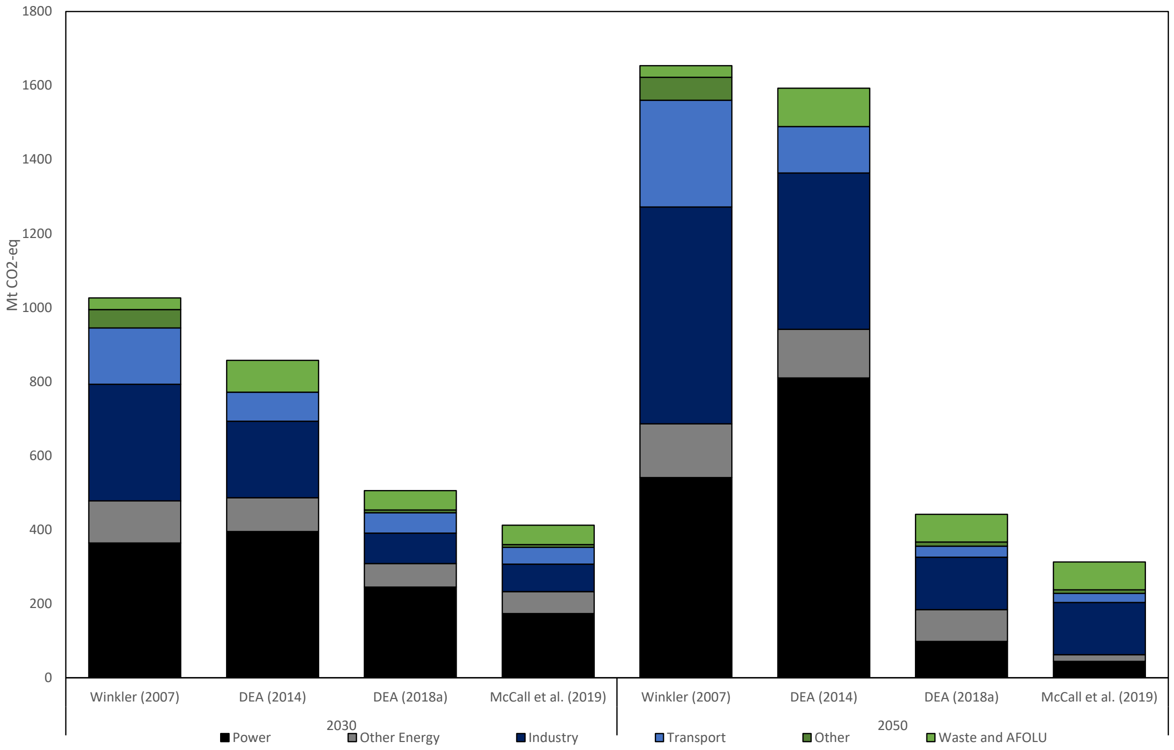

Figure 2: Estimated reference case emissions for South Africa by sector

The decarbonization of the power sector has been shown to have further-reaching decarbonization impacts beyond the power sector alone. One of these which has garnered increased investigation is the switch from fossil fuel use in transport to alternatives such as electricity, natural gas and hydrogen (DEA 2018b; CAT 2018 and McCall et al. 2019), particularly post-2030, with increased fuel efficiencies playing an important role before then. Decreased demand for fossil fuels domestically has implications for refinery production and emissions, resulting in further decarbonization.

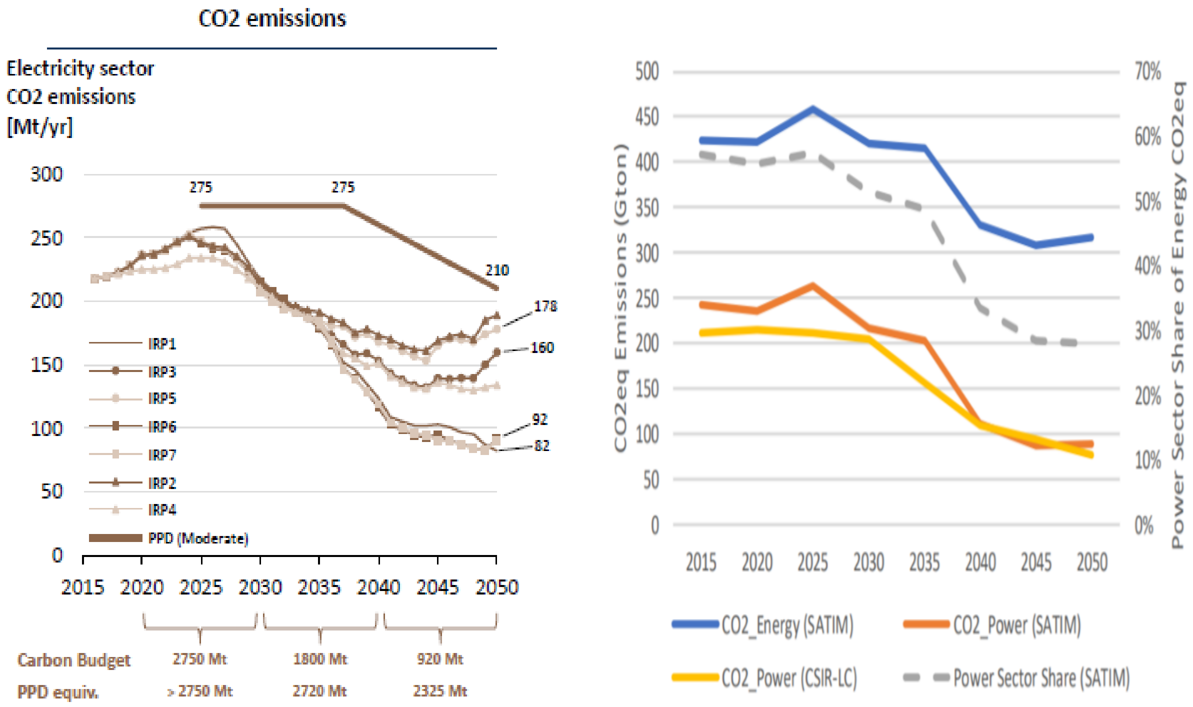

Figure 3: Emissions projections associated with a) 2018 IRP scenarios (Wright et al. 2018); b) 2018 ERC scenarios (Merven et al. 2018)

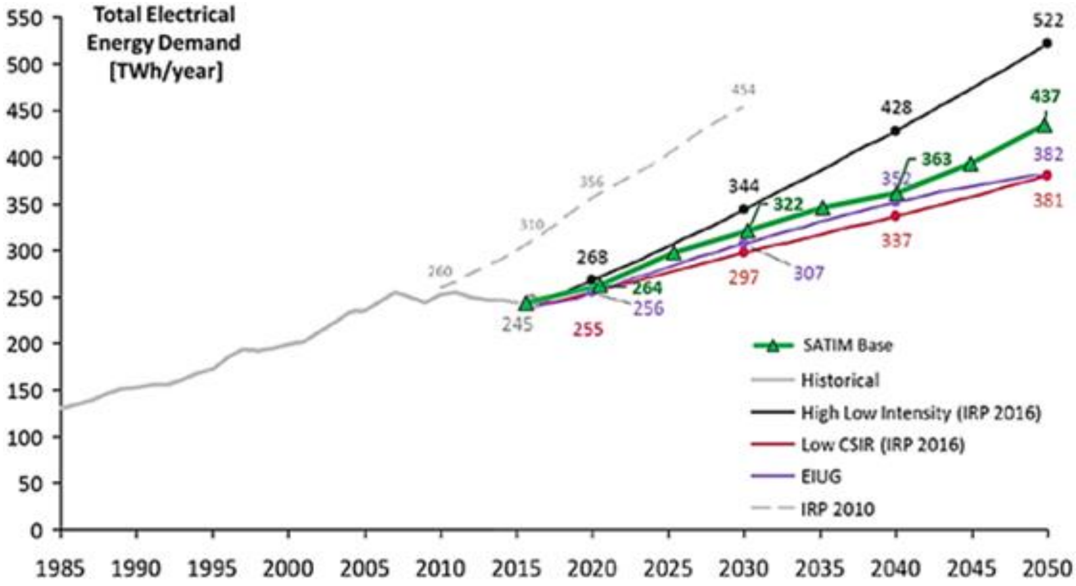

Figure 4: Historical and projected growth in electricity demand (Wright et al. 2017)

4 SENSITIVITY ANALYSIS AND ALTERNATIVE PATHWAYS

The discussion above has shown that reference case emissions are sensitive to the assumptions included in the analysis. This is particularly true for key drivers such as economic growth, the discount rate, and assumptions of technology costs. While the studies presented here have used the most recent and updated information and projections to inform their assumptions at the time, these projections in themselves include large amounts of uncertainty, particularly when considering such long time periods. For this reason, studies generally include sensitivity analysis to account for potential changes in the future or alternative futures. This is useful, as it provides policymakers with a better understanding of the uncertainty related to the mitigation requirements needed. The LTMS and MPA studies included sensitivity analysis on economic growth for the reference case and found significant reductions in emissions for lower growth assumptions, although these were still higher than what is currently expected. Merven et al. (2015) used Monte Carlo simulations to develop a probability distribution of baseline emissions for South Africa over the 2015–2050 period. Within the results from their study, the most recent reference emissions pathways suggested by 2018 PAMS and 2019 ERC scenarios (see Figure 3) only showed up as an outlier, despite the large array of economic growth assumptions (among others). This highlights the dramatic shift in the outlook for economic growth that could not have been predicted and stresses the importance of regular updates to the reference case scenario to ensure that changes in actual data, and more importantly expectations, are included.

Alternative mitigation pathways are also considered to assess the country level of ambition associated with existing and planned policies, and the potential to decarbonize emissions in line with that required by science. These scenarios allow for an analysis of more ambitious or best practice mitigation policy, which may not be the same as existing policy due to political will, costs, and potential macro- and socio-economic impacts. Alternative scenarios also allow for the inclusion of less ambitious policies where concerns over the ability to implement government policies are questioned or where the outcomes of such policies are vague. An example of this is the 2018 CAT study, which excludes a National Policy scenario for passenger transport.

The key levers used in alternative mitigation pathways scenarios have over time included technology options and costs, energy efficiency assumptions, economic growth and structure, market mechanisms, behavioural changes, and emissions caps/targets. These levers have been used in developing scenarios from two angles. The first has been a bottom-up approach, where the potential for the country is assessed given different conditions (e.g. Merven et al. 2015; DEA 2014). The second approach is where an emissions cap or target is placed on the economy or certain sectors and mitigation measures needed to achieve this are identified. This approach was taken in the 2007 LTMS which used an overarching emissions target to reduce emissions by 470 Mt CO_2-eq by 2020 and 264 Mt CO_2-eq by 2050, as required by science. This target was then broken down into phases (i.e. start now, scale up, use the market and reach for the goal) based on various levers – the probability or ease of which becomes increasingly hard as emissions decline. A similar approach is taken by the 2018 PAMS study (DEA 2018b), which first assessed the impacts of existing policies and measures and then assessed the potential of reaching a specified target, namely the lower PPD band. This study took an interesting approach in that it allowed the full sector energy model to find the least-cost method of achieving the emissions target.

Emissions caps/targets being analysed have become increasingly ambitious as reference case emissions have declined. This is evident in the shift of targets from the lower PPD in DEA (2018b) to 7.75 GT in McCall et al.)2019), which included zero power sector emissions by 2050. Zero power sector emissions have also been studied in Oyewo et al. (2019), and CAT (2018) comes close to zero with a 97% reduction in power sector emissions – based on the “Decarbonised scenario” of Wright et al. (2017) and the IPCC 1.5 degrees report. This increase in ambition is aligned to the most recent calls for global mitigation efforts to reduce global warming levels below 1.5 °C by 2100 (Fifth Assessment Report of the Intergovernmental Panel on Climate Change) which requires global GHG emissions to decline to zero by 2060-2080 with energy and industrial CO_2 emissions reaching zero by 2050 (Rogelj 2015). Oyewo et al. (2019) find that a fully renewable energy base power system is a real option for South Africa. When accounting the GHG emissions cost, a fully renewable system is not only cost-competitive but also reliable. Without the GHG emission cost, renewable energy accounts for 95.6% of power generation, with the balance of 4.4% being made up by coal and gas turbines. More recent work has shown that phasing out coal in the power sector by 2040 is possible at marginal cost increases (Meridian Economics 2020; McCall et. al 2019).

Scenarios with increased ambition have also focused on developmental implications, specifically the impact on economic growth and employment. Some have taken the view of assessing the impacts on the economy of various mitigation efforts to find a balanced approached to mitigation pathways. Others have considered the need for a changing economic structure to support a low-emissions pathway for the country. An example of the latter is the 2015 DDPP study, which considers alternative economic structure scenarios that enable a low emissions pathway. Recent alternative economic growth assumptions have been found to affect the level of emissions and energy needed rather than the optimal composition of technologies and trend of emissions (Wright 2017).

As the optimal pathway for the power sector seems to be converging, more scenarios are broadening to consider the impact on the second- and third-largest-emitting sectors, namely transport and industry. This is evident in CAT (2018), which focuses on passenger transport, as do Zhang (2017) and Ahjum et al. (2018; 2019). Mitigation efforts in industry (excluding refineries) are understudied in South Africa, due to the lack of competitive technology substitution options available. Further research of industry options outside of energy efficiency improvements is required, particularly in relation to the use of coal for thermal heating needs. This is illustrated by DEA (2018b), which shows continued coal use in the industrial sector across scenarios.

5 METHODOLOGY

In this paper, the linked energy-economic model for South Africa, SATIMGE, is used to assess the mitigation potential of the energy sector in the country and the associated macro- and socio-economic impacts related to changes in the energy system. SATIMGE is a hard-linked coupling of the South African TIMES (SATIM) and computable general equilibrium models (eSAGE) (see Arndt et al. 2016 and Merven et al. 2017). SATIM is a bottom-up integrated energy systems model which captures both energy sector and process emissions. eSAGE is dynamic recursive, economy-wide of South Africa, based on the generic static and dynamic CGE models described in Lofgren et al. (2002) and Diao and Thurlow (2012). The modelling methodology, which follows that proposed by Lanz and Rausch (2011), addresses the shortcomings of single or extended models that either do not consider the energy system in appropriate detail or provide an aggregate assessment of economic indicators, whilst providing a consistent framework for assessing energy and energy mitigation policies and measures. Key developments in SATIMGE have been made since previous mitigation assessments using the same methodology. These changes are detailed in Merven et al. (2018; 2019a; 2019b; 2020a; 2020b) and Hartley et al. (2019). To assess the full emissions impact, the energy model is further dynamically linked to spreadsheet models that (separately) model waste and AFOLU.[2]

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[2] Detailed specifications of all models are available on request.

5.1 Scenarios and assumptions

To assess the mitigation potential and mitigation-economic trade-offs facing South Africa, five scenarios are modelled where increasingly stringent energy emissions caps are placed on energy and industrial process and product use (IPPU) emissions. Whilst baseline scenarios are included in the analysis it is assumed that these do not change across the scenarios modelled here. No planned mitigation policies and measures (PAMS) are included in the scenarios. The scenarios are compared to a reference case in which no cap is placed on emissions. Table 3 presents a summary of the scenarios modelled.

Table 3: Scenario descriptions

Scenario name	Scenario description
NoPAMS	This is the reference case. The energy model solves for the least-cost plan to meet energy demand. No emissions cap is placed on energy and IPPU emissions. Sasol and coal power plants are allowed to endogenously retire based on relative costs.
NoPAMS-CAP10	This scenario is the same as the reference case except that a 10 GT emissions cap is placed on energy and IPPU emissions.
NoPAMS-CAP09	This scenario is the same as the reference case except that a 9 GT emissions cap is placed on energy and IPPU emissions.
NoPAMS-CAP08	This scenario is the same as the reference case except that an 8 GT emissions cap is placed on energy and IPPU emissions.
NoPAMS-CAP07	This scenario is the same as the reference case except that a 7 GT emissions cap is placed on energy and IPPU emissions.
NoPAMS-CAP06	This scenario is the same as the reference case except that a 6 GT emissions cap is placed on energy and IPPU emissions.

As no PAMS are directly included in the scenarios presented above, a second set of simulations is also run to include the impact of demand-side PAMS only. The key difference between the two sets is therefore the inclusion of energy efficiency improvements, in the transport, industry and building (residential and commercial) sectors. These efficiency improvements are based on a set of policies, regulations, programmes and strategies that are meant to be in place or are to be implemented at 2030 horizon. See Appendix section for more details. In the graphs and tables these scenarios are labelled CPAMS-CAP*xx* where *xx* presents the emissions cap. The emissions cap is an upper limit on the cumulative emission from energy sector and industrial processes between 2020 and 2050 inclusive.

The model is run to 2050 and the scenario ”NoPAMS” is treated as the reference case to which other scenarios are compared. In each scenario the energy model is allowed to solve for the least-cost energy plan to meet demand. Fuel switching is endogenous across all demand sectors including transport, within limits specified. The limits are set quite tightly in 2020 based on historical shares and relaxed over time. The power sector capacity expansion plan is solved simultaneously with demand. Existing and new coal plants are allowed to “endogenously[3]” retire if economic to do so. With regards to process emissions, currently only a switch in the iron and steel sector to hydrogen-based production can be endogenously selected if economic. Mode switching and autonomous efficiency improvements are exogenously specified. The assumptions underlying the economics and energy models can be found in Appendices A and B.

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[3] An endogenously retired coal plant would not incur any fixed maintenance cost once retired but would still incur investment repayments over the originally planned remaining life of the plant. It would also no longer contribute to the power system reserve margin requirements.

