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# The developing energy landscape in South Africa: Technical Report

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*Authors:*

ERC: Gregory Ireland, Faaiqa Hartley, Bruno Merven, Jesse Burton, Fadiel Ahjum, Bryce McCall and Tara Caetano.

CSIR: Jarrad Wright

IFPRI: Channing Arndt

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

Tel: +27 (0)21 650 2521  
Fax: +27 (0)21 650 2830  
Email: [erc@erc.uct.ac.za](mailto:erc@erc.uct.ac.za)  
Website: [www.erc.uct.ac.za](http://www.erc.uct.ac.za)

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## Executive summary

The global energy landscape has changed significantly in recent years and the transition to a decarbonised energy system is well underway. The costs of energy technologies especially solar, wind and battery storage have dropped significantly in recent times and have now become cost competitive with conventional fossil fuel alternatives. In South Africa, actual average tariffs from solar PV and wind electricity generation decreased from R3.65/kWh and R1.51/kWh in 2011 respectively to R0.62/kWh in 2015, making it cheaper than electricity produced from a new-build coal fired power plant (R1.03/kWh) as well as nuclear (R1.09/kWh) (DoE 2016). While LCOE measures are useful for comparing the overall observed and expected energy cost from different technologies, it can be misleading when comparing technologies with very different characteristics. To fully understand the implications of the advances in energy technologies on future electricity generation, a fully integrated energy systems assessment is required.

While South Africa's renewable energy program has been paused due to Eskom unwillingness to purchase any new electricity produced by independent producers; ongoing advances globally are expected to lead to further price reductions in solar PV, lithium-ion battery storage and wind in the next 10 to 20 years. Projections for coal costs and further learning imply that by 2030, many markets will also have reached the point where the unitised costs of new renewable capacity are lower than even the short run marginal costs of existing coal plants – resulting in the potential of significant stranded coal assets. In countries with a large amount of older stations, such as South Africa, this may happen sooner as the cost of coal increases and legislation changes to account for externalities not currently priced into the cost of coal for power generation.

Advances in renewable energy technologies have created an opportunity to rapidly transition to a low-carbon global energy system without the significant economic compromises as previously expected. This could have significant implications for future electricity generation in South Africa, where an ageing coal fleet and international climate change commitments requires the build of new and cleaner electricity generation capacity in the country. While South Africa has developed a draft energy planning document for the country to 2050 (i.e. the 2016 Draft Integrated Resource Plan), the role of renewables in this is limited as a result of annual new-build limitations on solar PV and wind, particularly, as well as inadequate consideration of the rapid advances made in these renewable technologies, both globally and in South Africa.

The variability of non-dispatchable energy is often used as a critique against using renewable energy for a large share of energy production. The extent of the impact of variability on overall energy system performance is dependent on the resource availability and demand profiles.

The combined wind and solar resources in South Africa are complimentary while matching the country's demand profile favourably, giving them a high value to the system without the need for significant additional system flexibility or storage (IEA 2016; CSIR 2016; GIZ & Eskom 2017). South Africa further possesses some of the best solar and wind resources in the world, with vast areas of the country suitable for generating electricity at low cost from particularly solar PV, CSP, and wind technologies (Hagemann 2008; Fluri 2009; WASA 2015; CSIR & Fraunhofer 2016).

Storage technologies further enable the use of renewable energy as they allow energy to be stored and used at a later time. South Africa already extensively uses pumped storage facilities to assist with peak demand. The USTDA (2017) identified that South Africa should focus on technologies with cycles in the order of 12 hours or less for bulk energy services such as arbitrage, schedulable capacity, and for grid infrastructure services. Among these applicable technologies are batteries (including the use of electric vehicles), pumped hydro storage, flywheels, super-capacitors, and compressed air storage.

The structural changes of energy systems resulting from the incorporation of large amounts of non-dispatchable renewable power generation into the electricity system bring new challenges and have potentially far-reaching implications. Understanding the complex interactions of the numerous interconnected factors involved, and the implications of various planning choices for the environment and national objectives are essential to prepare adequate national transition plans, roadmaps and policies. Transparent, flexible and integrated energy systems models are therefore essential tools for providing credible evidence-based knowledge for future energy infrastructure planning. Future research should therefore focus on assessing the impact of changes in renewable and storage technologies discussed in this report on potential electricity and energy pathways for South Africa as well as the economic implications of these pathways.

# 1. Introduction

The global energy landscape has changed significantly in recent years and the transition to a decarbonised energy system is well underway. Transparent, flexible and integrated energy systems models are essential tools for providing credible evidence-based knowledge for future energy infrastructure planning. This report outlines the most important aspects needed to be considered in the energy modelling processes used to inform future energy investment pathways of South Africa, while meeting national carbon emission commitments and socio-economic development priorities.

The costs of energy technologies especially solar, wind and battery storage have dropped significantly in recent times and have now become cost competitive with conventional fossil fuel alternatives. This has created an opportunity to rapidly transition to a low-carbon global energy system without significant economic compromises as previously expected. However, the structural changes of energy systems resulting from the incorporation of large amounts of non-dispatchable renewable power generation into the electricity system brings new challenges and potentially far-reaching implications. Understanding the complex interactions of the numerous interconnected factors involved, and the implications of various planning choices for the environment and national objectives are essential to prepare adequate national transition plans, roadmaps and policies. This requires a detailed understanding of available renewable resources, especially solar and wind; the flexibility requirements of the overall system; the projections for likely demand growth trajectories; and global commodity and fuel price uncertainties. The opportunities for energy storage to allow for improved co-ordination between supply and demand are considerable with electrochemical storage (batteries) and resulting controllable demand-resources in the electricity sector specifically being notable examples.

Technology costs reductions have been most significant for solar PV and lithium-ion battery storage. Between 2009 and 2015, the price of solar PV modules declined by 80%, while the unitized capital cost of lithium-ion batteries (per kWh) fell by 50% between 2014 and 2016. Ongoing advances are expected to lead to further price reductions in solar PV in particular along with wind in the next 10 to 20 years. The overall cost of energy provided by solar PV is expected to drop by as much as 60% over the next decade (IRENA 2016; Fraunhofer 2015) while the cost of lithium-ion battery storage is expected to fall by between 50% and 70% in the next 10 years (CSIRO 2015; IRENA 2017). The cost of on-shore wind is also expected to drop further by up to 50% by 2040 (BNEF 2017).

Price declines to date have resulted in new renewable capacity being competitive on an Levelised Cost of Energy (LCOE) basis with new coal in many countries, including South Africa (DoE 2017; Wright et al. 2017). Actual average tariffs from solar PV and wind electricity generation in South Africa decreased from R3.65/kWh and R1.51/kWh in 2011 respectively in 2011 to R0.62/kWh in 2015, making it cheaper than electricity produced from a new-build coal fired power plant (R1.03/kWh) as well as nuclear (R1.09/kWh) (DoE 2016). New renewable capacity is furthermore expected to be competitive with existing coal, nearly globally, by 2030 (BNEF 2017).

Current and expected developments in renewable technologies could have significant implications for future electricity generation in South Africa. An ageing coal fleet and international climate change commitments requires the build of new and cleaner electricity generation capacity in the country.

In November 2016, the South African government published a draft version of its Integrated Resource Plan, which serves as a guide to the building of new electricity generation infrastructure in

the country and the mix of technologies to be invested in to 2050. While this plan does include renewable sources of power generation (mostly solar PV and wind), their role is limited as a result of annual new-build limitations on solar PV and wind, particularly, as well as inadequate consideration of the rapid advances made in these renewable technologies, both globally and in South Africa.

The measure of LCOE can be useful for comparing the overall observed and expected energy cost from different technologies, but can be misleading when comparing technologies with very different characteristics e.g. non-dispatchable solar PV and wind do not provide the same value to the system as dispatchable generators. The actual value (and costs) to the energy system of any technology is a complex and dynamic combination of all prospective new and existing capacity and their overall ability to meet demand. Both demand and supply options change over time (over a day, week, month, year) as the structure of the overall power system evolves with particular importance placed on when supply and demand-side options produce and whether this is correlated with demand. To fully understand the implications of the advances in energy technologies on future electricity generation in South Africa, a fully integrated energy systems assessment is required.

There are several energy models currently in use in South Africa. These include a TIMES model, which is used by the Energy Research Centre (ERC) called SATIM; PLEXOS, which is used at the Council for Scientific Research (CSIR), Department of Energy (DoE) and Eskom; and OSeMOSYS, which is used by a different division within the DoE. PLEXOS models used in South Africa are highly detailed models specifically applied to the power sector. These models contain higher time resolution for energy profiles and also include detailed information on system constraints and reliability requirements. Given their fine time resolution and the focus on the power sector only, demand is often aggregated into total electricity demand, and therefore does not fully capture changes in the projected demand within individual sectors, behavioural responses to prices, or fuel switching. SATIM is a full sector energy model, which considers not only the demand for electricity and how this is met but also the demand for liquid fuels and other energy resources and how these impact the choice of fuels used within the electricity sector and vice-versa (for model and documentation: <http://energydata.uct.ac.za/organization/erc-satim>). In SATIM, the demand for energy services or useful energy (e.g. process heating), which has strong links to demand drivers (e.g. GDP and population), is specified. The final energy demand (e.g. the demand for electricity) is a result of the model, based on the least-cost demand technology mix (e.g. mix of boiler types or vehicle types). This provides a more holistic picture of the energy system and supply-demand interactions, allowing for endogenous fuel switching and the switch to more efficient technologies. SATIM, however, currently has a less detailed time resolution and does not currently account for certain technical constraints on the power sector such as ramp-rate constraints (although the model can be augmented to include this in future). TIMES was developed by the IEA, and is written in GAMS, which has some software licensing requirements. It has been around for a long time, it has a well-established community of users, and already includes many advanced features such as technology vintaging, stochastic programming, myopic optimization, elastic demand and ramp rate constraints among others (see [www.iea-etsap.org](http://www.iea-etsap.org)). The TIMES code is well documented and open-source with some restrictions. OSeMOSYS on the other hand is written in GNU mathprog, which does not require licensing. The model in its current form is easy to follow as it does not include as many advanced features, which makes it a bit more accessible. However, as it gets more of those features, it will probably end up looking a lot like the TIMES code. It has a growing community of users, including the DOE. The DOE's implementation includes the power sector, the liquid fuel

supply sector, with a relatively detailed representation of the transport sector. The other sectors have a relatively simpler representation, and it also has a very low time-resolution.

Despite these differences, all energy systems models require detailed inputs on a diverse set of variables including technology costs, global commodity prices, renewable resources as well as the existing energy system and any constraints it may face.

The objective of this technical report is therefore to:

- a) Provide an overview of the developments in renewable energy and storage technologies globally and in South Africa;
- b) Assess the implications of these developments for costs in South Africa and provide a consistent set of assumptions for renewable energy technologies; and
- c) Highlight the specific contextual constraints, systems details, and modelling methodologies that need to be incorporated.

The technical report is structured as follows:

Section 2: Provides an overview of global trends in renewable and storage technologies.

Section 3: Provides an overview of the South African energy system including new power sector investments and the constraints facing these.

Section 4: Discusses renewable energy in the context of South Africa and identifies the likely future costs of renewable technology in the country.

Section 5: Discusses some of the constraints facing the energy system in South Africa.

Section 6: Concludes by discussing potential future work.



## 2. Global renewable technology trends

In recent years, renewable energy costs and prices have fallen dramatically across the world. Cost reductions have taken place across technologies but have been most pronounced for solar PV and batteries (details throughout the report). Technology cost reductions have been reflected in steep declines in auction prices across various countries and technologies (IRENA 2017), with record-breaking prices for wind, solar PV, PV with batteries, and CSP being achieved through competitive bidding processes in countries such as South Africa, the USA, Australia, Morocco, and Abu Dhabi.

Figure 1 presents the average auction prices for solar PV between 2010 and 2017. While the lowest bid was reported to have been in Abu Dhabi at 2,42 USc/kWh for a 1.1GW plant (weighted for peak and off-peak production) (Dipaola 2016), this was recently beaten by the EDF/Masdar plant in Saudi Arabia which achieved 1,79 USc/kWh for a 300MW plant (Dipaola 2017) though the latter likely received several concessions. Solar plus storage has also delivered extremely low prices. In Arizona, a 100MW PV plant with 30MW/120MWh storage contracted at below 4.5 USc/kWh. Excluding storage, the cost of the plant was reported to be 3 USc/kWh (Parkinson 2017).

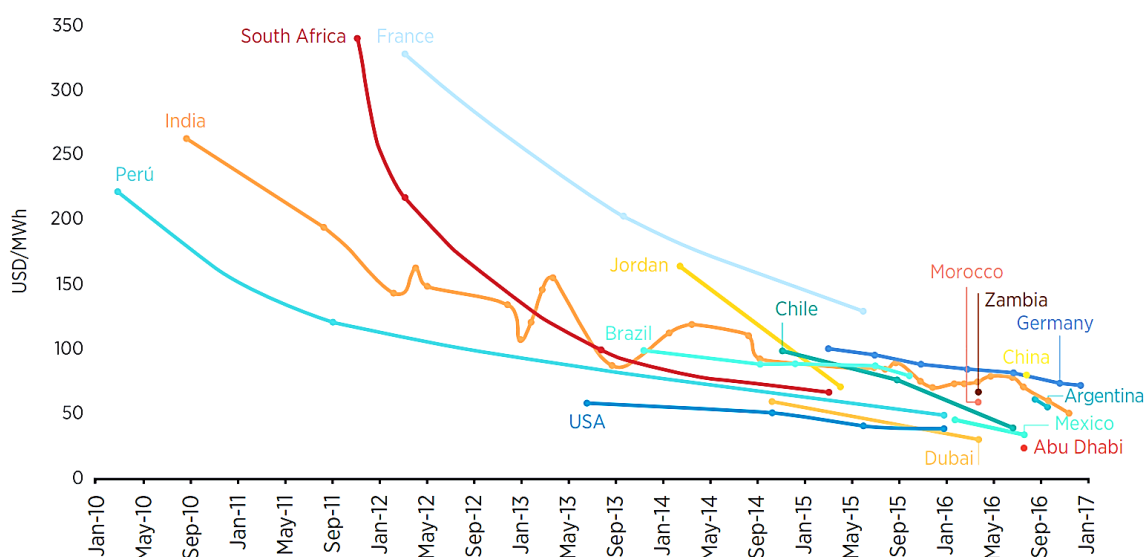


Figure 1: Evolution of average auction prices for solar PV, 2010-2017 (IRENA 2017)

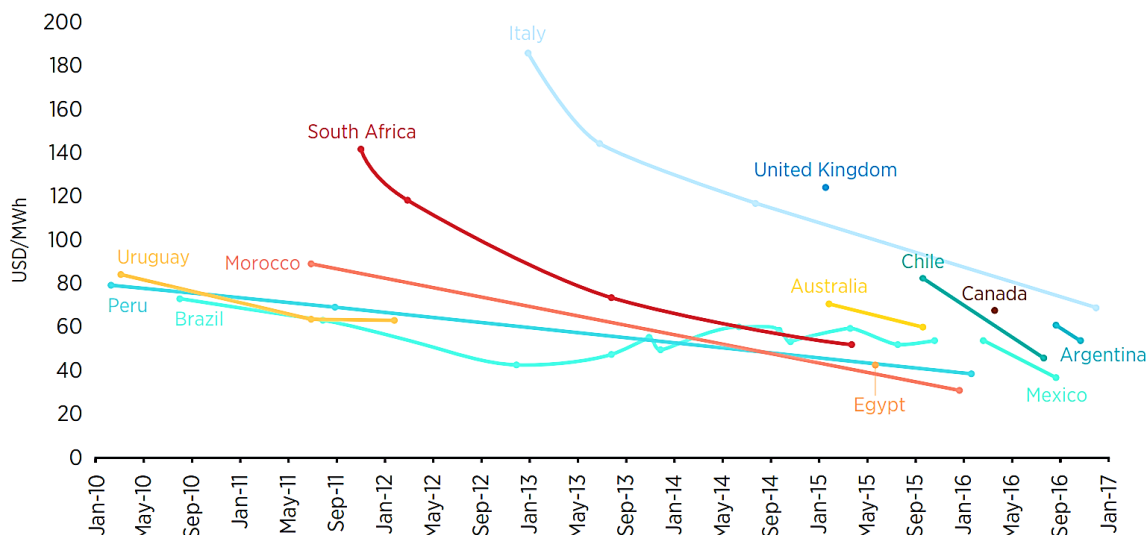


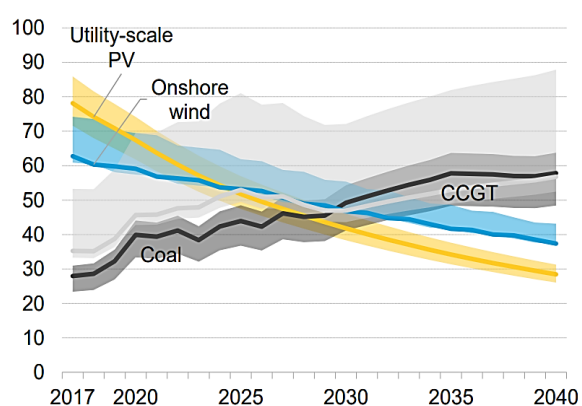
Figure 2: Evolution of average auction prices for onshore wind , 2010-2017 (IRENA 2017)

While auction prices for onshore wind have fallen less sharply than solar PV, reflecting the relative maturity of the technology, unsubsidised onshore wind has also achieved extremely low prices in some countries (see Figure 2). A 2016 auction in Morocco for example achieved a price of 3c/kWh (Parkinson 2016).

