TECHNICAL REVIEW OF SOUTH AFRICA INTEGRATED RESOURCE PLAN

（Phase I: Generation Expansion）

China Electric Power Planning & Engineering Institute (EPPEI)

July 2025

ACKNOWLEDGEMENT

This peer review report is based on an evaluation of the draft South Africa Integrated Resource Plan (IRP) 2024, conducted by the China Electric Power Planning and Engineering Institute (EPPEI). The review was commissioned by the Minister of Electricity and Energy and Department of Mineral Resources and Energy (DMRE) of South Africa. The authors of the report are Dr. LIU Chen (Leading Analyst and Author, Regional Director), and Dr. CHEN Ning (Analyst, Author, Model and Data Review). The study was reviewed internally by Dr. WANG Shunchao (Deputy Director of International Business) and Ms. LI Lan (Deputy Chief Engineer, Director of International Business), authorized by Mr. JIANG Shihong (Vice President of EPPEI), and approved by Mr. HU Ming (President of EPPEI). EPPEI would like to appreciate Department of Electricity and Energy (DEE), DMRE, South African National Energy Development Institute (SANEDI), Eskom, and National Transmission Company South Africa (NTCSA) for their significant support throughout the course of this review. This report is the outcome of close collaboration and extensive communication between the research team and Mr. Sonwabo Damba (Energy Planning Specialist, DEE) and Ms. Prudence Rambau (Chief Engineer, NTCSA). Their professional level, valuable insights and steadfast support were essential to formation of this report. We express our sincere gratitude to H.E. Minister Kgosientso Ramokgopa, Mr. Subesh Pillay, Mr. Jacob Mbele, Dr. Titus Mathe, and Prof. Prathaban Moodley for their instrumental support in bringing this report to completion.

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REVISION HISTORY

Rev	Date	Description
V0	2025.04.01	Preliminary Draft
V1	2025.06.20	Updated Draft
V2	2025.07.24	Final Report

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EXECUTIVE SUMMARY

For power systems with high penetration of renewables, robust planning rests on three indispensable pillars: model-based approaches, realistic data, and reasonable assumptions—each becoming increasingly critical within IRP framework as variable renewable energy (VRE) share rises

The IRP employs an integrated, model-based framework that combines long-term (LT) capacity expansion planning with detailed medium and short-term (MT-ST) simulations based on the PLEXOS platform. This modeling architecture reflects international mainstream practice by aligning strategic planning with operational feasibility.

The modeling methodology ensures the reliability of the optimization results, as it captures essential details of the economic operation of South Africa's power generation:

- **The LT model** applies scenario-based and least-cost optimization to identify cost-effective generation pathways under evolving technical, economic and policy constraints. **The MT-ST multi-node model** complements this with greater operational granularity, capturing features such as unit commitment, transmission congestion, and system adequacy.
- **Stochastic simulations** are employed in the MT-ST model to capture the stochastic nature of variable renewable energy (VRE) generation and conventional unit outages, which is essential for modelling South Africa's system where rising VRE penetration and low-EAF coal fleets present significant operational uncertainties. **The multi-node modeling approach**, incorporating more than 3,000 grid nodes, enables detailed evaluation of transmission congestions and its impact on dispatch, which is especially relevant in South Africa where grid constraints are often binding.

To improve coherence between the model-based planning and real-world requirement, EPPEI recommends targeted refinement on modeling framework in future planning studies:

- enhance the use of the MT-ST model for more extensive sensitivity analyses of generation portfolio configurations;

- incorporate key indicators such as VRE curtailment and system adequacy into the planning optimization framework, enabling better understand on system trade-offs;
- enhance closer integration between PLEXOS simulations and grid stability assessments in terms of the rolling IRP approach.

The IRP leverages credible and up-to-date data inputs to ensure traceability and policy relevance, building on a solid modeling foundation. **Assumptions are carefully constructed and justified** to support effective reproducibility and stakeholder engagement. Key factors such as demand forecasts, plant performance, existing and committed generation capacity, technology trajectories, are methodologically constructed and aligned with modeling needs.

- **Electricity demand forecast** demonstrates methodological rigor by integrating multi-dimensional drivers. Hourly temporal resolution and spatially disaggregation supports accurate modelling within in PLEXOS.
- **Coal availability** is reflected through differentiated EAF scenarios. The moderate EAF recovery scenario is considered achievable, but continuous performance monitoring is needed to validate planning assumptions.
- **Committed generation projects** form the foundation of system expansion modeling, and must be regularly updated to reflect implementation realities.
- **Gas-fired generation** faces uncertainties in fuel price, infrastructure, and cost. Sensitivity analyses on natural gas prices and capital costs are essential to strengthen planning robustness.
- **Energy storage** prioritize battery and pumped hydro, aligned with current deployment trends. Future IRP iterations could benefit from broader considerations of emerging technologies to diversify flexibility options.
- **Generation technology cost assumptions** account for South Africa's local capital costs, which are nearly double those in China. These highlights significant opportunities to reduce costs through local manufacturing, trade partnerships, and targeted incentives.
- **Power import** is included in the model with simplification, as its role is minimal considering energy security. More detailed model approach could be adopted if power interconnection is expanded in the future.
- **Grid data** is integrated into the MT-ST model using node-level information from PSS/E model developed for TDP. This allows accurate simulation of transmission congestions and spatial dispatch constraints.

- **Scenarios design** provides structured flexibility in planning by comparing diverse scenarios, including Reference Case, Gas at Risk Case, Nuclear Case, Aggressive Battery Learning, and Delayed Shutdown, which enhance the adaptability of IRP outputs to evolving technology, cost and policy conditions. Future iterations could expand to incorporate more scenarios such as emerging storage options and expanded regional interconnections to enhance planning adaptability.

IRP proposes a balanced, diversified, and ambitious energy transition pathway, anchored by VRE growth and supported by firm and flexible capacity. Particular efforts are required to address gas and nuclear uncertainty, mitigate VRE transmission bottlenecks, and ensure system stability in a high VRE-future

Multi-dimensional comparison across five modeled scenarios is presented in the IRP, covering key indicators including total system build capacity, costs, emissions, and water usage, offering a comprehensive view of trade-offs among technology choices and policy priorities.

- **The Gas at Risk scenario and Nuclear scenario** show promising benefits in improved generation diversity, lower emission, and reduced system costs. However, both pathways face major uncertainties in South Africa.
- **The Delayed Shutdown scenario** proposes the selective extension of existing coal plants under emission compliance. Although this scenario is the most expensive option in terms of modeled system cost, it offers the lowest required build capacity, and could serve as a form of system reliability insurance to hedge against uncertainties of gas and nuclear. Looking ahead, it is critical to explore alternatives to high-cost coal plant life extensions—such as a hybrid baseload source that integrates wind, solar, storage and gas in a complementary mode.
- **A Balanced scenario** is recommended in the IRP as the preferred pathway, synthesizing insights from all five scenarios to offer a pragmatic trajectory for South Africa's energy transition. It presents a diversified pathway that includes renewable energy, natural gas, nuclear, coal and storage to mitigate supply risks and enhance system flexibility. In support of this strategy, the IRP also outlines several interventions to ensure supply security during the transition period.

