An actuarial perspective of South Africa’s electricity system

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Foreword

The Actuarial Society of South Africa (ASSA) created a Public Interest Function (PIF) to enable the organisation to pro-actively participate in public policy discussions. ASSA seeks to inform debate on matters of public interest in South Africa, especially when it is deemed that actuarial expertise can add value. ASSA believes that its members can provide facts, figures, comments, and analyses of consequences on a wide range of topics where the actuarial skillset can provide unique insights.

The topic of energy modelling was identified by ASSA's PIF as a critical issue in public policy discussions. The research captured in this paper was conducted by a member of ASSA as part of the broader public interest work on which the PIF has embarked. This paper is provided for informational purposes only and should not be interpreted as professional, legal, or financial advice. In publishing this paper, ASSA makes no warranty and assumes no liability in connection with its use.

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1. Overview

1.1 Introduction

1.1.1 Energy is the lifeblood of our modern, interconnected, and complex global economies. At the time of writing this paper (2022/2023), the impact of the Russia-Ukraine conflict was at the forefront of many people's minds. This conflict has highlighted the reliance of countries on fossil fuels – such as Western Europe's reliance on gas imports from Russia (1). The conflict has further highlighted the centralised nature of many countries' electricity generation as has been illustrated by Ukraine's rolling blackouts during its 2022/2023 winter (2). Globally, humanity has dealt with several crises over the last few years, from the numerous ramifications of the COVID-19 pandemic, the increasing frequency and severity of extreme weather events, to the Russia-Ukraine conflict. These crises have caused a number of downstream impacts. For example, in September 2022, year-on-year international wheat prices were up by between 4 and 24%, which, for some developing countries translated to an increase in year-on-year prices above 40% (3).

1.1.2 In an attempt to curb the devastating economic impact of the COVID-19 pandemic, leaders reacted by implementing various monetary policies, such as quantitative easing (4). However, when coupled with a global economic downturn, this move to loosen monetary policy has resulted in inflationary pressures in developing and developed nations. These inflationary pressures have prompted central banks to increase interest rates in an attempt to curb the regressive impact of price inflation. The increase in the rate of inflation and reactionary interest rate hikes have impacted financial markets and, by implication, the assumptions that many actuaries use in their day-to-day work.

1.1.3 Locally, South Africans have not been spared the impact of the global downturn. Annual consumer price inflation (CPI) was at 7.8% in July 2022, the highest it has been since the global financial crisis of 2008/2009. Statistics South Africa (STATSSA) notes that the increase in CPI was mainly driven by price increases in food, non-alcoholic beverages, and transport (5). To make matters worse, South Africa's energy crisis suffered its worst period of load shedding[1] in 2022 (6) as the utility operator, Eskom, aims to maintain stability of the electricity grid.

1.1.4 In addition, there is the devastating impact of climate change that was highlighted at the Sharm el-Sheikh Climate Change Conference (commonly referred to as COP27) (7). Climatologists have indicated that global emissions need to hit net zero by 2050 to achieve the 1.5 ºC target agreed at the Paris Climate Convention (COP21). To meet this target, it would inter alia be necessary to change the way energy is consumed. It is clear that the issues of climate and energy are closely interlinked.

1.1.5 Actuaries are well-known for their focus on risk identification, measurement, mitigation, and management. Clearly, energy security and climate change are two immense challenges facing the world and actuaries are well-placed to provide a perspective that could be useful in solving some of these global challenges. Even though actuaries have mostly worked in the insurance and pension fields (64% of actuaries are still working in financial services) (8), a growing number of actuaries are

[1] Also known as rolling blackouts

moving into new practice areas, previously thought to be outside the domain of the actuary.

1.1.6 One of these practice areas is energy. It presents fresh challenges to actuaries who want to explore new opportunities and who are well-placed to provide alternative perspectives on risks in the energy sector. Actuaries have a deep understanding of risk, and by working with energy subject matter experts, are able to add value to the energy debate. In terms of current involvement in energy, the Institute and Faculty of Actuaries (IFoA) set up an Energy in the Economy Working Party tasked with developing the role of energy in the economy. The IFoA indicated that the purpose of this working party was to develop a project that would focus on the role of energy in the economy (9). However, as it is early days for actuaries in energy, the purpose of this paper is to introduce the challenges of South Africa’s electricity supply and demand to actuaries who find energy interesting and challenging.

1.2 Purpose

1.2.1 The intention of this paper is to achieve the following outcomes:

- To inform actuaries of the state of the South African electricity sector. This entails understanding the history of the electricity sector, trends of the last few decades in the electricity sector, and changes that are likely to occur in the electricity sector.
- To provide a high-level explanation of the available electricity technologies from a demand, supply, and storage perspective.
- To model various scenarios for the period from 2020 to 2050 to illustrate the impact of new generation and storage options.
- To promote constructive discussion relating to the South African electricity crisis.

1.2.2 The world has faced challenging headwinds over the last two decades. Due to a global financial collapse and a worldwide pandemic, many countries, including South Africa are in a vulnerable economic position. South Africa is also facing another pressing issue – the lack of sufficient and reliable electricity. While this might seem like a simple supply and demand issue, it is much more serious. A lack of electricity security will impact South Africa over the long term and has the potential of crippling the country and suppressing economic growth. This paper provides a starting point to discuss and understand the situation in South Africa and highlights the potential levers that can be used to alleviate the crisis.

1.2.3 The paper starts with an introduction to energy and an overview of South Africa’s energy consumption relative to the world. The paper then provides an in-depth view of the South African electricity sector from a supply and demand perspective and a discussion of various electricity generation and storage technologies, and how they interact with the grid. This is followed by an investigation into the electricity crisis and the presentation of a model that projects electricity demand and supply for the period 2020 to 2050. A range of potential options for alleviating the crisis are then presented.

1.3 Glossary

1.3.1 Various definitions of units and measures will be used in this working paper. The following table provides the reader with a list of and perspectives on commonly used terms, as details of some of these measures might not be obvious to individuals working outside the energy sector. Where acronyms are typically used, they are included in parentheses immediately following the applicable term.

Table 1.1: Glossary of terms

Term	Meaning/usage/application
watt (W)	The International System of Units (SI) expresses a watt (W) in terms of base units as $W = 1\ kg \cdot m^2 \cdot s^{-3}$, where the base units are kilogram (kg), metre (m), and second (s). Alternatively, a watt can also be expressed as one joule per second (J/s) (10). A watt is often used for measuring the energy consumption of small devices such as a cell phone charger or a light bulb (11).
kilowatt (kW)	$1\ kW = 1\ 000\ W$ kW is relevant when discussing residential and commercial electrical installations. kW is typically used for measuring energy consumption of high-draw appliances, such as ovens and geysers (11).
megawatt (MW)	$1\ MW = 1\ 000\ kW = 1\ 000\ 000\ W$ MW is relevant when discussing output of a power plant or electricity demand of a town or city (11). For example, the nominal capacity of Koeberg Nuclear Power Station in Cape Town was 1 854 MW (12) in 2022.
gigawatt (GW)	$1\ GW = 1\ 000\ MW = 1\ 000\ 000\ KW = 1\ 000\ 000\ 000\ W$ GW is relevant when discussing the total power output of several power plants or that of a country (11). For example, the nominal capacity of Eskom's coal-fired fleet is 39,9 GW (12), or 39 900 MW.
terawatt (TW)	$1\ TW = 1\ 000\ GW = 1\ 000\ 000\ MW = 1\ 000\ 000\ 000\ kW = 1\ 000\ 000\ 000\ 000\ W$ TW is relevant when discussing the worldwide energy capacity (11). For example, the total generation capacity of the world's power plants was 5,7 TW in 2017[2] (13).
Joule	$J = kg \cdot m^2 \cdot s^{-2}$
Exajoule	1 exajoule (EJ) = 1 quintillion joules (10^{18})
Wh, kWh, MWh, GWh, TWh	Each of these units represent a certain amount of electricity consumption based on an hourly measure. For example, 1 kWh represents 1 hour's use of 1 kW or 2 hours use of 0.5 kW. Note: kWh is pronounced kilowatthour and not kilowatt per hour.
Ramp-up/ramp-down rates	The ramp-up/ramp-down rates refer to the speed at which an electricity generator can bring additional generation online or take generation offline (14).

[2] The global generation capacity has increased significantly since 2017.

Electricity frequency	Electrical frequency is the measure of the rate of that oscillation and is measured in the number of changes per second – also called hertz (Hz) (15).
Peaking power plants	The term peaking refers to power plants that can react quickly to changes in demand and provide power to supplement that generated by baseload stations, which are coal and nuclear. South Africa's peaking power stations are hydroelectric, hydro-pumped storage and gas turbine stations (16).
Baseload power plants	Baseload power sources are those plants that operate continuously (24/7) to meet the minimum level of power demand. Baseload plants are usually large-scale and are key components of an efficient electrical grid. Baseload plants produce power at a constant rate and are not designed to respond to peak demands or emergencies. The baseload power generation can rely on both renewable and non-renewable resources (17).
Planned capability loss factor (PCLF)	Eskom defines the PCLF on their data portal as the ratio between the unavailable energy of the units that are out on planned maintenance over a period compared to the total net installed capacity of all units over the same period (18).
Unplanned capability loss factor (UCLF)	Eskom defines the UCLF on their **data portal** as the ratio between the unavailable energy of the units that are on unplanned outages over a period compared to the total net installed capacity of all units over the same period (18). Eskom defines UCLF in their **Annual Report** as the energy losses due to outages which are considered unplanned when a power station unit has to be taken out of service and which has not been scheduled at least four weeks in advance (19).
Other Capability Loss Factor (OCLF)	Eskom defines the OCLF on their data portal as the ratio between the unavailable energy of the units that cannot be dispatched due to constraints of power station management control, over a period compared to the total net installed capacity of all units over the same period (18).
Energy utilisation factor (EUF)	The EUF can be defined as the percentage of the electricity actually produced when the generator was available to produce electricity relative to the maximum amount that could have been produced (20).
Energy availability factor (EAF)	Eskom defines the EAF on their **data portal** as the difference between the maximum availability and all unavailability (PCLF, UCLF & OCLF) expressed as a percentage. This excludes renewables, IPPs and international imports (18). Eskom defines EAF in their **Annual Report** as the measure of power stations availability, taking account of energy losses not under the control of plant management and internal non-engineering constraints (19). EAF can be defined in equation form as: $EAF = 1 - (PCLF + UCLF + OCLF)$
Capacity factor (CF)	CF can be defined as the ratio of electricity generated divided by the maximum electricity that could have been generated had the generator been operating at full power continuously. A CF of

	100% implies that the generator had been operating at full capacity over the full period (21). Eskom defines the CF as how hard the plant is running against its maximum possible output (22). CF can be defined in equation form as: $CF = EAF \times EUF$
World	"World" refers to the aggregate of all countries available in a specific dataset.
Independent Power Producer (IPP)	Private power producers sell power directly to Eskom. They are also able to sell directly to customers. IPPs have generation licences from the National Electricity Regulator of South Africa (NERSA) and have Power Purchase Agreements (PPAs) with Eskom. IPPs are typically appointed through public-private partnerships such as the Renewable Energy Independent Power Producers Procurement Programme (REIPPPP). IPPs do not, by default, include embedded generation. Private behind-the-meter generators are not typically referred to as IPPs in the South African context.

1.4 Rounding

1.4.1 The tables presented in this paper may contain rounding errors, where, due to rounding, the individual amounts may not add up to the total indicated. These rounding errors are inevitable when rounding numerical values to a limited number of decimal places.

1.4.2 Whilst every effort has been made to minimise rounding errors and to ensure the accuracy of our data, some discrepancies may exist. Therefore, readers are advised to exercise caution when interpreting the data and are encouraged to refer to the original sources whenever possible.

2. Energy in South Africa

2.1 Definition of energy

2.1.1 The Oxford English Dictionary defines 'energy' as "the potential or capacity of a body or system to do work by virtue of its motion, position, chemical structure, etc., frequently regarded as a quantifiable attribute or property which can be acquired, transferred, and expended" (23).

2.1.2 Energy can neither be created nor destroyed; it can however be transformed into different forms – this is more generally known as the law of conservation of energy (24). Throughout this paper, reference will be made to various energy sources – this is meant to signal a change in the form of energy (such as the conversation of solar radiation to electricity through solar panels (25)).

2.1.3 As a society, we typically measure consumption in terms of sources that we actively consume (such as oil), rather than sources that we "passively" consume (such as sunlight for crops or solar heating for water). In this paper we did not attempt to quantify the energy use for passive sources. However, in some cases, we implicitly incorporated passive sources (such as where we assumed efficiency gains).

2.1.4 Energy comes in many forms – it can either be defined as kinetic energy (energy in movement) or potential energy (energy in position). Forms of energy[3] include:

- Chemical energy
- Electrical energy
- Mechanical energy
- Radiant energy
- Thermal energy
- Nuclear energy
- Magnetic energy
- Gravitational energy
- Elastic energy

2.1.5 Electricity is typically considered to be a secondary source of energy (26) as it is usually produced by primary sources (such as coal, gas, or oil). Some operators split electricity into primary and secondary sources based on how the electricity is generated (27). For the purposes of this paper and in the context of South Africa's broader energy industry, electricity is considered to be a secondary source of energy.

[3] This list is not intended to be exhaustive as energy can take on a wide range of forms.

2.2 Energy use in South Africa

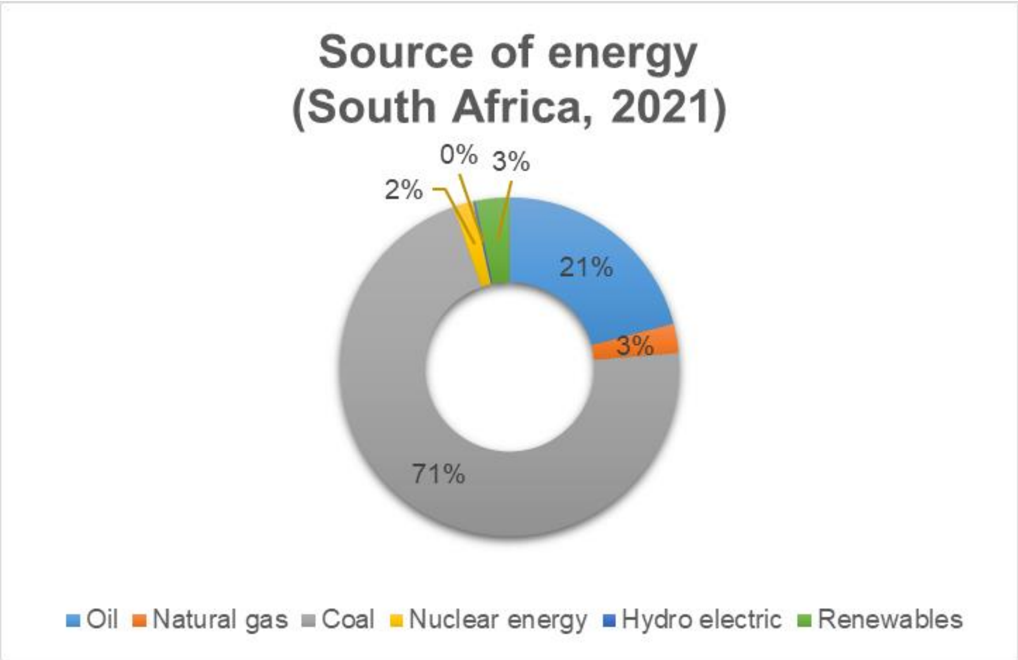
2.2.1 The 2022 BP Statistical Review of World Energy (28) ranked South Africa 21st out of 79 countries in terms of total primary energy consumption. South Africa's primary energy consumption is similar to countries such as Thailand, Taiwan, and the United Arab Emirates. However, when considered on a consumption per capita basis, South Africa ranks 53rd – similar to countries such as Chile and Latvia. South Africa's primary energy consumption is shown below in Table 2.1 and Figure 2.1.

Table 2.1: Energy consumption in exajoules in 2021 for South Africa and the "World"

Energy source	South Africa (exajoules)	World (exajoules)	South Africa (% of total)	World (% of total)
Oil	1.04	184.21	21%	31%
Natural gas	0.14	145.35	3%	24%
Coal	3.53	160.10	71%	27%
Nuclear energy	0.09	25.31	2%	4%
Hydro electric	0.01	40.26	0%	7%
Renewables	0.16	39.91	3%	7%
Total	**4.98**	**595.15**	**100%**	**100%**

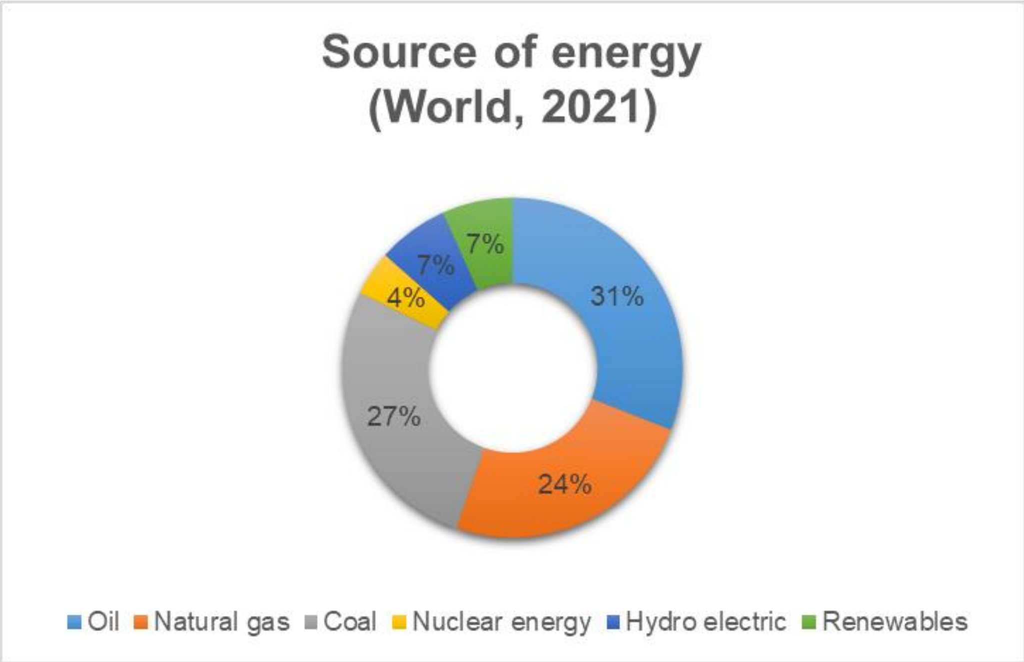
(Source: BP Statistical Review of World Energy June 2022 (28))

Figure 2.1: South Africa's energy consumption by source



(Source: own chart, data from BP Statistical Review of World Energy June 2022 (28))

Figure 2.2: World energy consumption by source



(Source: own chart, data from BP Statistical Review of World Energy June 2022 (28))

2.2.2 From Table 2.1 and Figures 2.1 and 2.2 above, it can be noted that:

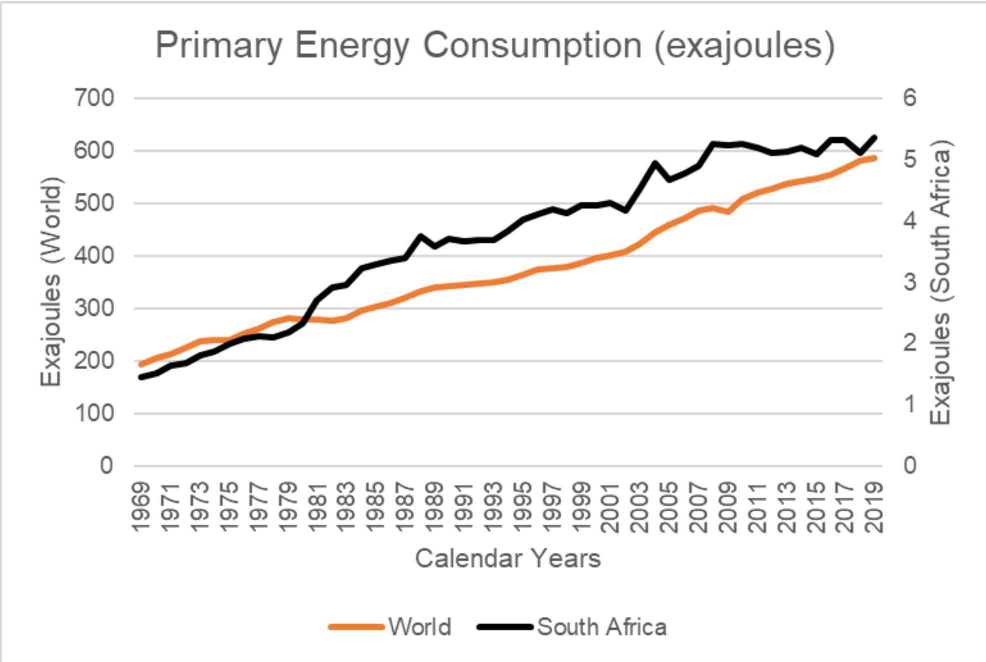
- South Africa relies heavily on coal and oil for its energy, which together comprise 92% of total energy consumption. In contrast, the combined coal and oil consumption of the World comprises 58% of total consumption.
- Globally natural gas comprises 24% of total energy consumption. In South Africa natural gas consumption is at 3%.
- South Africa's coal consumption at 71% of all energy consumption is particularly high when compared to the World's consumption at 27%. South Africa's coal consumption reflects the country's history of large coal reserves, many coal-fired power stations, and a lack of large gas reserves.
- Globally hydroelectric consumption comprises 7% of all energy consumption. At 0.3% of total energy consumption, South Africa has already developed a significant portion of its inland hydroelectric-generation potential (29).

2.2.3 It should be noted that, from an energy perspective, the 'World' comparison used above does not comprise a homogenous group of countries. Nevertheless, it provides a high-level comparison of energy consumption globally. For example, China is the largest consumer of energy by a significant margin as it consumes 70% more electricity than the United States, the second largest energy consumer. China has a large coal fleet, and if removed from the World category, would reduce the portion of global coal energy consumption substantially; from 27% to 17%.

2.3 Trends in energy use in South Africa

2.3.1 As reported in the 2022 BP Statistical Review of World Energy (28), South Africa's primary energy consumption has been moving in line with the global trend for much of the previous 50 years, other than the last 10 to 15 years. These trends are illustrated in Figure 2.3 below. The trend is further confirmed by the correlation coefficient between South Africa and the World of 96%[4] over the full period. However, there was a slight change in the South African trend compared to the global trend from 2009 until 2019 as can be noted in Figure 2.4 and Table 2.2 below.

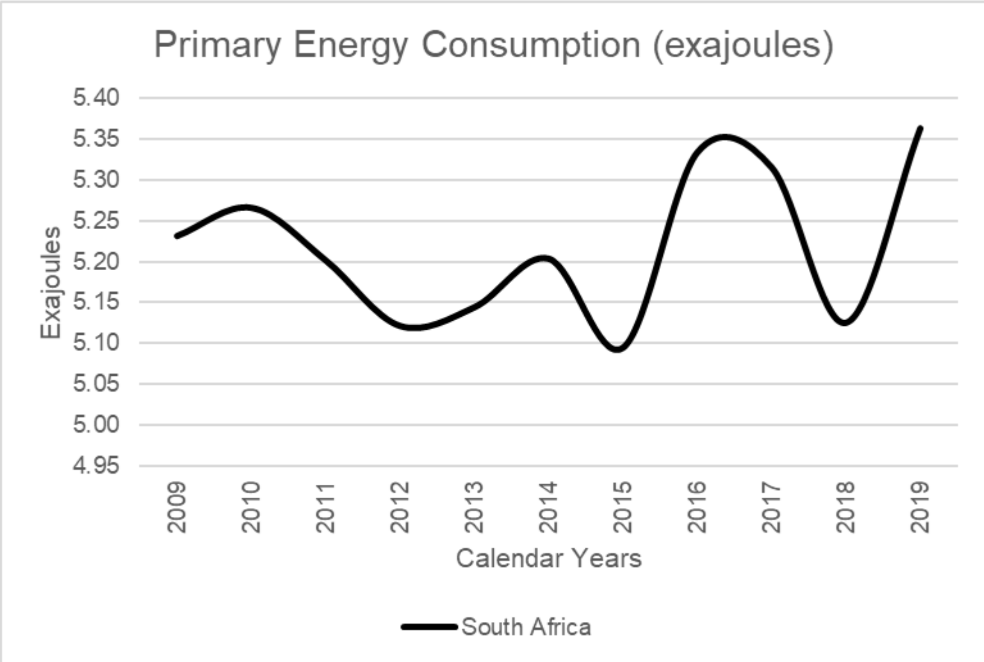
Figure 2.3: Primary energy consumption (exajoules) for South Africa and the World (1969-2019)



(Source: own chart, data from BP Statistical Review of World Energy June 2022 (28))

[4] One should be careful in drawing conclusions purely from a correlation coefficient as causation might not always be applicable.

Figure 2.4: Primary energy consumption (exajoules) for South Africa (2009-2019)



(Source: own chart, data from BP Statistical Review of World Energy June 2022 (28))

Table 2.2: Change in energy consumption for South Africa and the "World" measured as a compound annual growth rate (CAGR)

	Annualised change in energy consumption	
Period	**South Africa**	**The World**
1969 - 1979	4.14%	3.91%
1979 - 1989	5.11%	1.85%
1989 - 1999	1.74%	1.31%
1999 - 2009	2.07%	2.28%
2009 - 2019	0.25%	1.93%
1969 - 2019	2.65%	2.25%

(Source: own calculations, data from BP Statistical Review of World Energy June 2022 (28))

2.3.2 From Figures 2.3 and 2.4 as well as Table 2.2 above, it can be noted that:

- World energy consumption has been increasing steadily from 1969 to 2009 with South Africa outpacing World energy consumption growth from 1969 to 1999. However, South Africa's energy consumption slowed significantly between 1989 and 2009. The period from 2009 to 2019[5] was illustrated by a flattening out of energy consumption growth. The 2009-2019 slowdown is particularly stark when considering that World energy consumption grew by 21% in the same period, whilst South African energy consumption grew by only 3%. This period coincided with the start of the South African electricity crisis and ensuing load shedding.

[5] Although data were available post 2019, trends were analysed up to 2019 so as to avoid the impact of the Covid-19 pandemic.

Nevertheless, as there could be many reasons for the slowdown in energy consumption it is specifically investigated in more detail in Section 2.4 below.

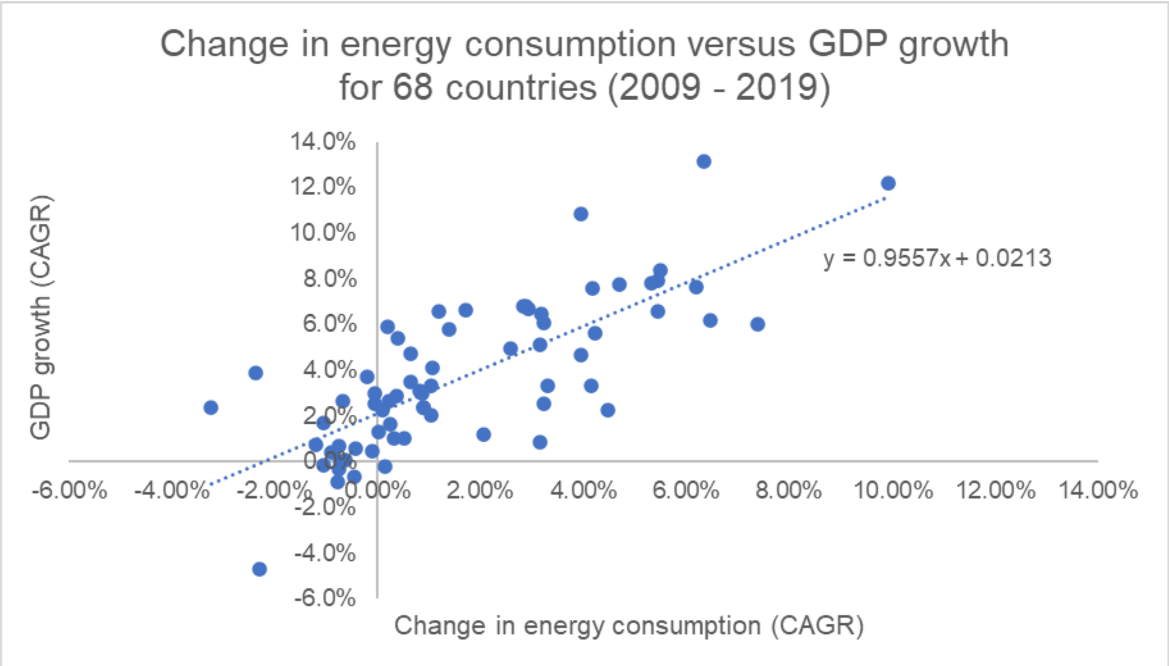
- South Africa's energy consumption from 2009 until 2019 was volatile. Initially, it decreased from 2011, then took a dip in 2015, whereafter it showed a recovery in 2016/2017.

2.4 Energy use and gross domestic product in South Africa

2.4.1 It is worth discussing the slowdown in energy consumption in South Africa from 2009 until 2019 to establish the underlying cause. According to the 2019 Integrated Resource Plan (IRP) (30), there was a significant divergence between projections done in the 2010 IRP and the actual gross domestic product (GDP) and electricity generation figures. The reasons given for the reduced energy demand relative to the projections were supply constraints, improved energy efficiency, increased embedded generation, substitution of energy sources (fuel switching), and generally depressed economic conditions. Nevertheless, it seems that GDP was again used as a key metric for the projection of electricity consumption in the 2019 IRP.

2.4.2 In their research, Nayana, Kadir, Ahmad, and Abdullah (31) found that GDP is a significant driver of energy consumption but that the inverse does not necessarily hold true. In contrast, an article by McKinsey (32) highlights certain nuances in the relationship between energy consumption and GDP growth and proposes that a potential decoupling of GDP and energy growth could occur. McKinsey attributes such decoupling to a range of factors, including a substantial decrease in energy intensity, an increase in energy efficiency, an increase in levels of electrification, and the incorporation of renewables into the energy mix. From McKinsey's perspective it seems that the focus was on primary energy consumption and that renewable sources were excluded. The trend between GDP growth and energy consumption is illustrated in Figure 2.5 below.

Figure 2.5: Change in primary energy consumption versus GDP across 68 countries (2009-2019)



(Source: own chart, energy consumption data from BP Statistical Review of World Energy June 2022 (28), GDP data from the World Bank (33))

2.4.3 GDP and energy consumption data were available for 68 countries[6] (73% of overall energy consumption globally). The compound annual growth rate (CAGR) for both GDP and energy consumption was plotted in Figure 2.5 above to provide a view of the relationship between GDP and energy consumption.

2.4.4 From Figure 2.5 above, it seems that there is a strong linear trend between GDP growth and energy consumption across a number of countries. However, for certain countries, a significant increase in GDP did not show a corresponding increase in energy consumption. Nevertheless, of the top 20 countries in terms of GDP growth, 70% (14) were also in the top 20 countries that showed the greatest increase in energy consumption from 2009 to 2019. Bangladesh, Vietnam, China, Turkmenistan and the Philippines were the top five countries in terms of GDP growth. These countries represented 26% of total energy consumption in the world during 2019. While it is not conclusive that there is a causal relationship between GDP and energy consumption, it is clear that there is a definite correlation.

2.4.5 Tables 2.3 and 2.4 and Figures 2.6 and 2.7 highlight GDP and energy consumption from 1969 to 2019 with a specific focus on South Africa relative to the World.

Table 2.3: Change in energy consumption and GDP for South Africa and the "World" measured in terms of a CAGR

Period	South Africa (energy consumption)	South Africa (GDP)	World (energy consumption)	World (GDP)
1969 - 1979	4.14%	12.59%	3.91%	13.88%
1979 - 1989	5.11%	5.54%	1.85%	7.22%
1989 - 1999	1.74%	3.44%	1.31%	4.95%
1999 - 2009	2.07%	8.09%	2.28%	6.38%
2009 - 2019	0.25%	1.65%	1.93%	3.72%
1969 - 2019	2.65%	6.19%	2.25%	7.18%

(Source: own calculations, energy data from BP Statistical Review of World Energy June 2022 (28), GDP data from the World Bank (33))

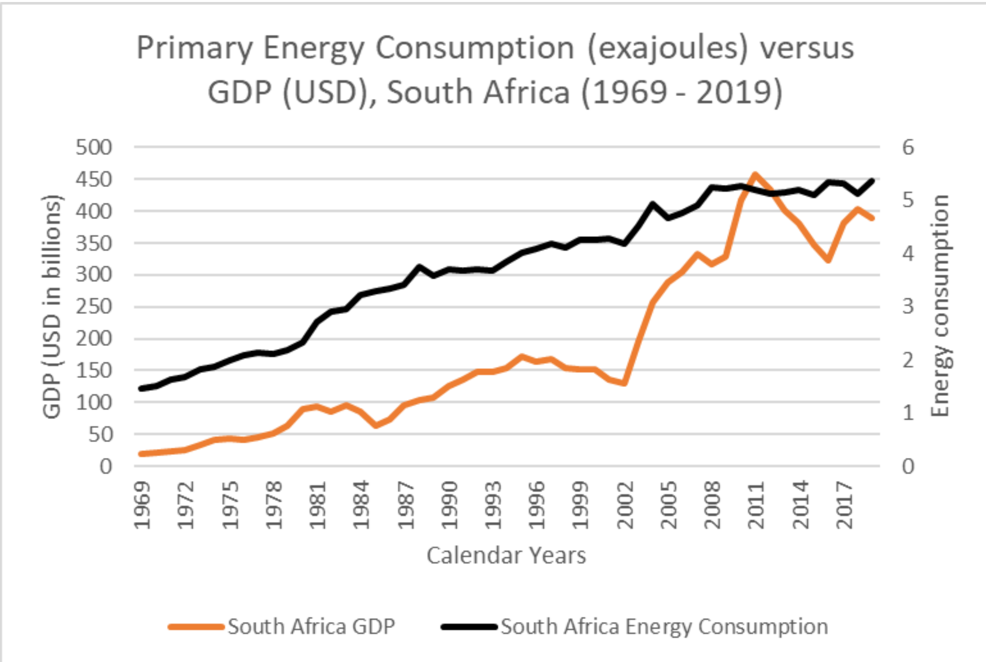
[6] Certain countries were excluded from the analysis due to data limitations.