The implications of these rapidly falling prices are profound. New renewable capacity is now competitive with new coal in many countries (including in South Africa, China and India). Projections for coal costs and further learning imply that by 2030, many markets will also have reached the point where the unitised costs of new renewable capacity are lower than even the short run marginal costs of existing coal plants – resulting in the potential of significant stranded coal assets (see examples of Germany and China in Figure 3). In countries with a large amount of older stations, such as South Africa, this may happen sooner as the cost of coal increases and legislation changes to account for externalities not currently priced into the cost of coal for power generation.

### Germany

\$/MWh (real 2016)



### China

\$/MWh (real 2016)

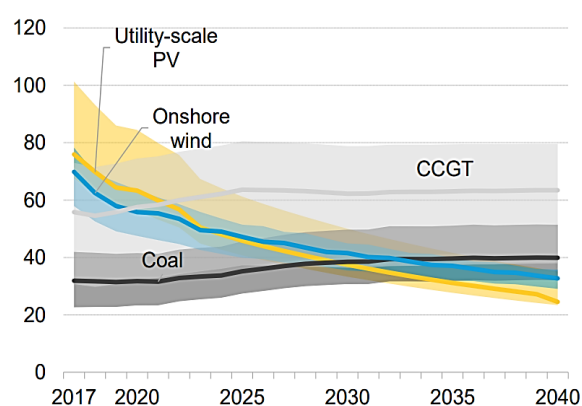
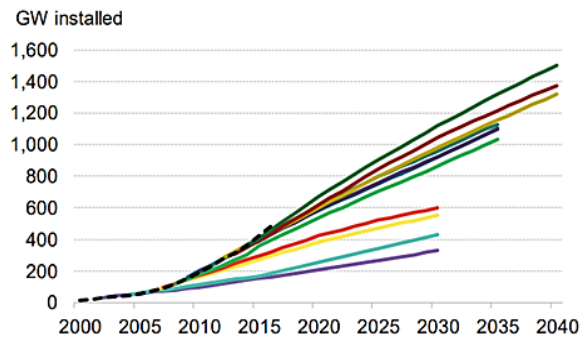


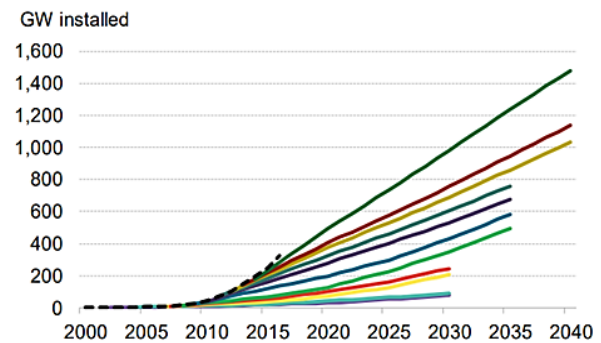
Figure 3: Tipping points for new and existing technologies in Germany and China (Liebrich 2017)

Various modeling exercises have typically underestimated the rate and scale of renewable energy uptake and overestimated the demand for conventional fossil fuels, in particular coal. Many organisations did not foresee the pace of price reductions for renewables nor the scale of the new-build that has been seen in recent years. The IEA for example, has consistently underestimated both solar and wind uptake, with projections falling far short of actual market trends. Figure 4 below shows the World Energy Outlook projections plotted against actual wind and solar PV build (Liebrich 2017). The IEA World Energy Outlook has been the most influential example of these consistent underestimates, but according to REN21, even the solar industry's own early projections have been surpassed by actual uptake (REN21 2017).

### Global cumulative wind installations



### Global cumulative solar installations



--- Historical    2004    2006    2008    2009    2010    2011    2012    2013    2014    2015    2016  
 Note: 2004-2009 Reference, 2010-2016 New Policies Scenario      Source: IEA World Energy Outlook

Figure 4: Expected IEA global wind and solar installations versus historical (Liebrich 2017)

The variability of non-dispatchable energy is often used as a critique for using the energy source for a large share of energy production. The extent of the impact of variability on overall energy system performance is dependent on country specific factors but general principles can be applied. The correlation between the resource availability and demand profiles which determines the necessary complementary resources is country specific and determined on a case-by-case basis but flexibility of these complementary resources is common. Since 2013, half of all new capacity built globally has been renewable in nature (REN21 2017) with annual average shares of non-dispatchable renewable energy exceeding 20% in several countries in 2015 (see Figure 5) (IEA 2016). Renewable energy in various countries now also regularly exceed 50% of total instantaneous electricity production. For example, very high contributions exist in Scotland (153% wind), Denmark (140% wind), Germany (70% wind and solar), South Australia (61% wind and solar), Spain (70% wind), ERCOT - Texas (45% wind) and CAISO - California (46% wind and solar) (Liebrich 2017). Denmark continues to see high contributions from non-dispatchable renewable energy despite weakly matched natural resource availability and demand profiles, using complementary flexible resources to support the energy system. South Africa has been identified as a country in which the renewable resource profiles and demand match relatively well both across diurnally and seasonally (IEA 2016) (see section 4).

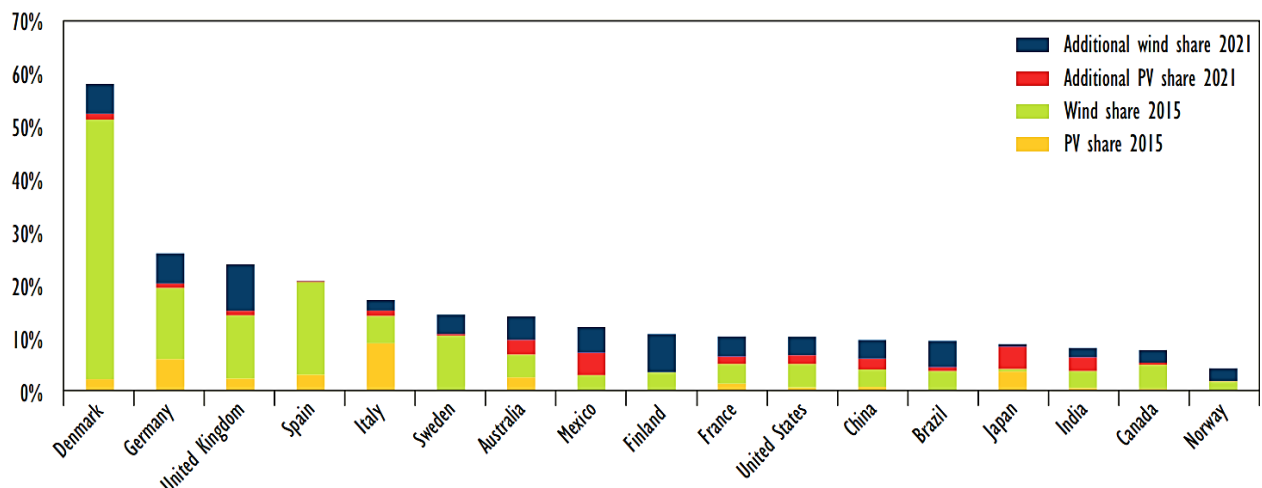


Figure 5: Share of VRE generation in 2014 and 2020 for selected countries (IEA 2016)

## **2.1 The implications for climate change mitigation**

Although rapid investment in renewable energy is underway, the pace and scale of these investments are still insufficient to deliver the necessary emissions cuts to limit warming to below 2°C. If countries meet their Paris commitments - and many are not on track to do so - then warming will be around 2.8°C. Current policies, on the other hand, lead to warming of 3.5°C (Climateactiontracker.org). This is substantially higher than the 1.5°C envisaged in the Paris Agreement, and has implications for South African electricity planning into the future.

The electricity sector is currently a large emitter but also a low-cost option for mitigation in South Africa. However, meeting 2°C consistent emissions cuts will require the stranding and underutilisation of some power plant capacity (Burton et al. 2016). This is in line with recent work on stranded assets and ‘committed emissions’ globally. In Pfeifer et al. (2016), for example, it is shown that unless the plants later become stranded, no new emitting electricity generation plant can be built from 2017 onwards for 2°C scenarios. Many other authors have shown that coal will have to be phased out by 2050 to limit warming to 2°C and even more rapidly to limit warming to 1.5°C (Rogelj et al. 2015; Pfeiffer et al. 2016; Johnson et al. 2015; Luderer et al. 2016, Iyer et al. 2015).

### 3. South African Energy Context

#### 3.1 Existing electricity system

The South African electricity system relies heavily on coal. In 2016, coal accounted for 74% of total generation capacity with the balance comprising of hydro and pumped storage, peaking plants such as Open Cycle Gas Turbines (OCGTs), nuclear and renewables - total capacity is reported to have been 49.8GW in 2016 (Wright et al. 2017).

Electricity generation is dominated by Eskom, which also functions as the system operator and owns and operates the transmission and distribution networks outside those owned and managed by the large metropolises. Eskom electricity generation comprises of around 38GW of coal, 1.8GW of nuclear, 1.3GW of hydro/pumped storage, 2,4GW of OCGTs and less than 1GW of non-dispatchable renewable energy (see Figure 6). Eskom sells electricity both directly to customers as well as to municipalities who then redistribute the power purchased.

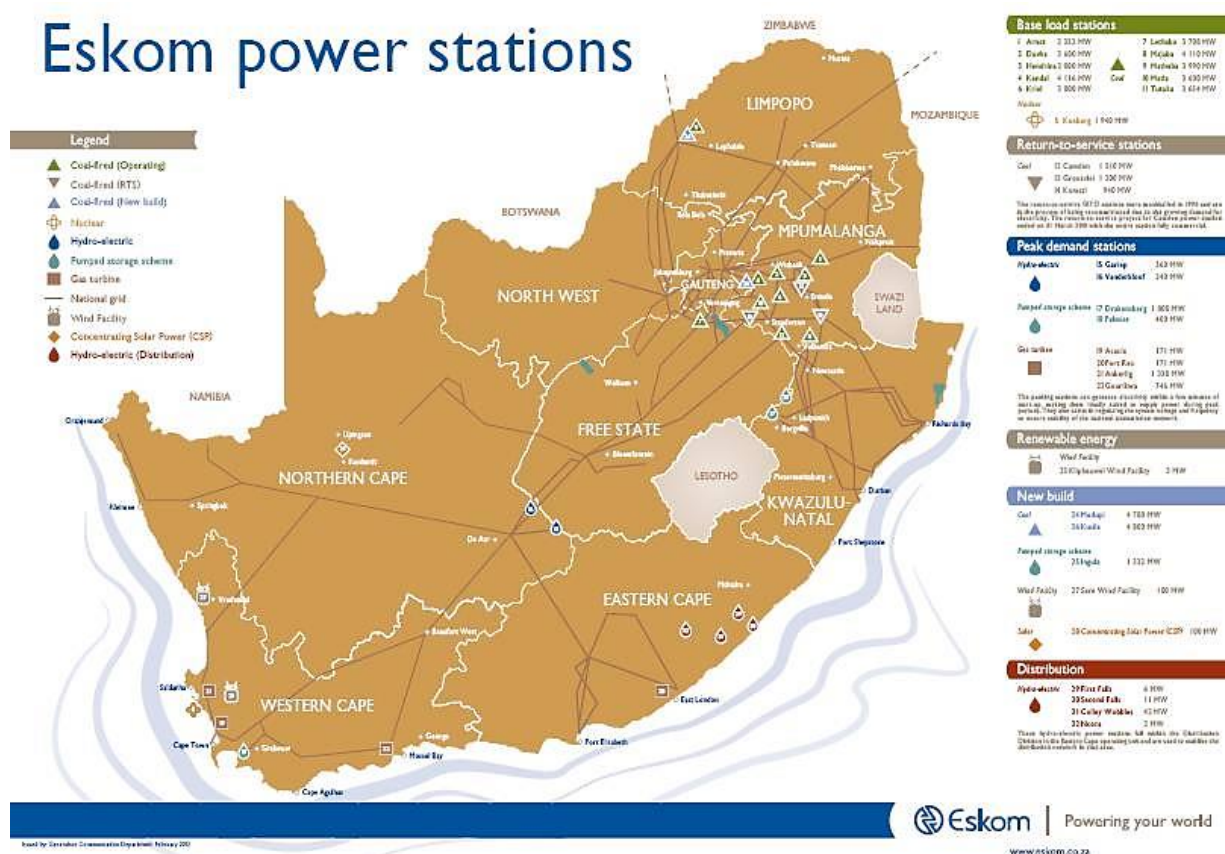


Figure 6: Eskom power plants (Eskom)

On average, South Africa has exported about 5.7% of electricity generated to neighbouring countries over the past decade supplying more than 40% of electricity used in Africa (StatsSA: Electricity generated and available for distribution; Eskom 2012). Imports account for around 4.2% of total supply and comprise primarily of hydropower from Mozambique (StatsSA: Electricity generated and available for distribution).

In 2012, the average age of the South African coal powered fleet was placed at 30 years and some plants were reported to have already reached 300% of their design life (Eskom 2012). As a result many power stations will be decommissioned over the next three decades. Based on information from Eskom, the DoE reports that by 2030, 9.6GW of existing capacity will be decommissioned, followed by 14.8GW by 2040 and 7GW by 2050. By 2050, less than 10GW of existing capacity will be in operation (see Figure 7). Rising coal prices as mines reach their end-of-life and cheaper alternative energy sources raises the risk for the earlier decommissioning of coal fired plants. This has already been seen by the reversed decision by Eskom to life-extend its Hendrina coal power plant. Potential challenges in securing sufficient coal for power stations by 2040 could also result in the stranding of power stations. Figure 8 presents the decommissioning schedule of the full South African generation fleet to 2050.

