INTEGRATED RESOURCE PLAN
OCTOBER 2025

“A comprehensive articulation of the energy mix that will power the South African future economy”

(Inspired by the Hon Minister of Electricity and Energy Dr Kgosientsho Ramokgopa)

electricity & energy
Department:
Electricity and Energy
REPUBLIC OF SOUTH AFRICA

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GLOSSARY OF **TERMS**

Air Pollutants	*Local pollutants resulting from combustion of fossil fuels.*
Curtailment	*Refers to the intentional reduction of electricity production despite the availability of resources to generate power. This typically occurs when the grid cannot absorb all the electricity being produced due to technical, economic, or regulatory constraints. These reasons may range from grid congestion or insufficient network infrastructure to evacuate electricity to load centres, compliance with codes that require maintaining voltage and frequency within stipulated thresholds or contractual obligations that take priority.*
Combined Cycle Gas Turbine	*A power plant that generates electricity using both a gas turbine and a steam turbine in a combined cycle, making it highly efficient.*
Determination	*Refers to a Ministerial Determination made under Section 34 of the Electricity Regulation Act and its 2024 Amendment (ERAA), which empowers the relevant Minister to make a determination regarding new or additional generation capacity, electricity transmission infrastructure and procurement of electricity from Independent Power Producers. A determination can be made to ensure security of supply in the national interest during an emergency or in the event of the market failure.*
Department of Forestry, Fisheries and the Environment	*A government department mandated to give effect to the right of citizens to an environment that is not harmful to their health or well-being and to have the environment protected for the benefit of present and future generations through reasonable legislative and other measures.*
Department of Electricity and Energy	*Government department mandated to stabilise the electricity system, lead the just energy transition and anchor South Africa's industrial renewal.*
Direct Current-Optimal Power Flow	*This methodology is motivated by observations that, for large high-voltage power systems, approximations can be made that transform the transmission network into a transport system, thus representing power flow equations in a linear programming framework. This is done to reduce power system simulation run times.*
Dump Energy	*Refers to excess energy that is generated but not used or stored, i.e., energy that is essentially wasted.*
Energy Availability Factor	*The percentage of the maximum energy a plant can supply to the grid when it is not on a planned or unplanned outage.*
Energy Efficiency Demand-Side Management	*Refers to optimising energy use and reducing electricity demand through targeted interventions. This must be achieved without hindering economic growth or negatively impacting the quality of life.*
Flue Gas Desulphurisation	*A technology used to remove sulfur oxides from exhaust flue gases of fossil-fuel power plants and other industrial processes.*
Generation Connection Capacity Assessment	*Triggered by the next bid window process, this refers to the amount of generation that can be accommodated on the transmission system at a given time and location without adversely affecting grid reliability and without requiring significant infrastructure upgrades.*
Green Hydrogen Gas	*Process of producing hydrogen gas using clean energy sources.*
Gross Domestic Product	*A key economic indicator that measures the total monetary value of all goods and services within a country's borders over a specific period.*
Interim Grid Capacity Allocation Rules	*Rules that were introduced by Eskom's Grid Access Unit in 2023 to address the growing demand for grid access amid severe grid constraints. The goal is to ensure that grid capacity is allocated to projects that are technically and commercially ready to connect to the grid — marking a shift from a 'first come, first served' to a 'first ready, first served' approach.*
Integrated Resource Plan	*A generation capacity expansion plan based on a least-cost electricity supply and demand balance over the long term, and incorporates government policy.*
Just Energy Transition	*The shift from a high- to a low-carbon-intensive energy system.*
Long-Term Operation	*The operation of a nuclear installation beyond the established time frame set forth by, for example, the licence term, design standards, or regulations, which has been justified by a safety assessment with consideration given to life-limiting processes or features of structures, systems, and components.*

Lesotho Highlands Water Project	*A bi-national project between Lesotho and South Africa designed to supply water to the Gauteng province and to generate hydropower for Lesotho.*
Nationally Determined Contributions	*Climate action plans submitted by each country to the United Nations Framework Convention on Climate Change., outlining targets to reduce greenhouse gas emissions.*
Net Present Value	*An economic decision-making metric that represents the difference between the present value of cash inflows and the present value of cash outflows over a specified period.*
National Energy Regulator of South Africa	*A regulatory authority mandated to regulate the electricity, piped-gas, and petroleum pipelines industries in terms of the Electricity Regulation Act, 2006 (Act No. 4 of 2006), Gas Act, 2001 (Act No. 48 of 2001), and the Petroleum Pipelines Act, 2003 (Act No. 60 of 2003).*
National Nuclear Regulator	*The legal entity established in terms of the National Nuclear Regulator Act, 1999 (Act No. 47 of 1999). A regulatory authority mandated to regulate nuclear safety, security, radiation and protection in South Africa.*
National Energy Crisis Committee	*A committee established to coordinate and accelerate the government's efforts to reduce loadshedding.*
Net Zero	*The balance between the amount of greenhouse gas emissions produced and the amount removed from the atmosphere. The focus is often on reducing as many carbon emissions as possible first, with offsetting residual emissions considered a last resort.*
Open-Cycle Gas Turbine	*A combustion-type turbine using liquefied or gaseous fuel, typically operated during emergency periods.*
Policies and Measures	*Strategies, regulations and actions that government departments and other stakeholders must implement to achieve the Sectoral Emissions Targets.*
Pumped Storage Scheme	*A hydroelectric power system that stores energy by pumping water to a higher elevation during periods of low electricity demand and releasing it to generate electricity during periods of high demand.*
Independent Power Producer Procurement Programme	*A programme established to procure electricity from appropriate energy sources from the private sector.*
Residual Load	*The portion of electricity demand that must be met by dispatchable power sources after subtracting non-dispatchable generation, typically from RE.*
Risk Mitigation Independent Power Producer Procurement Programme	*Emergency programme designed to implement the Minister's directive as identified by the IRP 2019 Gazette.*
Sectoral Emission Targets	*Qualitative and quantitative greenhouse gas emissions reduction goals assigned to specific sectors and sub-sectors of the economy.*
Small-Scale Embedded Generation	*Power generation facilities located at residential, commercial, or industrial sites, where electricity is generally consumed on-site and may be exported to the grid.*
South African Grid Code	*A Code that establishes the reciprocal obligations of industry participants regarding the use of the transmission system and the operation of the interconnected power system.*
South African Renewable Energy Master Plan	*An industrial development plan aimed at transforming South Africa's renewable energy and battery sectors by 2030, focusing on unlocking market demand, driving localisation, fostering transformation, and building skills and capacity.*
Transmission Development Plan	*A blueprint to guide investment in transmission infrastructure development to support the integration of new generation capacity.*
Unserved Energy / Energy Not Served	*A measure of electricity demand that cannot be reliably met due to supply-side shortages.*

ABBREVIATIONS **AND ACRONYMS**

BESS	*Battery Energy Storage System*
CCGT	*Combined Cycle Gas Turbine*
CCUS	*Carbon Capture and Utilisation Storage*
CO_2	*Carbon Dioxide*
COD	*Commercial Operation Date*
CSP	*Concentrating Solar Power*
DC	*Direct Current*
DC-OPF	*Direct Current-Optimal Power Flow*
DEE	*Department of Electricity and Energy*
DFFE	*Department of Forestry, Fisheries and the Environment*
DIRCO	*Department of International Relations and Cooperation*
DMPR	*Department of Minerals and Petroleum Resources*
DOT	*Department of Transport*
DPW	*Department of Public Works*
DSBD	*Department of Small Business Development*
DSM	*Demand Side Management*
DSTI	*Department of Science Technology and Innovation*
DTIC	*Department of Trade Industry and Competition*
EAF	*Energy Availability Factor*
EC	*Eastern Cape Region*
EPRI	*Electric Power Research Institute of the USA*
EIA	*Environmental Impact Assessment*
ERA	*Electricity Regulation Act*
ESI	*Electricity Supply Industry*
ESS	*Energy Storage System*
ESRG	*Energy System Research Group of the University of Cape Town*
FBC	*Fluidised Bed Combustion*
FGD	*Flue Gas Desulphurisation*
GCCA	*Generation Capacity Connection Assessment*
GDP	*Gross Domestic Product*
GW	*Gigawatt (one thousand megawatts)*
H_2	*Hydrogen Gas*
HSRM	*Hydrogen Society Road Map*
IGCAR	*Interim Grid Connection Capacity Rules*
IRP	*Integrated Resource Plan*
KNPS	*Koeberg Nuclear Power Station*

LHWP	*Lesotho Highlands Water Project*
LNG	*Liquefied Natural Gas*
LTO	*Long-Term Operation*
MES	*Minimum Emission Standards*
MTSAO	*Medium Term System Adequacy Outlook*
MW	*Megawatt*
NEMAQA	*National Environmental Management: Air Quality Act, 2004 (Act No. 39 of 2004)*
NERSA	*National Energy Regulator of South Africa*
NNR	*National Nuclear Regulator*
NPV	*Net Present Value*
NO_x	*Nitrogen Oxides*
NT	*National Treasury*
OCGT	*Open Cycle Gas Turbine*
OEM	*Original Equipment Manufacturer*
PF	*Pulverised-fuel coal technology*
PM	*Particulate Matter*
PV	*Photovoltaic*
PWR	*Pressurised Water Reactor*
REIPPPP	*Renewable Energy Independent Power Producer Procurement Programme*
RMIPPPP	*Risk Mitigation Independent Power Producer Procurement Programme*
RSA	*Republic of South Africa*
SAGC	*South African Grid Code*
SANIP	*South African Nuclear Industrialisation Plan*
SMR	*Small Modular Reactor*
SAREM	*South African Renewable Energy Master Plan*
SO_x	*Sulphur oxides*
SSEG	*Small-Scale Embedded Generation*
Tcf	*Trillion cubic feet*
TDP	*Transmission Development Plan*
TWh	*Terawatt hour*
vRE	*variable Renewable Energy*

FOREWORD BY THE **MINISTER OF ELECTRICITY AND ENERGY**

South Africa's Integrated Resource Plan, the IRP 2025, is presented as a balanced energy mix to stimulate the country's economy. Valued at R2.2 trillion, it is the single biggest post-apartheid government investment programme, constituting about 30% of South Africa's current GDP.

While the objective of this IRP is securing energy security for the sovereign state, it also demonstrates a commitment to lowering emissions due to electricity generation, contributing towards net zero by 2050.

Recent efforts of transforming the electricity sector from a structural constraint into a catalyst for growth, the plan aims to address poverty, unemployment, and enable the economy to grow by 3% or more by 2030. This is as envisioned by the Government, under the leadership of President Cyril Ramaphosa, to ensure no citizen is left behind.

The IRP 2025, as a long-term generation capacity build-out plan, projecting the addition of 105 Gigawatts (GW) of new capacity between now and 2039, pivots the country's energy mix decisively towards cleaner sources, providing various opportunities for the country to industrialise.

The success in executing this plan requires a collaborative effort to close the critical shortage of skilled labour and rejuvenate the limited capacity of the domestic construction and civil works industry. The Government is committed to addressing these challenges by engaging with universities, TVET colleges, and industry stakeholders to build the necessary pipeline and capacity.

On behalf of the Department of Electricity and Energy, I am pleased to present this policy that will shift South Africa to a cleaner electricity sector, enable its competitiveness, and provide for an economically prosperous future for the country.

I would like to thank all stakeholders for ensuring inclusivity and transparency in its development.

Dr. Kgosientsho Ramokgopa
Minister of Electricity and Energy

EXECUTIVE **SUMMARY**

In the South African context, an Integrated Resource Plan (IRP) is a living plan that is expected to be reviewed regularly when circumstances in the electricity sector and economy change. The IRP's main purpose is to ensure security of electricity supply by balancing supply and demand at the least cost to the economy whilst minimising environmental impact. The IRP's objective is to plan for an adequate power system that will satisfy electricity demand while enduring contingencies or disruptions without adverse interruptions of supply. This is carefully crafted in such a manner that both the cost of electricity to the economy and environmental (global and local emissions) impact of electricity supply are minimised.

In summary the Integrated Resource Plan can be defined as a comprehensive forward looking strategy that outlines the allocation of South Africa's primary energy resources, ensuring that the country's electricity demand is met both cost efficiently as sustainably.

Although the South Africa generation system is currently dominated by coal, its energy mix is fairly diverse, comprising nuclear, diesel-fired gas turbines, hydro, water pumped-storage, solar PV, Concentrated Solar Power, wind, biomass, landfill, etc. In the country's commitment to carving a strategic roadmap for ensuring long-term electricity security of supply while transitioning towards a more sustainable and low-carbon future, it is anticipated that the role of coal will reduce, and generation from clean technologies will increase.

With South Africa emerging from a heavily constrained power system, the IRP 2025 focusses on cementing the positive interventions to address immediate capacity constraints and planning for generation options, thus ensuring future security of supply and long-term goals such as achieving a Net Zero electricity sector by 2050.

This plan is informed by a comprehensive analysis of power system adequacy, the challenging dynamics of the national grid, domestic legislative frameworks, economic and energy trends, and the costs and performance characteristics of evolving generation technologies.

KEY OUTCOMES OF THE IRP 2025:

Energy availability factor of 66% to 68% from 2025 to 2030 makes it possible to meet the energy demand forecast of 255 TWh in 2030, resulting in expected CO_2 emissions of 168 Mt.

The quantum of RE technologies increases from about 17 GW to more than 45 GW by 2030, translating to approximately 5 GW per annum over this period.

The minimum annual Capacity Factor of the 6 GW Combined Cycle Gas Turbine (CCGT) plant is 51% from 2030 to 2040, with built-in flexibility beyond 2040.

Ensuring security of supply in the IRP 2025 hinges on the following critical levers:

- Sustaining the power system plant performance above 60% level, in the immediate- to medium-term.
- Commissioning 6 GW of CCGT capacity by 2030 to avoid supply shortfalls as the older baseload power stations reach end of life.
- Roll-out of committed generation capacity, including renewables and flexible resources such as peaking gas and storage.
- Implementation of long-lead time generation resources, such as nuclear and water pumped storage.
- Implementation of transmission grid infrastructure as per the Transmission Development Plan (TDP).

The IRP 2025 presents a R2.23-trillion investment plan that defines South Africa's energy mix to drive the government's deliberate effort to grow the economy for the future.

SECTION A

INTEGRATED RESOURCE PLAN LEGISLATIVE CONTEXT

1. STATUTORY FRAMEWORK OF THE IRP

The White Paper on Energy Policy of the Republic of South Africa,1998 (Energy White Paper), advocated for an integrated resource planning (IRP) approach to guide infrastructure investments in South Africa's electricity supply industry. It also encouraged private sector participation through Independent Power Producers (IPPs). To facilitate these objectives, the Energy White Paper mandated the government to establish IRP guidelines through new legislation and regulations.

In response, the Electricity Regulation Act, 2006 was enacted, repealing its predecessor (Electricity Act,1997). This legislation empowered the Minister to promulgate regulations governing new generation capacity. While initial regulations were introduced in 2009, they were subsequently replaced by the current Electricity Regulations on New Generation Capacity in 2011, with amendments in 2016 and 2020. These regulations stipulate the Minister's responsibility for developing and publishing the IRP. Following the merger of the electricity and energy portfolios, the President, pursuant to Section 97 of the Constitution, transferred the administrative functions related to the Electricity Regulation Act to the Minister of Electricity & Energy.

2. THE IRP: ADVANCING POLICY OBJECTIVES

2.1 IRP HISTORICAL CONTEXT

The Electricity Regulation Act, 2006, initially defined the Integrated Resource Plan (IRP) as a national-level plan aligned with national policy. Subsequent amendments in 2024 refined this definition to encompass a forward-looking and indicative plan for electricity generation that reflects national policy on electricity planning, energy sources, and generation capacities.

The overarching policy objective of the IRP is to ensure security of supply while considering environmental protection and economic impacts. The Integrated Resource Plan 2010 (IRP 2010) marked a significant departure from its predecessors, introducing a more comprehensive approach and incorporating renewable energy into the energy mix, reflecting national climate change commitments and facilitating private sector participation in electricity generation as envisioned in the Energy White Paper. It can be appreciated that the technical modelling outcomes in the development of the IRP 2010 did not favour renewable energy due to the costs of the technology at the time. The policy adjustment prerogative was therefore exercised and renewable energy was forced into the plan, ensuring alignment with the national policy objective to develop "... renewable energy sources to achieve a more sustainable energy mix". The implementation of the IRP 2010 ultimately contributed positively to the economy through job creation and the establishment of the renewable energy industry.

The Integrated Resource Plan 2019 (IRP 2019) further expanded renewable energy capacity, incorporated regional developments, and promoted distributed generation. This plan continued to advance energy security at both utility and small-scale levels. The IRP 2019, therefore, presented an opportunity and potential for the local manufacturing sector, which led to the development of the South African Renewable Energy Masterplan (SAREM). SAREM outlines an industrialisation strategy for the renewable energy value chain up to 2030, aiming to establish a sustainable manufacturing sector, create jobs, and boost economic growth through localised component manufacturing and battery storage integration.

Despite challenges faced during the implementation of the IRPs, amendments to Schedule 2 of the Electricity Regulation Act,2006, introduced an alternative IPP procurement model to encourage private sector participation in electricity generation. These amendments, along with the IRP 2019, provide the necessary framework for SAREM's successful implementation.

The draft Integrated Resource Plan 2023 (Draft IRP 2023) introduced a two-horizon approach and analysed the implications of various energy mix pathways on the IRP policy objectives. Horizon 1 prioritised energy security. It assessed the power system's supply and demand, quantified the supply shortfall, evaluated the impact of energy initiatives, and proposed interventions. These interventions emphasised implementing the Generation Recovery Plan to restore supply security, deploying dispatchable generation, retaining dispatchable capacity, and managing identified risks. Horizon 2 aimed to evaluate various pathways against the power system to assess their performance based on three IRP policy objectives: energy security, environmental considerations, and economic impact. Despite being a draft, the IRP 2023 provided valuable insights, proposed interventions and garnered public feedback on its alignment."

2.2 ROLE OF HYDROGEN IN THE SOUTH AFRICAN ECONOMY

Cabinet approved the Hydrogen Society Roadmap (HSRM) in 2021. The vision of the roadmap is an inclusive, sustainable and competitive hydrogen economy by 2050 with the goal of achieving a just and inclusive net zero carbon economic growth for societal wellbeing by 2050.

The purpose of the HSRM is to align stakeholders on a common vision on hydrogen related technologies in order to create an environment where investment decisions can be made to unlock the social economic benefits for the country. The high-level outcomes of the HSRM are as follows:

- Green and enhanced power sector and building: the lead department is the Department of Electricity and Energy (DEE)
- Decarbonization of the transport sector, heavy duty trucks, shipping, aviation and rail: the lead departments are the Department of Transport (DOT), supported by the Department of Trade, Industries and Competition (DTIC) and Department of Forestry, Fisheries and Environment (DFFE)
- Creation of a manufacturing sector for hydrogen products and components: lead departments are the Department of Science, Technology and Innovation (DSTI), supported by DTIC, the Department of Minerals and Petroleum Resources (DMPR) and the Department of Small Business Development (DSBD),
- Decarbonization of energy intensive industry: iron & steel, chemicals, mining, refineries,and cement: the lead department is the DTIC, supported by DFFE and DMPR,
- Creation of an export market for green hydrogen and green ammonia: lthe ead department is the DTIC, supported by the Department of International Relations and Cooperation (DIRCO) and National Treasury (NT), and
- Transition from grey to blue to green hydrogen: the lead department is the Presidency, supported by DSTI, DMPR, DTIC, DIRCO, DFFE, and the Department of Public Works (DPW).

Green hydrogen is emerging as a pivotal tool to decarbonise sectors that cannot be directly electrified, often termed "hard-to-abate" segments. South Africa's energy policy already identifies green hydrogen as an "essential component" of its transition strategy towards a low-carbon economy. By using renewable electricity to produce hydrogen (and derivatives like ammonia), the country can provide clean energy feedstocks for heavy industries and long-haul transport that currently rely on fossil fuels.

Major industrial processes – such as iron and steel production, cement and chemicals manufacturing – as well as heavy-duty transport (trucking, shipping, etc.) fall into this category and together account for a substantial share of South Africa's CO_2 emissions. Green hydrogen offers a pathway to cut these emissions by replacing coal, gas or oil in high-temperature processes and fuel applications, thus decarbonising sectors previously considered infeasible to decarbonize. In doing so, it opens opportunities for new industrial value chains and aligns the power sector with broader climate imperatives beyond electricity generation.

Accordingly, Department of Electricity and Energy will work in close collaboration with other Departments to ensure the successful realisation of the Hydrogen Society Roadmap.

3. THE IRP IN THE CONTEXT OF RECENT LEGISLATIVE DEVELOPMENTS

3.1 THE ELECTRICITY REGULATION ACT (ACT NO. 4 OF 2006) AS AMENDED

Section 34 of the Electricity Regulation Act, 2006, originally established the Determination as a Ministerial instrument for implementing the Integrated Resource Plan (IRP). The Determination specifies factors such as technology, capacity, procurement, and ownership for new generation facilities, as outlined in the New Generation Regulations.

The Electricity Regulation Amendment Act, 2024, expands the Minister's powers to include transmission infrastructure determinations. Determinations will now ensure optimal electricity supply by considering the IRP and Transmission Development Plan (TDP). Any deviations from these plans must be publicly announced in the Gazette for comment.

Similarly, transmission infrastructure determinations will detail the nature, type, extent, ownership, operation, maintenance, procurement, and usage of transmission infrastructure.

The significance of the IRP 2025 is, particularly in this context, in its incorporation of transmission infrastructure and the geographic location of supply capacity.

Moreover, the Electricity Regulation Amendment Act, 2024, introduced provisions for an open market platform. This platform aims to foster competitive electricity trading through a multi-market structure, encompassing market transactions, bilateral agreements, and regulated transactions.

These provisions build upon the foundations laid by the Licensing Exemption & Registration Notice, 2023, which amended Schedule 2 of the principal Act, to exempt privately procured generation facilities from the need for a generation license, regardless of capacity. However, these facilities are still required to register with the Regulator and adhere to the relevant Code. The Schedule 2 amendments thus established a private power procurement model alongside the government's procurement approach, enabling registered generation facilities to supply multiple customers.

In the context of the IRP, these privately procured projects had to be factored into generation assumptions as potential supply options to meet forecasted demand.