Table 2.4: Correlation between energy consumption and GDP for South Africa and the "World"

Period	South Africa (energy consumption against GDP)	World (energy consumption against GDP)
1969 - 1979	94%	97%
1979 - 1989	44%	97%
1989 - 1999	75%	95%
1999 - 2009	92%	98%
2009 - 2019	-26%	96%
1969 - 2019	90%	99%

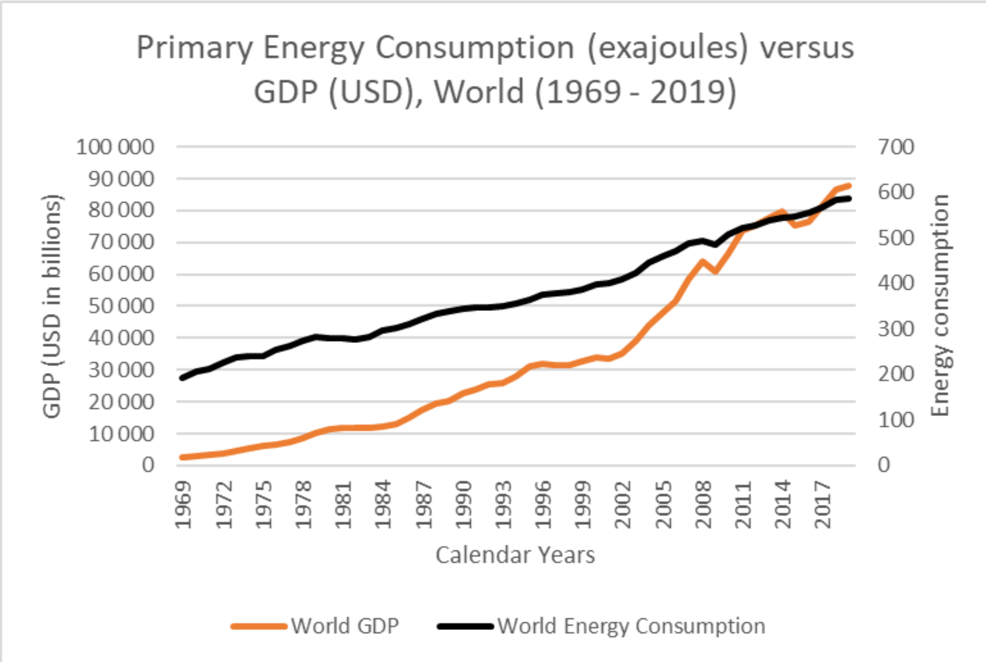
(Source: own calculations, energy data from BP Statistical Review of World Energy June 2022 (28), GDP data from the World Bank (33))

Figure 2.6: Primary energy consumption versus GDP for South Africa (1969-2019)



(Source: own chart, energy data from BP Statistical Review of World Energy June 2022 (28), GDP data from the World Bank (33))

Figure 2.7: Primary energy consumption versus GDP for the World (1969-2019)



(Source: own chart, energy data from BP Statistical Review of World Energy June 2022 (28), GDP data from the World Bank (33))

2.4.6 From Tables 2.3 and 2.4 and Figures 2.6 and 2.7 above, it can be noted that:

- Globally, there is a strong correlation between GDP and energy consumption. Energy consumption has been rising steadily as GDP grows. However, because energy often acts as a multiplier for growth, the rate of increase of GDP has historically outpaced the growth rate of energy consumption.
- For each 10-year period, the growth in GDP was higher than the growth in energy consumption for South Africa and the “World”.
- Prior to 2009, trends in South Africa’s energy consumption and GDP growth were similar. However, this deviated in the period from 2009 to 2019 when the growth rate of energy consumption stagnated. Although a sharp downturn in GDP was followed by a recovery during this period, not much change was noted in energy consumption. This could be due to the inelasticity of demand for energy and the base need for energy consumption. There might also have been significant increases in energy efficiency over this period or substitution of energy sources. The structure of the South African economy could have changed– driving down the need for energy consumption as a significant driver of economic growth.

2.5 Conclusion

2.5.1 South Africa’s energy consumption, which is dominated by coal and oil, is relatively high with the country ranking 21 out of 79 comparatives. Since 2009, South Africa’s energy consumption stagnated whereafter it started to reduce substantially. This has significant implications for future energy demand. As noted in the 2019 IRP, this reduction in energy consumption could be attributed to suppressed demand because of a shortage of electricity. In the rest of this paper the focus will be on electricity and the challenges in the electricity sector concerning supply, demand, storage, and transmission.

3. Electricity supply, demand, storage, and transmission in South Africa

3.1 The history of electricity in South Africa

3.1.1 Eskom's website provides a detailed account of its history in generating, transmitting, and distributing electricity (34). According to Eskom, electricity was first used in South Africa in the second half of the 1800s. Due to increased electricity demand from the mining sector, multiple power stations were constructed and in service by 1890. Initially, these power stations were islanded grids, erected for specific purposes (such as lighting mines). Interestingly, even wealthy individuals had their own "electric lighting plants" at their residences.

3.1.2 Mining companies soon realised that they required a larger electricity supply and "joined forces to build small power stations to supplement the existing supply" (35). In 1906, these power stations were acquired by the newly established privately-owned Victoria Falls Power Company (VFP). By 1915, VFP had built a total of 160 MW of installed capacity. VFP was a for-profit entity but, as determined by the Power Act of 1910 (34), the State would expropriate it 35 years later.

3.1.3 With the promulgation of the Electricity Act of 1922, the Electricity Supply Commission (ESCOM) was established in 1923. For the next 25 years ESCOM and VFP operated in a form of a public-private partnership; ESCOM provided capital whilst VFP built and operated power stations (36). Then, in 1948, a merger agreement was signed between VFP and ESCOM in terms whereof ESCOM acquired all VFP power stations and took over its full staff complement (37).

3.1.4 ESCOM's generating capacity increased from 1 127 MW in 1945 to 3 297 MW in 1959, an almost three-fold increase in the space of 15 years (38). Simultaneously, ESCOM's transmission network was extended and enhanced with new transmission technology. Some of the power stations brought online during that period have only recently been decommissioned. For example, Komati Power Station, commissioned in 1962, was only decommissioned 60 years later in 2022.

3.1.5 During the 1960s a national power network that linked the north-eastern parts of the country with the south-western parts was established. In the 1970s, ESCOM constructed some of the largest coal-fired power stations in South Africa, thus adding significant generation capacity to the grid (39). On 5 December 1975, a fault on a line of the interconnected transmission system caused a nationwide blackout which prompted ESCOM to build two gas turbine stations to assist in improving grid stability.

3.1.6 The early 1980s saw the construction of three more coal power stations[7] adding a total of approximately 12 000 MW to the grid (39). The 1980s also saw South Africa's nuclear power station, Koeberg, synchronised to the grid. In 1987, with the revision of the Electricity Act, ESCOM was renamed to Eskom. This was followed by more power stations being added to the grid in the 1980s and early 1990s.

3.1.7 From the mid to late nineties Eskom oversaw a programme of mass electrification – Eskom estimated that three million South Africans were being added to the grid each

[7] Lethabo, Matimba and Kendal

year. Apart from providing electricity to households, Eskom promoted and enabled the use of electricity across a range of business sectors, including agriculture, industry, hospitality, and bulk retailers (such as municipalities). According to Eskom reports it had assumed a position of excess generation by the late 1980s. However, it seems that these projections were not adequately reviewed in the light of the electrification programme of the 1990s (40,41).

3.1.8 By 2007, it was clear that there were electricity shortages. With a large number of plants that became unreliable (many were built in the 1970s and 1980s) and an increase in demand for electricity, Eskom entered a decade of deterioration in electricity supply capability generation (42). This was evident when Eskom had to start implementing rotational blackouts[8]. In their load-shedding statistics (43), the Council for Scientific and Industrial Research (CSIR) highlighted how load shedding started in 2007, was absent from 2009 until 2013, reappeared in 2014, to increase substantially in the following years (other than in 2016 and 2017). By 2022 there were more than 200 days (44) of load shedding. Early in 2023, the chairperson of the Eskom board, Mpho Makwana, reported that Eskom was planning to end load shedding within 24 months but that during this time, load shedding would remain at stages two or three, i.e., shedding between 2 000 and 3 000 MW (45).

3.1.9 An article by the AmaBhungane Centre for Investigative Journalism (46) provides a perspective of how the performance of the coal fleet has deteriorated since the 1980s. They attribute Eskom's deterioration to a range of factors, including ageing power plants, a lack of political will to fund new power stations, inaccurate projections and inappropriate planning, unrealistic targets, cost cutting of critical maintenance, gross mismanagement, state capture and corruption, a lack of revenue, and more. These allegations are serious and, if true, have crippled one of the most important parastatals in South Africa.

3.1.10 The Council for Scientific and Industrial Research (CSIR) has an Energy Research Centre that provides decision support to policymakers (47). The CSIR publishes various analyses relating to energy research, including an analysis of Eskom's load-shedding statistics. This Centre produces a biannual document (43) that provides an overview of Eskom's electricity generation and demand. This document is particularly insightful and highlights many of the key performance indicators (KPIs) communicated by Eskom. From this document it can be noted that since 2010, Eskom's annual electricity production has decreased substantially and that Eskom produced 249 TWh of electricity in 2010 but only 233 TWh in 2022. While the 6% decrease might not seem significant in nominal terms, when viewed as a measure of economic growth against the global increase of 33% over the same period (48), it is alarming that there has been a decrease in electricity usage in South Africa. This decrease in electricity generation aligns with the trends in South African energy consumption noted in Section 2.

3.1.11 Given the critically important nature of Eskom and its central role in the economic future of South Africa, the reliability, stability, and ample supply of electricity is currently a focus area for South Africa. There are opportunities for both the public and private sectors to work together to ensure that South Africa urgently achieves

[8] Colloquially referred to as load shedding

electricity security. This paper explores some of these options and provides a range of scenarios for the future.

3.2 Electricity generation overview

Table 3.1: Electricity generation in GWh by source (2021)

	South Africa (GWh)	World (GWh)	South Africa (% of total)	World (% of total)
Oil	1 567	720 286	1%	3%
Gas	-	6 518 496	0%	23%
Coal	209 568	10 243 971	86%	36%
Nuclear	10 424	2 800 268	4%	10%
Hydro	1 401	4 273 828	1%	15%
Renewables	16 518	3 657 224	7%	13%
Other	4 843	252 223	2%	1%
Total	**244 322**	**28 466 295**	**100%**	**100%**

(Source: BP Statistical Review of World Energy June 2022 (28))

3.2.1 The following can be noted from Table 3.1 above:

- Coal dominates electricity generation in South Africa at 86% of total generation. Coal is also the largest fuel source for the World's electricity generation but it comprises only 36% of total generation.
- Oil, gas, and coal (fossil fuels) constitute approximately 87% of sources in South Africa and 61% globally. If you consider non-renewables (i.e., fossil fuels plus nuclear), the proportion increases to 91% for South Africa and 71% globally.
- Renewables and hydro represent a relatively small portion of overall generation in South Africa (less than 8%) whereas globally, they represent closer to 28%.
- South Africa's electricity generation is not particularly diversified when compared to global averages.

3.2.2 The "World" category above is not comprised of a set of homogenous countries. The "World" category is provided as a broad indication of global trends and will be used as a comparison throughout this paper for illustrating those trends. Readers are encouraged to compare South Africa to a subset of the "World" category (e.g., developing nations). Future research could focus on how South Africa has fared relative to nations deemed to be similar.

3.3 Factors impacting electricity supply and demand

3.3.1 Introduction

3.3.1.1 The electrical grid is a complex system that requires large-scale infrastructure capable of delivering electricity to consumers whilst ensuring that the grid is dynamically balanced. It is a feat of engineering that, in many countries, one can flip a switch and a light comes on. Electricity is not stored in its electrical form; it is converted to a different form of energy and then reconverted to electricity when needed. To balance the system, only sufficient electricity is produced to satisfy electricity demand; this could also be described as "just-in-time generation". There are numerous ways in which demand can be managed and supply consumed but the electrical frequency (hertz) and voltage (volts) are the typical metrics by which grid operators balance the grid. Oversupply would typically result in an increase in frequency and undersupply would result in a reduction in frequency. Frequency regulation is critical to the stability of the grid.

3.3.1.2 Supply and demand are not level, fixed quantities. Demand varies over time and is based on the consumption of the end-user. Supply must continually match demand. Supply is constrained by available generation capacity. Supply planning is done to ensure that there is sufficient generation capacity to meet the expected demand plus some margin. In times with higher demand (e.g., sunrise and sunset), a combination of additional generation and storage are typically dispatched to meet this demand.

3.3.1.3 In managing demand and supply, the grid operator and generators have various levers they can use to ensure stability. In anticipation of the increased demand, the grid operator could dispatch peaking generation plants that have quick ramp-up rates and are able to meet the demand over the peak periods. Once demand has subsided, these plants can be switched off and fuel can be conserved for the next demand peak. However, where the generation capacity is insufficient to meet the demand, demand must be reduced (shed) to ensure grid stability.

3.3.1.4 Eskom charges time-of-use tariffs (TOU) by season for certain customers (49). These tariffs provide economic (price) signals to users indicating the cost of running various plants at certain times. Grid operators should ensure that electricity consumers are aware of the variation in supply and demand over time and price accordingly. Demand-side management is further discussed in Section 4.4.

3.3.1.5 The level of availability of electricity impacts every South African. The lists below provide points of departure to consider when investigating the demand, supply, storage, and substitution of electricity. They are not intended to be exhaustive; they are meant to assist the reader when discussing electricity. The factors are grouped under the following headings: economic factors; economic signals; policy, regulation, and awareness; and other considerations.

3.3.2 Economic factors

3.3.2.1 Economic factors influence the electricity system in various ways. Some considerations from an economic perspective include:

- Economic growth is often linked to the availability of energy. Suppressed supply could suppress demand for certain sectors. High economic growth is also often accompanied by significant increases in energy consumption, although this would be dependent on the structure of the economy.
- Energy certainty is often seen as a requirement for business confidence and expansion. Countries that can reliably provide electricity at cost effective rates are advantageous from a business expansion perspective (50).
- Industrial and mining customers base their decisions on long-term projections of likely return on investment. Regulatory and execution certainty around long-term electricity generation, transmission, and distribution provide these customers with the confidence to invest in that country (51). A lack of certainty, on the other

hand, reduce long-term prospects and drives capital to other countries that can provide such certainty.

- Different economic sectors have different electricity consumption requirements and usage profiles. Some customers consume small amounts of electricity but require uninterrupted electricity connections (e.g., hospitals), other customers consume more electricity in certain critical business cycles (e.g., agriculture), and certain customers (e.g., smelters) are extremely high electricity consumers. Changes in the structure of the economy can alter the electricity consumption profile of the country.
- When investigating electricity consumption, it is useful to split electricity demand between formal and informal economic sectors. Furthermore, it is useful to investigate how demand varies by time across geographical areas – especially when considering embedded generation.
- Changes in wealth can drive changes in electricity consumption. An increase in wealth can change the way in which electricity is consumed. This change can be driven by the duration of use (use of appliances for longer or shorter periods), level of use (increased or decreased power consumption per hour), and the increase or decrease in the number or type of appliances.
- Changes in the end-use of electricity can drive demand. Examples include changes in energy sources (i.e., substitution) for electricity, heating, cooling, transport, industry, manufacturing, and cooking. An increase in the prevalence of electric cars drives demand for electricity. Some proponents argue that a move away from liquid fossil fuels to large scale electrification is required to reduce the global carbon impact. McKinsey argues that, at present, it is possible to electrify up to 50% of the industrial fuel consumption (52).

3.3.3 Economic signals

3.3.3.1 Economic signals (i.e., pricing) are important in incentivising consumer behaviour. Some factors to take into account when considering economic signals include (53):

- Projected power plant availability for electricity generation, allowances for planned maintenance, expected unplanned maintenance, artificial limitations (e.g., load shedding, load reduction), and unfulfilled or suppressed demand.
- Reliability of generation
- Cost of generation (fuel cost, operating cost, capital expenditure, cost of financing)
- Cost of transmission, distribution, and storage
- Impact of transmission and distribution losses
- Capacity and resilience of grid transmission and distribution
- Availability of capital for allocation to new projects
- Project risk of new generation projects
- Availability and cost of ancillary services (e.g., voltage and frequency regulation)
- Forecasted and predictability of supply
- Guarantees of electricity availability
- Demand (available demand response measures, accuracy of demand forecasting, changes in the electricity demand profile)
- Quality of power
- Season of the year and associated weather conditions
- Penetration of renewable energy

- Pricing structures and its substantial impact on electricity demand, such as:
    - Time of use (TOU) tariffs
    - Peak electricity use tariffs
    - Subsidies (free electricity) for lower-income households
    - Inclining block rate (IBT) tariffs
    - Basic, maximum demand, capacity charge, and energy charge tariffs
    - Fixed tariffs
    - Prepaid electricity
- Energy market
- Currency of payment
- Regulatory limits on pricing
- Grid and hub connection size
- Technology solutions available and the integration and implementation of these new technologies (e.g., smart grids, smart meters)
- Private energy production (e.g., home rooftop solar, microgrids)
- Availability of infrastructure from manufacturers, imports, and distributors

3.3.4 Policy, regulation, and awareness

3.3.4.1 As with many industries, legislation and the accompanying regulations play a critical role in electricity. The following acts and regulations are some of the documents to consider when analysing electricity in the South African context:

- Petroleum Products Act 120 of 1977
- White Paper on Energy Policy of the Republic of South Africa (1998)
- Nuclear Energy Act 46 of 1999
- Basic Electricity Policy (2001)
- Gas Act 48 of 2001
- White Paper on Renewable Energy (2003)
- Electricity Regulation Act 4 of 2006 as amended
- Nuclear Energy Policy for the Republic of South Africa (2008)
- National Energy Act 34 of 2008
- Electricity Pricing Policy (EPP) of the South African Electricity Supply Industry (2008)
- Integrated Resource Plan (2019)
- Carbon Tax Act 15 of 2019
- Climate Change Bill[9]

3.3.4.2 New generation capacity is typically initiated by the Minister of Mineral Resources and Energy (Minister) and approved by the National Energy Regulator of South Africa (NERSA). NERSA is bound by section 34 of the Electricity Regulation Act (ERA) (54) to approve any new generation in consultation with the Minister.

3.3.4.3 In terms of Schedule 2 of the ERA, certain entities are exempt from having to apply for and hold a generation licence but requires that the generation activities be registered with NERSA. Initially, this exemption applied to generation facilities with an installed capacity of no more than 1 MW. In 2021, this threshold was increased to

[9] At the time of writing, this bill was still under consideration in Parliament.

100 MW and later entirely removed (55), which means that private individuals, businesses, and municipalities are allowed to generate their own electricity and thus reduce their burden on the grid.

3.3.5 Other considerations

3.3.3.1 As mentioned above, there are many factors that impact electricity systems globally. As the scope of this paper is limited, the non-exhaustive list below are examples of more factors to consider. Above all the reader is encouraged to creatively approach challenges they encounter in the electricity sector.

- Environmental impact of electricity generation
- Climate change awareness of the general public
- Social impact of changes to electricity generation
- Electricity education and narrative communicated by grid operators
- Public perception, misunderstanding, misinterpretation, and targeted information relating to electricity
- Private power generation capacity and limits
- Availability of scarce skills related to the electricity system (public and private sector)
- Political motivations and interference in electricity grid operation and planning
- Mismanagement, crime, corruption, and policing relating to electricity infrastructure (generation, transmission, and distribution)
- Challenges in revenue collection
- Seasonality
  - Weather-driven consumption (e.g., cooling and heating)
  - Weather-driving generation (e.g., wet coal)
  - Cyclical industrial activity
- Population
  - Number of people
  - Number of households and family size
  - Age distribution, including changes in mortality/longevity
  - Immigration and emigration
  - Changing levels of wealth over time
- Level of urbanisation
  - Geographic differences (urban vs rural)
  - Impact of urban grids
- Technological improvement:
  - New technologies (e.g., improved power efficiency and uses)
  - Rate of adoption of new technologies (technology diffusion)
  - Ease of substitution of new energy sources
- Usage behaviour
  - Historical use of certain appliances (e.g., tradition, domestic space heating)
  - Preference for use of a certain service, legacy considerations, habits, changes in behaviour
- Other factors:
  - Changes to lifestyle and ways of working
  - Impact of global events (e.g., COVID-19)

- Changes in transport modalities (number and types of vehicles)
- Air quality

3.4 Electricity supply and demand

3.4.1 Introduction

3.4.1.1 To give context for the rest of the paper, section 3.4 provides the reader with detailed discussions and statistics of South Africa's electricity infrastructure, generation, and consumption.

3.4.2 Electricity infrastructure in South Africa

3.4.2.1 Eskom supplies the majority (90%) of electricity consumed in South Africa (56). Eskom's divisions are split between generation, transmission, and distribution (57).

3.4.2.2 Generation represents the actual electricity production. While this paper focuses on electricity generation, transmission and distribution are critical considerations for future expansion and substitution of generation sources. Eskom's fleet, detailed in Section 3.4.4, represents Eskom's own generation capability. Outside of Eskom, there are independent parties that produce their own electricity, either for own consumption (referred to as embedded generation) or to sell to Eskom. These parties are typically referred to as Independent Power Producers (IPPs). Some IPPs sell electricity directly to third parties but use Eskom's transmission infrastructure to do so; this is known as "wheeling" electricity. While Eskom provides the public with access to some of its data, information from private generators on embedded generation is not readily available. Embedded generation can take the form of anything from residential solar (rooftop solar) to utility-level solar that supplies mines and large industrial customers.

3.4.2.3 While the generation of electricity is important, it cannot be viewed in isolation; generation is dependent on grid stability. Each generator produces power at a certain voltage but all of them run at the system frequency. Ensuring frequency and voltage stability on a real-time basis is critical for Eskom to maintain a functioning grid. This allows typical home appliances in South Africa, operating at a frequency of 50 hertz (Hz) and a voltage of 220/240, to function. Control systems at generation plants, in the network, and at consumer premises ensure that the grid is protected from under or over-frequency through measures such as controlled load shedding (58). Eskom also maintains supply and demand reserves to ensure that it can meet quick changes in demand during high- and low-demand periods. Many of the functions related to ensuring grid stability are known as ancillary services. Eskom groups the following activities under ancillary services (59):

- Reserves
- Black-start
- Unit islanding
- Reactive power supply and voltage control
- Constrained generation

3.4.2.4 Eskom utilities use control systems to maintain the stability of the grid. These control systems can be separated into three groups:

- Regulation-type systems
- Load-following generators
- Unit commitment

3.4.2.5 Unlike many other commodities, electricity in the grid cannot be kept aside until there is demand for it. It can be stored; however this is often only possible through a conversion to a different energy type and is accompanied by conversion and storage losses. Therefore, electricity supply and demand must be balanced in real-time and at all times to ensure that the grid operates at 50 Hz and 220/240 V. Various control systems maintain the stability of the grid. Regulation-type control systems manage the variability in the very short term – from a few seconds to five minutes. Regulation is typically done using automated systems based on generation that is online at the time. Load following is the medium-term control system. Load-following plants must be able to come online and address demand within a period of five minutes to a number of hours. Load-following plants (mid-merit plants) typically lie between peaking plants and baseload plants. Finally, unit commitment (typically baseload plants) refers to power stations that take up to several days to synchronise to the grid (14). Most of Eskom's coal-fired stations (baseload) are used as mid merit.

3.4.2.6 Eskom's 2020-2029 Transmission Development Plan (TDP) (60) outlines the role of Eskom's transmission network. The TDP states that the Eskom Transmission Network "supplies electricity at high voltages to a number of key customers and distributors. Eskom is a vertically integrated company licensed to generate, transmit, and distribute electricity in South Africa." The TDP further defines the role of the transmission system as transporting "electricity in bulk from where it is generated to load centres throughout South Africa and the region". This bulk transmission of electricity occurs at very high voltage (between 132 and 765 kV) and over long distances.

3.4.2.7 Distribution of electricity is the last-mile activity of delivering power to the customer (either a distributor or end-use customer). In their presentation (61) to the Energy Portfolio Committee, Eskom noted that distribution is split between Municipalities and Eskom. Historically, Eskom supplied electricity directly to areas that fall outside the old municipal boundaries and bulk electricity to municipalities, who in turn, distribute electricity to its customers within their municipal boundaries. Since 1994, new municipal boundaries were defined which now cover the whole of South Africa. This means that Eskom now supplies to many consumers within municipal boundaries. These areas have been licensed to Eskom by NERSA. Distribution network voltages vary between 1 and 132 kV but can also exceed 132 kV in certain cases.

3.4.2.8 Whilst Eskom has historically operated as a vertically integrated entity, President Ramaphosa stated in 2019 that Eskom would be unbundled into three separate entities for generation, transmission, and distribution (62) even though they would remain under a holding company owned by the state (63). The National Transmission Company South Africa (NTCSA) would become a wholly-owned subsidiary of Eskom and apply for a new licence to operate as a transmission company in 2022. The distribution and generation unbundling should have occurred by 31 December 2022.

3.4.2.9 It is envisioned that this unbundling would create competition in the generation space as power purchases would be done in a dynamic market with multiple generators (Eskom and non-Eskom) and buyers. This market-based electricity approach is seen in a number of other jurisdictions, such as the intra-day electricity purchases market in the European Union (64).

3.4.3 Global generation comparison

3.4.3.1 Section 3.2 illustrated the electricity generation by fuel type. Electricity generation incorporates the impact of some power plants that are not constantly operating at full capacity. In general, Section 3.2 represents the consumption of electricity.

3.4.3.2 The World Resources Institute (WRI) maintains a global database of power stations with each power station's installed capacity (i.e., generation capacity). Even though the WRI database is somewhat outdated (generation is estimated in 2017) it still provides insight into the typical split of installed electricity capacity by source. In Table 3.2 below, the installed capacity (MW) per generation type as well as the number of power plants for South Africa and the World is listed. The relative size of each category is compared to the total generation for both South Africa and the World.

Table 3.2: Electricity generation capacity in 2017 measured in gigawatts (GW) and number of power plants

Type of generation	South Africa (GW)	World (GW)	South Africa (number of power plants)	World (number of power plants)	South Africa*	World*
Coal	39.79	1 965.54	17	2 330	79%	34%
Gas	0.34	1 493.05	2	3 998	1%	26%
Hydro	2.02	1 053.16	6	7 156	4%	18%
Nuclear	1.80	407.91	1	195	4%	7%
Wind	2.03	263.05	24	5 344	4%	5%
Oil	2.07	261.88	2	2 320	4%	5%
Solar	2.31	188.31	44	10 665	5%	3%
Biomass	0.01	34.28	2	1 430	0%	1%
Waste	0.04	14.75	6	1 068	0%	0%
Geothermal	-	12.69	-	189	0%	0%
Cogeneration	-	4.05	-	41	0%	0%
Other	-	3.61	-	43	0%	0%
Petcoke	-	2.42	-	12	0%	0%
Storage	-	1.71	-	135	0%	0%
Wave and Tidal	-	0.55	-	10	0%	0%
Total	**50.42**	**5 706.98**	**104**	**34 936**	**100%**	**100%**

** installed capacity per generation type as a percentage of total installed capacity*

(Source: WRI database (13))

Table 3.3: Electricity generation capacity and energy production in 2017 measured in GW and GWh

Type of generation	South Africa (GW)	World (GW)	South Africa (GWh)	World (GWh)	South Africa#	World#
Coal	39.79	1 965.54	229 710	9 653 452	89%	41%
Gas	0.34	1 493.05	-	6 021 910	0%	25%
Hydro	2.02	1 053.16	3 582	3 541 441	1%	15%
Nuclear	1.80	407.91	13 237	2 902 412	5%	12%
Wind	2.03	263.05	5 933	689 101	2%	3%
Oil	2.07	261.88	100	500 808	0%	2%
Solar	2.31	188.31	5 929	347 580	2%	1%
Biomass	0.01	34.28			0%	0%
Waste	0.04	14.75	-	8 174	0%	0%
Geothermal	-	12.69		60 096	0%	0%
Cogeneration	-	4.05			0%	0%
Other	-	3.61		16 527	0%	0%
Petcoke	-	2.42			0%	0%
Storage	-	1.71			0%	0%
Wave and Tidal	-	0.55		-	0%	0%
Total	**50.42**	**5 706.98**	**258 491**	**23 741 501**	**100%**	**100%**

#electricity consumed as a proportion of total consumption

(Source: WRI database (13))

3.4.3.3 The marked increase in global renewable generation is evident when comparing Tables 3.1 and 3.2. When only wind and solar are considered, renewable generation increased from around 4% in 2017 to 13% of total generation in 2021. South Africa has also seen an increase in renewables but not to the same extent – renewables in South Africa have only increased from 4% to 7% of total generation. It should be kept in mind that overall electricity consumption in South Africa has also decreased over the last decade.

3.4.4 Eskom generation overview

3.4.4.1 Given that the figures in Tables 3.2 and 3.3 from the WRI are outdated, further detail was obtained from Eskom's annual reports and capacity tables to provide a view of the generation capacity at Eskom as at 2022. Eskom publishes a capacity table that specifies the generation and nominal capacity of each of their power stations at a point in time. The table below is based on Eskom's 1 June 2022 capacity table (12). Eskom splits their generation fleet into baseload and peaking stations.

Table 3.4: List of Eskom's power plants with associated installed and nominal capacity as at 1 June 2022

Name of station	Location	Total installed capacity (MW)	Total nominal capacity (MW)
Baseload stations			
Coal-fired (15)		**44 602**	**39 930**
Arnot	Middelburg	2 220	2 100
Camden	Ermelo	1 561	1 481
Duvha	Emalahleni	3 000	2 875
Grootvlei	Balfour	1 180	570
Hendrina	Middelburg	1 723	1 098
Kendal	Emalahleni	4 116	3 840
Komati	Middelburg	990	114
Kriel	Bethal	2 790	2 640
Lethabo	Vereeniging	3 708	3 558
Majuba	Volksrust	4 110	3 807
Matimba	Lephalale	3 990	3 690
Matla	Bethal	3 600	3 450
Tutuka	Standerton	3 654	3 510
Kusile	Ogies	3 196	2 880
Medupi	Lephalale	4 764	4 317
Nuclear (1)			
Koeberg	Cape Town	**1 934**	**1 854**
Total baseload		**46 536**	**41 784**
Peaking stations			
Gas/liquid fuel turbine stations (4)		**2 426**	**2 409**
Acacia	Cape Town	171	171
Ankerlig	Atlantis	1 338	1 327
Gourikwa	Mossel Bay	746	740
Port Rex	East London	171	171
Pumped storage schemes (3)		**2 732**	**2 724**
Drakensberg	Bergville	1 000	1 000
Palmiet	Grabouw	400	400
Ingula	Ladysmith	1 332	1 324
Hydroelectric stations (2)		**600**	**600**
Gariep	Norvalspont	360	360
Vanderkloof	Petrusville	240	240
Wind energy (1)			
Sere	Vredenburg	**100**	**100**

Other hydroelectric stations (4)		**61**	**2**
Mbashe	Mbashe River	42	-
First Falls	Umtata River	6	-
Ncora	Ncora River	2.4	2.4
Second Falls	Umtata River	11	-
Total peaking		**5 920**	**5 835**
Total generation (baseload + peaking)		**52 456**	**47 619**

(Source: Eskom's 1 June 2022 capacity table (12))

3.4.4.2 Eskom's 2022 Integrated Report (for the year ending March 2022) (19) notes that Eskom has 30 power stations with a total nominal capacity of 47 145 MW. This aligns closely with the Eskom's capacity table (Table 3.4) above, although the nominal capacity quoted in the Annual Report is slightly lower than what was quoted in the capacity table. The difference between installed capacity and nominal capacity represents Eskom's own power consumption and reduced capacity caused by the age of various power plants (12). For example, the Komati Power Station (which has since been decommissioned (65)), had only 114 MW nominal capacity of the total 990 MW installed capacity.

3.4.4.3 Eskom's Annual Report further indicates that IPPs have a total of 6 831 MW of generating capacity (not included in Table 3.4). A breakdown of the generation capacity of IPPs is indicated in Table 3.5 below.

Table 3.5: IPP nominal capacity at 31 March 2022

	Nominal capacity (MW)
Biomass	25
Concentrated solar power	500
Gas/liquid fuel	1 005
Hydroelectric	18
Landfill	8
Solar PV energy	2 212
Wind	3 063
Total	**6 831**

(Source: Eskom's 2022 Annual Report (19))

3.4.4.4 When aggregating the 6 831 MW of IPPs with Eskom's 47 619 MW, the total nominal capacity is 54 450 MW. This 2022 figure is close to 10% higher than the 2017 figure quoted by the WRI, assuming that the WRI figures included IPPs. Table 3.6 below provides a summary of the generation capacity of Eskom and IPPs.

Table 3.6: Summary of Eskom and IPP generation capacity at 31 March 2022

Owner	Source of fuel	Total nominal capacity (MW)	Proportion of total nominal capacity
Eskom	**Coal-fired**	39 930	73%
	Nuclear	1 854	3%
	Liquid fuel stations	2 409	4%
	Hydro & pumped storage	3 326	6%
	Wind	100	0%
IPP	**Biomass**	25	0%
	Concentrated solar power	500	1%
	Gas/liquid fuel	1 005	2%
	Hydro	18	0%
	Landfill	8	0%
	Solar PV	2 212	4%
	Wind	3 063	6%
Total nominal capacity		**54 450**	**100%**

(Source: Eskom's 1 June 2022 capacity table (12), Eskom's 2022 Integrated Report (19))

3.4.5 Eskom electricity generation and sales

3.4.5.1 According to Eskom's 2022 Integrated Report, Eskom generated 205 688 GWh during its 2022 financial year. The following table was extracted from Eskom's report and it disaggregates the 205 688 GWh into the various sources. In addition, it shows the electricity produced by Independent Power Producers (IPPs), imported electricity, and the amount of wheeled electricity (19).