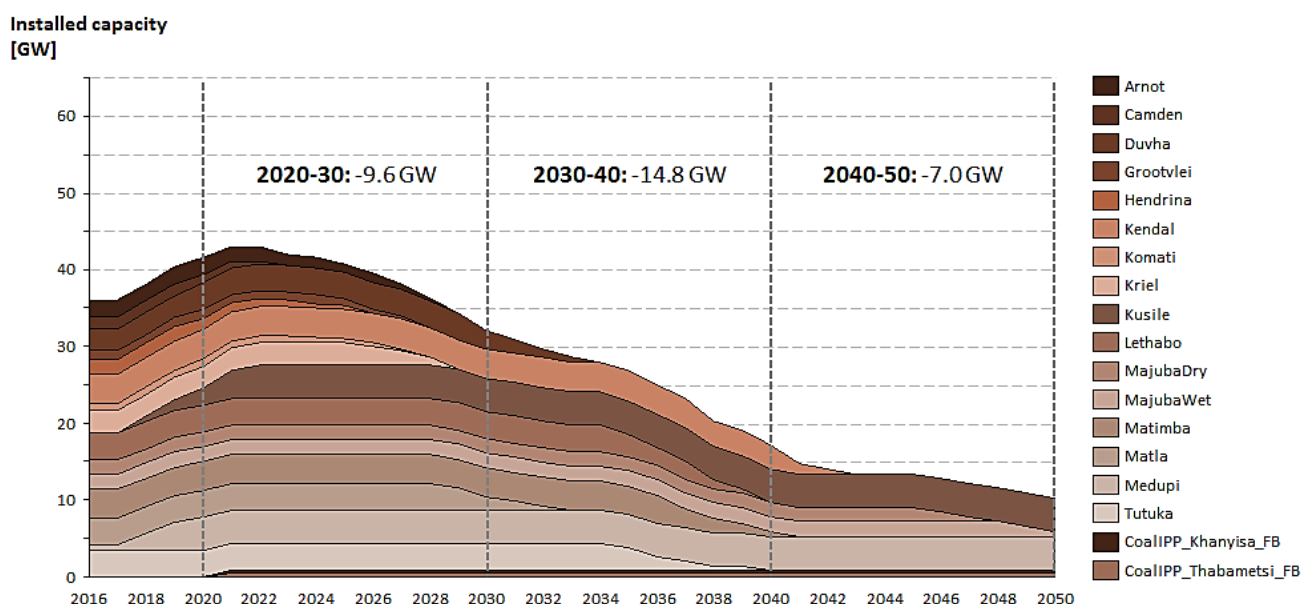


Figure 7: Planned coal decommissioning schedule for South Africa (DoE 2016; Wright et al. 2017)

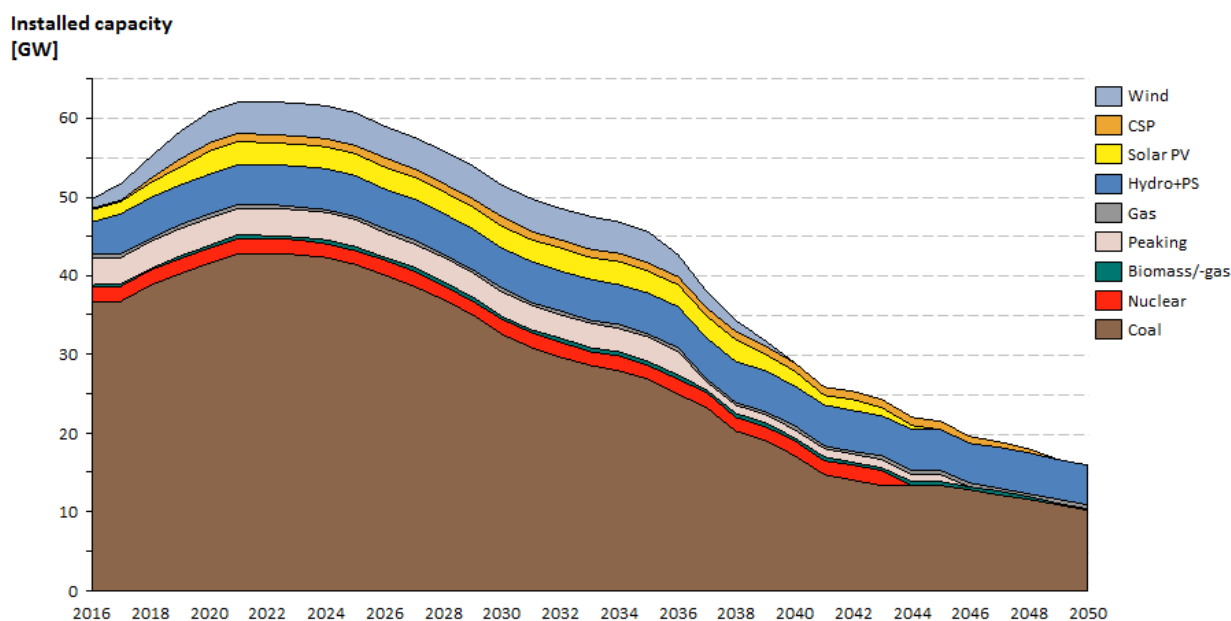


Figure 8: Planned power decommissioning schedule for South Africa (DoE 2016; Wright et al. 2017)

Apart from the decommissioning of coal discussed above, nuclear is expected to be fully decommissioned by 2044 and peaking plants are expected to reach the end of their lives slightly later in 2046. Existing and currently under-construction wind and solar PV capacity is also expected to be retired by 2044, while solar CSP runs through to 2048.

### 3.2 New power sector investments in South Africa

The ageing coal fleet, expected decline in installed capacity and a growing demand requirement in future means that South Africa needs to build new power capacity to replace retiring plants and meet new expected demand growth. This new build also needs to be less carbon intensive given South Africa's international climate change commitments and that the electricity sector accounts for a significant proportion of national emissions (these are discussed briefly below).

There are two policy contexts guiding national emission reductions in South Africa. The first is the “Peak, Plateau and Decline” (PPD) trajectory - South Africa’s national benchmark emissions trajectory range as outlined in the National Climate Change Response White Paper (NCCRWP) - and the second is South Africa’s Nationally Determined Contribution (NDC) as communicated to the UNFCCC in 2015. The latter comprises a limit on emissions of between 398 and 614 Mt CO<sub>2</sub>-eq for the years 2025 and 2030 respectively; and is consistent with the PPD resulting in a peak in emissions between 2020 and 2025, plateau for approximately a decade and decline in absolute terms thereafter (see Figure 9). Also included in Figure 9 is the trajectory for emissions from the power sector. This is based on the assumption made in the 2016 Draft IRP which assumes that the electricity sector contributes 45% to total emissions. The trajectory of electricity sector emissions therefore align to that of the Upper and Lower PPD limits reaching 210 and 140 Mt CO<sub>2</sub>-eq by 2050 respectively.

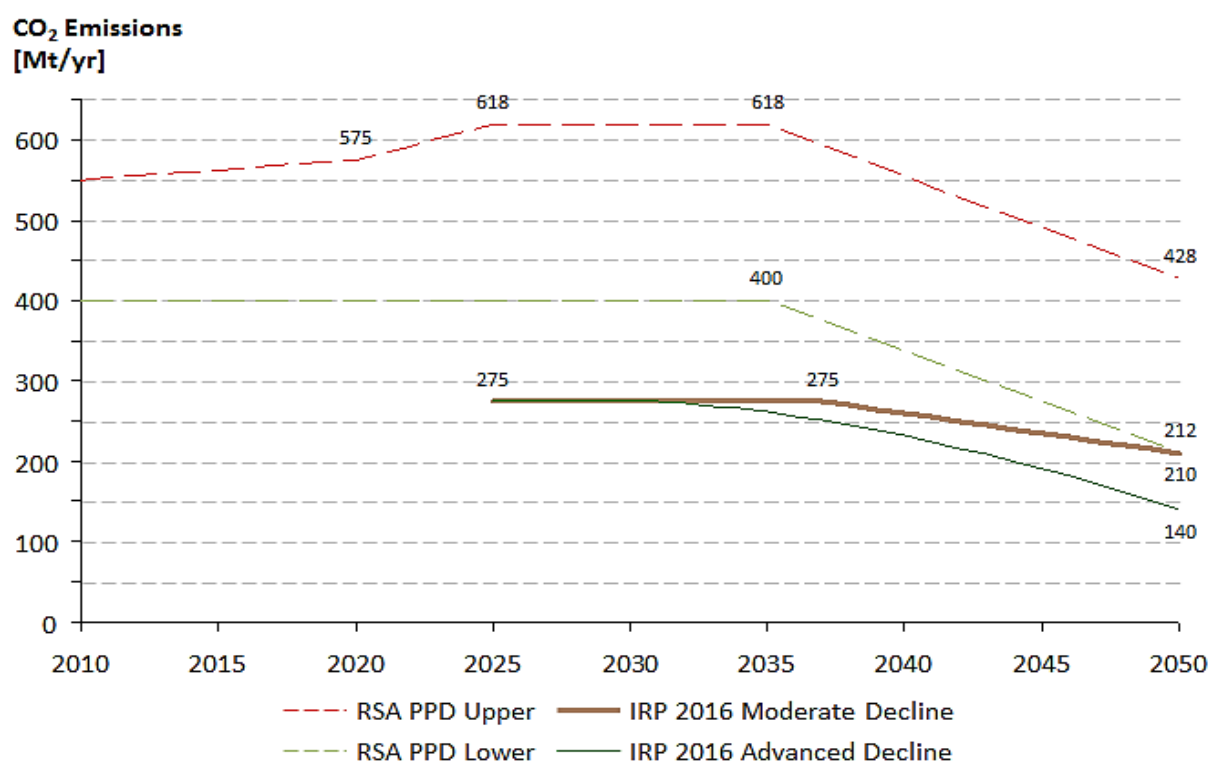


Figure 9: South African Peak, Plateau and Decline trajectory (Wright et al. 2017)

As previously discussed, the electricity build plan in South Africa is informed by the IRP and is intended to be a living plan with ongoing updates and public review. The most recent promulgated IRP was released in 2010 and covers electricity planning to 2030. An update to this is currently being developed and is in draft form (i.e. the 2016 Draft IRP).

### 3.2.1 Conventional technologies

The 2010 IRP included 8.6 GW of new coal fired power plants (specifically the currently under construction Medupi and Kusile power plants) as well as 6.3GW of other new-coal-fired power plants. Medupi and Kusile were originally expected to be running at full capacity by 2017 and 2020 respectively. However, building delays have resulted in these expectations shifting to 2020 and 2022 respectively (see Table 1). Kusile is currently running ahead of the schedule presented in Table 1 as the first unit came online in August 2017. Delays in this new-build programme have however resulted in cost overruns increasing the expected price of electricity from these sources considerably. The DoE (2017) report an estimate of the levelised cost of electricity from Medupi to be R1.21/kWh (April 2016 Rands). Other estimates place the levelised cost of Medupi and Kusile including FGD at R1.05/kWh and R1.16/kWh respectively (May 2016 Rands) (EE publishers, 21 July 2016). Any further delays would be expected to increase these further.

Table 1: Committed new build dates (DoE 2016)

	<b>Medupi</b>	<b>Kusile</b>	<b>Ingula</b>
<b>1<sup>st</sup> Unit</b>	Commissioned	July 2018	Jan 2017
<b>2<sup>nd</sup> Unit</b>	Mar 2018	July 2019	Mar 2017
<b>3<sup>rd</sup> Unit</b>	July 2018	Aug 2020	May 2017
<b>4<sup>th</sup> Unit</b>	June 2019	Mar 2021	Jul 2017
<b>5<sup>th</sup> Unit</b>	Dec 2019	Nov 2021	-
<b>6<sup>th</sup> Unit</b>	May 2020	Sep 2022	-

The Draft IRP 2016 Base Case proposes the capacity expansion plan presented in Figure 10. This is based on conventional technology costs reported in Table 2 (amongst other technical assumptions) and the well documented annual new-build limits placed on solar PV and wind in particular.



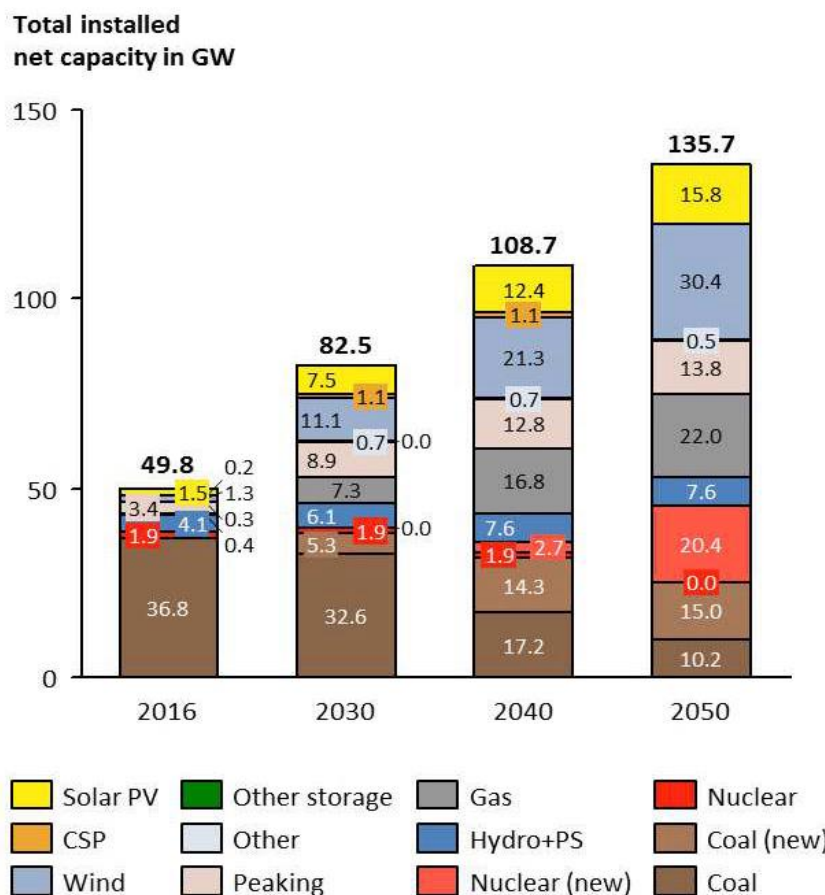


Figure 10: Installed capacity to 2050 from the Draft IRP 2016, GW (Wright et al. 2017)

Table 2: Conventional technology input cost assumptions from 2016 Draft IRP (DoE 2016)

Property		Conventionals										
		Coal (PF)	Coal (FBC)	Coal (PF with CCS)	Coal (IGCC)	Nuclear (DoE)	OCGT	CCGT	ICE (2 MW)	ICE (10 MW)	Demand response	Inga
Rated capacity (net)	[MW]	4 500	250	4 500	644	1 400	132	732	2	9	500	2 500
Overnight cost per capacity	2016 [ZAR/kW]	35 463	42 806	68 598	55 051	60 447	8 173	8 975	12 751	13 667	0	45 372
	2030-2050 [ZAR/kW]	35 463	42 806	53 771	66 436	58 816	8 173	8 975	12 751	13 667	0	45 372
Construction time	[a]	9	4	9	4	8	2	3	1	1	1	8
Capital cost (calculated) <sup>1</sup>	2016 [ZAR/kW]	39 328	47 354	76 074	60 900	78 023	8 777	9 956	12 751	13 667	0	67 249
	2030-2050 [ZAR/kW]	39 328	47 354	59 631	73 495	75 917	8 777	9 956	12 751	13 667	0	67 249
Fuel cost	[ZAR/GJ]	27	14	27	27	8	126	126	126	126	0	0
Heat rate	[GJ/MWh]	9 812	10 788	14 106	9 758	10 657	11 519	7 395	9 477	8 780	4	0
Fixed O&M	[ZAR/kW/a]	924	621	1 576	1 423	968	161	165	422	475	9	907
Variable O&M	[ZAR/MWh]	80	173	148	75	37	2	22	70	120	1 441	0
Load factor (typical)	[./]	82%	82%	82%	82%	90%	6%	36%	36%	36%	2%	70%
Economic lifetime	[a]	30	30	30	30	60	30	30	30	30	1	60

### 3.2.2 Renewable energy procurement

Since 2011, 6,328MW of renewable capacity has been procured through the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) with construction underway for a large proportion of this capacity (Eberhard & Naude 2016). While South Africa’s prices were relatively high at the start of the REIPPPP programme, prices fell dramatically over the competitive bid rounds, in particular for solar PV (see Figure 11). This is in line with international technology trends and the competitive nature of the auctions, but also highlights how capital costs fell substantially in South Africa over the bid rounds. The cost of solar PV decreased by more than 80% between 2011 and 2015 while the cost of wind decreased by almost 60%. These advances has resulted in renewable technologies being cost competitive with new coal IPPs as well as new builds identified in the 2016 Draft IRP (see Figure 12).