3.2 CLIMATE CHANGE ACT: 2024 (ACT 22 OF 2024)

The Climate Change Act, 2024, serves as the primary legislative framework guiding South Africa's transition to a lower-carbon economy. This Act aligns the country with its international climate change commitments and obligations. It empowers the Minister of Forestry, Fisheries, and Environment to establish Sector Emission Targets (SETs), which are crucial for achieving the Nationally Determined Contribution (NDC).

SETs, representing greenhouse gas emission targets for specific sectors or sub-sectors, rely on sector-developed policies and measures to facilitate their achievement and ultimately contribute to the NDC. For the electricity sector, the Integrated Resource Plan (IRP) is identified as a key policy and measure for meeting the sector's emissions target without compromising the security of supply.

The SETs are currently in draft form and have undergone public and intergovernmental consultations.

The draft update SETs for up to 2035 are currently in draft form and have undergone public and intergovernmental consultations. The IRP 2025 proposes CO_2 emissions for the electricity sector reduction from 168 Mt in 2030 to 142 Mt in 2035, or a 22% reduction. There is alignment between the Department of Forestry, Fisheries, and Environment (DFFE) and the Department of Electricity and Energy (DEE) regarding the targets within the SETs, as they are informed by the IRP.

SECTION B

OVERVIEW OF THE SOUTH AFRICAN IRP

1. OBJECTIVES

The main objective of IRP is to ensure security of electricity supply in South Africa, meaning planning for an adequate capacity to balance electricity supply and demand reliably, even during contingencies or disruptions without interrupting supply. However, the IRP is not a least-cost technology plan but seeks to minimise the overall system cost-taking into account the impact on the economy. Additionally, the IRP seeks to minimise the environmental impact of electricity supply by reducing global and local emissions.

2. IRP PROCESS & CONSULTATIONS

The IRP seeks to balance supply and demand in the medium to long term. In its development, the process collates planning assumptions, formulates and models scenarios, determines a reference plan derived from least-cost principles subject to specified constraints and relevant government policy objectives. In line with the Energy White Paper, public participation becomes an important milestone before the approval and gazetting of the IRP.

Following Cabinet approval for public comments in December 2023, the Draft IRP 2023 was gazetted on 04 January 2024. The public was invited to comment on the assumptions, scenarios studied, and model outcomes through various modes of communication. The deadline for submissions was originally set for 23 February 2024.

However, stakeholders requested an extension of time to allow for further participation. This request was granted, and the closing date was extended to 23 March 2024. During the 11 weeks consultation period, several engagements occurred, which included online public workshops, stakeholder-solicited bilateral engagements; industry hosted events; technical and data gathering meetings.[1] During such engagements, for instance those hosted by the Presidential Climate Commission, clarity seeking questions were addressed and insights were shared. The public consultation period resulted in 4 338 comments received from the stakeholders out of which 136 were considered substantive. The methodology employed to analyse the comments was thematic analysis[2] which resulted in 9 emerging themes. Comments expressing similar sentiments from different stakeholders were consolidated to a single view, with often differing perspectives per theme. The outcome of this analysis is a Response document attached as Annexure 1 (Comments Response Document). The stakeholders with substantive comments were invited to targeted workshops with the objective to:

- Unpack comments received on the Draft IRP 2023, starting from November to December 2023,
- Share updated assumptions and modelling parameters,
- Present the updated IRP 2023 outcomes.

Although targeted, the workshops were open to the rest of the public and held in virtual, hybrid, and in-person formats.

The Draft Integrated Resource Plan (IRP) 2024, which incorporated some of the inputs from stakeholders, was submitted to NEDLAC in February 2025. The NEDLAC consultation process began in March and officially ended on 18 June 2025, during which the PCC contributed with discussion framing presentations. The final NEDLAC report was received by the department on 3 July 2025.

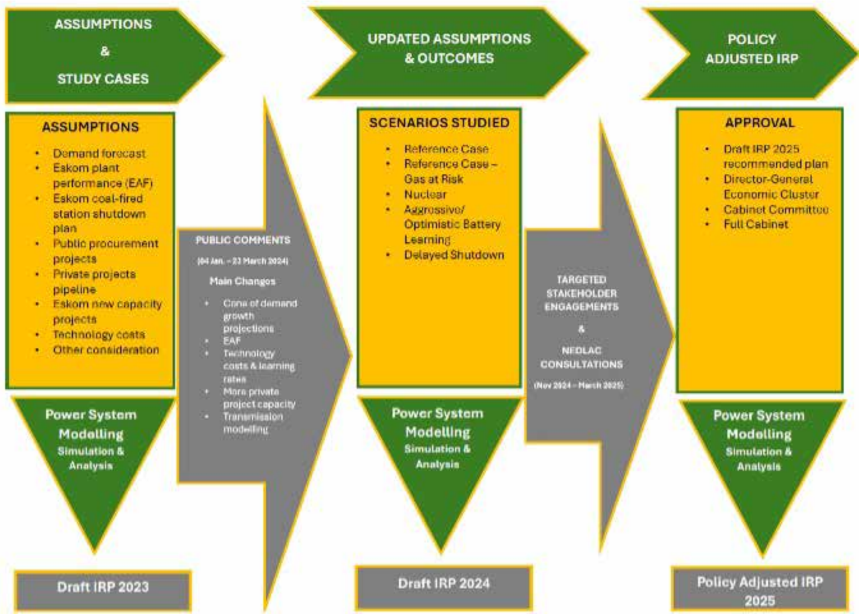


Figure 1: IRP Process & Consultations.

1 Non-Governmental Organisations, Industry Associations, Academic Institutions and Research Institutions.

2 A quantitative study methodology used to analyse differing perspectives

SECTION C

POWER SYSTEM ENERGY PLANNING

1. INTRODUCTION

In the short-to-medium term, the IRP's energy planning methodology involves assessing the balance between supply and demand on an hourly chronological basis, considering limitations on the transmission network. This is done to assess the information on the operational, capacity and energy adequacy of the power system security of supply. This exercise is conducted using a stochastic simulation technique (Monte Carlo) with Plexos® simulation tool on an hourly unit commitment and economic dispatch, which does an optimisation under uncertainties of the demand, variability of renewable generation production (wind and solar) and unplanned outages of dispatchable generation resources. Risk associated with shortages of generating capacity is identified and the level of risk is quantified in terms of capacity and energy inadequacy. If the level of risk is above the threshold, additional resources are then added until the level of risk is at acceptable levels.

The capacity and energy adequacy of the system are measured by the volume of unserved energy, the operation of peaking generators and the availability of contingency generator(s) of a dispatchable nature with the ability to operate as a baseload, if needed. The South African Grid Code: Preamble (2022) defines a credible multiple-unit contingency trip as a loss of three coal-fired units, or both Koeberg units, or the Cahora Bassa infeed. From a system operations perspective, this definition is informed by the impact of the event on system frequency and the ability to keep the system stable. However, in the event that the contingency persists for a prolonged period, the system is deemed energy adequate. The South African power system has been subjected to various multiple-unit contingencies in the recent past, namely the loss of three units at Kusile, delays in the Koeberg Long-term Operation, the loss of the Cahora Bassa infeed that cyclically occurs due to flooding and during cyclonic seasons, etc.

In the medium-to-long term, the IRP uses a linear optimisation algorithm in the Plexos® simulation tool to determine the optimal mix of new generation capacity and transmission expansion for the planning horizon up to 2050, subject to constraints. The objective is to minimise the total system costs (net present value), which include capital, fixed and operating costs. Given the long planning horizon, the model uses a chronological sampling approach to reduce the complexity of the mathematical problem while retaining as much detail as possible. This approach is crucial for long-term optimisation models as it captures temporal variability, ensuring the model accurately reflects changes over time. It maintains the sequence of events, including the seasonality of demand profiles and weather-dependent technologies. The resulting energy mix is then subjected to an economic dispatch type of analysis similar to that of the short-to-medium term to assess adequacy of the power system.

With the energy mix anticipated to include increasing levels of renewable energy sources like wind and solar, which can be variable and unpredictable, it is crucial to gather information for the system operator to anticipate the impact of these fluctuations and develop the necessary measures to optimise the use of available resources in ensuring grid stability and reliability. This report will analyse power system flexibility for this purpose, incorporating stochastic analysis to account for the inherent uncertainties in outage and demand patterns, and variability in renewable energy generation. The result of this analysis is provided in Section 7.

The representation of the transmission detail in the model is based on a linearised Direct Current - Optimal Power Flow[3] (DC-OPF) formulation, which essentially approximates it into an electricity transport model. Although this provides power flow equations of the transmission system into an electricity transport model, sufficient detail to determine transmission requirements, a comprehensive analysis is required to validate load flows and determine compensation[4] requirements. An introduction to this analysis is provided in Section 8 and a full report on the analysis will be published as Volume II of the IRP.

The operability of the power system considers the ancillary services technical requirements[5] as published by the System Operator. These requirements refer to various types of reserves used to balance the system when unexpected events occur, such as customer demand fluctuations, changes in the availability of supply capacity, and generation variations from variable resources. The types of reserves are mutually exclusive, each catering for different types of events based on the extent of that particular event in the power system. The requirements are for a 5-year period and the IRP makes assumptions that the quantum of the reserves will increase in proportion to the growth of the peak demand into the future. An introduction to the operability analysis, which considers other key factors not possible to assess in the Plexos® simulation tool, is provided in Section 9 and a full report on the analysis will be published as Volume III of the IRP.

3 The linearised DC-OPF model is motivated by the observations that in large high voltage power systems, voltage magnitudes are at 1.0 p.u; the line reactance is significantly larger than line resistance; and the phase angle difference over transmission lines is small.

4 Compensation of the network aids in increasing transfer power by adding reactive power devices, such as capacitors or inductors and improving the system's stability through devices such as condensers.

5 https://www.eskom.co.za/wp-content/uploads/2023/11/240-159838031_ASTR_2024-2028.pdf

2. IRP MODELLING APPROACH: GENERATION & TRANSMISSION

An IRP plan is based on a capacity expansion model that is used to determine the optimal electricity mix for South Africa. The evolution of this model is unpacked below.

The IRP 2010 was premised on balancing supply and demand without considering the implications of transmission requirements. These requirements were determined posthumously in a transmission development planning process. At the time, there was no credible information on the variability and location of renewable energy technologies and thus, a typical capacity factor for each renewable energy (RE) technology type was used.

In the IRP 2019 edition, as variable resources became more feasible, it became critical to capture the temporal variability of these resources in a chronological sampling approach, using an appropriate generation profile based on their location. The locations were limited to the 27 transmission supply areas. Since these resources are scarce in nature, they are typically connected to the sparse network through collector stations, which in turn feed into the transmission network. The total integration costs for all generation resources were added to the capital cost of generation. Although the modelling approach was an improvement from the IRP 2010, it did not account for limitations on the transmission infrastructure. Consequently, the RE IPPPP Bid Window 6 could not successfully procure wind and solar in the rich resource areas located in the Cape.

The Draft IRP 2023 sought to improve upon the spatialisation of resources and to capture the limitations hindering generation infrastructure development. However, due to limitations in the architecture of the Plexos® simulation tool used, a full transmission detail could not be incorporated. As such, available transmission capacity, as in the latest Generation Capacity Connection Assessment[6] (GCCA 2024), was used while the Transmission Development Plan (TDP) provided a basis for unlocking additional capacity up to 2032. Beyond this period, it was assumed that transmission could be rolled out with no limitations.

The Draft IRP 2023 approach was deemed insufficient according to stakeholder feedback. The remodeling of IRP 2025 began at an opportune moment, coinciding with the migration of the simulation tool to a cloud-based environment, the release of the latest TDP, and the processing of stakeholder comments. Consequently, the simulation tool's functionality was utilised to model and simulate the intricate generation and transmission details of the South African power system, including its import and export infrastructure.

Existing and committed generation and storage resources are located at their current or planned point of connection and the location of new options is based on the principle that generation is located in close proximity to the fuel source, pre-approved sites and/or logistical infrastructure. Consideration of new generation and storage options in the IRP 2025 model is as follows:

- **Wind and Solar:** These resources have potential for consideration everywhere in the country.
    - According to the Grid Survey[7], which surveys the interest of renewable energy development, including the type, location and quantum, there is up to 134 GW of potential. This indication of interest by developers was used as the basis for identifying nodes as options for consideration in the model. However, the quantum was not limited as per the survey, meaning more capacity per node could be considered.
    - The hourly wind and solar production profiles for each node considered in the modelling analysis are based on weather data from Renewables Ninja[8]. Profiles for existing installations consider actual generation, except in cases where sufficient history is unavailable, in which case the profile is based on the node of injection. Since generation is dependent on weather, which vary from year to year, data from multiple weather years is considered. Although extensive research has been conducted to establish the impact of changing climate conditions on future resource availability profiles, there is no definitive conclusion to consider in the IRP.
- **Storage:** battery storage is located possibly all nodes in the power system while water pumped storage is site-specific.
- **Gas:**
    - Gas Turbines: These are limited to the coastal areas close to existing ports.
    - Gas Engines: These are considered in the coastal areas close to existing ports, near identified gas finds, existing or planned pipeline or existing transmission infrastructure.

6 GCCA shows the potential capacity available on the transmission to facilitate the connection of generation projects in each province.

7 South African Renewable Energy Grid Survey conducted in July 2024 https://www.ntcsa.co.za/wp-content/uploads/2024/09/SA-Renewable-Energy-Grid-Survey-2024_Pub-1-1.pdf

8 https://www.renewables.ninja/

- **Nuclear:**
  - Pressurised Water Reactor: these are potentially located at identified sites on the coast for 'Once-Through Seawater' cooling. The timing of the technology accounts for regulatory approvals, including permitting, licensing and site preparation.
  - Small Modular Reactors: This technology is potentially located inland as they can be dry cooled.

The transmission details for the period beyond the TDP period were treated similarly to those in the Draft IRP 2023. The electricity demand forecast developed by ESRG[9] for the country is further disaggregated to regional[10] level, considering sectoral shifts as the economy grows. The TDP approach was used to finally disaggregate the forecast to substation levels. This disaggregation method helps optimise the use of existing infrastructure, identify potential transmission network bottlenecks, and determine new transmission infrastructure needs to minimise generation infrastructure requirements. This approach is a first step in determining the location of generation resources, as well as transmission requirements. These plans will be subjected to steady-state power flow analysis and dynamic studies.

9 ESRG refers to the Energy Systems Research Group at the University of Cape Town.

10 Regional refers to provinces and the hydra transmission corridor, which connects the north to the south of the country.

3. INPUT ASSUMPTIONS

A number of assumptions are collated and used in the system modelling tool, such as:

- Electricity demand is forecasted based on various economic growth scenarios, sectoral trends, electrification rates, deemed electricity sales across the South African borders, etc.
- Performance characteristics associated with expected generation capacity consisting of the existing Eskom fleet; non-Eskom generation used for self-use such as municipal, Sasol and others; public procurement projects, smalls[11].
- A 'basket' of new technology options with defined and specified costs and performance characteristics adjusted for South African conditions. These datasets are often benchmarked with datasets published by other reputable sources[12].
- Carbon tax information used a proxy for externalities.

A detailed overview of the assumptions is unpacked below.

3.1 ENERGY AND DEMAND FORECAST

Forecasting of the demand side is a key component of long-term integrated resource planning. At its core, it predicts future energy needs and peak demand to ensure that sufficient resources of an appropriate nature are procured to meet those needs reliably and cost-effectively. The IRP 2025 electricity forecasting methodology is detailed in a full report accompanying this publication. Briefly, the forecast is based on historical consumption data of all systems connected to the transmission and distribution grid, excluding pumping of pumped-storage stations, battery charging, power stations' auxiliaries, but including losses in the network. Future forecasts are developed considering projections on economic indicators such as GDP, population growth, behind-the-meter developments, sectoral shifts (including the loss of major loads or the penetration of electric vehicles), demand management initiatives, and policy changes (such as the National Treasury's reforms on industrialisation). The results are shown in Figure 2.

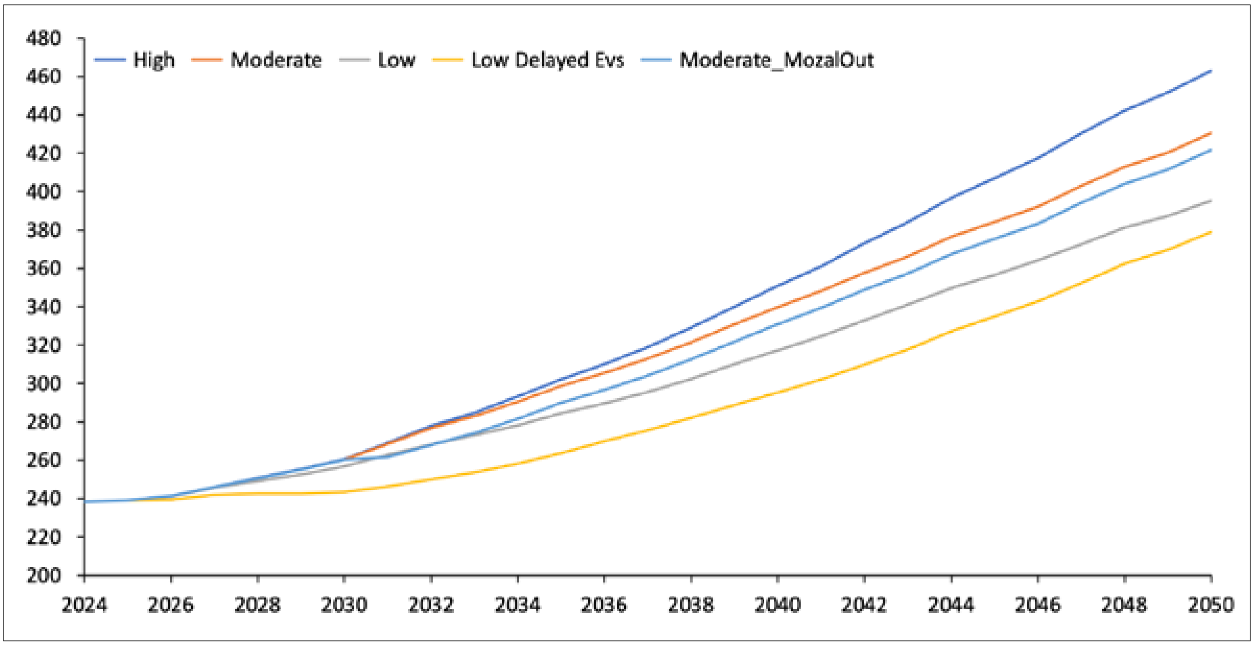


Figure 2: Electricity Demand Forecast and Sensitivities.

11 Smalls of Cogen, biomass and small hydro

12 Lazard (June 2024), NREL ATB

The moderate GDP growth serves as a baseline for the IRP 2025, reflecting a steady growth rate of 1.5% to 2% in the long term. Due to the uncertainty of the economic growth outlook, sensitivities with a lower and higher GDP growth were developed, called Low and High demand forecasts. The high-demand forecast is identical to the Moderate demand forecast up to 2032, with a long-term projected increase in GDP growth of 2.6%. Further sensitivities test the impact on the Moderate demand in the event that the Mozal smelter contract located in Mozambique is not renewed, as well as the result of the electrification of the transportation sector, such as the introduction of electric vehicles, buses and trains. On the supply side, the removal of Mozal is linked to no supply from the Hydro Cahora Bassa contract.

3.2 EXISTING GENERATING CAPACITY

The existing generation mix in South Africa is dominated by coal-fired power stations, accounting for over 75% of the total electricity production. Other sources include nuclear power, hydro, gas, storage and renewable energy sources. The details of the existing generation sources, as assumed for the IRP 2025, are provided below.

3.2.1 FOSSIL FUEL SOURCES

3.2.1.1 COAL-FIRED GENERATION

3.2.1.1.1 COAL TECHNOLOGY DESCRIPTION

Coal-fired power stations generate electricity by converting chemical energy present in coal into electrical energy through a series of processes. Coal is first delivered to the plant and pulverised into a fine powder to increase its burning efficiency. This pulverised coal is then burned in a boiler, producing heat that transforms water into high-pressure steam. The steam is directed onto the turbine blades, causing the turbine to spin and convert the thermal energy into mechanical energy. The turbine, which is connected to a generator through a shaft, causes the generator to rotate and during this rotation, mechanical energy is converted into electrical energy. After passing through the turbine, the steam is cooled and condensed back into water in a condenser, often using a cooling system such as cooling towers (water-cooled) or cooling fans (air-cooled). The condensed water is then recycled back to the boiler, completing a continuous cycle. In this process, flue gasses such as Carbon Dioxide (CO_2), Nitrogen Oxide (NO_x), Sulphur Dioxide (SO_x), and Particulate Matter (PM) are released to the atmosphere. To minimise the environmental impact of the flue gases, emission control systems such as Flue Gas Desulphurisation (FGD) systems, low NO_x burners, baghouse filters, etc are employed to reduce the pollutants.

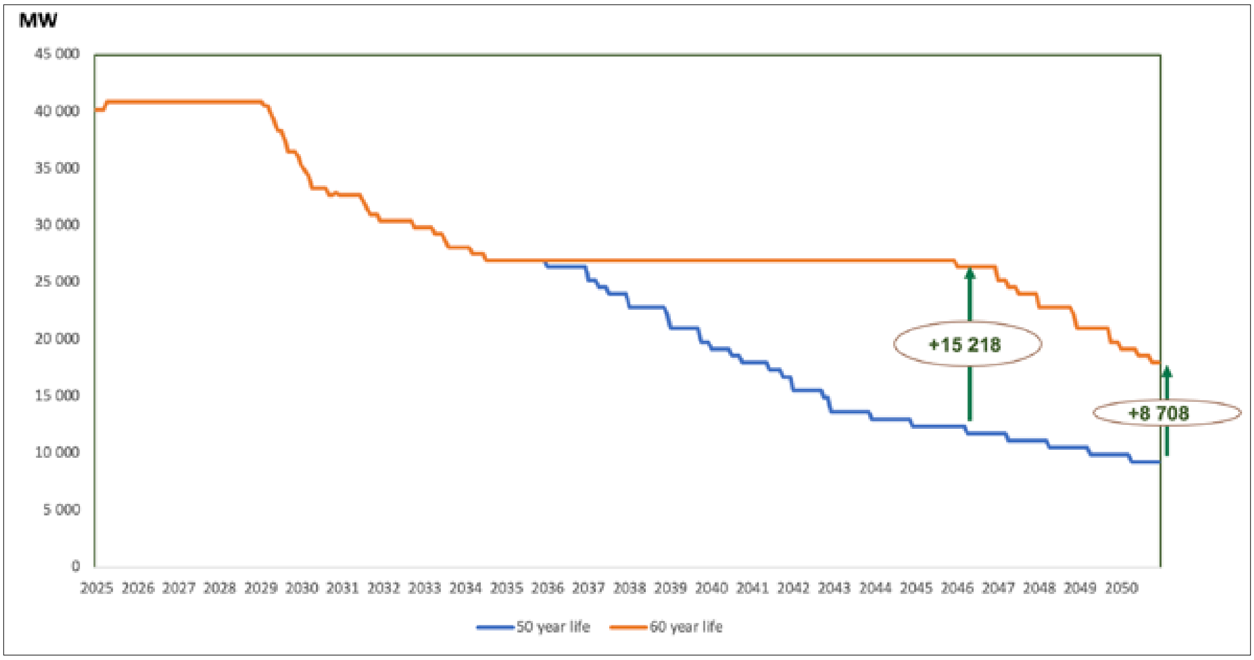


Figure 3: Eskom Coal-Fired Station Shutdown Plan Based on a 50-year life.