A significant transition towards high VRE penetration is envisioned in the Balanced scenario. The installed capacity of VRE is projected to increase significantly—from 12 GW in 2023 to 54 GW by 2035, raising its share of total installed capacity from 20% to 49%. This prompts EPPEI to conduct independent analysis for deeper technical insights:

- **Each major dispatchable source plays a distinct role in the transition**
  - **Coal** remains essential for near-term baseload, but requires monitoring performance improvement (e.g., EAF), enhanced flexibility for healthy units, and pathways for gradual decarbonization;
  - **Gas** is critical for peaking, flexibility and backup as coal phases down and VRE rise, especially during coal outages or extreme weather;
  - **Nuclear** offers a strategic option for long-term security and low emission, requiring early feasibility study to preserve future optionality.

- **Challenges related to VRE development are increasingly acute, calling for comprehensive solutions for VRE integration and transmission**
  - **VRE curtailment rate arises** to nearly 30% by 2035 due to transmission congestions, especially transformer capacity insufficiency;
  - **Reduced firm capacity and sharper net load ramps** raise more requirements for system adequacy and flexibility in the future;
  - **Rising instantaneous shares of VRE** (more than 60% by 2035) are expected to weaken system frequency, voltage and dynamic stability, requiring close operational attention and proactive mitigation measures.

Drawing on China's experience in power system planning, innovation and modernization, it is recommended that South Africa's energy transition pay more attention to coordinated generation-transmission planning, flexibility upgrades of dispatchable sources, diversified energy storage deployment, enhanced regional interconnection and market, and dedicated studies to address emerging technical and policy challenges.

Translating IRP's strategic direction into action calls for targeted technology and policy measures. The following recommendations highlight key priorities:

- **Strengthen generation and transmission coordination**
  - coordinate transmission planning with generation, and execute transmission in advance for VRE integration to avoid bottlenecks;

  - strengthen SANEDI's role in integrated power system planning, and establish closed-loop planning mechanism linking modeling, validation, and implementation tracking;
  - develop a modernized dispatch and operation system to improve system flexibility and reliability with high VRE penetration.

- **Enhance coal-fired power flexibility and reliability**
  - retrofit selected units to improve flexibility and environment compliance;
  - repurpose partially retired units as strategic reserve for contingencies;
  - treat EAF as a binding target to ensure alignment between planning targets and operational reliability.

- **Optimize gas-fired power development**
  - prioritize CCGT over OCGT for better efficiency and long-term cost-effectiveness, given limited reserve and high cost of gas in South Africa;
  - explore innovative solutions on baseload source (e.g., VRE + storage + CCGT) to mitigate potential uncertainties and lower cost.

- **Facilitate VRE development, integration and transmission**
  - enhance investment environment supported by effective curtailment mitigation measures and strengthened system-level coordination;
  - encourage international partners with competitive financing and provision of advanced VRE integration and transmission technologies;
  - explore new VRE development modes, such as developing large-scale VRE bases in resource-rich areas with existing flexible resources, and transferring power to load centers by dedicated transmission corridors;
  - promote pilot demonstrations of innovative technologies, equipment, standard and regulation to facilitate large-scale VRE development

- **Diversify energy storage portfolios**
  - establish compensation mechanisms for storage services;
  - build a diversified storage portfolio across types, durations, locations, etc., to support VRE integration and system flexibility.

- **Promote regional interconnection and market development**
  - act as a regional energy hub and contribute to broader energy security;
  - support regional hydro development and facilitate inter-regional grid interconnection and interoperability;
  - advance power market reforms and regulations for transparency, flexibility and competition.

- **Conduct dedicated supporting studies**
    - IRP transmission and system stability studies (IRP Volume 2 and 3)
    - Coal plants power retrofitting and functional transition study
    - Gas-fired generation dedicated study
    - VRE development, integration and transmission study
    - Cross-technology energy storage portfolio study
    - Multi-energy complementary baseload power study
    - Cross-border power interconnection study
    - Exploring the application of AI in IRP modeling and analysis

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ACRONYMS AND ABBREVIATIONS

ACRONYMS of INSTITUTIONS

DEE	Department of Electricity and Energy
DMRE	Department of Mineral Resources and Energy
NTCSA	National Transmission Company South Africa
SANEDI	South African National Energy Development Institute
EPPEI	China Electric Power Planning and Engineering Institute

ABBREVIATIONS

BESS	Battery Energy Storage System
CapEx	Capital Expenditures
CCGT	Combined-cycle Gas Turbine
EAF	Energy Availability Factor
EAP	Energy Action Plan
GRP	Generation Recovery Plan
IBR	Inverter-based Resource
ICE	Internal Combustion Engine
IPPPP	Independent Power Producer Procurement Programme
IRP	Integrated Resource Plan

LOLP	Loss of Load Probability
LT	Long Term
MES	Minimum Emission Standard
MT	Medium Term
NDA	Non-disclosure Agreement
NPV	Net Present Value
OCGT	Open-cycle Gas Turbine
PASA	Projected Assessment of System Adequacy
PCC	Presidential Climate Commission
PV	Photovoltaic
PWR	Pressurized Water Reactor
SAPP	Southern African Power Pool
SMR	Small Modular Reactor
ST	Short Term
TDP	Transmission Development Plan
UCED	Unit Commitment and Economic Dispatch
VO&M	Variable Operation and Maintenance
VRE	Variable Renewable Energy

INTRODUCTION

1. Background

In September 2024, a delegation led by H.E. Minister Kgosientsho Ramokgopa visited to Beijing during the 2024 Summit of the Forum on China-Africa Cooperation, and held a productive and fruitful meeting with China Energy International Group Co., Ltd and China Electric Power Planning & Engineering Institute (EPPEI). Both parties recognized the value and necessity of collaboration on the energy and power sector.

Figure 1. Photos of meeting with Minister Kgosientsho Ramokgopa

On this basis, a Memorandum of Understanding (MOU) between South African National Energy Development Institute (SANEDI) and EPPEI was signed to initiate cooperation on technical exchange, joint research, and technological innovation & application for South Africa's power transition. Subsequently, EPPEI was entrusted by Department of Mineral Resources and Energy (DMRE) to conduct peer review of South Africa's Draft Integrated Resource Plan (IRP). In addition, EPPEI has maintained close technical exchanges on enhancing power system flexibility and grid resilience with ESKOM and NTCSA.

Figure 2. Signing of MoU between SANEDI and EPPEI

EPPEI is a leading taskforce supporting clean energy and power transition, serving Chinese central government in research and development for National Energy and Power Development Plans. EPPEI has also been entrusted by overseas governments and system operators to conduct power system planning & modelling studies, assisting these authorities in formulating tailored power system development roadmaps and providing forward-looking technical solutions. After nearly a year of technical exchanges with SANEDI, ESKOM and NTCSA, EPPEI has gained a comprehensive understanding of South Africa's power system. Through this technical review, EPPEI aims to leverage its expertise and capabilities to contribute to advancement of South Africa's power sector, and also seeks to support South Africa in gaining a comprehensive understanding of Chinese and global energy transition experiences.