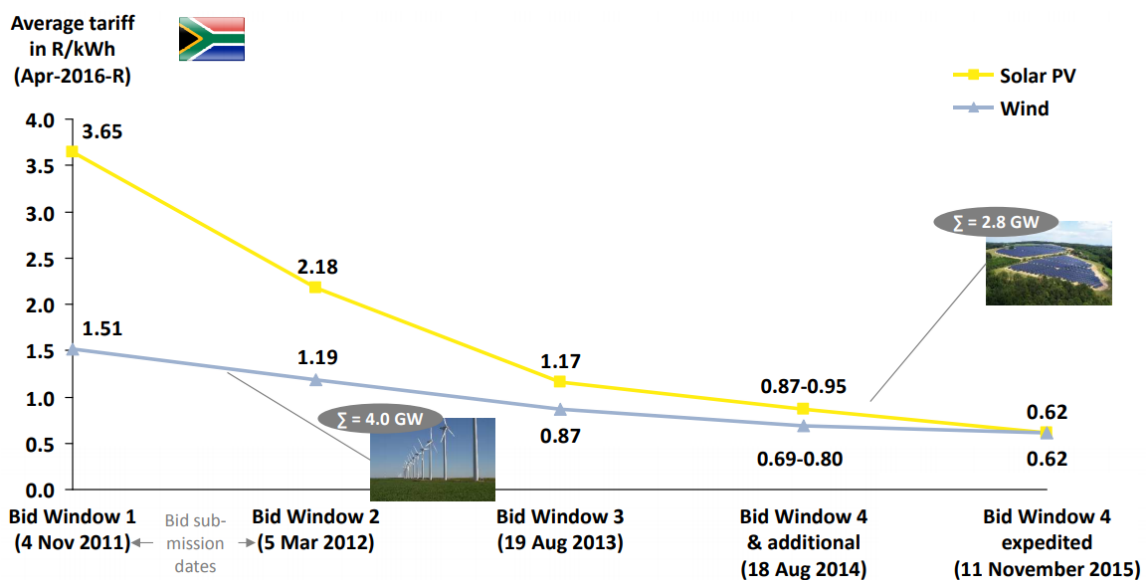


Figure 11: Actual average tariffs, R/kWh (April, 2016) (Wright et al. 2017)

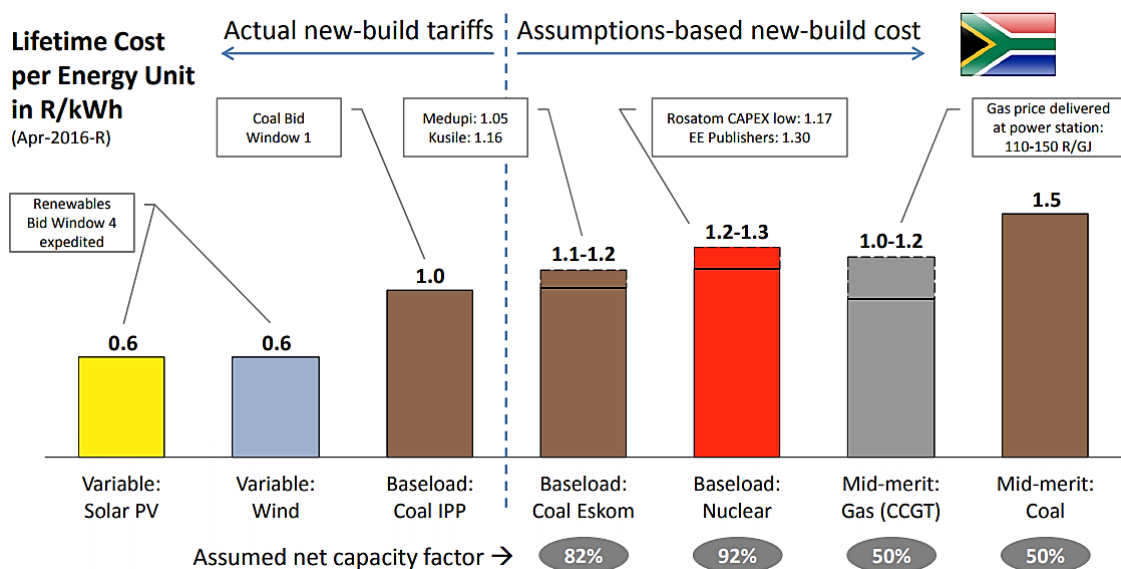


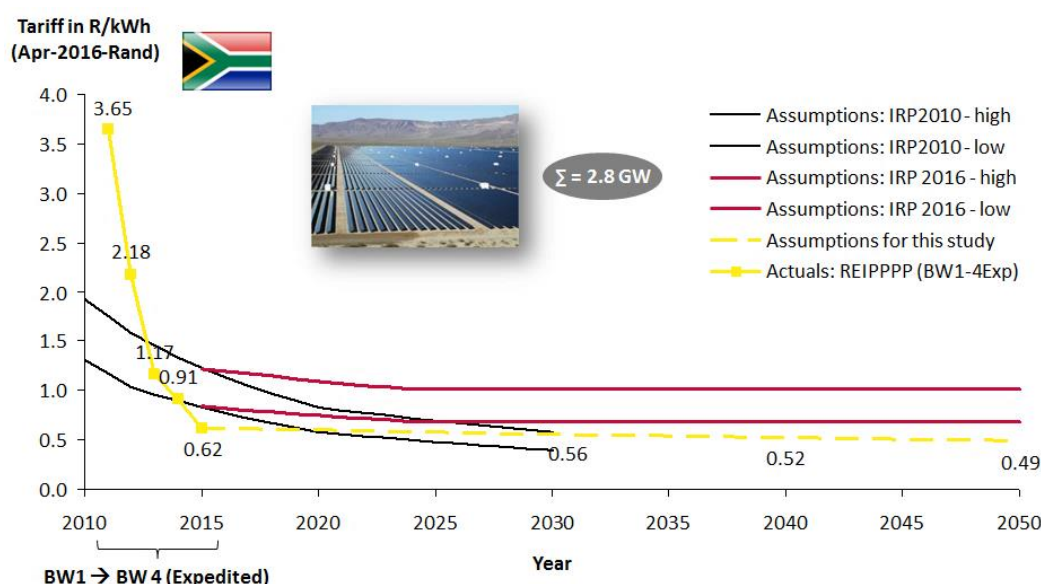
Figure 12: Comparison of lifetime energy costs per technology (R/kWh) (Wright et al. 2017)

In 2016, Eskom announced that it would not sign several power purchasing agreements (PPAs) citing costs and electricity overcapacity in the country as reasons for its decision (Business Day, 5 June 2017). This has effectively halted the REIPPPP and South Africa has since been overtaken by many countries where auctions have continued to deliver substantial cost related benefits for both wind and solar PV. Eskom's refusal to sign further agreements stops expected capacity from bid windows 4 and onwards, with an investment value of R58 billion (Business Day, 5 June 2017), from coming online and places uncertainty on the future of the REIPPPP and increasing investor risk.

Since recent developments in renewable energy in South Africa, Wright et al. (2017) conservatively estimate renewable energy technology cost assumptions presented in Table 3. The observed average tariffs achieved, future cost curves, and their comparison to the assumptions made in the IRP2010 and IRP2016 are shown for Solar PV, Wind and CSP in figures 14, 15, and 16 below. The overnight costs are based on the most recent renewable energy prices in South Africa, i.e. REIPPPP Bid Window (BW) 4 (expedited). A discount rate of 8.2% with a load factor of about 20% for solar PV, 60% for CSP and 36% for wind is assumed. Moderate learning is assumed for solar PV while no further learning is assumed on wind. Wright et al. (2017) indicates that further learning is likely and will further reduce these costs.

Table 3: Technology cost input assumptions (Renewables) (Wright et al. 2017)

Property		Wind	Solar PV (tracking)	Solar PV (fixed)	CSP (tower, 9h)	Biomass (forestry)	Biomass (MSW)	Landfill Gas	Biogas	Bagasse (Felixton)	Bagasse (gen)
Rated capacity (net)	[MW]	100	-	10	125	25	25	5	5	49	53
Overnight cost per capacity	2016 [ZAR/kW]	13 250	-	9 243	93 260	43 893	143 004	31 048	12 751	17 821	34 165
	2030-2050 [ZAR/kW]	13 250	-	8 274	55 402	43 893	143 004	31 048	12 751	17 821	34 165
Construction time	[a]	4	-	1	4	4	4	1	1	2	3
Capital cost (calculated) <sup>1</sup>	2016 [ZAR/kW/a]	13 648	-	9 243	103 169	48 557	158 199	31 048	12 751	18 303	35 589
	2030-2050 [ZAR/kW/a]	13 648	-	8 274	61 288	48 557	158 199	31 048	12 751	18 303	35 589
Fuel cost	[ZAR/GJ]	0	-	0	0	32	0	0	114	81	81
Heat rate	[GJ/MWh]	0	-	0	0	12 386	18 991	12 302	11 999	26 874	19 327
Fixed O&M	[ZAR/kW/a]	500	-	200	1 009	1 655	6 470	2 373	422	172	390
Variable O&M	[ZAR/MWh]	0	-	0	0	66	114	62	52	9	27
Load factor (typical)	[./]	36%	-	20%	60%	85%	85%	85%	20%	55%	50%
Economic lifetime	[a]	20	-	25	30	30	30	30	30	30	30



Notes: REIPPPP = Renewable Energy Independent Power Producer Programme; BW = Bid Window; bid submissions for the different BWs: BW1 = Nov 2011; BW2 = Mar 2012; BW3 = Aug 2013; BW4 = Aug 2014; BW4 (Expedited) = Nov 2015. Sources: StatsSA for CPI; IRP2010; South African Department of Energy (DoE); DoE IPP Office; CSIR analysis

Figure 13: Solar PV tariffs – observed and projected (conservative learning) (Wright et al. 2017)

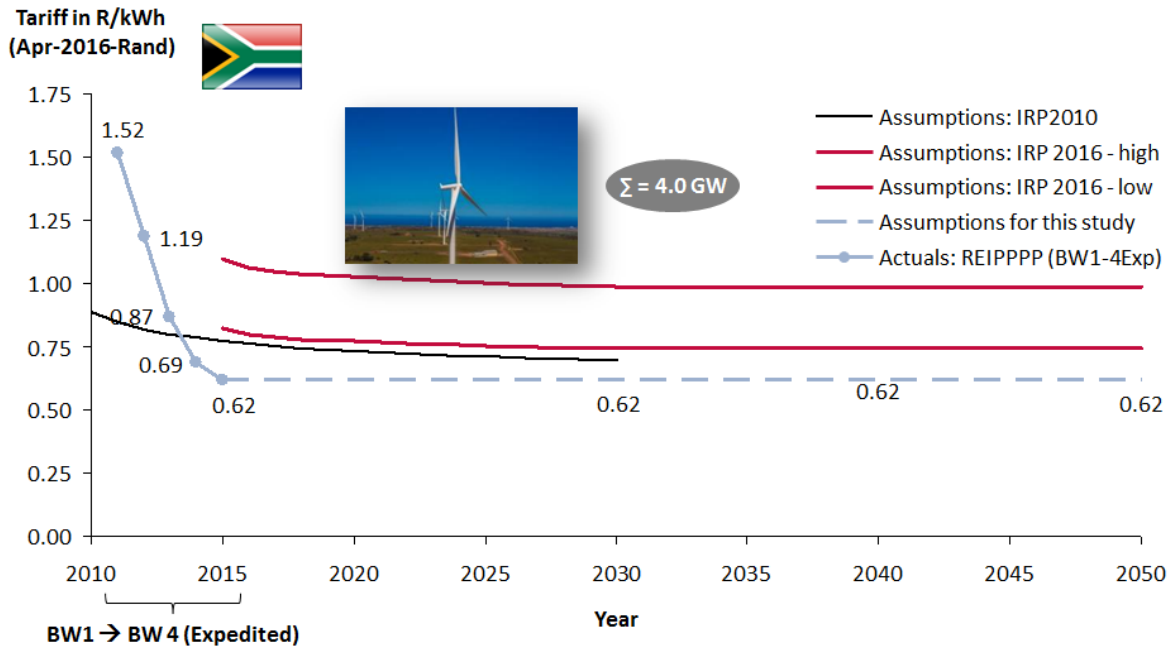


Figure 15: Wind tariffs - observed and future projections (conservative learning) (Wright et al. 2017)

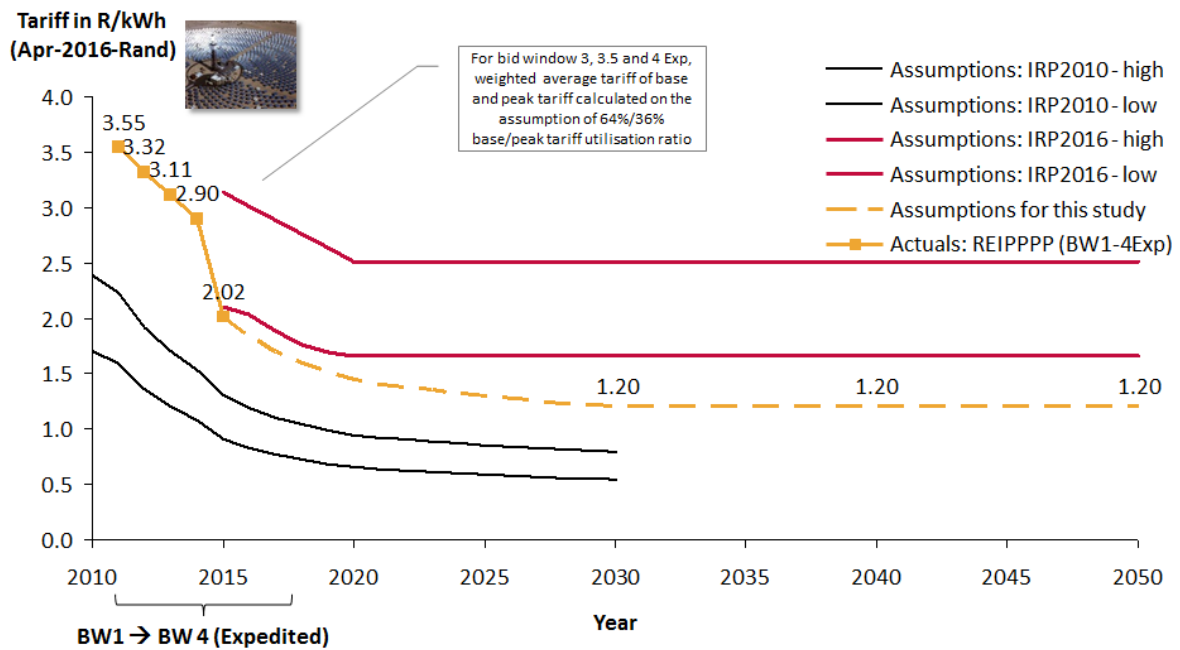


Figure 16: CSP tariffs - observed and future projections (conservative learning) (Wright et al. 2017)

### 3.2.3 Nuclear

Estimates from a UNEP study (2015) indicate the overnight costs of nuclear could range between \$4500/kW and \$8500/kW by 2050. Their assessments are based on the 2013 IRP Update's overnight investment cost of \$5800/kW to which distributions based on international assessments are applied. As noted in their study, while international assessments may not be directly comparable to South Africa, the expected future trends and uncertainties in costs are likely to be roughly comparable given the small number of nuclear facilities built. The DoE (2013) reports a range of between \$5,100/kW and \$7000/kW. Costs per unit quoted by Rosatom are aligned with these when accounting for owner's costs. Owner's costs cover expenses that fall outside of the engineering, procurement and construction (EPC) costs such as site preparation, Environmental Impact Assessments, decommissioning costs, and the costs of setting up/augmenting regulatory frameworks. For nuclear, this could make up between 10% and 20% of the total overnight costs (Black & Veach 2012). Eskom estimates owner's cost to be about 15% of the total overnight cost (Loyiso Tyabashe 2016, pers.comm., April).