Table 3.7: Electricity generation by source

Source (GWh)	2022	2021	2020
Coal-fired stations	184 568	183 553	194 357
Nuclear power	12 355	9 903	13 252
Pumped storage stations	4 743	4 795	5 060
Hydro stations	1 943	1 387	688
Open-cycle gas turbines (OCGTs)	1 826	1 457	1 328
Wind	253	305	283
Eskom generation	**205 688**	**201 400**	**214 968**
Pumping by pumped storage stations	-6 434	-6 625	-6 629
Net sent out by Eskom	**199 254**	**194 775**	**208 339**
Independent power producers (IPPs)	15 973	13 526	11 958
Imports	8 500	8 812	8 568
Wheeling	2 499	2 310	2 491
Energy available for distribution	**226 226**	**219 423**	**231 356**

(Source: Eskom's 2022 Annual Report (19))

3.4.5.2 Eskom's Annual Report (19) also provides a breakdown of electricity purchases by type of customer for 2022.

Table 3.8: Electricity purchases by type of customer

	Number of Eskom customers	Electricity sales (GWh)	Electricity sales (% of total)
Distributors	799	83 931	42%
Residential	6 833 928	10 520	5%
Commercial	52 736	9 872	5%
Industrial	2 601	45 120	23%
Mining	926	28 030	14%
Agricultural	77 692	5 382	3%
Rail	471	2 128	1%
International	11	13 298	7%
Total	**6 969 164**	**198 281**	**100%**

(Source: Eskom's 2022 Annual Report (19))

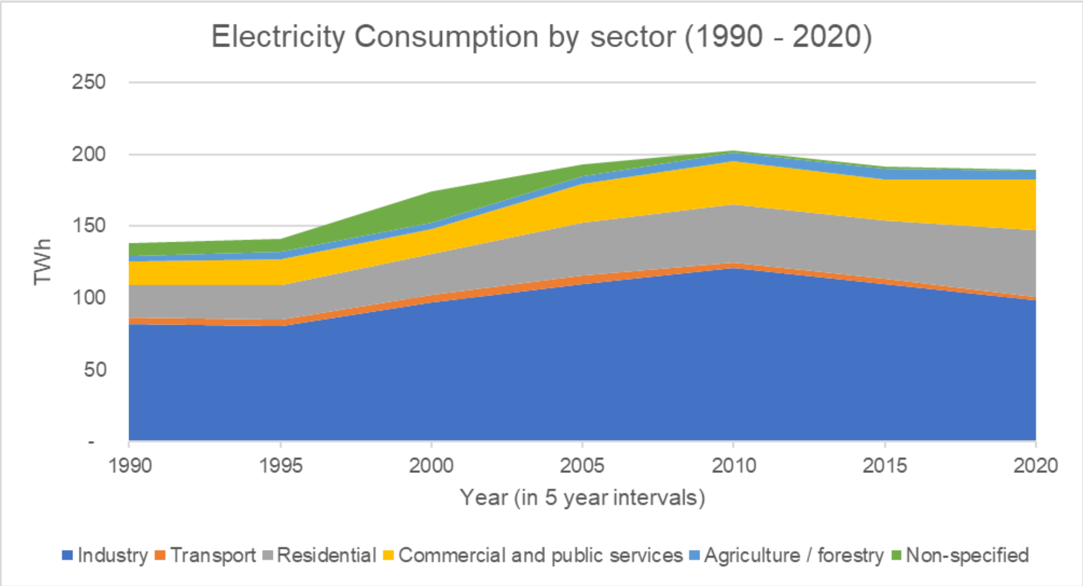
3.4.5.3 Distributors in Table 3.8 above refer to municipalities, who would typically distribute electricity and service residential customers within their municipal boundaries. The number of residential customers referred to in Table 3.8 includes customers that Eskom services directly, but excludes customers serviced by municipalities. Therefore, care should be taken when drawing conclusions from the above table. Furthermore, electricity purchases are not entirely reflective of total electricity consumption. Certain consumers (including municipalities) are able to generate their own electricity (through embedded generation) or purchase electricity directly from IPPs. These amounts are assumed to be excluded from Table 3.8.

3.4.5.4 Eskom also exports and imports electricity from neighbouring countries. The international electricity sales are noted under "International" in Table 3.8 above.

3.4.6 Electricity consumption by sector

3.4.6.1 While Eskom's split of data provides some insight into the electricity usage by different sectors of South Africa, it is still limited by Eskom's view of sales. In order to understand the underlying factors driving energy demand, it is helpful to consider various sectors of the economy and how changes in these sectors drive demand. Unfortunately, granular data at a sectoral level were not readily available. The International Energy Agency (IEA) provides data on electricity consumption by sector aggregated at five-year intervals. Together, the following graph and tables provide a sector-based view of electricity consumption in South Africa.

Figure 3.1: Electricity consumption by sector in five-year intervals (1990-2020)



(Source: IEA Electricity Consumption (66))

Table 3.9: South Africa's electricity consumption by sector (TWh) (1990-2020)

Year	Industry	Transport	Residential	Commercial & public services	Agriculture & forestry	Non-specified	Total
1990	82	4	22	17	4	9	**138**
1995	81	4	24	17	5	9	**141**
2000	97	5	29	17	4	22	**174**
2005	110	5	37	27	6	8	**193**
2010	121	4	41	30	6	2	**203**
2015	110	3	40	29	7	2	**191**
2020	99	2	46	35	6	1	**189**

(Source: IEA Electricity Consumption (66), converted from Terajoules to TWh)

Table 3.10: South Africa's electricity consumption by sector (percentage of total) (1990-2020)

	Industry	Transport	Residential	Commercial & public services	Agriculture & forestry	Non-specified	Total
1990	59%	3%	16%	12%	3%	7%	**100%**
1995	57%	3%	17%	12%	4%	6%	**100%**
2000	56%	3%	16%	10%	2%	13%	**100%**
2005	57%	3%	19%	14%	3%	4%	**100%**
2010	60%	2%	20%	15%	3%	1%	**100%**
2015	58%	2%	21%	15%	4%	1%	**100%**

2020	52%	1%	25%	19%	3%	0%	**100%**

(Source: own calculations, data from IEA Electricity Consumption (66))

3.4.6.2 The following can be noted from Figure 3.1 and Tables 3.9 and 3.10 above:

- The industrial sector accounts for the majority of electricity consumption at 52% of overall consumption in 2020. However, the industrial sector's share of the overall electricity usage has decreased from 2010 until 2020. When viewed as a proportion, the decrease in the industrial sector's share of electricity consumption is masked by the decrease in overall electricity consumption. Electricity consumption of the industrial sector decreased by close to 20% over the 2010-2020 period from 121 TWh to 99 TWh.
- In contrast, residential electricity usage has more than doubled in the period from 1990 to 2020. This is likely driven by Eskom's mass electrification campaign and the population growth from 1990 to 2020.
- The category of commercial and public services has also increased substantially over the period from 1990 until 2020 – in line with the increase in residential demand.
- The categories of transport, and agriculture and forestry represent a small portion of the total demand. However, transport is likely to become more substantial in future with a shift towards electric vehicles.

3.4.6.3 Eskom's sales data and the IEA data are compared in Table 3.11 below. To improve comparability, the following adjustments were made:

- Eskom's industrial and mining categories were aggregated to correspond to the IEA's industry category.
- Both Eskom's 'international' sales and the IEA's 'non-specified consumption' were removed.
- The IEA's transport category was mapped to Eskom's rail.

Table 3.11: Eskom electricity sales versus IEA electricity consumption as a percentage of total

	Eskom electricity sales (% of total)	IEA (% of total)
Distributors	42%	
Residential	5%	25%
Commercial	5%	19%
Industrial & mining	37%	52%
Agricultural	3%	3%
Rail	1%	1%
International	7%	0%
Total	**100%**	**100%**

(Source: own calculations, IEA Electricity Consumption (66), Eskom's 2022 Annual Report (19))

3.4.6.4 The figures from Eskom's electricity sales and the IEA as presented in Table 3.11, do not reconcile. This is primarily due to a lack of transparency in terms of sector usage within the distributors (municipalities). Ideally, data should be available at a more granular level.

3.4.6.5 Although Eskom supplies the majority of electricity in South Africa, there are a number of private power generators. Section 3.4.7 expands on private sector power generation.

3.4.7 Private power producers

3.4.6.6 South Africa has many private producers of electricity. These are entities that generate electricity for their own consumption or for resale. The entities that sell electricity either sell directly to (i) businesses or municipalities (distributors), or (ii) to Eskom for resale to its clients.

3.4.6.7 For purposes of this paper, the types of private generation capacity have been split as follows:

1. **Municipality-linked infrastructure**
   Certain municipalities have their own generation capabilities and facilities which they operate without Eskom intervention. These municipalities can optimise their usage of the Eskom grid by strategically generating electricity from their own facilities at certain times (e.g., when Eskom electricity is expensive or unavailable). It is worth noting that some of these facilities are not owned by the municipalities but by private consortiums of investors.

2. **Independent power producers (IPPs)**
   IPPs typically represent non-utility generators (i.e., not owned by Eskom) that sell power to Eskom by means of a power purchase agreement (PPA). The IPP awarding and contracting process has typically been by way of auctions, known as bid windows (67). The IPP programmes are further discussed in Section 5.4.1.

3. **Large-scale embedded generation**
   In this paper, large-scale embedded generation refers to projects that are not formally classified as IPPs (mainly due to being "behind-the-meter") but are larger than those projects typically referred to as small-scale embedded generation (SSEG). As referred to in Section 3.3.4 above, the removal of the generation limit for private producers has increased the ability of private entities to generate their own electricity.

4. **Small-scale embedded generation (SSEG)**
   SSEG is colloquially understood to refer to rooftop solar but can take the form of diesel generators, wind, and other alternative forms of small, embedded generation. The SSEG terminology is often used for installations that have installed capacities of under 1 MW.

3.4.6.8 Table 3.12 below provides a list of power stations indicated by WRI data that are not owned by Eskom. Although it is not clear whether all of these power stations are operational, the list is provided to give the reader a sense of the magnitude of existing installations in South Africa. SSEG has not been included in Table 3.12 as it will be discussed separately. Only installations with installed capacity of 75 MW and above were listed in Table 3.12.

Table 3.12: List of power stations not owned by Eskom (2017)

Power station name	Primary fuel	Installed capacity (MW)
Kelvin Power Station	Coal	600
Rooiwal Power station	Coal	300
Pretoria West Power Station	Coal	180
De Aar 2 North	Wind	144
Khobab Wind	Wind	140
Loeriesfontein 2	Wind	140
Cookhouse	Wind	139
Gouda Wind Farm	Wind	138
Jeffrey's Bay Wind Farm	Wind	138
Amakhala Emoyeni Wind Farm	Wind	134
Dorper Wind Farm	Wind	100
KaXu Solar Power Plant	Solar	100
Kathu CSP	Solar	100
Kathu Solar Park	Solar	100
De Aar Maanhaarberg	Wind	100
Xina One	Solar	100
Jasper Solar Power Plant	Solar	96
Tsitsikamma Community Wind Farm	Wind	95
Sishen Solar Power Plant	Solar	94
West Coast 1	Wind	94
Mulilo Sonnedix Prieska	Solar	86
Prieska Solar Plant	Solar	86
Adams Solar PV Project	Solar	83
Paleisheuwel Solar Power Plant	Solar	83
Pulida Solar Park	Solar	83
Noupoort Wind Farm	Wind	80
Red Cap	Wind	80
De Aar 3 Solar Power Plant	Solar	75
Dreunberg Solar Power Plant	Solar	75
Kalkbult Solar Power Plant	Solar	75
Konkoonsies II Solar Facility	Solar	75
Lesedi Solar Power Plant	Solar	75
Letsatsi Solar Power Plant	Solar	75
Solar Capital De Aar I	Solar	75

(Source: WRI database (13))

3.4.6.9 The total installed capacity listed on the WRI database in 2017 was 4 845 MW, excluding Rooiwal and Pretoria West Power Stations as they are assumed to be non-operational. However, according to an article published in 2022 (68), a significant number of new renewable generation projects are in the pipeline, as the "pipeline of embedded generation projects has more than doubled to 100 confirmed projects, with a total capacity of more than 9 000 MW, due to the removal of the licensing threshold for generation facilities". The total generation capacity that is in the pipeline is not definitively known due to the private nature of many of these projects, the speed at which facilities are being planned and constructed, and the removal of the formal approval process for embedded generation. Nevertheless, the point that should be emphasised is that any embedded generation coming online would assist in reducing the need for utility-based electricity generation.

3.4.6.10 While large industrial-scale renewable projects are sometimes publicly marketed, it is not clear what the overall size of small-scale rooftop solar PV is. Aradhna Pandarum has authored and co-authored a number of articles dealing with the challenge of estimating the impact of small- to medium-scale PV. In her 2018 conference paper (69), Pandarum highlighted the acceleration of rooftop PV between 2003 and 2017. She further projected installations to reach approximately 2.3 GW by 2025. Based on the increased levels of load shedding and price increases between 2018 and 2022, it is likely that this trend has accelerated. Pandarum's research was used as a basis for projecting embedded generation, which is discussed in Chapter 6.

4. Electricity technologies

4.1 Non-renewable electricity generation

4.1.1 Introduction

4.1.1.1 At the time of writing this paper, the majority of electricity (91% locally and 71% globally[10]) was generated by using non-renewable fuels to convert a chemical or nuclear energy source (through combustion or fission) to electricity. Non-renewable energy sources are usually not reliant on weather and can generate electricity regardless of the time of day or the season[11]. These non-renewable electricity generators are typically able to bring electricity generation online at the request of grid operators and these generation methods are often referred to as dispatchable generation. Cogeneration, the harvesting of excess heat released during energy intensive processes, is sometimes used to increase the efficiency of production plants. While cogeneration has not been considered in detail in this paper, it should be noted that cogeneration can improve efficiency of production plants substantially (70).

4.1.1.1 In this paper, the following non-renewable generation fuels will be discussed:

1. Coal
2. Oil
3. Gas
4. Nuclear

4.1.2 Coal

4.1.1.1 Coal (known as a solid fuel) starts its life as plant matter. This matter undergoes various stages of decomposition and is compressed under tremendous force to eventually become coal. Coal is ranked in terms of its energy content. Hilt's law notes that the deeper the coal seam, the higher the coal's grade. Below are the different types of coal ranked from lowest to highest grade (71):

[10] See section 3.2 above

[11] Except in extreme weather events that disrupt plant operations

1. Peat[12]
2. Lignite (carbon content between 25 and 35%)
3. Sub-bituminous coal (carbon content between 35 and 45%)
4. Bituminous coal (carbon content between 45 and 86%)
5. Anthracite (carbon content up to 97%)
6. Graphite

4.1.1.2 Of South Africa's coal reserves, 96% are estimated to be bituminous coal (72). According to the 2022 BP Statistical Review, South Africa produced close to 93% of all coal produced in Africa in 2021. With China (50%), India (10%), and Indonesia (8%) dominating the landscape, South Africa represents close to 3% of the global coal production. Coal can be mined using surface mining (such as opencast mining) or underground mining (such as longwall mining) techniques (71). South Africa has both opencast and underground coal mines (72).

4.1.1.3 To produce electricity, coal power stations burn coal to heat water into superheated steam under high pressure. The steam is then used to drive a turbine to generate electricity. Thus, electricity is generated by turning chemical energy (from coal) into thermal energy (superheated steam) into kinetic/mechanical energy (turning a turbine using the steam) which is then turned into electricity (using a generator) (73).

4.1.1.4 Coal and nuclear generators typically have slow ramp-up rates and are often used for baseload (74). In South Africa, coal power stations are the dominant source for electricity generation representing 86% of the fuel used for electricity generation (based on BP's Statistical Review). Globally, coal represents 36% of all fuel sources for electricity generation. This illustrates how highly reliant South Africa is on coal. Eskom had a total of 15 coal-fired power stations as of 1 June 2022 (see Table 3.4 for details relating to Eskom's coal fleet).

4.1.1.5 Coal power stations typically have long planning and construction times. A paper by Lee, Lee and Alleman (75), published in 2018, found that there was a 85% likelihood that a 1 000 MW coal power plant could be constructed within 64 to 68 months in a Korean context. This timeframe seems to be significantly shorter than the time it took to build the most recent coal power stations in South Africa. For example, construction on Medupi Power Station[13] (Medupi) started in May 2007. It was planned that Medupi would have full capacity by 2020 (implying a total build time of around 14 years) (76). However, Medupi was only fully operational by 2021 (77). Since becoming operational, certain design defects were identified at Medupi, which had to be fixed for the power station to run at full capacity. Then in August 2021 an explosion at unit four of Medupi took a portion of generation capacity offline (78) (79). The issues surrounding the Medupi Power Station have highlighted the immense challenges in the design, construction, and operation of large coal power stations in South Africa.

4.1.1.6 Various harmful by-products are produced during the coal mining and combustion processes. Based on a lifecycle assessment by the United Nations Economic Commission for Europe (UNECE) (80), coal produces the highest greenhouse gas (GHG) emissions by a significant margin when compared to other generation

[12] Technically not coal but considered as part of the "coal family" as it can be transformed into coal under the right conditions
[13] A 4 764 MW coal power station

methods currently used. Clean coal technologies provide a way of reducing the emissions during operation, however this does not include the embodied emissions that form part of the infrastructure (80) (81). Although this paper does not attempt to deep dive into the complex topics of greenhouse gases, environmental pollution, and global warming, it is still important to understand the carbon impact of different generation methods as this has a significant impact on any future planning of power generation plants. Some of the techniques used to de-carbonise coal generation include carbon capture and storage (CCS), use, and storage (CCUS), as well as high-efficiency low-emission (HELE) technologies.

4.1.1.7 In 2022, Eskom reported that their coal plants (excluding Medupi and Kusile) had an average age of 43 years (19), a number of their plants did not meet the required emissions standards, and many were approaching end-of-life. Many of the coal plants were designed with a 50-year lifecycle and a number of the plants that were built in the 1970s and 1980s are reaching the end of their planned lifecycles. Eskom plans on decommissioning over 8 GW[14] of nominal capacity by 2030 (30).

4.1.1.8 As Eskom's COO noted in Eskom's Annual Report (19), many of these plants have, since 2002, been operating above their design parameters (above 80% capacity). Eskom's COO also reported that the old age of these plants, the amount of stress placed on them, poor quality coal, inexperienced personnel and contractors, poor workmanship and a lack of maintenance, amongst other reasons, have contributed to the poor performance of Eskom's coal fleet (19). Together these factors contribute to what is known as boiler-tube failures (82), one of Eskom's "leading factors of unavailability of generation capacity" (83). Without going into the specific technical designs of coal boilers and the significant challenges in ensuring that boiler tubes are correctly repaired, it is sufficient to say that boiler-tube repairs can take a number of days during which time the generator is fully offline (84).

4.1.1.9 The performance of Eskom's fleet will be discussed in more detail in Chapter 5.

4.1.2 Nuclear

4.1.2.1 Electricity can be generated from nuclear energy in three ways – through nuclear fission (splitting of atoms), nuclear decay (as radioactivity reduces over time), or nuclear fusion (fusing of atoms) (85). Nuclear fusion is still in its infancy and requires additional research before it can be used as a source of energy for utility-scale electricity generation. Nuclear decay can be used for specific niche applications (such as for an atomic battery) but is typically not used for utility-scale generation. Globally, nuclear fission is currently the method used to generate electricity from nuclear sources and further reference in this paper to nuclear energy should be interpreted as nuclear fission, unless indicated otherwise.

4.1.2.2 Nuclear reactors produce electricity by converting atomic energy (typically using Uranium-235 as fuel) into thermal energy, thermal energy into kinetic or mechanical energy, and finally kinetic energy into electrical energy. This process (other than the atomic component) is similar to that of coal-based generation. Simply stated, the process of nuclear fission produces heat. This heat is then used to produce superheated steam which drives turbines. These turbines generate electricity by

[14] This comprises the following power stations: Arnot (2.1 GW), Camden (1.5 GW), Grootvlei (0.6 GW), Hendrina (1.1 GW), Komati (0.1 GW), and Kriel (2.6 GW)

turning generators (85). Various nuclear reactor designs are used across the world. A popular design, known as a Pressurised Water Reactor (PWR) was used at the Koeberg Nuclear Power Station in South Africa. PWR designs use higher pressure and therefore have higher thermodynamic efficiency than some other designs, such as boiling-water reactors (86).

4.1.2.3 Similar to coal-based generation, nuclear power stations typically have consistent power generation over time but have slow ramp-up rates. They are furthermore largely unaffected by general variations in weather. Therefore, these power stations are often used for baseload power generation (74) and are ill-suited to operate as peaking plants. Due to long operating lifetimes (usually between 20 and 40 years) (87) and high construction costs, nuclear plants require guarantees and long-term power purchase agreements (PPAs) to ensure commercial viability.

4.1.2.4 The full nuclear electricity generation cycle involves uranium mining, uranium enrichment, power generation, and the management and disposal of used fuel. As noted in Section 4.5 below, the GHG emissions of nuclear electricity generation are low in comparison to alternative non-renewable generation options. Most nuclear GHG emissions are incurred at the 'front end' of the process of nuclear electricity generation (i.e., during construction and mining).

4.1.2.5 Whilst nuclear energy presents a compelling case for electricity generation, it also has significant barriers to new generation; including technical and political challenges. There have been some significant nuclear incidents, such as Chernobyl (Ukraine), the Three Mile Island accident (USA), and Fukushima (Japan). These have raised concerns around safety and environmental impacts relating to nuclear power plants. Adding to the safety concerns is the difficult topic of how to deal with nuclear waste effectively and permanently; a problem which must still be solved (88) (89).

4.1.2.6 Nuclear power plant construction costs can be particularly high, especially with the significant safety and very specific technology requirements (88). In their 2011 paper (90), Carajilescov and Moreira analysed the construction time of PWR nuclear plants and estimated that construction would take approximately 80 months (6,6 years) for countries such as Germany, France, and Russia. They emphasised that countries which did not have the technology to build their own reactors would have to depend on foreign contractors and imported materials which often increased construction time and cost. The authors illustrated the potential for poor outcomes by providing a list of nuclear plants with excessive construction time. The excessive construction times ranged from 198 months (16½ years) for the MOCHOVCE-2 plant in Slovakia to 301 months (25 years) for the ANGRA 2 reactor[15] in Brazil (91).

4.1.2.7 Koeberg, South Africa's only nuclear power station, is located near Cape Town on the West Coast. Construction of Koeberg commenced in 1976 and the first unit was synchronised to the grid in 1984 (92). And although this 8-year construction period was slightly longer than Carajilescov and Moreira's estimate of 6,6 years, it was significantly shorter than some of the excessive construction durations indicated by the same authors.

4.1.2.8 Koeberg has two reactors, with an installed capacity of 964 MW and 970 MW, giving a total of 1 934 MW. Both of Koeberg's reactors have PWR-based designs.

[15] Construction started in 1976 and commercial operation was achieved in 2001.

Koeberg's reactors use fuel rods that are enriched with uranium dioxide (UO2) pellets containing gadolinium. Prior to 1997, Koeberg's uranium was produced locally and internationally. Since the closure of the domestic uranium enrichment facilities in 1997, Eskom has been obtaining its nuclear fuel on the international market (93). Koeberg's licence to operate expires on 21 July 2024, however Eskom has submitted a request to operate Koeberg for an additional 20 years, i.e., until 2044 (94).

4.1.2.9 The IRP 2010 (95) envisioned bringing a total of 9.6 GW of new nuclear generation onto the grid. This was planned as 1 600 MW every year from 2023 until 2029 with the exception of 2027. However, the 2019 IRP (30) backtracked on these plans and no new nuclear power stations were envisioned (96).

4.1.3 Liquid fuel generation (oil and gas)

4.1.3.1 One should note that the definition of gas is often used in a generic context. Different types of gases are typically used for heating and electricity generation (97):

1. Liquified petroleum gas (LPG)
2. Liquified natural gas (LNG)
3. Compressed natural gas (CNG)

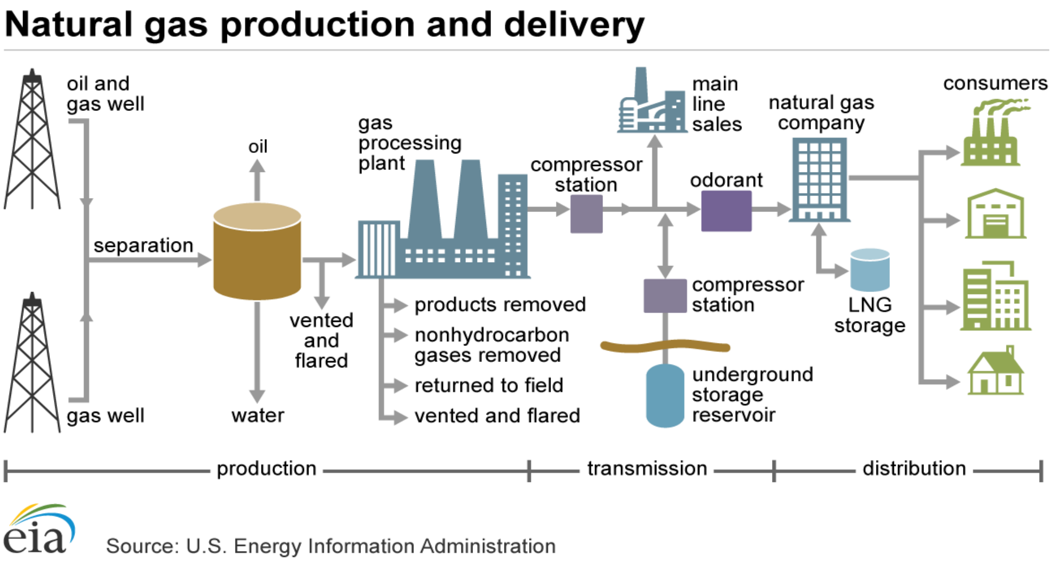
4.1.3.2 Natural 'wet' gas (before separation) is usually found deep underground; once separated, the methane (CH4) is termed natural gas. The composition of natural 'wet' gas can vary significantly and depends on the location, depth, and type of geological structure that it originated from. Gas can be found in large cracks between rocks, within tiny pores of certain sedimentary rock formations, or within oil wells. Gas can be found on land or offshore (98) (99). By cryogenically freezing natural gas to -161 ^{o}C, it compresses to LNG and becomes 1/600th the volume of natural gas. LNG requires special cryogenic tanks to ensure that the LNG remains in liquid form until it is required (100). CNG, however, is not frozen but rather compressed; it remains in a gaseous form when compressed and does not require cryogenic tanks.

4.1.3.3 LPG is produced by separating gases during the refinement of crude oil through a process of coal liquefaction (101), or as a by-product of natural gas refinement. LPG is comprised of propane (C3H8), butane (C4H10), propylene (C3H6), and butylene (C4H8), or a mixture of these gases (102). Once compressed, the gases liquify into LPG. LPG, LNG, and CNG are all gaseous at normal temperature and pressure (97).

4.1.3.4 LPG has more than twice the energy content of natural gas. CNG is typically compressed to a much higher pressure than LPG to compensate for the difference in energy content (97). CNG is often delivered to homes and businesses via pipelines and is critical to the energy systems of many countries worldwide. In this regard, Europe's reliance on CNG has been illustrated by the 2022 Ukraine-Russia war (103).

4.1.3.5 Figure 4.1 below neatly illustrates the process of the production and delivery of natural gas.

Figure 4.1: Natural gas production and delivery



(Source: EIA (99))

4.1.3.6 A detailed discussion of the full gas production and delivery cycle is outside the scope of this paper. However, it is important to note that, at the time of writing, South Africa had limited natural gas resources available.

4.1.3.7 As noted in Table 2.1, South Africa obtains only 3% of its energy from natural gas, compared to the World's 24%. South Africa has few proven oil and gas reserves – presently there is only one LNG producer, since many of the local refineries have closed down or stopped production. For example, PetroSA's gas-to-liquids (GTL) plant in Mossel Bay stopped operating in 2020 as the offshore gas fields that used to supply the plant, ran dry (104). Nowadays the plant is in maintenance awaiting potential future gas discoveries which could see it being restarted. It seems that Sasol's Secunda refinery is the only remaining local supplier of LPG in South Africa. The rest of South Africa's LPG is imported (105).

4.1.3.8 There was a recent trend towards offshore exploration for gas and oil reserves along South Africa's shores (106). Some oil and gas reserves have recently been discovered at the so-called Block 11B/12B prospects, approximately 175 km off the coast of the Garden Route (107). Successful extraction from these discoveries could enable PetroSA to restart its GTL plant. A predictable and stable gas supply could potentially be used for gas-based electricity generation leading to a reduction in cost when compared to the diesel-based generators currently used.

4.1.3.9 Halsey, Bridle, and Geddes (108) provide a perspective on the potential role of gas in the South African industry. The authors note that, at the time of writing (2022), "South Africa does not have gas-fired power" and that the supply of gas[16] in South Africa relies on imports piped from Mozambique to Mpumalanga, Gauteng, and

[16] Halsey, Bridle, and Geddes refer to natural gas in this context.

Kwazulu-Natal. They further state that there is “no existing infrastructure for large-scale liquefied natural gas (LNG) importation via the sea”. They conclude that new-build gas plants should not be considered and that renewable alternatives are better placed to provide bulk supply, peaking, and balancing functions.

4.1.3.10 Various designs are used for gas powered turbines. Three popular designs are (109):

1. Open cycle gas turbines (OCGT)
2. Combined cycle gas turbines (CCGT)
3. Combined heat and power systems (CHP)

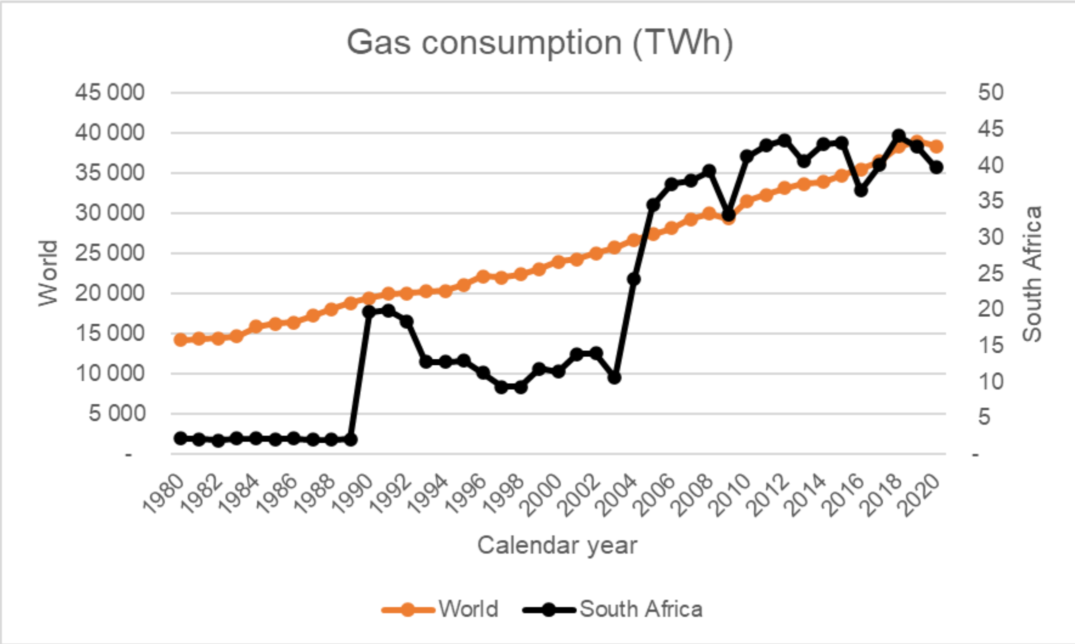
4.1.3.11 OCGTs are the most inefficient with CCGT and CHP-type generators utilising more of the energy released by the fuel with increasing efficiencies. While a large portion of this section is dedicated to gas generation, it should be noted that gas turbines can operate on various fuels, including oil-based derivatives (such as diesel).

4.1.3.12 As noted in Section 3.4.3, Eskom has four liquid fuel turbine stations. Of these, Ankerlig and Gourikwa (both in the Western Cape) use diesel as their primary fuel. Ankerlig (1327 MW) and Gourikwa (740 MW) provide a total of 2 067 MW of generation capacity (110). As opposed to coal and nuclear, OCGTs have quick ramp-up times and could synchronise with the grid within 5 to 7 minutes, reaching full load in as little as 12 minutes. Ankerlig and Gourikwa were designed to be converted to CCGT-based systems if a reliable supply of gas is obtained.

4.1.3.13 The other two liquid power stations, Port Rex and Acacia, with a generation capacity of 171 MW each, are significantly smaller than Ankerlig and Gourikwa. These power stations use kerosene as their main fuel. However, both Port Rex and Acacia operate mainly in what is known as synchronous condenser mode (SCO). SCO is used to assist with grid stability and to provide voltage regulation. For the interested reader, Eskom’s fact sheets provide further details on the technical specifications of each of these plants (111). SCO is simply one role that OCGTs play as part of Eskom’s grid management. OCGTs can also be used as emergency reserves, for example if there are unplanned capacity losses in the generation fleet.