3.2.1.1.2 COAL GENERATION IN SOUTH AFRICA

Coal-fired power stations form the backbone of South Africa's energy supply, with an installed capacity of approximately 42 GW. The dominance is largely attributed to the country's abundance of coal reserves, which have made coal an affordable and accessible energy source, encouraging its use for electricity generation. It enabled energy-intensive industries, such as mining and manufacturing, that require continuous and stable electricity to operate efficiently. Although its advantages have positioned coal as the primary choice for electricity generation over the past decades, the majority of these power stations are approaching the end of their operational life. The IRP 2025 assumes partial compliance to Minimum Emission Standards as published in terms of section 21 of the National Environmental Management: Air Quality Act, 2004 (Act No. 30 of 2004), without impact to capacity as provided by Eskom.

3.2.1.1.3 SHUTDOWN PLAN OF COAL-FIRED STATIONS

Under Eskom's Generation Continued Operations (GCO) shutdown plan, the phased 50-year end of life of the coal fleet will start in 2029 and continue over several years, as illustrated in Figure 3. This plan indicates a significant reduction of 8 GW in coal capacity between 2029 and 2030, followed by a further decline of 15 GW between 2034 and 2042.

3.2.1.2 GAS-FIRED GENERATION

The operation of gas-fired power stations is similar to that of coal-fired stations, except that the primary energy source is either natural gas or liquid fuels, such as kerosene or diesel. Gas-fired plants can operate as either Open-Cycle or Combined-Cycle systems, differing in efficiency, design, and application. Open-Cycle systems generate electricity by burning fuel to drive a turbine, releasing exhaust gases directly into the atmosphere. These systems are simpler, have lower capital costs, and can start up quickly, making them ideal for low-capacity-factor operation. However, they operate with lower efficiency, as they do not reuse exhaust heat. In contrast, combined cycle systems capture exhaust heat to produce steam, which powers a secondary turbine for additional electricity generation. This configuration achieves higher efficiency but comes with comparably higher capital cost and slower start-up times.

These systems are better suited for conditions requiring continuous supply, where the fuel efficiency benefits associated with operating at higher capacity factors justify the initial investment. This technology is considered relatively environmentally friendly. In terms of local emissions, this technology complies with the MES for now power plants, while CO_2 emissions are about half that of coal-fired without carbon capture.

3.2.1.2.1 GAS GENERATION IN SOUTH AFRICA

South Africa currently operates six Open Cycle Gas Turbine (OCGT) plants, which are fuelled by diesel. Four of these plants, Ankerlig, Gourikwa, Port Rex, and Acacia, are owned by Eskom and have a combined capacity of 2.4 GW. The remaining two plants, Avon and Dedisa, with a total installed capacity of 1 GW, are privately owned and operated under a public programme. These plants primarily serve as peaking power stations, providing flexible and rapid-response electricity to meet short-term peaks in demand. Their usage is intentionally limited due to the high fuel costs associated with their operation.

3.2.1.2.2 SHUTDOWN PLAN OF GAS-FIRED STATIONS

Port Rex and Acacia, with a total of 314 MW, are due to reach end of life between 2025 and 2026, while Ankerlig and Gourikwa are due in the mid-40s. Avon and Dedisa, procured under a 15-year contract, are due to expire between 2030 and 2031.

3.2.2 NUCLEAR POWER

A nuclear power plant generates electricity by harnessing energy from nuclear fission, a process in which the nucleus of a uranium atom splits into smaller atoms when struck by neutrons, releasing significant heat energy. In the case of Pressurised Water Reactors (PWR), this heat is absorbed by the moderator, typically high-purity water, circulating through the reactor core. The purpose of the moderator is to slow down neutrons to enable an efficient chain reaction and transport heat generated through nuclear fission to the steam generator. To ensure safety, the reactor is heavily shielded within a containment building, and spent fuel, which remains radioactive, is managed through secure storage. Another type of reactor that has gained traction in development is the Small Modular Reactor (SMR).

These reactors operate similarly to PWR but are designed to be smaller and more flexible. Due to their size, they can be manufactured in factories and assembled on site, thereby reducing construction time and costs. However, SMRs are not yet commercially viable, with EPRI estimating commercial deployment post-2030. In South Africa, as the regulatory framework needs to be developed, the technology is projected to be available post-2035.

3.2.2.1 SHUTDOWN PLAN OF NUCLEAR STATIONS

Koeberg was designed with an operational lifespan of 40 years, originally expected to shut down by 2025. However, in order to keep nuclear power in the energy mix going into the future, the design life of Koeberg was extended by 20 years to between 2045 and 2046.

3.2.3 HYDRO POWER

A hydropower plant generates electricity by harnessing the energy of flowing or falling water naturally in run-of-river systems. The water is directed through an intake and into pipes, which guide it towards turbines. The high-speed water then strikes the turbine blades, causing them to spin and convert the kinetic energy into mechanical energy. This mechanical energy drives a generator, which produces electricity. After passing through the turbine, the water is discharged back into the river or downstream without being consumed, maintaining its role in the ecosystem. While hydropower is a clean and renewable energy source, its ouput can be intermittent in nature owing to natural water availability which can vary seasonally and impacted by climatic changes. Consequently, factors such as droughts or reduced rainfall can significantly impact water flow and, therefore, electricity generation.

3.2.3.1 HYDRO GENERATION IN SOUTH AFRICA

There is currently 0.6 GW of installed hydro capacity in South Africa. Although the country is semi-arid, there are years with flood risk. During these periods of increased flood risk, hydropower stations are used to produce baseload energy, thereby preventing the dams from overflowing. During low water levels, power plants face challenges as priority is given to downstream water users. In such circumstances, hydropower stations can be utilised for short-duration operation to stabilise the grid if needed for emergencies.

Although South Africa is a semi-arid country, some of its neighbours are endowed with water resources. Currently a bilateral agreement exists with Mozambique to allow import of power from their Hydro Cahora Bassa with an allocated capacity of 1 GW.

There's potential to partner with Lesotho on the development of a water pumped storage scheme, Kobong, as part of the LHWP (Lesotho Highlands Water Project) Phase 2.

3.2.3.2 SHUTDOWN PLAN OF HYDRO STATIONS

Hydro plants typically have a long operating life. Thus, the IRP 2025 assumes the 0.6 GW capacity will not shut down during the planning horizon. However, as the Hydro Cahora Bassa is linked to a power purchase agreement, its consideration is associated with the duration of this agreement.

3.2.4 ENERGY STORAGE SYSTEMS

Energy Storage Systems (ESS) are technologies designed to store electrical energy in a different form for later use. During the process of conversion back to electricity, there are energy losses with varying efficiencies, making the technology a net energy consumer. The basic principle of an ESS involves drawing electricity from the power system when prices are low, typically during off-peak periods and generating when prices are high during peak periods. In addition to peak shaving, other uses of an ESS are to provide essential services such as frequency and voltage regulation, but it can also play a role in the deferral of grid investments.

3.2.4.1 PUMPED STORAGE SCHEMES

Pumped Storage Schemes (PSS) are considered for sites that meet key factors, including the availability of a reliable water source and suitable topography with appropriate elevation. The operation of a PSS is similar to that of a hydro power plant, but it consists of an upper and lower reservoir at different elevations. During periods of low electricity demand or when excess power is available, surplus energy is used to pump water from the lower reservoir to the upper one, storing potential energy. When electricity demand increases, the stored water is released from the upper reservoir, flowing back down to the lower reservoir through turbines and generating electricity. The operational costs of a PSS include the cost of pumping at the marginal system cost.

3.2.4.2 BATTERY ENERGY STORAGE SYSTEMS

Battery Energy Storage Systems (BESS) work by storing electrical energy in rechargeable batteries. During periods of low electricity demand or when surplus power is available, the system charges the batteries by converting electrical energy into chemical energy. When electricity demand rises, the stored chemical energy is converted back into electrical energy. Due to their modular nature and scalability, the technology is increasingly being used to enable the integration of distributed energy resources.

3.2.4.3 STORAGE SYSTEMS IN SOUTH AFRICA

There are currently four pumped storage schemes with a combined capacity of 2.9 GW. Of these, three plants are owned by Eskom, contributing a total of 2.7 GW, while the remaining plant, with a capacity of 0.2 GW, is owned by the City of Cape Town. Pumped storage schemes, like hydro power stations, can respond quickly to changes in electricity demand, making them ideal as peaking stations. Their ability to rapidly synchronise with the grid allows them to play a crucial role in maintaining grid stability. Given South Africa's water scarcity, the development and operation of hydro schemes are particularly valuable when linked to water transfer projects for consumption, thereby maximising the usage of limited water resources.

The BESS phenomenon is a relatively new concept for the SA power system, with the country only having 0.2 GW of BESS installed, all owned by Eskom. This capacity is expected to increase in the coming years, as procurement programmes by the public, private and Eskom to develop the systems intensify. These plans are detailed in the assumptions on committed capacity in the pipeline.

3.2.5 VARIABLE RENEWABLE ENERGY SOURCES

Variable Renewable Energy (vRE) sources refer to energy generation methods that rely on natural resources whose availability fluctuates depending on environmental conditions. These sources include Wind and Solar energy.

3.2.5.1 WIND ENERGY

A wind power plant generates electricity by converting the kinetic energy of the wind into electrical energy using wind turbines. The turbines consist of large blades mounted on a tower, designed to capture the wind's kinetic energy. As the wind blows, the blades rotate, causing a shaft connected to them to spin. This mechanical energy is then transferred to a generator, which converts it into electrical energy. Wind power plants are typically located in areas with consistent and strong winds, such as coastal regions. While wind energy is a clean and renewable source of power, it is variable, requiring careful grid integration and a flexible backup system to ensure a stable supply.

3.2.6. SOLAR ENERGY

A solar power plant generates electricity by converting radiation energy from the sunlight into electrical energy through two main technologies, namely photovoltaic (PV) systems and concentrated solar power (CSP) systems. In a PV solar plant, solar panels absorb sunlight, causing electrons in the material

to move and generate direct current (DC) electricity. This DC electricity is then converted into alternating current (AC) by an inverter, making it suitable for grid integration and distribution. On the other hand, CSP plants use mirrors or lenses to concentrate sunlight onto a small area, heating a fluid, such as molten salt, to high temperatures, a form of thermal energy storage. The heated fluid produces steam, which drives a turbine connected to a generator, producing electricity. Solar power plants are generally located in regions with abundant sunlight and produce electricity only during daylight hours, except in the CSP case, where stored energy can be used in the evenings. Although a typical daylight remains consistent, solar energy production is variable as it can be impacted by cloud cover, extremely high temperatures, or whether it is fitted with tracking of the sun.

3.2.6.1 VARIABLE RENEWABLE ENERGY IN SOUTH AFRICA

South Africa is one of the most endowed countries for solar and wind generation due to the country's higher-than-average wind speeds and solar radiation. The country experiences some of the highest levels of solar radiation globally along the northwestern regions, while strong and consistent wind patterns are prevalent in the Cape areas.

Currently, South Africa has a combined capacity of 6.2 GW from utility-scale plants (plants greater than 1 MW). Of this, wind energy accounts for 3.3 GW, PV systems contribute 2.3 GW, and CSP systems provide the remaining 0.6 GW. In addition, a significant number of Small-Scale Embedded Generation (SSEG) systems with an estimated 6 GW of rooftop PV are installed across the country. This capacity is expected to grow in the coming years as the cost of the technology continues to decline.

3.2.7 BIOENERGY

Bioenergy works by converting organic materials, such as plant and animal waste, into usable energy through various processes, including combustion, anaerobic digestion, and biofuel production. In a combustion process, biomass materials like wood or agricultural residues are burned to produce heat, which generates steam that drives a turbine to produce electricity. Anaerobic digestion breaks down organic material, such as food waste or manure, in the absence of oxygen, producing biogas that can be used for heating or electricity production. Biofuels, such as ethanol and biodiesel, are produced by fermenting crops like corn or sugarcane. As a renewable energy source, bioenergy helps reduce greenhouse gas emissions by utilising waste materials that would otherwise produce methane in landfills and are thus referred to as emission-neutral. However, its sustainability depends on factors such as feedstock sourcing, land use changes, and emissions from the conversion processes. In South Africa, these technologies make up a small percentage of the energy mix.

3.3 COMMITTED PUBLIC GENERATING CAPACITY

South Africa's public procurement process for the electricity sector is espoused in the National Development Plan (NDP) 2030[13]. The plan aims to create a strong foundation for South Africa's future development, ensuring that infrastructure supports economic growth, social equity, and environmental sustainability. In so doing, it identifies energy as a cornerstone of economic activity, stressing the need for a reliable and affordable energy supply to meet the demands of the economy. This involves investing in both traditional energy and renewable energy sources to ensure sustainability and resilience. In response, this has given birth to the Independent Power Producers Procurement Programme (IPPPP) Office, mandated to secure electrical energy from the private sector, including renewable, traditional and storage energy sources. The total capacity already developed is 6.2 GW, procured from the Renewable Energy IPPP.

In addition, several projects are in progress at various development stages. A snapshot is shown in Figure 4 for different technologies.

- Bid Window (BW) 5 projects, with a total capacity of 1.2 GW from renewable energy sources, are currently in the execution or construction phase. Of this capacity, 0.8 GW comes from wind, with the remaining 0.4 GW from solar PV.
- A 0.4 GW of solar PV capacity has been committed under BW 6.
- The Risk Mitigation IPPPP, comprising hybrid systems designed to provide dispatchable capacity between

13 National Development Plan 2030 I South African Government (www.gov.za)

periods defined by the system operator, has a combined capacity of 0.4 GW. The initial offer was for 2 GW, however, some of the projects did not reach financial close and were thus not included in the IRP 2025.

- The Ministerial Determination for the procurement of gas was gazetted for 3 GW of capacity through the GAS IPPPP BW1; however, currently, 2 GW has been offered to the market, with the balance to be provided at a later date. The IRP 2025 assumes all 3 GW will be available on the grid by 2030. A scenario where the gas capacity does not materialise in the system is studied.
- The Energy Storage IPPPP (ESIPPPP) concluded BW 1-3 with a total capacity of 1.7 GW. In addition to the ESIPPPP BW 1-3, an additional 2 GW capacity with 4-hour storage from the Draft IRP 2023 has been provisioned for grid support. This is aligned to the transmission requirements earmarked at unlocking capacity in the rich resource areas of the Cape.
- Capacity offered to the market under BW 7 has not been included as part of the committed capacity.

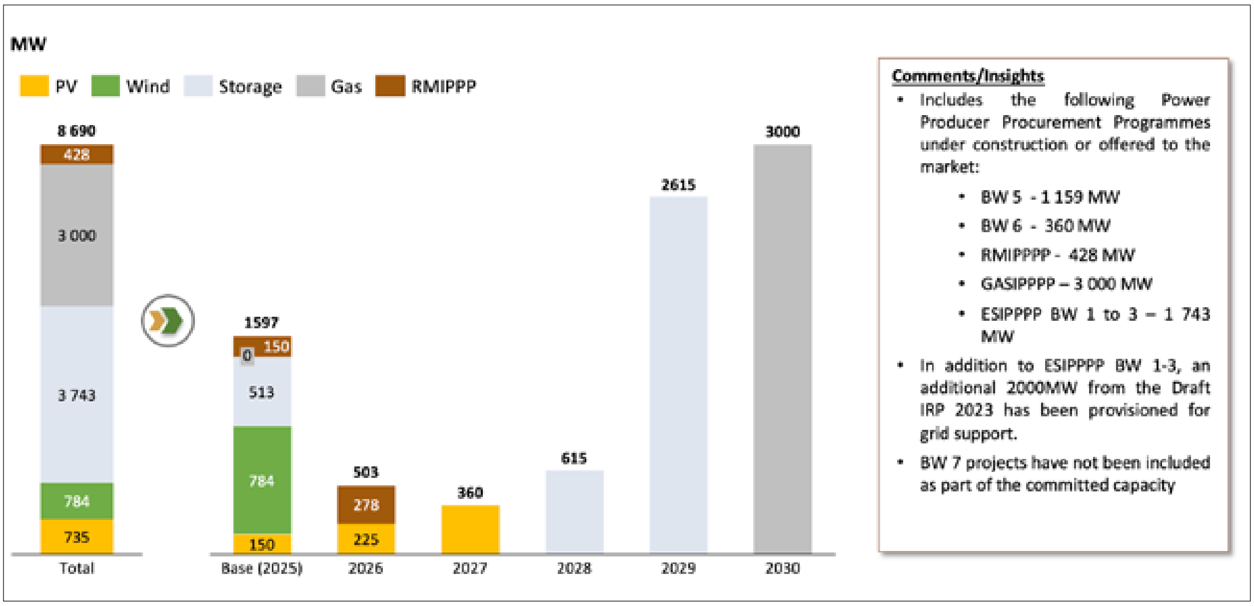


Figure 4: Committed Public Generating Capacity.

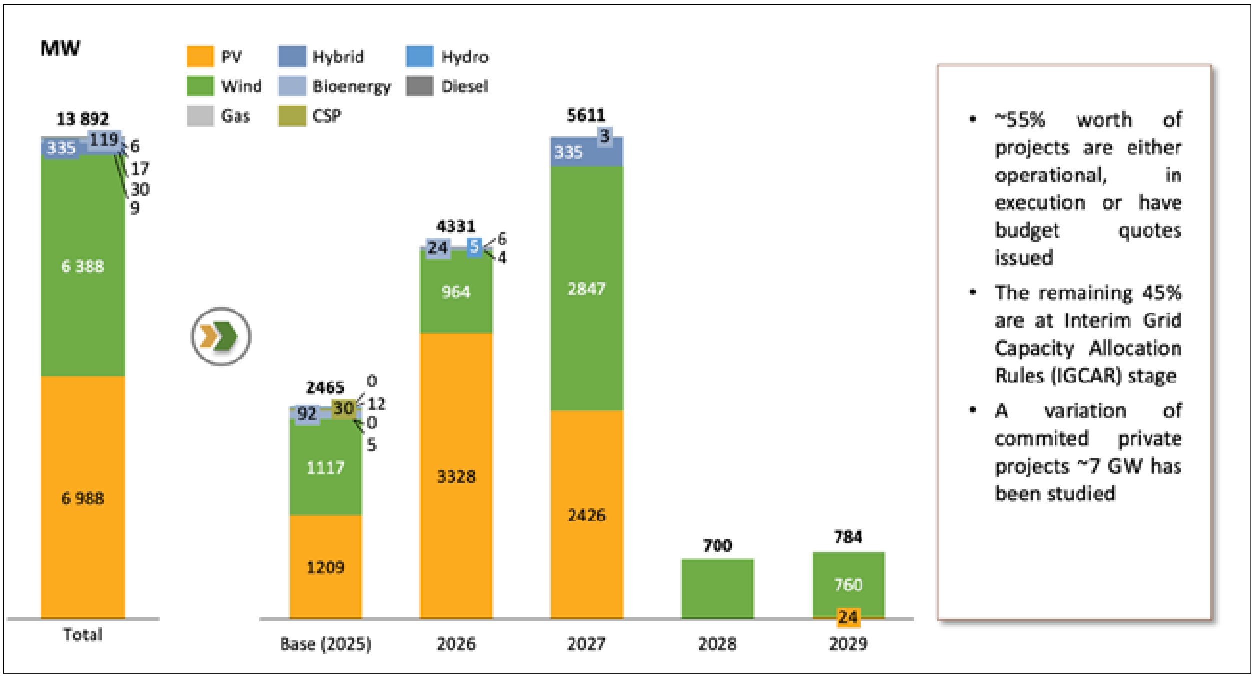


Figure 5: Committed Private Generation Capacity.

3.4 COMMITTED PRIVATE GENERATING CAPACITY

Development of private generation projects is enabled by the amended Schedule 2 of the Electricity Regulation Act 4 of 2006, which allows for embedded generation projects to be developed without needing a license. This move is meant to encourage more private sector participation in the energy sector. Private projects in the pipeline, with all permitting and licensing secured, have also advanced in securing grid capacity allocation, totalling 13 GW, as shown in Figure 5.

Those already operational, are under construction or have an issued budget quotation. Make up approximately 55% or 8 GW. The remaining 45% are at the Interim Grid Capacity Allocation Rules (IGCAR)[14] stage. The IGCAR is designed to ensure a fair and efficient allocation of grid connection capacity. They operate on a first-come, first-served basis, prioritising projects ready for grid connection.

As a sensitivity, a variation of committed private projects where those at the IGCAR stage are excluded was studied to get comfort that the security of supply impact is minimal should they not materialise.