Table 4: Summary of expected nuclear overnight costs

	<b>Overnight cost range (US\$/kW, 2012)</b>
<b>UNEP (2015)</b>	4500-8500
<b>2013 IRP Update</b>	5100-7000
<b>2016 Draft IRP<sup>1</sup></b>	~5942

<sup>1</sup>DoE overnight cost = R55,260/kW (January 2015 Rands). Deflated to 2010 using headline CPI (.88) and converted to US dollars using an exchange rate of R8.21/US\$.

### 3.2.4 Networks and Distributed Energy

Electricity distribution in South Africa is managed by Eskom and municipalities who redistribute electricity purchased from Eskom. Municipalities are responsible for around 50% of electricity distribution (Newbery & Ebenhard 2008). Newbery and Ebenhard (2008) report a deterioration in transmission and distribution performance due to a lack of maintenance, inappropriate past investment criteria and lack of required skills. Between 2010 and 2014, average losses recorded were 8.7% while in the 1980s, 1990s and 2000s these were 6.2%, 7.3% and 8.5% respectively. Losses have however started decreasing more recently, recording 8.4% in 2014 from 9.8% in 2010 (World Bank Data). Eskom reports that further loss reductions have been made to date due to programs such as Operation Khanyisa (Eskom 2016).

Recent advances in distributed energy costs, mini-grid technology and innovative business models have made decentralised solutions a strong and economically viable opportunity for rural electrification as it avoids expensive MV network extension, purchases from Eskom and allows new smart-grid networks to be developed. The latter will increase the share of low-carbon electricity generation, if renewable; provide local clean jobs; allow the potential for future grid-interconnection to strengthen end-of-grid networks; and allow flexible resources to balance supply (ERC 2017; Carbon Trust 2017). Distributed generation further provides municipalities with the opportunity to control their own new energy infrastructure plans (can include own distributed generation, storage, smart distribution grids and mini-grids), reducing their dependence on Eskom and changing their business models in this sector to address their own financial sustainability.

## 4. Renewable Energy and Storage in South Africa

### 4.1 Renewable energy resources

Africa has some of the best solar resources in the world, resulting in high solar PV energy yields. However, this resource has yet to be adequately exploited. A PV project at a typical location in Africa generates almost twice as much energy as the same project in Germany. An illustration of significant underutilization of solar power in Africa as a continent as compared to Germany as a single country can be noted in the fact that Germany currently has around 45GW of installed solar PV, nearly equivalent in capacity to the total power system capacity of South Africa. This is graphically illustrated in Figure 17.

South Africa possesses some of the best solar and wind resources in the world, with vast areas of the country suitable for generating electricity at low cost from renewable energy, in particular using solar PV, CSP, and wind technologies (Hagemann 2008; Fluri 2009; WASA 2015; CSIR & Fraunhofer 2016).

Potential for solar PV in South Africa is extensive with over 220 GW of potential identified in Renewable Energy Development Zones (REDZ) that have already completed Environmental Impact Assessments (CSIR & Fraunhofer 2016), the total resource is thus significantly higher than this. Additionally, 72GW of solar PV has been identified as installable on rooftops in South Africa (CSIR & Fraunhofer 2016).

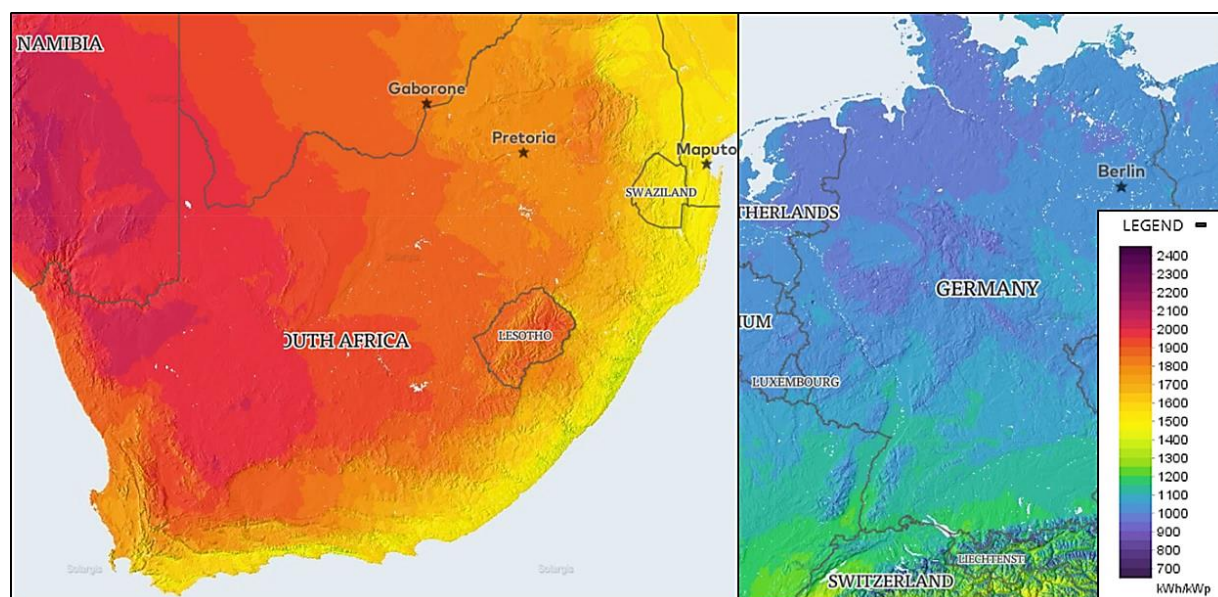


Figure 17: Comparison of the long-term solar PV production potential from a typical solar PV project in South Africa (left) compared to the same project in Germany (right) (SolarGIS 2017)

Recent studies have also shown that the South African wind resource is significantly greater than previously estimated with vast inland resources beyond the previously assumed high resource sites along the coast. The CSIR and Fraunhofer (2016) extended the existing work done by the Wind Atlas of South Africa (WASA) project (2015) and showed that between 55% and 65% of South Africa’s land area has technically recoverable wind capacity exceeding a 35% load factor (totalling ~3500-4500GW and ~11500-14500 TWh/a) .

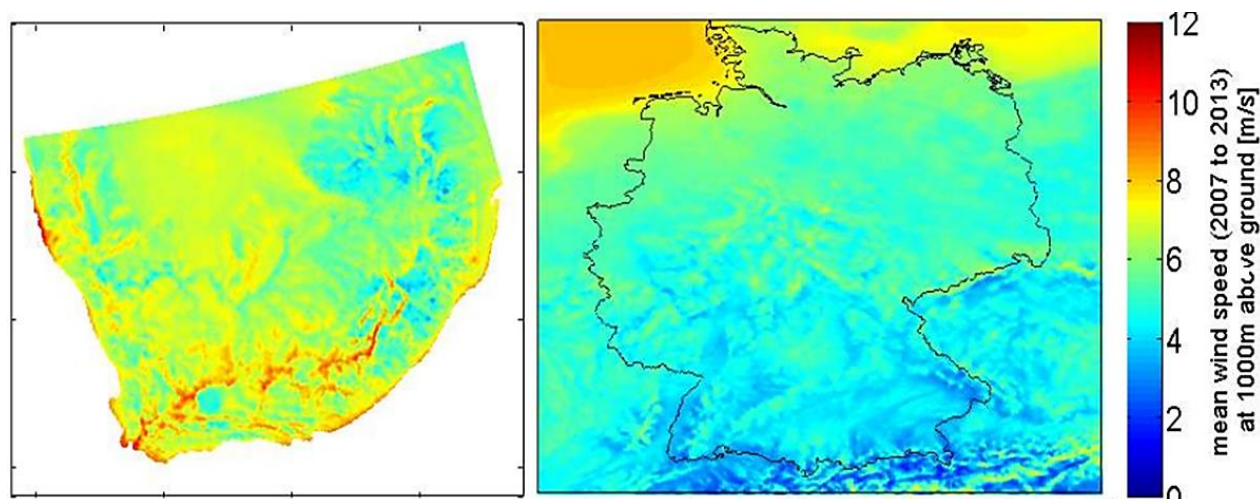


Figure 18: Comparison of wind speed averages across South Africa (left) compared to Germany (right) (WASA 2015; CSIR & Fraunhofer 2016)

## 4.2 Renewable production performance in South Africa

The aforementioned wind and solar PV aggregation research undertaken in CSIR and Fraunhofer(2016) characterises wind and solar PV power profiles for South Africa where a country wide resource assessment. For the grid-focussed scenario in this research, the resulting wind and solar PV profiles had annual capacity factors of 36% and 20.4%, respectively. It is acknowledged that sites chosen in the REIPPPP would have higher capacity factors, and that ideally one would want to have a more detailed representation of the different sites in the optimization model. This is left for future work. The figures below show sample time series of the aggregate wind and solar profiles for both summer and winter days in South Africa.

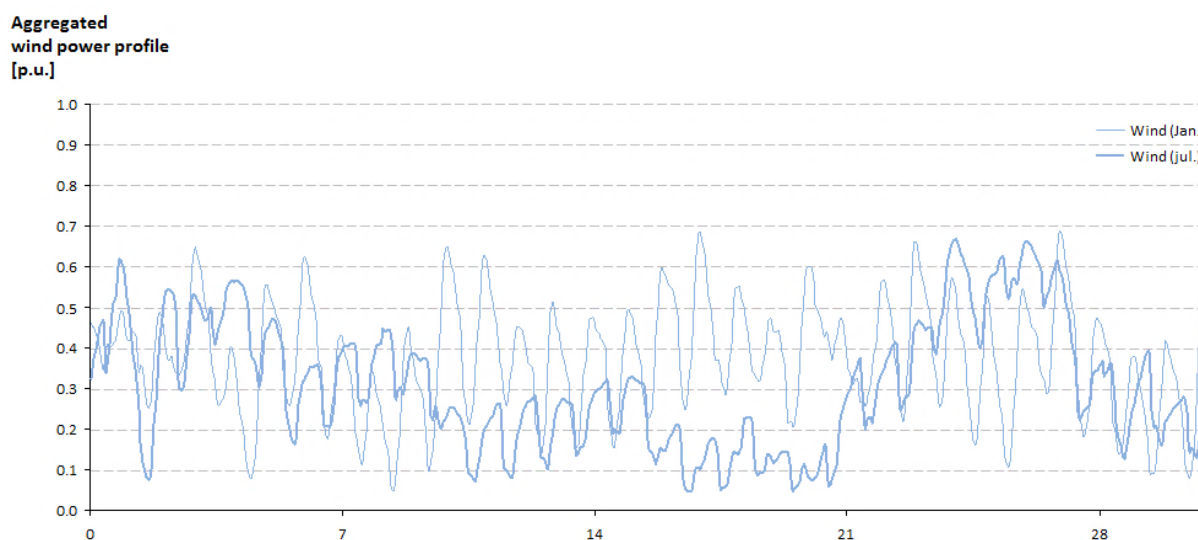


Figure 19: Aggregated winter/summer wind power profiles for South Africa (Wright et al. 2017)

Aggregated  
Solar PV power profile  
[p.u.]

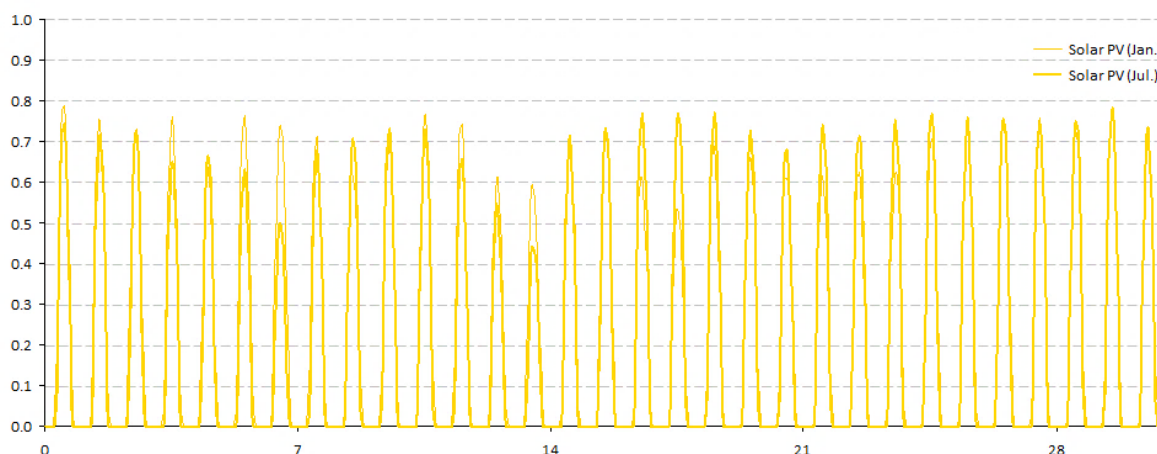


Figure 20: Aggregated winter/summer solar PV power profiles for South Africa (Wright et al. 2017)

The combined solar and wind resources are also highly complimentary, with the combination of their typical daily outputs matching the country’s electrical demand surprisingly well, with the demand coverage factor typically matching ideally for 50% of weeks in the year (see Figure 21 where a relative comparison to Denmark is made). Including a balanced combination of variable wind and solar PV will not contribute significantly to rapid fluctuations in the power system due to the aggregating effect if they are distributed across the country (Mushwana et al. 2015; CSIR & Fraunhofer 2016). Very high peak penetrations of variable renewables have already been achieved in Denmark and Germany (140% wind on 9 July in Denmark in 2015 and 67% wind and solar in May 2016 in Germany). Improved matching of the demand profile with wind and solar PV profiles in SA combined with relatively low seasonality makes system integration easier as a lower level of flexible complementary resources are required.

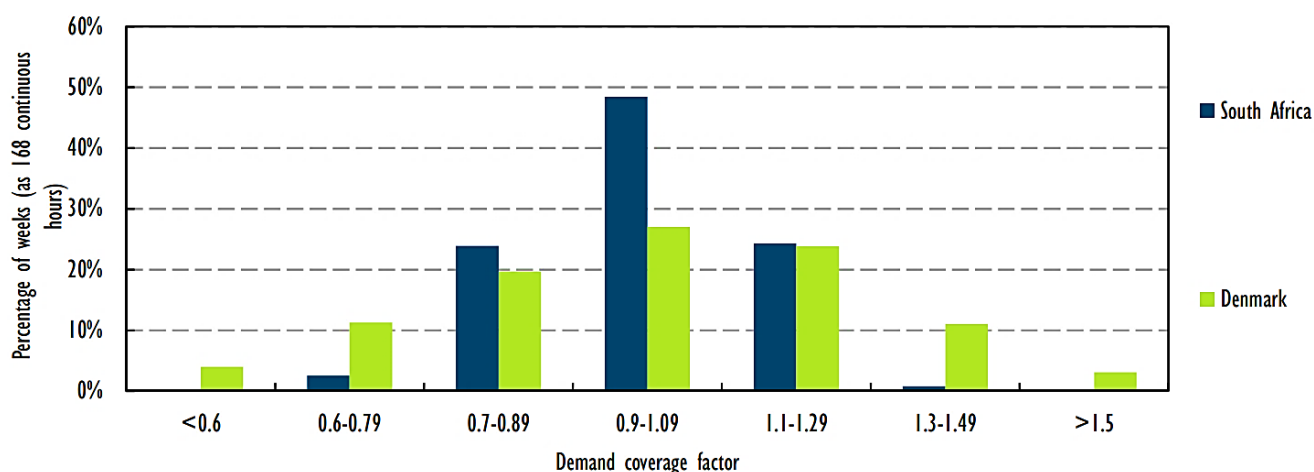


Figure 21: Demand coverage factors for South Africa and Denmark: wind and solar (IEA 2016)



### 4.3 Storage technologies

Energy storage technologies allow for energy in the form of electro-chemical, thermal, mechanical, gas/liquid or gravitational to be stored and used at a later time. The value in storing electrical energy is the ability to shift the supply of energy to times when it is most needed by demand.. Energy storage technologies can also provide stability to the electrical grid by allowing for a faster response, provision of ancillary services as well as sector coupling with other energy end-use sectors (heating, transportation). Energy storage technologies are thus a strong enabler but not necessarily a pre-requisite for the broad rollout of renewable energy to mitigate climate change (IRENA 2017b).