The IRP process is mainly divided into three phases, i.e., Phase 1: Generation Expansion (Volume 1), Phase 2: Transmission Planning (Volume 2), Phase 3: System Operability and Stability (Volume 3). This peer review report is limited to the IRP Volume 1, and EPPEI has been provided with material (documents and PLEXOS models) related to this part of the IRP. Accordingly, EPPEI's technical evaluations are based these inputs. EPPEI is also committed to making contributions to the subsequent IRP volumes.

2. Principles and Objective

In the course of engagement with SANEDI and IRP technical team, EPPEI fully understands and endorses the five key priority areas highlighted by the Ministry of Energy and Electricity, i.e.,

- Achieve Universal Access, Availability, Affordability and Quality
- Attain sovereign and regional energy security
- Drive industrialization and lead innovation
- Qualitatively transform energy demographics
- Assert South Africa, Continental and global energy leadership

EPPEI believes these five priority areas not only reflect South Africa's energy development goals but also form the guiding principles for the IRP technical evaluation. Throughout the technical assessment, EPPEI has adhered to these principles as the foundation of its approach.

The primary objective of the technical review is to offer comprehensive insights and actionable suggestions to enhance the final IRP, and add value to South

Africa's efforts on improving availability, affability and sustainability of the power system.

3. Main Contents of the Review

EPPEI aims to provide an impartial and objective technical evaluation of IRP, ensuring a reliable and sustainable power system, while also maintaining technological feasibility and economic viability. By utilizing the IRP model, data, and documents provided by South Africa, EPPEI conducts a thorough validation through data analysis and model simulations. This process is also informed by the specific characteristics of South Africa's power system and China's experience in energy transition.

The technical review is divided into three parts, i.e.:

Part A: Technical Review of the Model & Methodology, Input & Assumption

- model & methodology review
- input & assumption review

Part B: Review and Independent Analysis on IRP Results

- review of IRP results
- independent analysis on generation mix of Balanced Scenario

Part C: Actionable Suggestions & Insights

- actionable suggestions for next steps
- insights from China's experiences

The detailed structure of the review process is shown in Figure 3.

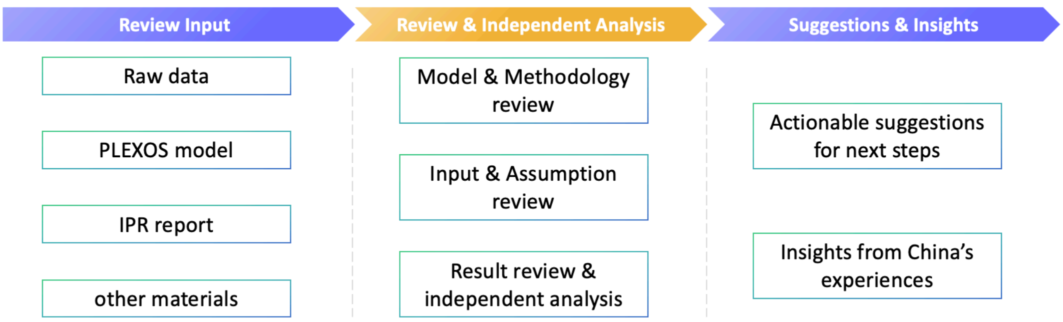


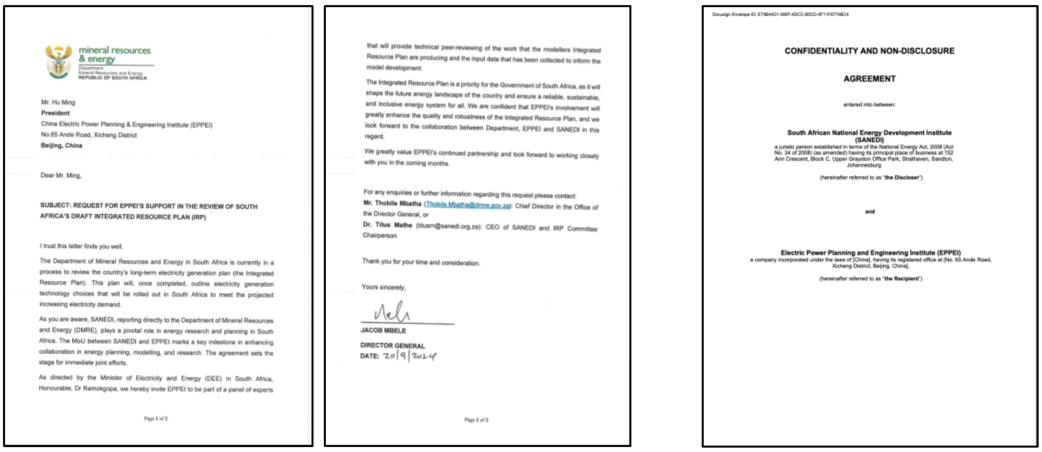
Figure 3. Structure of the review process.

4. Work Modality and Process

To achieve optimal outcome, SANEDI, EPPEI and IRP technical team established a joint working group to advance the IRP technical review process. SANEDI played a pivotal role in organizing a series of workshops and coordinating activities. EPPEI, in collaboration with the IRP technical team, conducted a series of productive technical engagements and discussions, transferring knowledge and data. This close-knit collaboration and seamless coordination among all parties were instrumental in completing the technical review of the IRP.

The main work process is as follows:

- On 20 September, 2024, EPPEI received the Entrusted Letter from the DMRE on requesting support for the review of South Africa's Draft IRP.
- On 26 September, 2024, the IRP peer review kick-off meeting was held. After that, multiple online meetings were organized by SANEDI, where IRP technical team and EPPEI were involved high-level in-depth discussions and analysis, providing valuable insights regarding the IRP background, methodology, key assumptions, specified constraints, input data, detailed model parameters and settings, etc.
- On 12 December, 2024, EPPEI signed a Confidentiality and Non-disclosure Agreement (NDA) with SANEDI to enabling the receipt of relevant data and information related to the Draft IRP.



mineral resources & energy
Department
Mineral Resources and Energy
REPUBLIC OF SOUTH AFRICA

Mr. Hu Ming
President
China Electric Power Planning & Engineering Institute (EPPEI)
No.65 Ande Road, Xicheng District
Beijing, China

Dear Mr. Ming,

SUBJECT: REQUEST FOR EPPEI'S SUPPORT IN THE REVIEW OF SOUTH AFRICA'S DRAFT INTEGRATED RESOURCE PLAN (IRP)

I trust this letter finds you well.

The Department of Mineral Resources and Energy in South Africa is currently in a process to review the country's long-term electricity generation plan (the Integrated Resource Plan). This plan will, once completed, outline electricity generation technology choices that will be rolled out in South Africa to meet the projected increasing electricity demand.