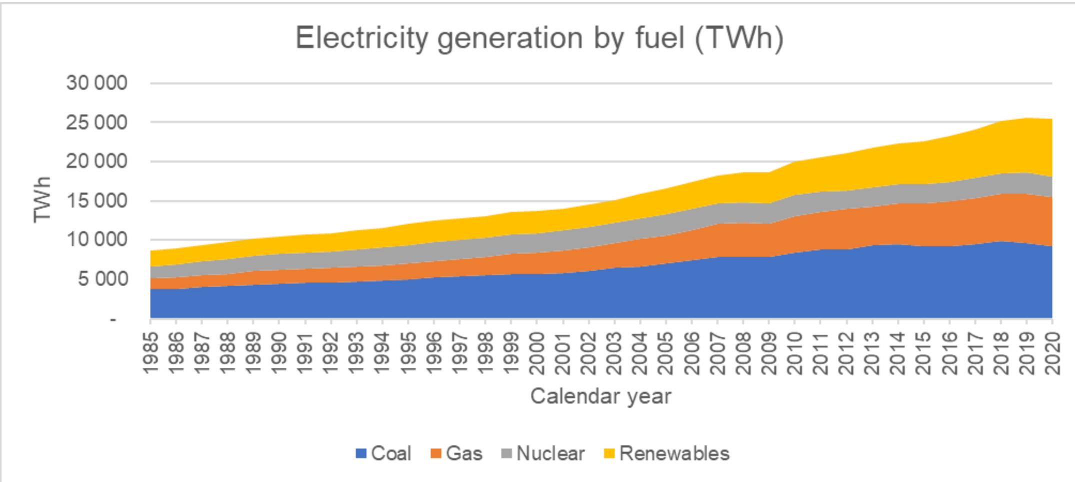
4.1.3.14 In Figure 4.2 below, South Africa’s gas consumption relative to the world is illustrated. While South Africa’s gas consumption has been increasing over time, it relates to uses other than electricity generation.

Figure 4.2: Gas consumption in South Africa and the World



(Source: own chart, data from Our World in Data (48))

Figure 4.3: Global electricity generation by fuel



(Source: own chart, data from Our World in Data (48))

4.1.3.15 Globally, electricity generation has been shifting from fuels that have higher GHG emissions (such as coal) to more environmentally friendly fuels (such as gas) (see Figure 4.3 above comparing the different sources of electricity generation over time). From 2010 to 2020 there was an increase in coal generation by 11%, gas by 30%, and renewables by 79%, whereas nuclear has decreased by 2%. In terms of non-renewable fuels, there is a clear shift towards gas. When compared to coal, natural gas-based generation has significantly lower GHG emissions (see Section 4.5 for lifecycle GHG emissions), much shorter build times (110) (1 to 3 years as opposed to 10 years+ for baseload plants), and potentially cheaper running costs (depending on the availability and price of gas). However, OCGT plants in South Africa have been significantly more expensive than coal-based generation (see Section 5.4 in this regard).

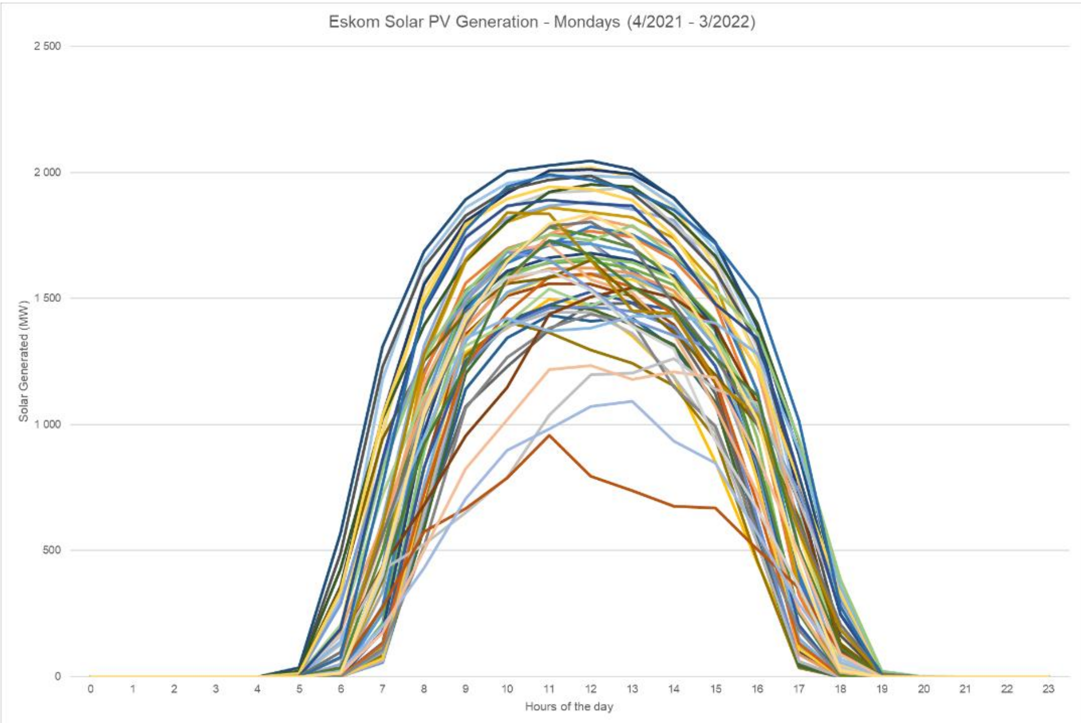
4.1.3.16 In terms of future generation capacity in South Africa, the 2019 IRP (30) proposed that 3 000 MW of additional gas generation be installed – split between 1 000 MW in 2023 and 2 000 MW in 2027. These projections and the IRP will be discussed in more detail in Chapter 5.

4.2 Renewable electricity generation

4.2.1 Renewable energy (RE) generation comes in many forms and, depending on the source of energy, the predictability of RE generation varies significantly. Renewable generation that is dependent on weather is usually variable in terms of the season and time of day and would typically be referred to as variable renewable energy (VRE) (112). However, there are also forms of renewables that are less variable and more alike to dispatchable generators, such as geothermal energy. A specific country's geography, abundance of natural resources, electricity infrastructure, and climate are some of the factors that impact the type of renewable sources that can be utilised efficiently.

4.2.2 Figure 4.4 illustrates Eskom's solar generation on successive Mondays from April 2018 to March 2019.

Figure 4.4: Solar generation by time of day from April 2021 to March 2022



(Source: own illustration based on Eskom data)

4.2.3 Figure 4.4 illustrates the variability of solar generation with regard to the time of day and season of the year. With longer days and more sunlight, solar PV typically generates more electricity during the summer compared to the winter. To ensure that demand is appropriately matched by supply, the specific technological characteristics of the generation ability of the generation technologies must be considered. Because the operational efficiency of PV panels usually decrease with heat, maximum generation from PV panels could be obtained on days when there is a combination of cool weather, clear skies, long hours of sunlight, and high solar irradiance (113). These periods might not always be in the middle of summer; they could be late spring or early summer or late summer or early autumn. The peak generation day in Figure 4.4 above was 29 November 2021. For the period under consideration (April 2021 to March 2022), 7 out of the 10 top solar generation days were in spring 2021 (October and November 2021).

4.2.4 The following is a non-exhaustive list of potential renewable energy sources:

- Wind
  - Moving:
    - Onshore
    - Offshore
  - Solid state[17]
- Solar
  - Thermal energy
  - Electricity generation:
    - Photovoltaic (PV)
    - Fixed
    - Tracking (single axis and dual axis)
    - Floating solar arrays
    - Agrivoltaic-based (e.g., using bifacial PV panels)
    - Concentrated solar power (CSP)
- Water
  - Wave
  - Tidal
  - Current
  - Thermal
- Hydro
  - Run-of-the-river (ROR)
  - Pumped storage[18]
- Biomass (plant materials)
- Geothermal

4.2.5 South Africa has substantial solar and wind resources – said to be some of the best in the world (114). Unfortunately, this is not true for hydro sources, and although South Africa has some pumped hydro and ROR hydro plants, the country is drought-prone, making hydro energy less appealing when compared to solar and wind energy. According to a 2021 Power Sector report (115), the same could be said about South Africa’s limited geothermal resources.

[17] Some examples of solid state wind include vortex induced vibration, resonant wind generation and electrostatic wind generation.
[18] In addition to providing generation and grid stability, pumped storage is also a form of energy storage.

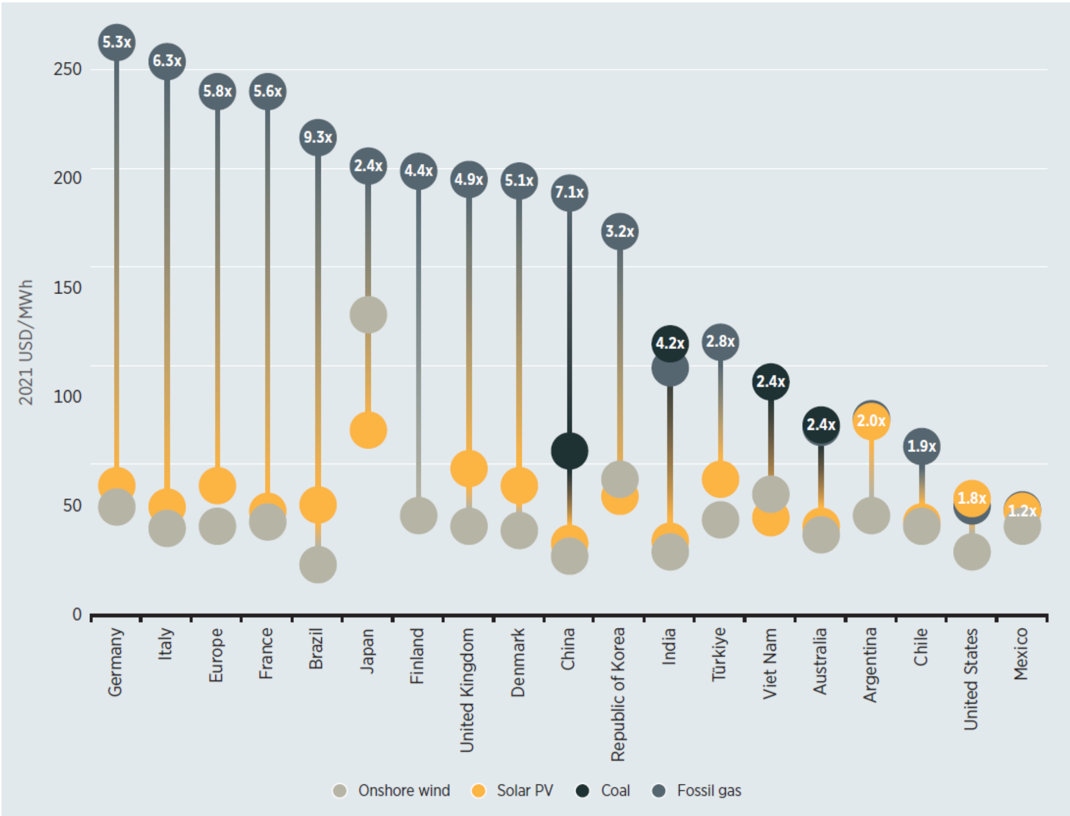
4.2.6 The International Renewable Energy Agency (IRENA) is a multinational intergovernmental agency that acts as a platform for international cooperation on the transition to renewable energy. In 2022, IRENA had 168 members, including the largest countries in the world (116). As South Africa is a member of IRENA, the agency developed a renewable energy roadmap (dated June 2020) for South Africa (117). Highlights from this document include:

- Renewables as a share of total electricity production could increase from 9% in 2015 to 49% in 2030.
- The two main power generation technologies could be onshore wind and utility-scale PV.
- The cheapest new-build generation options are solar PV and wind.
- The costs for all key energy commodities are expected to increase significantly between 2015 and 2030 (and further to 2050), pointing to a growing need to deploy alternative carriers (including renewables) to replace fossil fuels for heating and cooling, industry, and transportation.
- There is an abundance of solar irradiation and wind resources in South Africa. These resources are distributed across the entire country. South Africa has identified different renewable energy development zones (REDZs) where generation projects may be developed with minimal risk of disturbing the environment. The potential for solar PV and wind-based power generation is effectively unlimited, to a degree that supply can be integrated into the power system without risking grid stability. South Africa also has significant potential for further bioenergy deployment (from different resources) and some limited specific sites that are well-suited for small-size and medium-size hydropower generation.

4.2.7 The rest of this section will focus on wind and solar generation. Pumped storage will be discussed in more detail in Section 4.3.

4.2.8 In 2021, IRENA published a report (118) in which they discussed the costs of renewable energy. In section 1 of IRENA's report, various trends relating to the cost of generating electricity from renewable sources were highlighted. In particular, they compared the fuel-only generation costs for coal and gas relative to the levelised cost of electricity (LCOE) for new solar PV and wind commissioned in 2021 as shown in Figure 4.5.

Figure 4.5: USD per MWh (2021) relative to coal and gas



(Source: IRENA Power Generation Costs 2021 (118))

4.2.9 Unfortunately, IRENA did not include South Africa in the above comparison. However, when discussing the economic competitiveness of renewables, the general trend is insightful. Whilst there are a number of assumptions underlying the above analysis, it is clear that, for the majority of countries, the cost of constructing and operating renewables is significantly lower than operating (never mind constructing) existing coal and gas plants.

4.2.10 Furthermore, most renewables are not dependent on fuel sources that are by-products or that relate to industrial processes. Rather, renewables receive their fuel 'without cost' from nature. This 'free' source makes renewables particularly attractive as, once the initial capital outlay has been invested, the ongoing costs of renewables are often minimal.

4.2.11 With a global demand for cheaper additional electricity generation and an urgency to reduce GHG emissions, a move away from fossil fuels towards renewable energy sources seems inevitable (119). Whilst nuclear fusion shows promise, the technology is still in its early days and it is unclear how long it will take for nuclear fusion to become feasible for use in grid-scale electricity generation.

4.2.12 Some of the challenges (such as boiler-tube failures) faced by Eskom's coal fleet are partly addressed by solar and wind. Instead of a few large generators (coal boilers with turbines), solar and wind have thousands of smaller generators (solar panels and wind turbines). By diversifying electricity generation across smaller generators, different geographic areas, and types of generation, the overall unplanned outages of the system could be reduced. Thus, if there is a fault on a single panel or group of panels, it will have a smaller impact on the overall system. Furthermore, when compared to a coal boiler, solar is physically more accessible and provides cyclical downtime (overnight), during which defects can be quickly identified and addressed.

4.2.13 Renewables are not without their challenges, which include:

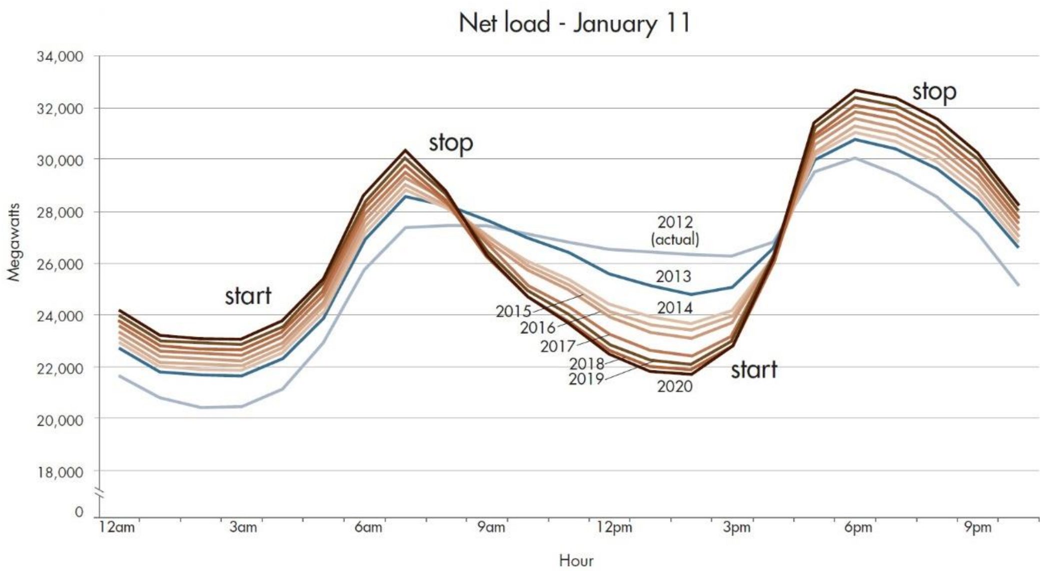
- Solar and wind energy rely on inverters to convert the electricity generated to match the operating parameters of the grid. These inverters do not provide the rotating mass inertia that is typically used to regulate frequency and reduce power fluctuations. To combat the lack of inertia, fast frequency response inverters can be installed.
- South Africa has some of the best wind and solar resources available. However, these resources are typically located in the western, and south-western parts of the country (mainly the Northern, Western, and Eastern Cape provinces) (120). These provinces are far from the north-eastern parts of South Africa where most of the industrial and mining activity occurs with associated electricity consumption. Because the transmission of electricity from the south-western to the north-eastern parts of South Africa is limited, it puts the grid under pressure and limits the installation of solar and wind generation facilities in the areas most suited for this generation (121). Long-distance transmission of electricity also results in transmission losses that further reduce the electricity available for distribution.
- To overcome grid congestion, individual entities could install renewables for their own consumption. Thus, mines and commercial entities could construct and operate their own solar and wind farms, however, this requires specialist skills, reduces economies of scale for large renewable producers, and adds to the overall cost of doing business.
- Based on the research done by Pandarum (69), households and businesses are investing in embedded generation at an accelerated rate. This presents a challenge for municipalities that have historically been reliant on revenue from electricity as a means to cross-subsidise other programmes. The per kWh tariff that municipalities charge is meant to recoup the cost of generation and part of the distribution infrastructure cost. Where electricity is fed back into the distribution network, municipalities must be able to appropriately plan and expand their distribution networks to manage the increase and reversed direction of power flow. Many municipalities are applying inclining block rate tariffs where the latter block prices significantly exceed the energy cost from Eskom. This practice exposes the municipalities to significant revenue losses as the incentive to install renewables increases. The Electricity Pricing Policy of South Africa (EPP) stipulates that tariffs must be cost reflective.
- If overall revenue from electricity reduces, the per kWh tariff must increase (or the fixed cost must increase), creating a loop of increasing tariffs and entities opting to reduce consumption. This could create a situation in which municipalities are not aligned with customers and are not incentivised to encourage the transition to renewables and distributed generation but might see the need to retain customers on grid power. This is a difficult political and social challenge that must be addressed upfront, if not, it could lead to a “municipal death spiral”[19] and a significant reduction in municipal revenue. There are alternative pricing models that can assist in reducing this risk. However, because end consumers are sensitive to changes in pricing, adequate buy-in must be

[19] Author’s own words.

obtained. Municipalities are now starting to apply cost reflective tariffs, and applying TOU energy rates for SSEG consumers, which limits the exposure to losses in the markup on the energy cost. By setting the buy-back (feed-in) tariff to be less than the avoided cost of Eskom bulk purchases on a TOU basis, the savings in purchase costs can largely off-set the losses in revenue. This encourages consumers to reduce consumption and sell power back to the utility during more expensive peak times.

- Energy sources classified under VRE typically include solar, wind, tidal, wave, and ROR hydro. VRE is challenging for a grid operator to include as part of the overall generation as VRE generation is often not aligned with demand. High levels of VRE require that the grid operator expand and upgrade transmission, distribution, and grid stability infrastructure (i.e., ancillary services). This creates challenges for the grid operator as it needs to focus on ensuring grid stability whilst managing variable generation. In extreme weather cases, VRE can also be unpredictable. For example, wind turbines have a certain rated speed and cut-out speed. At wind speeds between the rated speed and cut-out speed, they operate at full generation capacity, at wind speeds above the cut-out speed, they shut down (122). A grid operator must have sufficient reserve capacity to endure fluctuations of this kind, especially if renewable generators are concentrated in a small geographic area where they are all subject to similar weather conditions.
- As embedded solar PV generation increases, the electricity demand from the utility starts to reduce during the middle of the day. This characteristic curve is known as a “duck curve”. This is aptly illustrated in the dip during the middle of the day in Figure 4.6 below (123).

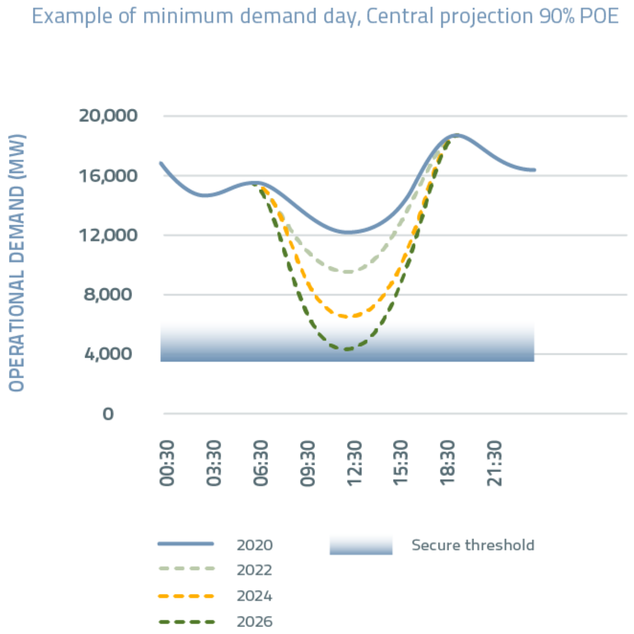
Figure 4.6: Electricity usage by hour on January 11 from 2012 to 2020 (California)



(Source: California Independent System Operator info sheet (123))

- Australia is one of the global leaders in terms of solar PV embedded generation (124). In a 2021 document (125) the Australian Energy Market Operator (AEMO) illustrated how this duck curve can create low operational demands during the middle of the day. This projection is shown in Figure 4.7 below.

Figure 4.7: Projected minimum demand by hour from 2020 to 2026 (Australia)



(Source: AEMO 2021 Electricity Statement of Opportunities (124))

These scenarios also create challenges for grid operators that must ensure stability during periods when demand is particularly low. Low demand scenarios create opportunities for grid operators to increase demand during these periods and take advantage of "cheap" electricity, such as pumping water for PHS systems or producing green fuels (such as hydrogen).

As noted above, one benefit of SSEG is that it not only reduces behind-the-meter demand; it also reduces the demand on the larger grid. Operators that allow feed-in can benefit by purchasing excess electricity from SSEG generators, even further reducing reliance on a central utility. Pandarum (69) notes that there are 34 municipalities in South Africa that have an approved registration process for SSEG PV. She also reports that there are seven municipalities[20] with a buy-back scheme to compensate customers for exporting energy onto the distribution grid.

4.2.14 In 2022, President Ramaphosa stated that "Eskom will develop rules and a pricing structure – known as a feed-in tariff – for all commercial and residential installations on its network". He further noted that there "is significant potential for households and business[es] to install rooftop solar and connect this power to the grid" (126). To increase the take-up of rooftop PV, allocating subsidies and structuring appropriate financing would assist in accelerating the rate at which homes move to embedded generation. In a Reuters article (127), the potential impact of SSEG PV based on the value of imported solar PV panels was noted when the article indicated that solar PV panels worth close to R2.2 billion and estimated to have a generating capacity equivalent to 500 MW, were imported during the first five months of 2022. The article further mentioned the missed opportunity of exporting the excess PV-generated electricity back onto the grid.

[20] These include City of Cape Town, Theewaterskloof, EThekwini, City of Tshwane, City Power, Nelson Mandela Bay, Overstrand.

4.2.15 Germany is a country with much poorer solar resources than South Africa (120), yet, during the first nine months of 2022, Germany added around 5.6 GW of solar (128). Germany has also provided significant subsidies; it is now also subsidising the installation of balcony solar modules (129).

4.2.16 Power-to-X (PTX) is a concept that encompasses a wide range of applications that can be used to turn electricity into a different form of energy (such as hydrogen) (130). Therefore, while the duck-curve poses a challenge for grid operators, this can be overcome by implementing smart approaches to energy demand and storage (such as PTX). Energy storage technology is dealt with in more detail in Section 4.3.

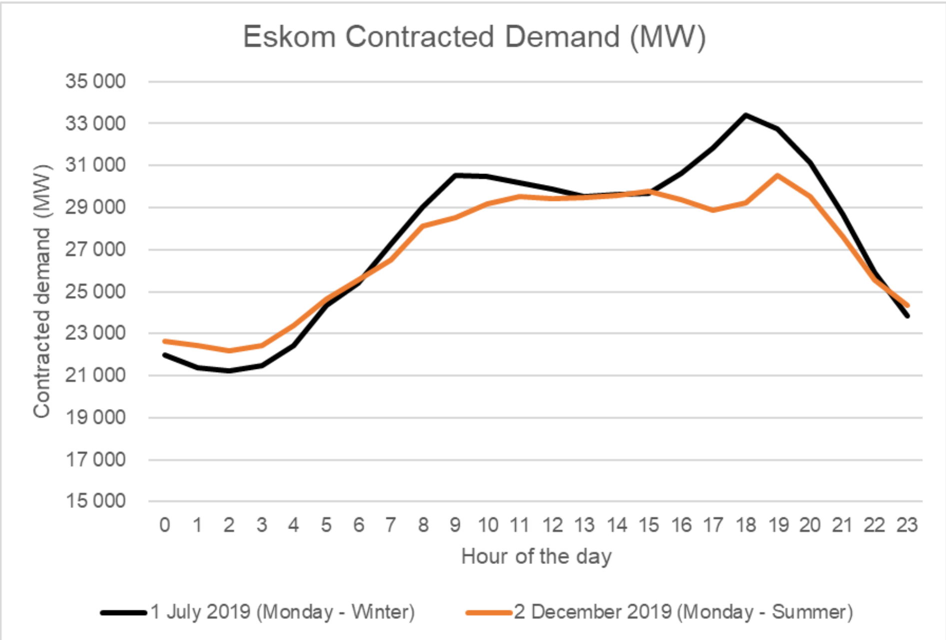
4.3 Electricity storage technology

4.3.1 Electricity is not stored in its electrical form but rather converted to potential or kinetic energy in other forms. Then, when there is a demand for electricity, the stored energy is converted back into electricity and supplied to the grid.

4.3.2 As variable renewable energy (VRE) penetration on the South African grid increases, electricity generation will become increasingly weather-dependent. In turn, this will emphasize the importance of storage. Even in a world without renewables, the existence of pumped storage systems illustrates the need for strategically shifting excess electricity generation in one period to match electricity demand in other periods. Pumped hydro storage (PHS) works by pumping water into an upper reservoir during periods when there is excess generation capacity and reversing the flow of water from the upper to the lower reservoir during periods with peak demand for electricity.

4.3.3 South Africa has a clear electricity demand curve with twin peaks in the morning and evening. The following graphs (based on Eskom's 2019 data), illustrate the changing demand over a period of 24 hours. Two Mondays were chosen in 2019 (1 July 2019 and 2 December 2019) to illustrate the hourly demand in winter and summer.

Figure 4.8: Eskom contracted demand in MW per hour

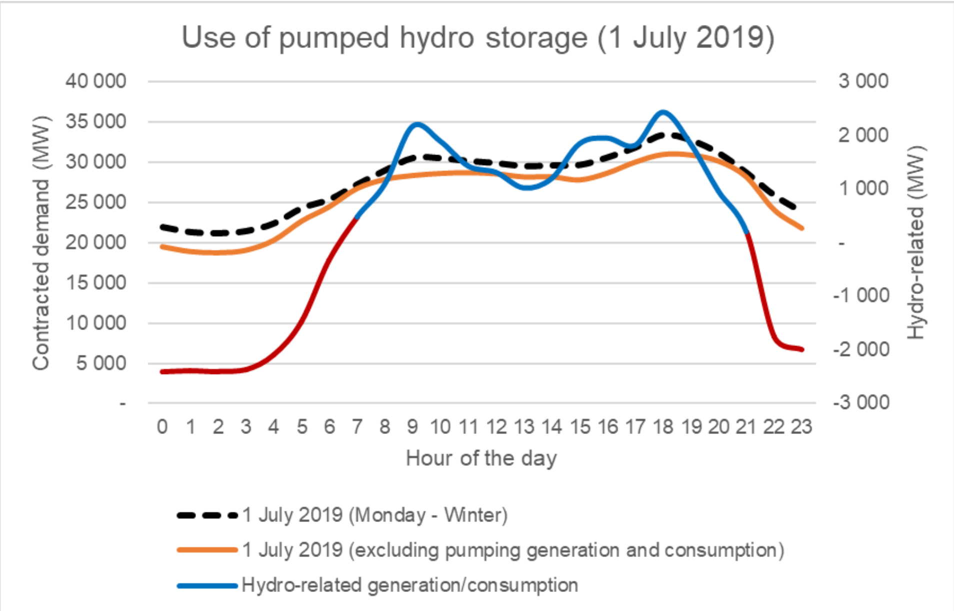


(Source: own illustration, based on 2019 Eskom data)

4.3.4 From Figure 4.8 it can be noted that:

- Demand peaks twice a day at 9:00 and again at around 18:00.
- Demand is slightly lower in the middle of the day and at its lowest in the late evening and early morning.
- Assuming the above is representative of the typical summer and winter demands, winter peak demand is substantially higher than summer peak demand, which is most likely driven by increased heating requirements.

Figure 4.9: Pumped storage generation and consumption compared to overall demand



(Source: own illustration, based on 2019 Eskom data)

4.3.5 From Figure 4.9 the following can be noted:

- The dashed line illustrates the demand as shown in Figure 4.8. The orange line represents the same demand without the generation contribution and the pumping demand from hydro and pumped storage. The red and blue line represents the net hydro-related generation and consumption (for pumping water to the upper reservoirs). The red portion of the line represents the pumping whereas the blue portion represents the generation.
- Hydro and pumped storage are used to supplement the baseload power plants during peak demand periods. This is why these plants are sometimes referred to as peaking plants.
- The dotted line, aligned with the secondary axis, indicates how hydro is used to generate electricity during the daily peaks and reversed at night to pump water back to the upper reservoir.

4.3.6 Even in the current electricity system (without high VRE penetration), it is clear that storage is important to improve efficiency and to reduce the need for building oversized baseload power stations (or substantially more OCGT plants). This system works on the basis that there is sufficient overall generation to meet the average demand over an extended period and that additional generation is required for peak demand. When viewed in isolation, PHS comes at a net cost as there are losses in pumping and generation. There is an industry concept of round-trip efficiency. Simplistically, round-trip efficiency can be described as the losses incurred in converting electricity to a different form and back again. PHS has been estimated to have a round-trip efficiency of approximately 80% whilst lithium batteries typically have round-trip efficiencies of above 90% (up to 96% in some cases) (131).

4.3.7 Pumped storage is popular as it offers long-term storage that is not particularly reliant on weather and that can be dispatched by the operator at will (assuming that sufficient water is available in the upper reservoir) to match generation and demand. VRE often has a mismatch in generation and demand – the sun does not shine for 24 hours and the wind does not blow consistently. Hybrid systems, such as pumped storage coupled to a floating solar installation, could also be more effective in matching demand and supply. The key to an effective storage system is to charge the storage with excess generation during periods with low electricity demand and high generation potential.

4.3.8 Energy storage can take many forms and some particularly innovative solutions are being developed in this field. Here is a list with current and future energy storage solutions:

- Pumped hydro storage (PHS)
- Battery storage (e.g., lithium battery, flow battery, liquid metal battery, supercapacitors)
- Concentrated solar power (CSP)
- Thermal energy storage (e.g., molten salt, water, ice, sand, brick, rock)
- Deep sea pumped hydro storage (StEnSea)
- Buoyancy Energy Storage Technology (BEST)
- Compressed air storage
- Chemical storage (e.g., hydrogen, methane)
- Kinetic storage (e.g., flywheel)
- Gravity storage
- Superconducting magnetic energy storage (SMES)

4.3.9 Depending on the specific needs, storage can be implemented at various grid levels. A 2017 report (131) by IRENA highlights some potential applications, these include integrating energy storage at the following levels:

- Grid-scale balancing
- Grid-scale bulk storage
- Distributed storage
- Commercial storage
- Thermal storage
- Residential storage

4.3.10 In each case the storage technology must be matched to the application. For example, PHS is not appropriate for residential customers, but would often be better suited to a distributor or utility. Different battery chemistries favour certain discharge and recharge cycles (131). Therefore, a detailed design specification should be drawn up based on the specific application. It is often not a single storage technology but a hybrid approach that can provide the most cost-effective, reliable, and appropriate energy storage solution for a specific application.

4.3.11 As noted in Table 3.4, Eskom currently has 3 PHS schemes in operation, providing a total of 2 724 MW of nominal generating capacity. Eskom also has a number of hydroelectric stations that can provide storage (assuming sufficient rainfall). Furthermore, IPPs have developed 500 MW of CSP; a form of generation and storage.

4.3.12 Eskom has embarked on a battery storage project, known as Battery Energy Storage System (BESS). In Eskom's Annual Report (19), the COO notes that the first phase of 800 MWh of BESS is forecasted to be completed by June 2023 and the second phase of 616 MWh by December 2024. As part of the same project, 60 MW of PV capacity will be added to the system.

4.3.13 A general move towards energy storage has various direct and indirect implications for generators and users of electricity. Some of these impacts include (132) (131):

- Increased awareness – when investing in storage, users and generators analyse electricity generation and consumption patterns as part of the due diligence process. This means they can often identify potential efficiency improvements and highlight options for electricity users to shift their loads to times when there is excess generation capacity and so take advantage of cheaper electricity pricing, or simply replace inefficient appliances with energy efficient versions.
- Certainty of supply – load shedding has become a challenge for South African entities that are reliant on a stable and uninterrupted power supply. Storage allows users to continue business as usual in the absence of grid connectivity.
- Pricing arbitrage – as pricing models become more sophisticated in dealing with the variability of certain energy sources and as the grid operator is able to offer competitive feed-in tariffs for users that produce excess electricity, storage becomes advantageous as it can be used to increase grid stability and provide revenue for storage operators.
- Peak shaving – grid operators can incentivise consumers to reduce their peak load through appropriate pricing (e.g., time-of-use tariffs). Storage can be used by consumers during peak times to alleviate the increased pricing.
- Load levelling or energy shifting – storage can be used as an alternative or supplement to peaking power plants to assist with peak demand. Storage can be 'charged' during periods of low demand and utilised during periods of high demand.
- Seasonal storage – certain geographic areas (such as the arctic areas) require seasonal storage. This allows the grid operator to store energy in the months in which excess generation is available. During the seasons when there is high demand or insufficient generation, the stored energy could be used to generate additional electricity.
- Reduced grid-reliance – some areas do not have grid connections or it would be too costly to obtain; storage combined with self-generation would provide those consumers with a source of reliable electricity. These electricity sources are sometimes referred to as community storage, village electrification, nano-grid applications, off-grid applications, and island electrification.