There are a variety of mechanical and electrochemical storage technologies that have been proven and are in use today with sub-second, daily, weekly, or seasonal applications (USTDA 2017). Pumped hydro storage technology is the most mature large scale energy storage technology currently employed - making up 96% of the storage capacity in the largest 10 countries (Table 5).

Table 5: Storage capacities (GW) by technology type, 10 largest country capacities, (IRENA 2017b)

	<b>Electro-mechanical</b>	<b>Electro-chemical</b>	<b>Thermal Storage</b>	<b>Pumped hydro storage</b>	<b>Total</b>
<b>China</b>		0.1	0.1	32.0	5.1
<b>Japan</b>		0.3		28.3	5.8
<b>United States</b>	0.2	0.7	0.8	22.6	6.4
<b>Spain</b>	0.0	0.0	1.1	8.0	7.0
<b>Germany</b>	0.9	0.1	0.0	6.5	7.1
<b>Italy</b>		0.1	0.0	7.1	7.6
<b>India</b>		0.0	0.2	6.8	9.1
<b>Switzerland</b>	0.0	0.0		6.4	24.2
<b>France</b>	0.0	0.0	0.0	5.8	28.5
<b>South Korea</b>		0.4		4.7	32.1
<b>Grand Total</b>	1.1	1.6	2.3	128.1	133.1

In South Africa, there are four pumped hydro storage (PHS) facilities located around the country with a total installed capacity of 2912 MW, and approximately 58.4GWh of storage capacity (Table 6). These facilities are used for bulk electricity storage and are usually dispatched during peak demand periods with weekly recharging cycles (in South Africa this is early evening).

Table 6: Pumped hydro storage facilities in South Africa (Eskom)

<b>Facility</b>	<b>No. Units</b>	<b>Total MW</b>	<b>GWh storage</b>
<b>Drakensberg</b>	4	1000	25.5
<b>Palmiet</b>	2	400	10
<b>Steenbras</b>	3	180	1.9
<b>Ingula</b>	4	1332	21
<b>Total</b>	13	2912	58.4

The storage assesment report by the USTDA (2017) identified that very long (seasonal) storage capacity was not applicable in South Africa's context, and rather going forward the focus should be on

technologies with cycles in the order of 12 hours or less for bulk energy services such as arbitrage, schedulable capacity, and for grid infrastructure services. Among these applicable technologies are batteries, pumped hydro storage, flywheels, super-capacitors, and compressed air storage - see Figure 22 for details on the range of storage technologies considered (USTDA 2017).

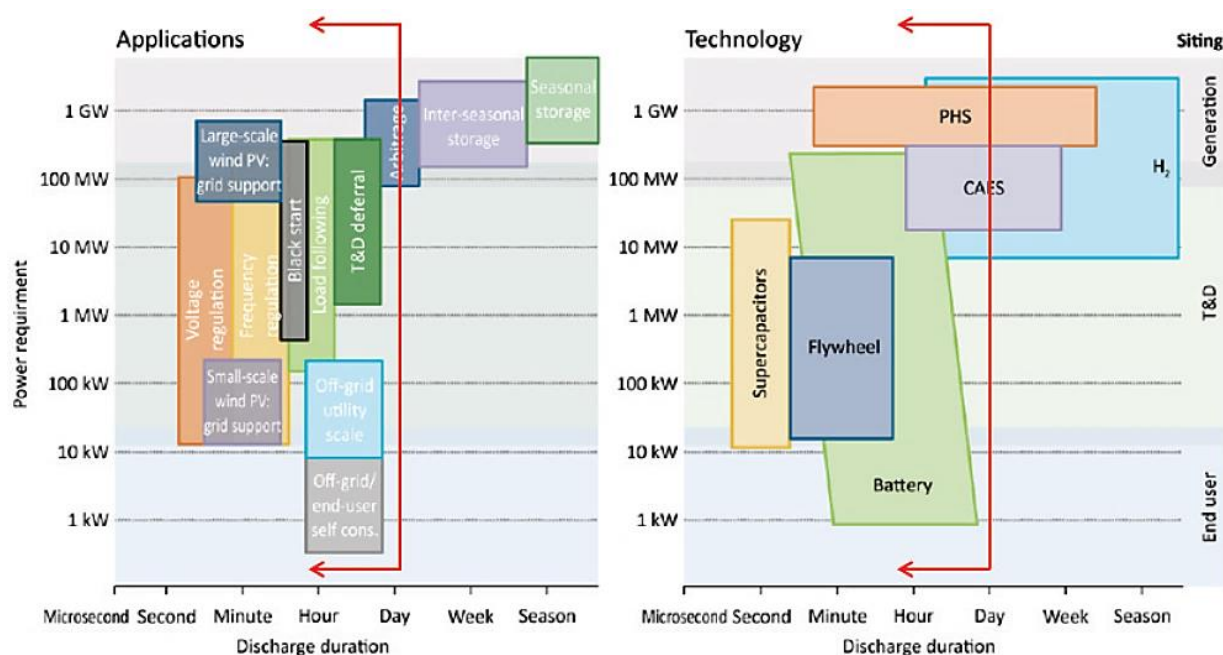


Figure 22: Energy storage technologies and their potential applications (USTD 2017)

PHS and CAES technologies are typically applied as bulk storage options, while batteries can be applicable for either bulk or distributed use. Table 7 presents the potential storage technologies for adoption in South Africa over the medium to long-term. Both bulk and/or distributed applicable storage technologies are included. PHS is not included.

Table 7: Potential storage technologies for South Africa (USTDA 2017)

Technology	Current technology maturity	Applicability
<b>Lithium-Ion battery*</b>	Commercial - proven	Utility, Distributed
<b>Compressed Air (tank)*</b>	Demonstration	Utility
<b>Vanadium redox flow battery</b>	Demonstration	Utility, Distributed
<b>Zinc-bromine flow battery</b>	Demonstration	Utility, Distributed
<b>Iron-chromium flow battery</b>	Demonstration	Utility, Distributed
<b>Liquid Air</b>	Demonstration	Utility
<b>Liquid Metal battery</b>	R&D	Utility, Distributed

\*Included in IRP process

The CSIR has estimated updated costs for stationary storage technologies considered as part of the Draft IRP 2016 in South Africa in Table 8.

Table 8: Technology cost input assumptions for storage (*Wright et al. 2017*)

Property		Storage technologies			CAES (8h)
		Pumped Storage	Battery (Li-Ion, 1h)	Battery (Li-Ion, 3h)	
Rated capacity (net)	[MW]	333	3	3	180
Overnight cost per capacity	2016 [ZAR/kW]	22 326	9 891	24 301	24 492
	2030 [ZAR/kW]	22 326	2 000	6 000	
	2040 [ZAR/kW]	22 326	1 000	3 000	
	2050 [ZAR/kW]	22 326	800	2 400	
Construction time	[a]	8	1	1	4
Capital cost (calculated) <sup>1</sup>	2016 [ZAR/kW]	27 841	9 891	24 301	27 672
	2030 [ZAR/kW]	27 841	2 000	6 000	27 672
	2040 [ZAR/kW]	27 841	1 000	3 000	27 672
	2050 [ZAR/kW]	27 841	800	2 400	27 672
Fuel cost	[ZAR/GJ]	0	0	0	150
Heat rate	[GJ/MWh]	0	4 045	4 045	4 444
Round-trip efficiency	[%]	78%	89%	89%	81%
Fixed O&M	[ZAR/kW/a]	201	618	618	212
Variable O&M	[ZAR/MWh]	0	3	3	2
Load factor (typical)	[./.]	33%	4%	12%	22%
Economic lifetime	[a]	50	20	20	40

### 4.3.1 Lithium-Ion Battery Storage

Unprecedented recent cost reductions have occurred for lithium-ion batteries in particular, largely spurred by the recent uptake of electric vehicles, with the unitised (per kWh) capital cost cut by half between 2014 and 2016. Further reductions of at least 30% - 50% in the next 5 to 10 years are expected (CSIRO 2015; Lazards 2016) and by 73% by 2030 (BNEF 2017). Global lithium-ion battery production is expected to grow by more than a factor of five by 2020 with more than 60% coming from China (Visual Capitalist 2017).

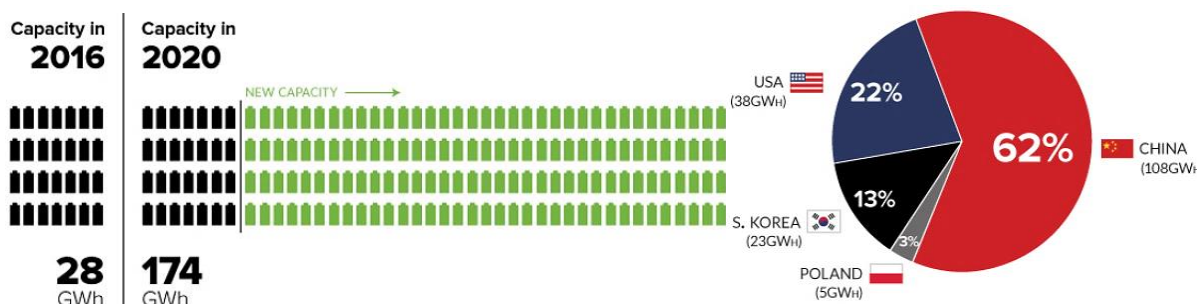


Figure 23: Expected global lithium-ion battery production (IRENA, Visual Capitalist 2017)

Shown and referenced below is a compilation of recent cost projection estimates for lithium-ion batteries by international energy technology and market research organisations. These are available as potential scenarios and for use in model validation.

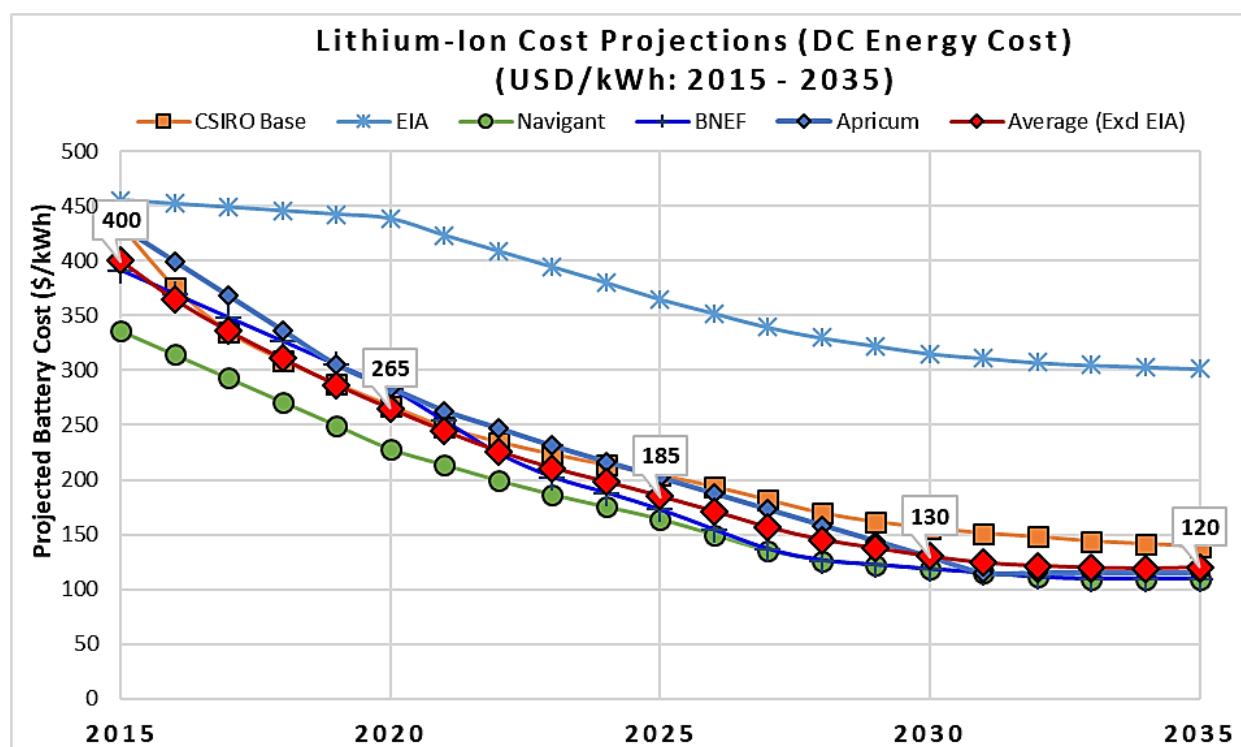


Figure 24: Lithium-ion cost projections, 2015-2035 (Adapted from CSIRO 2015; EIA; Apricum 2017)

## 5. Energy System Model Considerations

Several important considerations may have significant impacts on the modelling of the power sector, the expected optimal infrastructure build plans and the requirements of the rest of the system to meet adequacy and flexibility requirements. This is especially true when high penetrations of non-dispatchable renewables (solar PV and wind) are included in the mix. Electric vehicles and flexible demand resources can also provide additional benefits to the system if economical. Practical build-out limitations for particular technologies may also be implemented including annual capacity build-out limits, transmission expansion limitations, port infrastructure limitations and local skills capacity (amongst others). The application of any limitations on any technology would need to be sufficiently justified in order to be legitimately considered or sub-optimal outcomes would result with the resulting impacts on energy system costs. The absolute availability of finance for large-scale infrastructure projects may also be a constraint, however this is an area that requires further research and is therefore not discussed in detail in this section.

### 5.1 System Reliability and Flexibility

Energy or power system “reliability” and “flexibility” are often used collectively to describe a system’s overall ability to deliver energy services to end-users. More particularly, these can be decomposed to provide a more complete description via the use of the terms stability, flexibility, adequacy, resilience and robustness (Deane 2015).

*Stability* describes the system’s physical capability to withstand short term disruptions or faults such as short circuits, sudden plant failure or sabotage. This includes maintaining the system frequency and voltages within acceptable limits and preventing blackouts. In this regard, with high penetrations of inverter-connected renewable energy (wind and solar PV), a particular concern is a significantly higher Rate of Change of Frequency (ROCOF), caused by the removal of system inertia provided by synchronous generators (O’Sullivan 2014).

*Flexibility* is the system’s ability to continuously maintain the balance of supply and demand. This requires having flexible resources available (either on the supply or demand side) to respond to short term changes in the expected demand, production of variable renewables and planned or unplanned infrastructure outages. Flexible resources with which to achieve this include:

- Dispatchable power plants with appropriate ramp-rates, sufficiently low minimum stable levels and short minimum up/down times;
- Demand side response;
- Storage; and
- Transmission interconnections over a sufficiently large geographical area.