As you are aware, SANEDI, reporting directly to the Department of Mineral Resources and Energy (DMRE), plays a pivotal role in energy research and planning in South Africa. The MoU between SANEDI and EPPEI marks a key milestone in enhancing collaboration in energy planning, modelling, and research. The agreement sets the stage for immediate joint efforts.

As directed by the Minister of Electricity and Energy (DEE) in South Africa, Honourable, Dr Ramokgopa, we hereby invite EPPEI to be part of a panel of experts

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that will provide technical peer-reviewing of the work that the modellers Integrated Resource Plan are producing and the input data that has been collected to inform the model development.

The Integrated Resource Plan is a priority for the Government of South Africa, as it will shape the future energy landscape of the country and ensure a reliable, sustainable, and inclusive energy system for all. We are confident that EPPEI's involvement will greatly enhance the quality and robustness of the Integrated Resource Plan, and we look forward to the collaboration between Department, EPPEI and SANEDI in this regard.

We greatly value EPPEI's continued partnership and look forward to working closely with you in the coming months.

For any enquiries or further information regarding this request please contact:
Mr. Thobile Mbatha (Thobile.Mbatha@dmre.gov.za): Chief Director in the Office of the Director General, or
Dr. Titus Mathe (titusm@sanedi.org.za): CEO of SANEDI and IRP Committee Chairperson

Thank you for your time and consideration.

Yours sincerely,

JACOB MBELE

DIRECTOR GENERAL
DATE: 20/9/2024

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CONFIDENTIALITY AND NON-DISCLOSURE

AGREEMENT

entered into between:

South African National Energy Development Institute (SANEDI)
a juristic person established in terms of the National Energy Act, 2008 (Act No. 34 of 2008) (as amended) having its principal place of business at 152 Ann Crescent, Block C, Upper Grayston Office Park, Strathaven, Sandton, Johannesburg

(hereinafter referred to as "**the Discloser**")

and

Electric Power Planning and Engineering Institute (EPPEI)
a company incorporated under the laws of [China], having its registered office at [No. 65 Ande Road, Xicheng District, Beijing, China],

(hereinafter referred to as "**the Recipient**")

(a) Entrusted Letter from DMRE (b) NDA signed with SANEDI

Figure 4. Agreements to conduct peer review of Draft IRP

- On 21 January 2025, IRP technical team provided the draft Scope Document of IRP peer review to EPPEI, and an online meeting was organized by SANEDI to discuss the transfer of IRP model and data, as well as the subsequent review work arrangements.
- On 31 January 2025, IRP technical team sent the original version of input data to EPPEI.
- On 5 February 2025, EPPEI provided feedback on the received data, including clarifications and additional documents suggested for a more comprehensive review. EPPEI also provided suggestions on the Scope Document which highlights the structure of data-model review, scenario-result review and recommendation-suggestion review.
- On 7 February 2025, an online meeting was held to discuss and clarify the IRP model and data for technical review. After the meeting, IRP technical team sent additional input data and PLEXOS model to EPPEI.

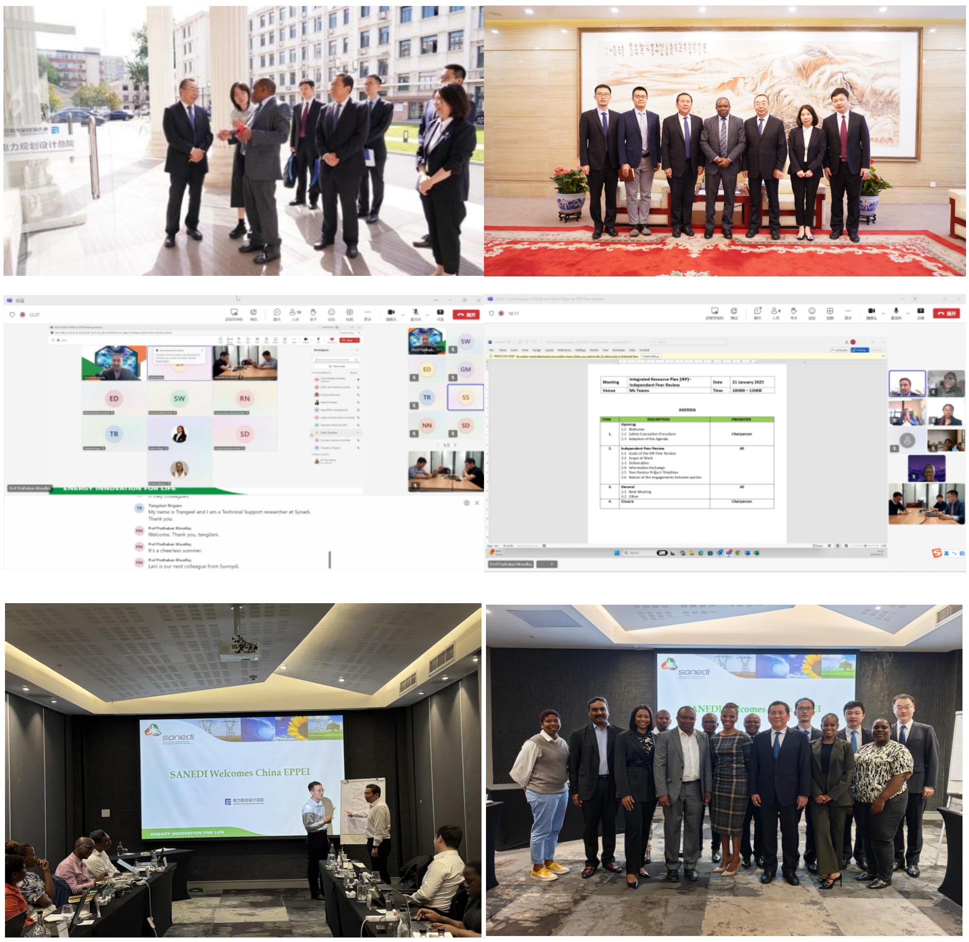

Figure 5. On-site and online engagements for IRP peer review between EPPEI, SANEDI and IRP Technical team

- On 14 February 2025, EPPEI, SANEDI and IRP technical team held an online meeting to discuss and clarify the detailed information on the data exchanges and modeling methodology.
- From 4th to 6th March 2025, EPPEI visited to South Africa and held a series of IRP technical workshops with SANEDI and IRP technical team. During the engagements, SANEDI provided a comprehensive introduction to South Africa's key priorities in energy and power development, and shared the framework and main considerations on IRP process. IRP technical team shared valuable insights on IRP model process, demonstrated the completed multi-node model for power generation planning, and provided insightful instructions on Phase 2 and Phase 3 of IRP. EPPEI presented the progress made in the IRP peer review, shared insights into China's exploration and experiences on power system transition and their implications for South Africa, and provided suggestions on advancing the IRP peer review process. Both sides shared deep exchanges on the detailed IRP model, data and methodologies.
- On 6 March 2025, SANEDI sent a draft copy of the IRP report.
- On 3 April 2025, EPPEI completed the initial draft IRP peer review report (for generation expansion).
- On 22 April 2025, EPPEI received the IRP multi-node MT-ST model used for adequacy assessment sent by IRP technical team.
- From 24 April to 13 June 2025, a series of online workshops and email exchanges were held between EPPEI and IRP technical team for in-depth discussions on the IRP multi-node MT-ST model.
- On 20 June 2025, EPPEI developed the updated version of IRP peer review report, incorporating latest technical input from IRP technical team.
- On 24 July 2025, EPPEI completed the final IRP peer review report.