14 The Grid Capacity Allocation Rules in South Africa are designed to manage the allocation of grid connection capacity for new electricity generation projects https://www.eskom.co.za/distribution/wp-content/uploads/2023/11/Grid-Capacity-Allocation-Rules-Publication-Version-July-2023.pdf

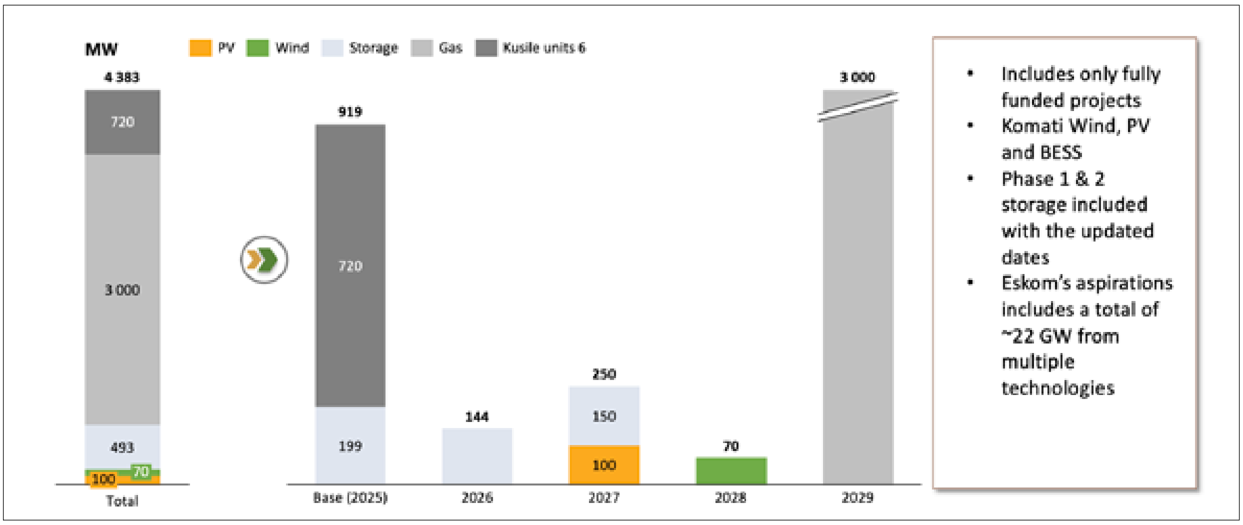


Figure 6: Committed Eskom Generating Capacity.

3.5 COMMITTED ESKOM GENERATING CAPACITY

The Eskom projects considered as committed are those under construction and those that are fully funded. These include commercialisation of the remaining Kusile units, a hybrid concoction of wind, solar PV and BESS inked to the Komati rehabilitation project[15], Phase 1 and 2 of BESS storage at various locations as well as the gas CCGT with a Ministerial Determination. Figure 6 shows the committed capacity assumed in the IRP 2025. A scenario where the gas CCGT is unavailable to the power system is studied.

3.6 TOTAL COMMITTED GENERATING CAPACITY

The assumptions of total committed generating capacity assumed in the IRP 2025 are shown in Figure 7, adding up to 44 GW by 2030. Included in the total committed generation capacity is rooftop PV rollout with an actual estimated installation capacity of approximately 6 GW as of end 2024. Beyond the actual, a forecasted growth of 0.9 GW per year is assumed up to 2035, based on the GreenCape[16] projections.

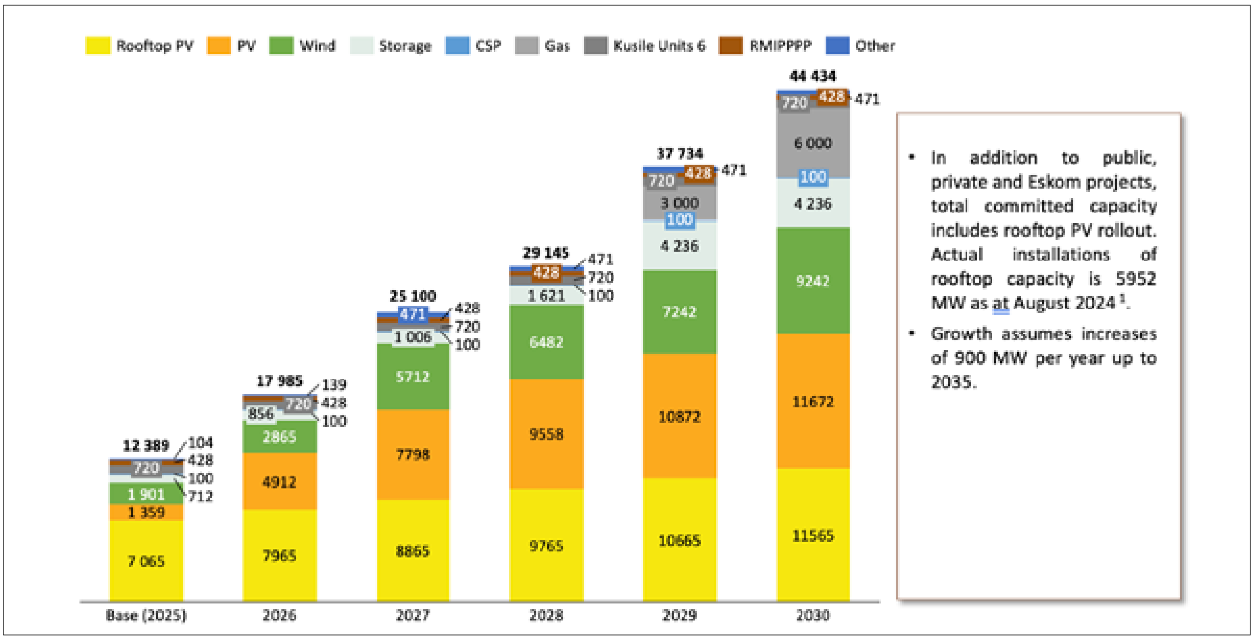


Figure 7: Total Committed Generating Capacity.

15 System Operator publication

16 as published on Eskom Weekly status

3.7 PLANT PERFORMANCE OF COAL-FIRED STATIONS

The historical performance of Eskom's Generation fleet has been on a declining trajectory since 2008, with some short-lived recovery lasting three years. More recently, the performance reached levels that led the country to reach stage six loadshedding[17]. The main driver of Eskom fleet plant performance is correlated to that of coal-fired stations.

Since 2019, several external expert reviews have been conducted to understand and identify the challenges behind the declining plant performance. The details and proposed actions from these reviews were conceptualised and implemented through the Generation Recovery Plan in March 2023. Primarily, the proposal was to sustain performance at stations that already deliver reliable performance and to recover performance at eight identified priority stations that contributed more than 50% of unplanned load losses, thereby providing the biggest and most immediate benefit to the system.

The focus on ancillary plant performance, improved risk management, spares availability, quality of outage execution and the necessary skills has greatly assisted with the recovery in performance. This plan was enabled by government debt relief that improved cash flow, aiding outage planning and funding for spares. National Treasury's concession to work with Original Equipment Manufacturers (OEMs), improved security at power stations and renewed Eskom leadership enhanced maintenance efforts. The Generation Recovery Plan, driven by the Eskom Board and the President's Energy Action Plan overseen by the National Electricity Crisis Committee (NECOM), has significantly boosted the reliability, efficiency, and availability of the coal-fired generation fleet.

Eskom submitted two forecasts of the energy availability factor (EAF[18]) as shown in Figure 8. The low scenario assumes continuation of the historical trend and assumes the efforts of the Generation Recovery Plan fail to turn around the declining trend. This forecast remains unchanged from the draft IRP 2023 submission. The base scenario is considered a moderate EAF pathway, assuming partial success of the Generation Recovery initiatives. Eskom has provided a scenario assuming full EAF recovery; however, the base EAF was recommended for the country's energy plan as it factors the risks associated with meeting the objectives of full recovery.

The risk associated with the low EAF of the Eskom fleet on the power system security of supply has been fully demonstrated in the analysis of the draft IRP 2023. The publication noted the recovery of the EAF as the only measure with the potential to bring immediate relief to loadshedding. Since then, the EAF turned around, with the financial year-to-date EAF as of November 2024 at 63.1% and the country having been relieved of loadshedding since March 2024. Based on this ongoing positive trend, supported by the statistically forecasted plant performance, the IRP 2025 assumes the base EAF pathway as the basis for all case studies.

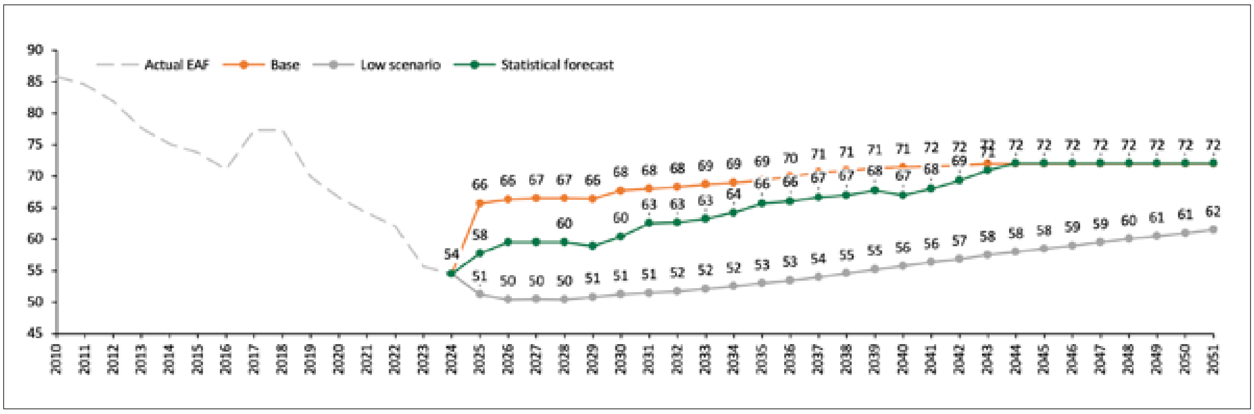


Figure 8: Overview of Existing Fleet EAF Assumptions (%).

17 A reduction of 6 GW on the demand side due to shortfall on the supply side to prevent the national grid from collapsing. This results in longer and more frequent hours of power interruptions.

18 A measure of plant performance of power plant. It represents the percentage of time that a power plant is available to produce electricity over a year.

3.8 NEW TECHNOLOGIES

The main source for new technology options in the IRP 2025 is the Electric Power Research Institute (EPRI) report on Supply-Side Cost and Performance Data[19]. The report focuses on evaluating various power generation technologies whilst highlighting local market conditions and material costs. However, as EPRI evaluation is limited to technologies developed in the West, it lacks the global reflection, particularly of the East, where technology advancements have been made in recent times. Further, where local development of any technology is available, such as in the case of wind and solar, these procurement processes are used to draw costs and lessons learnt on permitting and construction lead times. The pumped storage assumptions, as they are site-specific, are based on the last development at Ingula PSS. In the case of CSP, the lack of recent development both in the country and globally hinders this approach and EPRI projections were used. Although BESS has recently been developed in South Africa, a sufficient trend has not been established. The nuclear costs were based on a request for information (RFI) following a study commissioned by the department. These costs were adjusted to 2024 South African monetary terms using appropriate indices.

The overall assumptions are shown in Figure 9. The lithium-ion and solar PV assumptions use the low end of the range. The ranges across all other technologies are for different models, configurations, or manufacturers and thus each is considered in the optimisation.

As technology deployment increases, it is generally expected that the cost of the technology reduces over time. This is referred to as the technology learning rate. For mature technologies, which have been in use for a long time and are widely deployed, have typically lower or no additional learning rates compared to newer, emerging technologies. As an example, coal technology is considered mature, however, the carbon capture addition has potential for learning.

The assumptions for learning rates for different technologies are provided in the EPRI report, with those considered shown in Figure 9. The nuclear assumption on learning rate refer to the SMR technology, since PWR is considered mature and there is no South African experience to validate the role of accumulated experience in reducing costs of additional unit deployment. A sensitivity on BESS learning is provided since the technology cost was affected significantly by the supply chain constraints, including shortages of raw materials and logistical bottlenecks, etc. Therefore, the lowest end of the optimistic trajectory was used[20].

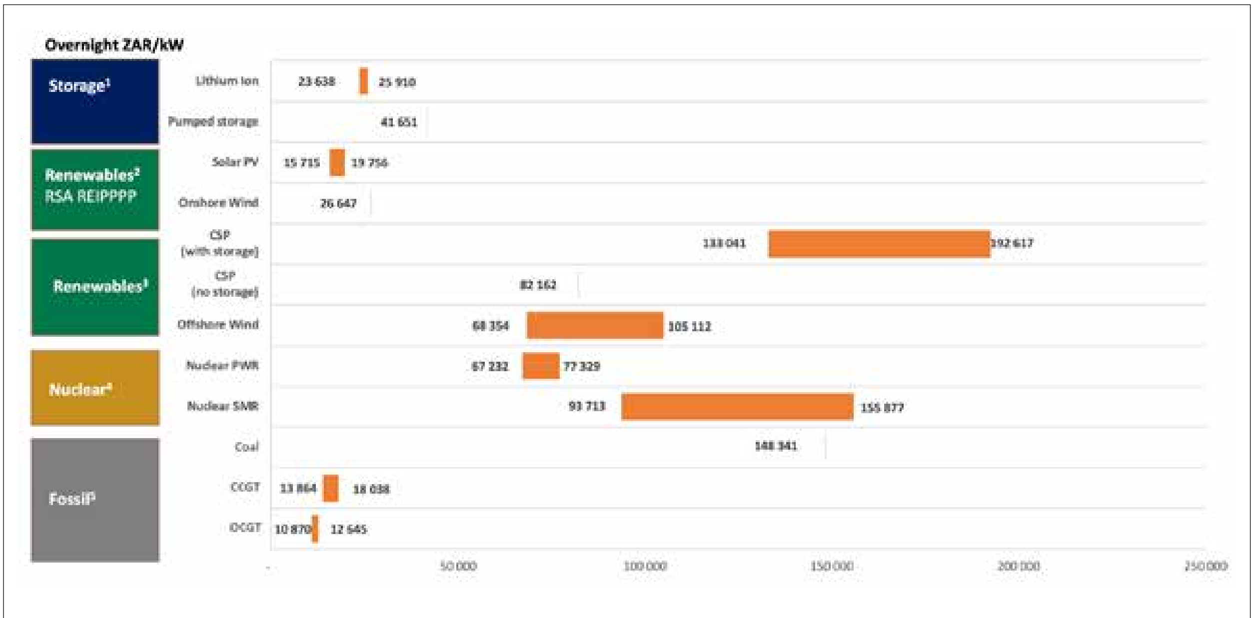


Figure 9: New Technology Cost Assumptions.

19 The EPRI report is published alongside this IRP 2025 report.

20 EPRI assumes a further ±5% error bar to the base, optimistic and pessimistic cone to capture additional uncertainty at the ends of the projected cost range.

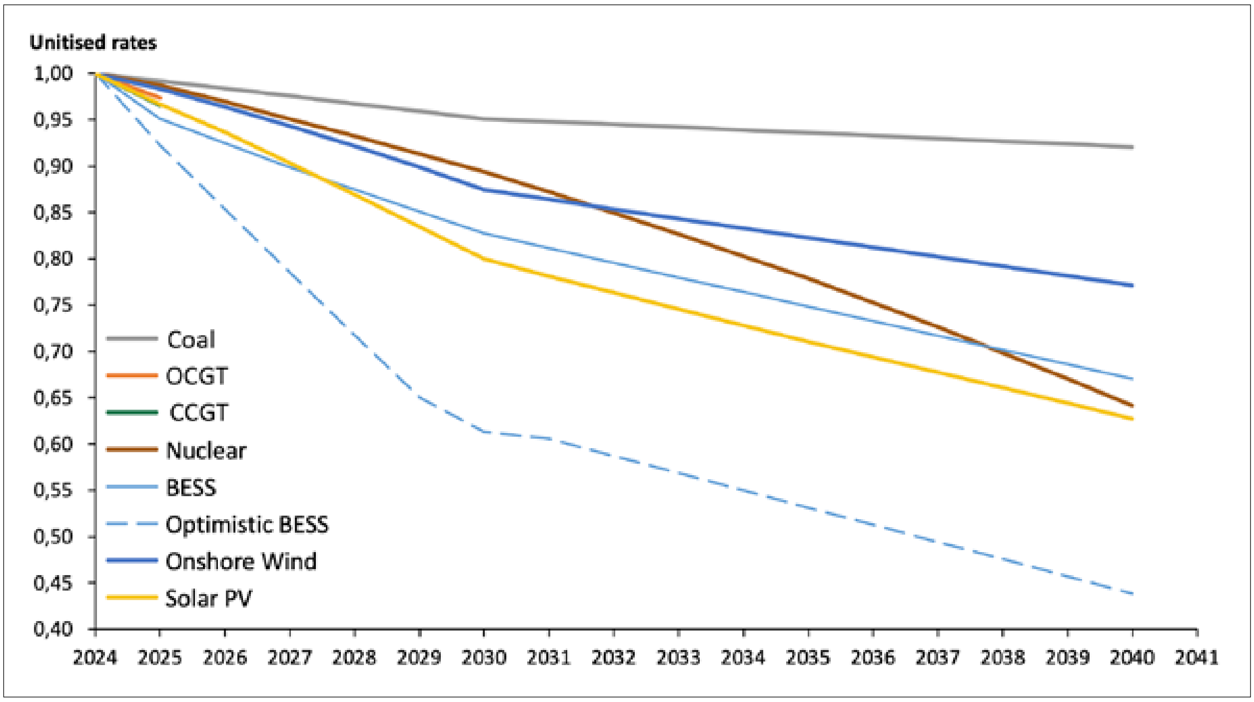


Figure 10: New Technology Cost-Learning Rates.

4. IRP SCENARIOS

The IRP assumptions are arranged in a credible manner to create a reference case based on the hierarchy of the IRP objectives and several scenarios (as shown in Figure 11) are studied for the planning horizon up to 2050 to test specific government policy objectives. These objectives include ensuring security of supply by diversifying the energy mix, promoting localisation and industrialisation, job creation, beneficiation of minerals, technology transfer, skills development, reduction of emissions, reduction of usage of scarce resources such as water and non-dependence on non-indigenous resources, at the lowest possible cost to the economy. The different scenarios are then benchmarked against the reference case to establish the degree and the extent to which they deviate from the IRP and policy objectives.

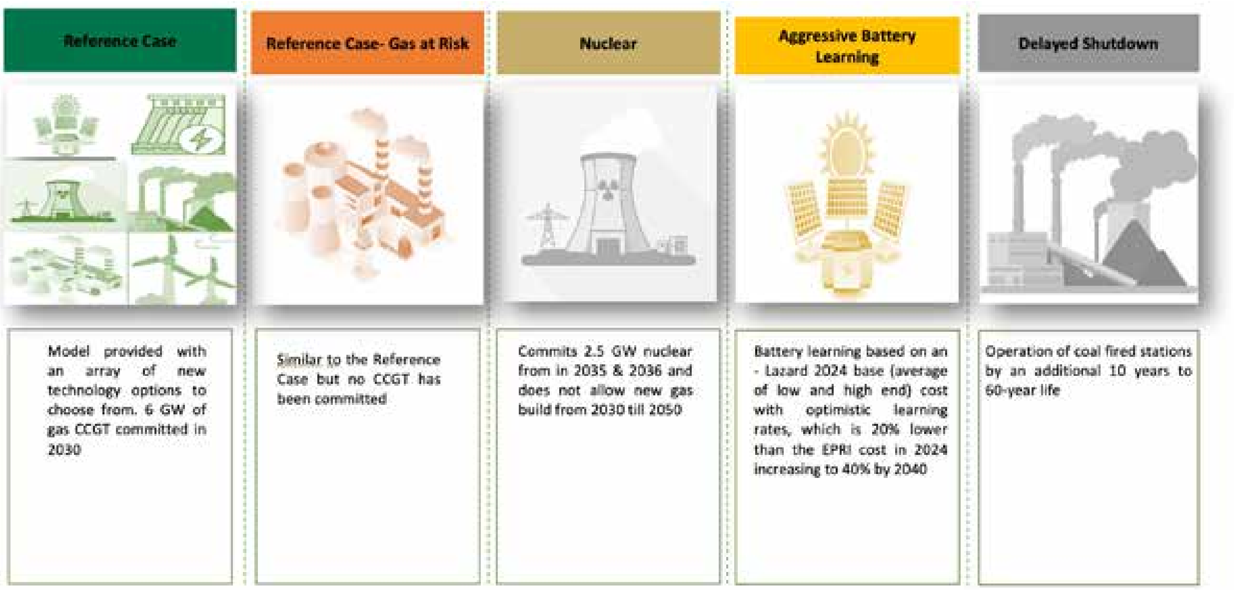


Figure 11: IRP Scenarios.

The assumptions common to all scenarios are the following:

- Electricity demand forecast
  - The moderate electricity demand growth forecast averages 2.3% per annum
- Existing and committed generating capacity
  - Continued operation of coal stations reaching 50-year life by 2030
  - A 20-year life extension of Koeberg units,
  - The base plant performance reaching 68% by 2030
  - All private committed generation capacity
  - Rooftop PV penetration of 900 MW per annum until 2035
- Economic Parameters and Costs
  - a discount rate of 11.3%
  - an exchange rate of R18.35 to the US dollar
  - A gas price of $15/Gj
  - All costs are estimated to be in January 2024 rand terms

4.1 REFERENCE CASE

The Reference case provides an analysis of the power system based on existing and planned policies over the planning horizon. In addition to the common assumptions, additional assumptions applicable to the Reference case are listed below and their variation are considered in the different scenarios:

- A 50-year life of plant for all Eskom's coal-fired stations operating post 2030.
- All public projects detailed in Figure 4 of the report, including all Section 34 Determinations concurred to by NERSA including 6 GW gas CCGT.
- Base learning rates applied to new technology capital costs, where applicable.

The scenarios studied are shown in Figure 11 and the details that distinguishes them from the Reference case are provided.

4.2 GAS AT RISK CASE

This case is premised on the Reference case except that the 6 GW gas CCGT is not committed, and it assesses the impact of the loss of 8 GW of coal-fired units as shown in figure 3 to the system by 2030 should the gas implementation be at risk. The loss of capacity to the system is a result of the end of life of continued operation units between 2029 and 2030. The risk associated with the implementation of the gas programme includes securing an adequate supply at the appropriate price with the required gas infrastructure and the transmission readiness to integrate the capacity onto the grid.

4.3 NUCLEAR CASE

This case uses similar assumptions as the Reference case, including committing 6 GW of gas. Beyond 2030, no generic additional gas technologies are made available in the optimisation model due to their cost range on the screening curves[21]. The nuclear case explores the implications of expanding the power system with a combination of nuclear and other cleaner generation technologies, including storage.