6 RESULTS

This section discusses the results of the five scenarios modelled. All scenarios are compared to the reference case NoPAMS. While several sets of indicators are available for analysis, we focus on the GDP-emissions trade-off, sectors emissions mitigation required, technology options that enable mitigation, and the change in sector structure and employment. As government PAMS only go to 2030, we use this as our point of analysis. To place the emissions results in a global effort perspective, we compare the outcomes to the fair share calculations of the different level of effort scenarios defined by Climate Action Tracker (CAT) and the Climate Equity Reference Project's Climate Equity Reference Calculator (CERC).[4] Figure 5 presents the CAT fair share ranges. Estimates from CERC place South Africa's fair share well below 2 ◦C, 1.5 ◦C "Standard" and 1.5 ◦C "Low energy demand" (LED) pathways at 478, 430 and 401 $MTCO_2$-eq, respectively. Land use, land-use change, and forestry (LULUCF) emissions are excluded from the results as they are not included in CAT or CERC and because the focus of the emission cap scenarios is on the energy system.

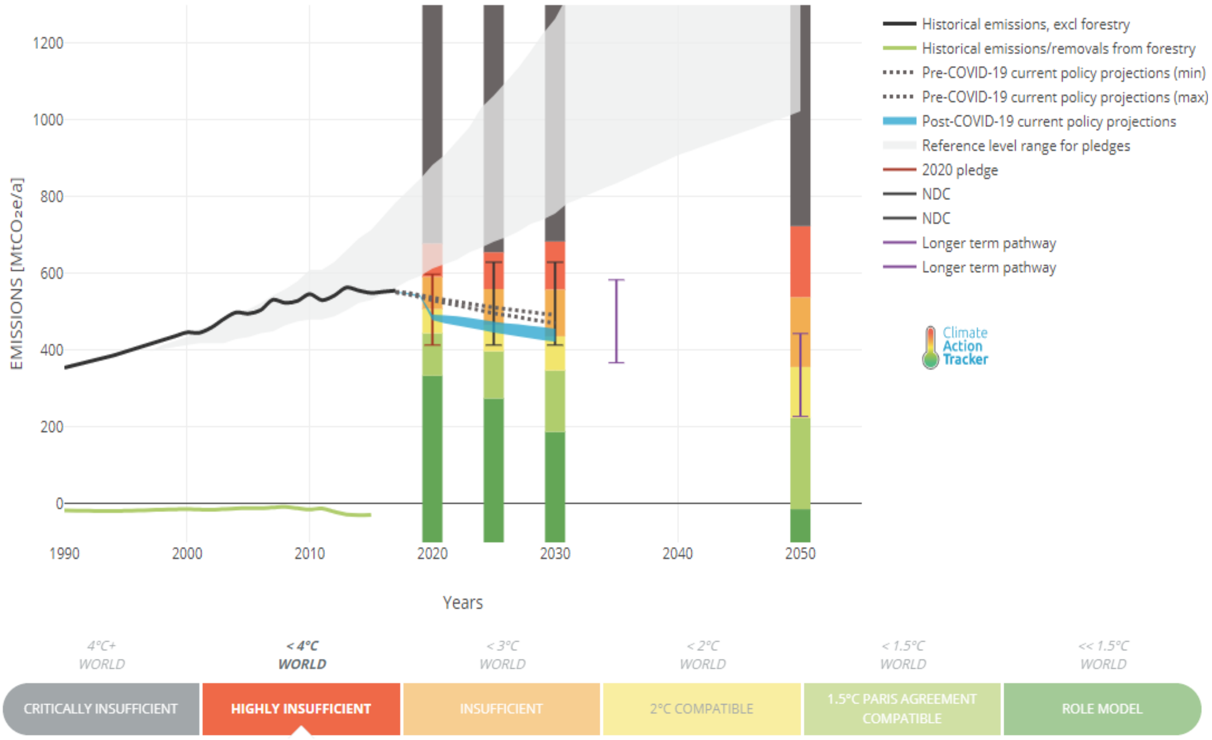

Figure 5: Climate Action Tracker fair share ranges for South Africa vs historical and committed

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[4] See https://calculator.climateequityreference.org/. CERC is an online equity reference tool and database designed to examine the potential 'fair share' of contributions of countries, regions or other international groupings to the global mitigation requirement (measured in $MtCO_2$-eq (excluding LULUCF)) estimated to achieve the Paris Agreement temperature goals, as interpreted by a selection of three global mitigation pathways.

6.1 Aggregate impact of increasing mitigation ambition

Figure 6 plots the level of emissions achieved in 2030 against the impact on the level of real gross value added (GVA) (relative to the NoPAMS scenario). In scenarios where PAMS are not considered, i.e. NoPAMS-CAP*xx*, increasing the level of mitigation ambition has a negative impact on real GVA. The impacts under the 10, 9 and 8 GT emissions caps have small negative impact on the level of real GVA of 1.4% or less. This is equivalent to achieving the reference case level of GDP less than a year later. The additional negative GVA impacts of shifting between these caps are also small compared to the large emissions gains experienced. Emissions under the 10 and 9 GT cap scenarios, as with the NoPAMS scenario, lie in the range of “insufficient” action (3 ◦C temperature increase) according to CAT, while 8GT shifts into the upper range of a 2 ◦C compatible range.

The GDP losses do, however, begin to outweigh the additional mitigation gains when shifting beyond the 8 GT cap. This can be seen by the larger GDP loss of 3.5% under the 7 GT scenario, which is nearly three times the loss under the 8 GT cap, with gains in emissions mitigated being close to double. The economic cost rises more under the 6 GT cap. Under the 7GT cap emissions are close to the lower end of 2 ◦C compatible, while a 6 GT cap is on the upper end of a 1.5 ◦C Paris Agreement-compatible commitment as defined by CAT.

The rising cost to the economy under the 7 and 6 GT cap scenarios is mainly driven by having to fast-track investment in clean energy and the early retirement (stranding) of “dirty” assets (existing coal power plants).

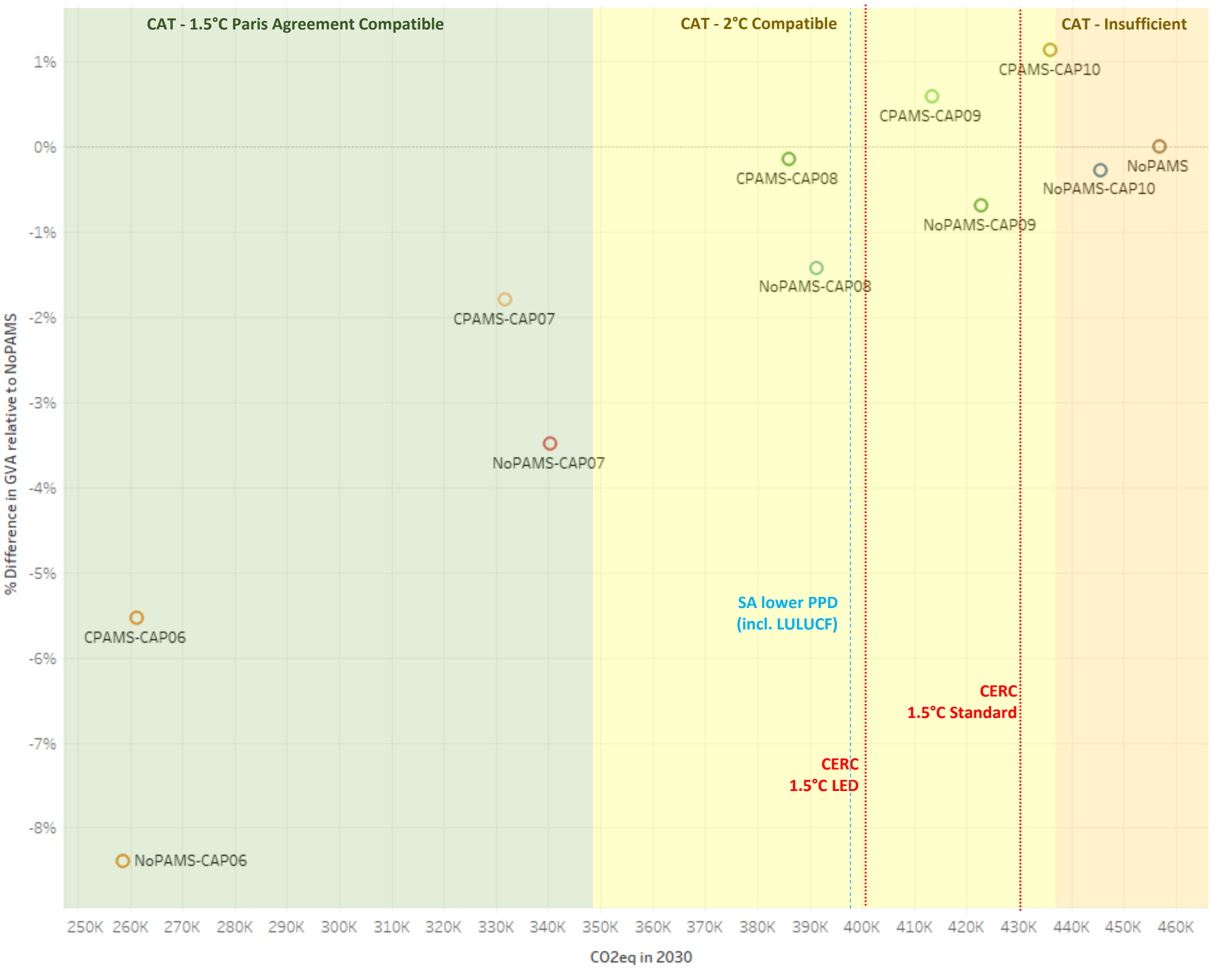

Figure 6: GVA impact and emissions (excluding LULUCF) by scenario, 2030

The inclusion of PAMS, namely increased energy efficiency, reduces the negative impact of increased mitigation on the economy. This can be seen by the upward shift in GVA between the NoPAMS-CAP*xx* and CPAMS-CAP*xx* scenarios in Figure 6. Increased energy efficiency reduces energy demand and gives the system more carbon space, which results in fewer existing generation assets having to be stranded, less new clean energy capacity is needed, so less investment, and smaller increases in energy prices. It is important to note that we assume that the cost of switching to more energy efficient capital is the same as replacing old capital. If it is more expensive, the positive shifts seen in Figure 6 would be dampened. This is an area that is left for future improvements in the linked modelling framework. When PAMS are included, the 10 and 9 GT scenarios have a positive impact on GVA relative to the NoPAMS scenario. The GVA loss per CO_2-eq gain is also smaller when PAMS are included, with more emissions reductions taking place.

6.2 Sector emissions and power generation

Figure 7 presents the change in emissions by broad sector (left) and detailed energy sector (right). The graph highlights that the driver of change in emissions seen in Figure 6 is driven by changes in emissions in the energy sector, although industrial processes and product use (IPPU) emissions do also visibly decline in the 6 and 7 GT scenarios. This result is, however, likely because of the steeper declines in GVA.

Within energy, the bulk of emissions savings take place in energy industries, particularly electricity generation, which accounts for between 62% and 95% of energy emissions savings. When no PAMS are included more emissions savings are required by the electricity generation sector (92–95%). In the PAMS scenario this burden is shared with Transport, which accounts for between 5% and 30% of emissions savings. Commercial and manufacturing and industry account for small shares of energy savings – although increased energy efficiency in the PAMS scenarios enable these shares to be larger, adding to the relief of the electricity sector.

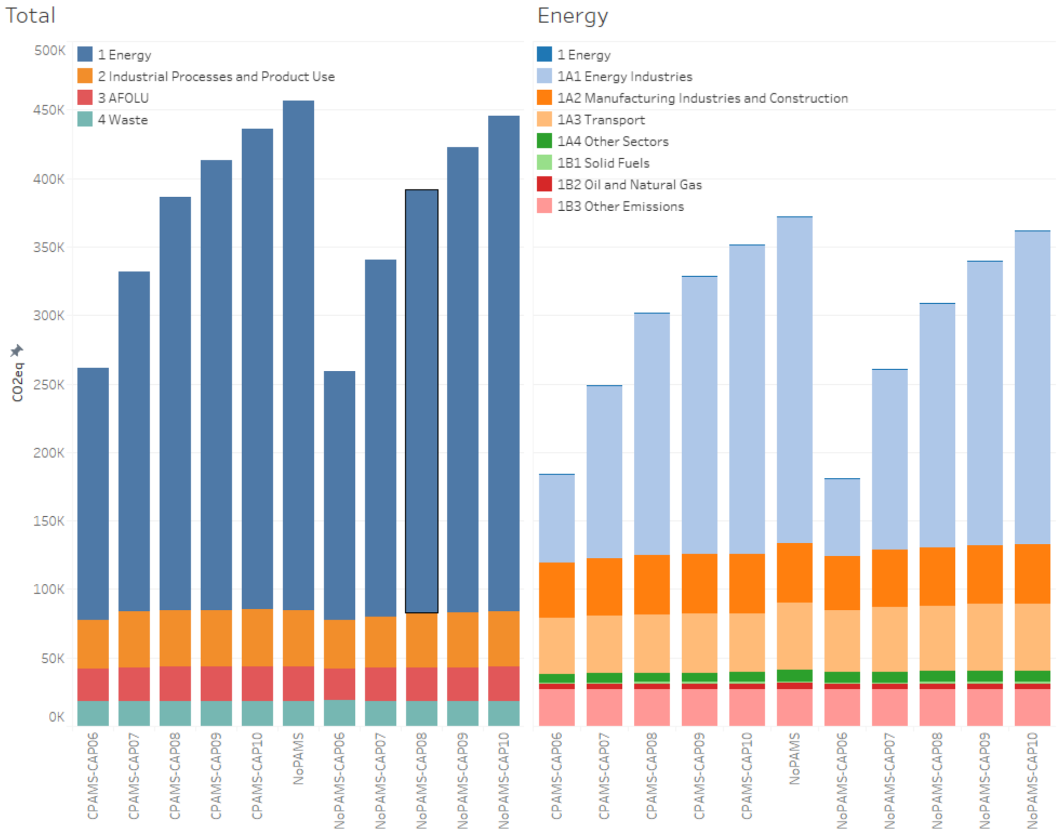

Figure 7: Emissions (excluding LULUCF) by sector and scenario, 2030

6.2.1 Power sector

Figure 8 presents the change in power generation by technology. Increased energy mitigation targets require a faster shift away from coal power. Without PAMS, the share of coal in power generation decreases from 76% in the NoPAMS scenario in 2030 to 9% in the 6 GT scenario. When PAMS are included, the decline is marginally smaller, falling to 12%. Energy efficiency improvements included in the PAMS scenarios reduces the demand for generation by between 8% and 11% in comparable scenarios (e.g. NoPAMS-CAP10 vs CPAMS-CAP10).

The decrease in coal power generation is replaced with rising shares of, primarily, solar PV and wind power generation, although imports and battery storage also increase. In the 6 GT scenarios, solar PV and wind account for roughly 60% of power generation (with and without PAMS) from 10% in the NoPAMS reference case. An interesting observation from the analysis is that battery storage is only chosen when emissions caps are very stringent – in the no PAMS scenarios this occurs under the 7 GT cap. When PAMS are included this comes online under the 6GT cap.

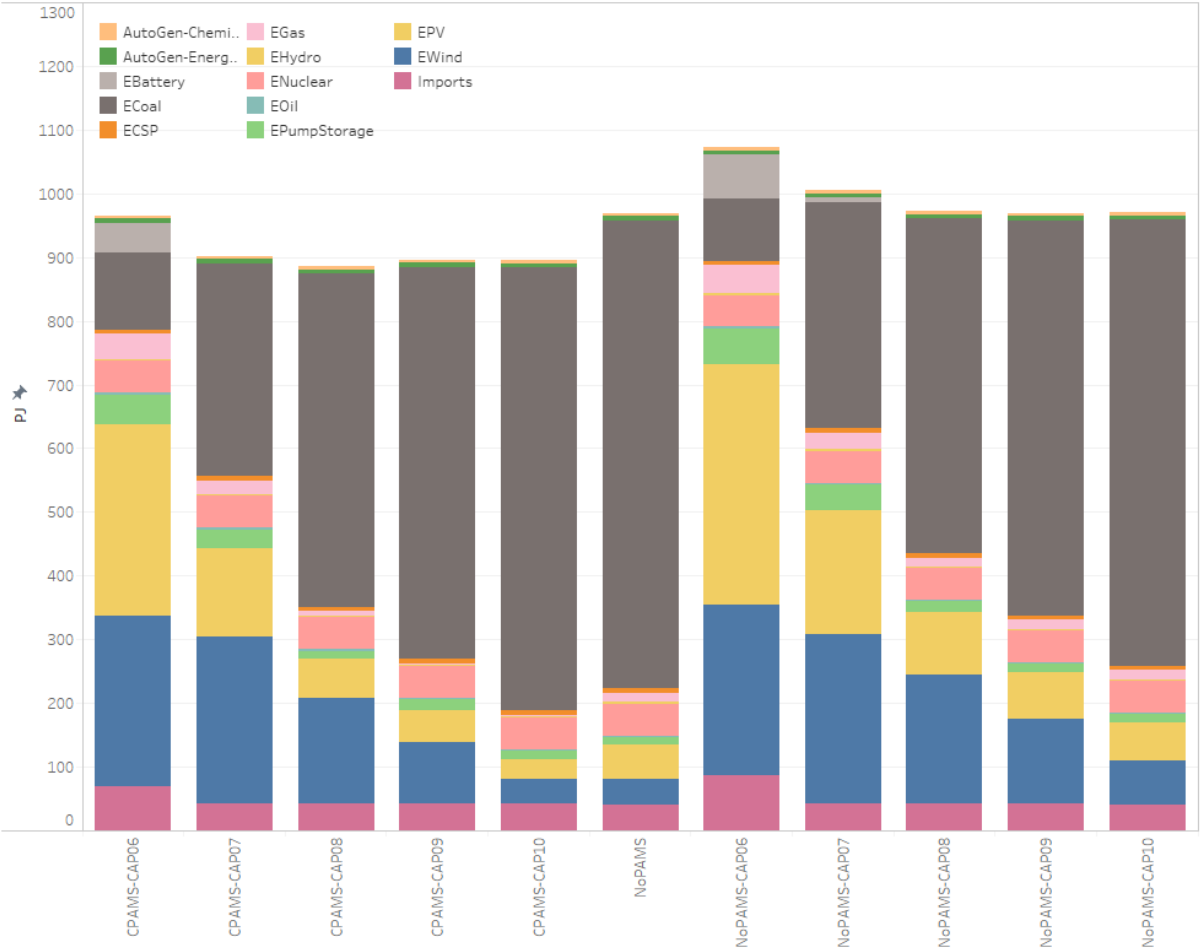

Figure 8: Power generation by technology, 2030

Table 4 provides a detailed view of the make-up of coal power generation by plant for each scenario in 2030. Rising mitigation efforts forces a reduction in power from coal, although the result show that earlier coal decommissioning only takes place under the 7 GT and 6 GT caps. The TIMES model endogenously chooses the cheapest options for decommissioning. These are identified as Duvha, Kusile, Majuba WET and DRY, and Tutuka. Under the PAMS scenario Medupi is also decommissioned under the 6 GT scenario. An interesting finding is the significant decrease in production by the Medupi and Kusile coal plants as well as the decommissioning of these under more stringent emissions caps. This is primarily driven by the higher fuel costs associated with these plants, despite them being less emissions intensive.