The received Data, Model and Documents for this review are listed in Annexure I. The peer review is based solely on these files, with no additional files included in the evaluation.

PART A: TECHNICAL REVIEW OF THE MODEL & METHODOLOGY, INPUT & ASSUMPTION EMPLOYED IN THE IRP

I. MODEL & METHODOLOGY REVIEW

The importance of the modeling approach in power planning becomes more and more prominent, particularly as variable renewable energy (VRE) sources are developed and integrated on a large scale. With the increasing complexity of planning scenarios and the inherent uncertainties, traditional intuitive planning methods are no longer sufficient. The accuracy and fidelity of the models used in this process are crucial to effectively capture numerous dynamic factors that influence power system development.

South Africa's adoption of a model-based approach in the IRP process makes the evaluation of these models and methodologies all the more critical. This review is key to determining the robustness, applicability, and limitations of the models, while also ensuring that innovative and diverse perspectives are incorporated into the power system planning process.

1. Model Methodology Used in IRP

1.1 PLEXOS Model

Phase 1 of the IRP process was undertaken using PLEXOS modelling tool. The PLEXOS® is a globally recognized software employed for power system planning, production simulation, and electricity market simulation, among other applications.

Four unique simulation modules of PLEXOS include:

- **LT Plan** (Long Term Plan) aims to solve the capacity expansion problem over the planning horizon, typically expected to be in the range of 10 to 30 years. It finds the optimal combination of generation new builds (and/or retirements), AC and DC transmission upgrades (and/or retirements) that minimizes the net present value (NPV) of the total system costs over a long-term planning horizon subject to reliability and/or other constraints such as emission limits or prices. LT Plan runs before the PASA/MT Schedule/ST Schedule phases, and is fully integrated with these other simulation phases. Thus, LT Plan can be run either separately or in sequence with these other simulation phases in a single simulation.
- **PASA** (Projected Assessment of System Adequacy) schedules maintenance events such that available generation capacity is optimally shared between interconnected regions across all peak periods. It is also a

model of discrete and distributed maintenance, and forced outage of generators and transmission lines. PASA can also calculate reliability metrics such as the Loss of Load Probability (LOLP).

- **MT Schedule** (Medium Term Schedule) is a simulation based on a temporal simplification, which is able to simulate over long horizons and large systems in a short execution time. Its results can be used to decompose medium-term constraints including storages and emissions, objectives and hydro release policies so that they can be properly accounted for in the full chronological simulation ST Schedule.
- **ST Schedule** (Short Term Schedule) is a fully-featured chronological unit commitment and economic dispatch (UCED) model based on mixed-integer programming. It is able to resolve time periods as short as one minute and model the full detail of the power system.

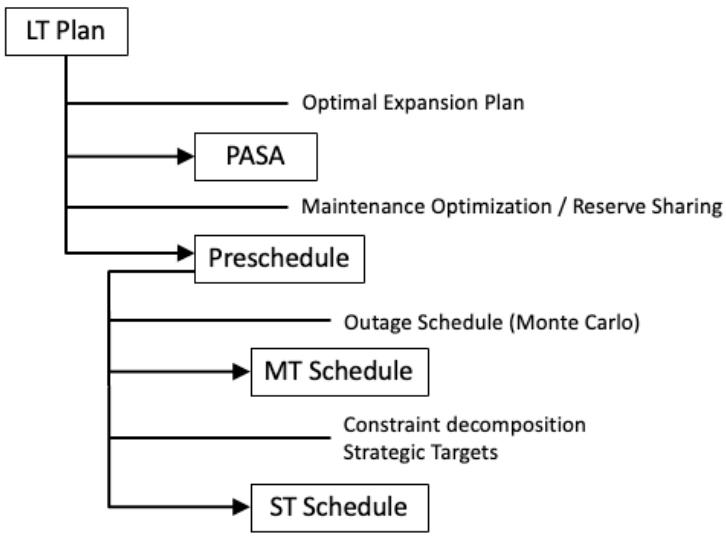

Figure 6. Integration of simulation phases in PLEXOS (from PLEXOS instruction)

1.2 IRP Methodology Review

1.2.1 IRP LT model

Given that the IRP prioritizes long-term generation capacity expansion, the LT plan model is employed to optimize the generation mix and develop the strategic plan. The LT plan is implemented in PLEXOS as a Mixed-Integer Linear Program, with its objective function designed to minimize the NPV of construction costs, fixed operations and maintenance costs, and production costs, while satisfying constraints related to energy balance, feasible energy dispatch and generation profiles, or specific policy imperatives.

For the key settings of the received LT model, the chronology method is configured to "sampled", with a sample size of 200 days per year. The selection of sample days represents a compromise between accuracy and computational efficiency. The discount rate is established at 11.3%, with the discount and expansion period set to an annual basis. The capacity expansion optimization does not have a clear end point and is intrinsically an infinite-horizon problem. As a result, the end effect method is configured as "perpetuity" in PLEXOS to assume that the last year of the planning horizon repeat indefinitely. The expansion algorithm is set to "linear," indicating that the model resolves the capacity expansion formulation through its linear relaxation.

The LT model received by EPPEI to perform IRP technical review is a simplified single-nodal LT model, where all generators and loads are connected to a single node, and load distributions and transmission constraints are not taken into account.

1.2.2 IRP MT-ST model

The IRP technical team developed multi-node MT-ST models to evaluate hourly system operations for individual years over the planning horizon. However, for technical evaluation purposes, EPPEI was only provided with a model for the 2035 year. The PSS/E[1] case files are developed for each year separately, to reflect changes in transmission strengthening up to that year. All recommended simulation phases, including PASA, MT, and ST, are incorporated and simulated within the model, making it a more comprehensive method to analyze and evaluate South Africa’s power generation. Particularly, the ST Schedule employs mixed-integer programming (MIP) for chronological optimization, allowing it to model days of the horizon at full resolution compared with LT model.

It is noteworthy that a very detailed grid data derived from the PSS/E case file, has been incorporated into the IRP MT-ST model. Some necessary changes, such as bus aggregation within the Main Transmission Substation (MTS), are conducted when importing PSS/E data into the PLEXOS model. In the 2035 MT-ST model, the transmission system is represented by 3090 nodes, 2967

[1] PSS/E (Power System Simulator for Engineering) is a well-recognized software tool used for the simulation and analysis of power system transmission networks.

transformers, and 1131 lines, with properties such as Max Flow, Resistance, Reactance, and Rating reflecting their physical characteristics.