- Cost savings – in some cases, own generation coupled with a storage system can be more cost effective than using grid power.
- Reduced transmission losses and transmission load – transmission losses can be sizable if power generators are located at a significant distance from electricity users. In these cases, behind-the-meter power generation coupled with storage would reduce both the distribution and transmission load, providing capacity on the grid to other users. With strategic feed-in and consumption times for storage (i.e., flattening out demand over time), a fixed amount of transmission capacity can provide substantially more electricity without having to immediately embark on large transmission projects. This can be effective in areas where transmission capacity is at a premium or additional generation capacity is urgently required.
- Increased ability to offer ancillary services – these services would include enhanced frequency response, emergency reserves, etc.
- Grid storage is critical when moving towards a "smart grid" – certain examples of smart grids include using the batteries in electric vehicles (EVs) to supplement the grid during times when EVs are not being driven. For example, to reduce grid congestion, a consumer could use the power from their EV batteries to power their homes during peak times.

4.3.14 As generation and storage of power are being decentralised, it provides an opportunity for grid operators, with appropriate permission, to optimise the resources available in the private sector to manage the grid. Using advanced demand and supply controls, a grid operator can form a Virtual Power Plant (VPP). A VPP is formed by combining renewable energy sources, power storage, and controllable loads. By combining generation, storage, and load, utilities and consumers can benefit through optimisation of the grid. By connecting these systems to a centralised operator, electricity trading markets can be constructed, these markets would then be able to sell excess generation and reduce load at times when there is insufficient generation (133).

4.3.15 As VPPs could allow for more advanced grid management, they would enable operators to implement an optimisation approach known as virtual power lines (VPLs). VPLs reduce grid congestion and allow large-scale VRE capacity additions by intelligently storing and distributing electricity throughout the day. Rather than transporting electricity at the time of generation, VRE generators store the energy for transmission at times when the grid is less congested – this is sometimes known as supply side-storage. Demand-side storage can assist by reducing load during times of high grid congestion. A 2020 report (134) by IRENA indicated that, as of 2019, a number of countries are piloting VPL projects with total storage capacity of 3 GW under consideration.

4.3.16 According to the IEA, a total of 6 GW of grid-scale storage was added globally in 2021. The IEA projects that, in a net zero scenario, grid-scale storage capacity must increase 44-fold between 2021 and 2030 to a total of 680 GW. This would mean an annual addition of an average of 80 GW per year over the period from 2022 to 2030 (135).

4.4 Demand-side management

4.4.1 The above sections have mostly focused on supply-side interventions and how different forms of generation and storage can be adapted to suit the demand of users. Energy storage is a hybrid between supply and demand as it can fulfil both generation and load-shifting roles. Pure demand-side management focuses on how incentives and controls can be used to reduce both peak and overall electricity demand. Initiatives that are typically used to reduce electricity demand include:

- Load shedding – a form of rotational blackouts (referred to as Manual Load Reduction (MLR) by Eskom (18))
- Load reduction – requesting / controlling demands on the customer-side (referred to as Interruptible Load Shed (ILS) or Interruption of Supply (IOS) by Eskom (18))
- Load- / peak-shifting – shifting the use of certain appliances to times when there is less demand
- Automation of certain activities (e.g., charging of electric vehicles) – by automating activities that are otherwise dependent on human input, those activities can run during periods with the lowest demand (typically late evening)
- Minimum efficiency requirements of appliances – implementing regulations to restrict the sale of appliances that do not meet a minimum energy efficiency threshold
- Subsidies – subsidising energy efficient technology could help increase the take-up and subsequently reduce the overall electricity demand
- Size of connection – reducing the size of connections restricts customers to a maximum load
- Pricing – when pricing is appropriately implemented and communicated it can incentivise efficient behaviour
- Educational initiatives – educating the public can assist in reducing or shifting demand
- Substitution – for certain applications, customers are able to substitute electricity for other fuels, reducing the load on the grid[21]
- Minimising grid losses

4.4.2 Some of these approaches are more analogue whereas others require substantial digitalisation of the current technology. While wide-scale digitalisation can bring about considerable benefits, policymakers should be aware of the risks of technology lock-in and ensure that the technologies remain competitive in an ever-changing landscape. This needs to be balanced with regulatory and policy certainty to incentivise long-term capital investment (136).

4.4.3 More advanced grid management techniques, such as VPPs and VPLs, are only possible when advanced measurement, monitoring, and control technologies are in place (i.e., through digitalisation efforts). These new technologies would also only make a marked difference if a critical mass of users are willing to buy into them. According to the diffusion of technology theory these critical users are the innovators (2.5%), early adopters (13.5%), and early majority (34%). To build the trust of the early majority it is necessary to illustrate success stories from the innovators and early adopters (137). Therefore, a clear narrative is required for individual electricity users to be willing to adapt their behaviour. Feedback loops providing real-time grid information to these users through internet-based platforms (such as smartphone apps) can have a substantial impact on building trust. With sufficient traction, network effects can quickly change behaviour in large-scale distributed systems.

[21] This can be a contentious point when introducing fossil fuels. Many climate change advocates recommend that society should be increasing electrification rather than substituting electrical demands for fossil fuel-based alternatives (such as gas).

4.4.4 Eskom's recent move to install Internet of Things (IoT) devices on its network is a step in becoming a data-driven entity (138). Implementing VPPs and VPLs could become an option once these devices and the necessary smart meters provide a granular view of electricity supply and demand. This puts Eskom on the path towards becoming what is known as a smart grid operator (139).

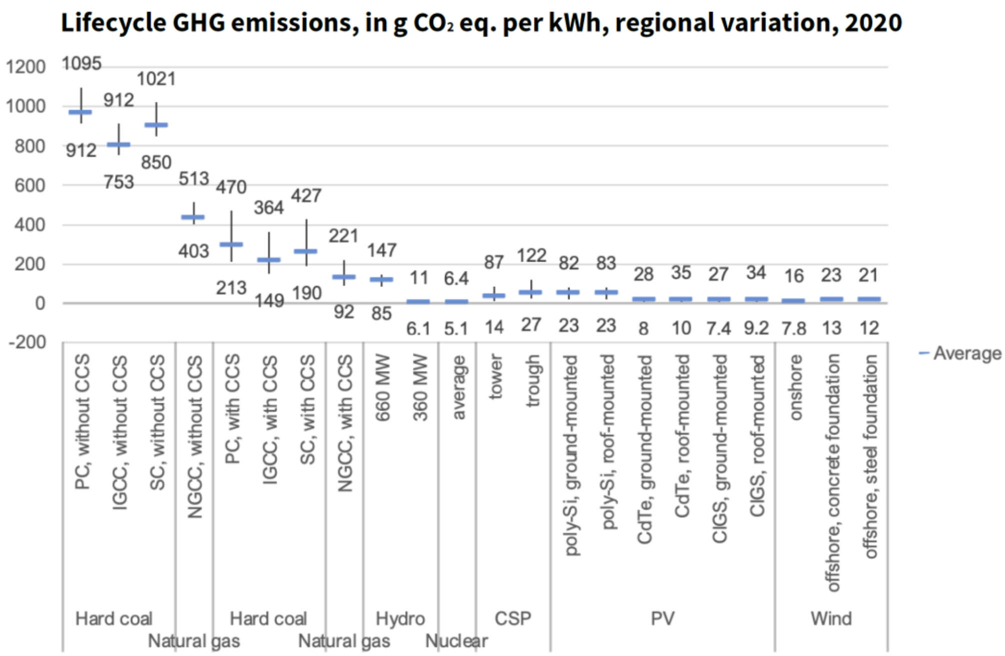
4.5 Greenhouse gas emissions

4.5.1 The "greenhouse effect" has been identified as the major cause of a rise in global warming since the twentieth century (140). Fossil fuels have been identified as the main contributor to climate change. The United Nations (UN) attributes over 75% of greenhouse gas (GHG) emissions to the use of fossil fuels. Furthermore, the UN estimates that fossil fuels produce nearly 90% of all carbon dioxide emissions. While this paper does not intend to provide a detailed insight into the mechanics of a transition to a low carbon economy, it is important to be aware of the GHG emissions of each electricity generation fuel type as this impacts the viability of financing and constructing new power plants. In this section some considerations relating to GHG emissions and the potential impact on new generation projects are highlighted.

4.5.2 One of the ways countries aim to combat climate change is by transitioning their electricity systems to renewable sources (141). As these countries are looking to drive down global emissions, they are less inclined to provide financing for fossil fuel-based electricity generation. A clear example of this is the recent €600 million in financing that France and Germany provided to South Africa to "support SA's transition from coal" (142).

4.5.3 The graph below, sourced from a report by the United Nations Economic Commission for Europe (UNECE) (80) on life-cycle assessment of electricity sources, highlights the cradle-to-grave GHG emissions for different generation sources.

Figure 4.10: Lifecycle GHG emissions across various generation technologies



(Source: (80))

4.5.4 When considering Figure 4.10 above and further commentary in the UNECE report, the following should be noted:

- Hard coal without carbon capture and storage (CCS) produces the highest GHG emissions by a significant margin.
- Natural gas without CCS produces around half of the GHG emissions of hard coal without CCS. Interestingly, hard coal with CCS produces less GHG emissions than natural gas without CCS – emphasising the importance of carbon capture technology.
- For renewable technologies, most of the GHG emissions are embedded in the construction of the infrastructure.
- Nuclear has the lowest GHG emissions. However, there are a number of issues related to the disposal of nuclear waste that must still be considered. These issues are not explicitly considered in the analysis done by the UNECE.

4.5.5 South Africa has taken various steps to reduce its GHG emissions. Being a party to the Paris Agreement, South Africa must establish a climate action plan, known as the Nationally Determined Contribution (NDC), and update it every five years (143). South Africa submitted its first NDC in September 2015 and updated it in September 2021. The 2021 NDC highlights that South Africa has taken the following steps to curb its GHG emissions (144):

- Declared GHG emissions as air pollutants under the National Environmental Management Act
- Adopted a Green Transport Strategy in 2018
- Established a Presidential Climate Commission to oversee a just transition together with a Just Transition Plan
- Drafted the Climate Change Bill
- Advanced the planning for the decarbonisation of the electricity sector with the gazetting in 2019 of an updated IRP that considers climate change mitigation amongst multiple objectives and that allocates large shares of the future energy mix to renewable energy technologies
- Acknowledged that implementing the NDC will require South Africa to implement its IRP (updated in 2019), which contemplates investment in largely renewable energy over the next decade.

4.5.6 As mentioned above, the Presidential Climate Commission (PCC), set up in December 2020, designed a Just Transition Framework for South Africa. According to the Just Transition Framework PCC report (119) a 'Just Transition' is defined as follows:

> A just transition aims to achieve a quality life for all South Africans, in the context of increasing the ability to adapt to the adverse impacts of climate, fostering climate resilience, and reaching net-zero greenhouse gas emissions by 2050, in line with best available science.
>
> A just transition contributes to the goals of decent work for all, social inclusion, and the eradication of poverty.

A just transition puts people at the centre of decision making, especially those most impacted, the poor, women, people with disabilities, and the youth—empowering and equipping them for new opportunities of the future.

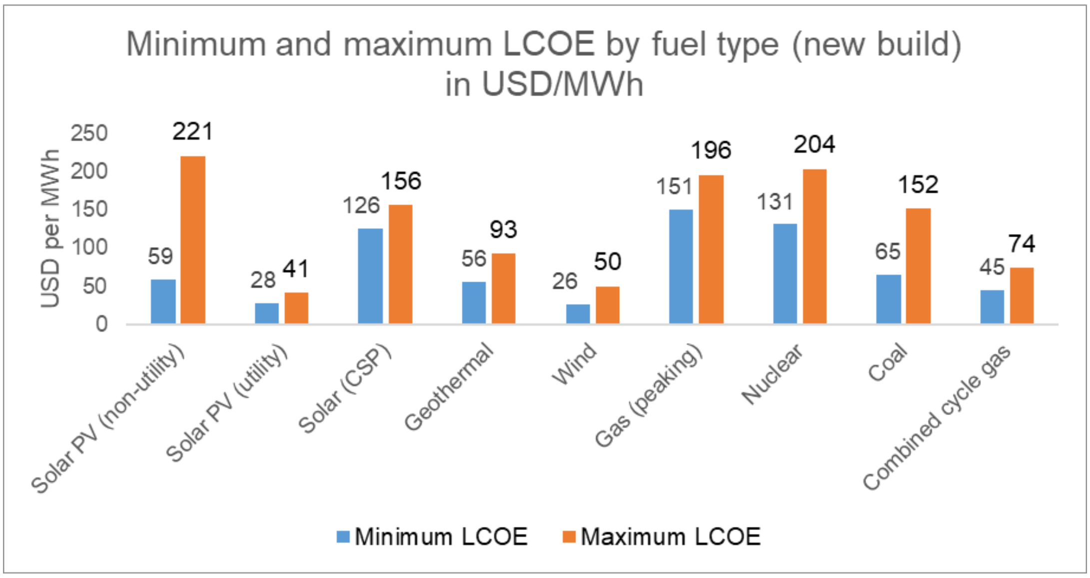
A just transition builds the resilience of the economy and people through affordable, decentralised, diversely owned renewable energy systems; conservation of natural resources; equitable access of water resources; an environment that is not harmful to one's health and well-being; and sustainable, equitable, inclusive land-use for all, especially for the most vulnerable.

4.6 Costing

4.6.1 A US-based financial advisory and asset management firm, Lazard[22], performed levelised cost analyses for generation, storage, and hydrogen production (145). From a generation perspective, Lazard analysed the levelised cost of energy for new-build power plants across both conventional and renewable energy. They also performed an analysis of the marginal cost (i.e., fuel and operational expenses) of operating fully depreciated conventional generation (i.e., coal, nuclear, and gas). The sensitivity of competitiveness of various renewables with respect to changes in subsidies (for the United States), fuel prices, carbon pricing, and cost of capital were furthermore analysed. Finally, they considered geographic location and dispatchable characteristics of various electricity generators (146).

[22] https://www.lazard.com/

Figure 4.11: Levelised cost of energy (LCOE) (2021)



(Source: own chart, Lazard data (146))

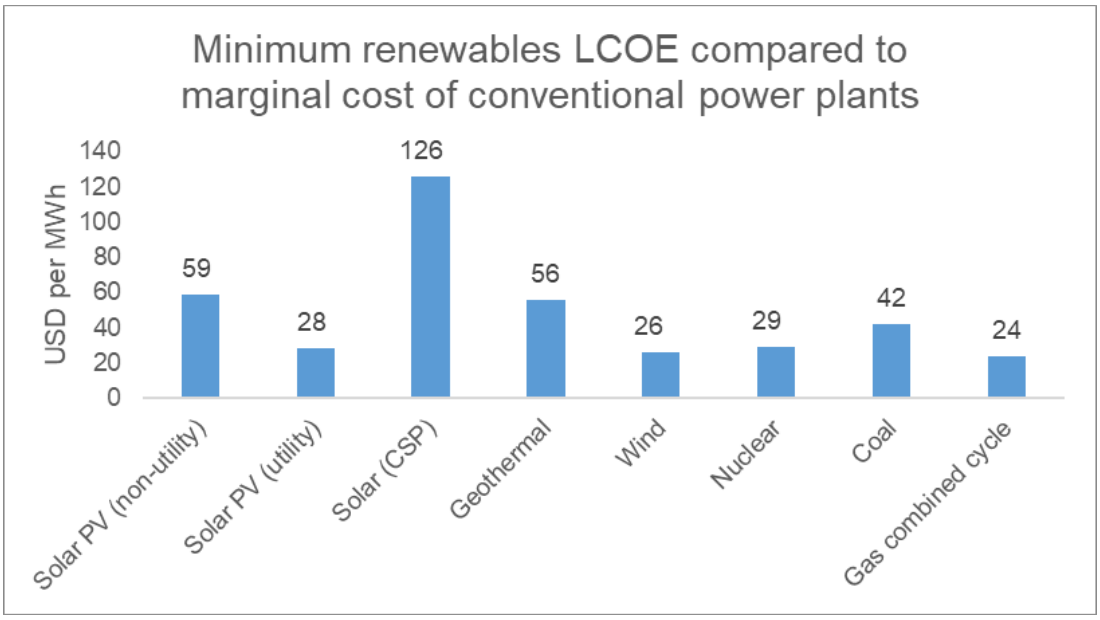
4.6.2 When considering Figure 4.11 above and the analyses of Lazard, the following should be noted (146):

- The first five columns in Figure 4.11 relate to renewables and the remaining four to conventional (non-renewable) power plants.
- Solar (CSP) represents both a form of generation as well as storage which should be kept in mind when making comparisons.
- The minimum and maximum LCOE for both utility solar PV and wind are below the minimum cost of new build conventional power plants, apart from combined cycle gas. The minimum LCOE for utility solar PV and wind are less than half of conventional coal power plants.
- While the analyses cover a significant portion of the lifecycle of each fuel source, not all factors were considered. Some factors excluded from the analyses are network and transmission upgrades, social and environmental externalities, nuclear waste disposal, and the impact of GHG emissions.
- Various assumptions for each of the fuel sources were included when the analyses were done. These assumptions include construction time, fuel price, operational cost, capital cost, capacity factor, and facility life.

4.6.3 Whilst the analyses done by Lazard were not specifically focused on South Africa, it can be assumed that the general trends also apply to South Africa, given the global interconnectedness of trade and the cost of infrastructure and fuel.

4.6.4 In Figure 4.12 below, the cost of new-build conventional power plants is compared with the marginal cost of running fully-depreciated conventional power plants (excluding gas peaking plants).

Figure 4.12: Renewables LCOE compared to marginal cost of conventional power plants (2021)



(Source: own chart, Lazard data (146))

4.6.5 The data in Figure 4.12 indicate that the marginal cost of nuclear and gas are broadly similar to the cost of utility-scale renewables, other than Solar CSP. The marginal cost of coal is substantially higher than utility solar PV and wind. The low marginal cost of gas combined cycle plants is notable. This cost analysis excludes the impact of carbon taxes and the potential long-term impacts that both renewables and fossil-fuel based plants would have on the environment. Lazard (146) also conducted an analysis considering the total cost with illustrative carbon pricing; the added carbon tax increased the LCOE for fossil fuel-based plants by up to 32%.

5. South Africa's electricity crisis

5.1 Overview

5.1.1 The central role of the grid operator is to ensure that the electrical system is stable whilst providing sufficient and reliable electricity at a competitive cost (147). To keep the grid stable there must be a high level of electricity quality of supply and ample capacity for generation. To ensure that the grid remains stable, grid operators must adhere to strict technical parameters.

5.1.2 Eskom's purpose is defined in its 2022 Annual Report as ensuring "a stable electricity supply in an efficient manner, to contribute to lowering the cost of doing business and enable economic growth" (19).

5.1.3 As noted in Chapter 3 of this paper, South Africa's coal fleet provides close to 90% of the total electricity generated in South Africa. At the same time, the coal plants are ageing and many (other than Medupi and Kusile) are approaching end-of-life. Eskom's 2022 financial statements (19) indicate that they currently have R382 billion in net interest-bearing debt and that their average cost of debt has increased to over 10% per year. Net finance cost in 2022 was R33 billion, approaching 14% of revenue (R247 billion) and 50% more than operating profit (EBIT: R20 billion). By purely considering the long-term nature of electricity planning, it is clear that, as these plants are decommissioned, significant additional generation and associated capital expenditure will be required.

5.1.4 In Section 3.1 of this paper, a perspective of Eskom's history was given, starting in 1906 with the establishment of VFP, a utility that largely provided electricity to South African mines, that eventually transformed into Eskom, a nationwide utility responsible for electricity stability; an entity critical to economic development in South Africa.

5.1.5 However, from the content of Section 3.1 it also became clear that Eskom is in the midst of an electricity crisis as the utility is unable to generate sufficient electricity to meet demand. To ensure stability of the electricity grid, Eskom opted to implement load shedding. According to Eskom's 2022 Annual Report (19), Eskom chairperson, Mpho Makwana, attributed Eskom's lack of generation capacity mostly to its poorly performing coal fleet.

5.1.6 In the same report, Eskom's COO, J Oberholzer, noted that the plant availability declined to 62.02% in 2022. He further stated that the coal-fired plant performance was "deeply disappointing and really concerning". He attributed the poor performance of the coal fleet to the following factors (19):

- Poor coal quality and coal tampering
- Aged power stations – average age of 43 years for the coal fleet (excluding Medupi and Kusile)
- Running of plants above design parameters – above 80% capacity since 2002
- Deferred maintenance and poor maintenance
- Deferred midlife refurbishment
- Lack of adequate spare generation capacity to undergo maintenance

- Lack of spares to effectively execute maintenance
- Lack of funds
- Criminal and illegal actions – electricity and equipment theft, illegal electrical connections, asset vandalism

5.2 Eskom's coal fleet performance

5.2.1 To envision potential solutions to the electricity crisis, it would be useful to explore the Key Performance Indicators (KPIs) published by Eskom. A power utility is a data-rich environment where thousands of sensors and measurements are constantly monitored. This granular data are then aggregated to KPIs that are used to communicate the performance of the utility.

5.2.1 EAF

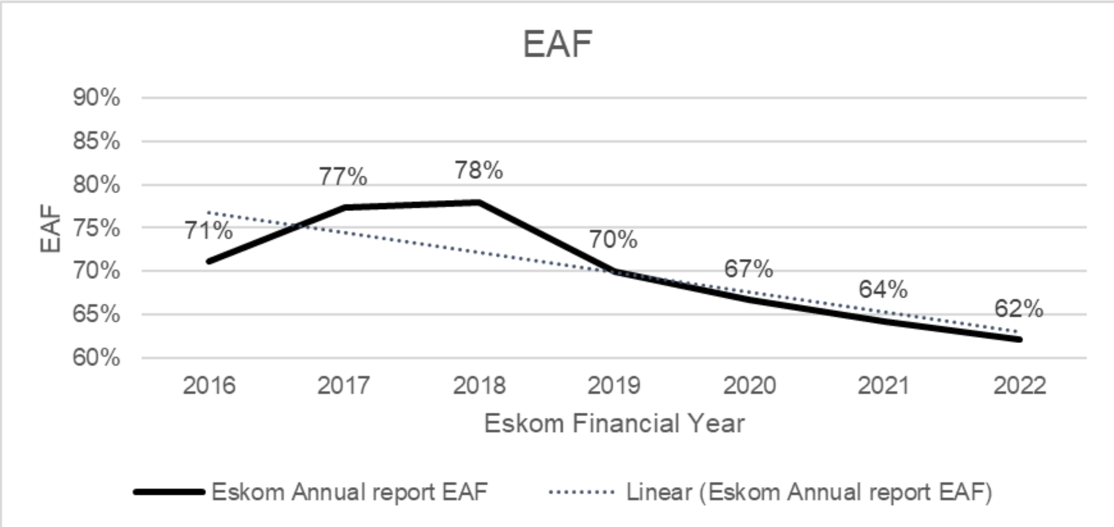
5.2.1.1 The Energy Availability Factor (EAF) is a key metric[23] that is often used to monitor the availability of a plant for electricity generation. The EAF measures the ratio of time available for generation relative to the total time available. Stated differently, the EAF is the remainder after subtracting planned maintenance (PCLF), unplanned outages (UCLF), and other loss unavailability (OCLF). Mathematically the EAF can be defined as follows: $EAF = 1 - (PCLF + UCLF + OCLF)$.

5.2.1.2 The EAF is a popular metric to use, as it provides a concise view of Eskom's performance. However, the EAF also masks a number of underlying factors. The following list includes some of challenges using the EAF could cause:

- The EAF does not measure the load of the power plant; it measures whether the power plant is available for generation. Where power plants do not have a significant variation in load levels (i.e., on and off), this is less of a concern. However, where power plants can be run at various utilisation rates, the EAF does not capture this nuance. The utilisation rate can have a substantial impact on plant reliability (148) and is discussed in Section 5.2.2 below.
- The EAF can be calculated as an equally weighted average or as a weighted average based on the capacity (installed or nominal) of the power plant. This means that the EAF could be skewed during periods that the performance between smaller and larger power plants was very different. Different stakeholders could be calculating the EAF differently which could skew the EAF figures.
- Comparing the EAF across power plants within a certain generation fuel type can be insightful but comparing the EAF across different fuel types can be misleading. For instance, VRE might have a relatively high EAF (depending on the definition in the context of VRE) but can only generate electricity when the sun shines or the wind blows. Therefore, an aggregated EAF across coal and a form of VRE would not be a particularly insightful metric.

[23] See the glossary in Section 1.5 for further definitions of some of the metrics used.

Figure 5.1: Eskom EAF by Eskom's Financial Year

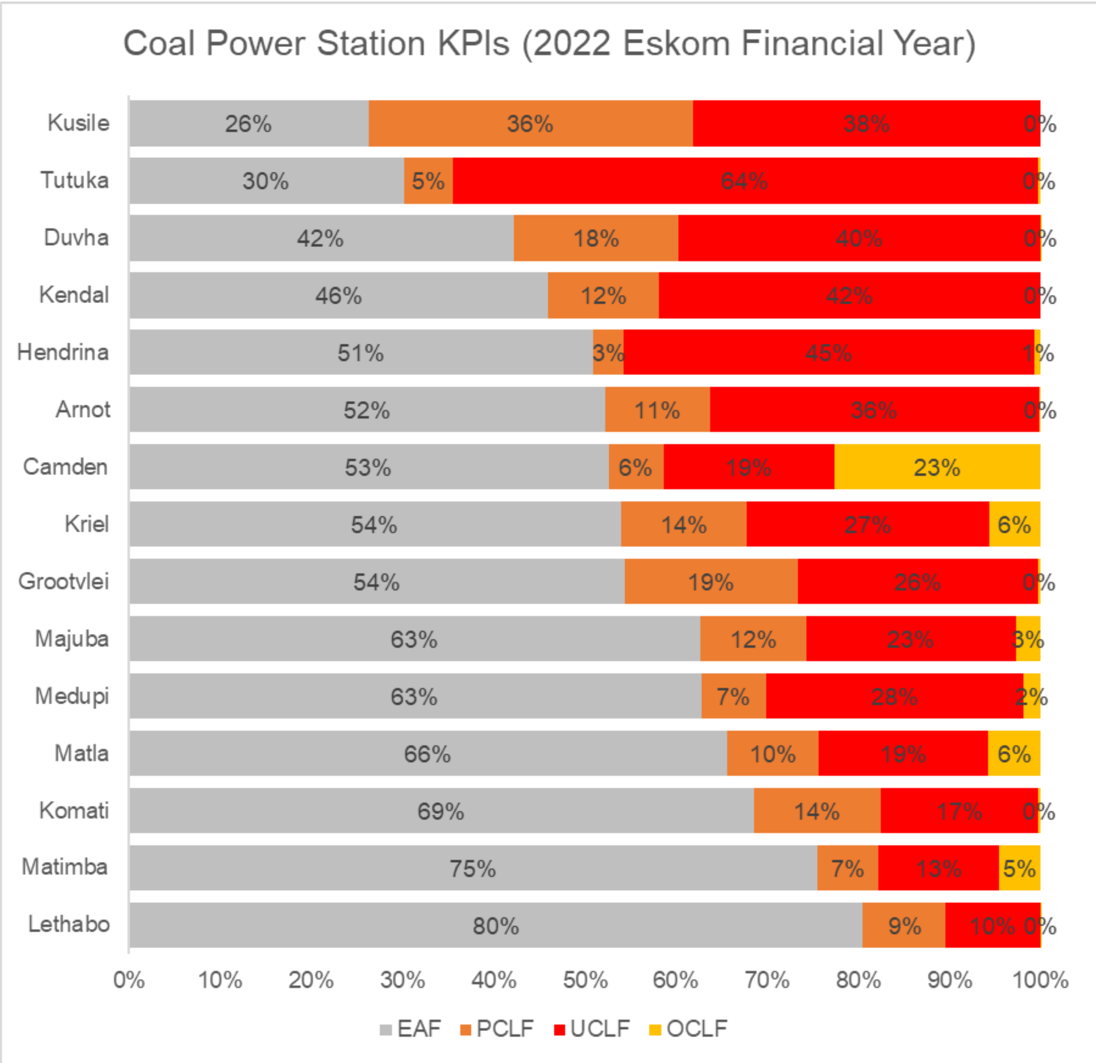


(Source: Eskom annual reports 2016-2022 (19))

5.2.1.3 Figure 5.1 indicates that Eskom's EAF has been decreasing at an alarming rate since 2018. The decrease of the EAF can potentially be attributed to poor plant performance or to a more aggressive maintenance strategy. Eskom calculated the above EAF based on the performance of the whole fleet. However, a utility-average EAF would mask the different underlying sources of electricity and the performance of the underlying power plants. While the aggregate view is insightful in terms of the trend, it is also important to understand the underlying factors driving the decrease in the EAF.

5.2.1.4 The team at Amabhungane (46) highlighted the performance of the different coal power stations from an EAF perspective. Based on data obtained from Amabhungane, the following chart and tables provide detail of the KPIs for the coal power stations for Eskom's 2022 financial year (ending March 2022); they also highlight some concerns.

Figure 5.2: KPI by coal power station for the 2022 Eskom financial year



(Source: own analysis based on Eskom data)

Table 5.1: Power stations by installed capacity, nominal capacity, EAF, PCLF, and UCLF over Eskom's 2022 financial year

Power station	Total installed capacity (MW)	Total nominal capacity (MW)	EAF*	PCLF*	UCLF*	Age**
Kusile	3 196	2 880	26%	36%	38%	5
Tutuka	3 654	3 510	30%	5%	64%	37
Duvha	3 000	2 875	42%	18%	40%	42
Kendal	4 116	3 840	46%	12%	42%	34
Hendrina	1 723	1 098	51%	3%	45%	52
Arnot	2 220	2 100	52%	11%	36%	51
Camden	1 561	1 481	53%	6%	19%	55
Kriel	2 790	2 640	54%	14%	27%	46
Grootvlei	1 180	570	54%	19%	26%	53
Majuba	4 110	3 807	63%	12%	23%	26
Medupi	4 764	4 317	63%	7%	28%	7
Matla	3 600	3 450	66%	10%	19%	43
Komati	990	114	69%	14%	17%	60
Matimba	3 990	3 690	75%	7%	13%	34
Lethabo	3 708	3 558	80%	9%	10%	36
Total	**44 602**	**39 930**				
Arithmetic average			**54.9%**	**12.2%**	**29.8%**	**39#**
Nominal capacity weighted average			**55.2%**	**11.8%**	**30.3%**	**33**
Installed capacity weighted average			**55.4%**	**11.9%**	**30.2%**	**34**

(Source: own analysis based on Eskom data)
** averaged over the 12-month period*
*** age was calculated based on the period between the date of commissioning of the first unit and 31 March 2022*
 # average power station age excluding Kusile and Medupi is 43,7 years

Table 5.2: Six worst performing power stations by EAF (weighted-average KPIs)

Total installed capacity (MW)	Total nominal capacity (MW)	EAF	PCLF	UCLF	OCLF
17 909	16 303	41%	12%	46%	0%

(Source: own analysis based on Eskom data)

5.2.1.5 Figure 5.2 and Tables 5.1 and 5.2 illustrate the vast differences in EAF by coal power station. The following is evident from these analyses:

- Kusile and Tutuka stand out as being particularly unreliable with EAF ratios at or below 30%. From an unplanned outage perspective, Tutuka seems to be the worst performer by a significant margin with a UCLF of 64%.
- The six worst performing coal power stations represent 41% of the total nominal capacity of Eskom. These power stations have an average EAF of 41% and a

UCLF of 46%. Of these six power stations, two represent power stations older than 50 years. However, the two oldest power stations are the best performing power stations out of the six worst performing power stations. Although age impacts performance, it is clear that age could not be the only factor impacting the coal fleet's poor performance.

- While a low EAF number is concerning, the high level of unplanned outages (UCLF of 46%) is alarming. The level of unplanned outages is a measure of grid reliability and stability, as unplanned outages represent capacity that must be sourced elsewhere over a short period. In situations where generators shut down unexpectedly and alternative supply is not available, demand has to be reduced which typically manifests as load shedding.
- Komati was still included in Table 5.1 as this power station was only shut down after the 2022 financial year. Hendrina, Arnot, Grootvlei, and Camden are all already past their 50-year design lifetime and must be decommissioned in the near future. The 2019 IRP (30) provides a decommissioning schedule indicating the imminent decommissioning of these power stations.

Table 5.3: Power stations by installed capacity, nominal capacity, EAF, PCLF, and UCLF for the 2022 financial year

Generation type	EAF	PCLF	UCLF	OCLF
Coal*	55%	12%	30%	3%
Hydro*	96%	3%	0%	0%
Nuclear*	76%	14%	10%	1%
OCGT*	96%	2%	0%	1%
Pumped hydro*	88%	11%	0%	0%
Coal average (weighted by installed capacity)	**57%**	**11%**	**30%**	**3%**
Baseload average (weighted by installed capacity)#	**57%**	**11%**	**29%**	**3%**
Average (weighted by installed capacity)	**62%**	**10%**	**25%**	**2%**

(Source: own analysis based on Eskom data)
* unweighted arithmetic averages over the 12-month period
# coal and nuclear

5.2.1.6 Eskom reported an EAF figure of 62.02% in their 2022 Annual Report (19), very similar to the calculated 62% in Table 5.3 when based on installed capacity. Due to physical, logistical, and financial constraints, OCGT, pumped hydro, and hydro cannot typically run continuously even if they were available for the proportion of time indicated by the EAF. This is illustrated in Table 5.4 below.

Table 5.4: Maximum available generation capacity versus actual generation

Generation type	Theoretical maximum GWh per year (GWh x EAF) (1)	Theoretical proportion of total generation based on EAF (2)	Actual generation by fuel type (3)	Actual proportion of total generation (4)
Coal	186 212	76%	184 568	90%
Hydro	5 025	2%	1 943	1%
Nuclear	12 399	5%	12 355	6%
OCGT	20 599	8%	1 826	1%

Pumped hydro	21 270	9%	4 743	2%
Total	**245 504**	**100%**	**205 435**	**100%**

(Source: own analysis based on Eskom data (excluding renewables))

5.2.1.7 If Eskom were to utilise their power plants in line with the EAF implied in their Annual Report, then the generation split would be closer to column 2 in Table 5.4. However, the actual generation split during 2022 is illustrated in column 4 in Table 5.4.