Table 4: Coal power generation by plant, 2030

	Coal power generation, PJ										
		Without PAMS					With PAMS				
	NoPAMS	10GT	9GT	8GT	7GT	6GT	10GT	9GT	8GT	7GT	6GT
Duvha	54.6	54.6	54.6	54.6	36.3	0.7	54.6	54.6	54.6	36.3	0
Kendal	88.3	88.3	88.3	79.4	48.4	29	88.3	88.3	57.9	48.4	3.7
Kusile	93.4	57.9	54.6	54.6	0	0	57.9	54.6	54.6	0.9	0
Lethabo	82.3	82.3	82.3	82.3	44.9	31.2	82.3	82.3	82.3	62.9	29.9
Majuba DRY	41	41	41	23.1	23.1	0	41	41	23.1	23.1	0
Majuba WET	45	45	45	25.4	25.4	0	45	45	25.4	25.4	0
Matimba	92.4	92.4	92.4	92.4	46.5	46.5	92.4	92.4	92.4	46.5	31
Matla	63.2	63.2	58	36.3	36.3	12.4	63.2	63.2	36.3	36.3	0
Medupi	110.7	106.1	54.6	29.8	39.7	0	110.7	54.6	54.6	54.6	32.2
Tutuka	64.2	64.2	44.3	44.3	33.7	0	64.2	44.3	44.3	19.5	0
Total	735.1	695	615.1	522.2	334.3	119.8	699.6	620.3	525.5	353.9	96.8

6.2.2 Transport

The decrease in transport emissions is driven by the decline in road transport emissions. In the NoPAMS scenarios, road transport emissions decrease by between 1% and 9% relative to the NoPAMS reference case. These reductions are larger in the PAMS scenarios, where energy efficiency is improved, and more mode switching from private to public and from road to rail takes place. In 2030, road transport emissions are between 14% and 17% smaller than the NoPAMS reference case. Emission declines are led by declines in energy demanded from private passenger transport, which under the PAMS scenarios are double that of the road freight sector.

By 2030, in the NoPAMS reference case, the bulk of fuel for road transport, freight and private, still comes from traditional petrol and diesel sources (see Figure 9). Gas and electricity enter the fuel mix of freight in the last five years of the analysis period (hydrogen in the last three) but at small levels. As energy emission caps are imposed, the demand for gasoline and diesel decreases and is replaced with electricity. These shifts are larger in the freight sector where gas use also increases. As presented at the start of this section, transport only significantly contributes to the decline in emissions by 2030 when energy efficiencies are included.

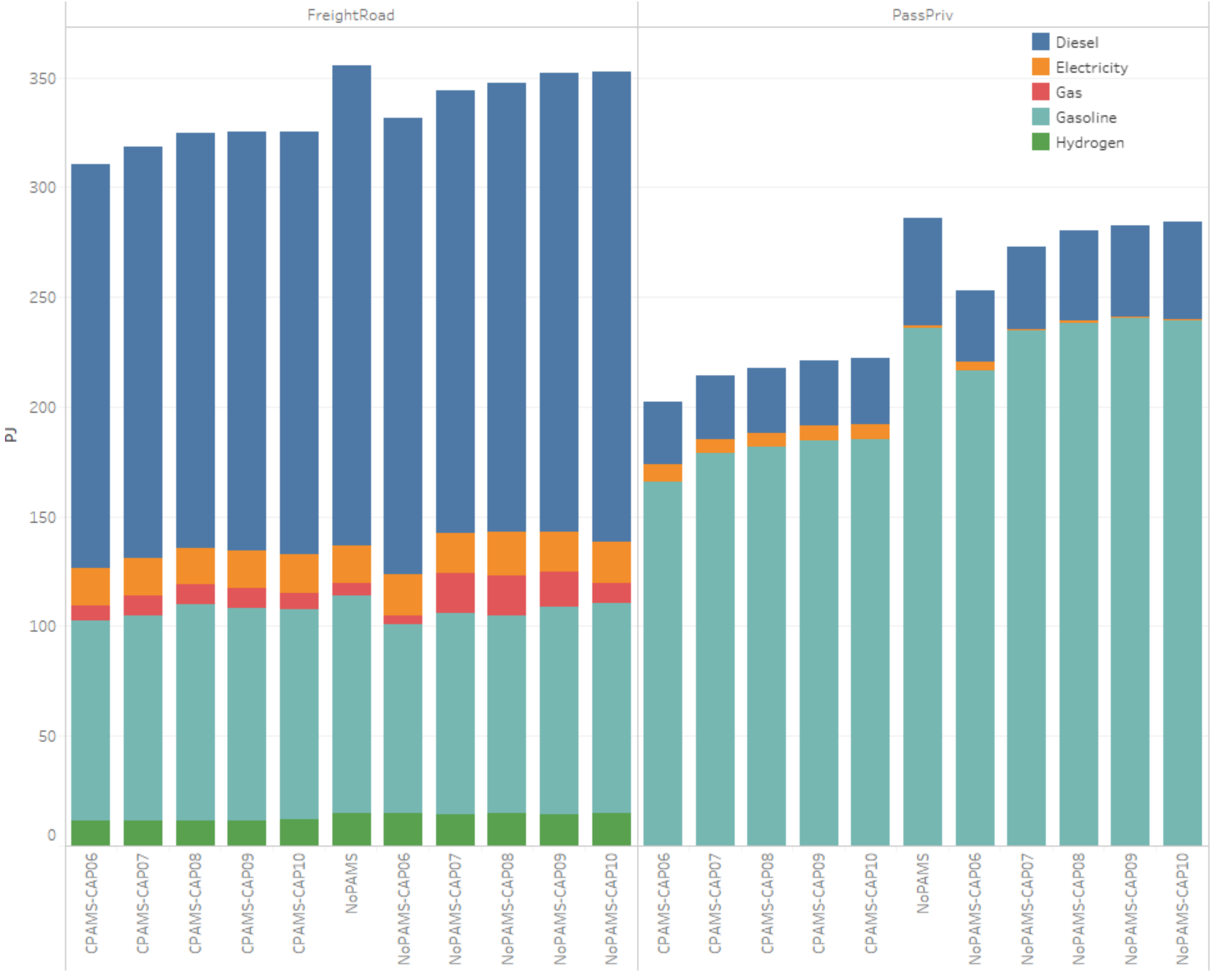

Figure 9: Energy demand by road freight and private passenger transport

6.3 Sector growth and employment

***Table 5* and** **Large changes in hydrogen production are due to small values*

Table 6 present the GVA and employment impacts by sector. As expected, the coal-mining sector is the worst affected by the implementation of emissions caps as demand from the power sector decreases. This is followed by declines in energy-intensive sectors such as non-ferrous metals. Declines in activity are broad-based under the no PAMS scenarios, as higher levels of investment and electricity prices (relative to the NoPAMS reference case) are experienced. The decline in electricity production as emission caps rise is due to the decline in economic activity. In scenarios where the PAMS are included, declines in activity (relative to the NoPAMS reference case) are experienced in coal mining and electricity predominantly. The latter is due to the rise in energy efficiency which leads to a decrease in power demanded. Employment impacts are aligned to the changes in GVA. Employment losses range between 23 000 and 1.4 million in the no PAMS scenarios. In scenarios including PAMS, employment increases in the 8, 9 and 10 GT scenarios. The increase in jobs in the 10 GT scenario (with PAMS) is primarily to due to continued growth in less energy-intensive sectors such as commerce, which are also large employers of labour.

Table 5: Sector GVA impacts, 2030

	GVA (% difference in level relative to NoPAMS)									
	Without PAMS					With PAMS				
	10GT	9GT	8GT	7GT	6GT	10GT	9GT	8GT	7GT	6GT
Agriculture	-0.3	-0.6	-1.2	-2.9	-7.0	1.2	0.7	0.1	-1.3	-4.6
Coal mining	-1.0	-3.6	-7.6	-13.1	-23.0	-2.2	-4.9	-8.3	-15.0	-22.2
Other mining	-0.4	-1.0	-1.7	-3.4	-7.7	0.3	-0.2	-0.6	-2.0	-5.7
Food, bev. & tob.	-0.3	-0.6	-1.1	-2.8	-7.0	1.1	0.7	0.1	-1.2	-4.3
Pulp and paper	-0.3	-0.8	-1.3	-3.3	-8.3	1.5	0.9	0.2	-1.1	-4.9
Refineries	-0.1	-0.1	-0.1	0.0	-0.1	-0.4	-0.4	-0.3	-0.3	-0.3
Hydrogen*	2.6	-2.1	0.1	-2.0	0.6	-20.3	-21.9	-22.5	-23.7	-24.2
Chemicals	-0.3	-0.7	-1.4	-3.5	-8.4	1.6	1.1	0.4	-1.3	-5.0
Non-metallic minerals	-0.3	-0.6	-1.3	-3.4	-8.3	1.4	0.9	0.2	-1.4	-5.2
Iron and steel	-0.3	-1.0	-1.9	-4.7	-10.6	1.0	0.3	-0.4	-2.5	-8.2
Non-ferrous metals	-1.1	-3.0	-5.3	-12.2	-22.9	2.0	0.6	-1.6	-8.6	-20.0
Other industry	-0.3	-0.6	-1.3	-3.4	-8.4	1.7	1.2	0.4	-1.2	-5.0
Electricity	-0.2	-0.5	-0.9	-2.2	-9.8	-2.4	-3.0	-4.0	-5.0	-10.7
Transport	-0.4	-0.9	-1.9	-4.2	-9.8	0.0	-0.7	-1.7	-3.6	-7.8
Commerce	-0.2	-0.6	-1.2	-3.3	-8.1	1.3	0.8	0.2	-1.4	-5.1
Total	**-0.3**	**-0.7**	**-1.4**	**-3.5**	**-8.4**	**1.0**	**0.5**	**-0.2**	**-1.9**	**-5.7**

**Large changes in hydrogen production are due to small values*

Table 6: Employment impacts by sector, 2030

	Employment (level difference relative to NoPAMS, '000s)									
	Without PAMS					With PAMS				
	10GT	9GT	8GT	7GT	6GT	10GT	9GT	8GT	7GT	6GT
Agriculture	-1	-1	-4	-18	-44	9	8	5	-5	-26
Coal mining	-1	-2	-5	-9	-15	-1	-3	-5	-10	-15
Other mining	-1	-3	-6	-12	-28	-3	-4	-5	-9	-22
Food, bev. & tob.	-1	-1	-3	-11	-30	6	5	3	-3	-16
Pulp and paper	0	0	-1	-2	-6	1	1	0	0	-3
Refineries	0	0	0	0	0	0	0	0	0	0
Hydrogen	0	0	0	0	0	-1	-1	-1	-1	-1
Chemicals	-1	-2	-4	-10	-24	5	3	1	-4	-14
Non-metallic minerals	0	-1	-1	-5	-12	3	2	1	-1	-7
Iron and steel	-1	-2	-3	-8	-17	2	1	-1	-4	-13
Non-ferrous metals	0	-1	-1	-3	-5	0	0	-1	-2	-5
Other industry	-5	-12	-31	-97	-248	66	54	33	-17	-132
Electricity	1	5	10	20	22	-6	-4	0	11	16
Transport	-1	-3	-6	-15	-36	-2	-4	-8	-15	-31
Commerce	-14	-44	-107	-370	-969	200	165	87	-113	-550
Total	-23	-65	-161	-538	-1410	278	223	110	-173	-816

7 DISCUSSION

The analysis in this paper has illustrated that over the past decade the reference pathway for emissions in South Africa has been revised downward from the information available at the time of the development of the NDCs. These downward shifts have largely emanated from the increased ability to cost effectively lower emissions in the power sector – the largest-emitting sector in South Africa. The change in reference case emissions over time highlights the importance of conducting sensitivity or scenario analysis for the reference case, as well as the importance of consistent updates to reference case projections such that changing trends can be captured, with policy adjusted accordingly. Clearly, three primary drivers need to be assessed to understand future emissions trajectories, namely economic growth and structure; technology costs; and implementation of mitigation policies and measures.

The NoPAMS reference case presented here indicates that by taking a least-cost approach to energy planning, South Africa can reach an emissions level of 431 MT CO_2-eq by 2030, well within its NDC commitment (below the mid-point thereof), and below the CERC 2 °C fair share allocation. Research by Merven et al. (2019b; 2020a; 2020b) and Hartley et al. (2019) has shown that energy pathways such as these, while negatively affecting the coal sector, do not negatively affect overall economic growth and employment in the country. It also highlights that the current NDC, which is insufficient for meeting the requirements as set out by science, need to be revisited in terms of ambition.

Decreasing energy emissions beyond the NoPAMS reference case point are found in this analysis to have a negative impact on economic growth and employment, although these impacts are small for energy emissions caps of up to 8GT – delaying the level of real GDP by less than one year. Declines in energy sector emissions beyond this point have increasing costs for the economy, relative to emissions gains.

The negative impacts on the economy can, however, be mitigated by increasing energy efficiency in line with government policies and measures. This is presented by the positive impact of the 9 and 10 GT energy emission cap scenarios relative to the reference case and smaller negative impacts of the 8, 7 and 6 T energy emission cap scenarios. With energy efficiency in place, it is possible to meet the 7 GT limit (within the CAT – 1.5 °C range), at a similar cost to that of the 8 GT without energy efficiency. The result highlights the importance of demand-side measures in reducing energy demand, and hence emissions, in the country. In the most stringent case modelled in this paper, i.e. 6 GT, the real level of GVA is delayed by 2–3 years relative to the reference case when energy efficiency improvements are accounted for, relative to 45 years when they are not. It is important to note that the role for climate financing has not been included in this analysis and could assist in further reducing the negative impacts of larger declines in emissions.

Future work is needed around how to increase the level of mitigation ambition for South Africa at the 2050–2060 horizon, while still meeting other development objectives, at least meeting South Africa's other SDGs of access to clean energy and poverty alleviation, given setbacks caused by the 2020 COVID-19 pandemic.

Areas to explore include in the energy model are other technology options on the demand side, which are not currently included, especially in the sectors which are hard to decarbonize, such as minerals and metals. Also, there should be exploration in more detail as to how the manufacturing sector could wean itself from the use of coal and how one could also reduce emissions from the Secunda coal-to-liquid complex, assumed in this study to continue as is until 2050.

In the CGE model, we need to further improve on work already done on households in long-term models (Merven et al. 2020a), to account for changes in consumer preferences over time and how this impacts consumption, energy demand and trade. The CGE would also be a good platform to explore scenarios of efficiency gains in material use outside of the energy sector, as done by Le Treut (2017) for steel and cement. The current CGE model used in this analysis has an almost fixed structure of the economy based on the underlying input data (i.e. 2012 SAM). While the linked modelling framework ensures that energy input changes are accounted for, the future evolution of the different sectors could be made more responsive to changes in demand for different types of goods domestically and internationally, as specified in improvements mentioned above. Allowing for this transformation may lower the observed cost to the economy of a more ambitious low-carbon transition in the medium-to-long term.