4.4 AGGRESSIVE BATTERY LEARNING

This case applies more aggressive learning rates to reduce the capital cost of BESS. Unlike solar and wind which have an established presence in South Africa with recent updated costs, the procurement and development of BESS is still in early stages. Furthermore, various publications cite differing learning rates for the BESS technology. EPRI reports an optimistic and conservative trajectory and further includes a ±5% error bars to capture additional uncertainty at the end of the projected range. For this case, the lowest cost was used, which results in a reduction of 20% in 2027 and an additional 40% by 2040.

4.5 DELAYED SHUTDOWN

This case is informed by the anticipated shutting down of 15 GW of additional capacity from coal-fired stations between 2031 and 2042 when they reach the end of their 50-year operational life. These candidate stations are assumed to operate beyond 50- year life by an additional 10 years. The consideration applies to Kendal, Majuba, Lethabo, Matimba and Tutuka and the cost assumptions include maintenance and emission abatement retrofits to enable a further 10-year operation and compliance to Section 21 of the National Environmental Management: Air Quality Act, 2004[22] (Act No. 39 of 2004) (NEMAQA), were provided by Eskom. The relevant information provided is the capitalised maintenance costs, the cost of Sulphur Oxide abatement equipment, outages and updated water and emission rates following the retrofits.

4.5.1 RESULTS

The draft IRP 2023 considered two-time horizons, the first being the period up to 2030 focused on addressing the then prevailing generation capacity constraints facing the South African power system. Assessments done provided a basis for identifying impactful interventions to be made in the system to close the electricity supply gap. The second horizon covered the period from 2031 to 2050, mainly focusing on the country's long-term electricity pathways to guide long term policy choices regarding the future energy mix for South Africa. The power system has had the longest stretch without interruption of supply; this means these interventions have resulted in a resilient power system that is capable of sustaining itself without compromising the security of supply even when a cluster of generation units fail. This is testament to the efforts championed by the Presidential Energy Action Plan including considerable improvements of the Eskom coal-fired plant performance, unlocking of a pipeline of private projects that are at various stages of development, etc. It is expected that Eskom fleet will continue to improve as per the Base EAF projection, and that development of new generation will be sustained at acceptable levels. It is for these reasons that the IRP 2025 has been developed with a deviation from the two-time horizon.

21 To be publshed seperately.

22 According to this Act, all coal- and liquid fuel-fired power stations are required to meet the Minimum Emissions Standard published in the list of activities that result in atmospheric emissions within the specified timeframes. This applies to Particulate Matter, Nitrogen Oxides and Sulphur Oxides.

4.6 ANALYSIS OF THE SHORT– TO MEDIUM–TERM PERIOD

With a power system that is currently able to adequacy meet demand, the assessment in the period up to 2030 is to determine the extent to which the specified interventions can sustain the current growth and unlock further economic growth. The results in Figure 12 show that the level of unserved energy is negligible and that the power system has the potential to enable additional growth. Further, the usage of peaking capacity is at acceptable levels and there is sufficient contingency of dispatchable capacity in reserve.

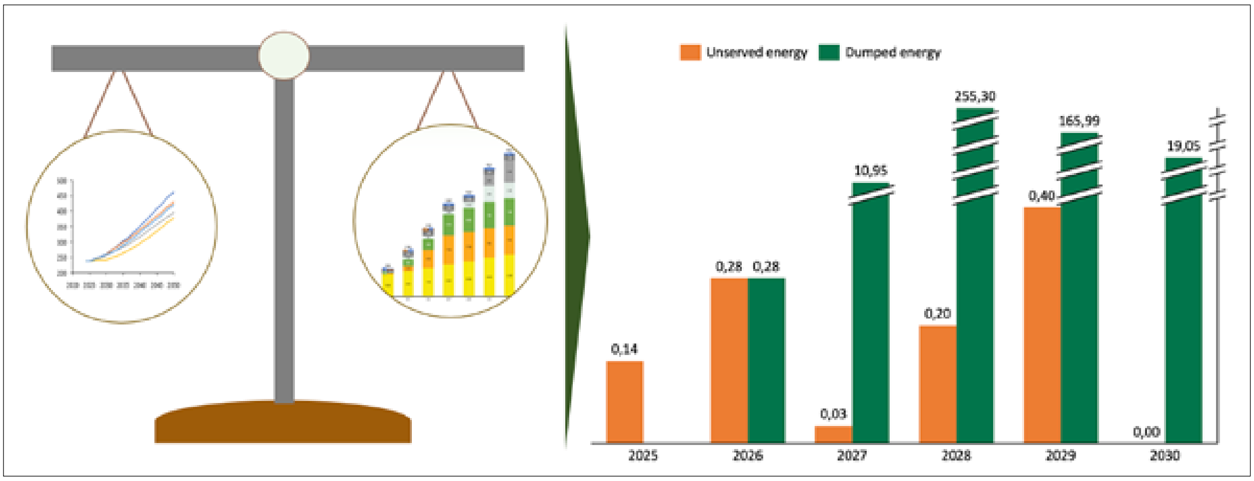


Figure 12: Analysis of the Short- to Medium-Term Period.

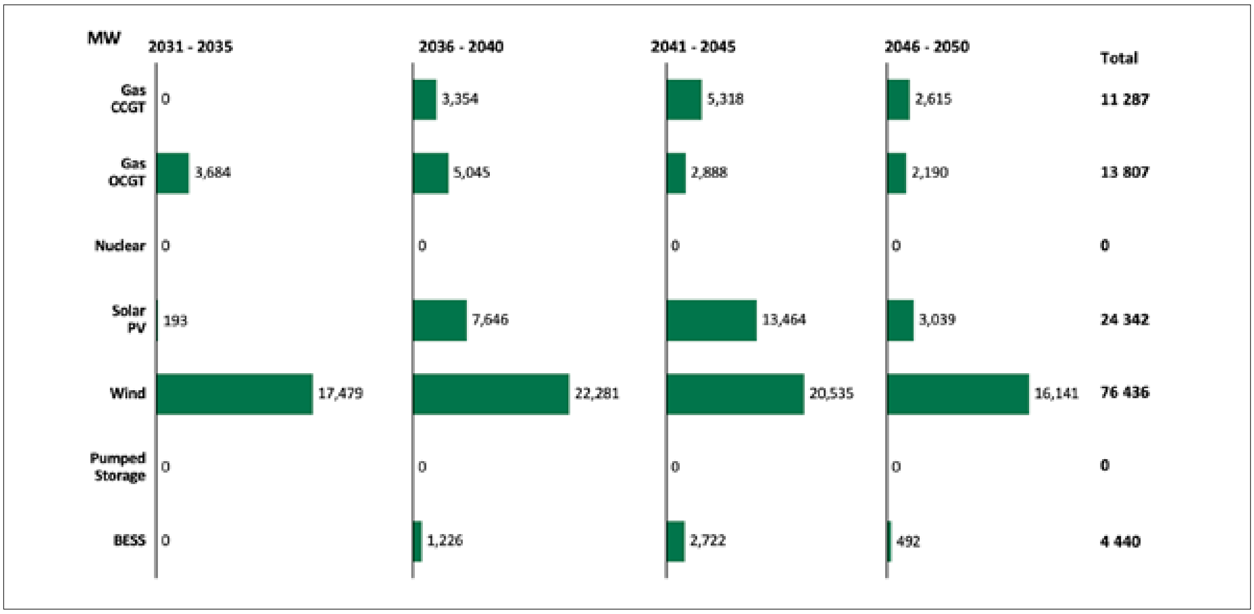


Figure 13: Reference Case Build.

4.7 ANALYSIS OF THE MEDIUM– TO LONG–TERM PERIOD

The analysis of the medium to long-term period's objective is to inform the country's policy choices or decisions for a secure and sustainable energy mix. A few scenarios, based on policy objectives, were tested to understand the extent to which they ensure security of supply while reducing emissions in line with the country's path towards a net-zero future. The emerging technology mix from the analysis shows that wind, solar PV, gas and storage are preferred options. This is in line with the expectation based on the cost production basis resulting from the screening curves. The CO_2 emissions are generally on a reducing trend, albeit at varying reduction rates. Further, the total system costs are much lower than those reported in the draft IRP 2023 due to improved security of supply in this analysis.

The Reference case established a benchmark against other scenarios and included committed 6 GW of gas CCGT, did not consider any implementation technology build constraints and was based on least cost. Comparison with the Reference case considered built plans, overall system costs which include cost of unserved energy to the economy and emissions. The results of the Reference case are detailed in Figure 13 and scenarios benchmarked against it are shown in Figure 14 to Figure 17.

4.7.1 BUILD PLAN

Figure 13 above shows the required build in the Reference case. This scenario evaluates all technology options and associated costs to ensure security of supply. In the initial period between 2031 and 2035, mid-merit gas is not required due to the already committed 6 GW gas capacity.

The Reference case projects over 17 GW of wind capacity will be needed in the next decade, with a continued high demand for wind capacity through to 2050. The highest Solar PV and Gas build is from 2036 to 2045, where majority of the coal stations shutdown occurs. The requirements for new energy storage are based purely on energy arbitrage and more capacity may be provisioned when detailed transmission studies are concluded. No new nuclear, coal and pumped storage options are built in this case.

The risks around new Gas and timelines are noted and incorporated in the next scenario which highlight the implications of not committing 6 GW of CCGT. The results are shown in Figure 14 below.

If Gas is not committed, the system builds approximately 3.5 GW of CCGT in the period between 2031 and 2035, highlighting the immediate need for a mid-merit gas option. Further, the build rate up to 2040 is more aggressive than in the Reference case. Other technology builds remain comparable to the Reference case, with significant wind capacity growth through to 2050.

The Nuclear scenario, which assumes a committed nuclear build of 2.5 GW by 2036, builds an additional ~12 GW of nuclear by 2050. The highest nuclear build (~8 GW) is from 2036 to 2045, where the second cliff of coal shutdown occurs. Compared to the Reference case, this scenario:

- Builds 4 GW more Solar PV by 2050 and 6 GW less wind.
- Has higher storage requirements, with 2 GW of pumped storage and 10 GW more BESS than the Reference case.

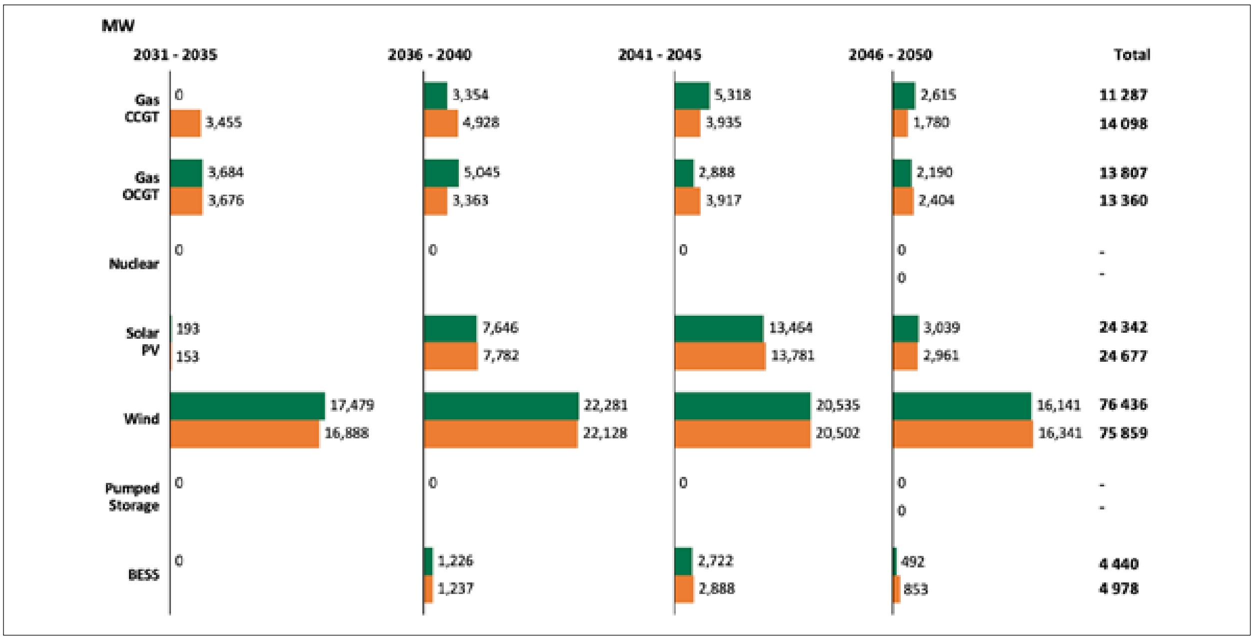


Figure 14: Reference Case and Reference Case with Gas at Risk.

The Optimistic BESS scenario, which assumes a cost reduction of 20% in 2027 and an additional 40% by 2040, results are shown in Figure 16 on page 28.

Compared to the Reference case, the scenario with a higher battery learning rate builds the following:

- Less Gas (OCGT and CCGT), especially from 2036. This is the period when the battery starts ramping up faster than the Reference case, building ~6.5 GW more than the Reference case.
- More Solar PV (~4 GW more) spread across the different years and less Wind (~6 GW) from 2036.

In this scenario, variable renewable technologies are supported by high BESS, given that the Gas build is lower.

Lastly, the delayed shutdown scenario, which outlines the required build for specific coal stations with a 60-year life is shown in Figure 17 on page 28.

In the period between 2031 and 2035, abatement retrofits result in longer outages than the Reference case. Therefore, this scenario builds more wind than the Reference case to ensure security of supply in this period. However, delaying dispatchable coal shutdown reduces the required build across the different technologies throughout the planning horizon. In 2046, when the stations that were delayed start shutting down, this results in an immediate increase in the required build.

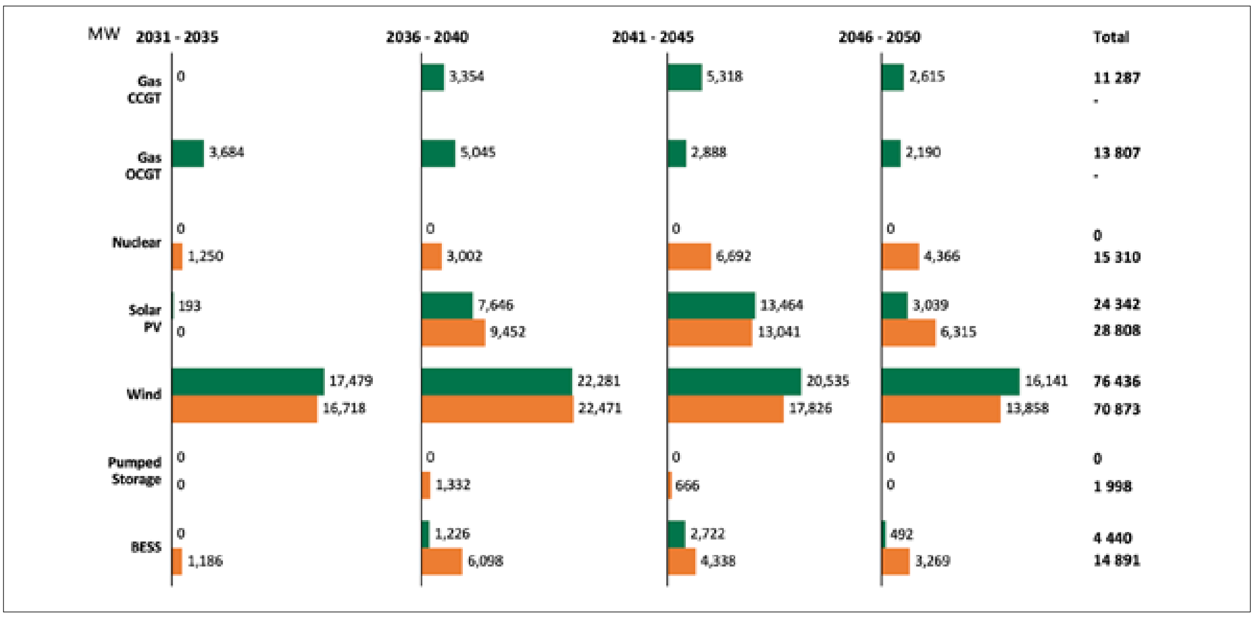


Figure 15: Reference Case and Nuclear.

4.7.2 COSTS

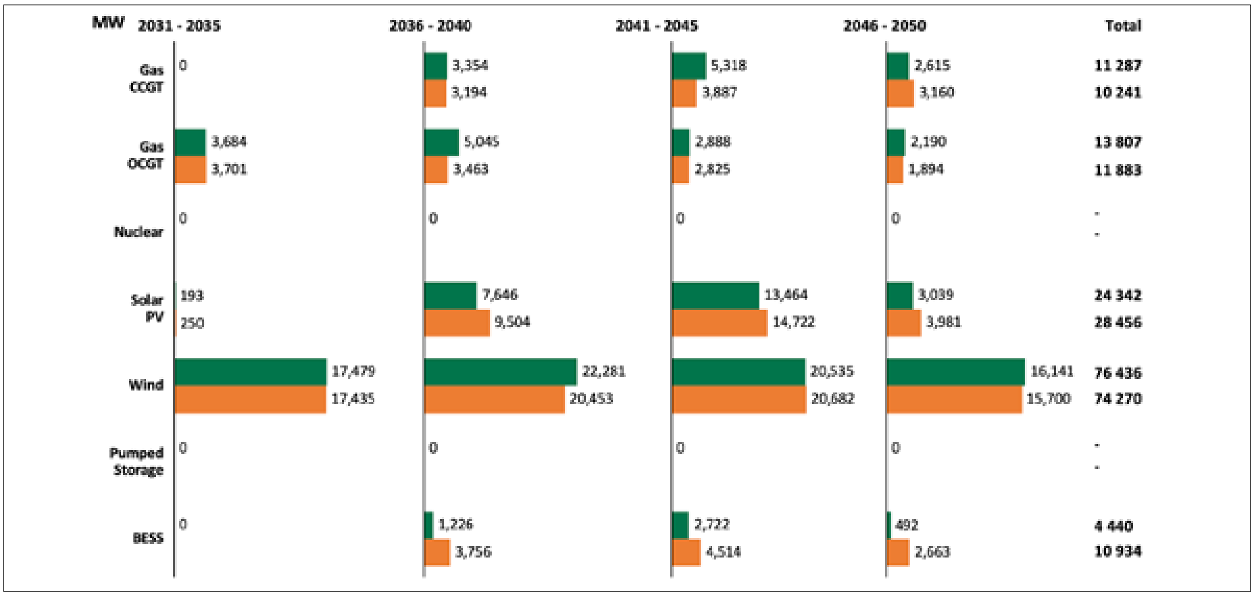


Figure 16: Reference Case and Optimistic Battery Learning Rate.

A total system cost is determined by taking into account the capital costs, fixed costs, operational costs that include maintenance, fuel and environmental impact costs. However, additional economic benefits such as job creation and industrial growth are conducted outside the realm of the IRP process, in conjunction with other relevant departments. Figure 18 shows that when the 6 GW of gas is not committed, the total system cost is the lowest. This is a reflection that sufficient contingency in the system comes at a cost. Although the Delayed Shutdown case has the least new build requirements, it has the highest system cost due to fuel, variable, fixed, externalities and unserved energy. This case would be a suitable candidate for an economic benefit analysis that takes into account socio-economic impact.

Figure 18 shows the cost of each scenario with the associated breakdown. The unserved energy cost has reduced significantly due to improved security of supply. All scenarios have similar total costs with the Delayed shutdown showing higher costs due to SO_x abatement retrofits.

4.7.3 EMISSIONS

Climate Change Act (No. 22 of 2024) legislates the national emissions trajectory, sector emission targets (SETs) and allocation of carbon budgets. These are key mechanisms to achieve the NDC and they are implemented through the emission sector policies and measures (PAMs). The IRP is

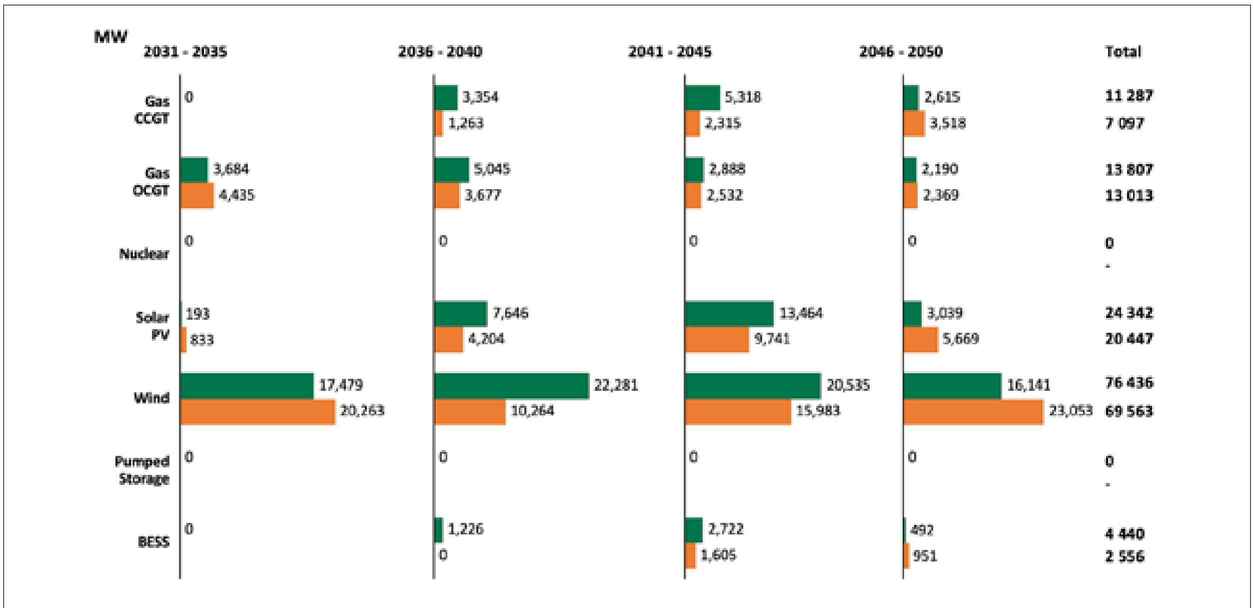


Figure 17: Reference Case and Delayed Coal Shutdown.

considered a policy and measure for achieving SETs in the power sector. The SETs are currently in draft and therefore the application of the Carbon Tax Act (Government Gazette No. 42483 of 2019) is used as a proxy in the IRP 2025 to account for externalities associated with carbon emission.