In addition, the stochastic method is employed in the model to evaluate randomness in VRE profiles and forced plant outages, which enables a more effective evaluation on system adequacy from a probabilistic view.

For the key settings, the chronology method is configured as full hourly chronology for a year with 52 weeks. The transmission detail is set to nodal. The stochastic method is configured as 'stochastic' with a sample number of 1000, indicating that the model is solved as a stochastic optimization problem with 1000 samples calculated.

EPPEI received a multi-node MT-ST model with a transmission network planning horizon set for 2035, implying that the analysis on the MT-ST model in this peer review report is based on that year.

2. Remarks

The IRP employs an integrated, model-based framework that combines long-term (LT) capacity expansion planning with detailed medium and short-term (MT-ST) simulations based on the PLEXOS platform. This modeling architecture reflects international mainstream practice by aligning strategic planning with operational feasibility. The models form a solid foundation for analyzing potential future energy mixes and for evaluating the system's performance under different scenarios.

2.1 IRP LT model

The PLEXOS LT model is a tool for long-term power system planning, providing a framework for meeting South Africa's IRP requirements on generation capacity expansion. By incorporating a diverse range of energy sources, the IRP LT model ensures a comprehensive view of the future energy landscape. It allows for simulation of various potential scenarios, helping to analyze system performance, identify vulnerabilities, and evaluate different energy mixes over extended time horizons. As a result, the IRP LT model provides critical insights into the strategic development of South Africa's power sector.

However, considering large time horizons of the LT model, a balance between computational accuracy and efficiency is required. As a result, in the IRP LT model, some compromises on the unit properties and mathematical modeling were made to ensure that the model can be solved, which may lead to some distortion in the results:

- The model uses linear programming to solve the unit commitment problem considering computational efficiency. It limits accurate simulation on the start-up and shutdown of thermal power plants, which may pose challenges for systems with a high share of thermal power generation.
- The model cannot accurately account for the seasonal characteristics of hydro power and long duration energy storage. Considering that there is very limited hydro power in South Africa’s power system, this limitation can be disregarded.
- The model faces challenges in fully assessing the system's reliability and adequacy, considering the low energy availability factor (EAF) of coal-fired power plants in South Africa, as well as the high penetration of VRE in future’s energy mix.

The capacity expansion of power system with high penetration of renewable energy remains a global challenge that has not yet been fully addressed. For long-term planning over a 20-year horizon, the LT model provides a reasonable level of accuracy and generates results that are generally considered reliable for evaluating the economic optimization of generation mix on a high-level, long-term perspective. Additionally, the LT model provides a solid foundation for subsequent MT-ST analysis, which can more accurately assess operations and facilitate necessary optimization to the planning results.

2.2 IRP MT-ST model

The IRP multi-mode MT-ST model, as an extension analysis of the LT model, focuses on shorter horizon (a single year) with short simulation step (one hour). MT-ST uses a pre-defined generation capacity mix, which is usually an optimization results from LT model. This enables the MT-ST model to more accurately capture dynamic system changes, offering valuable validation for the long-term strategies developed by the LT model.

- The MT-ST model incorporates the simulation phases recommended by PLEXOS, including PASA, MT, and ST simulation. This comprehensive approach ensures that the model can accurately simulate maintenance schedules, forced outages, medium-term constraints, unit commitment, economic dispatch, and power grid operations.

- The use of Monte Carlo Stochastic method in the MT-ST model enables the simulation of inherent uncertainties in generator availability, such as the VRE profiles and unit outages. This is particularly relevant for South Africa, where the VRE penetration significantly increases, and coal fleet exhibits low EAF which reflects frequent unavailability and unplanned outages. This method of handling the uncertainties and intermittencies offers a more robust assessment of system adequacy and reliability, which can be seen as a state-of-the-art approach for modern power system modeling and planning.
- The MT-ST model with detailed grid data represents a significant advancement compared to previous IRP efforts. With this detailed multi-node model, the regional transmission bottlenecks, location-specific generation dispatch, and inter-regional power flows can be effectively captured. This level of spatial resolution is particularly valuable in assessing the operational feasibility of high VRE penetration scenarios, where transmission lines may become bottlenecks to integrate VRE in the mid- and long-term. This model also makes it possible to coordinate generation expansion with grid development by considering the grid data proposed in the Transmission Development Plan (TDP).

However, the multi-node MT-ST model also faces certain challenges. Its multi-node transmission modeling is based on a linearized DC Optimal Power Flow, which is effective for estimating transmission capacity requirements but does not capture critical system security constraints—such as frequency stability, voltage stability, and other dynamic behaviors. This simplification limits the model's ability to assess grid’s operational resilience under contingencies.

For example, in some extreme scenarios, PLEXOS may recommend solutions that completely phase out coal-fired generation in favor of 100% renewable energy sources, driven by cost-minimization objectives. While these scenarios may appear economically optimal, they often fail to ensure system stability during disturbances such as sudden generator trips or renewable output fluctuations. As the share of VRE in the generation mix increases, these stability concerns become even more pronounced, highlighting the risks of relying solely on economic optimization without a parallel evaluation of system operability.

Therefore, while the MT-ST model remains a powerful tool for analyzing short-term dispatch and the economic implications of VRE integration, it must be complemented by detailed system security and stability assessments. This underscores the necessity of completing Phase 2 and 3 of the IRP.

3. Observations

Relying solely on models and simulations in the planning process is not enough. While economic optimization models, such as those used in long-term capacity expansion, are valuable tools for identifying least-cost solutions, they often provide gaps to real-world power planning needs. Key power generation indicators, such as system adequacy, VRE curtailment, and carbon emission, are difficult to monetize accurately. Although penalty terms or constraints can be introduced into the models, the assumed economic values of these parameters can significantly influence the outcomes, potentially skewing the results away from practical feasibility.

Moreover, effective power system planning requires more than just quantitative modeling, it demands a broader mindset that incorporates operational experience, stakeholder input, and international best practices. These real-world perspectives are critical for interpreting and validating model results, ensuring that strategies and investment decisions are grounded in both analytical rigor and operational realism. In other words, planners must “think outside the model” to develop actionable and robust energy transition pathways.

Accordingly, the following actions are recommended to refine the IRP process:

- **Enhance Robustness Through Sensitivity Testing of non-Monetizable Factors.** Given the difficulty in monetizing technical indicators such as adequacy, curtailment and emissions, it is recommended to conduct structured sensitivity analyses. Starting from the LT model results, assumptions of key parameters should be adjusted to generate multiple near-optimal capacity plans. The MT-ST model can then be used to simulate these plans to identify the most technically and economically actionable path.
- **Develop a Multi-Criteria Performance Evaluation Framework.** As the IRP must balance multiple objectives—such as cost, reliability, and sustainability—it is important to develop a transparent indicator system independent from the optimization engine. Metrics such as reserve margin, emissions intensity, and curtailment rate should be derived from ST model outputs. These indicators will support comparative analysis of candidate plans and ensure that the selected pathway achieves a balanced performance across all policy priorities.