5.2.1.8 Table 5.4 illustrates that coal produces significantly more electricity as a proportion of total electricity than the allocation that was provided based on Eskom's EAF calculation. Therefore, a more appropriate EAF KPI calculation would incorporate the weighted contribution of each type of power plant. Eskom's reported 62% EAF would be closer to 57% if weighted by the actual amount of electricity generated by the various fuel types. This leads us to Section 5.2.2 where the Energy Utilisation Factor (EUF) and Capacity Factor (CF) are discussed.

5.2.2 Energy utilisation factor

5.2.1.9 Two additional metrics that are useful to understand are the Energy Utilisation Factor (EUF) and the Capacity Factor (CF). The EUF represents "how hard" the power stations are being run, i.e., how close to maximum output the power station is being operated.

5.2.1.10 The CF is the product of the EAF and EUF. Stated differently, the CF is the ratio of the power generated relative to its maximum possible generation. Mathematically, the CF can be defined as follows: $CF = EAF \times EUF$

5.2.1.11 Unfortunately, sufficient granular data were not available to provide a view of the CF by power station. The CSIR calculates the CF by generation type and publishes it in their biannual power generation report (43). It should be noted that the CSIR calculations are done based on a calendar year basis rather than Eskom's financial year. The comparison of the capacity factors reflected below in Table 5.5 is based on the CSIR report. This table illustrates the capacity factors of Eskom's various supply sources.

Table 5.5: Capacity factors by fuel source for 2019-2022 calendar years

	Calendar year			
Fuel source	**2022**	**2021**	**2020**	**2019**
Coal	50%	54%	56%	60%
Hydro	60%	30%	15%	13%
Nuclear	62%	75%	71%	83%
OCGT	12%	11%	6%	7%
Pumped hydro	19%	20%	21%	20%
Wind	34%	36%	35%	36%
CSP	33%	38%	37%	37%
Solar PV	25%	26%	26%	26%

(Source: CSIR data)

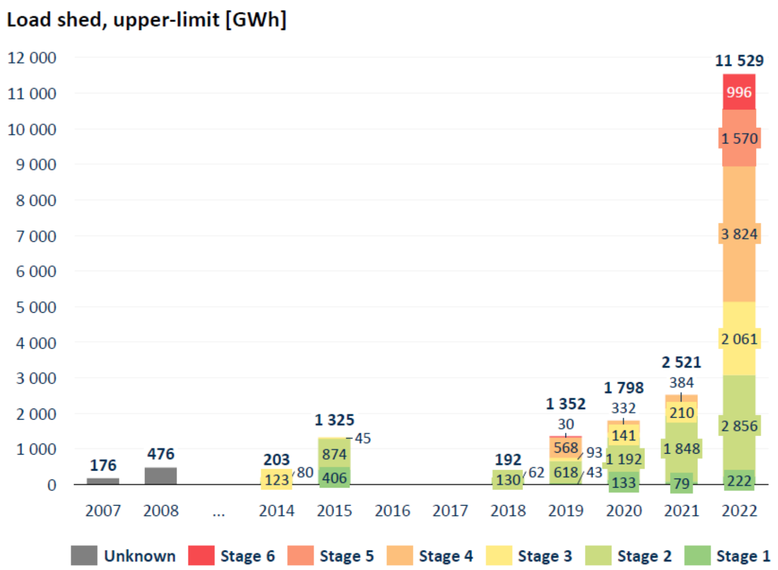
5.2.1.12 The following should be noted:

- Eskom reported an EAF of 62.02% for the overall fleet. The EAF for the coal fleet, based on Eskom data at a power station level, was estimated at 55% for the 2022 financial year. The EAF for the coal fleet, recalculated on a calendar year basis, was 56.4%. When comparing the EAF of 56.4% to the CF of 54% calculated by the CSIR (2021), a particularly high EUF (close to 96%) is illustrated. Eskom reported a year-to-date EUF of 93% (slightly lower than the 96%) as at October 2021.
- The coal CF reduced from 60% to 50% from 2019 to 2022. The nuclear CF reduced from 83% to 62% between 2019 and 2022. As the coal and nuclear CF reduced, the hydro and OCGT capacity factors increased substantially to offset the reductions in the baseload power plants.
- Eskom highlighted the deteriorating coal fleet EAF and the increasing coal fleet EUF in a presentation on 25 October 2021 (149). It is noted in the presentation that the coal fleet EAF decreased from 85% in 2010 to below 60% in 2021. The EUF increased from 85% in 2010 to 93% in 2022. In a benchmarking exercise by VGB PowerTech[24] (included as part of Eskom's October 2021 presentation), it was made clear that Eskom has been running its fleet harder than comparable generators in the benchmarking exercise (performed over a period from 2000 to 2019).
- Had Eskom not run its coal fleet at a higher intensity (i.e., increased its EUF), the capacity factor would potentially have deteriorated even further.

5.3 Load shedding

5.3.1 Eskom has been forced to implement demand-side reduction measures. As previously mentioned, one of the most evident forms of demand-side reduction is load shedding. Load shedding has increased significantly over the last few years. The CSIR includes the chart below as part of their report on utility-scale power generation (43).

Figure 5.3: Load shedding by year



Year	Duration of outages (hours)	Energy shed (GWh)	DSR (GWh)
2007	-	176	Not available
2008	-	476	Not available
....	....	....	....
2014	121	203	Not available
2015	852	1 325	Not available
....	....	....	....
2018	127	192	392
2019	530	1 352	1 362
2020	859	1 798	1 426
2021	1 169	2 521	1 936
2022	3 773	11 529	8 301

[24] An international technical association for power generation and power storage

(Source: CSIR Statistics of utility-scale power generation in South Africa in 2022)

5.3.2 At the time of writing this paper, 2022 has had the most days of load shedding since 2007, when Eskom started their rolling blackouts. Table 5.6 below highlights the increase in number of days, hours, and GWh of unserved electricity based on Eskom data from 2019 to 2022. These numbers differ slightly from the CSIR analysis in Figure 5.3 above.

Table 5.6: Load shedding summary from 2019 to 2022 (calendar years)

Calendar year	Number of days during which load shedding occurred	Number of hours of load shedding	GWh unserved ("shedded")
2019	30	545	1 090
2020	54	871	1 269
2021	75	1 165	1 775
2022	205	3 782	8 116
Total	**364**	**6 363**	**12 251**

(Source: Eskom data)

5.3.3 Experts have already attempted to estimate how much load shedding is costing the South African economy. Based on a 2020 paper, the cost of unserved power was estimated to be between R90 and R100 for every kWh not served (150). A rough calculation puts the cost of load shedding during 2022 at R771 billion (approximately equal to twice Eskom's debt). This translates to just under R4 billion per load-shedding day.

5.4 Supply-side interventions and constraints

5.4.1 IPP Programmes

5.4.1.1 As noted in Section 5.3 above, load shedding was introduced in 2007 as a demand-side measure to manage the grid and reduce electricity consumption. One of the supply-side responses to the start of load shedding in 2007 was to introduce the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP or REI4P). The REI4P was developed by the Department of Mineral Resources and Energy (DMRE) and its purpose was to create a framework to add renewable private generation sources to the grid (151).

5.4.1.2 Authors Eberhard and Naude provided some insightful perspectives in their report (152) that focused on the experiences gathered from the first four bid windows of the REI4P. The following was noted:

- South Africa's electricity generation and procurement programme is centralised and its responsibility is allocated to the Minister of Mineral Resources and Energy (the Minister). The Minister publishes documents known as "determinations" on new generation capacity and allocates new generation between Eskom and IPPs. As noted in Section 3.3 above, NERSA is bound by the ERA to approve new generation as allocated by the Minister.

- The REI4P operates through a closed-auction process. Each auction is known as a bid-window (BW). At the end of 2016, the REI4P had run a total of four[25] BWs.
- The REI4P was particularly successful and achieved more investment in RE in four years than Sub-Saharan Africa achieved in two decades.
- The REI4P was regarded "as being well designed and managed, and the process as being transparent and fair". The REI4P team included a range of local and international private sector advisors with experience in technical, legal, and financial aspects of energy procurement and management. The REI4P was run as a somewhat independent unit within the DMRE, managed by a team from the Public-Private Partnership Unit of National Treasury.
- The REI4P had strict requirements for bidders; each bidder was required to have various agreements in place and to provide upfront guarantees. Prior to awarding projects, bidders would collect detailed site data for evaluation and value for money assessments were compulsory. If a bidder did not perform, the DMRE would impose penalties for non-performance.
- Successful bidders were awarded Preferred Bidder Status. Signing of contracts and financial close (FC) were expected to occur within 9 to 12 months after being awarded Preferred Bidder Status. Commercial Operation Dates (CODs) were expected within 24 to 30 months of FC.
- Based on the first four BWs, the REI4P had added a total of 6 328 MW (6.3 GW) capacity from 92 projects with a total investment of R192bn.

5.4.1.3 Eberhard and Naude (152) further noted that the most recent REI4P pricing[26] was among the lowest cost RE in the world. The prices of the recent winning bids are below Eskom's cost of supply and significantly lower than the cost of new coal power stations. While the tariffs were not particularly price-competitive on BW 1, they have since reduced substantially. The following table shows how solar PV and wind RE BW tariffs have reduced over time.

Table 5.7: Rand per MWh by energy source per bid window

Bid window	Solar PV (R per MWh)	Wind (R per MWh)
BW 1	2 760	1 140
BW 4(a)	790	620
BW 5 (153)	375	344
Percentage reduction: BW 1 to BW 5	**86%**	**70%**

(Source: Eberhard & Naude's REI4P report (152), Eskom 2022 Annual Report (19))

5.4.1.4 As can be noted in Table 5.7 above, solar PV and wind reduced by 86% and 70% respectively between BW 1 and BW 5. In its 2022 Annual Report (19), Eskom highlights that its operating cost is R990.31 per MWh. The unit operating cost of coal was R440 per MWh and nuclear was R99 per MWh. The unit cost amounts are not directly comparable to those shown in Table 5.7 above as the unit costs exclude capital expenditure (or depreciation and return on assets). Nevertheless, it is

[25] Technically there were 6 bid windows as there was a 3.5 window and bid window 4 was split into 4(a) and 4(b). As at the end of 2022, there were 6 formal bid windows (1 to 6) but 8 windows in total (including the 3.5 and the split of 4 into 4(a) and 4(b).
[26] Assumed to be BW 4 at the time (2016) of finalising their report

important to note that the new build costs of both solar PV and wind were lower than the running costs of coal power stations. Table 5.8 below compares the Rand per MWh across current Eskom technologies versus the new solar PV and wind bids on the REI4P BW 5.

Table 5.8: Rand per MWh across various technologies

	Tariff (R per MWh)	Source
Solar (BW 5)[27]	375	REI4P BW 5
Wind (BW 5)[28]	344	REI4P BW 5
Coal	440	Eskom Annual Report
Nuclear	99	Eskom Annual Report
Eskom-owned OCGT	4 708	Eskom Annual Report
IPP OCGT	4 574	Eskom Annual Report
IPP Renewables	2 027	Eskom Annual Report
International purchases	625	Eskom Annual Report

5.4.1.5 The relationship between new VRE and conventional power plants (other than nuclear) highlighted in Table 5.8 above align closely with the analysis done by Lazard (highlighted in Section 4.6 above). The reason for the discrepancy on nuclear was not obvious and access to Eskom cost data were limited.

5.4.1.6 While the REI4P was largely successful, it did not adequately address the generation shortfall experienced over the period up to 2020. With the public sector realising the magnitude of the electricity shortfall, the DMRE established the Risk Mitigation Independent Power Producer Procurement Programme (referred to as the RMIPPPP or RMI4P) in August 2020. The requirements to fulfil the RMI4P was for 2 000 MW of generation capacity to be added to the grid by June 2022 based on the expected shortfall highlighted in the 2019 IRP (154). Given the latest load-shedding experienced in 2022 up to stage 6 (6 000 MW shed), it is clear that the RMI4P has not yet addressed this generation shortage sufficiently.

5.4.1.7 It is important to note that IPP programmes do not represent behind-the-meter embedded generation. IPP programmes represent electricity that Eskom purchases from IPPs to provide electricity to the grid (155). While embedded generators register their installations with NERSA, it is understood that they do not need to obtain a generation licence after the removal of the cap on embedded generation.

5.4.1.8 While generation capacity is the key issue considered in this paper, available grid capacity can have a significant impact on whether additional VRE can be added to the grid. In this regard it is useful to look at the example of the latest auction on the REI4P; specifically BW 6. BW 6 was intended to add a total of 2 600 MW to the grid, split into 1 600 MW from wind and 1 000 MW from solar. The request for proposals (RFPs) for BW 6 was communicated on 6 April 2022 and the bid submission date was 11 August 2022. As part of the questions and answers document released by the DMRE, it was noted that Eskom's Generation Connection Capacity Assessment (GCCA) would provide additional certainty for the market (156). A total of 9 666 MW of capacity was submitted. Of the 9 666 MW, 230 MW related to unsuccessful

[27] Based on the lowest tariff in BW 5. The capacity-weighted average tariff for solar PV was R431 per MWh.

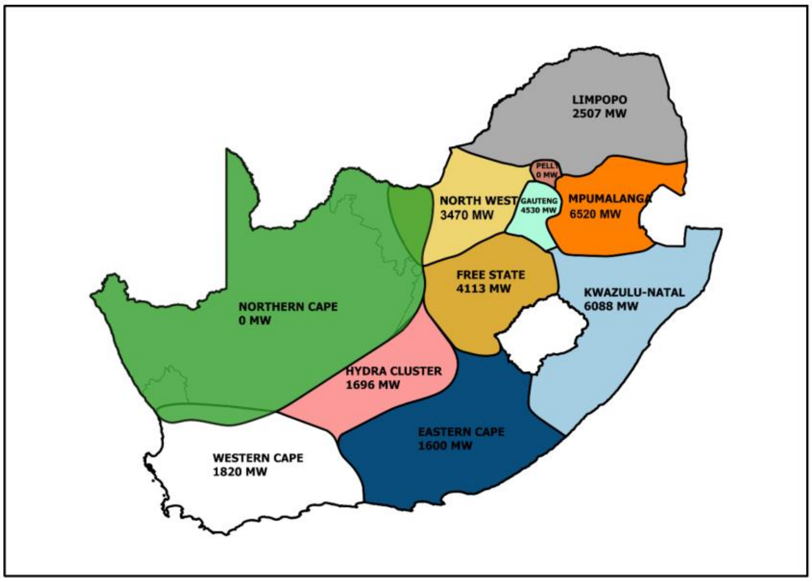
[28] Based on the lowest tariff in BW 5. The capacity-weighted average tariff was R491 per MWh for wind.

bidders, 860 MW of solar PV was listed as preferred bidders, and 8 576 MW was rejected. Of the total bids, 5 550 MW was submitted for solar PV and 4 116 MW was submitted for onshore wind. The DMRE did not approve any wind generation and only approved 15% of the solar PV submitted (157) (158). It is reported that, due to the removal of the 1 MW generation limit for embedded generators, private embedded generators were able to obtain accelerated access to the Eskom grid and saturated the grid prior to BW 6 closure (159). In other words, Eskom's grid is saturated in the areas where additional generation was envisaged and the transmission grid is limiting new electricity capacity. This has hampered the REI4P and it is unclear when a new bid window will be announced. Electrical grid constraints are discussed in Section 5.4.2 below.

5.4.2 Electricity grid constraints

5.4.2.1 As noted in Section 5.4.1 above, Eskom's grid capacity has become saturated. The GCCA, although outdated, still provides an insightful perspective of the state of the grid (121). Eskom provided the following map, released in March 2022, with the grid capacity per province outlined in the GCCA.

Figure 5.4: Eskom grid capacity



(Source: Eskom GCCA 2024)

5.4.2.2 Whilst 69% of submissions related to projects in other provinces, the REI4P only approved projects in the Free State and North-West. Notably 4.8 GW (50%) of the submitted capacity related to the Western Cape – a province in which no generation was approved. Assuming that this is due to capacity constraints, as indicated in Section 5.4.1 above, then the available capacity in the Western Cape and Eastern Cape has already been allocated to embedded generators. Therefore, the north-eastern parts of the country seem to be the only areas in which new generation capacity can be added. However, as has been noted, solar resources are more efficient and reliable in the north-western parts of the country and wind resources are more efficient and reliable in the south-western and southern parts of the country (120). More reliable VRE will result in a lower cost of electricity generation.

Nevertheless, it is also important to obtain geographically diversified VRE. By allocating new capacity to provinces without capacity constraints, the overall stability of the grid could be improved.

5.4.2.3 It was not entirely clear whether more advanced approaches to grid capacity were considered to address the grid capacity constraints, such as VPPs and VPLs. These approaches for immediate storage and delayed transmission should be considered until more grid capacity is available.

5.4.3 Integrated energy and resource plans

5.4.3.1 Chapter 3 of the National Energy Act (2008) (160) (NEA) deals with integrated energy planning. Chapter 3 requires that the Minister of Mineral Resources and Energy develop, and on an "annual basis, review and publish the Integrated Energy Plan" (IEP) (160) (161). The South African National Energy Association (SANEA) notes in their 2021-2022 Energy Risk Report that an IEP has not yet been finalised. This has created policy uncertainty in terms of the long-term trajectory of the energy sector in South Africa (162) (163). In the conclusion to SANEA's 2022-2023 Energy Risk Report (163) six main points were noted. These were summarised as follows:

1. There is still policy uncertainty due to an unfinished IEP and outdated IRP. The actions taken thus far "are not sufficient and change is not rapid enough".
2. Policy design has not aligned itself with global markets and is handled in a siloed manner.
3. The new required infrastructure has not been considered in an "integrated manner and [is] therefore not adequately resourced". SANEA highlights the need for a Grid 2050 plan and for long-term development that should align with global trends.
4. Skills development is challenging because there is no clear energy roadmap.
5. Many strategies and plans addressing energy security have been tabled over the past decade, however, symptoms are addressed and not root causes which has led to slow implementation and a lack of sustainable improvement.
6. Planning that considers integrated implications and that focuses on the biggest impact issues is required at all levels of government and business.

5.4.3.2 The 2019 IRP (30) provided a projection up to 2030 as indicated in Figure 5.5 below. However, as noted above, SANEA indicated that the 2019 IRP is out of date and should be revised, taking into account the tremendous changes in technology since the release of the 2019 IRP. As per the requirements of the NEA, these plans should be revised annually to ensure that South Africa is on a path to energy security. Figure 5.5 highlights the installed capacity projections done for the 2019 IRP.

Figure 5.5: IRP 2019 projected installed capacity

	Coal	Coal (Decommissioning)	Nuclear	Hydro	Storage	PV	Wind	CSP	Gas & Diesel	Other (Distributed Generation, CoGen, Biomass, Landfill)
Current Base	37 149		1 860	2 100	2 912	1 474	1 980	300	3 830	499
2019	2 155	-2373					244	300		Allocation to the extent of the short term capacity and energy gap.
2020	1 433	-557				114	300			
2021	1 433	-1403				300	818			
2022	711	-844			513	400 1000	1600			
2023	750	-555				1000	1600			500
2024			1860				1600		1000	500
2025						1000	1600			500
2026		-1219					1600			500
2027	750	-847					1 600		2000	500
2028		-475				1000	1 600			500
2029		-1694			1575	1000	1 600			500
2030		-1050		2 500		1 000	1 600			500
TOTAL INSTALLED CAPACITY by 2030 (MW)	33364		1860	4600	5000	8288	17742	600	6380	
% Total Installed Capacity (% of MW)	43		2.36	5.84	6.35	10.52	22.53	0.76	8.1	
% Annual Energy Contribution (% of MWh)	58.8		4.5	8.4	1.2*	6.3	17.8	0.6	1.3	

Installed Capacity
Committed / Already Contracted Capacity
Capacity Decommissioned
New Additional Capacity
Extension of Koeberg Plant Design Life
Includes Distributed Generation Capacity for own use

Source: IRP 2019 (30)

5.4.3.3 The following can be noted from Figure 5.5 above:

- In terms of baseload power stations:
  - More than 11 GW of coal power generation will be decommissioned from 2019 to 2030. Only 750 MW coal generation will be added to the grid from 2024 onwards.
  - No nuclear will be added to the grid.
  - New gas and diesel generation of 3 000 MW will be added between 2024 and 2027.
- 14.4 GW of wind and 6.4 GW of solar is expected to be added to the grid between 2022 and 2030.

5.4.3.4 The National Planning Commission released an Energy Report in 2018 in which they stated that South Africa should ideally not pursue mega-projects but focus on smaller, more manageable projects that would still provide economies of scale (164).

6. Modelling

6.1 Overview

6.1.1 As a response to the preceding chapters, an electricity model (the "Model") was constructed to project electricity supply and demand for the period from 2020 to 2050 ("modelling period"). The purpose of this Model is to provide a high-level view of the potential impact of implementing various supply, demand, and storage scenarios taking into account the decommissioning of the coal and nuclear generation fleet.

6.1.2 In considering the approach to modelling the South African electricity system, a wide range of models currently in the market were reviewed. Of the models considered, three specific models were noted. These are the Low Emissions Analysis Platform (LEAP) (165), the Open Source Energy Modelling System (OSeMOSYS) (166), and the South African Integrated Markal Efom System (SATIM) (167).

6.1.3 LEAP is a proprietary software package but is freely available to academic organisations. LEAP reports that their model is used for NDC scenario modelling for at least 32 countries. LEAP typically works on an annual time-step and is intended as a medium- to long-term planning tool. However, LEAP can be used at a more granular level (up to hourly) (165).

6.1.4 OSeMOSYS is an open source optimisation model for long-term energy planning. At the time of writing, free "starter-kit" datasets for African countries could be obtained. An Africa-wide model called TEMBA was developed on the OSeMOSYS platform (166). OSeMOSYS's functionality can be extended by combining it with various other software packages in the market such as FlexTool (for assessing flexibility of the energy system) and clicSAND (user-friendly interface for OSeMOSYS) (168).

6.1.5 The SATIM model is a single region Integrated Markal Efom System (TIMES) model, a bottom-up model that uses linear programming to solve for a least cost energy solution (169). The TIMES model was initially developed by the IEA after which researchers at the University of Cape Town adapted it for the local environment. SATIM is well-known and was used as part of the modelling in the Just Transition Investment Plan (119) (167).

6.1.6 After the available models in the industry were evaluated, it was decided that a basic model (further referred to as the "Model") could be developed in Microsoft Excel. This approach ensures that the model is user-friendly and straightforward to operate. The Model is flexible so that the user can adapt it to specific use-cases or situations.

6.1.7 The Model was constructed to reflect the generation and demand components of the South African electricity system. At its core, the Model projects annual supply and demand over the modelling period. Stated differently, it provides a view of the demand and total potential generation on an annual basis. This view of supply projects the maximum energy generation for each year rather than truncating generation to demand (as would be the case in practice). The Model's annual view does not consider variation in demand and supply within that year.

6.1.8 Apart from the annual view, the Model also provides an hourly view of supply, demand, and storage. The hourly view uses the annual view as a basis and then allocates demand and supply into hourly segments to provide the user with a granular view of demand and supply within that year. With the hourly view, the user can assess the excess or shortfall of electricity on an hourly basis within a certain year after allowing for the use of pumped hydro storage (PHS) and battery storage (BESS). When modelling on an hourly basis, it is assumed that any excess electricity (after allowing for charging PHS and BESS) is stranded (i.e., unused). As Excel does not lend itself to computationally complex models, hourly projections were limited to a single year. The year is a variable in the model and can be selected between 2020 and 2050.

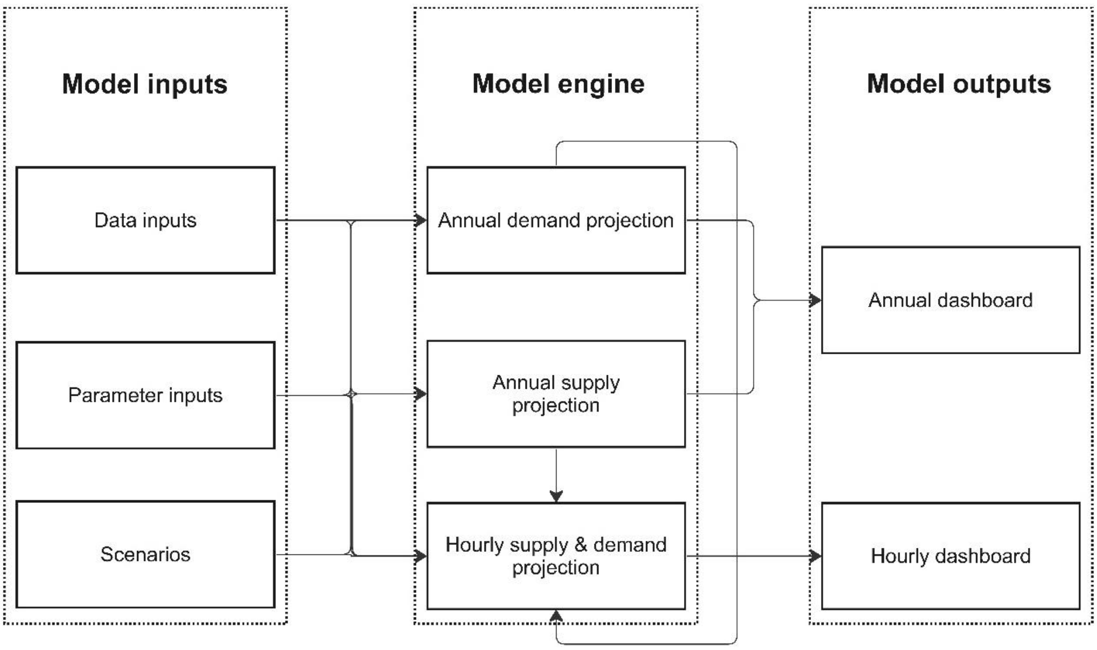
6.1.9 Initially, a bottom-up methodology was considered for constructing the model based on electricity end-use. However, after careful consideration of the additional data requirements and the overarching purpose of the model, it was decided that a top-down approach would be more appropriate for the envisioned user. The rest of this chapter reflects the top-down and pragmatic nature of the model.

6.2 Model assumptions and methodology

6.2.1 Model structure

6.2.1.1 Figure 6.1 provides a simplified view of the Model inputs, the Model engine, and the Model outputs. Each of the Model components are described in the sections below.

Figure 6.1: Simplified model flow diagram

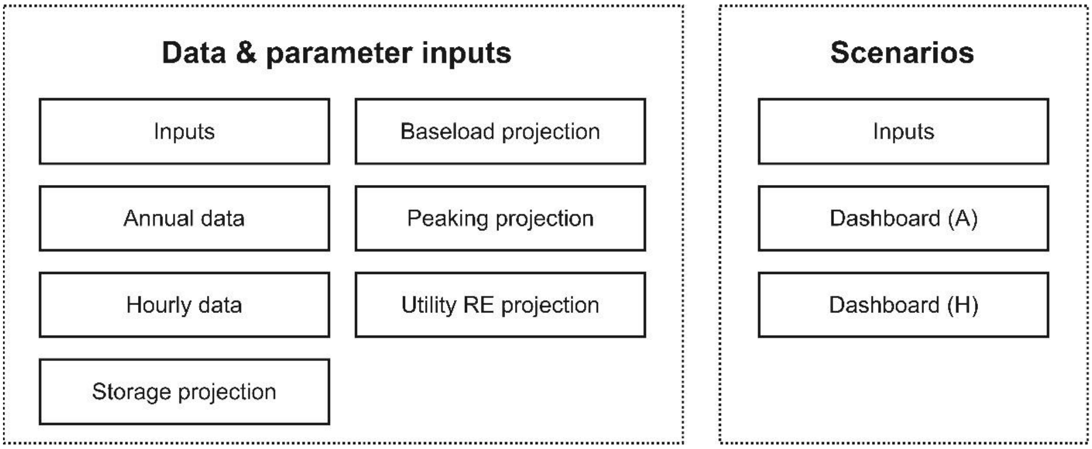


(source: own diagram)

6.2.2 Model inputs

6.2.2.1 Model inputs were split into data inputs, parameter inputs, and scenarios in Figure 6.1 above. Although there are two main data input sheets, there are a number of sheets that allow for more granular changes to the model. Figure 6.2 below provides a mapping for these categories (data and parameter inputs are combined).

Figure 6.2: Mapping to model sheets



(source: own diagram)

6.2.2.2 The sheets that have data and assumptions inputs (as shown in Figure 6.2 above) are described below:

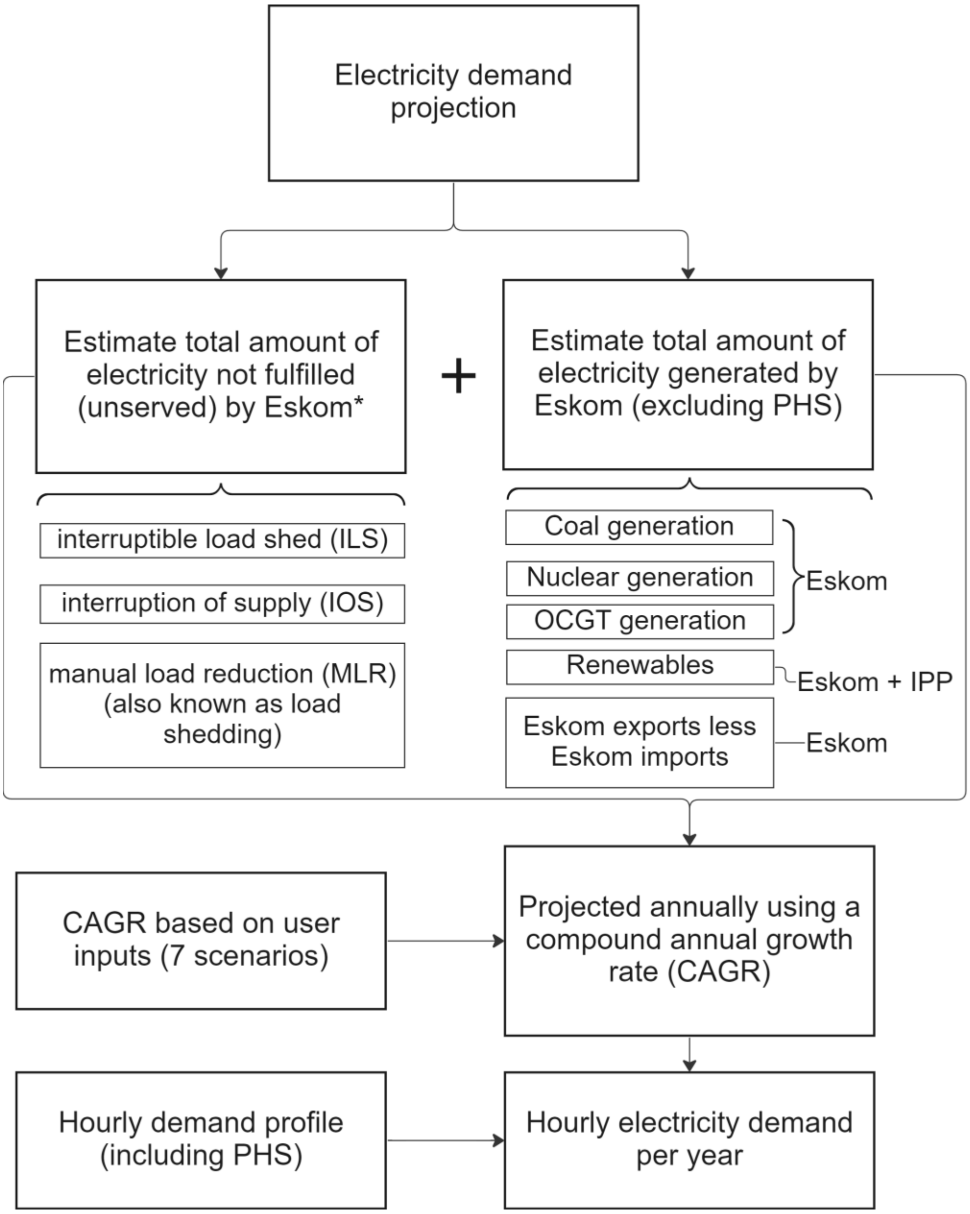
- Annual data: This sheet allows the user to input annual historic and projected data obtained from external sources. Key indicators (including GDP, population size, electricity generation, energy consumption, etc.) are included with the data sources.
- Hourly data: This sheet provides inputs for hourly supply and demand. The default data included are sourced directly from Eskom's hourly data. The hourly data in this sheet is used for apportioning supply and demand over a year (i.e., estimating the impact of daily and seasonal variations in generation and demand).
- Inputs sheet: The inputs sheet is the main sheet for adjusting model assumptions, setting parameters, and selecting scenarios. The inputs sheet has the following sections:
  - Base assumptions
  - Electricity demand growth parameters
  - Embedded generation
  - Hourly parameters
  - Peaking plants
  - Pumped hydro storage (PHS)
  - Battery storage
  - New build generation
  - Scenario selection
  - Key indicator analysis
- Baseload, peaking, and utility RE projection sheets:
  - Each of these sheets have a similar design. They project the generation capacity for each type of generation source over the modelling period. Baseload refers to coal and nuclear, peaking refers to OCGT generation, and utility RE refers to VRE sources.
  - Each sheet allows the user to input the type of generation source, year of commissioning, estimated lifetime, installed capacity, nominal capacity, energy availability factor, and energy utilisation factor. Both total energy

production (MWh per year) and nominal capacity (MW) are projected from 2020 until 2050.
    - Peaking and utility RE obtain new build inputs from the input sheet.
- Storage projection:
    - This sheet projects both the PHS and BESS over the projection period.
    - The sheet has inputs for type of storage, year of commissioning, estimated lifetime, installed generation capacity, nominal generation capacity, storage capacity, round-trip efficiency, charge current, and total charge duration.
- Dashboard (A):
    - Dashboard (A) provides a view of annual electricity demand and generation without considering seasonality. It is intended to provide a high-level view of total demand and supply over the full projection period.
    - Although scenario selection can be done in the inputs sheet, the scenario choices in the input sheet have been linked to dashboard (A) to make it easier for the user to change scenarios within the dashboard. This allows the user to investigate the impact of changes in assumptions on a real-time basis.
- Dashboard (H):
    - Dashboard (H) allows the user to explore scenarios on an hourly basis for a specific year. The dashboard has a “year” input so that the user can change the specific year under consideration.