The Act imposes carbon tax on fossil fuel combustion emissions, with a basic tax-free allowance for the first 60% of emissions. The carbon tax rates are published in the Taxation Laws Amendment Bill (B26-2022), applicable from the first emitted tonne of emissions. The rates for the fossil fuel combustion emissions are ef fective from January 2026.

The Bill was targeting a $30/tonne and up to $120/tonne CO_2 beyond 2050. Similar to the draft IRP 2023, the IRP 2025 assumes $50/tonne in 2040 and $100/tonne in 2050 based on the National Treasury guidance. These costs were extrapolated to obtain rates between 2030 and 2040 and then again between 2040 and 2050 as the exact trajectory has not been published. The externality costs used in the calculation of system costs are based on these numbers up to 2050.

Figure 19 on page 30 shows the declining CO_2 emissions trajectory across all scenarios from 2030 to 2042 with

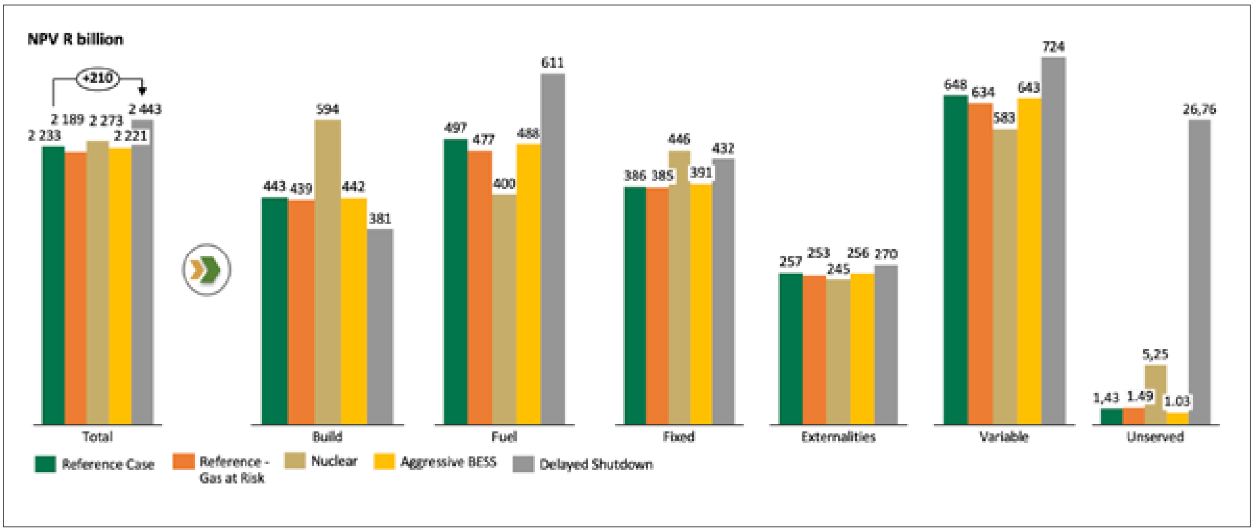


Figure 18: Costs per Scenario (R billion).

a reduction of 59%, 53% and 39% in the Nuclear case, the Reference case and the Delayed Shutdown case, respectively. The Delayed Shutdown case shows a slight CO_2 emission reduction compared to the Reference case during period when retrofits are carried out but this trend reversed when units on prolonged return to service.

5. OVERALL OBSERVATIONS

- The overall observation from this analysis indicates that the power system will remain adequate till 2030 if the Eskom Plant Performance remains within the forecasted range in the base EAF scenario. This means that the system should be able to absorb shocks resulting from multiple unit trips without being adversely compromised. Additional economic growth can be unlocked because of the stable power system
- The installed capacity share of variable renewable energy capacity increases substantially across all the scenarios
- The total system costs (NPV) is more than 2 trillion in all scenarios
- When the anticipated shutdown of Eskom coal-fired stations materialises as a result of the 50-year life of plant between 2030 and 2040, the power system will be the most vulnerable. High bouts of unserved energy and higher utilisation of gas fired plant will be observed and will impact the resilience of the power system negatively. For these reasons, policy decisions should be carefully crafted to mitigate against this.
- Delaying of shutdown of existing coal-fired capacity provides contingency for the following:
  - Requirement for future new build generation capacity to maintain security of supply in the power sector
  - Risk in the roll out of the transmission infrastructure projects as envisioned in the current Transmission Development Plan

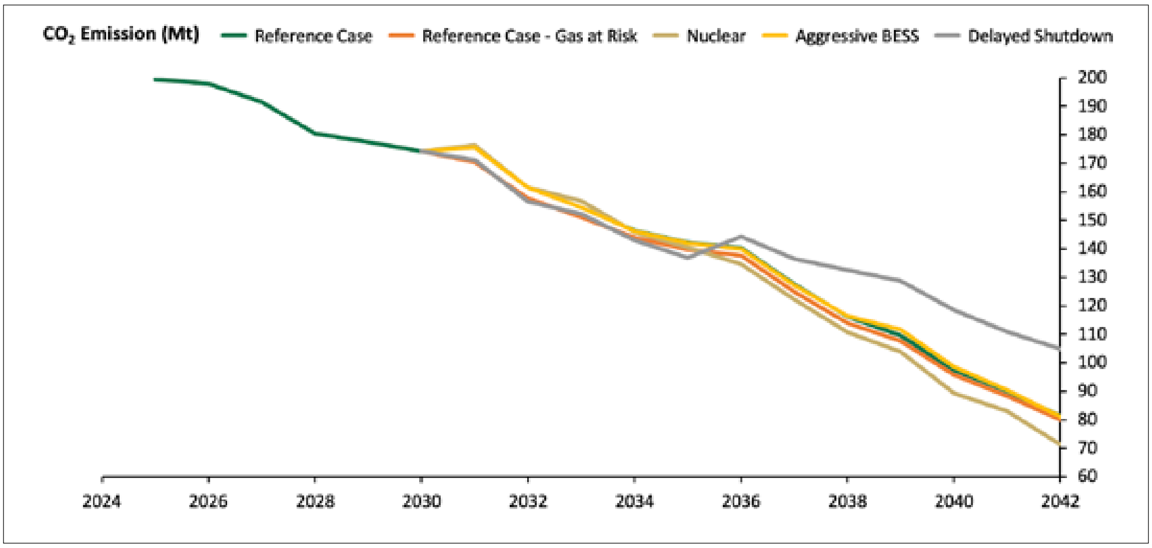


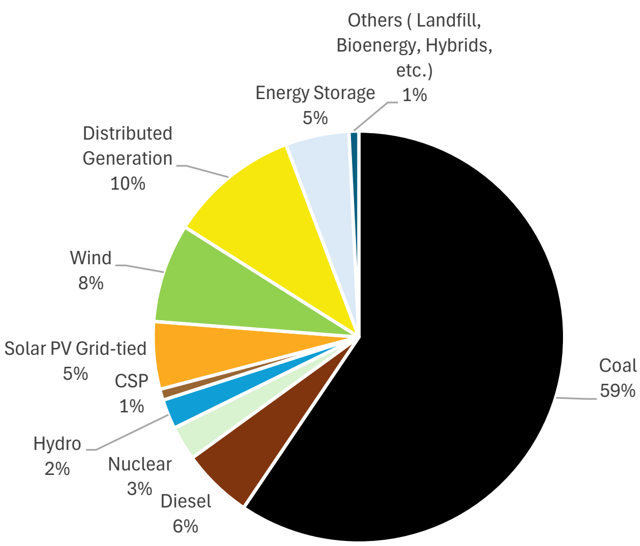
Figure 19: CO_2 Emissions Trajectory (Mt).

  - Risk in the implementation of gas to power programme
  - Foreseeable risk in the roll out of other future generation options as per government policy, e.g. RE, nuclear build programme
- However delaying of coal-fired station shutdown capacity results in the following:
  - Reduced rate of CO_2 emissions reduction compared to the reference case
  - More expensive total system costs over the study horizon
  - Higher water consumption
- Improvement in EAF and deployment of dispatchable generation options such as gas to power provide adequacy to the system and hence low or no unserved energy is observed in the short to medium term

5.1 THE PROPOSED BALANCED PLAN

The Proposed Balanced Plan can be categorized into the medium-term horizon up to 2030, the transition horizon between 2031 and 2040, and the long-term period beyond 2040.

South Africa's current energy mix, although dominated by coal, is diversified, with conventional technologies such as nuclear, diesel-fired turbines, small hydro and water pumped storage, and renewable technologies in the form of utility-scale wind power generation, solar photovoltaic power generation (including rooftop), concentrated solar power generation and others such as battery energy storage, landfill and bio energy. A snapshot of this energy mix in 2025 is shown in Figure 1.



Coal	*40960*
Diesel	*3830*
Nuclear	*1860*
Hydro	*1600*
CSP	*600*
Solar PV Grid-tied	*3646*
Wind	*5344*
Distributed Generation	*7065*
Energy Storage	*3444*
Others (Landfill, Bioenergy, Hybrids, etc.)	*532*

Figure 20: South Africa's Installed Capacity by Technology Diversity in 2025.

Table 1: Proposed Balanced Plan (New Generation Capacity in MW)

	Coal	Gas – IPP Programme	Gas - Eskom	Nuclear	Hydro	Pumped Storage	CSP	Solar PV	Wind	Hybrid IPP Programme	Distributed Generation	Energy Storage	BESS - Eskom	Other private projects (Includes Diesel, Bioenergy etc.)
Current Base (MW) (End 2025)	*40,960*	*1,005*	*2,825*	*1,860*	*1,600*	*2,732*	*600*	*3,646*	*5,344*	*428*	*7,065*	*513*	*199*	*104*
2026								*3,553*	*964*		*900*		*144*	*35*
2027								*2,886*	*2,847*		*900*		*150*	*332*
2028								*1,760*	*770*		*900*	*615*		
2029			*3,000*					*1,314*	*760*		*900*	*2,615*		
2030		*3,000*						*800*	*2,000*		*900*	*200*		
Total (2026 - 2030)	**-**	**3,000**	**3,000**	**-**	**-**	**-**	**-**	**10,313**	**7,341**	**-**	**4,500**	**3,723**		**367**
2031								*1,000*	*2,500*		*900*	*200*		
2032		*1,250*						*1,200*	*2,600*		*900*	*200*		
2033		*1,250*						*1,400*	*2,600*		*900*	*200*		
2034		*1,250*						*1,600*	*3,000*		*900*	*200*		
2035		*1,000*						*2,000*	*3,000*		*900*	*200*		
2036		*1,250*		*1,250*				*1,600*	*2,000*			*500*		
2037		*1,500*		*1,250*		*1,332*		*1,600*	*3,000*			*500*		
2038		*1,250*		*1,350*				*1,600*	*3,000*			*500*		
2039		*1,250*		*1,350*				*1,600*	*3,500*			*500*		
2040		*1,250*						*1,600*	*3,500*			*500*		
2041		*500*						*1,600*	*3,500*			*500*		
2042		*500*						*1,600*	*3,500*			*500*		
Total (2031 - 2042)	**-**	**12,250**	**-**	**5,200**	**-**	**1,332**	**-**	**18,400**	**35,700**	**-**	**4,500**	**4,500**		**-**
Grand Total	**-**	**15,250**	**3,000**	**5,200**	**-**	**1,332**	**-**	**28,713**	**43,041**	**-**	**9,000**	**8,223**		**367**

New Capacity
Distributed Generation Capacity for own use
Current base (includes installed capacity, capacity under construction and deemed to come online 2025)

Table 2: Scoring of the Scenarios

Pathway	Cost (R'bn)	Capacity Built (GW)	CO_2 Emissions (Mt)	Capacity Diversity Score	Overall Score
Reference	*2233*	*130*	*81*	*3*	*3*
Gas at risk	*2189*	*133*	*79*	*4*	*3.5*
Optimistic Battery	*2221*	*136*	*81*	*2*	*2.25*
Nuclear	*2273*	*132*	*71*	*5*	*3.5*
Delayed shutdown	*2443*	*113*	*104*	*1*	*2*

The period up to 2030 is characterised by committed new generation resources, driven primarily by independent power producers' (IPPs) participation. To maintain power system stability, this period is projected to be sufficiently enabled by existing policy and initiatives already in place. Key amongst these are:

- sustain progress made on the Eskom Recovery Plan as directed by the Energy Action Plan.
- ensure commited generation projects (public, private and Eskom) are executed expeditiously.
- advance the gas-to-power programme to maintain power system resilience. Any delays to the gas-to-power programme may require appropriate short-term risk mitigation options such as emergency procurement programme with appropriate characteristics to maintain power system stability.
- advance the Independent Transmission Project initiative to allow investment in expanding and strengthening the electricity infrastructure.

To ensure security of supply in the period beyond 2030, the energy mix is determined using a mathematical optimisation process. From the scenarios studied, it is evident that there's competing output parameters emanating from the analysis in meeting the three IRP objectives.

In crafting a Balanced Plan, energy planning principles dictate consideration of multiple objectives derived from ranking the scenarios using the following four metrics:

- least total system cost (NPV R'bn),
- lowest total new capacity build (MW),
- reduced CO_2 emissions (Mt), and
- most diverse energy mix.

The scenarios were evaluated against four metrics using a rating scale from 1 (poor) to 5 (excellent). An average score was calculated for each scenario to enable comparison, with the highest-scoring scenario considered the most favourable. Both the Gas at Risk and the Nuclear scenarios scored best, each with an average score of 3.5. Therefore, the Proposed Balanced was derived using characteristics of both these scenarios.

- Although the Gas at Risk scenario has the least total NPV costs, it fails to provide a resilient power system in the early 2030s when the initial 8 GW of coal-fired stations is shutdown. It is for this reason that the 6 GW of gas programme was committed by 2030 in the Proposed Balanced Plan.
- The Nuclear Scenario scores best in the lowest CO_2 emissions and most diverse energy mix metrics. It is the only scenario that builds water pumped storage and significant BESS options by 2040. However, challenges associated with nuclear options lead times were taken into account and resulted in the commencement of new nuclear build being delayed by an additional year to 2036. This should provide sufficient preparatory time for South Africa to meet all the required conditions to start the new nuclear build programme.

The Proposed Balanced Plan in the transition horizon between 2031 and 2040 shows the need to retain diversity in the energy mix. However, this period is characterised by a high expected shutdown of coal-fired stations, with no new coal proposed, thus reducing the share of coal in the energy mix.

The Balanced Plan does not make proposals on the energy mix for the period beyond 2040. This is to make provision for enhancements and new technology developments that may occur in the transition horizon to supplement wind and solar photovoltaic. Globally, there is increased focus on research to unlock cleaner and flexible solutions to support the transition.

For South Africa, it is imperative that local research and development entities stay abreast of these developments and identify several technology options that the country may play a key role and benefit from the transition. This could include piloting technologies to establish compatibility with South African conditions and exploration of natural resources; in particular:

- piloting the emissions reduction technologies; positive results from this pilot will influence country policy on sustainable use of coal to power.
- Demonstration of SMR's cost-competitiveness and scalability of may lead to industrialisation of the sector.
- Harnessing of indigenous gas reserves recently discovered will reduce the risks associated with reliance on foreign imports and may lead to policy that encourages gas investment.

5.2 THE PROPOSED BALANCED PLAN AND THE NDC[23]

PERIOD UP TO 2030

During the height of loadshedding in 2022, The President established a National Energy Crisis Committee (NECOM) to ensure that the five identified measures referenced in the Energy Action Plan (EAP), comprising of five Key Pillars, are implemented in a coordinated manner to urgently resolve electricity supply-demand imbalance. These measures were necessary to revive economic growth and create jobs.

23 Nationally Determined Contributions.

Three of these five pillars are relevant in the context of the current IRP review, outlined as follows:

- Pillar 1 - fixing Eskom's existing power stations plant performance (energy availability factor (EAF)).
- Pillar 2 - enable and accelerate private investment in new generation capacity.
- Pillar 4 - encourage and fast track businesses and households to invest in rooftop solar photovoltaic.

These three of the five pillars are specifically addressed in the IRP 2025 with the intention to espouse the EAP's objectives of ensuring energy security in the medium- to long-term.

The IRP 2025 assumptions consider electricity energy demand forecast of 255 TWh by 2029, the updated EAF range starting at 66% in 2025 and progressing to 68% by 2030, and 44 GW of new committed generation capacity by 2030. These parameters (electricity demand projection and EAF range) support the recent Cabinet decision of June 2025 for government to support the restoration of ferrochrome industry as well as the general restoration of South Africa's industrialisation and beneficiation capacity in the sector. Building on these parameters in the IRP modelling work resulted in 168 Mt CO_2-eq emissions by 2030.

Studies reveal that energy efficiency and demand-side management (EEDSM) could play a critical role in reducing carbon emissions further in the future. Nevertheless, the current iteration of the IRP could not incorporate EEDSM impacts due to limited data availability; it is anticipated that the next IRP iteration will explicitly account for these measures, subject to data being available.

ALIGNMENT OF IRP 2025 AND NDC 2030 TARGET

South Africa's 2030 NDC projections exclude accounting for natural disturbances within their emissions pathways. This is what is referred to as the Natural Disturbance provision.

On an annual basis, GHG emissions from Natural Disturbances are estimated to be in the region of 20-30 Mt CO_2-eq. According to the 2013 IPCC Kyoto-Protocol Supplement on accounting rules, adopted in South Africa's NDC framework, Natural Disturbances are natural circumstances that cause significant emissions in forests, which may include wildfires, insect and disease infestations, extreme weather events and/or geological disturbances, beyond the control of, and not materially influenced by, a country, and exclude harvesting (deforestation) and prescribed burning. However, emissions resulting from carbon stock losses arising from land-use changes and activities such as deforestation, are included in national totals.

The 2030 NDC target range of 350–420 Mt CO_2-eq, as well as the proposed 2035 target range of 320–380 Mt CO_2-eq, explicitly exclude the direct impact of natural disturbances. Accordingly, if natural disturbances increase in frequency and intensity due to climate change and winter dryness, actual emissions could be considerably higher than what the NDC currently reflects. More importantly, studies reveal that fires compromise natural carbon sinks, including grasslands, savannas, and forests, thereby reducing South Africa's ability to offset emissions.

The implication of achieving the IRP 2025 GHG emissions target of 168 Mt CO_2-eq in 2030 and applying the natural disturbance provision as per the 2030 NDC accounting rules, then total net GHG emissions by 2030 are likely to be approximately 418 Mt CO_2-eq if the lower end (20 Mt CO_2-eq) of the average annual Natural Disturbances range is considered or 408 Mt CO_2-eq if the upper end (30 Mt CO_2-eq) of the Natural Disturbance is considered. These two outcomes will be within the 2030 NDC target range of 350-420 Mt CO_2-eq. This ensures that the IRP aligns with the 2030 NDC target objectives

IRP 2025 AND DRAFT SECOND NDC

In line with fulfilling the country's obligation under Article 4.9 to communicate NDCs every five years, South Africa has prepared its second NDC[24] under the Paris Agreement covering the period 2031 to 2035. To this effect, the draft second NDC gazette was published for comments in July 2025 as required under Article 4.2 of the Paris Agreement NDC to consistently maintain successive NDCs.

24 The second NDC builds on the country's first NDC and reflects updated commitments to climate action across mitigation, adaptation, and loss and damage, while also outlining support needs for implementation. It proposes, between years 2031–2035: emissions target range of 320 to 380 Mt CO_2 eq. The lower end of the range is conditional on international support (e.g., climate finance).

South Africa's draft second NDC maintains the range in the 2021 updated NDC for (2026 to 2030), of 350- 420 Mt CO_2-eq in 2030 and communicates a new target range for the next five-year period (2031-2035), of 320- 380 Mt CO_2-eq in 2035. On the upper range, a move from 420 Mt in 2030 to 380 Mt in 2035 represents approximately 10% reduction. In comparison, in the same period, the draft IRP 2025 proposes CO_2 emissions for the electricity sector reduction from 168 Mt in 2030 to 142 Mt in 2035, or a 22% reduction. Figure 21 shows the figures above.

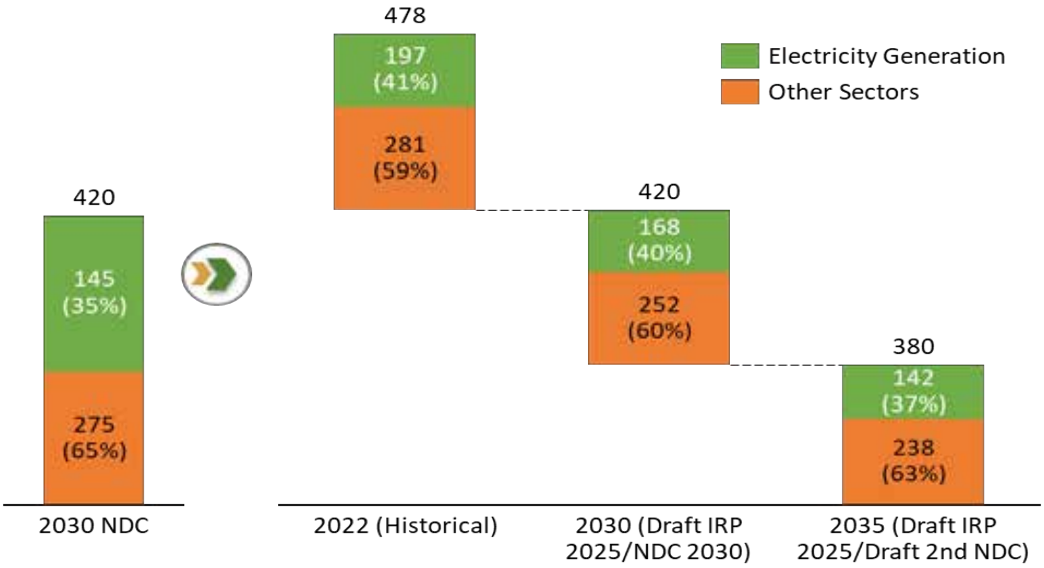


Figure 21: IRP vs NDC Targets.

In the 9th National Greenhouse Gas Inventory Report (2000–2022), the 2022 emissions levels are reported as 478.30 Mt Nationally, with the Electricity Generation contributing 196.98 Mt, a share of 41.2%.

- The committed emissions target in 2030 of 420 Mt, with the Electricity Generation share of 145 Mt, is an apportionment of 34.5%
- In contrast, the proposed 168 Mt in the IRP 2025 Balanced Plan in 2030, is an apportionment of 39.9%.