- **Emphasize Reliability and Adopt a Rolling Planning Framework:** System reliability must be integrated more deeply into the IRP, especially as coal units retire and VRE penetration increases. It is recommended that Phases 1 and 2 of the IRP be developed in parallel, so that transmission constraints—such as thermal unit minimum commitment levels, spinning reserve needs, and transmission capacity limits—can inform generation expansion decisions. Furthermore, the findings from Phases 2 and 3 of the IRP should feed back into the following year's Phase 1. This rolling update mechanism will help the IRP remain adaptive to evolving grid conditions and emerging challenges.

II. INPUT & ASSUMPTION REVIEW

The evaluation of the IRP input data and key assumptions is a critical component of the peer review. For South Africa, understanding the operational characteristics of thermal power plants (coal-fired plants and gas-fired plants) is particularly important, as these may undergo significant changes in coming years. Accurately forecasting their future performance is essential for ensuring a reliable and realistic power generation plan. Furthermore, wind, solar and energy storage technologies have seen rapid decline in costs and are poised to further decrease in the future. Accurately estimating both the future costs and technical performance of these technologies is essential, as it is needed to ensure that the future energy mix reflects these advancements and provides a more realistic foundation for the IRP.

Therefore, careful consideration and validation of input data and assumptions are necessary to develop a robust and future-proof power system that balances both economic and technical requirements. EPPEI evaluated the following aspects of the IRP input data and assumptions:

- **Reasonability, Robustness, and Coherence of Key Input Data and Assumptions:** assess whether the input data and assumptions are technically consistent and align with South Africa's current and projected energy landscape.
- **Manipulation of Raw Data Based on Proven Concepts:** review the processes and methods used to convert multi-year historical operational data into model parameters and examine the methods and data sources used for projecting future costs.
- **Accurate Input Data and Assumptions Captured in the Model:** verify whether the input data and assumptions are accurately captured in the IRP model, and examine the model execution to ensure sufficient detail of input data and assumptions is captured in the optimization.

1. Input Data of the IRP

The raw data received from the IRP technical team contain partial but important input data for the IRP, including the shutdown plan for power units, heat rates, costs, and other key parameters of the units. The basic data for existing coal-fired plants and system reserve requirements primarily come from Eskom, and new technology cost data is sourced from the Electric Power Research Institute

(EPRI). These data sources are reliable, and most of the data has been accurately reflected in the model.

Based on our analysis of the received IRP models, the model input and parameter settings for each unit are well-defined, and the model's solution parameters are appropriately configured. Although several mismatches are found between raw data and model input, the IRP technical team has provided reasonable responses. Detailed comments from EPPEI and responses from IRP technical team are available in the Annexure II.

2. Key Assumptions of IRP

2.1 Demand forecast

The IRP document presents five different demand forecast scenarios, with the moderate forecast ultimately selected for modeling purposes. According to the IRP document, the forecast is based on historical consumption data from all systems connected to the transmission and distribution grids, taking into account network losses. In addition, it incorporates projections of economic indicators, which add a layer of relevance to the forecast.

The hourly load curves extending to 2050 are established as inputs for the model. From 2025 to 2050, the electricity demand is projected to sustain an average annual growth rate of 2.5%, which is basically in accordance with the assumption proposed at the IRP document. In the multi-node MT-ST model, the demand details are distributed across 161 nodes, with the total load at each hour aligning with the load specified in the LT model.

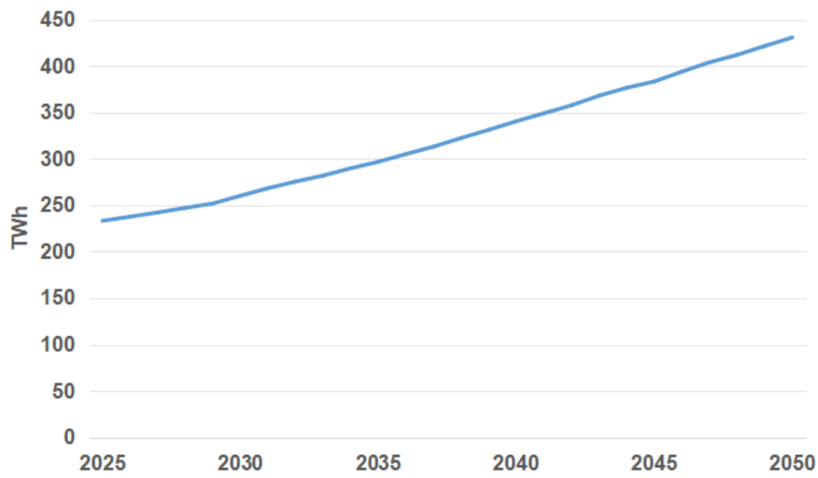

Figure 7. The projected electricity demand (aggregated) in the model

2.2 Plant performance of Coal-fired stations

In PLEXOS LT Plan model, the Generator Forced Outage Rate property defines the anticipated level of unplanned outages, leading to loss of generating capacity due to random outages for a specified duration. Additionally, the Maintenance Rate property defines the plants are expected to be out-of-service due to scheduled maintenance events. These two properties are linked to the EAF, a key performance indicator for power plants.

The average forced outage rate and maintenance rate of Eskom's coal-fired plants used in the IRP LT model and MT-ST model are consistent as follows.

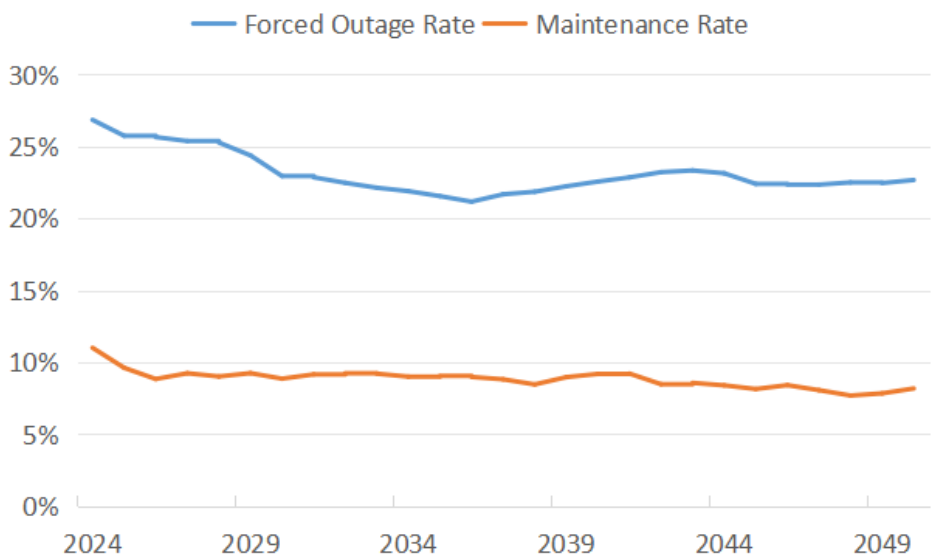

Figure 8. Average Forced Outage Rate and Maintenance Rate of ESKOM's Coal Plant used in LT model

2.3 Generation profile of VRE

The generation profile of VRE represents the time-varying expected output of the VRE plants, mainly driven by local resource availability. It serves as a key input for VRE modeling in the IRP.