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APPENDIX A: ECONOMIC ASSUMPTIONS

eSAGE

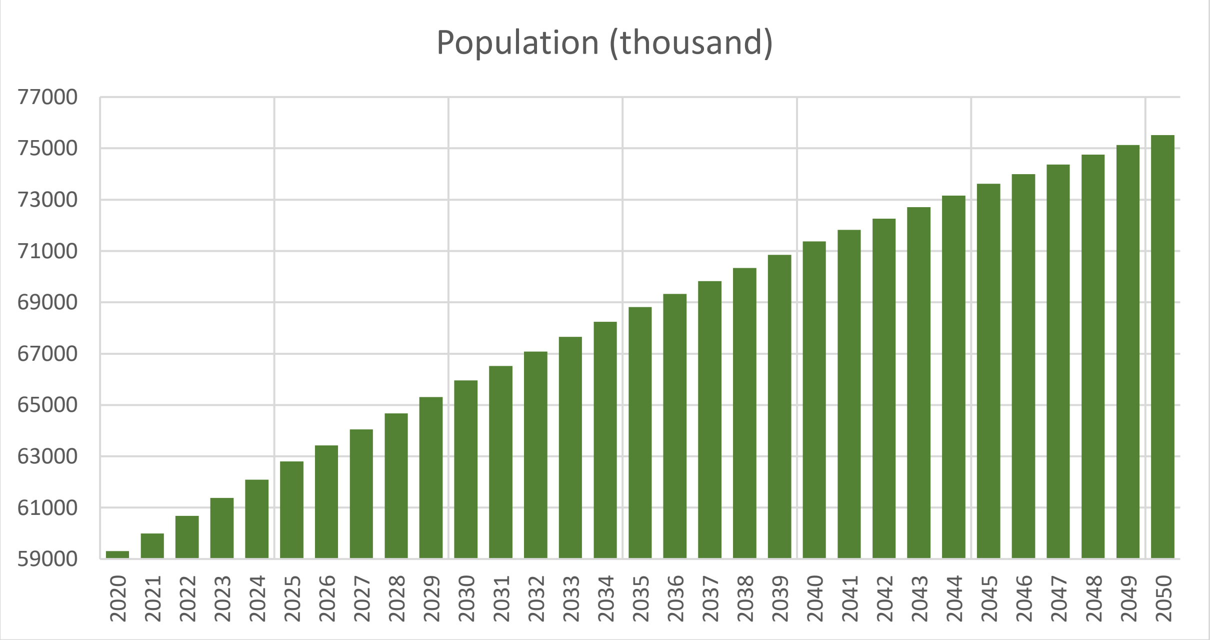
The growth rate in the Reference scenario is targeted to meet actual growth between 2012 and 2017, whilst growth between 2018 and 2050 is based on a combination of projections from the 2020 Supplementary Budget (National Treasury, 2020) and the April 2020 Bureau for Economic Research extended forecast, and optimistic extrapolations of these outlooks considering the country's weak domestic fundamentals, constrained fiscal space, electricity supply issues and weaker global growth in light of the COVID-19 pandemic. In the 2020s, the economy is assumed to grow at an annual average rate of 2.2% rising to 2.6% in the 2030s and 2.9% in the 2040s. Between 2020 and 2050, the average annual growth rate is 2.6% – 0.4 percentage points (%points) below the historical energy planning growth rate of 3%.

Exogenous assumptions are the same across scenarios. The supply of labour is assumed to increase by 2.5%, although upward sloping labour supply curves are assumed for all skill categories, given the long-term nature of the analysis, which means that increases in wages resulting from higher labour demand increase the labour force participation rate. Government spending and foreign savings increase by 2.4% and 1.7% per annum, respectively. Total factor productivity is adjusted in the Reference scenario to reach the real GDP growth forecasts discussed above.

The macroeconomic closures included are aligned to the stylized facts for South Africa: investment is driven by the total level of savings in the economy although investment and government expenditure as shares in total absorption are fixed (balanced savings-investment closure); government savings are flexible and no fiscal rule is imposed; the exchange rate is flexible with the level of foreign savings (in foreign currency) rising by an exogenous growth rate which decreases over time as South Africa repays its foreign debt. Existing capital is assumed to be fully employed and activity specific. A least-cost optimal energy pathway from the South African Times model is included. The latter provides information on energy production and investment, and electricity prices.

Population

Population projections are taken from Table A.1 in the United Nations Department of Economic and Social Affairs "World Population Prospects 2019", vol. 1, and are presented below.



APPENDIX B: ENERGY ASSUMPTIONS - SATIM

Electricity sector parameterization

Within SATIM, the power sector is split into generation, transmission and distribution, shown graphically in Figure A1. Operating power plants are represented individually and the power sector in SATIM includes the expected decommissioning schedule of coal-fired power plants, all planned new builds, planned retrofits as well as plant technology characteristics (efficiency, capacity factors, individual cost components etc).

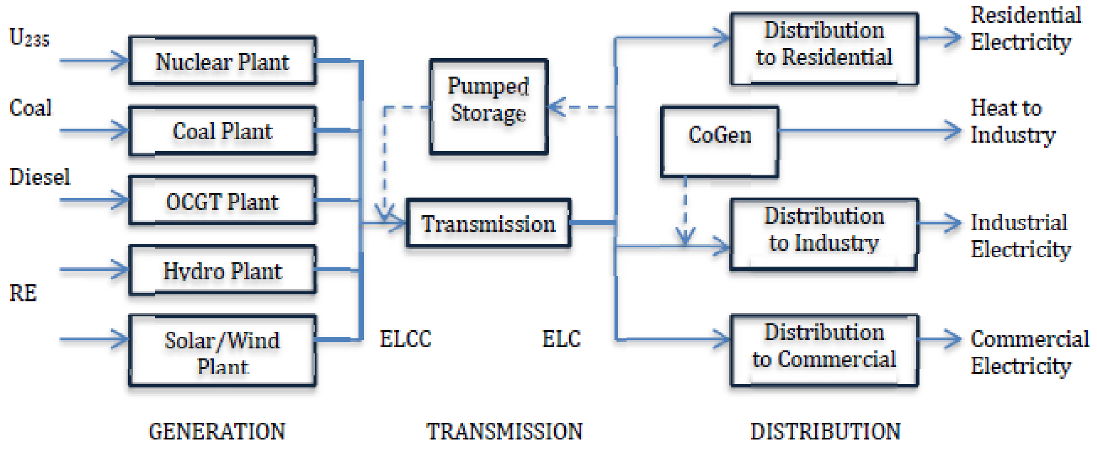


Figure A1: RES diagram of power sector in SATIM

Existing capacity

Capacity values and decommissioning dates are taken from Eskom (2018), NERSA (2018), and the IRP 2019 (DMRE, 2019) reports. Availability for the plants has been taken from Table 6 of the IRP 2019 report, combined with data from Eskom CDM webpage (Eskom 2018).

Table A1: Existing power sector capacity and plant availability

Station	Type	Capacity (GW) - 2020	End of life	Maximum availability %		
				2020	2025	2030
Camden	Coal	1.481	2028	57	60	-
Grootvlei	Coal	0.570	2022	38	-	-
Komati	Coal	0.205	2022	35	-	-
Arnot	Coal	2.232	2029	55	66	-
Duvha	Coal	2.875	2034	57	61	60
Hendrina	Coal	1.293	2026	58	61	-
Kendal	Coal	3.840	2044	77	74	73
Kriel	Coal	2.850	2030	54	64	64
Lethabo	Coal	3.558	2041	64	75	71
Majuba (dry)	Coal	1.833	2048	73	77	71
Majuba (wet)	Coal	2.010	2051	73	77	71
Matimba	Coal	3.690	2042	83	78	79
Matla	Coal	3.450	2034	68	71	70
Tutuka	Coal	3.510	2041	56	61	58
Kelvin b	Coal	0.600	2027	32	32	-

Station	Type	Capacity (GW) - 2020	End of life	Maximum availability %		
				2020	2025	2030
Sasol SSF coal plant	Coal	0.600	post 2050	73	73	73
Sasol Infrachem coal plant	Coal	0.128	post 2050	56	56	56
OCGT liquid fuels	Diesel	2.460	2040	96	96	96
Hydro - South Africa	Hydro	0.665	post 2050	12	12	12
Hydro - imported	Hydro	1.500	post 2050	69	69	69
Koeberg	Nuclear	1.860	2045	84	84	84
Pumped hydro storage	Storage	1.580	post 2050			

The costs for coal supply are defined for each plant and are based on Eskom (2019), since this is not made available in the Integrated Resource Plan.

Committed new build

This is capacity that has come online since 2012 and/or is under construction, which includes new coal power, diesel peaker turbines, micro-hydro, pumped hydro, and renewable energy.

Table A2: Committed new capacity additions (GW)

	2012–2017	2018	2019	2020	2021	2022	2023	Total
Medupi	1.44	0.72	0.72	0.72	0.72	-	-	4.33
Kusile	0.72	-	-	1.44	0.72	0.72	0.72	4.33
Pumped storage - Ingula	1.32	-	-	-	-	-	-	1.32
DoE peakers (diesel)	1.01	-	-	-	-	-	-	1.01
Micro hydro	-	-	-	-	0.005	-	-	0.005
CSP 9 hrs storage	0.30	0.10	0.10	-	-	-	-	0.50
Solar PV fixed	1.92	-	-	-	-	-	-	1.92
Solar PV tracking	0.51	-	-	0.11	0.30	0.40	-	1.33
Wind	2.64	-	-	0.24	0.30	0.82	-	4.00

Source: DMRE (2019)

Combining the existing stations with the committed new build the total installed capacity in South Africa is 56.82 GW of which 40.5 GW is coal capacity (i.e. 71% of installed capacity).

Table A3: Total capacity in 2020 (GW)

	Committed build – commissioned by 2020	Existing stations	Total
Coal	5.78	34.725	40.50
Pumped hydro	1.32	1.58	2.90
OCGT	1.01	2.46	3.47
Hydro (incl. Imported hydro power)	-	2.165	2.17
CSP	0.50	0	0.50
Solar PV	2.55	0	2.55
Wind	2.88	0	2.88
Nuclear	-	1.86	1.86
Total	14.03	42.79	56.82

The Medupi and Kusile power stations, together representing the largest share of new generation capacity in South Africa, have been reporting low availability factors while technical problems in construction and commissioning are addressed. We assume that the maximum availability factors rise from 55% and 40% respectively in 2020, to 80% each by 2025. Availability factors for the power stations on the system are taken from DMRE (2019).

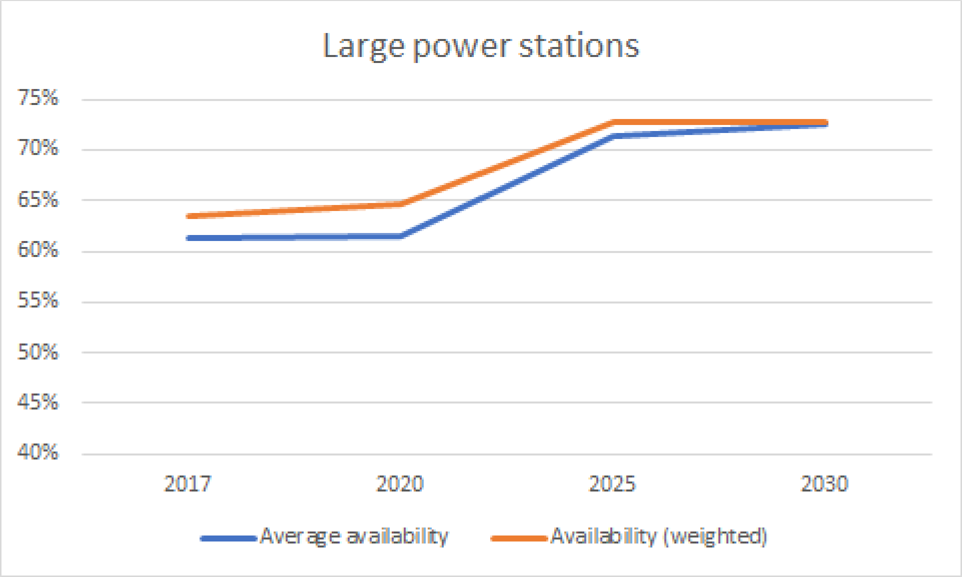


Figure A2: Availability of coal stations and Koeberg (excluding proposed IRP coal capacity)

New build options for SATIM

The costs for new build options are aligned with the IRP 2019 (DMRE, 2019), based on EPRI (2017), adjusted for inflation and including 10% owner's development costs. The costs for Medupi and Kusile are updated based on capital expenditure profile in Steyn et al. (2017).

Table A4: New power capacity build options (DMRE, 2019)

	Efficiency	Variable Cost R/GJ (2015 ZAR)	Fixed Cost mR/GW per year (2015 ZAR)	Overnight Investment Cost R/kW (2015 ZAR)	Lead time	Life of plant
Medupi*	37%	80.66	845	36 529	6	30
Kusile*	37%	80.66	845	36 529	6	30
Generic supercritical Waterberg coal plant	44%	80.66	933	39 335	4	30
Pumped storage new Ingula *	78%		183	22 451	6	50
DOE peakers*	31%	2.41	162	9 066	2	30
Fluidised bed Combustion coal	33%	174.55	568	46 960	4	30
Micro hydro*	100%	0.00		11 516	2	50
Nuclear mid	35%	37.29	977	68 550	9	60
Solar central receiver 09 hrs storage	100%	0.89			3	30
Solar PV fixed	100%	0.00	270	See Table A3	1	25
Solar PV tracking	100%	0.00	286	See Table A3	1	25
Wind	100%	0.00	611	See Table A3	2	20
Inga III	100%			51 227	5	50
Open cycle gas Turbine - LNG	31%	2.41	162	9 066	2	30
Combined cycle gas Turbine – LNG	49%	22.06	167	9 955	3	30
Gas engines – LNG	45%	70.57	425	14 144	2	30
Biomass municipal waste	45%	115.14	1594	18 911	3	25
Landfill gas	45%	62.26	1594	18 911	3	25

* Committed new build capacity, for information.

New renewable energy generation plant costs and performance are based on Ireland and Burton (2018). Solar PV and wind technology cost reduction projections for the reference scenario learning can be seen in the figure below, shown in April 2016 ZAR/kWh, model inputs are in January ZAR 2015. National wind and PV temporal energy production profiles and the removal of total resource constraints are based on (DoE REDIS, 2018) and (CSIR, 2016).

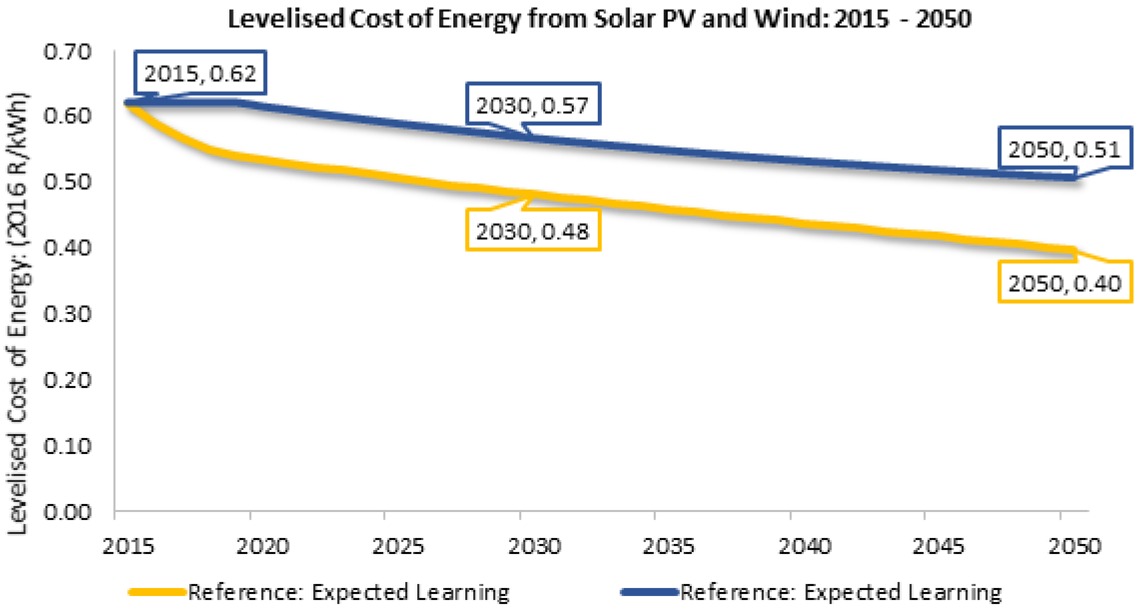


Figure A3: Projected levelised costs of electricity from centralised single-axis tracking solar PV and onshore wind from 2015 to 2050

Solar PV reference scenario technology assumptions

- Annual capacity factors are assumed to be 28% using single-axis tracking solar PV technology, and 25% for fixed-tilt. This is based on existing South African plant performance, using historical hourly production data from 2015-2017 (DoE REDIS, 2018). Plant life is 25 years, and construction time one year. The earliest date for new centralised solar PV capacity to come online is assumed to be 2023.
- Plant cost and performance parameters are modelled to start at calculated 2015 Round 4-expedited REIPPPP values, and improve, using adapted projected rates of change according to the National Renewable Energy Laboratory (NREL) Annual Technology Baseline (NREL ATB, 2018)

Onshore wind reference scenario technology assumptions:

- Annual capacity factors for new onshore wind farms are assumed to start at 36% for plants of size 100MW+ (DoE REDIS, 2018). This increases to 43% in 2050. Plant life is 20 years, and construction time 2 years. The earliest date for new wind capacity to come online is assumed to be 2024.
- Plant cost and performance parameters are modelled to start at calculated 2015 REIPPPP values and change using adapted projected rates of improvement according to the NREL Annual Technology Baseline (NREL ATB, 2018), and IEA Wind (2018).

Table A5: New renewables and battery storage overnight investment cost and capacity factor

	Annual capacity factor (%)	**Cost in mR/GW**					
Technology		2017	2020	2025	2030	2040	2050
Solar central receiver 09 hrs storage	47	57 809	52 631	43 999	35 368	35 368	35 368
Solar PV fixed	25	12 570	8 900	8 355	7 849	6 973	6 160
Solar PV tracking	28	14 788	10 471	9 829	9 234	8 203	7 247
Wind	36 (2020) – 43 (2050)	15 313	12 500	12 286	12 126	11 966	11 859
Utility scale storage - 4hrs	NA	27 165	20 310	14 179	9 963	9 197	9 197
Solar PV rooftop (Commercial)	20	14 581	10 324	9 691	9 105	8 088	7 146
Solar PV rooftop (Residential)	20	21 997	15 576	14 621	13 736	12 202	10 780
Solar PV rooftop (Industry)	20	14 581	10 324	9 691	9 105	8 088	7 146

Utility-scale storage costs and performance are based on multiple sources as described in ESRG (2019) and are modelled as lithium-ion batteries with four hours of storage, 89% round-trip efficiency, 15 year operating life, and fixed maintenance cost of 0.6% of CAPEX per year.

Additional power sector constraints and assumptions

A 15% firm reserve margin is imposed for the grid from 2025, i.e. the installed dispatchable capacity must be at least 15% higher than the expected peak demand, to account for plant maintenance, breakdowns, or periods of higher than expected demand, in line with global norms and work by the CSIR (2020).