6.2.3 Demand projection

6.2.3.1 Figure 6.3 below provides a visual representation of demand projection over the modelling period.

Figure 6.3: Demand projection



(source: own diagram)

* To avoid potential double-counting, embedded generation (EG) has not been included in the unserved electricity module.

6.2.3.2 The inputs sheet provides the user with up to seven different electricity demand growth scenarios. The demand growth rate is a CAGR used for projecting the demand from the latest Eskom data (currently 2022) up to 2050. There are four default scenarios – three based on growth rates from the 2019 IRP (30) and one based on South Africa's primary energy consumption CAGR over the period from 2009 to 2019. These scenarios are described in further detail in Section 6.3.1 below.

In addition, there are three placeholders where the user can input their own growth projections.

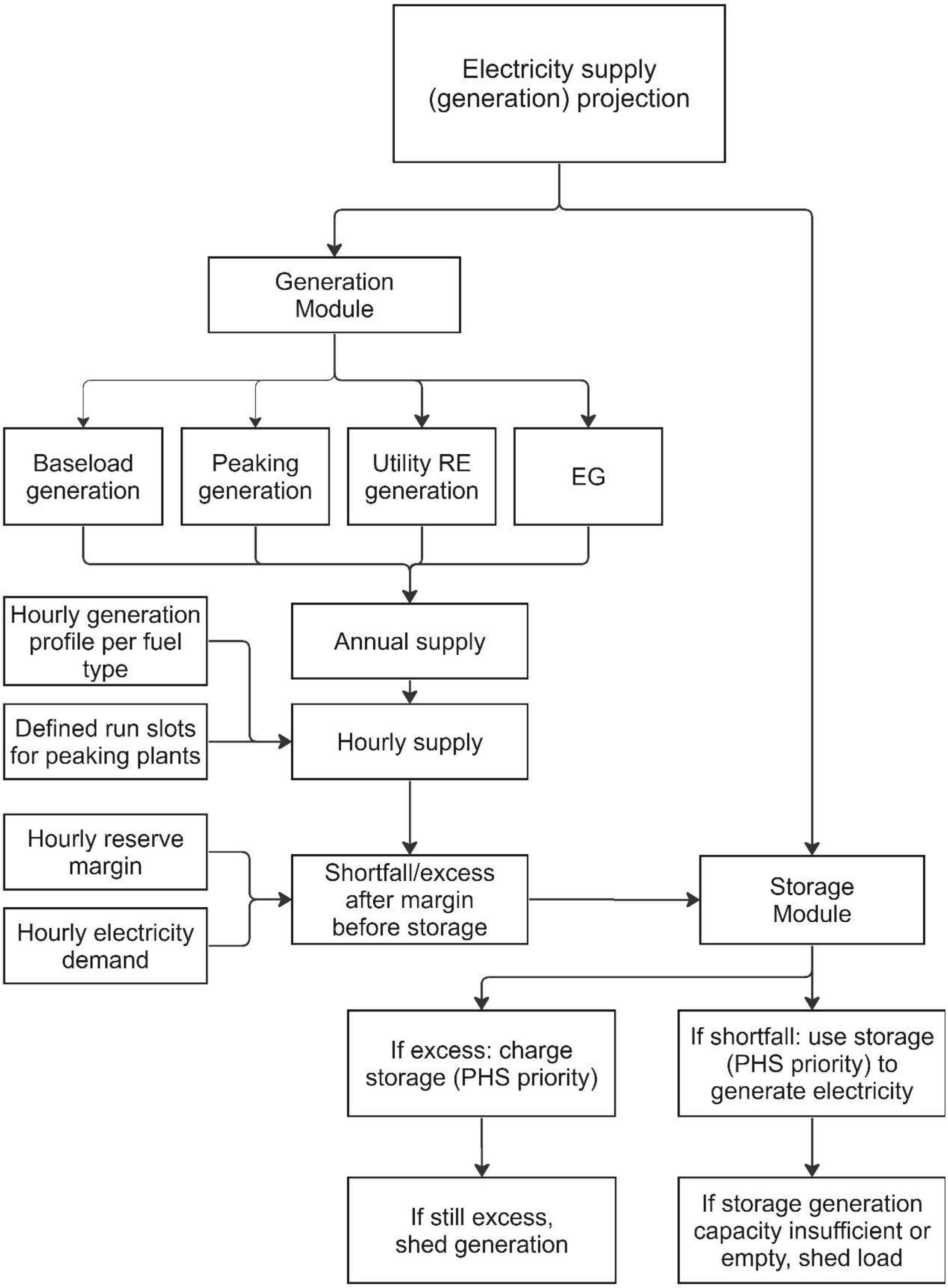
6.2.3.3 Hourly demand is projected for a specific year selected by the user. The hourly demand profile is based on the proportion of annual demand consumed within one hour as a ratio of total annual demand. Demand in MW for a specific hour during a specific year is estimated as the annual demand multiplied by the hourly proportion. The hourly proportion is an input to the model and is based on Eskom's 2019 actual hourly demand profile. Whilst data from 2020 to 2022 were available, it was assumed that those years were impacted by the COVID-19 pandemic and were thus not likely to be a true reflection of the typical demand profile in future. Therefore, it was decided that 2019 would form the basis for the hourly demand profile projections.

6.2.3.4 Whilst PHS demand and supply were ignored from an annual perspective (as PHS reflects a net drain on the system), PHS demand was included when calculating the hourly demand profile to reflect the demand profile evident from peak generation from PHS.

6.2.4 Supply projection

6.2.4.1 Figure 6.4 below provides a visual representation of the supply projection module.

Figure 6.4: Supply projection



(source: own diagram)

6.2.4.2 Total electricity supply is calculated by aggregating electricity supply across baseload, peaking, utility renewables, and embedded generation. Annual electricity supply ignores the net impact of generation and simply provides an annual view of total generation (not truncated for demand). Hourly supply incorporates storage and the impact of hourly excess and shortfall by either charging or discharging the storage.

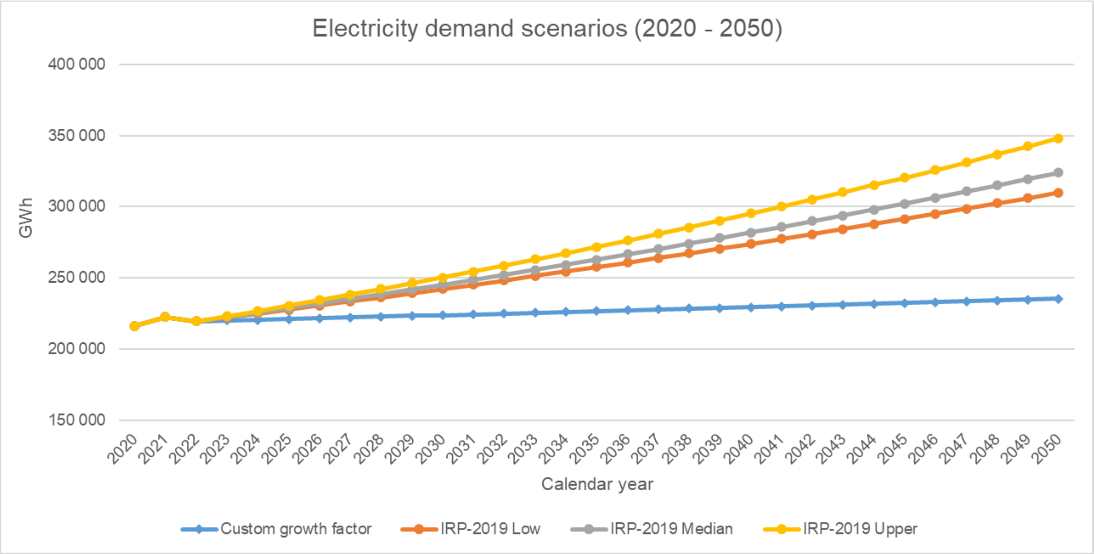
6.3 Model output

6.3.1 The Model is sensitive to certain input assumptions. These assumptions, such as the demand growth rate, auxiliary reserve margin, new build generation, and storage capacity, have a significant impact on the annual and hourly excess or shortfall in capacity.

6.3.1 Demand projection

6.3.1.1 The four default demand scenarios, as described in Section 6.2.3 above, are shown graphically in Figure 6.5 below.

Figure 6.5: Annual demand projection



(source: own chart)

6.3.1.2 From Figure 6.5 above, it can be noted that the three IRP scenarios have a significantly higher electricity growth rate (between 1.24% and 1.66%) than the custom growth factor (0.25%). The custom growth factor scenario is based on the change in overall energy consumption growth in South Africa over the period from 2009 to 2019 whilst the IRP scenarios are based on the 2019 IRP which was assumed to have been based on CSIR modelling. Hereafter the scenarios will be referred to as follows:

- Scenario D1: Custom growth factor (CAGR: 0.25%)
- Scenario D2: IRP-2019 Low (CAGR: 1.24%)
- Scenario D3: IRP-2019 Median (CAGR: 1.40%)
- Scenario D4: IRP-2019 Upper (CAGR: 1.66%)

6.3.1.3 All further scenario analyses in this paper were based on scenario D1. This assumes a higher rate of electricity growth than was seen in the last decade although it is substantially lower than the growth rates in scenarios D2, D3, and D4. There were two reasons why the default model projections were based on a relatively low CAGR, namely, (i) when comparing actual electricity growth to past IRP projections, it seems that the IRPs have substantially overestimated electricity demand growth and (ii) electricity demand is constrained by growth in supply. Growth in electricity supply has historically been constrained. It was only recently that a marked increase in financially viable options for embedded generation (largely rooftop solar) prompted a surge in adoption of embedded generation and storage. Future research could focus on a bottom-up approach to electricity demand growth over time, taking into account pricing impacts, suppressed demand, and growth in embedded generation.

6.3.2 Supply

6.3.2.1 The model is parameterised with the following three main build scenarios:

1. Supply scenario S1: No new build
2. Supply scenario S2: New build was partially based on the 2019 IRP and extended to 2050 by assuming constant additional supply. Based on the new build for generation and storage, S2 can be described as follows:
   a. Solar PV: 1 GW per year in 2023, 2025, 2028 and every year thereafter
   b. Solar CSP: 0.1 GW per year from 2025 onwards
   c. Wind: 1.6 GW per year from 2023 onwards
   d. OCGT: total of 3 GW by 2027, no further build
   e. Battery: 513 MWh in 2023, 1.575 GWh in 2029, 2.5 GWh in 2030 and every year thereafter
3. Supply scenario S3: This is an accelerated new build programme. Based on the new build for generation and storage, S3 can be described as follows:
   a. Solar PV: 1 GW in 2023, 1.5 GW in 2024, and every year thereafter
   b. Solar CSP: 100 MW in 2025, increasing steadily to 0.5 GW per year by 2033 and every year thereafter
   c. Wind: 1.6 GW in 2023, increasing to 3 GW per year by 2026 and every year thereafter
   d. OCGT: total of 3 GW by 2027, 0.1 GW per year thereafter
   e. Battery: 513 MWh in 2023, increasing steadily to 5 GWh per year by 2028 and every year thereafter

6.3.2.2 The Inputs sheet of the Model will provide the specific details of each of the supply scenarios. The supply scenarios (S1, S2 and S3) described above include an allowance for storage. Scenario S1 could be characterised as being a ‘no response’ scenario to the electricity crisis, Scenario S2 a slow to medium response, and Scenario S3 a quick response to the electricity crisis. These scenarios were intended to provide a view of the sensitivity of the electricity system to various levels of additional generation and storage capacity.

6.3.2.3 In the figures below, the total new installed generation and storage capacity in MW and MWh respectively, and cost (Rm) are shown separately for each of the scenarios above.

Table 6.1: New build generation (MW) by scenario

	New build generation (MW) (solar PV & CSP, wind, OCGT)		
Period	**Scenario 1**	**Scenario 2**	**Scenario 3**
2023 - 2030	-	21 400	37 250
2031 - 2040	-	27 000	50 850
2041 - 2050	-	27 000	51 000
Total	**-**	**75 400**	**139 100**

Table 6.2: New build generation cost (Rm) by scenario

	New build generation cost (Rm) (solar PV & CSP, wind, OCGT)		
Period	**Scenario 1**	**Scenario 2**	**Scenario 3**
2023 - 2030	-	516 061	913 818
2031 - 2040	-	659 272	1 453 166
2041 - 2050	-	659 272	1 466 905
Total	**-**	**1 834 604**	**3 833 889**

Table 6.3: New build storage (MWh) by scenario

	New build storage (MWh) (BESS)		
Period	**Scenario 1**	**Scenario 2**	**Scenario 3**
2023 - 2030	-	4 588	27 565
2031 - 2040	-	25 000	50 000
2041 - 2050	-	25 000	50 000
Total	**-**	**54 588**	**127 565**

Table 6.4: New build storage cost (Rm) by scenario

	New build storage cost (Rm) (BESS)		
Period	**Scenario 1**	**Scenario 2**	**Scenario 3**
2023 - 2030	-	23 457	144 608
2031 - 2040	-	111 250	222 500
2041 - 2050	-	86 250	172 500
Total	**-**	**220 957**	**539 607**

6.3.2.4 The overall build cost of S3 is markedly more costly than S2 but also reduces the impact of load shedding significantly. The overall cost estimates of new build cost per generation and storage type were obtained from various public sources. In Table 6.5 below, the capital expenditure and cost of unserved electricity for S1, S2, and S3 from 2023 until 2035 are compared.

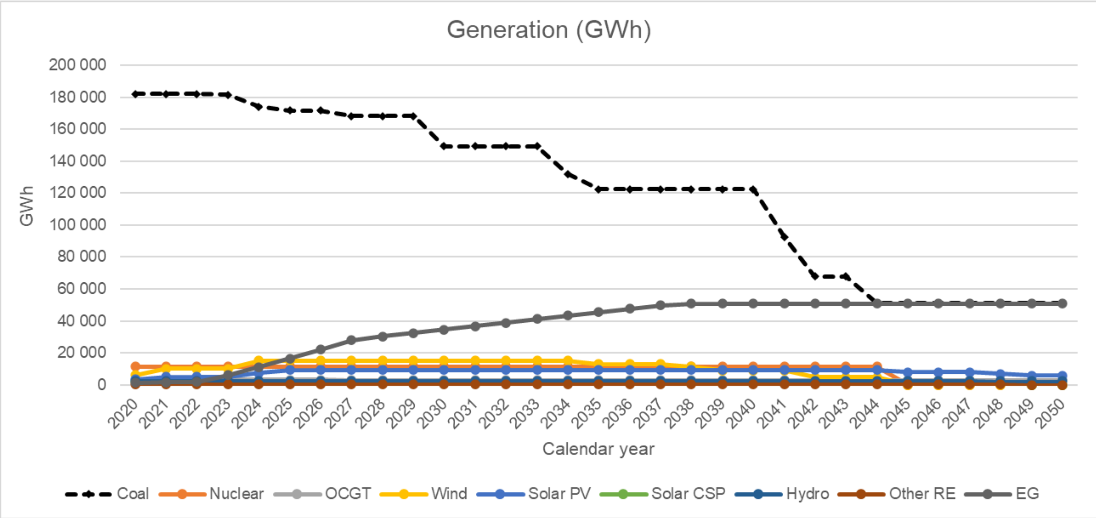
Table 6.5: Cost comparison of demand scenarios per year (2023-2035)

Build scenario	Scenario S1			Scenario S2			Scenario S3		
Year	**Unserved electricity cost (Rm)**	**New build cost (Rm)**	**Total (Rm)**	**Unserved electricity cost (Rm)**	**New build cost (Rm)**	**Total (Rm)**	**Unserved electricity cost (Rm)**	**New build cost (Rm)**	**Total (Rm)**
2023	505 872	-	505 872	165 101	59 692	224 793	165 103	59 692	224 795
2024	368 959	-	368 959	43 501	59 089	102 589	22 045	108 019	130 064
2025	326 296	-	326 296	17 383	65 927	83 310	3 866	110 367	114 233
2026	278 422	-	278 422	7 061	44 915	51 976	128	131 269	131 397
2027	414 961	-	414 961	5 233	91 581	96 815	-	187 464	187 464
2028	425 766	-	425 766	3 480	65 927	69 407	-	149 792	149 792
2029	438 127	-	438 127	1 418	73 960	75 377	-	153 872	153 872
2030	1 486 541	-	1 486 541	47 903	78 427	126 330	-	157 951	157 951
2031	1 493 969	-	1 493 969	26 759	78 177	104 936	-	162 031	162 031
2032	1 503 765	-	1 503 765	15 497	77 927	93 425	-	166 111	166 111
2033	1 515 581	-	1 515 581	9 416	77 677	87 093	-	170 191	170 191
2034	2 523 729	-	2 523 729	68 549	77 427	145 976	-	169 691	169 691
2035	3 233 374	-	3 233 374	135 225	77 177	212 403	284	169 191	169 474
Total	**14 515 364**	**-**	**14 515 364**	**546 527**	**927 903**	**1 474 430**	**191 426**	**1 895 639**	**2 087 065**

6.3.2.5 Table 6.5 illustrates the exponentially increasing cost of not building new generation. While the cost of unserved electricity is a crude metric, it provides a broad indication of the downside risk of not taking action. At higher levels of electricity shortfall, the economic impact might be reduced as more of the formal sector moves off grid and various other second-order impacts dominate the electricity landscape. This would require a more granular approach where energy substitution is explicitly modelled. Whilst scenario S2 is 'cheaper' than scenario S3 (R1.5 trillion relative to R2.1 trillion), it still results in significant unserved electricity (load shedding) over time and potentially inhibits economic growth. Both S2 and S3 assume substantial additional generation coming online from 2023 onwards. Practical limitations are likely to have an impact on the speed at which generation and storage capacity can be brought online. In this regard, the output from this model is not intended to be used as advice but rather to explore different demand, supply, and storage scenarios.

6.3.2.6 Figure 6.7 below illustrates the annual supply across various fuel types. This provides a view before any new generation build (S1). The reference to "new build" generation does not include embedded generation (EG) as new build EG is incorporated into all scenarios.

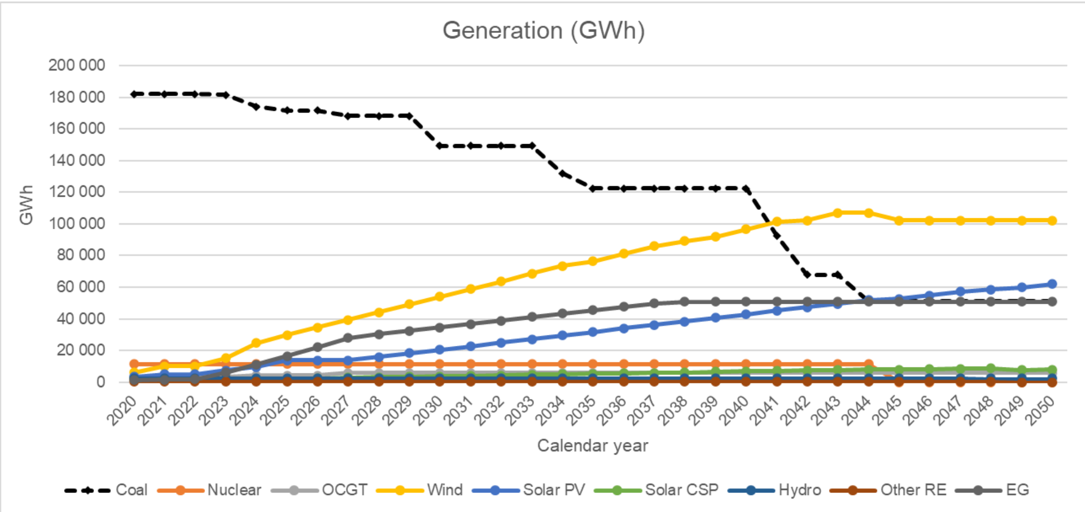
Figure 6.7: Annual generation without new build (S1)



(source: own chart)

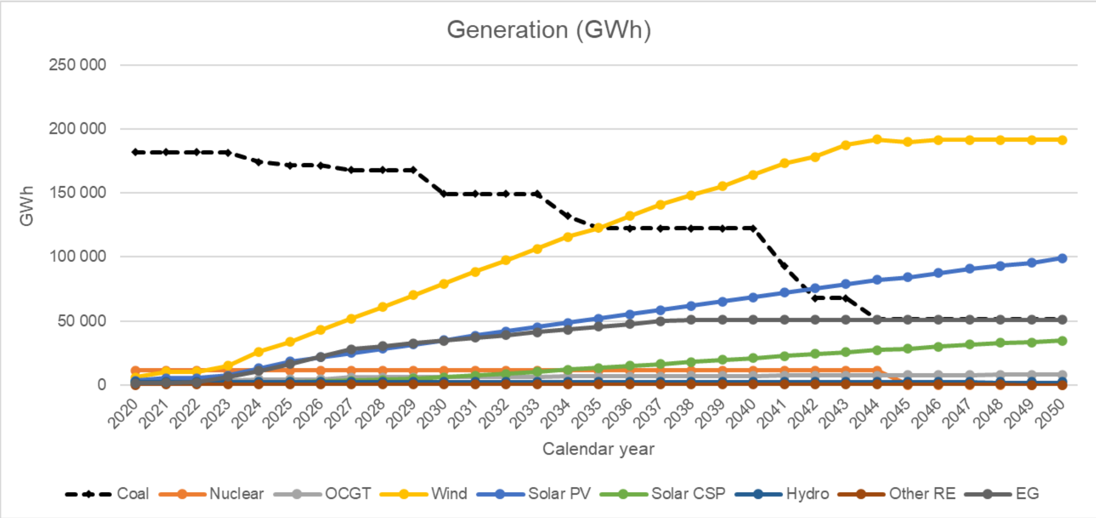
6.3.2.7 Given the dominance of coal in the South African electricity generation context, it is clear from Figure 6.7 that additional generation will be required (assuming level or increasing demand) as Eskom's old coal generation fleet is decommissioned. Based on Table 6.5, 2030 marks a critical turning point in terms of electricity security. Under scenario S1, annual shortfall increases from 4 533 GWh in 2029 to 16 434 GWh in 2030 (equivalent to approximately twice the load shedding recorded in 2022).

Figure 6.8: Annual generation with new build (S2)



(source: own chart)

Figure 6.9: Annual generation with new build (S3)



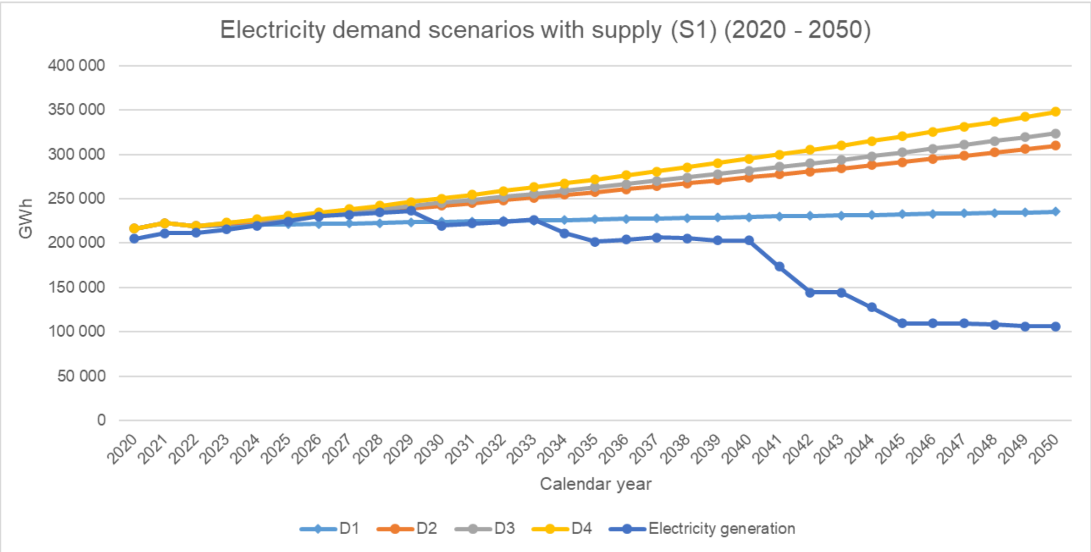
(source: own chart)

6.3.2.8 Figures 6.8 and 6.9 illustrate the substantial new wind and solar generation introduced in scenarios S2 and S3.

6.3.3 Demand and supply – Scenario S1

6.3.3.1 Annual supply is illustrated against annual demand in Figure 6.10 below. This is the view before incorporating any new power plants (other than embedded generation).

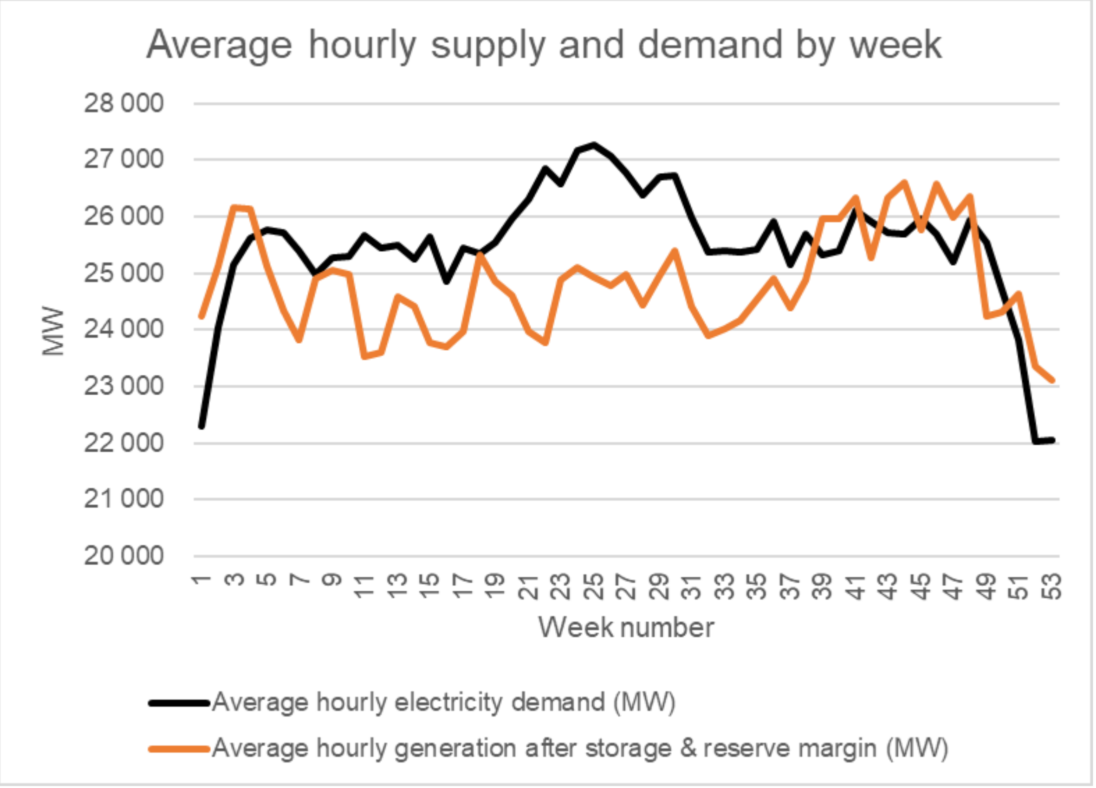
Figure 6.10: Annual generation (scenario S1) and various demand scenarios (D1, D2, D3, D4)



(source: own chart)

6.3.3.2 From Figure 6.10 above, it can be noted that, up to 2029, the total annual generation (due to increases in embedded generation) almost meets demand. Thereafter supply starts decreasing with the accelerated decommissioning of the coal fleet. However, this view implicitly assumes that generation can be shifted between seasons as needed. It should be emphasised that the above graph does not reflect seasonal and daily variation in electricity supply and demand. There is substantial electricity shortfall when viewing average electricity demand and supply on a weekly and hourly basis as illustrated in Figure 6.11 below, shown for 2030.

Figure 6.11: Average hourly electricity supply (S1) and demand (D1) by week for 2030



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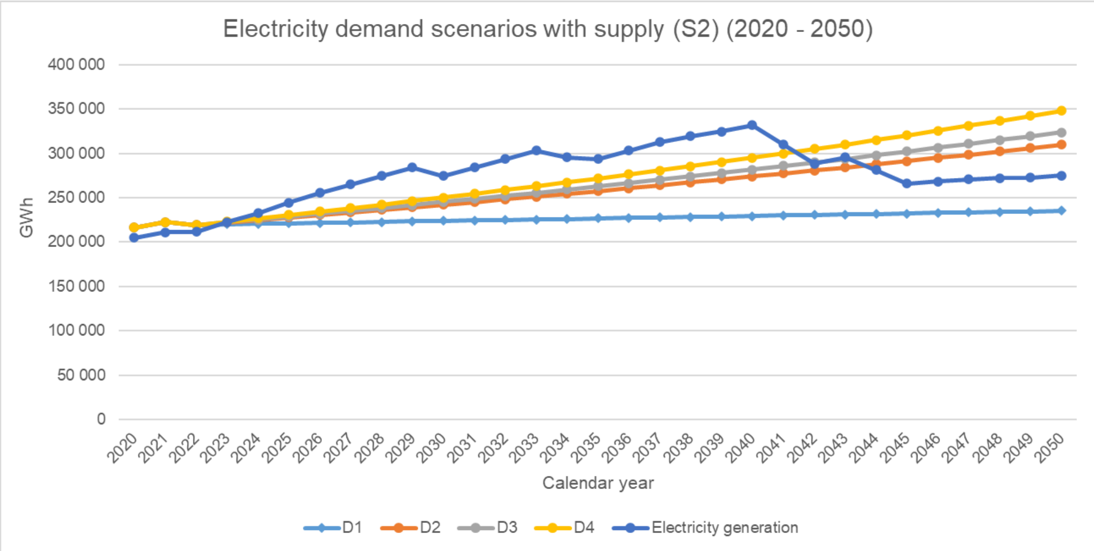
6.3.4 Demand and supply – Scenario S2

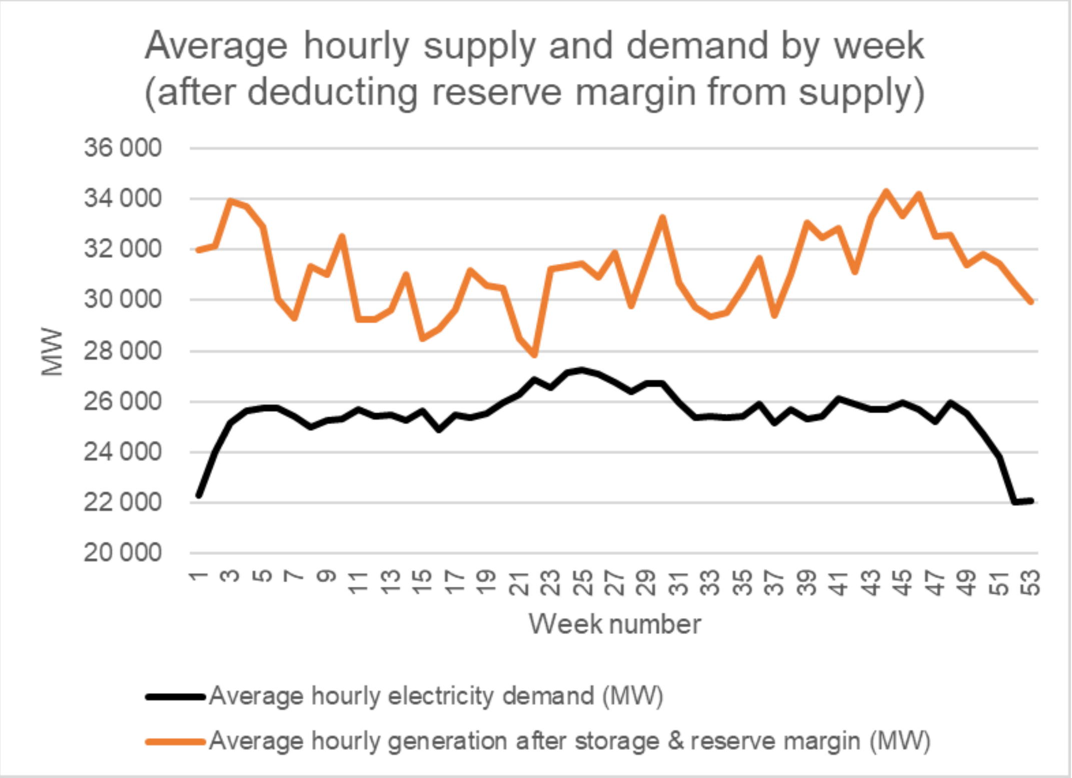
Figure 6.12: Annual generation (S2) and various demand scenarios (D1, D2, D3, D4)



(source: own chart)

6.3.4.1 Figure 6.12 shows the impact of scenario S2, i.e., a slow to medium response to new generation capacity. As previously stated, generation is not truncated to supply. Up to 2040, total generation capacity increases substantially, but then it reduces as significant portions of the coal fleet are decommissioned. While annual generation exceeds annual demand for scenario D1, it does not appropriately address potential energy shortfalls under the other three scenarios.