South Africa's GHG emissions have reduced from approximately 526 Mt to about 478 Mt between 2010 and 2022. This trend will continue as the power sector is set to reduce its emissions as per the IRP 2025.

6. SUMMARY OF THE ANALYSIS

6.1 CASE FOR GAS CCGT

The requirement for gas CCGT in the South African power system by 2030 is critical in lieu of the impending decommissioning of 8 GW of baseload coal-fired plant. Due to new technology options lead times, there are limited credible options of a dispatchable nature that can fill the gap by 2030.

The analysis, with a variation of committing the 6 GW gas CCGT by 2030 shows that if:

- The gas CCGT is committed by 2030, then an additional 1 GW of gas-to-power new generation capacity commissioned per annum is required between 2030 and 2040.
- The gas-to-power is not committed by 2030; approximately 2 GW per annum is required between 2030 and 2040.

Risks that can hinder gas-to-power installation in South Africa are identified below:

- As gas is currently not indigenous to South Africa, a case for gas-to-power, particularly to enable integration into the power system by 2030, requires consideration for appropriate infrastructure development to enable the delivery of gas molecules. In the longer term, the potential for gas development can be unlocked through the Gas Master Plan.
- Development of electricity transmission infrastructure in synchrony with the delivery of gas molecules and completion of the generating plant.
- For the initial 6 GW of Gas CCGT, a load factor that enables a business case for upstream gas infrastructure is determined to be minimum 50%. Exposure to fluctuations in gas market prices and foreign exchange rates reduces certainty on the electricity tariff trajectory, this risk must be mitigated through flexible gas supply beyond the initial 6 GW.

- Securing Liquefied Natural Gas (LNG) and associated infrastructure in South Africa by 2030 remains a risk and may require policy adjustment to ensure timelines are met.

Besides the determined new gas-to-power programme as outlined above, there is a need to consider converting the existing diesel-powered peaking plants to natural gas as primary energy. This will further bolter the business case for upstream natural gas infrastructure development and increase the economies of scale benefits which could reflect as lower electricity tariffs over time. Plans are being developed at most of these peaking plants, such plans are encouraged to be progressed to execution stage.

6.2 CASE FOR NUCLEAR

South Africa has an excellent experience in operating a nuclear power plant safely and securely for more than forty years. Koeberg power plant has not only provided continuous, stable and reliable base load capacity to the power grid but is also one of the cheapest sources of generation within South Africa's power system.

The nuclear scenario has demonstrated that nuclear technologies provide reliable baseload power whilst complementing intermittent renewable energy generation and energy storage.

One of the advantages of nuclear power plants is that they can be operated between forty and sixty years, offering long term energy solutions. Nuclear applications are not limited to the power sector but also supports sectors like healthcare, manufacturing, and infrastructure. It complements renewable energy by offering frequency regulation and grid resilience.

Recently, the global arena is considering nuclear power as key in decarbonisation of the electricity grid, an important tool in mitigation against climate change and assisting different jurisdictions in realising commitments in drastically reducing greenhouse gas emissions and is increasingly viewed as essential for achieving net-zero emissions. The European Union has, under the Complementary Delegated Act (CDA), included nuclear energy as a transitional activity that is necessary for the transition to a low carbon economy and considered nuclear as a green investment under the EU's sustainable finance taxonomy.

The World Bank has, since June 2025, officially lifted its longstanding moratorium on financing nuclear energy projects, marking a major policy shift in global energy development strategy.

The development of Small Modular Reactors (SMRs) has been seen as a promising solution for different economies due to lower upfront capital costs, flexible operation, safer and more efficient energy production; and potential for standardisation and scalability (can be added incrementally to match rising demand growth).

To implement the nuclear build capacity beyond the capacity outlined in the Proposed Balanced Plan (5 GW), South Africa must develop a Nuclear Industrialisation Plan (NIP) that outlines a roadmap towards a generation capacity quantum sufficient to achieve the development of nuclear economy across the entire nuclear fuel cycle value chain. A case for 10 GW of nuclear rests on the economic viability of re-establishing the nuclear fuel cycle, using nuclear for both power and industrial applications (non-power). This case will be elaborated further in the Nuclear Industrialization Plan.

6.3 CASE FOR RENEWABLE ENERGY

The RE technologies remain consistently favourable in all cases, dictating that a minimum threshold can be established with the analysis showing a range of 4.2 GW to 5.5 GW per annum for all cases. The rollout of the technology provides an opportunity for localisation and industrialisation of the manufacturing sector as per the SAREM.

However, their variability requires the support of other technologies of a dispatchable nature to ensure a continuous and reliable supply of electricity. Further, the technologies lack sufficient grid support and ancillary services, creating a challenge for power system operability with high penetration of these resources. A further analysis to assess the impact of such high RE penetration in the power system is done and the results are reported in the next Chapter.

6.4 CASE FOR STORAGE

With the anticipated increased penetration of variable generation, more storage will be required (battery and pumped storage). This technology provides a flexible generation, and this is evident in the Nuclear Case, where the gas option is limited. In this case, an additional 10 GW of storage is required to support variable RE and the dispatchable nuclear.

The linkage between generation and transmission development, particularly with regard to the wide role of BESS, dictates more storage capacity to provide support to the grid and offer ancillary services to improve the operability of the power system.

6.5 CASE FOR DELAYED SHUTDOWN

The adequacy of the South African power in the period up to 2030, depends on three levers as proven in the analysis:

- An improving system EAF beyond 60% levels
- Roll-out of 6 GW CCGT capacity by 2030
- Roll-out of other capacity as per Figure 7 (Total Committed Capacity)

Of the three above levers, the first two play an important role in maintaining security of supply in different stanzas of the period. Firstly, in the near and medium term it is crucial that the system EAF remains above 60%, failing which system security of supply will be compromised as experienced in the previous years. When EAF falls to levels below 60%, there are currently no identified credible (supply) options with quick turnaround times to restore system adequacy and as a result the System Operator may be forced to resort to implementing interruption of supply measures including as a last resort loadshedding.

In 2030 when 8 GW of coal-fired capacity reaches end of continued operation life, it is important that the anticipated 6 GW of CCGT generating capacity is operationalised so that security of supply is maintained. Currently, some of the best performers in Eskom's coal-fired fleet are the units of the stations earmarked for the 2030 shutdown, with EAF often exceeding 75%. Should the development of the 6 GW of gas to power be delayed beyond 2030, it may be prudent that operation of some of these units be extended beyond year 2030 until such time as the 6 GW GTP is available. One of the enablers for this, is when a successful demonstration of cleaner coal technologies that will drastically reduce emissions is proven before 2030.

Beyond 2030 when an additional 15 GW of coal generating capacity is shutdown between 2034 and 2042 and the economy is projected to grow at the forecasted levels, requirements for new generation and transmission infrastructure may be onerous. The delay shutdown of some of the identified coal-fired stations maybe the best tactic to mitigate against this by utilising existing resources prudently.

7. POWER SYSTEM FLEXIBILITY

A flexible power system is one that can adapt quickly and reliably to changes in electricity demand or supply. This means being able to ramp power output up or down or switch between different energy sources to make sure the grid is always balanced. A measure of flexibility is assessing how quickly a dispatchable power plant can change its output from zero to maximum when required. South Africa's power system is dominated by older coal-fired plants that are generally not designed for rapid changes in output or ideally should be operated above their minimum stable level, thus making them less flexible. As the energy share of variable renewable energy resources increases in the grid, a more flexible type of generation is necessary to ensure a reliable power system.

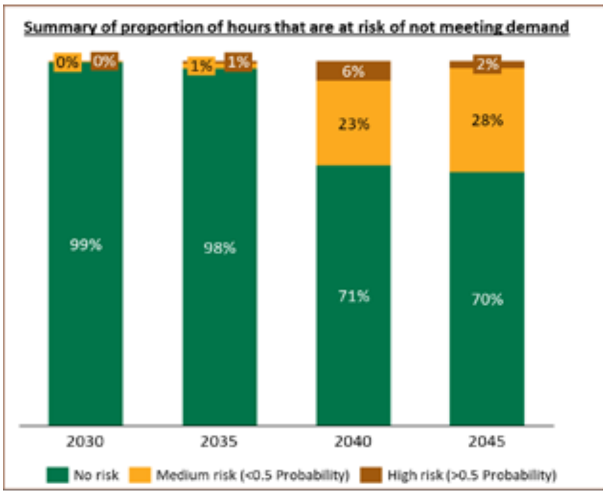


Figure 22: Results of the flexibility analysis.

7.1 METHODOLOGY FOR FLEXIBILITY ASSESSMENT

The methodology used to assess the flexibility of the South African power system as penetration of variable RE increases is premised on determining the probability that available dispatchable capacity at any given time is higher than the residual load. Residual load refers to the amount of electricity demand that remains after accounting for production from RE sources like wind and solar, whose production can be unpredictable and varies with weather conditions. In other words, it is the leftover demand that needs to be supplied by other sources, such as coal, gas, storage, etc. Available capacity refers to the remaining capacity after accounting for planned and unplanned outages from the dispatchable resources.

As discussed in the IRP modelling approach section, profiles of RE resources are based on their location and future production projections are derived from historical data. This data is used to determine statistical parameters such as standard deviation, which provides a measure of data dispersion relative to the mean; and autocorrelation, which measures the correlation of a variable with a lagged version of itself over successive time intervals. As an example, for wind profiles, autocorrelation measures how wind speed or its direction at a given time is related to its values at previous times. This is crucial for understanding patterns and predicting future wind behaviour. The electricity demand China has added 11 GW of nuclear power over the past five years while being heavily invested in new coal. https://www.iea.org/reports/world-energy-investment-2024/china profile variability is premised on the upper end error (5% error standard deviation) that the System Operator targets on its forecasting. The stochastic method uses time-series data and stochastic parameters to create 1000 random variable samples as well as 1000 outage and demand patterns. Then, a unit commitment dispatch is conducted in the Plexos® simulation tool to balance supply and demand and the results are reported per sample for the Reference Case.

When generation exceeds supply, the excess is curtailed. Curtailment occurs when excess energy cannot be utilised due to oversupply or operational constraints of thermal generating resources, such as minimum operating levels or ramp rates, or energy cannot be evacuated due to transmission congestion. The case where supply and demand balance or where there is an excess, is not addressed further.

7.2 SHORT- TO MEDIUM-TERM FLEXIBILITY

Presently, the South African power system is dominated by dispatchable coal-fired capacity that is less flexible, particularly around minimum generation. However, the energy mix does include generation resources which are more flexible such as diesel-fired gas, pumped storage as well as hydro power plants.

7.3 MEDIUM- TO LONG-TERM FLEXIBILITY

In 2030 when 8 GW of coal-fired stations shut down, the contribution of variable RE in the energy mix increases to 23%. This coincides with the planned commissioning of 6 GW of new gas CCGT.

The outcomes of an assessment to determine the power system's capability to meet future residual demand and variability with a significant level of certainty, given a combination of existing and planned dispatchable resources, are depicted at 5-yearly intervals in Figure 22. In 2030 and 2035, with a steady increase of variable RE in the energy mix, the level of risk associated with available supply meeting residual demand remains insignificant. The magnitude of the shortfall ranges from 1.4 GW to 3.8 GW and from 2.7 GW to 8 GW in 2030 and 2035, respectively, occurring over the peak period.

With a further shutdown of power stations, including coal and gas, the ability of the remaining dispatchable capacity to meet the residual load is reduced. This is evident in the significant probability of dispatchable available capacity meeting demand. In addition to the number of events, the magnitude of risk increases with 2040 showing a shortfall ranging between 6.5 GW to 12.7 GW and 2045 shortfall ranging between 9 GW and 12 GW.

In summary, although the adequacy of the power system meets the defined criteria for the South African power system, the statistical analysis demonstrates that the probability of risk increases as the share of variable RE resources increases in the energy mix. Further, the magnitude of risk also increases. It is therefore imperative that resources that provide flexibility services of a dispatchable nature are procured as more RE is integrated.

8. POLICY STATEMENTS

8.1 SOCIO ECONOMIC IMPACT PLANS FOR SUPPORTING CONTINUED COAL SHUTDOWN BY 2030

The Integrated Resource Plan (IRP) 2025 is premised on the assumption that Eskom intends to shut down 8 GW of coal-fired power stations, including Camden, Hendrina, Grootvlei and Arnot, by the financial year 2030. The Department of Electricity and Energy is actively engaging with provincial and local governments, alongside other key departments, to accelerate industrialisation, and stimulate economic growth and allocate transitional funds to areas where the stations are to be shut down.

In addition, Eskom has developed a comprehensive Just Energy Transition (JET) strategy to guide the phased shut down of coal-fired power stations up to 2030 and beyond. As it prepares for this shift, the utility is focused on repurposing and repowering several coal-fired power stations to support cleaner energy solutions. Drawing on valuable insights from the Komati Power Station transition, Eskom is committed to ensuring that the process is responsible, inclusive, and sustainable, thus prioritising community upliftment, workforce reskilling, and long-term economic resilience.

This approach is anchored on the principles of South Africa's JET framework aiming to mitigate environmental, social, and economic impacts while transitioning to cleaner energy sources with a focus on repowering, repurposing, and revitalising impacted communities.

KEY STRATEGIC PILLARS FOR SHUTDOWN, REPURPOSING AND REPOWERING

1. Early Planning and Decoupling Operations: Fully recognising that early planning and execution is essential. Shutdown and repurposing activities will be decoupled from ongoing station operations, allowing repurposing and repowering efforts to proceed independently, efficiently and prior to shut down dates.
2. Repowering with primarily cleaner technologies: Repowering initiatives are underway at Arnot, Camden, Grootvlei, and Hendrina, using cleaner technologies.
3. Skills Development and Training: Training centres are being established to equip employees and communities with future-ready skills. Partnerships with TVET colleges are expanding the scope and reach of these programmes.
4. Community Engagement and Co-Creation: Prioritizing social dialogue and co-creation with affected communities. Engagements around the power stations ensure that local stakeholders are actively involved in the transition journey.
5. Funding and Partnerships To mitigate against similar delays experienced at Komati, is there is a need to secure upfront funding through engagements with Multilateral Development Banks. The approved JET partnership strategy is fostering collaboration across sectors, with successful initiatives like the Grootvlei horticulture centre serving as proof of concept.

8.2 POLICY DECISIONS

After careful consideration of the observations made from the technical analysis done to produce the Proposed Balanced Plan, the following policy statements can be made with a high degree of certainty to ensure a resilient power system (now and in future) that will lead to a sustained economic growth:

POLICY DECISION 1:

The Energy Availability Factor (EAF) of the current Eskom fleet to be maintained at levels above 60%. Any levels below 60% will result in a fragile power system that will not only be able to absorb negative contingencies but will also not able to support aspirations to grow the economy.

POLICY DECISION 2:

The 6 GW of gas CCGT by 2030 is crucial in ensuring and maintaining security of supply when the 8 GW of baseload operation of coal-fired stations is shutdown.

Minimum load factor of 50% is necessary for this initial gas-to-power programme to ensure security of supply and to anchor upstream gas processing infrastructure.

This approach should also have a built-in flexibility, in the medium to long term, to adjust the load factor should the need arise at any time of the contracting period. Introduction of variable load factor gas to power facilities to be considered at a later stage.

POLICY DECISION 3:

Demonstration plant on clean coal technologies by year 2030 as the country explores other options which are potentially cheaper and efficient to significantly reduce both global and local emissions.

Crucial to demonstrate domestic operational conditions such as compatibility, economics, effectiveness in reducing emissions. May lead to operating coal-fired stations beyond the 50-year life of plant.

POLICY DECISION 4:

Develop a Nuclear Industrialization Plan to plot a roadmap determining the minimum capacity to reach the economies of scale for the entire nuclear fuel cycle value chain within the country.

Demonstration of multiple purpose nuclear reactors by 2032, as the country positions itself to adopt nuclear energy for net zero by 2050. This is important to demonstrate viability to implement a successful full value chain nuclear programme.

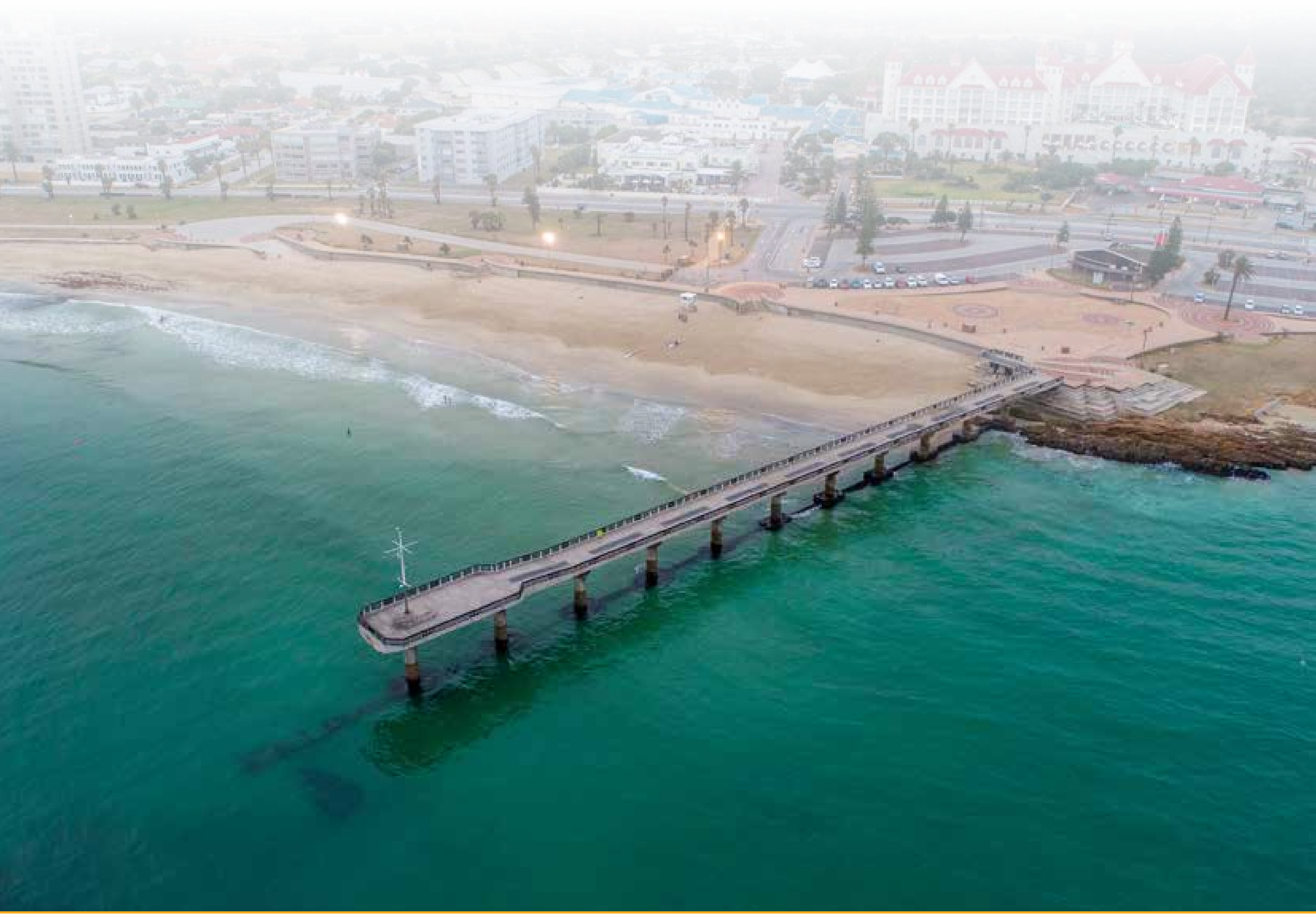
A case for 10 GW of nuclear rests on the economic viability of re-establishing the nuclear fuel cycle, using nuclear for both power and industrial applications (non-power).

POLICY DECISION 5:

Ensure effective implementation and monitoring of the South African Renewable Energy Industrialization Masterplan (SAREM).

POLICY DECISION 6:

Consider implementation of transformative opportunity for "mega bid window" that not only accelerates energy deployment but also fast-tracks industrialisation, localisation, and job creation across the energy infrastructure value chain.



SECTION D

POWER SYSTEM
GRID PLANNING

1. INTRODUCTION

This report discusses the 10-year Transmission Development Plan (TDP) for the South African power system. This TDP covers the calendar years 2025 to 2034 and is referred to as TDP 2024. Its aim is to meet the long-term requirements of electricity consumers in South Africa by maintaining the legislated adequacy and reliability standards for the transmission grid. These standards emanate from the South African Grid Code: The Network Code Version 10.1 (January 2022) which mandates the National Transmission Company (NTC) to annually publish a five-year-ahead Transmission System (TS) development plan by the end of October as a minimum, indicating the major capital investments planned (but not necessarily approved). In alignment with this requirement, the TDP's primary objectives are to:

- Attain Grid Code compliance by resolving both substation and line violations (N-1).
- Determine new network infrastructure requirements to sustain and allow for future demand growth.
- Determine new network infrastructure requirements to integrate new generation capacity and address system stability requirements.
- Consider asset replacement requirements to ensure reliability of supply and network optimisation.

1.1 METHODOLOGY

The TDP process is illustrated in Figure 23. It shows how the expected generating capacity and spatial distribution, expected electricity demand and spatial distribution, stakeholder inputs from various sources such as Integrated Resource Plan, Eskom Generation Plan, Annual Renewable Energy survey, etc and previous TDP's and other planning activities are used to evaluate the current and future state of the network over the 10-year study horizon to identify network problems such as equipment overloading, voltage constraints, high fault levels, high technical losses, and inadequate redundancy. For each identified problem, various solutions are proposed and rigorously evaluated both technically and financially. The solution that provides the greatest network strength at the lowest life-cycle cost is selected. The outcome of the TDP is therefore a list of projects with a high-level scope, cost, and timeline for the new infrastructure requirements, ensuring the network will operate within the perimeters of the grid code.

1.2 ASSUMPTIONS

Several reasonable assumptions, primarily regarding electricity demand and supply, were made during the development of the TDP 2024. The plan evaluated various demand scenarios, and a sensitivity analysis was conducted to determine the most likely scenario within the TDP's study horizon. Based on this analysis, the moderate-high demand scenario was identified as the most probable and selected for evaluation for the TDP 2024. This scenario assumes steady growth rates of 1.5% in the short term and 2% in the long term. With this scenario, peak demand is projected to reach 43 GW by 2034 and grow further to 52 GW by 2050, aligning closely with the reference case outlined in the 2023 Integrated Resource Plan (IRP) draft.