*Adequacy* of a system is a measure of whether the system is developing in the medium and long term in a way that will ensure its ability to continuously meet demand on the system. This requires that sufficient generation and transmission investments are made, are of the right technology mix, in the correct amounts, in the correct locations and will be available at the appropriate time. This also includes the upstream value chain of fuels and primary energy sources necessary to support the required system adequacy.

*Resilience* is the ability for a system to recover from sudden unexpected contingencies and return its ability to effectively fulfill its purpose. Examples may include a sudden unavailability of fuels, system wide blackout, sudden shutdown of large power plants, sabotage or destruction of power plants or transmission lines.

*Robustness* is the entire energy system’s ability or durability to withstand geo-political or economic strain. Examples could include commitments to much more stringent CO<sub>2</sub> targets, significant changes in long term fuel prices, or a permanent phase out of particular power plants e.g. nuclear, coal.

Figure 25 illustrates the technical constraints that can be included in a detailed modelling environment for each generating unit at each power plant to ensure the necessary system flexibility is captured. Key technical constraints typically considered include run-up/down rates, ramp-up/down rates, minimum up/down times and minimum stable levels.

In order to ensure sufficient system adequacy, a pre-defined amount of capacity reserves is necessary both in the short-term and long-term. These reserve requirements are normally defined by the System Operator to ensure a sufficient level of risk is removed from the likelihood of insufficient supply capacity in key timeframes (instantaneous, regulating, ten-minute, operational, and emergency reserves).

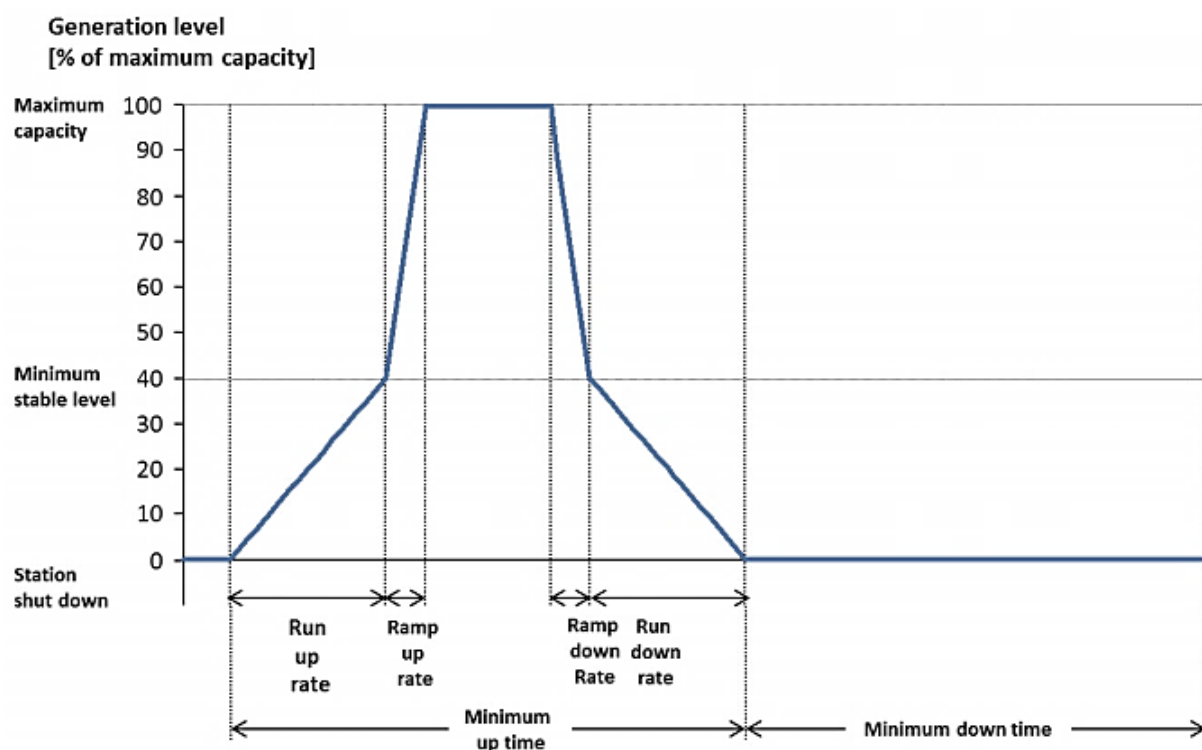


Figure 25: Key technical characteristics included in high-resolution model for dispatchable generators.

The results of the high-resolution modelling will allow a better representation of these requirements in SATIM through a typical ‘soft-linking’ methodology (Deane 2012). Of particular importance are the dispatch and fuel requirements of gas generation that may otherwise be underestimated in SATIM due to its coarser time-resolution.

## 5.2 Demand-side flexibility

The inclusion of flexible demand in future electricity systems is considered to be an important low-cost opportunity for the accommodation of large amounts of variable generation such as wind and solar PV with a reduced requirement for flexible generators or purpose-built storage devices (Göransson 2014; Zerrahn 2015). Furthermore, the exploration of this resource is justified by many potential benefits including the reduction of the overall electricity price, peaking plant utilization, reduced or delayed infrastructure capacity requirements, reduction of transmission and distribution congestion, reductions in emissions and improved overall economic efficiency (Albadi 2008; O’Connell 2014).

The inclusion of demand response in the South African grid is currently limited however electric water heaters (EWHs) present a good opportunity for providing demand side flexibility to the system during peak hours and have been included in the high-resolution modelling completed by the CSIR (Wright et al. 2017) and shown in Table 9.

Table 9: Electric Water Heaters - CSIR modelled uptake demand shaping (Wright et al.)

Property	Unit	2016-2019	2020	2030	2040	2050
Population	[mln]	55.7 - 57.5	58.0	61.7	64.9	68.2
Number of HHs	[mln]	16.9 - 18.1	18.5	22.4	26.0	27.3
Residents per HH	[ppl/HH]	3.29 - 3.17	3.13	2.75	2.50	2.50
HHs with EWH	[%]	28 - 33	34	50	75	100
HHs with EWH	[mln]	4.7 - 5.9	6.3	11.2	19.5	27.3
Demand shaping adoption	[%]	-	2	25	100	100
Demand shaping	[TWh/a]	-	0.4	5.4	28.3	26.4
Demand shaping	[GWh/d]	-	1.1	14.9	77.4	72.3
Demand shaping (demand increase)	[MW]	-	371	4 991	25 970	24 265
Demand shaping (demand decrease)	[MW]	-	46	620	3 226	3 015

Many other promising opportunities for demand response resources exist including (amongst others):

- Residential/commercial and industrial HVAC and refrigeration.
- Large industry such as smelters (contracts already exist) and other industry especially with large process heating requirements, Sasol and pulp/paper industry also have on-site generation, some also have fuel-switching ability.

These are being investigated as part of an ERC-SANEDI flexible demand project. The potential impacts and significance of these flexibility options will be investigated therein and may inform future iterations of the SATIM model.

### 5.3 Electric vehicles

The global stock of electric vehicles (EVs) increased by 60% between 2015 and 2016, breaching the 2 million mark (IEA 2017). New registrations also hit an all-time high of 750,000 vehicles in 2016 with the uptake of EVs leading to a continuous increase in both public and private charging infrastructure. While the growth in deployment slowed in 2016, relative to previous years, the IEA estimates that global sales will remain robust to 2020 as the cost gap between electric and internal combustion engine (ICE) vehicles narrows (IEA 2017).

The EV battery accounts for approximately a third of the upfront vehicle cost and these have come down significantly over the past decade (Figure 26). While EVs cost more than conventional ICEs in all regions in 2015, continued decreases in battery costs are forecasted based on continuous improvements from technologies currently being researched. The IEA estimates that by 2030 battery EVs and plug-in hybrid electric vehicles (PHEVs) will become fully cost competitive with ICEs in Europe (IEA 2017). ERC modelling suggests that EVs could provide close to 20% and 5% of passenger travel and freight tkm (predominately light commercial vehicles) by 2030 respectively with an increasing share approaching 2050 (Ahjum et al. Forthcoming).

**Batteries make up a third of the cost of an electric vehicle.  
As battery costs continue to fall, demand for EVs will rise.**

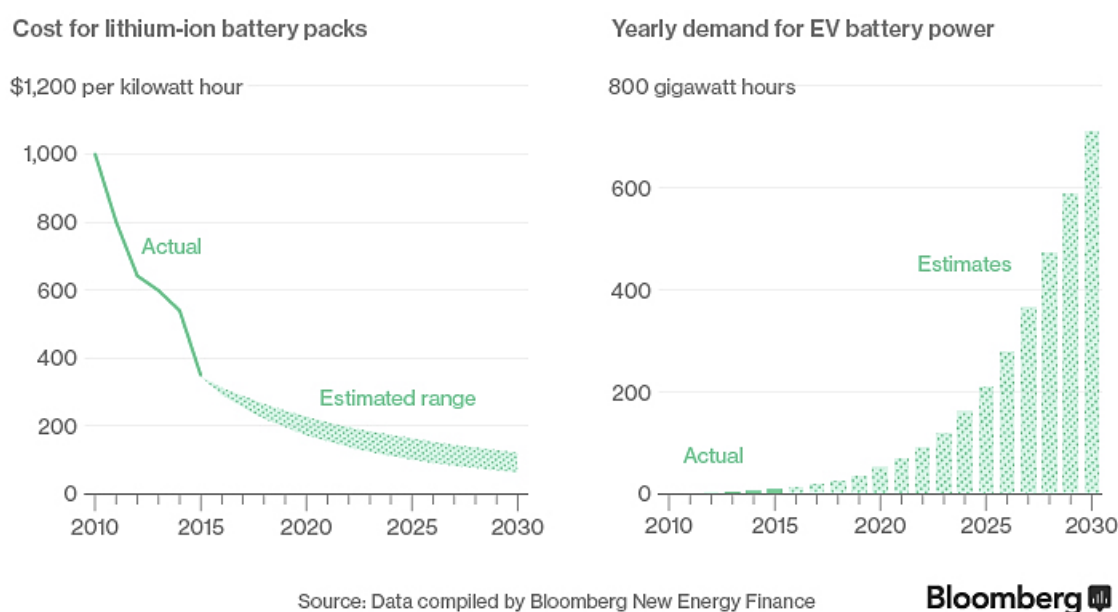


Figure 26 Actual and estimated future EV battery cost and consumption (Bloomberg 2016)

The CSIR's comments on the Draft IRP 2016 included EVs as "a demand side flexibility resource in the form of mobile storage". Modelled similarly to domestic Electric Water Heaters (EWHs) the study suggests that EVs may provide EV demand shaping potential of ~48 GW/1.7 GW (demand increase/decrease) with ~40 GWh/day of dispatchable energy by 2050. Key input parameters for the CSIR EV modelling are current population, expected population growth, current number of motor vehicles, expected motor vehicles per capita, adoption rate of electric vehicles to 2050, electric vehicle fleet capacity (MW), electric vehicle energy requirement (GWh/day), proportion of electric vehicle fleet connected simultaneously.



The SATIM transport model requires similar parametrisation but instead models the battery component separately as indicated in Figure 27.

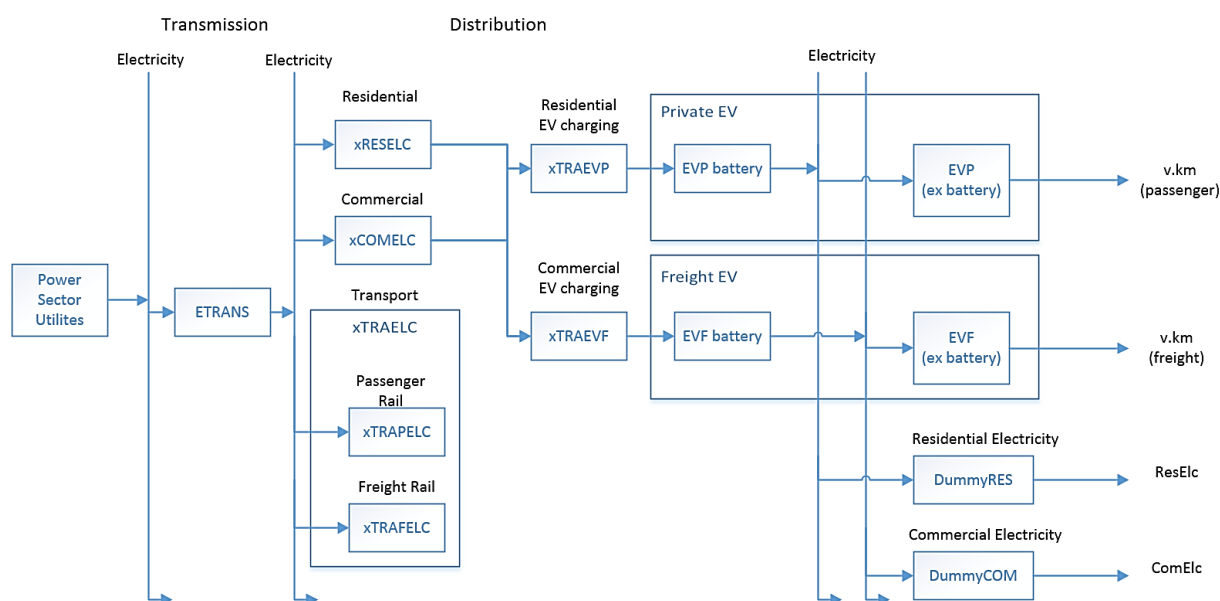


Figure 27: Representation of EV technologies in SATIM displaying their integration as a component of a future electricity supply system

In addition to offering potential GHG emission reductions (if coupled with appropriate electricity generators) and improved local air quality, EVs also offer the additional utility of electricity storage (as mentioned previously). EVs can function as a class of distributed pumped storage supplying electricity directly to distribution networks when stationary. Foley et al. (2013) ascribe EV charging into three main categories:

- *Peak charging which is uncontrolled or unconstrained and assumes vehicle owners will charge their cars immediately after arriving home from work coinciding with peak electricity consumption;*
- *Off-peak charging which is controlled or delayed and assumes vehicle owners will charge their cars at a later time to avail of cheaper electricity tariffs or utility companies will use smart metering to control the charge of EVs and fill in the night valley;*
- *Opportunistic charging assumes vehicle owners will charge their cars in a continuous or stochastic manner.*

Charging and discharging behaviour (i.e. driver behaviour) and its concomitant effects on distribution networks is therefore important to understand and has been the subject of numerous studies (Kempton et al. 2001; Paevere et al. 2012; Ogden 2014; Markel 2015). These studies have demonstrated the value of a more detailed energy consumption time profile representation and should be pursued further in future.

## 5.4 Build constraints on renewable energy deployment

The Draft IRP 2016 appears to be quite stringent on annual new-build constraints for solar PV and wind, limiting their annual uptake with little justification to 1000MW and 1800MW respectively (Table 10). Although in the short-term, transmission capacity, port limitations and local skills capacity could be considered constraints to the rate at which the technologies could be deployed there has not yet been any quantifiable and reasonable justification provided. It could be argued that in the medium to long-term these barriers to more rapid expansion could be overcome by planning accordingly and making investments in the supporting infrastructure and skills, if it can be shown that it makes economic sense to do so.

Table 10: Annual new-build constraints placed on solar PV and wind in IRP 2016 (DoE 2016)

Year	System Peak Load	New-build limit	Relative new-build	New-build limit	Relative new-build
	<i>(High (Low Intensity)</i>	Solar PV	limit Solar PV	Wind in MW/yr	limit Wind
	[MW]	[MW/yr]	[%/yr]	[MW/yr]	[%/yr]
2020	44 916	1 000	2.2%	1 800	4.0%
2025	51 015	1 000	2.0%	1 800	3.5%
2030	57 274	1 000	1.7%	1 800	3.1%
2035	64 169	1 000	1.6%	1 800	2.8%
2040	70 777	1 000	1.4%	1 800	2.5%
2045	78 263	1 000	1.3%	1 800	2.3%
2050	85 804	1 000	1.2%	1 800	2.1%

## 5.5 Future fuel costs and uncertainties

A common set of fuel cost assumptions must be used in an analysis aiming to assess the impacts of renewable energy developments on potential energy pathways for South Africa. For consistency and hence comparability with official energy pathways it is therefore best to use the Draft IRP 2016 assumptions as a basis for comparison. This being said, the future of fuel costs is very uncertain and influenced by a number of factors such as international developments, mining costs, Eskom's contracting practices (for coal in particular) as well as institutional and national financial constraints. This section highlights the uncertainties in key fuel prices, namely coal, crude oil, gas and uranium; and provides a potential set of likely fuel price pathways.