We conservatively assume that variable renewable energy cannot contribute to meeting peak demand. Wind and solar generators are modelled to be fully backed up by dispatchable generation or storage regardless whether their profiles may contribute during peak times (i.e. a 0% capacity credit is used). Battery storage is modelled to have only 70% of its capacity contributing to the reserve margin constraint, to account for the potential of extended periods of low national wind and solar generation.

It is assumed that for all coal-fired power plants there is a 40% minimum utilization of capacity for it to be available to contribute to the peak demand reserve margin, and stay online in the system and not be decommissioned.

In SATIM the centralised bulk electricity transmission system is modelled as a single node and sized to meet the projected peak electrical demand in each year. The cost of replacement and additional transmission lines and transformers are costed as a single R/kWpeak value based on Eskom integrated annual reports (9 700 R/kW) and central transmission energy losses are set according to Eskom integrated reports [2]. Additional “deep grid strengthening” costs (such as RE collector stations) are added for the total generating capacity which exceeds the peak transmission system capacity able to meet peak demand (2 000 R/kW) – these costs are aligned with Eskom work done for the IRP 2018/19 (Eskom, 2017).

Distribution systems are sized and invested in within each economic sector to meet their respective peak demands. Their costs are based on the split of costs for Eskom scaled up by the distribution capacity of Metros. The historical capital repayment costs and maintenance costs are calibrated to Eskom reported costs and values observed in the Social accounting matrix for 2012. A different distribution cost (and losses) apply to different sectors. Lower voltage residential sector grid costs are more labour- and equipment-intensive and so are more expensive. Distribution system energy losses, technical and non-technical (i.e. theft), are modelled on aggregate per sector and aligned with NERSA (2012).

New renewable generation build limits
In the base dataset for SATIM (i.e without a specific scenario affecting RE build rates) an upper limit on the build rate is applied to wind power of 1 GW per year starting in 2020 and ramping up gradually to 2 GW by 2025, 3 GW by 2030 and finally 4 GW per year by 2040.

For solar PV, these rates are applied as well, however, it is assumed that solar PV can be rolled out faster in the early 2020s – with 2 GW per year assumed starting from 2020, 2.5 GW by 2025, 3 GW in 2030, and 4 GW in 2040 and thereafter. These build rates are also applied equally to rooftop PV in residential, commercial, and industrial rooftop PV each at 1 GW/year in 2020, 2 GW/year in 2025, 3 GW/year in 2030 onward.

Note that different scenarios may include adjusted build rates for RE technologies, which are explained in their respective scenario descriptions.

Additional reliability constraints and assumptions
Variable wind and solar power production need to be complemented with effective storage capacity or flexible generation. In this methodology, an assumption on utilization of storage and gas technologies is used to provide effective backup to large scales of renewables on the grid.

Gas turbines and diesel peakers are required to provide at least 8% of the total generation from wind and solar power. This is set conservatively using an indicative “worst case scenario” of an optimized electricity system in South Africa fully supplied by wind, solar, flexible gas, and battery storage of a full year in 2050 using hourly renewable production and demand profiles to test the flexibility and backup requirements needed for a system with 90%+ variable renewable electricity supply.

The power sector build plan results will be validated further using the high resolution IRENA FlexTool (IRENA, 2018) to ensure that sufficient flexible dispatchable capacity is available at all times to ensure adequacy and reliability of the suggested build plans from SATIM. The minimum requirements for additional flexible generation or storage will be adjusted based on this validation.

Transport sector parameterization

The transport sector in SATIM includes energy used for passenger and freight transport by road and rail. It also includes energy used in pipeline transfers, aviation and a general “other” sector (incorporating maritime fuel use). Energy demand for passenger and freight transport is driven primarily by two factors, a) vehicle-kilometres travelled and b) the efficiency of travel. The vehicle-kilometres travelled is driven by the needs of society and the economy to move people and goods around. Conversion efficiency differs with vehicle type, fuel type and the age of the vehicle parc and to some degree the patterns of utilization of different vehicle types, as described by Stone et al. (2018) and Ahjum et al. (2018)

Aspects of transport included in the parc model are the size of the existing vehicle fleet, annual vehicle sales, annual vehicle scrapping, distance travelled per vehicle, fuel sales and vehicle fuel efficiency. Outputs of the vehicle parc model are total kilometres travelled, the average age of vehicles in the vehicle fleet and the average efficiency of the vehicle fleet. These components allow efficiency or intensity of transport to change with vehicle stock changes and an increase or decrease in vehicle ownership in response to population and income changes.

Certain factors affecting the distance travelled and fuel efficiency, for instance traffic congestion, are difficult to quantify as they are not well understood. To accommodate the unknown impact of tangible and intangible influences on efficiency, the vehicle parc model is calibrated by adjusting variables such as vehicle occupancy and ownership assumptions until the output (annual distance travelled by vehicles) in combination with vehicle fuel efficiency matches known fuel sales data. The annual distance travelled by vehicles is translated into a demand for passenger kilometres by assuming average occupancy rates for the different vehicle types in SATIM.

The energy service demand in SATIM is defined in terms of passenger kilometres and tonne kilometres. The ownership of passenger cars in the passenger demand projection model is split between three income groups and a miscellaneous category to accommodate commercially- and government-owned cars. With population projections for each of the income groups, the passenger demand projection model uses assumptions around private vehicle ownership by income group, vehicle mileage, vehicle occupancy, public mode shares, average mode speeds, and a travel time budget to derive vehicle-km demand by passenger vehicle class for households. This is combined with a transport-GDP linked projection of the non-household owned cars to give a total passenger vehicle-km demand projection for road vehicles. The passenger-km projections by rail are derived from assumptions around future mode shares. The freight demand projection model takes sector GDP projections and, based on assumptions around load factors and mode shares, makes projections of vehicle-km for different freight vehicle classes. The projections for ton-km are derived from assumptions around future mode shares. Vehicle-km projections for road vehicles are then exogenously imposed in SATIM, which is used to project the least-cost technology and fuel mix to meet the projected vehicle-km demand.

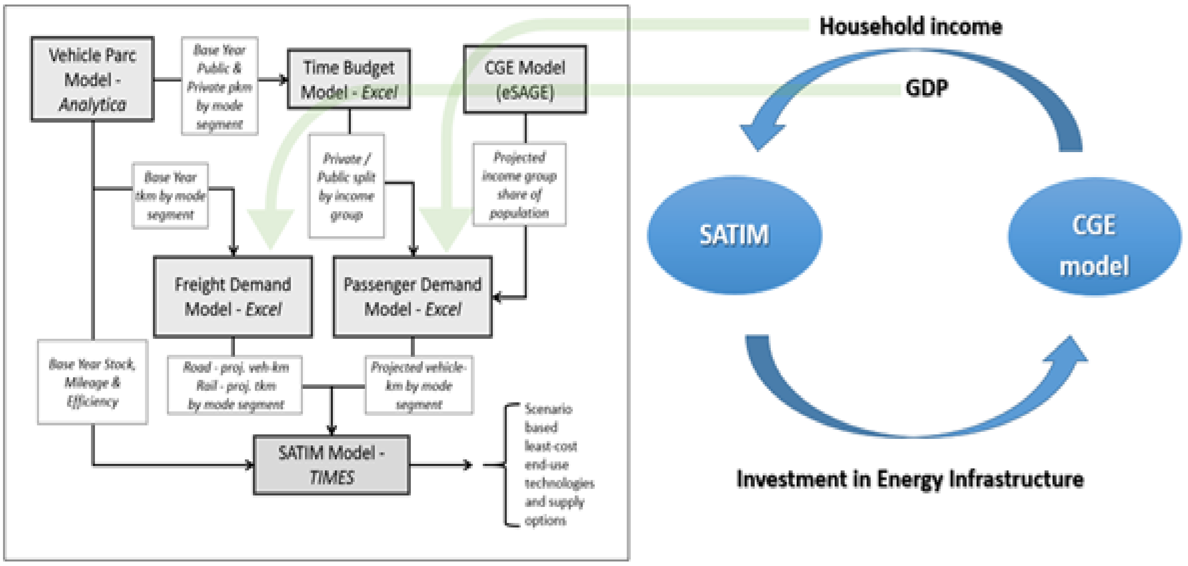


Figure A4: Overview of the SATIM transport sector model (Merven et al. 2012)

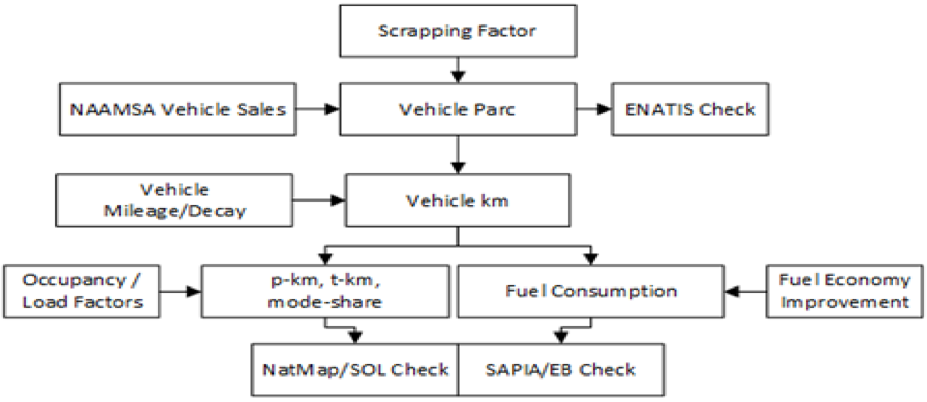
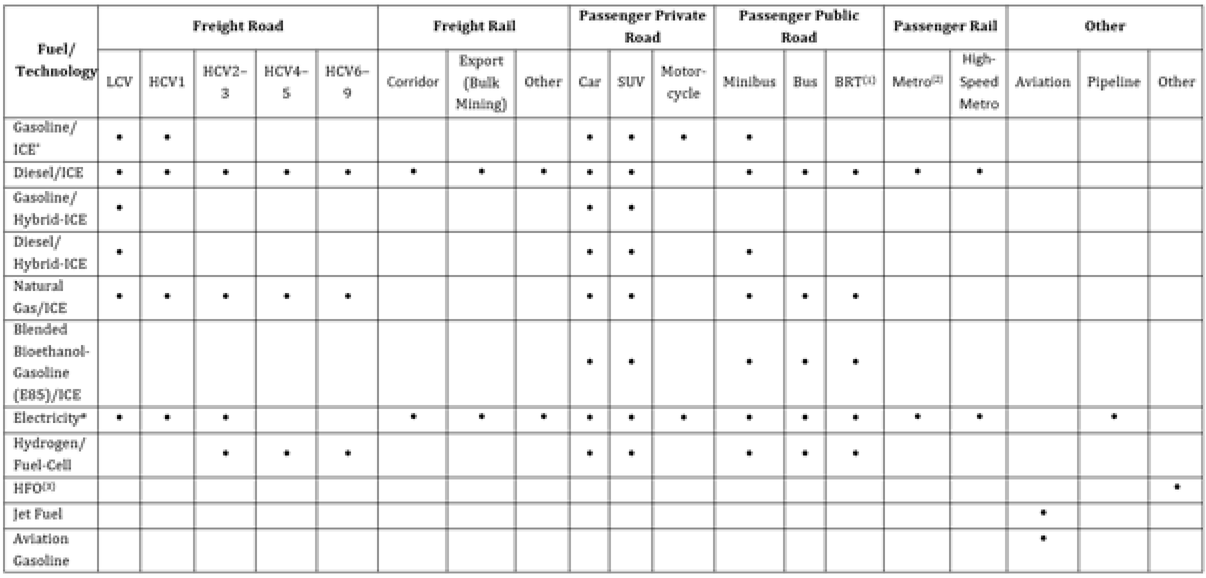


Figure A5: Schematic representation of the vehicle parc mode, data inputs and validations[5]



Fuel/ Technology	Freight Road					Freight Rail			Passenger Private Road			Passenger Public Road			Passenger Rail		Other		
	LCV	HCV1	HCV2–3	HCV4–5	HCV6–9	Corridor	Export (Bulk Mining)	Other	Car	SUV	Motor-cycle	Minibus	Bus	BRT(1)	Metro(2)	High-Speed Metro	Aviation	Pipeline	Other
Gasoline/ ICE*	•	•							•	•	•	•							
Diesel/ICE	•	•	•	•	•	•	•	•	•	•		•	•	•	•	•			
Gasoline/ Hybrid-ICE	•								•	•									
Diesel/ Hybrid-ICE	•								•	•		•							
Natural Gas/ICE	•	•	•	•	•				•	•		•	•	•					
Blended Bioethanol-Gasoline (E85)/ICE									•	•		•	•	•					
Electricity*	•	•	•			•	•	•	•	•	•	•	•	•	•	•		•	
Hydrogen/ Fuel-Cell			•	•	•				•	•		•	•	•					
HFO(3)																			•
Jet Fuel																	•		
Aviation Gasoline																	•		

Figure A6: Transport classes, technologies and fuels represented in the SATIM model

(1): BRT: Bus Rapid Transport; (2): Metro: Metropolitan i.e. intra-city; (3): Used for Coastal & Inland Navigation; * Internal Combustion Engine; #: Battery Electric for Road Vehicles; HCV1: Medium commercial vehicle of 3 000–7 500kg GVM; HCV 2: Heavy commercial vehicle of 7 501–12 000 kg GVM; HCV 6: Heavy commercial vehicle of 24 001–32 000 kg GVM. SUV: Sport Utility Vehicle (usually 4X4 and >1ton in mass)

Calibration year 2017

Subsequent to the release of the draft national inventory 2017 (DEFF, 2020), the SATIM transport model has been refreshed, conforming to the calibration method described, incorporating recent data for the year 2017 to allow for a more robust comparative analysis of the NIR 2017. Key modelling updates and their assumption about transport fuels are described.

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[5] NAAMSA = National Association of Automobile Manufacturers of South Africa, eNaTIS = electronic NationalAdministration Traffic Information System, SAPIA = South African Petroleum Industry Association, NatMap =National Transport Master Plan, SOL = State of Logistics Survey for South Africa, EB = National Energy Supply and Demand Balance, Department of Energy

Aviation, pipelines and 'other'

These transport categories are not disaggregated further as for road vehicles and do not have a technology representation. Fuel demand rather than service demand is instead directly correlated to GDP growth. Aviation is further distinguished by international and domestic demand. The SATIM representation of aviation and maritime fuel usage has previously been informed by DMRE published data. The 2017 SATIM data for these sectors reflect the recent 2018 DEFF fuel consumption study (FCS). Pipeline activity, in contrast, is currently based on historical trends as reported by Transnet (2019).

Road transport: Gasoline (petrol) and diesel

The 2017 SATIM revision notably departs from the NIR2017 which reflects the 2018 DEFF FCS for road transport fuels. The 2018 FCS, which relies on a method that utilizes national and municipal estimates of vehicle kilometres travelled (VKT) and assumptions of activity by vehicle class, reports higher fuel sales volumes than reported by DMRE and SAPIA. It was therefore decided, in consultation with DEFF, to proceed with the previous SATIM calibration method described in the above section. The 2017 revision, as before, attributes ~100% of DoE and SAPIA consumption volumes for gasoline to road transport. With reference to the SATIM energy balance (2017), diesel fuel is, however, more widely used across other sectors. Of the total reported volume consumed domestically (DMRE 2018), the share of transport diesel is derived from the 2016 DEA FCS for which fuel sales data was extended from 2015 to 2017. The method chiefly relies on assumptions of shares of sales by trade category (by magisterial district) that is presumed to be for road transport. The diesel sales shares assumed in SATIM are taken from the GIZ 2015 coefficients as listed in Table A6. Of note, diesel usage by Eskom is accounted for in the aggregate volumes prior to the disaggregation by sector (Eskom 2019).

Table A6: Comparison of sources for road transport share of total diesel sales for SAPIA trade categories

Magisterial trade category	SATIM 2017 GIZ 2015 Coeff. DEA (2016)	ERC 2012 Coeff. Merven et al. (2012)	Stone (2001)
Agricultural Co-ops	30%	0%	50%
Construction	0%	0%	90%
Farmers	30%	0%	50%
General dealers	100%	100%	100%
Government	100%	0%	100%
Independant LPG marketers	100%	100%	0%
Local authorities	80%	100%	100%
Local marine fishing	0%	0%	50%
Mining	0%	0%	70%
Public transport (by local auths)	100%	100%	100%
Public transport (non-local auths)	100%	100%	100%
Remainder of general trade	90%	100%	100%
Retail – garages	100%	100%	100%
Road haulage	100%	100%	100%
Transnet	0%	100%	0%

Key transport fuels, and their data sources are summarised in Table A7 and Table A8.

Table A7: Key model parameters and data sources

Model parameter	Attribute	Source
Road transport	Diesel	DMRE; SAPIA
Road transport	Gasoline	DMRE; SAPIA
Road vehicle population	Existing population: Private; Public; Freight	NAAMSA e-Natis
Freight rail	Diesel Electricity	Transnet
Pipelines	Electricity	Transnet
Water borne navigation	HFO	DEFF FCS (2018)[1]
Aviation (domestic & international)	Jet Fuel	DEFF FCS (2018)

1. DEFF Fuel Consumption Study (2018)

Table A8: Fuel demand in transport for 2017

Fuel	Demand (TJ)	Source
Gasoline	382 151	SAPIA
Diesel	341 081	UCT from DEA FCS (2016)
Electricity	12 535	StatsSA (SUT)[1]; Transnet
Jet fuel domestic aviation	20 465	DEFF FCS (2018)
Jet fuel international aviation	68 939	DEFF FCS (2018)
Hfo – domestic maritime	4 509	DEFF FCS (2018)
Hfo – international maritime	21 947	DEFF FCS (2018)

1. SUT: Supply and use tables (derived from rand value)

Residential

Residential sector energy demand in SATIM is based on a demand for household energy services, which is driven by population growth and household income. In 2017, the population was 55.6 million, increasing to 62.8 million in 2030 and 75.2 million in 2050. The estimated number of households in 2017 is 17.4 million, of which 84.7% are assumed to be electrified.