Figure 6.13: Average hourly electricity supply (S2) and demand (D1) by week (2030)

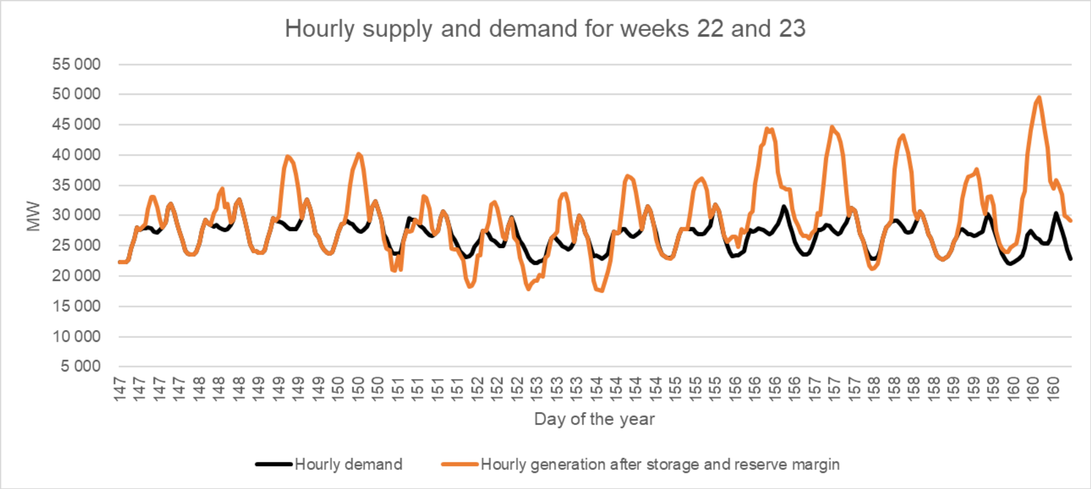


(source: own chart)

6.3.4.2 When comparing Figures 6.11 and 6.13, the impact of new generation is clearly seen in Figure 6.13 with the widening of the margin between supply and demand. This is most prevalent in the summer months (first and last 12 weeks of the year) due to the high penetration of solar.

6.3.4.3 Figure 6.13 indicates that average electricity demand significantly exceeds average electricity supply across all weeks of the year. However, the weekly averaging masks the shortfall that is evident when viewed on an hourly basis during certain winter weeks. Based on the demand profile in the model, weeks 22 and 23 are particularly problematic from a supply perspective (see the dip in Figure 6.13 above). Figure 6.14 below illustrates the demand and supply over weeks 22 and 23; the generation shortfall on days 152, 153, and 154 is evident.

Figure 6.14: Hourly electricity supply (S2) and demand (D1) during weeks 22 and 23 (2030)



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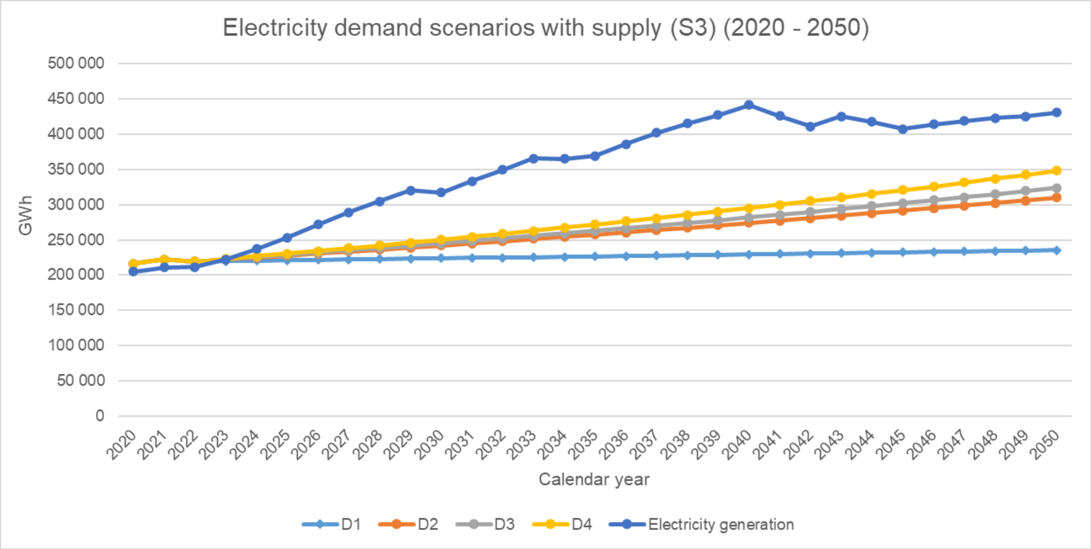
6.3.4.4 As illustrated in Figure 6.14 above, generation substantially exceeds demand during most days. However, the dips where generation is insufficient to match demand typically occur overnight (during the early morning hours) due to insufficient storage capacity. If additional storage capacity was added it would assist in bridging this gap. Alternatively, additional peaking plants (such as OCGT) would be able to assist to bridge this gap during times of insufficient storage.

6.3.4.5 Future research could focus on analysing winter months and the potential shortfall due to lack of VRE generation during cloudy and wind-still days. Ideally, green fuels (such as hydrogen) produced during times with excess generation capacity would be stored and then consumed during those times when there is insufficient VRE generation capacity. Additional modelling that specifically focuses on the winter months could be done to estimate the impact of extreme climate events (such as weeks without wind coinciding with long-duration cloud cover). Diversified generation sources such as biomass, wave, and tidal, would assist in reducing the impact of specific climate events. To provide diversification in the generation mix, the generation capacity from these sources should ideally not be highly positively correlated. Geographically diversified VRE would also reduce the risk of localised weather events having a disproportionate impact on generation and grid stability.

6.3.5 Demand and supply – Scenario S3

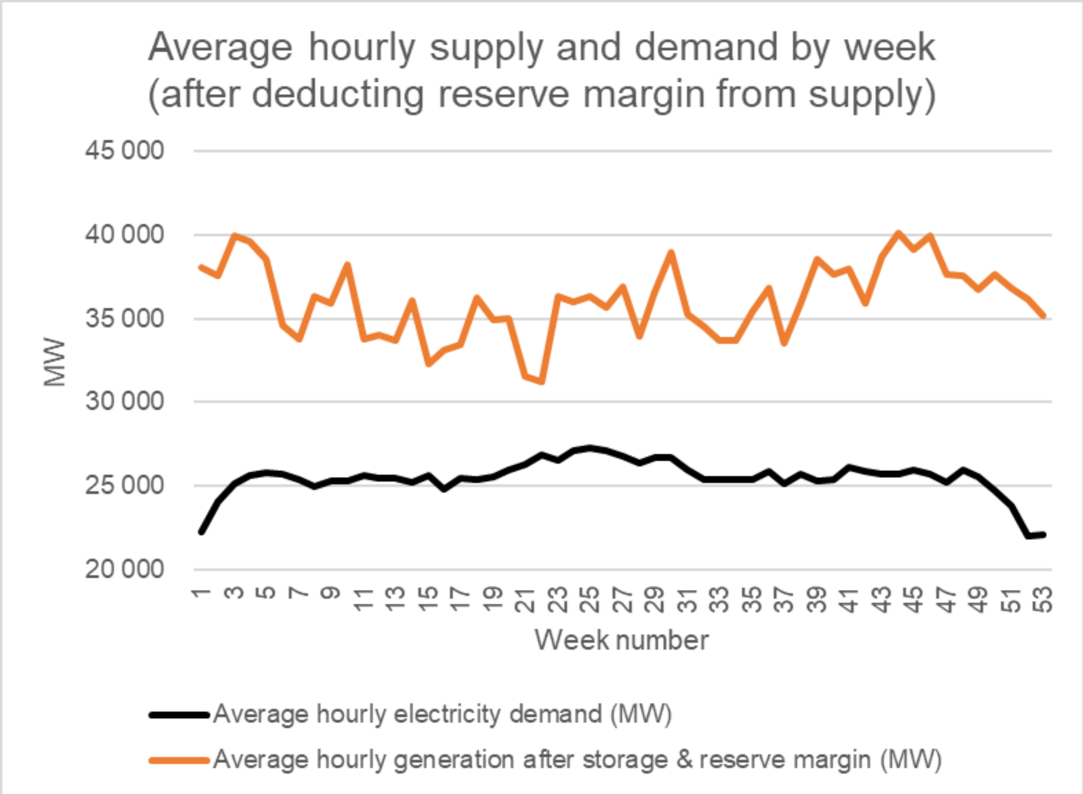
Figure 6.15: Annual generation (scenario S3) and various demand scenarios (D1, D2, D3, D4)



(source: own chart)

6.3.5.1 When compared to Figure 6.12, the significant additional investment in new generation in scenario S3 is evident in Figure 6.15. Even when compared to the highest-demand growth scenario (D4), generation still outstrips demand on an annual basis. Nevertheless, it is again important that the adequacy of generation and storage capacity should take seasonal and daily fluctuations into account.

Figure 6.16: Average hourly electricity supply (S3) and demand (D1) by week (2030)

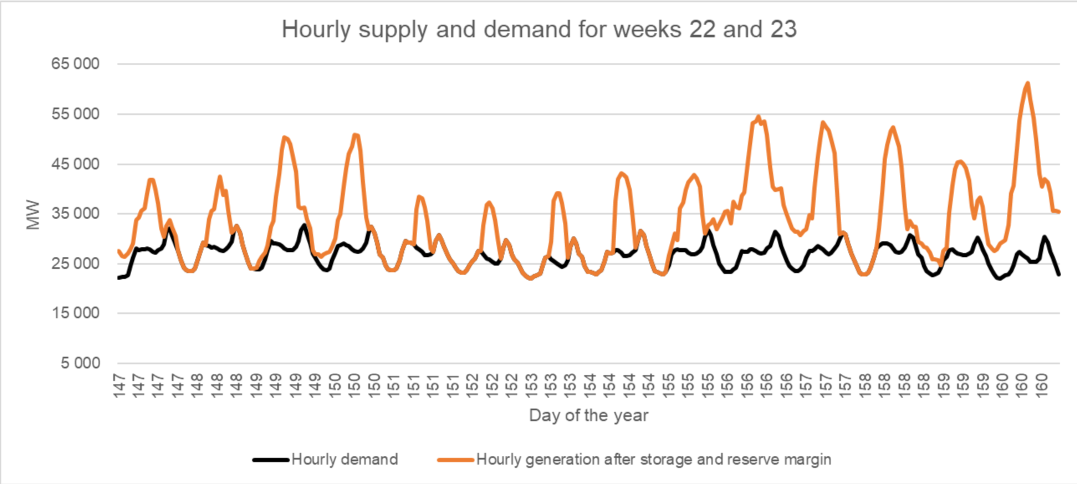


(source: own chart)

6.3.5.2 Under scenario S3, the peak hourly generation exceeds 60 GW and average hourly generation varies between 32 and 41 GW. In contrast, demand varies between 25 and 34 GW. As previously illustrated, VRE generation substantially exceeds demand at times but introduces substantial daily and seasonal variation in supply.

6.3.5.3 Scenario S3 provides sufficient generation in 2030 to ensure that generation and storage exceed demand for every hour. Figure 6.17 below illustrates supply and demand during weeks 22 and 23 and provides an interesting comparison when contrasted to Figure 6.14 above. Whilst the dip in weeks 22 and 23 is still clearly seen, there is a sufficient buffer (i.e., storage) to ensure that supply exceeds demand even on days with little VRE generation.

Figure 6.17: Hourly electricity supply (S3) and demand (D1) during weeks 22 and 23 (2030)

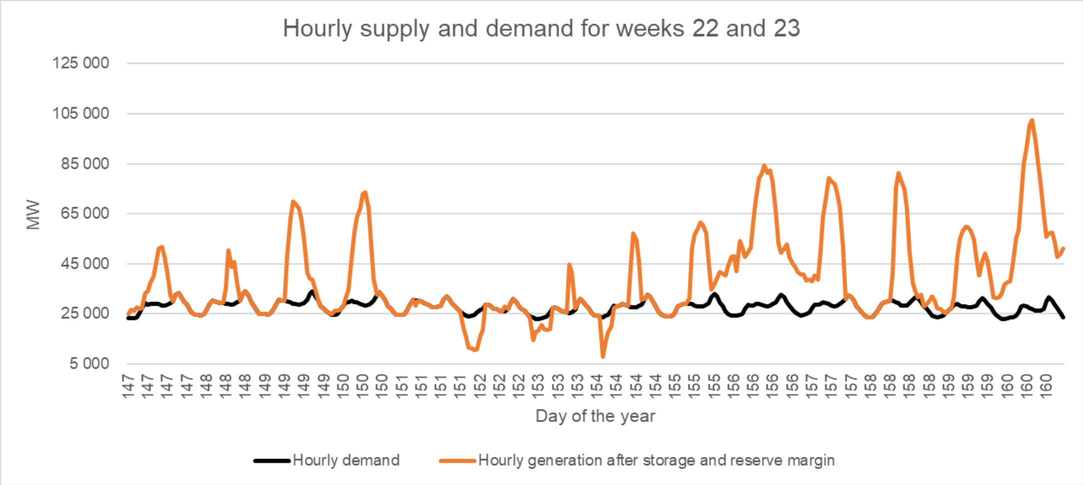


(source: own chart)

6.3.5.4 Under scenario S3, the electricity generation matches demand throughout 2030. In this scenario, renewables and non-renewables have approximately equivalent generation penetration in 2030 (i.e., a 50/50 split). This split is aligned with the IRENA renewable energy roadmap for South Africa mentioned in Section 4.2.

6.3.5.5 Post 2040, the renewable penetration level exceeds 70%. For comparison, the hourly supply and demand for weeks 22 and 23 were investigated in 2045. At this point, the high level of VRE creates challenges in terms of managing the grid during extreme weather conditions. The supply shortfalls in Figure 6.18 relative to Figure 6.17 can be noted. The supply shortfalls in 2045 are partly due to the fixed demand profile that was assumed over time. It would be expected that electricity usage patterns would look different by 2045 as consumers become more aware of the cost of using electricity during the winter and overnight. Nevertheless, this view highlights the challenges that VRE brings to any electricity system and the need for storage and innovative solutions to be developed to deal with non-dispatchable variable generation.

Figure 6.18: Hourly electricity supply (S3) and demand (D1) during weeks 22 and 23 (2045)



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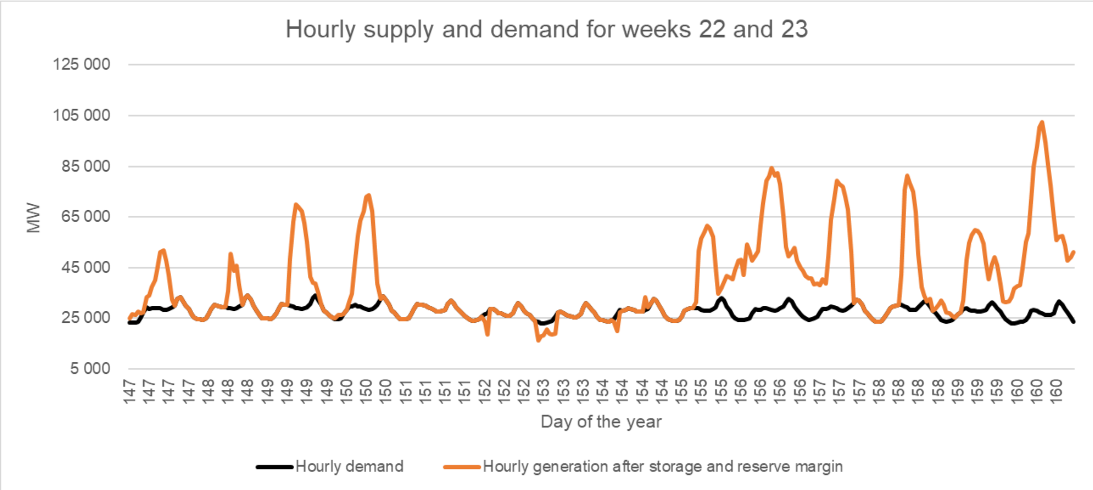
6.3.5.6 Figure 6.18 illustrates the highly variable nature of renewables. This is a problem that must be solved – one solution would be to add more storage. If additional storage was not capped at 5 GWh per year but at 10 GWh, the generation profile would improve. This revised view is shown in Figure 6.19 below. Constructing 10 GWh of storage per year is very ambitious and this view is provided for illustrative purposes only.

Figure 6.19: Hourly electricity supply (S3) and demand (D1) during weeks 22 and 23 with extra storage (2045)



(source: own chart)

6.3.5.7 While some generation shortfall is still evident in days 152 and 153, it is largely eliminated by the incorporation of additional storage capacity. Assuming additional battery storage of up to 10 GWh per year results in a total of around 33 GWh of storage capacity by 2030 and 181 GWh of storage by 2045. Battery storage of 181 GWh would be equivalent to approximately three times the current pumped storage capacity.

6.3.5.8 IEA's grid-scale storage analysis (infrastructure deep dive) is still in progress (135). Their initial conclusion was that grid-scale battery storage "needs to grow significantly". As mentioned previously, this translates to a total of 680 GW of global storage capacity by 2030. At 33 GWh of storage in 2030, South Africa's proportion of global storage would equate to just under 5%.

6.4 Model limitations

6.4.1 The Model has certain limitations – these include several factors that can impact its performance and accuracy and real-world applicability. While the Model may be effective for certain analyses, it is important to be aware of its limitations in order to use it appropriately and effectively. The model's limitations include:

- The Model does not incorporate geographical variability in generation or grid capacity constraints. Therefore, any new generation build must first ensure that there is sufficient grid capacity. This is a significant limitation and must be considered when making conclusions based on the Model.
- The hourly supply and demand were estimated based on generation and demand profiles of the 2019 calendar year. The hourly profiles of the 2019-calendar year might not be reflective of changing supply and demand profiles in future. While supply profiles for a specific generation technology might not change substantially, even small changes in the demand profile can have marked impacts on generation and storage requirements.
- Certain simplifying assumptions have been made with regard to PHS. There are likely to be technical limitations to the ramp-up or ramp-down pumping and generation rates. In addition, there might be alternative water requirements that could limit generation capacity during certain periods of the year, or during droughts.
- Hourly projections assume that storage levels start at 100% each year. The storage level at the start of the year would naturally depend on the storage levels at the end of the previous year.
- No allowance was made for generation or storage capacity degradation over time.
- EAF and EUF were assumed constant from 2022 onwards. This would be expected to change and the Model can easily be adapted to cater for such changes.
- Demand management approaches were not used as part of the hourly demand projection. The excess or shortfall is shown prior to demand management (ILS, IOS, and MLR). Incorporating demand management would reduce the peak demand and reduce the size of the storage capacity required.
- The auxiliary and emergency reserve margins were treated rather simplistically. Eskom would be able to provide further perspectives on reasonable levels of margins at various load levels.
- The auxiliary reserve is calibrated by aligning the Model's 2022 load-shedding hours to the hours calculated by the CSIR. This results in an auxiliary reserve margin of around 3% – which is low when compared to Eskom's target of 15%. If the auxiliary reserve margin is increased to 15%, it results in unrealistically high load shedding (assuming that past reserve margins were appropriate). Future modelling could incorporate more nuance into the auxiliary reserve margin based on feedback from Eskom.

- No limitations on the availability of fuel supply have been incorporated into the Model. This would specifically be applicable to OCGT plant storage facilities that can only accept liquid fuels at a certain rate.
- Peaking plants have been assumed to run on a fixed schedule. Optimising use of peaking plants would assist in reducing energy shortages. As VRE increases, the use of peaking plants will become more important.

6.4.2 This Model provides a deterministic view of electricity supply and demand. The Model can, however, be extended to provide a stochastic view; incorporating stochastic elements would allow the user to investigate the impact of extreme events (e.g., adverse weather conditions) on both supply and demand. By simulating various weather, demand, and supply scenarios, grid operators could determine appropriate levels of supply and storage that would be able to shield the grid against downside risks based on a certain risk measure. Such a model would require a meteorological simulation that is mapped to generation and demand profiles.

6.4.3 More advanced simulation tools could include digital twin models that can be used to replicate the electrical grid and model localised impacts of extreme events. Ideally, grid capacity should be incorporated into such a model to ensure that electricity can be produced and transported to where it is required.

6.5 Model conclusions

6.5.1 Based on the Model's output, it was clear that there is a critical need for new generation capacity. The cost of unserved electricity is staggering and vastly outstrips the cost of building substantial additional generation capacity. The Model also highlights the challenges of maintaining a reliable and constant electricity supply with variable electricity generators. Of the three scenarios investigated, scenario S3 was the only one that succeeded in eliminating electricity shortages by 2030. Scenario S3 requires that new generation must be built at a scale that far exceeds the proposed infrastructure investments highlighted in the 2019 IRP. Scenario S3 would cost approximately R1.1 trillion over the period from 2023 to 2030 and bring 37 GW of generation online (at a cost of R25bn per GW) and 27 GWh of storage (at a cost of R5.25bn per GWh).

6.5.2 VRE is currently one of the cheapest and fastest ways of getting new generation capacity online. However, renewable generation that is dependent on weather conditions is variable by its nature. To balance the variable nature of VRE, storage becomes increasingly important. Integrating high levels of VRE onto the grid and ensuring stability is challenging but not unattainable. As embedded generation increases, the grid will progressively see new demand and supply profiles emerge. It therefore becomes inevitable that grid operators must develop the necessary resilience to adapt to this changing environment.

6.5.3 While storage is important for VRE, storage can also play a crucial role in alleviating grid capacity constraints. As noted in Chapter 4, the transformation of the grid into a smart grid coupled with storage will allow the grid operator to strategically start using solutions such as VPLs and VPPs. These are essentially ways of distributing storage and generation to improve the overall capacity of the grid in a cost-effective and efficient way.

7. The way forward

7.1 Overview

7.1.1 This paper started by providing a broad overview of the energy sector with a specific focus on the current status of the energy system in South Africa. It went on to highlight the various electricity generation and demand management technologies used globally to manage the electricity grid. This was followed by a brief discussion of South Africa's energy crisis and the approaches taken in an attempt to address the crisis. Potential solutions to alleviating electricity shortfalls were then discussed as part of the modelling chapter where electricity supply and demand were projected for the period from 2020 to 2050.

7.1.2 As noted in Chapter 1, electricity is critical to the operation of today's economy. Globally, economies are moving towards increased electrification in an attempt to reduce GHG emissions. Given the integral nature of electricity in South Africa, it is clear that a sufficient and reliable electricity supply is critical to the growth of South Africa's economy.

7.2 Potential avenues to alleviating the electricity crisis

7.2.1 Chapter 5 painted a bleak picture of the electricity situation in South Africa. Section 5.4.1 highlighted the success of the REI4P but emphasised the urgent need for new generation capacity. This raises the question of what possible solutions are available to improve electricity security in South Africa as quickly as possible, while taking into account the overall constraints.

7.2.2 It should be noted that, although this paper has delved into some of the more technical aspects of electricity supply and demand, most actuaries are not technical experts on electricity. Therefore, the solutions proposed in this paper should be subjected to rigorous technical modelling by electricity experts. Nevertheless, this section highlights what has been discussed and offers potential solutions to the electricity crisis we face.

7.2.3 South Africa is facing an acute electricity shortage. This is attributable to a variety of factors, including poor performance of the coal generation fleet, lack of new generation capacity, running of current plants above design specification, low quality and inadequate maintenance, lack of grid capacity, poor planning, sabotage, theft, and corruption.

7.2.4 Coal has historically been used to produce the bulk of South Africa's electricity. However, Eskom's coal fleet has become unreliable for various reasons. A significant portion of the coal fleet is scheduled to be decommissioned over the next 30 years due to the age of most of the power plants. Globally, coal power plants are viewed as high GHG emitters and many countries are weary of constructing new coal power plants. Coal power plants are capital intensive with long construction timelines. South Africa's modern coal power plants (i.e., Medupi and Kusile) have proven to be unreliable. It is also likely that obtaining financing for coal power plants would be challenging as many countries have committed to reducing their GHG impacts and are avoiding investments into coal-based generation. In this regard, South Africa has formally committed to move to renewables as evidenced in its NDC.

7.2.5 From an emissions perspective, nuclear energy does not face the same challenges as coal. However, nuclear power plants have very long build durations, are capital intensive, and are complex to operate and maintain. In addition, nuclear has become less popular due to the number of nuclear disasters over the last few decades as well as the radioactive waste produced as part of the fission process.

7.2.6 South Africa does not have any new coal or nuclear plants under construction. With build durations often exceeding 10 years for coal or nuclear, these are not viable options for addressing South Africa's electricity shortage in the short term (within the next 10 years).

7.2.7 Gas power plants are popular across the world due to their relatively short construction timelines, reduced GHG emissions when compared to that of coal, and existing supply and infrastructure of natural gas in many developed countries. South Africa does not have utility-scale power plants that operate on natural gas and the liquid-based generators that are currently operational in South Africa either use diesel or kerosene as their fuel source. There are also no large operational gas extraction facilities (although the prospecting seems to be promising) in the country. For gas to become a dominant source of generation for South Africa, our generators would require an abundant source of natural gas, something that is presently not readily available. One potential source of gas for South Africa is the gas pipeline from Mozambique. Alternatively, gas could be shipped in – this could require substantial investment in gas infrastructure.

7.2.8 Renewable energy sources have become the worldwide solution to reducing GHG emissions. Large solar and wind installations are becoming commonplace due to the significant reduction in the cost of VRE over the last decade. The commissioning of various projects in the REI4P together with the contribution of embedded generation are adding to a significant increase in VRE penetration in South Africa. However, VRE requires significant storage to be able to approach grid-scale generation. Globally, a large number of different types of energy storage projects are in various stages of development.

7.2.9 The 2019 IRP (30) noted the following factors in relation to projecting electricity demand and intensity:

- The prevalence of embedded generation is increasing. Household, commercial, and industrial customers are installing PV systems to supplement Eskom electricity.
- Higher electricity prices are driving electricity customers to move to energy efficient appliances.
- There is an increasing trend in using LPG for cooking and heating. This could decrease overall energy consumption as well as peak demand.

7.2.10 When analysing the output from the Model, the need for immediate new generation is apparent. Due to the impact of load shedding, private electricity producers (embedded generation) are projected to bring significant new behind-the-meter generation online in the next few years. This additional generation is projected to alleviate a portion of the generation shortfall.

7.2.11 Embedded generation will not be sufficient to offset the decommissioning of large portions of South Africa's coal fleet. A reduction of 11 GW in coal generation capacity in the period between 2029 and 2034 is forecasted and the impact of this is already evident in the substantial increase in the projected cost of unserved electricity from 2030 (as noted in Section 6.3.2). Supply scenario S3 alleviates load shedding by 2030 by assuming new generation of 37 GW and new storage of 27 GWH by 2030 at a cost of R1.1 trillion. However, this will not meet electrical demand indefinitely as the challenges of variable generation become evident at high levels of VRE penetration (post 2040). A supply-side-only intervention will not be efficient in ensuring sufficient and reliable electricity. Demand-side behavioural changes in electricity use accompanied by a range of smart technologies could assist in managing the mismatch between electricity supply and demand.

7.2.12 It is unlikely that a single energy source or storage solution will be the panacea for the electricity crisis. The author envisions that a hybrid solution must be developed to tackle the problem from all sides with buy-in from all members of society. In developing a solution, the following factors could be considered:

1. Data should be considered critical for the electricity utility. Eskom should move towards becoming a platform that brings together electricity suppliers and consumers in a data-centric way. Developing a real-time electricity market will require advanced artificial intelligence models that can assist in grid planning and the optimisation of supply and demand. A smart grid will require data monitoring, measurement, and electricity management hardware and software to ensure that Eskom can implement advanced real-time management of the grid.
2. Short-, medium-, and long-term solutions must be considered. Certain, potentially inefficient solutions might need to be implemented to bridge the electricity shortfall in the short run whilst being entirely replaced over the long run. This will require parallel planning, oversight, and execution.
3. Load shedding hinders economic development. Ongoing and widespread load shedding has been particularly detrimental to the South African economy. More intelligent demand-side solutions should be developed to reduce electricity demand while having a minimal impact on the economy. For example, Internet of Things (IoT) solutions that can switch devices on and off based on the electricity demand and supply, could be considered. This can mimic a low level of load shedding (a type of “soft” load shedding) without having to turn off essential services, which will reduce the impact of load shedding on critical infrastructure such as water and sewage.
4. Currently, utility-scale solar PV and wind are the cheapest energy sources available with a short-build duration and low lifecycle carbon emissions. To reduce the reliance on a single source for generation purposes, a balance of technologies would have to be deployed, i.e., solar, wind, hydro, wave or tidal, biogas, etc. Significant VRE investment will be required in order to produce electricity at prices that are globally competitive and again achieve the international leader status that Eskom once had.
5. Generation should be geographically diversified. This reduces transmission losses, grid congestion, the impact of regional weather variability, and provides the transmission operator with time to expand the grid. In areas where limited grid capacity is available an intelligent way of allocating grid capacity should be considered. For example, rather than only considering the maximum MW coupling to the grid, the grid congestion on a real-time basis should also be considered. This will allow certain generators, using storage, to shift supply to times when the grid is not congested.
6. A substantial increase in VRE will also require substantial new transmission and distribution infrastructure. In addition, due to the intermittent nature of VRE, it will

require large-scale long-term energy storage solutions. Having significant extra supply during midday will allow new industries to take advantage of such near-free electricity to build business models that cater to long-term grid storage. While grid-level long-term storage solutions are still in their infancy (other than PHS), testing of potential options should be done as early as possible to start building the internal capability to manage grid stability. For example, renewable power-to-hydrogen (using electrolysis) is a promising solution (albeit currently inefficient) that can store energy for seasonal variations in electricity consumption. Concepts such as VPPs and VPLs should be investigated as these can improve the efficiency of the current grid. To be able to consider these more advanced grid management concepts, data management should be prioritised (as per point 1 above).

7. South Africa already has electricity links to neighbouring countries from which it imports and exports electricity. These links can be used to form a super-grid (170), allowing countries across Africa to take advantage of renewable energy and limit their dependency on fossil fuels. If South Africa is able to generate excess renewable energy at cost-effective tariffs, this energy can be sold across borders to bolster energy security of other countries. Not only can this be advantageous for South Africa; it could also potentially lift millions of people out of poverty in Southern Africa (171). When used in tandem with other generators (such as the Cahora Bassa Dam in Mozambique), South Africa might be able to further diversify its electricity generation and storage geographically.
8. A range of new storage solutions are being developed, however at this stage it is not clear which storage technology will be most cost-effective and efficient. The approach to implementing new storage solutions should also be diversified. Certain storage solutions can provide ancillary services to improve grid stability whilst others are better suited to slow-ramping long duration supply. The storage solution should be matched to the generator. For example, in high-heat scenarios, flow batteries can perform better than lithium batteries. This use case would be applicable to solar PV as these installations are often located in high-heat areas.
9. The continued operation of the current coal fleet will remain instrumental in improving South Africa's energy security over the short- to medium-term. Whilst the coal fleet will be decommissioned over time, it will provide the necessary electricity generation during the transition period over which new generators can be constructed and the grid be adapted. The EAF of the current coal fleet can be improved if the EUF of the operating plants are reduced to sustainable levels. Possible life extensions could furthermore be considered, if appropriate maintenance is performed and if the corruption and criminal elements in Eskom are dealt with. This can only be done if there is sufficient spare generation capacity available. It is envisioned that this spare capacity could come from renewables.
10. In shifting to a VRE-based electricity generation solution, an increased focus on grid stability will be required.
11. Moving to a new way of operating will require buy-in across various stakeholders in the industry. It will be particularly important to obtain buy-in from Eskom's customers, including individuals, commercial entities, and industrial operators. It cannot be overstated how important it is to ensure that Eskom is not misaligned to the needs of the end-customer. An inclusive and open communication approach should be considered. Peak shaving and demand shifting can be incentivised by sending appropriate economic signals. Intelligently incentivising demand during certain time periods (e.g., through TOU interruptible, day ahead tariffs) can have a substantial impact on the way customers use electricity. Aligning demand with embedded generation in solar rooftop PV and battery

systems will reduce the load on the grid and improve plant performance. This could be further incentivised through subsidies.

12. Regulatory red tape should be reduced and IPPs be provided with regulatory certainty in order to invest in long-term VRE power plants. Governance frameworks, such as those implemented for the REI4P, are of paramount importance in ensuring that projects are successful.
13. All forms of sabotage, theft, corruption, and inappropriate operating practices in the electricity industry must be eliminated and a highly professional operating model must be implemented. As highlighted in the PCC Just Transition Framework, South Africa has committed to reach net-zero GHG emissions by 2050 whilst ensuring that those that are most affected by climate change are put at the centre of the decision-making. The poorest in South Africa are impacted the most by the lack of green and reliable electricity.

7.3 Conclusion

7.3.1 South Africa needs a reliable and sufficient source of electricity to enable long-term economic growth. This paper explored some of the challenges in providing such a source of electricity. South Africa also needs to challenge its historic way of thinking of electricity as an unlimited resource. This requires a paradigm shift across both public and private sectors whereby all users, i.e., individuals, households, businesses, industries, and government become aware of their electricity usage.

7.3.2 Coal has historically provided a cheap and reliable source of electricity to South Africa, yet its coal fleet is ageing and is being plagued by unpredictable breakdowns. Whilst South Africa has an abundance of coal, it will become increasingly challenging to build new coal power stations, given the global shift away from greenhouse gas emitters (such a coal) towards renewable energy sources. Nuclear is an alternative to coal but brings with it its own challenges (such as nuclear waste disposal). Both nuclear and coal power stations are expensive to build and have particularly long construction times. Many countries have shifted their electricity generation to natural gas, however, South Africa currently does not have the natural gas resources or the necessary infrastructure to shift large portions of generation from coal to gas.

7.3.3 South Africa has the option of tapping into an abundance of renewable electricity, mainly from solar and wind energy sources. The challenge with solar and wind energy is their variable nature. Variability of generation drives the need for energy storage. In turn, increased storage requires a more intelligent approach to energy measurement, monitoring, and control. Economic signals (such as electricity pricing) can be used to drive consumer behaviour towards sustainable electricity usage.

7.3.4 It is unclear what combination of technologies will provide the most effective solution to South Africa's energy challenges. As technology is developing at a rapid pace and new breakthroughs in energy are occurring on a regular basis, a flexible mindset is required as these new innovations reach commercial scale. There are multiple solutions to the problem and each solution will have trade-offs and unforeseen downstream impacts that must be considered.

7.3.5 Ensuring long-term energy security will require cooperation across public and private sectors. Broader society will need to reconsider the consumption of energy and the sustainability thereof. As much as there is hope for a single solution that can fix the range of challenges South Africa faces, electricity security will only be achieved with structural reform of the energy sector.

7.3.6 The electricity system is complex and interconnected with a wide range of stakeholders. The accumulation of many small changes can have large-scale impacts over the long term. It is critical for each South African to take immediate action in working towards improving South Africa's electricity security.

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