Key drivers of this demand growth include the expansion of data centres, hydrogen production for domestic use, localised beneficiation from increased steel production, photovoltaic (PV) manufacturing, and the development of motor vehicles and battery industries.

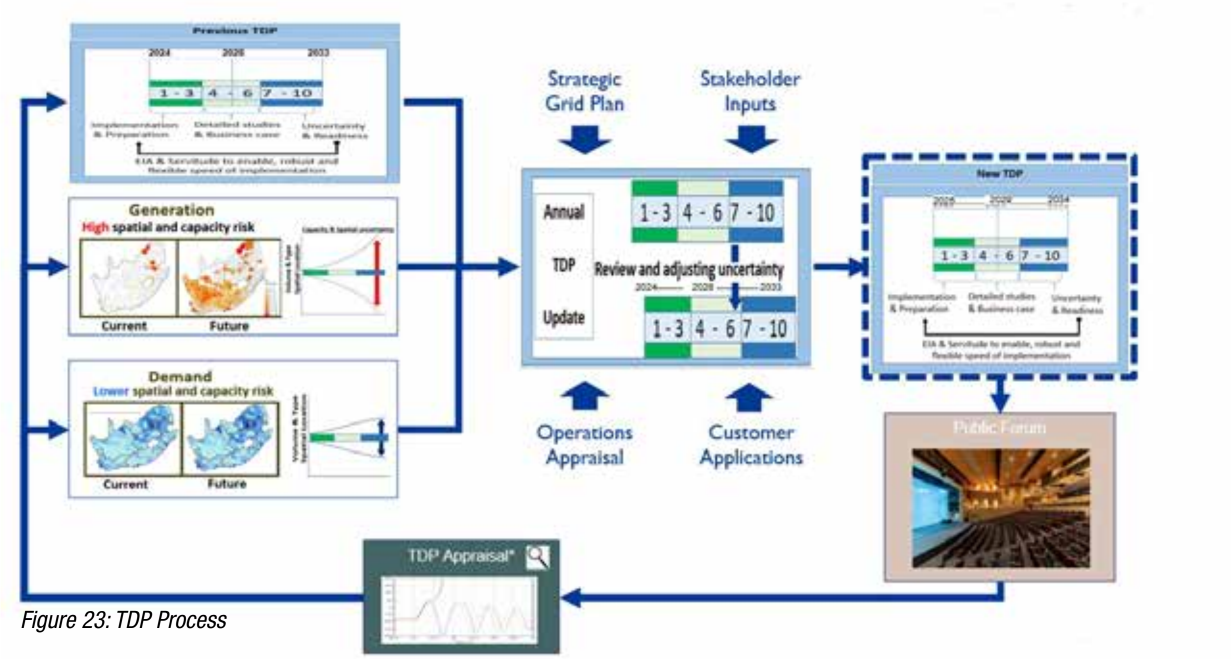


Figure 23: TDP Process

Furthermore, the TDP 2024 projects a significant increase in generation capacity, from 66 GW in 2024 to 107 GW by 2034, accompanied by substantial changes in the generation technology mix. A significant portion of this increase will come from new wind and solar projects, as well as Battery Energy Storage Systems (BESS), which are expected to contribute a combined 41 GW by 2034. This aligns closely with the 2023 Integrated Resource Plan (IRP) draft reference case, which anticipated 39 GW from these sources over the same period. To remain consistent with the draft IRP reference case, the TDP 2024 assumes no additional nuclear or pumped storage developments during this horizon. However, it does include provisions for 17 GW of new gas-fired generation capacity by 2035, aligning with the assumptions in the IRP 2023 draft. Regarding the planned decommissioning of Eskom's coal fleet, the TDP 2024 is aligned with the Generation Continued Operations (GCO) shutdown plan. This plan sees a decline in the coal fleet from 42 GW in 2024 to 28 GW in 2034 and the ramping down of coal in Mpumalanga is envisaged to be replaced by wind and solar plants from the broader Cape regions. It is anticipated that the next revision of the IRP 2023 draft will also adopt the GCO plan as a reference for its base case development.

1.3 RESULTS

The anticipated increased penetration levels of wind and solar in the broader Cape regions will require the development of new transmission corridors or lines to transport power from these regions to load centres in the northern part of the country. Specifically, TDP results showed the following:

- 14 494 km of new lines will be required by 2034 to accommodate the increased generation and demand requirements. 5 044 km of these lines are required by the year 2029.
- Transformer capacity totalling 132 730 MVA will be required by the same period to cope with increasing generation and demand requirements. 41 325 MVA of this capacity is required by the year 2029.
- Eight synchronous condensers, of which seven are required by 2029, 40 capacitors and 59 reactors will be required within the study period to maintain system security and stability.

1.4 IMPLEMENTATION CHALLENGES AND SOLUTIONS

The primary risk to the successful delivery of the TDP 2024 lies in the anticipated challenges associated with servitude acquisition. As this process involves multiple layers and stakeholders, it is expected to significantly influence the pace at which TDP projects are implemented. To mitigate this risk, proactive engagement with the Department of Public Works and Infrastructure (DPWI) will be essential, particularly concerning land expropriation and access to government-owned land. Resource constraints, such as global supply chain constraints and local engineering capacity constraints, pose another significant challenge. To address these issues, key mechanisms such as project prioritisation based on impact and cost, as well as securing contracts for critical commodities like transformers, will be employed. The implementation of TDP projects also entails substantial capital expenditure requirements. This necessitates effective collaboration with regulatory bodies such as NERSA to secure cost-reflective tariffs. In addition, engagement with the shareholder will be critical to ensure adequate capitalisation and financial support to meet the funding demands of the plan.

SECTION E

POWER SYSTEM OPERATIONS PLANNING

1. INTRODUCTION TO POWER SYSTEM OPERATIONS APPRAISAL

The main purpose of the power system operations appraisal is to ensure a continuous supply of power with an acceptable quality to all the consumers in the power system in accordance with the South African Grid Code (SAGC): Version 10.1 Network Code (January 2022) and the System Operator Security Guideline. The guideline, which is a condensed version of the network code, requires all generation connections to be planned in such a manner that the consequences of the next contingency, with reference to the system's healthy condition, are as follows:

- No base load or mid-merit generation should be lost following the forced outage of any transmission circuit.
- No base load or mid-merit generation should have to be removed from service for the planned outage of any single section of busbar.
- The loss of generation that may occur as a result of a forced outage of any single generation circuit or single section of busbar should not result in a frequency drop to below 49.5 Hz.

Compliance with the above requirements necessitates conducting a stability analysis on the power system to ensure the IRP plan can provide a continuous supply of power both during normal conditions and following single contingencies.

1.1 STABILITY ANALYSIS

A power system is considered stable if it reaches equilibrium after being subjected to a disturbance. Stability analysis assesses the ability of the power system to return to normal operations following some form of disturbance. A full assessment of the power system stability comprises steady-state and dynamic analyses.

1.2 STEADY-STATE ANALYSIS

The objective is to assess whether the power system is operating within operational limits and targets as set for the transmission system. The assessments are conducted for normal operating conditions and during contingencies. In particular, the steady state studies for the appraisal will include the following study cases:

- **N-0:** Base case scenario, which represents a fully intact power system with no equipment out of service. It evaluates whether line and transformer loadings and busbar voltages remain within acceptable limits under normal operating conditions.
- **N-1:** Single contingency, which represents a scenario where a single piece of equipment (transmission line, transformer, or shunt equipment) is out of service. It assesses the power system's compliance with operational limits during the N-1 scenario. Specifically, it determines if the thermal loading on the transmission lines and transformers is still within acceptable limits, and it checks if the busbar voltages are within the acceptable range.
- **N-2:** Double contingency, which represents a scenario where a second piece of equipment is out of service while the first piece is already unavailable. Similar to a single contingency analysis, this scenario evaluates the system's compliance to operational limits but under more severe and challenging conditions.

In accordance with the SAGC Network Code and the System Operator Security Guideline, the reliability evaluation criteria in Tables 2 and 3 shall apply when performing the steady-state analysis.

Table 3: Equipment Loading Limits

EQUIPMENT	NETWORK CONDITION (SYSTEM HEALTHY)	NETWORK CONDITION (CONTINGENCY)
Transmission lines	*100% of line continuous rating (Rate A)*	*100% of line emergency rating (Rate B)*
Transformers	*100% of transformer rated capacity*	*100% of transformer rated capacity*
Switchgears	*Terminal equipment and busbar nameplate rating*	*Terminal equipment and busbar nameplate rating*
Series capacitors	*Up to the continuous rating*	*8 hours in 12-hour rating*

Table 4: Busbar Voltage Limits

NOMINAL (Un)	Maximum (Un)	DESIRED OPERATION	MINIMUM VOLTAGES
220 kV	*245 kV*	*225 kV*	*209 kV*
275 kV	*300 kV*	*281 kV*	*261 kV*
400 kV	*420 kV*	*410 kV*	*380 kV*
765 kV (Alpha and Beta)	*800 kV*	*750 kV*	*727 kV*
765 kV	*800 kV*	*765 kV*	*727 kV*

1.3 DYNAMIC STABILITY ANALYSIS

While there are various types of dynamic analyses, the IRP focuses specifically on the transient stability and frequency stability analyses.

1.3.1 TRANSIENT STABILITY ANALYSIS

Transient stability refers to the ability of the Integrated Power System (IPS) to maintain synchronisation following a major disturbance, such as a transmission equipment failure, generation loss, or a substantial load loss. The SAGC: Version 10.1 System Operator Code (January 2022) mandates the System Operator to ensure the safe and efficient operation of the IPS. It further requires that credible outages be analysed, and, where feasible, that the IPS is operated to prevent instability, uncontrolled separation, and cascading failures. A key metric for evaluating transient stability is the Critical Clearing Time (CCT); a maximum time a fault can be cleared before a power station(s) becomes unstable and loses synchronism. Power stations are deemed compliant if they maintain transient stability when a three-phase line or busbar fault is cleared within a duration that protection equipment can safely respond to.

Power stations selected for transient stability studies will be system-wide representatives, ensuring coverage of all generation pools across the network. These studies will analyse the system under varying load scenarios, including light, mid-day, and peak loading conditions, under system healthy and critical contingencies.

1.4 FREQUENCY STABILITY ANALYSIS

The System Operator Code requires the System Operator to maintain the system frequency above 49.50 Hz following a credible single contingency. A credible single contingency is defined as the loss of the largest unit (Koeberg unit) on the system, operating at full load. Other single contingencies include the loss of a coal unit at Medupi or Kusile. The loss of the Cahora Bassa infeed is not classified as a single contingency loss but as a multiple-unit trip. Additionally, SAGC: Version 3.1 Grid Connection Code for Renewable Power Plants (RPPs) January 2022 stipulates that RPPs must remain connected to the National Interconnected Power System (NIPS) during a rate of change of frequency (RoCoF) of up to 1.5 Hz per second, provided the frequency remains within the minimum operating ranges specified in the code.

As a result, frequency stability analysis is conducted to assess the System Operator grid code compliance and to determine the instantaneous reserve requirements under various dispatch conditions. These studies consider the proposed generation mix and transmission development plans to evaluate the ability of available resources to maintain frequency above 49.50 Hz, following a credible single contingency. The analysis is performed under minimum load, peak load, and midday system conditions. Frequency stability violations can result from either inadequate reserve provision or low power system inertia, each requiring specific mitigation strategies. Solutions may include procuring additional reserves or introducing resources with rotating mass capabilities. Reserves are typically provided by online generation units or demand-side responses triggered by frequency deviations. Reserve requirements for a five-year planning horizon are outlined in the Ancillary Services Technical Requirements document[25]. Inertia, on the other hand, is supplied by synchronous machines such as generators and synchronous condensers.

25 The Ancillary Services Technical requirements document is accessible on the NTCSA website (https://www.ntcsa.co.za/reliability-services)

SECTION F

ELECTRICITY LANDSCAPE: A GLOBAL PERSPECTIVE

1. INTRODUCTION TO GLOBAL ELECTRICITY LANDSCAPE

As of 2023, approximately 8% of the global population remains without access to electricity, according to the World Bank's Sustainable Development Goal 7 (SDG 7)[26] report. This is down from 13% in 2015 and 10% in 2020, showing the successes of small-scale, decentralised systems. The electricity shortages over the years have motivated System Operators to develop strategic and technical measures to deal with situations where electricity supply is less than demand, to maintain grid stability and avoid blackouts. Some of these measures include demand management, reserve acquisition and, as a last resort, load shedding. However, the rapid roll-out of decentralised generation has introduced novel challenges for managing the integrity of the grid. A scan of recent experiences across the globe has identified some commonalities, a selection of which are detailed below.

2. EXCESS ENERGY

Cases of oversupply, when generation exceeds demand, have increased significantly in the last five years. In an extreme case, Germany has been forced to dump electricity to its neighbouring countries through incentives such as negative electricity pricing. This practise is not ideal, as the financial implications of negative pricing were borne by the German consumer. Further, this mechanism works for a country that has strong interconnections and neighbours that are technically able to receive the power flow. As an example, France, with a large nuclear fleet, was unable to receive the free electricity because its nuclear plants could not generate below their minimum generation. Excess energy can be classified as either curtailed energy or dumped energy. However, global reports seem to use the definition interchangeably.

Curtailment refers to the intentional reduction of electricity production, despite the availability of the resources to generate power. This typically occurs when the grid cannot absorb all the electricity being produced due to technical, economic, or regulatory constraints. These reasons may range from grid congestion or insufficient network infrastructure to evacuate electricity to load centres, to compliance with codes that require maintaining voltage and frequency within stipulated thresholds or contractual obligations that take priority. Dump energy, on the other hand, refers to excess energy that is generated but not used or stored, i.e. energy that is essentially wasted.

Challenges of curtailment are evident across many jurisdictions. In China, high curtailment rates are experienced in remote provinces due to transmission bottlenecks, with regional extremes experiencing more than 30%. Curtailment in Australia arises from both network constraints and in some areas, negative market prices. The impact on residential solar systems losses ~1.5% of energy, with some areas losing up to 25%. For utility-scale solar plants, curtailment is around 8%, with capacity factors around 22%. The Australian Energy Market Operator is investing in transmission infrastructure and is promoting predictive analytics and hybrid systems to optimise dispatch and reduce curtailment. Brazil is one of the few developing countries with 24% penetration of renewable energy resources, excluding hydro. The National System Operator reports that curtailment of solar output was proportionally higher in 2025, rising 12% in August 2024 to 20% in August 2025, driven by transmission bottlenecks and low demand in renewable-rich regions like the Northeast. In response, the country is considering reforms that include curtailment auctions, negative pricing, and vehicle-to-grid systems.

Curtailment or dump energy is not a new concept for South Africa. Historically, in order to manage "night-minimum", a period of low load, typically in the early hours of the morning, it was necessary to curtail or dump generators with a lower short-run marginal cost that are more flexible. This was necessary to maintain the integrity of the grid, while in anticipation for the morning peak, making available inflexible generators that would otherwise take longer to restart. In addition to inflexible generators, curtailment occurs due to grid congestion. A case in point is that in the midst of loadshedding, the System Operator was forced to implement curtailment.

As South Africa moves toward higher penetration of variable renewable energy, it can learn from these jurisdictions and invest in strengthening grid infrastructure and modernising connections to renewable-rich areas. The existing compensation mechanism for the REIPPPP programme, allows the System Operator to curtail up to a certain number of hours, for whatever reason without compensation, and beyond those hours a "deemed energy" fee is payable. However, as the electricity sector liberalises, it is imperative that a policy position be developed to establish clear rules for curtailment compensation to deal with the inevitable increase in curtailed or dumped energy and to provide revenue certainty for developers. Further, South Africa should develop regulatory frameworks that provide incentives for appropriate capacity in balancing markets.

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3. POWER SYSTEM FLEXIBILITY

A flexible power system is one that can adapt quickly and reliably to changes in electricity demand or supply. This means being able to ramp power output up or down, or switch between different energy sources to make sure the grid is always balanced. A measure of flexibility is the assessment of how quickly a dispatchable power plant can change its output from zero to maximum when required. South Africa's power system is dominated by older generating units of coal-fired plants that are generally not designed for rapid changes and are not ideally or ideally operated below their minimum stable level, thus making them less flexible. As the energy share of variable renewable energy resources increases on the grid, a more flexible type of generation is necessary to ensure a reliable power system.

To gain a broader perspective on power system flexibility, it is helpful to look at how other countries address this challenge, examining successes and failures to best equip South Africa with possible solutions based on best practices.

a) Germany, Denmark, and Norway are heavily invested in renewable energy. To manage variability, they have invested in a range of strategies, including demand response and energy storage solutions, coupled with strong interconnections with neighbouring countries that allow the import and export of power when needed to smooth out the fluctuations in their own renewable energy production.

b) China's rapid renewable energy integration is driven primarily by government policy. These policies focus on creating a low-carbon energy system, which has also contributed to driving down the costs of renewable energy technologies globally. However, the focus remains heavily linked to retaining and improving grid flexibility. This is evident in the continuation of investment in various other technologies, including nuclear, hydropower and coal. Additionally, China has embraced the electrification of various sectors and industrial processes, effectively utilizing the abundant energy generated from renewable sources.

c) The United States' approach has a strong focus on developing grid infrastructure, investing heavily in expanding and upgrading the grid. Particularly in states with high potential for renewable resources. This focus on transmission development aims to facilitate the flow of clean power across the country. The federal government sets out policy for renewable energy integration while the different states develop and implement these policies. This approach can accelerate progress through effective partnerships and technology transfer, but it can also face challenges such as regulatory hurdles and infrastructure bottlenecks.

The parallel between the U.S. and South Africa lies in the fact that renewable resources are geographically dispersed, located in one part of the country, with load centres in other parts, thus requiring a strong focus on transmission requirements to unlock renewable energy. While other countries such as Germany and Denmark have integrated significant amounts of RE, South Africa is at an early stage of this transition, placing it at an opportune time to draw on lessons learnt from others.

4. SYSTEM FAILURES & MAJOR BLACKOUTS OF 2025

Globally, the reliability of power systems is central to each country's economic development. However, in recent years, despite advances in technology, there has been a notable increase in the frequency and severity of blackouts. Some notable events that occurred in 2025 are, inter alia:

The Iberian Blackout of 28 April 2025 was a massive power outage that plunged mainland Portugal, peninsular Spain, and parts of southwestern France into darkness. The failure originated from cascading grid collapses following a substation trip in Granada, compounded by subsequent failures in Badajoz and Seville. The event led to the disconnection of the Iberian grid from the European network, causing a total loss of 31 GW of power. Restoration efforts were swift, with Portugal regaining full power within 12 hours and Spain within 23 hours, aided by hydro and gas resources and interconnection. It is important to note that Portugal is much smaller, with a peak of approximately 8 GW, compared to over 38 GW for Spain. In the week prior to the blackout, Spain reported 100% renewable energy production for its demand.

Prior to the collapse, the system experienced voltage instability and oscillations due to inadequate reactive power reserves and delayed voltage control measures. Maintenance outages of key transmission lines and the absence of backup synchronous generation further weakened the grid. Attempts to stabilise the system, including switching transmission lines and adjusting HVDC operations, proved insufficient. Due to the scale of this incident, particularly as it occured central in Europe, it amassed global interest, including investigations by ENTSO-E and national regulators to establish the course and develop measures against future systemic failures.

On 25 February 2025, Chile experienced its worst power outage in over 15 years, affecting up to 98% of the population across 14 of its 16 regions. The blackout was triggered by a malfunction in the electronic and software protection systems of a critical transmission line, which led to cascading failures throughout the national grid.

What is worth noting between the Chilean blackout and Iberian blackout is that both events were marked by cascading grid failures that occurred within a very short period of time. Chile's interconnections are not as strong as those of Spain, which benefits from strong interconnections with France, a grid with a significant amount for nuclear generators.

Planning for a secure and reliable grid while pursuing cleaner, inverter-based resources requires understanding potential technical weaknesses and being cognisant that South Africa's grid dynamics include weak interconnections with neighbouring countries, and that estimates by the System Operator indicate that at least two weeks would be required to fully restore the power system following a complete blackout.

5. ENERGY TRANSITION: DECARBONISATION

The energy transition faces many challenges of a technical, socio-economic and political nature. The following have been identified as having a potential impact on the successful implementation of South Africa's electricity masterplan:

- **Replacement of existing generation with cleaner technologies:** The default option has been the installation of wind and solar PV resources supported by storage and flexible generation such as gas. For example, Germany has aggressively pursued the energy transition by phasing out coal and nuclear power while ramping up wind and solar capacity. Similarly, Australia has become a global leader in rooftop solar adoption and is investing heavily in battery storage to support its renewable energy goals.
- **Increasing penetration of variable energy resources:** Due to their variability, the design of a power system with increasing RE requires that the magnitude of installations far exceed the peak demand. This has created challenges for System Operators in balancing supply and demand in real time, requiring flexible generation and the provision of grid-supporting and ancillary services.
- **Rapid Transmission Infrastructure Development & Grid Modernisation:** Existing electricity grids were designed for one-way power flow from large, centralised plants directly to load centres. The increase in decentralised energy resources requires 'centralising' generation, which necessitates speedy development of grid infrastructure. This has led some jurisdictions to develop reforms that alleviate these bottlenecks, including acquisition of servitudes, issuing of permits and the development of relevant skills. Further, the transition requires smarter management of the grid, involving upgrading the grid to smarter technologies to manage variability.
- **Scaling and Cost Reduction for Emerging Technologies:** Development of technologies that are cleaner, flexible, and provide a full suite of grid support services is still in early commercial stages, is capital intensive and are not standardised sufficiently to be deployed at scale. Many countries and organisations are investing significant capital into research and development of new technologies that can enable the energy transition. The same is true for technologies that address residual emissions or those that actively remove historic emissions from the atmosphere.
- **Supply Chains and Resource Scarcity:** The drive towards clean energy generation has increased the demand for a secure supply of resources and placed strain on supply chains. In particular, the demand for critical minerals such as rare earth elements, lithium, cobalt, nickel, etc., has sparked increasing mining activity. Further, the supply chain for these materials is currently geographically concentrated, raising geopolitical and supply security risks, and posing technical challenges around sustainable mining, processing, and recycling to avoid resource depletion.

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