Households are split into low-, middle- and high-income household groups. This is done to capture both the shift in fuel use as household income rises as well as increases in appliance ownership and the corresponding increase in energy use (MJ/household) as income rises. The low-, middle- and high-income groups correspond to a mean income of around R37 000, R85 000 and R530 000 respectively. In 2017, 48.5% of households fell in the low-income group, 31.5% were in the middle-income group and 20% were in the high-income group.

All household income groups are assumed to use energy for cooking, lighting, space heating and cooling, water heating, refrigeration and for "other" uses, such as television, and clothes washing. "Other", refrigeration and lighting in the high-income group are distinct from all other energy services in that they are only met by electrical appliances. Lighting in the low- and middle-income groups is met by paraffin and electricity, however the use of electricity dominates consumption. Households in the low- and middle-income groups use a range of fuels for water heating, space heating and cooking, these are electricity, wood, coal, paraffin and gas. The percentage of households using each fuel for water heating, space heating and cooking is calibrated using StatsSA data from the 2016 community survey and 2011 Census.

The total energy use assigned to households in 2017 is provided in Table A10. The energy consumption attributed to households in the GHG Inventory is also shown in the table. There is a large difference in coal use, between the Inventory and the Fuel use study. According to the 2016 Community Survey, roughly 3% of households use coal (fewer than 2% use coal as a main fuel). The 2011 Census also reports that less than 2% of households use coal as their main fuel for either cooking or space heating.

Assuming that 520 000 households used coal in 2017, the fuel use study is in line with a daily consumption of coal of 3.4 kg a day, whereas the Inventory estimate would require these households to use around 63 kg a day.

Table A9: Fuel consumption in the residential sector

Total (PJ)	Electricity	Paraffin	Gas	Wood	Coal
2020 update	172.33	9.64	17.98	83.77	15.62
DEFF inventory		9.64	17.98	83.77	294.42
DEFF Fuel use study					15.62

The allocation of fuel used to income groups is shown in Figure A7.. The figure shows both the movement away from solid fuels towards electricity and gas as income rises, as well as the far higher use of electricity in higher income households compared to the other household groups. It is clear from this figure that a large increase in average household income would translate to a large increase in electricity consumption in the residential sector. Any policies aimed at improving the efficiency of electrical appliances will therefore also have the greatest impact on electricity consumption in the high-income group.

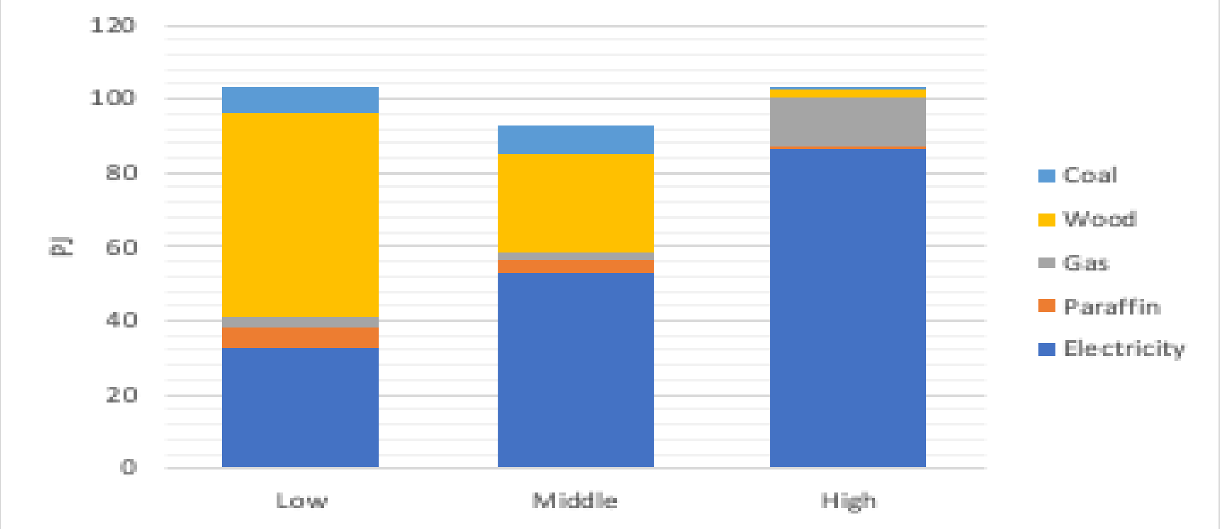

Figure A7: Energy use in the residential sector

The relative share of fuels supplying each energy service is shown in Figure A8. The share of energy services delivered is shown in Figure A9. The difference between the two figures reflects the efficiency at which energy services are delivered by different fuels.

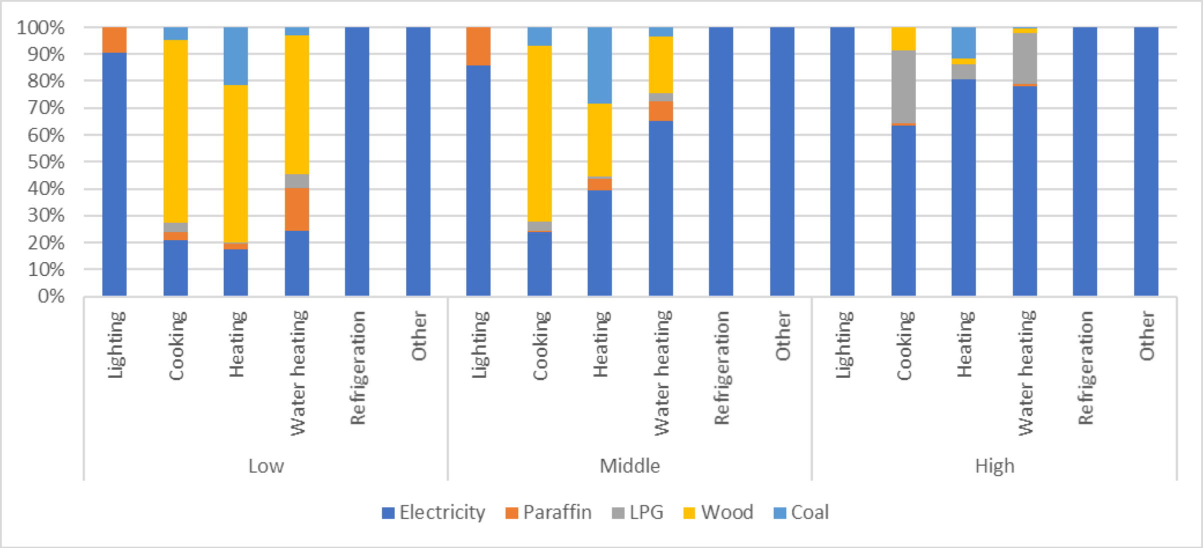

Figure A8: The relative share of fuels supplying energy services in the residential sector

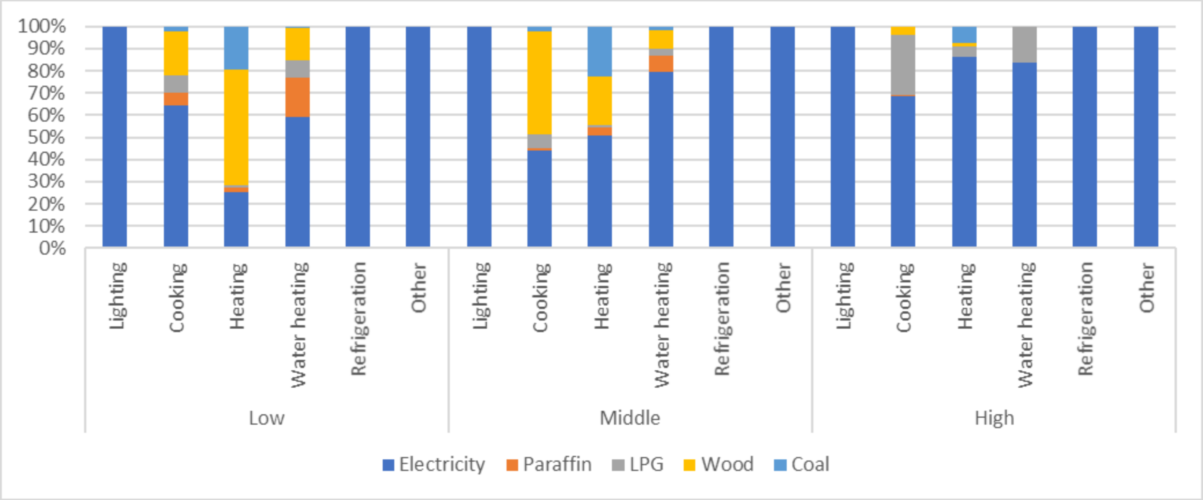

Figure A9: The relative share of energy services delivered by fuel in the residential sector

In the residential sector the relative share of each fuel supplying energy services, as well as the efficiency at which households derive energy services, changes over time. There are two primary shifts occurring that drive the relative share of fuel supplying energy services. Firstly, the share of households in income groups changes as GDP grows or shrinks. With growing GDP, this shift is primarily households moving into the higher income group from the middle-income group and households transitioning from the lower-income group to the middle-income group. It has the effect of increasing the amount of energy consumed by the sector as well as the fuels used to supply energy services. In addition, the electrification rate is assumed to continue to increase over time. This has the effect of increasing electricity consumption relative to the consumption of other fuels in each income group, as it is assumed that electrified households will use energy similarly to those already electrified in the income group.

The efficiency of refrigerators and other appliances is assumed to increase over time. In addition, the share of solar water heaters and heat pumps increases over time, in particular in high-income households, as does the share of efficient lights, in particular LED’s. In the reference case the increase in efficiency is modest, and is assumed to be primarily driven by the MEPS and Standards and Labelling programmes. A modest 13% efficiency improvement by 2030 is assumed across all income groups, but this is not applied to all fuels and energy services. For cooking it is applied to electric hot plates and stoves, biomass and coal use, for water heating it is applied to electric geysers. It is applied to all refrigeration and other electric appliances.

Industrial

The industrial sector in SATIM consists of several energy-intensive sectors, such as the iron and steel and aluminium sectors, and the less energy-intensive but more numerous producers such as the food and beverages or general manufacturing industries. In SATIM, two methodologies are applied to model either of these industrial sectors. Methodology 1 relies on estimates of *energy service* requirements for cooling, compressed air, lighting, or process heat etc.; methodology 2 utilizes an estimate of the *energy intensity* of industrial technology processes. Methodology 2 is typically applied to sectors where products are more uniform and the energy intensity of production is high, like iron and steel.

Methodology 1 is applied to the mining, chemicals, food beverages and tobacco, precious and non-ferrous metals (excluding aluminium) and general manufacturing. In this approach an estimate of the total useful energy service requirement (e.g. Process heat, compressed air, etc), per unit of output, and the efficiency at which energy services are met are exogenously specified and allow the model to endogenously determine final energy consumption for each energy service in the sub-sector. The driver of industrial energy consumption is therefore the demand for useful energy services. This is demonstrated in Figure A10 where the level of useful energy services needed, in this case process heating, and the efficiency of the boiler, determines the amount of final energy (coal) consumed.

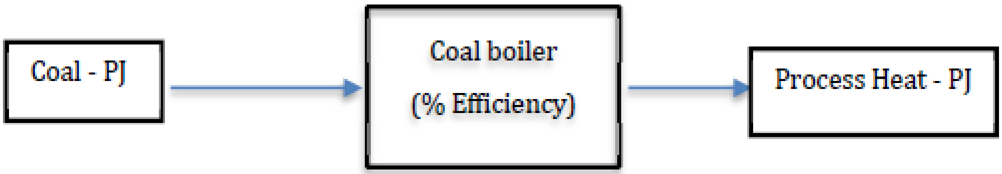

Figure A10: Methodology 1 example of representing energy service requirements in industry

Methodology 2 is used for the iron and steel, ferroalloys, aluminium, non-metallic minerals (cement, glass, lime, and brick), and pulp and paper sectors. The demand for final energy in these sectors is calculated endogenously based on the energy intensities specific to technology processes and their level of production (tonnes of steel produced etc.). For example in Figure A11, the demand for coal and coke by blast furnaces in the production of iron is calculated based on the technology-specific energy intensity (GJ/t) of iron production in South African blast furnaces. In order to apply methodology two, the share of production by technology type and the energy intensity of production in South Africa must be known or estimated.[6]

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[6] A large portion of the Methodology 2 sector industries for SATIM were first characterised by Dr Tamaryn Napp, a visiting post-doctoral researcher from Imperial College London. She interviewed many local industry stakeholders in the heavy industries of South Africa and collated much of the literature used for these industrial sector representations. Some of the texts in these sections are based on her notes and documents.

Figure A11: Methodology 2 example of representation of energy intensive industries

Energy services for methodology 1 sectors

Table A10: Split of end-use electricity consumption by subsectors for methodology one (EIA, nd)

	Mining (%)	Chemicals (%)	Non-ferrous metals (%)	Food and Beverages (%)	Other (%)
Electric heating	2	2	1	7	10
Compressed air	19	15	0	4	11
Lighting	5	4	1	5	8
Cooling	8	5	0	23	5
HVAC	8	2	1	6	8
Pumping	18	35	0	28	13
Fans	7	8	0	4	6
Other motive	34	20	7	21	37
Electrochemical	0	8	90	0	1
Boiler/process heating	0	1	0	2	1
Total	100.0	100.0	100.0	100.0	100.0

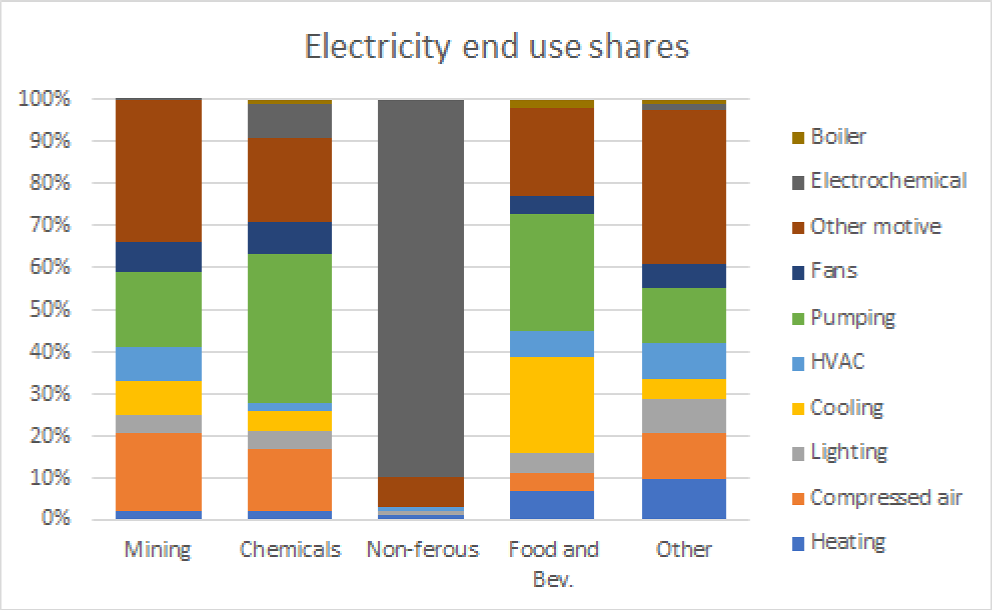

Figure A12: Electricity end use shares by sector

For thermal fuels such as coal, gas, and LPG, these are assumed to be used in boilers in these sectors, producing process heat.

The methodology 2 subsectors each have more detailed representation of energy flows and technologies to represent the major components of industrial systems for example the clinker kilns in the cement manufacturing route or the boilers for steam in the pulp and paper sector. Figure A13 below gives the basic overview of these sectors.

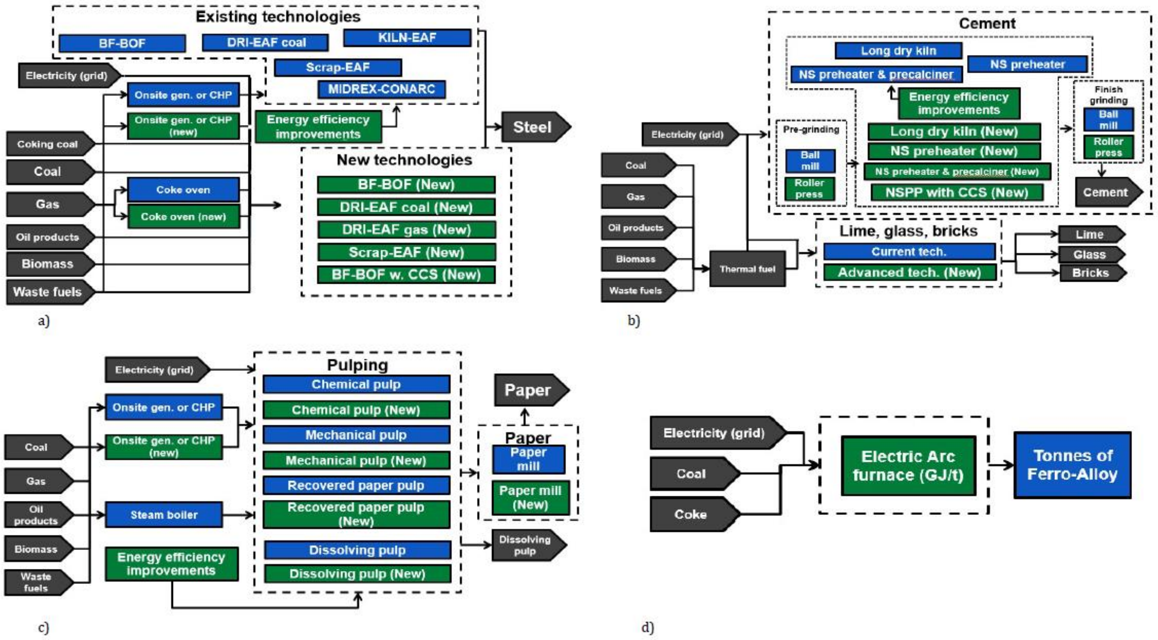

Figure A13: Schematic of methodology 2 industrial sectors (iron and steel, cement, pulp and paper, ferroalloys)

Energy consumption and calibration for the industrial subsectors in SATIM is calculated using known and estimated energy use from the energy balance and from company or industrial association reports available publicly for the methodology 2 sectors, and from stakeholder engagement.