### 5.5.1 Coal

Coal mines were initially tied to power stations, which were built to use the specific type of coal supplied. Eskom and mining houses entered into long-term contracts that were either 'cost-plus' (tied mines with Eskom-only supply) or 'fixed price' (where Eskom uses an intermediate product produced from washing coal for export).

Coal has become more expensive in recent years as companies need to mine deeper to extract the resource and mining costs have outstripped inflation substantially. Political pressure to expand coal suppliers to include smaller black empowered mines coupled with the underperformance of long-term contracts has resulted in Eskom shifting its coal procurement away from long-term contracts towards increased short- and medium-term coal contracts (Burton & Winkler 2014). These contracts are typically more expensive on a delivered basis because they require coal to be railed or trucked to stations, and now make up almost 30% of Eskom's supply. Eskom's financial constraints have also limited its investment into new long-term supplies, making it difficult for the utility to secure a sufficient supply of low cost coal (UNEP 2015). The long-term price of coal for electricity generation in South Africa is therefore still relatively uncertain.

Eskom's most recent revenue application projects that coal costs will rise from R393/ton in 2016/17 to R430/ton in 2018/19. However, several new contracts need to be negotiated and large mines developed in the short-term to secure Eskom's supplies, and it is likely that coal prices will exceed this thereafter. Average prices will depend, however, on demand and thus the dispatch of particular stations.

Estimates from a UNEP (2015) study suggest that by 2050 the potential band of coal prices facing the domestic market could range between around R300/ton and R600/ton (see Figure 28).

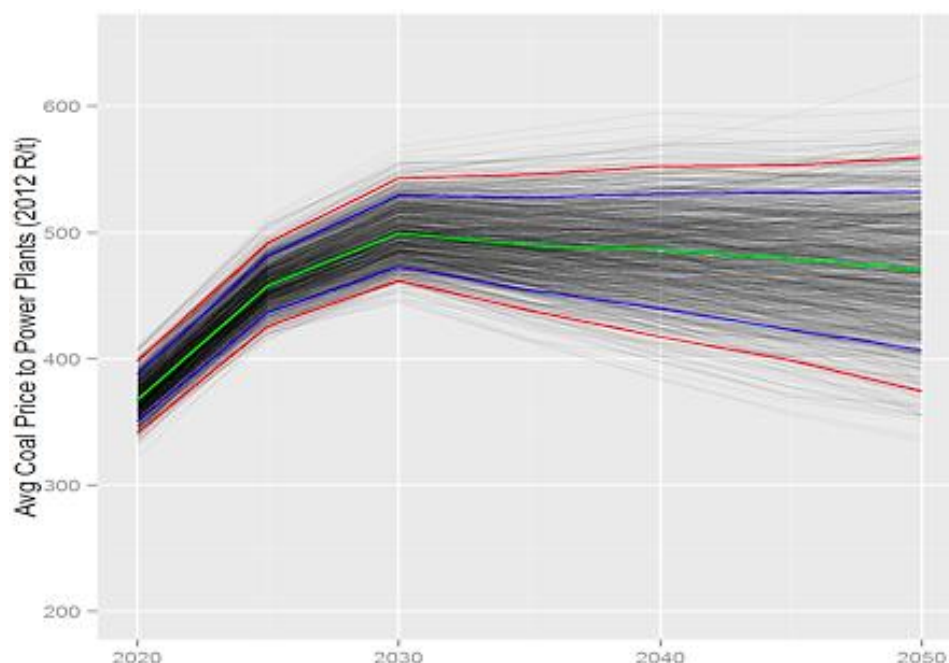


Figure 28: Average coal price projections faced by the power sector, 2020-2050 (UNEP 2015)

### 5.5.2 Natural Gas

Natural gas prices are driven by a number of factors including the type and origin of the gas, the costs of extraction and transportation including related infrastructure and the level of supply and demand domestically, regionally and internationally. In the case of using gas for electricity production, the price is significantly determined by the demand from alternative uses. In this section we focus on the price of conventional deposits and pipeline imports as these are primarily used in South Africa while a discussion on shale gas and LNG imports is also provided as future possible sources of natural gas supply.

Current strategic planning around gas in South Africa centers on the development of LNG import infrastructure, large domestic shale deposits and even larger deposits of conventional gas in Mozambique. Given the size of the available deposits and the current political climate, shale deposits are highly unlikely to be developed in the short to medium-term but likely to be a long-term option if necessary. Mozambican gas is currently imported via pipeline but is almost at full capacity. Expansion plans are however being considered in the form of additional pipeline capacity as well as LNG trains planned for 2020 and beyond.

Large gas deposits are also available in Northern Mozambique. These are unlikely to be transported by pipeline due to distance. Transportation via LNG to South African ports (Richard's Bay initially) provides a more likely option for transporting. However, this requires significant infrastructure and regional co-operation. South Africa will also have to compete with other customers for Mozambican gas on the open market as ownership of these deposits are shared by the Mozambican government and private gas development companies.

Conventional gas deposits in South Africa have thus far been limited and expected to stay this way. Coal-bed methane is expensive and location-dependent with high environmental and water treatment costs, and while quicker to develop than shale, it will not likely become very significant in South Africa in future.

Figure 29 presents potential conventional and shale gas price pathways estimated by UNEP (2015). The conventional gas price ranges between US\$5/MMBtu and US\$15/MMBtu by 2050, while the price of shale is expected to range between US\$4/MMBtu and US\$18/MMBtu. Uncertainty ranges on gas price forecasts are relatively constant through time, in contrast to other commodities like oil and coal. This is because the gas price is effectively set at the producer's marginal cost of production (including capital).

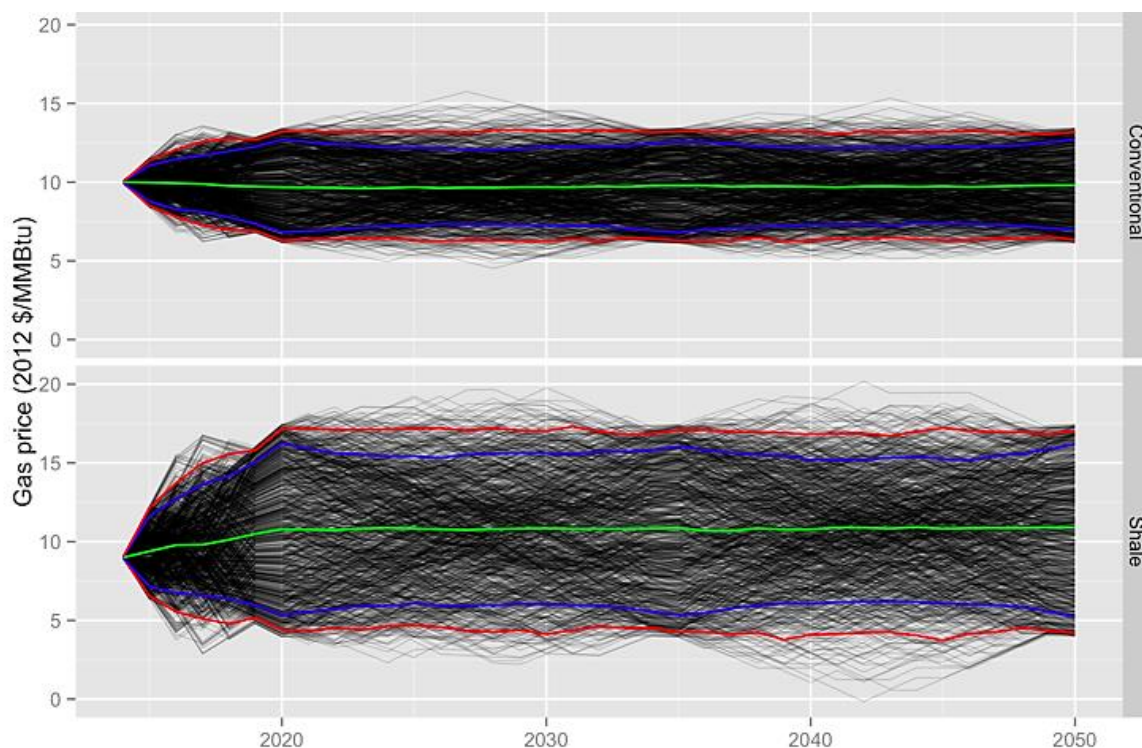


Figure 29: Potential conventional and shale gas price projections, 2014-2050 (UNEP 2015)

## 5.6 General economic parameters

### 5.6.1 Macroeconomic conditions

Assumptions around general macroeconomic variables, primarily economic growth, which determines energy demand, and the exchange rate are also needed for systems modelling exercises. In a forthcoming study assessing the impact of policies and measures on emissions reductions and economic growth, the ERC developed a consistent growth and exchange rate path for South Africa to inform the project reference case. Using a version of the South African General Equilibrium (SAGE) model of the National Treasury and the assumptions listed in Table 11, average annual growth in the reference was recorded to be 3% between 2013 and 2050 in line with 2016 Draft IRP moderate growth forecast.

Table 11: Assumptions informing macroeconomic reference case. (ERC Forthcoming)

Variable	Average annual change (%)	Reference
<b>Total factor productivity</b>	0.54	Historical estimates, 1993-2013 (Gabriel et al., Forthcoming)
<i>Agriculture</i>	1.00	
<i>Mining</i>	(2.40)	
<i>Manufacturing</i>	1.45	
<i>Services</i>	0.15	
<b>Population</b>	0.45	UNEP Report, 2015
<b>Labour supply</b>	1.70	Historical QLFS estimates, 2008-15
<b>Foreign investment</b>	3.00	

### 5.6.2 Demand forecast

While SATIM requires a growth forecast - as final energy demand (e.g. electricity) is estimated endogenously as it can choose to use fuels other than electricity - other energy systems models require a projection of electricity demand (or set of projections). Figure 30 presents historical and future energy demand projections including estimates by the ERC (i.e. SATIM Base) and CSIR. An interesting observation from the graph below is the continued over-estimation of electricity demand in the planning process.

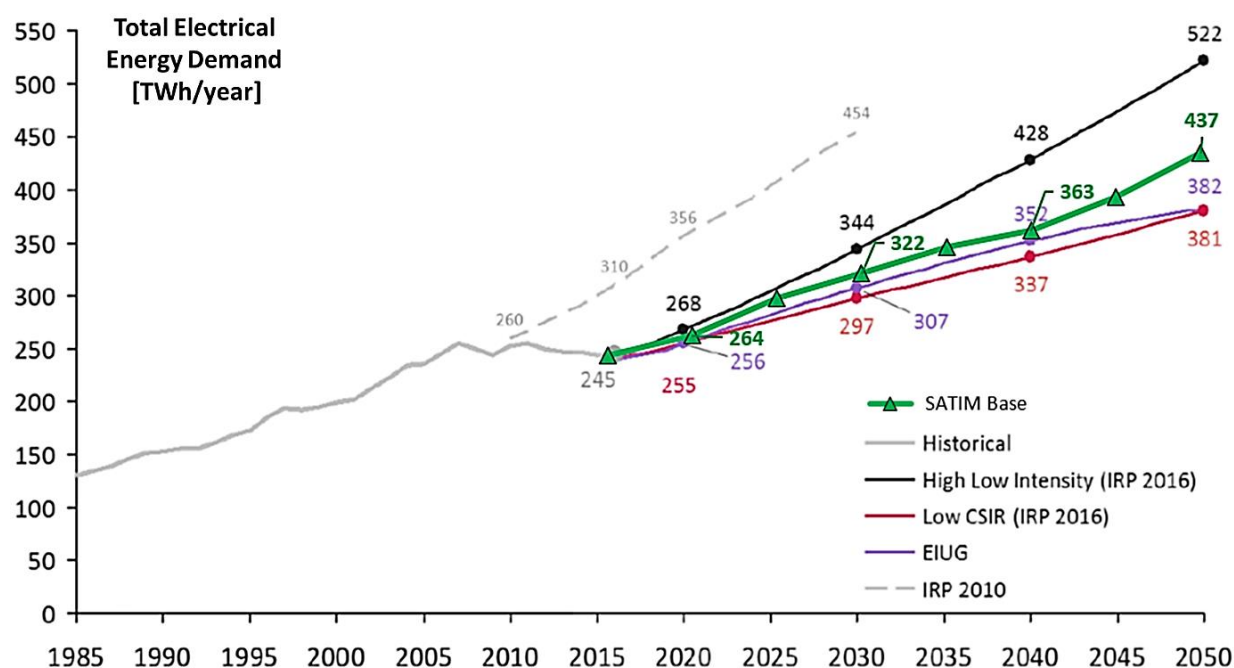


Figure 30: Electricity demand projections and history (Wright et al. 2017)

### 5.6.3 Discount rate

The discount rate is a critical factor influencing any analysis of economic effects over time. Discount rates effectively express a time preference for money and impact future expenditures. The National Treasury has advised that a discount rate of 8.2% be used for the Draft Integrated Energy Plan (IEP) 2016 as well as Draft IRP 2016. This discount rate was estimated by the National Treasury and accounts for the economic opportunity cost of capital (EOCK). The EOCK methodology for the discount rate was preferred to the social rate of time preference methodology when the focus is on discounting future costs and not cost benefit or net present value (DoE 2016).

## 6. Future Work

This technical report provides an overview of the developments in renewable energy technologies globally and in South Africa. It highlights the significant advances made in these technologies, which are already resulting in structural shifts in energy systems globally. This is seen by the increased share of electricity being produced by non-dispatchable renewable energy, which in some countries exceeds 100% at times. The cost of renewable energy, globally and in South Africa, is currently competitive with that of new fossil-fuel power plants (coal in particular) and is expected to become comparable to existing coal power plants in the near future.

The most recent existing renewable energy costs for wind and solar PV (in particular) as part of the DoE REIPPPP as well as expected future technology cost reductions illustrate that the cost of these technologies in South Africa are below those included by the DoE in the Draft IRP 2016 today and into the future. In addition, annual new-build constraints placed on only these two technologies mean that outcomes from the Draft IRP 2016 do not fully account for the impact of the current state of renewable energy costs in South Africa nor does it include potential gains from learning that is currently being seen around the world.

Future work building on this would include a detailed energy systems assessment of the impact of these cost changes in renewable energy (with a particular focus on wind and solar PV) as well as storage technologies on potential electricity and energy pathways for South Africa

Throughout this report differences between the ERC's full energy sector model (SATIM) and the electricity sector model developed by CSIR in PLEXOS<sup>1</sup> were indicated. These differences, particularly the consideration of the electricity system only (in more detail) versus the full energy system, highlights the need for a comparative analysis of the impacts of changes in renewable energy and storage technologies across models to assess whether, if consistent assumptions are considered, models indicate similar optimal trends for South African electricity and energy planning infrastructure needs. To further assist this type of analysis, this report also discusses several other areas of importance for energy systems modelling that should be considered.

The techno-economically '*optimal*' or '*least-cost*' pathway for South Africa's future energy and electricity requirements is however only one dimension along which policymakers would make decisions on. Policymakers must also consider and quantify the impact of infrastructure investments and associated pathways on the macro-economic and socio-economic outlook of South Africa.

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<sup>1</sup> DoE and Eskom also implement South African electricity sector models in PLEXOS®.

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