Iron and steel

South Africa has about 10 Mt of crude steel capacity, much of which is under-utilized or even moth-balled as of 2020, with just 6.13 Mt being produced in 2019 (WSA). The major player of steel production is ArcelorMittal South Africa (AMSA), with a few independent scrap metal companies. AMSA produces iron from iron ore. EVRAZ Highveld historically produced virgin steel but closed in 2015 due to financial problems. It is reported some of the steel milling parts of the facilities are still being used as of 2020, but no production of virgin steel is taking place.

The Saldanha facility is a world-unique combination of iron-producing furnaces with lower material (coke) requirements in a combination of COREX and MIDREX technologies. The facility was an export market-based production site, being located at the Saldanha port, but closed down in 2020 for financial reasons.

A picture of capacity and production from the steel production routes for South Africa is derived based on annual reports by World Steel Association [WSA], and ArcelorMittal South Africa integrated reports [AMSA], and a variety of news articles pertaining to the operations of the major facilities.

Process routes description of the Iron and Steel sector in SATIM:

- DRI-EAF– Direct reduced iron to electric arc furnace
- BF-BOF – Blast furnace to basic oxygen furnace
- Corex - Conarc - Saldanha facility hosting a Corex, Midrex, an EAF and BOF
- Other - Evraz Highveld

Table A11: Steel production volumes and process route in South Africa (Mt/year)

	2012	2013	2014	2015	2016	2017	2018	2019	2020*

BF-BOF	3.30	3.38	3.09	3.16	3.16	3.03	3.20	3.03	3.03
Corex-Conarc	1.21	1.24	1.13	0.96	0.83	1.12	1.09	1.09	-
DRI-EAF	0.95	0.97	0.89	0.77	0.77	0.76	0.80	0.80	0.76
Other-EAF	0.62	0.63	0.58	0.14	-	-	-	-	-
Scrap-EAF	0.86	0.88	0.81	1.36	1.32	1.32	1.21	1.21	1.21
Total	6.94	7.10	6.50	6.40	6.09	6.23	6.30	6.13	5.00

*Estimate based on 2019 figures with Saldanha closing

The scrap ratio is the amount of steel being produced via scrap-EAF route in this methodology. This was estimated based on the amount of steel being produced that does not come from an iron ore production route like the BF or DRI. This is an estimate of 1.2 Mt out of 6.13 Mt in 2019.

Energy intensity of the process routes is adapted from Worrel et. al. (2008), combined with the energy balance, company reports (AMSA, 2018), and Scholtz et. al. (2006).

Table A12: Energy intensity of steel process routes (GJ/t steel produced)

	Coal bit	Electricity	Coke	LPG	Natural gas	Total GJ/t
BF-BOF	4.33	2.10	8.88	0.59	0.53	16.43
DR-EAF	20.60	4.86	-	-	2.29	27.74
SCRAP-EAF	-	4.09	-	0.71	0.69	5.49
COREX-CONARC	17.20	1.73	2.60	0.22	0.41	22.15
Other	20.61	20.61			3.44	44.66

New build options

For each process route, there is a new build option available for model optimization, with the same parameterization in energy and costs as existing options. Costs are based on IEA (2010). An additional new option for steel production is based on hydrogen direct reduced iron to electric arc furnace for steel production. Instead of coal and/or coke being used as the reducing agent for iron ore in the furnace, it is replaced with hydrogen. The gaseous products are water vapour, which can be recycled through an electrolyser. This is based on Vogl et. al. (2018). Data for the electrolyser, in this setup a platinum-based PEM electrolyser, is taken from IEA (2019). Storage of hydrogen is included in SATIM for this process as a simple energy storage technology, and no costs are associated with this component, as according to the IEA (2019) hydrogen storage is not a major cost burden if it is located at the source of hydrogen production (electrolyser) and is used onsite as well. Most of the costs in hydrogen storage are associated with the actual transportation part of the cycle – compressing, liquefying or transforming of hydrogen for transport to a different location.

Table A13: Hydrogen direct reduction of iron for steel production

	2030	2050
PEM electrolyser		
CAPEX - mR/GWe	18 480	11 088
Efficiency - %	63%	67%
Lifespan - hours	60000	75000
Direct reduction furnace		
CAPEX - mR/Mt	3 000.89	3 000.89
Labour cost - mR/Mt	619	619
Input H2 - PJ H2 per Mt	6.12	6.12
Input ore - Mt Ore per Mt	1.504	1.504
Electric arc furnace		
CAPEX - mR/Mt	2 606.89	2 606.89
Labour	619	619
Input - Electricity PJ/Mt	2.711	2.711

IPPU emission factors for the iron and steel sector are taken from the IPCC guidelines for iron and steel production for each technology and grouped for each process route (eg. BF-BOF includes BF and BOF factors). These combinations are given in the table below. The Saldanha (Corex-Conarc) route is a combination of a 50/50 split on steel route for BOF and EAF, and the iron production (Corex and Midrex) which is based on relative output proportions of those technologies (AMSA_1) with a 10% "efficiency" adjustment for the Corex (as an efficient BF) component and using standard IPCC guides. Emissions for the hydrogen based DRI route are equated to that of the 'scrap-EAF' route.

Table A14: IPPU emissions factors for the iron and steel sector in SATIM

	Tonne CO_2/tonne steel output
BF-BOF	2.81
DRI-EAF	1.61
Scrap-EAF	0.08
Corex-Conarc	2.12
Other-EAF	1.54

Coke production emissions resulting in IPPU emissions are taken from the IPCC guidelines of 0.52 t CO_2/t coke, with 30 MJ/kg assumption for coke giving 17.3 t CO_2/TJ coke produced.

Ferroalloys

South Africa is rich in chromite and manganese ores and has a well-established ferrochrome and manganese industry. South Africa is the largest exporter of ferrochrome, and the second largest producer in the world (DMR, 2019). Most of the ferro-alloy production in South Africa is in the form of ferrochrome - at about 3.3 Mt in 2017.

Table A15: Production (tonnes) of ferro-alloys in South Africa (DEFF 2020b)

	2015	2016	2017
Ferrochrome	3 685 000	3 334 706	3 370 941
Ferromanganese	615 000	847 156	862 616
Ferrosilicon	180 600	144 200	139 197
Total	4 480 600	4 326,061	4 372 754

Due to lack of data available, in this methodology the three alloys are grouped together as one technology which includes pre-reducing through to smelting phase. The energy inputs based on the energy balance and the studies by Lagendijk et.al. (2010) and Biermann et. al (2012) are used to calibrate this technology for the total production of 4.3 Mt of ferroalloys for 2017. Below are the energy intensity values used to estimate this grouping.

Table A16: Energy intensity (GJ/t product)

	Coal	Coke	Electricity
Chrome	17.98	9.90	14.04
Manganese	10.91	9.44	8.28
Ferrosilicon	10.91	9.44	8.28
Weighted avg.	16.36	9.80	11.87*

* Adjusted for calibration to the energy balance

Emissions

Process emissions from ferroalloys (FA) production are adopted from DEFF (2020), based on IPCC emissions factors, and are grouped in SATIM for the single ferroalloys technology.

Table A17: Process emissions for ferro alloys in SATIM

	t CO_2/tonne FA	kg CH_4/tonne FA
Ferrochrome	3.2	0
Ferromanganese	1.3	0
Ferrosilicon	3.6	1
Weighted total	2.88	0.03

No new technology build options are assumed in this methodology. The change in the consumption of energy, and production of emissions arising from a change in the demand for ferroalloys (driven by GVA factors).

Aluminium

South Africa has one aluminium producing facility in Richards Bay. All of the alumina is imported as there is no alumina production in South Africa. A total of 806 kt of primary and secondary aluminium was produced in 2017, with the primary production making up most of the production and energy consumption. In SATIM this is represented with a single node/technology with a total of 53 GJ per tonne of aluminium as the energy intensity. Electricity is the main source of energy for reducing alumina to aluminium using carbon anodes in this process. Process emissions factors for this technology are taken from the IPCC guidelines (as adopted in the National Emissions Inventory) (DEFF, 2020), and are as follows:

- GHG: tonnes GHG per kt product
- CO_2: 1641
- CF_4: 0.410

- CF_6: 0.041

It is assumed that production of aluminium is constant through the modelling period. No new build options are available for this technology.

Non-metallic-minerals: Cement

The cement manufacturing process has been divided into three stages: pre-grinding, clinker kiln, and blending. For the pre-grinding and blending stages two technologies were modelled: The less efficient ball mill and the more efficient roller press. Three kiln types have been modelled: 1) The older, less efficient long dry kiln; 2) new suspension rotary kiln with preheater; and 3) new suspension rotary kiln with preheater and pre-calciner. The new build technology assumes that the existing capacity is replaced with entirely new plant built at best available technology (taking into account South Africa-specific limitations).

Installed capacity

Installed capacity of current technologies was determined based on input from the industry and consultation of industry websites. These were then aggregated into the different kiln types. A 95% annual availability for all plants was assumed. The table below gives the total installed capacity for cement kilns and mills for this representation in SATIM, along with the energy intensity of the processes. For energy intensities, Napp's work was the basis for this representation, and was originally based on energy intensities of the different technologies according to values obtained from the literature (EU commission, 2010; Worrel et al. 2000, 2001). These had since been updated and adjusted against the energy balance calibration efforts (see section on Energy balance).

The energy supply to both the pre-grinding and blending stages was assumed to be 100% electricity. For the kilns, a share of electricity and thermal fuel is supplied. Thermal fuel was assumed to be a mix of coal, natural gas, and fuel oil with coal making up the majority of the input at 71% and gas the remaining. It is known that industry is using solid waste in the form of things like used car tires, but owing to lack of information this is not represented. Biomass is an option as well, but this is set to zero initially, and assumed it can make up at most 20% of maximum thermal fuel requirements.

Table A18: Cement production technologies, capacities and energy intensities

		Existing technologies							New build technologies	
		Pregrinding-crushing		*Kiln*			*Finish grinding*		*Kiln*	
		Ball mill	*Roller press*	*Long dry kiln*	*NSPreheater*	*Nspreheater, precalciner*	*Ball mill*	*Roller press*	*NSPreheater*	*Nspreheater, precalciner*
Inputs	Unit									
Current installed capacity	Mt	6.6	4.1	0.8	7.4	2.5	9.2	5.6		
Availability	-	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Energy intensity (2017)	GJ/t	0.079	0.059	4.2	3.4	3.1	0.2	0.13		
New build energy intensity)	GJ/t								3.20	3.00
Fuel mix shares										
Thermal fuel	-	0	0	0.98	0.98	0.97	0	0	0.98	0.97
Electricity	-	1	1	0.02	0.02	0.03	1	1	0.02	0.03
Costs										
Installation cost	2015 ZAR/t		36.4					27.5	2520	2853

The production of cement in South Africa amounted to about 14.8Mt in 2017, with the clinker ratio at 69% (DEFF, 2020).

Table A19: Tonnes of cement, and clinker production (DEFF, 2020)

	2012	**2013**	**2014**	**2015**	**2016**	**2017**
Mass of cement produced	12 358 000	13 037 000	13 099 000	14 522 000	14 646 757	14 759 961
Clinker fraction	0.69	0.69	0.69	0.69	0.69	0.69
Mass of clinker in the cement	8 527 020	8 995 530	9 038 310	10 020 180	10 106 262	10 184 373

Non-metallic-minerals: Lime

South Africa produced 1.36 Mt in 2017, most of which was quicklime (DEFF, 2020). The energy intensity for lime production is 2.7 GJ/t of aggregate lime production. 94% of the energy requirement is in the form of thermal fuels, the remainder as electricity for motors and other non-thermal requirements. Thermal fuel requirement is assumed to be 95% coal, and 5% Gas.

Process emissions factors are adopted from DEFF (2020):

- Quicklime – 0.75 tCO_2/t product
- Hydrated lime – 0.97 t CO_2/t product

Using a weighting for the production of each product the combined process emission factor is 0.769 t CO_2/t combined product.

Non-metallic-minerals: Glass

About 1.1 million tonnes of glass (plate, sheet, and container) was produced in 2017 in South Africa. The cullet (amount of recycled glass used) ratio in South Africa has been assumed to be constant from 2012 to 2017. All data on production is taken from DEFF (2020).

Table A20: Glass production in South Africa (DEFF, 2020)

Production - tonnes	2012	2013	2014	2015	2016	2017
Glass (w/ cullet)	1 095 264	1 095 264	1 095 264	1 095 264	1 146 296	1 162 436
Cullet ratio	0.48	0.48	0.48	0.48	0.48	0.48
Virgin glass production	569 533	569 533	569 533	569 533	596 070	604 463

The glass sector is represented by a single technology ‘furnace’ which consumes electricity and thermal fuel to produce glass. The intensity is 7 GJ/t of glass produced and the split is assumed to be 90% thermal fuel and 10% electricity. The electricity consumption is calibrated to Eskom sales data. Thermal fuels is based on Napp with a split of 77.55% gas and the remaining as coal.

Table A21: Glass sector energy intensity in SATIM

	PJ/Mt
Electricity	0.003
Coal	1.41
Gas	4.89

Process emissions

The emissions factor used is based on DEFF (2020) which is IPCC derived. Weighting the emissions factor of 0.2 t CO_2/t for virgin glass, with the overall production which includes the cullet, the resulting process emissions factor is 0.103 t CO_2/t of glass.

Non-metallic-minerals: Bricks

Using the life cycle reports for the clay brick industry (CBASA, 2016), and assuming that 50% of production is clamp kiln, with the other 50% spread evenly across Tunnel, TVA, Hoffman, VSBK and ‘zigzag’ kilns (CBASA, 2016; Hibberd, 1996), the following table for energy intensity was constructed for the representation of bricks production in South Africa:

Table A22: Energy intensity in brick production

	PJ/Mt
Coal	2.0769
Electricity*	0.03997
N gas	0.1044
HFO+LFO	0.0011
Total	2.2223

* Eskom source

A total of 9.61 billion kg of bricks, or 3 494 million units, were produced in 2016 (CBASA, 2016).

The methodology setup for SATIM is one where the producing technology for bricks requires thermal fuel made up of the non-electricity energy sources in the table above, and the thermal source is allowed to change over time from 95% coal (as above) to gas should gas become more economical – at most 50% thermal fuel share by 2030 and thereafter.

Pulp and paper

The pulp and paper sector representation in SATIM is given by the figure below showing the major technological nodes for producing paper (and pulp) products. Cogeneration, and heat/steam production are a major component and have been explicitly included in the sector.

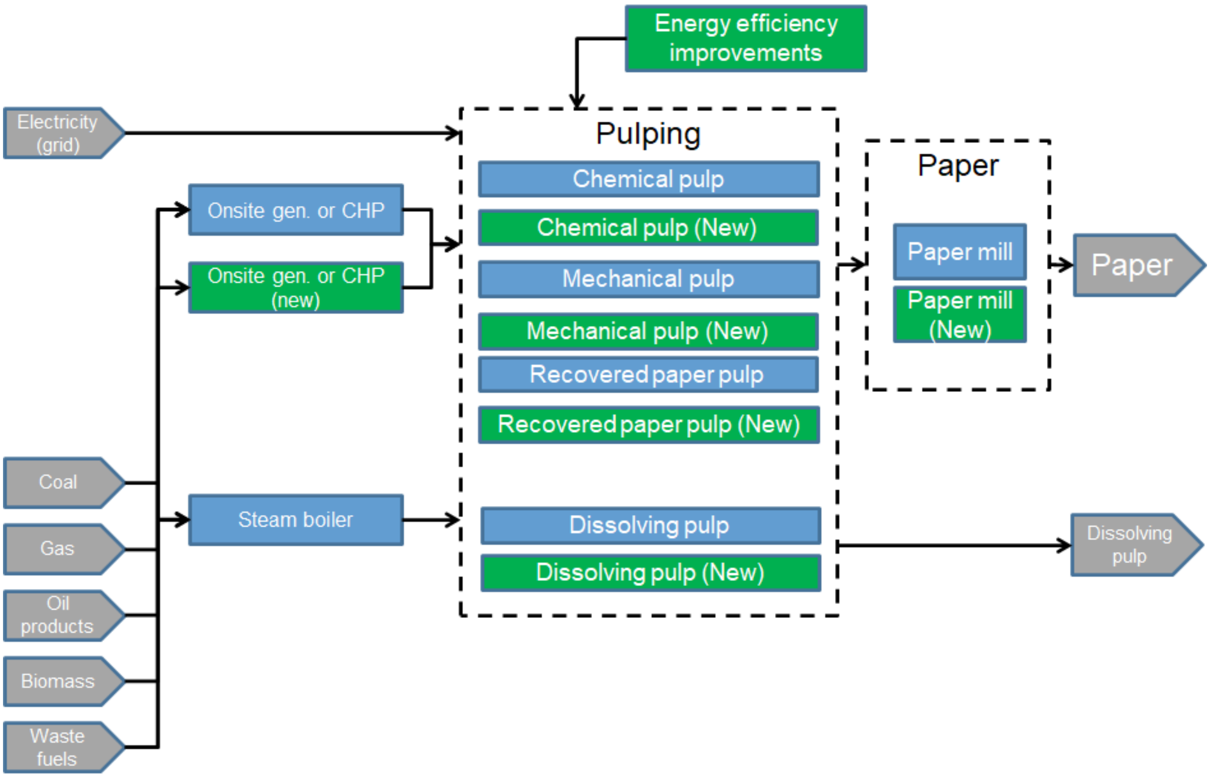

Figure A14: Pulp and paper sector representation in SATIM

The following energy balance table for the sector is based on energy intensity values for the various technology nodes (such as boilers) originally derived from Napp, and from known sales to the sector in electricity and coal (see energy balance section).

Table A23: Pulp and paper energy balance for SATIM for 2017

		Coal	Biomass	Gas	Black liquor	HFO	Steam	Elec
Plants producing pulp or paper	Chemical (& NSSC)	-3.91					-15.57	-4.10
	Mech (& thermo)						-1.51	-3.32
	Dissolving pulp	-2.27					-8.77	-2.18
	Recovered paper						-1.26	-0.77
	Paper mill	-1.96					-23.11	-5.51
	Subtotal	-8.14					-50.22	-15.88
Boilers producing steam	Biomass		-3.36				2.42	
	Coal	-31.75					21.88	
	Coal/HFO	-12.01				-0.44	8.67	
	Gas			-2.02			0.64	
	Black liquor				-41.39		23.31	
	Subtotal	-43.76	-3.36	-2.02	-41.39	-0.44	56.92	
CHP							-15.49	7.92
	Total	-51.9	-3.36	-2.02	-41.39	-0.44	-22.19	23.80

Commercial

Energy use in the commercial sector includes private and public commercial building energy use, as well as energy use for water treatment and public lighting. The demand for energy in the commercial sector is driven by growth in commercial building floor area, which is driven in turn by increases in commercial GDP. In 2017, the commercial floor area is assumed to total 139 million m^2, of which 20% is assumed to be public. Floor area increases to around 156 million m^2 in 2030 in the reference case.

Floor area is divided into existing and new floor area, allowing the model to respond to building standards and changes in building design that would, for example allow modern heating or cooling. All buildings built after 2017 are “new” buildings. In addition to increases in commercial floor area “new” building floor area also replaces old building floor area over time. This is done to accommodate cases where older buildings are either demolished or undergo a large retrofit that would allow the buildings to match the energy intensity anticipated in “new” buildings. The figure below shows the increase in floor area over time, with 2017 as the index base year. It also shows the decrease in existing floor area from 2017 onwards.

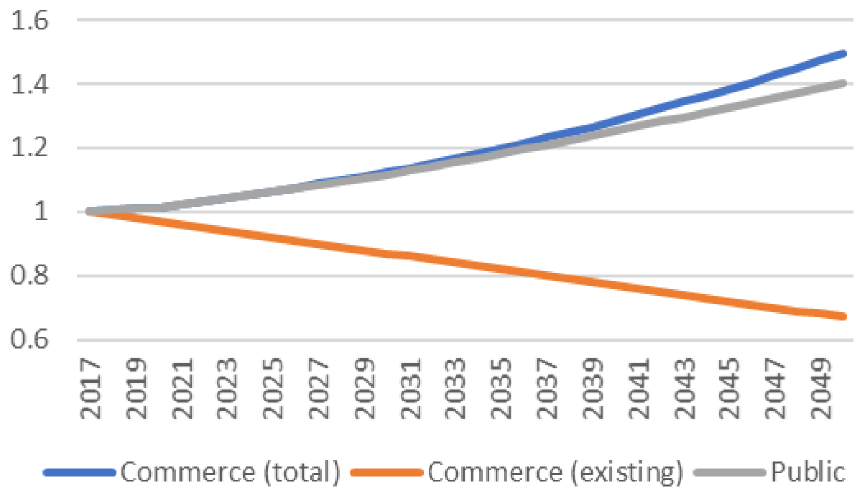

Figure A15: Growth in commercial floor area indexed to 2017

Commercial and public buildings are assumed to have an energy need for space heating and cooling, cooking, lighting, water heating, refrigeration and for “other” uses. The majority of energy is used for cooling and lighting (38.5% and 33.5% respectively) and therefore any improvements in energy efficiency in these areas has a large savings potential.

The total energy use assigned to commerce in 2017 is shown in Table A25. The energy consumption assigned to commerce in the GHG inventory is also shown in the table. There is a large difference in diesel use, between the inventory and SATIM. This is largely because SATIM only allocates the use of diesel in buildings to this sector. Commercial use of diesel for transport is included in the transport sector.

Table A24: Fuel use in the commercial sector

PJ	Coal	Diesel	Electricity	Gas	HFO	Paraffin	LPG
2020 update	26.66	1.50	129.04	1.23	0.23	2.56	4.03
DEFF inventory	As above	196.8			20.1	0.5	

There has been a large drop in electricity consumption assigned to buildings between 2012 and 2017, from 143 TJ to 123 TJ. This implies an 18% reduction in the electrical intensity of buildings (MJ/m^2) between 2012 and 2017. Over the same period coal use assigned to commerce has increased from 15TJ to 26TJ in 2017 to match the figure used in the Inventory.

The assignment of fuels to building services is shown in Figure A16. Cooling, lighting and refrigeration are assumed to be met solely with electrical appliances, whereas space heating and water heating are assumed to rely primarily on coal. LPG and natural gas are used only for water heating, space heating and cooking. Energy use for lighting and water treatment is assumed to be 4% of total electricity demand in the sector in 2017.

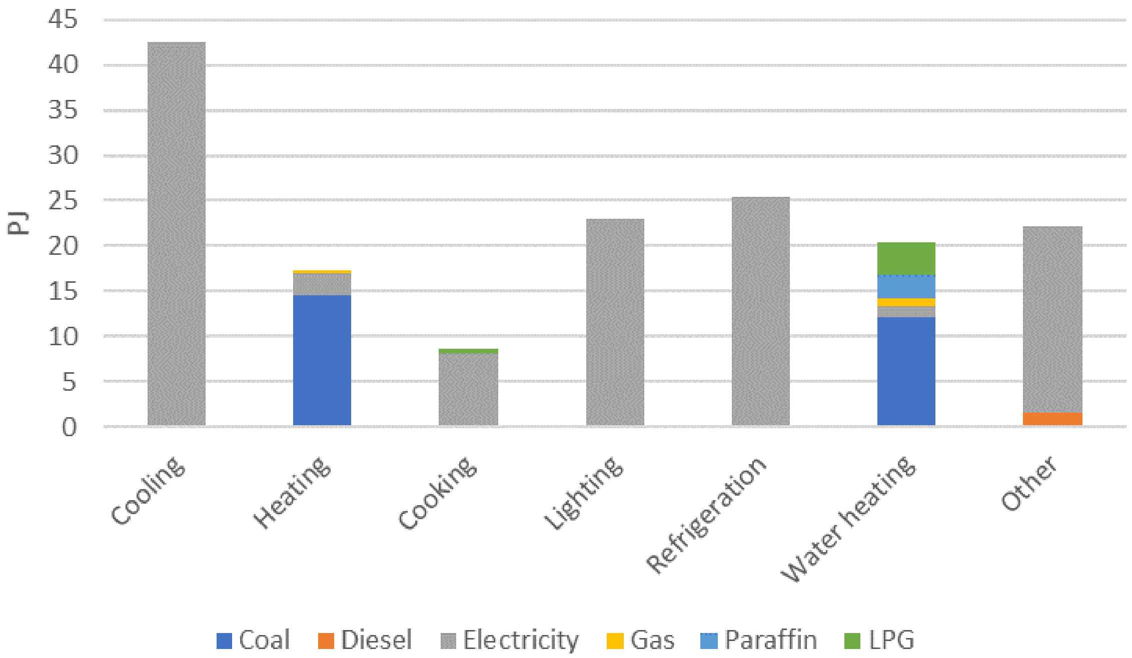

Figure A16: Fuel use for energy services in the commercial sector (excludes public water services and public lighting)

In the reference case, new buildings have the same demand for energy services as the 2017 building stock. This does not mean that the energy intensity remains the same, as energy services can be met by more efficient appliances.

Agricultural energy

Agricultural energy demand within SATIM has no subsector disaggregation but instead end-use service demand is divided into: Irrigation; Heating; Processing; Traction and Other. Table A25 details the fractional share of fuel use for each of the end-use activities. Traction specifically refers to off-road activity as road vehicles are captured in the SATIM transport sector. The estimated total energy utilization by fuel type for agriculture in 2017 is provided in Table A26.

Table A25: End-use fractional shares for agricultural activity (Winkler, 2007)

Fractional shares	Coal	Diesel	Electricity	Gasoline[1]	HFO	Paraffin	LPG
Heating	25.5%	0.0%	0.0%	0.0%	33.5%	40.4%	0.6%
Processing	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%
Traction	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Irrigation	0.0%	17.8%	82.2%	0.0%	0.0%	0.0%	0.0%
Other	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%

1. Gasoline is allocated to the transport sector, which captures road vehicles in-use.

Table A26: Fuel demand in agriculture for 2017

Fuel	Demand (TJ)	Source
Coal	1 998	DMRE
Electricity	20 772	StatsSA (SUT)[1]
Diesel	49 181	UCT from DEA FCS (2016)[2]
LPG	45	UCT from DEA FCS (2016)
Paraffin	3 162	UCT from DEA FCS (2016)
HFO	2 624	DEFF FCS (2018)

1.SUT: Supply and use tables (derived from rand value).

2. Extension of the 2016 DEA fuel consumption study.

No agricultural energy utilization PAMS are modelled.

Refineries

Liquid fuel production by domestic refineries is modelled in SATIM at the aggregate process level. That is, key energy commodities such as crude oil, coal, gas and electricity as feedstock are transformed into energy products such as gasoline, diesel, jet fuel, paraffin and LPG for end-use. Process emissions factors as listed in Table A27 are calculated in terms of the energy content of the product slate per refinery type where the coastal refineries are presently grouped as a single process. Production, imports and exports of liquid fuels is matched to SAPIA data.

Table A27: Refinery process emissions factors used in SATIM

Facility	Process emission factor CO_2 (kt/PJ_{out})	Process emission factor CH_4 (kt/PJ_{out})	Key data source
CTL (Secunda)	99.5	0.397	Sasol
Inland crude refinery	4.76	0	Sasol
Coastal refineries	4.29	0	SAPIA
GTL	6.49	0.0045	PetroSA; DEFF

Coal-to-liquids (CTL)

Emissions from the CTL process are calibrated to match the NIR 2017 submission by SASOL (2018). The SATIM model has a disaggregated representation of the CTL complex, in which commodities such as coal and natural gas are transformed into a product slate comprising a detailed energy commodity slate (e.g. petrol, diesel and jet fuel) and aggregated non-energy products. Coal and gas are prime feedstock commodities, which are split into four main activities, namely: material use for the Fischer-Tropsch (FT) process; steam generation for the FT process; steam generation for general process use; and steam generation for onsite electricity production. The commodity usage is based on the SASOL submission summarised below in Table A29. This data is cross referenced with other published data to balance the commodity usage by activity (Bultitude 2013; NERSA 2018, SASOL 2018a,b; Sasol 2019a,b,c,d; Sasol 2017). A process emissions factor (IPPC 1B3) is derived from the balance of emissions reported by Sasol for its facilities (Sasol 2019b).

Table A28: 2017 SASOL GHG inventory as applied in SATIM calibration, tonnes/year (Sasol, 2018a)

IPCC category	CO_2	CH_4	N_2O
1A	28 478 205	360	456
1B	25 578 843	9 888	-
2B	241 415	7 962	692
4D	188 027	3 853	-
Total	54 486 490	112 063	1 148

Crude oil

As per CTL, crude oil refineries are modelled similarly to electricity and crude oil key feedstock commodities. A process emissions factor, specified in terms of product output for the inland crude oil refinery, Natref, is derived from Sasol submission data (Sasol 2019c). SAPIA (2018) is the main source for refinery production and emissions data for the remaining refineries. The product slate for the refineries is based on the comprehensive assessment conducted by Lloyd (2001).

Gas-to-liquids (GTL)

Production (activity) data - published by PetroSA (2007; 2012; 2018; 2019) in conjunction with activity data provided in the NIR 2017 is the basis for the emissions factor derivation.

Gas supply

Domestic gas supply for the year 2017 is derived from PetroSA (2018) and importation via Sasol (2017). PetroSA reports production of 24.7 Bscf (~26 765 TJ at LHV), compared to the DMRE 2017 value of 25,838 TJ. Gas supply from Sasol is illustrated in Figure A17.

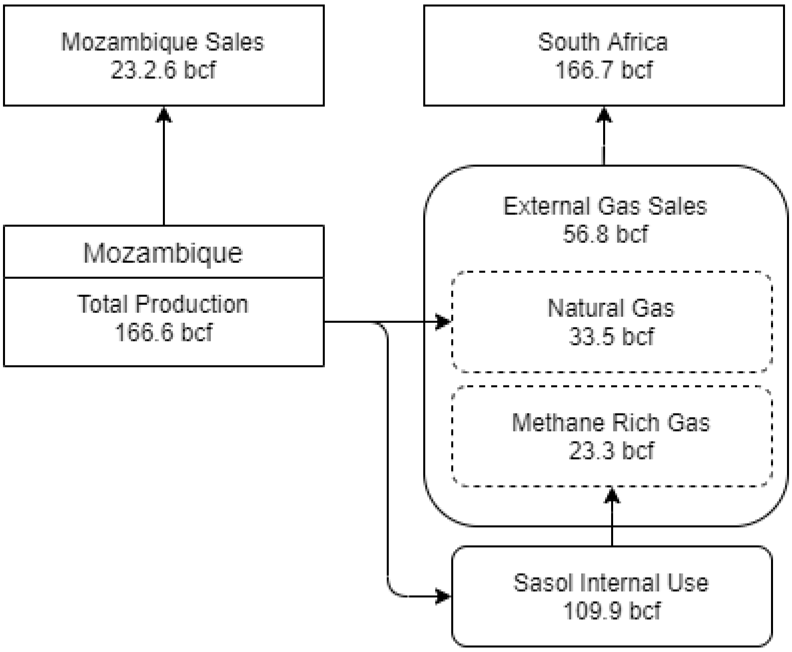

Figure A17: Gas mass balance for Sasol's gas supply (Sasol, 2017)

Fugitive emissions

Methane (CH_4) as a fugitive emissions GHG is included in SATIM for transport, storage and distribution of gas. A constant EF of 0.07 $ktCH_4/PJ_{out}$ (0.0972 gCH4/MJ) as derived by Skone et al. (2011) (after DEA (2014b)) is applied for all sectors. We assume that there is an unintentional leakage of 1% of gas activity from the natural gas system, noting that, for a proper accounting, the percentage of emissions that emanate from operations such as the movement of trucks, compressor stations, etc is necessary to improve the modelling of fugitive emissions.

Table A29: Refineries policies and measures (low, central, ambitious)

Refinery	Central	Low	Ambitious
CTL	Existing capacity and utilization remains until 2050	Existing capacity and utilization remains until 2050	Existing capacity and utilization remains until 2050
Crude oil	Existing capacity and utilization remains until 2050	Existing capacity and utilization remains until 2050.	Production allowed to decrease after 2030.

The crude oil refineries are presumed to continue operating until 2050, with the possibility of early retirement for an ambitious scenario, given the investment required to meet the Clean Fuels 2 (CF2) standard.

SATIM allows for the refurbishment or retirement of crude-oil refineries commencing in 2030. A staged retirement/refurbishment profile as depicted in Figure A18 is implemented. Capex is estimated at \$3.7 billion for fuel complying with the Euro 5 emissions standard at ±40% accuracy (DoE, 2011). In addition, an emissions penalty of ~0.003 t CO_2/bbl is associated with the fuel improvement (SAPIA, 2018b)

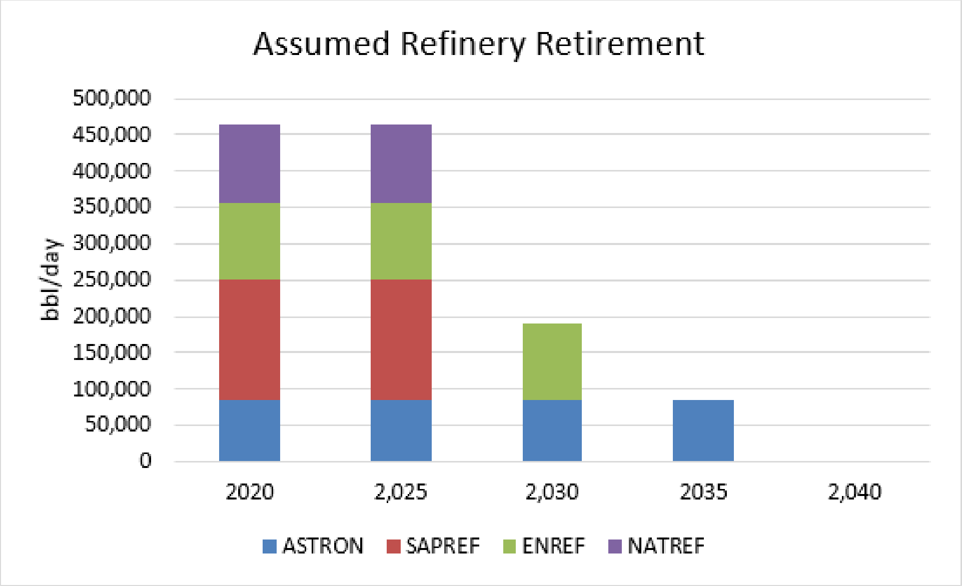

Figure A18: Assumed refinery retirement (or upgrade) profile

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