In the IRP LT model, each VRE plant is associated with an hourly generation profile from 2025 to 2050, based on repeating representative years. The capacity factor for each plant in every year is illustrated in Figure 9 and Figure 10. In the MT-ST model, a Monte Carlo-based approach is adopted to simulate the stochastic variability of VRE output. To ensure consistency across modeling stages, the long-term average capacity factors of VRE technologies are kept aligned with those used in the LT model.

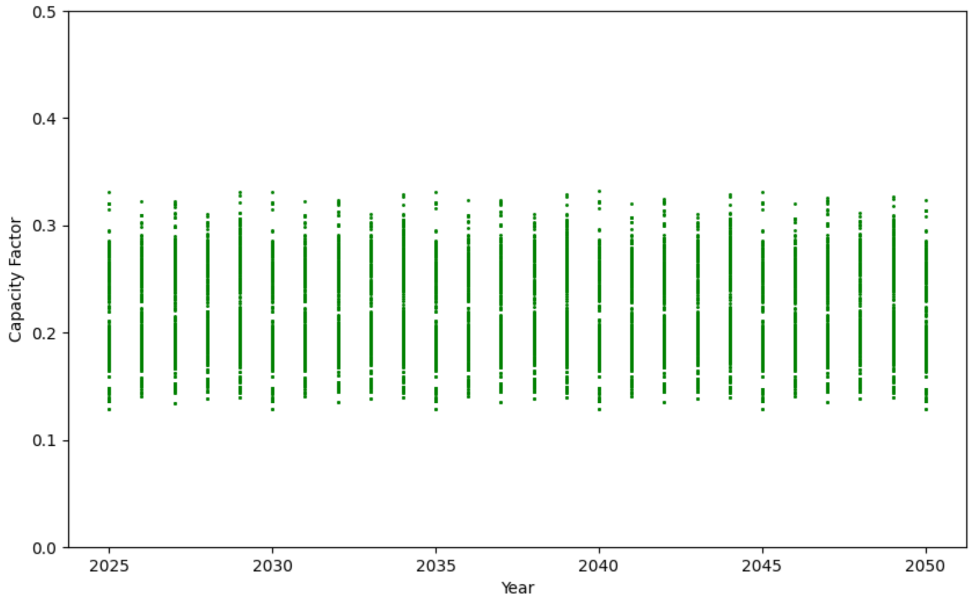

Figure 9. Capacity factor of the solar generation profiles in the input files

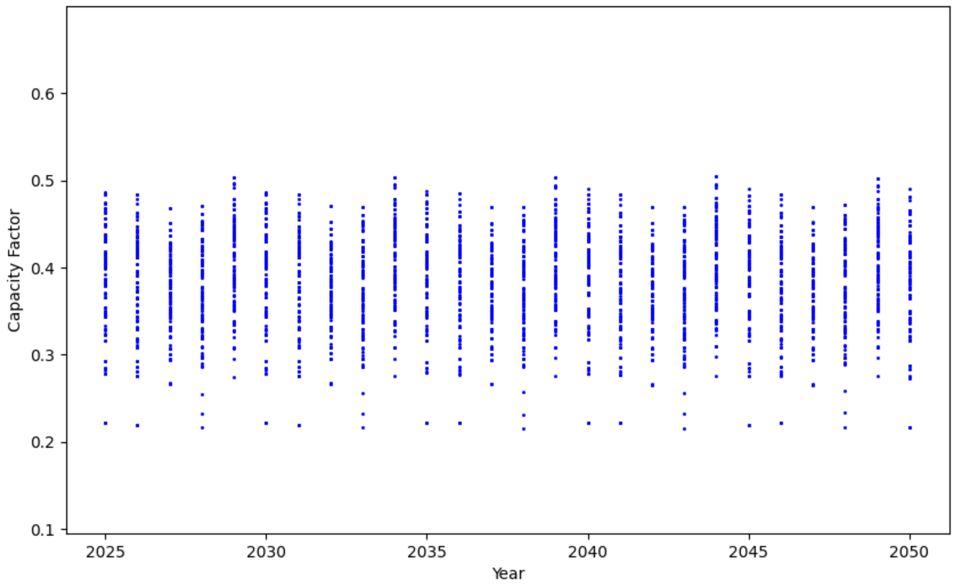

Figure 10. Capacity factor of the wind generation profiles in the input files

2.4 Overnight cost

(1) Gas-fired plant

Open-cycle gas turbine (OCGT), combined-cycle gas turbine (CCGT), and Internal Combustion Engine (ICE) are incorporated into the IRP, with their S-curve[2] costs presented in Figure 11. These costs are fixed at 12,336 ZAR/kW, 16,069 ZAR/kW, and 52,226 ZAR/kW, respectively.

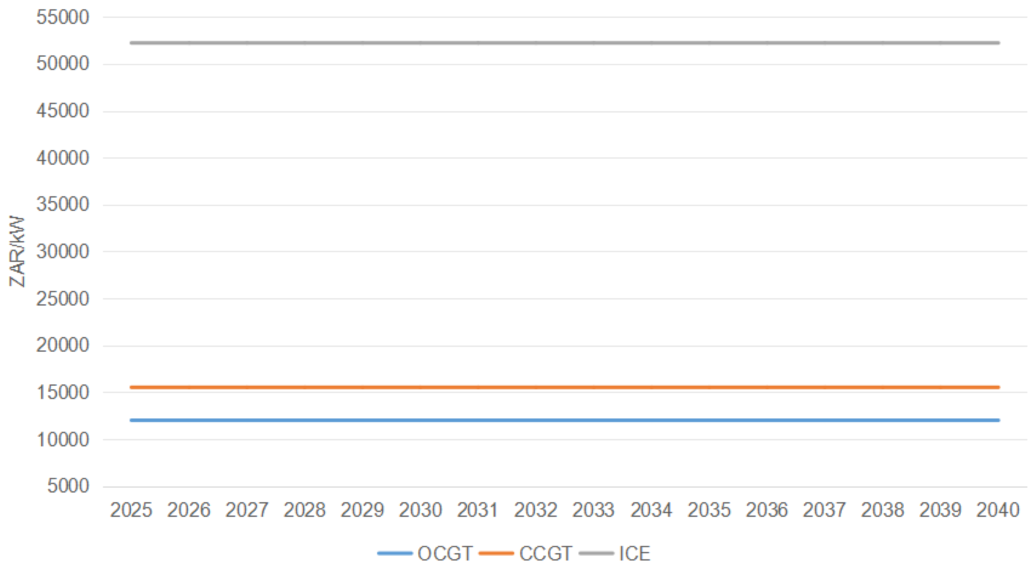

Figure 11. Overnight cost of gas

(2) Nuclear

Pressurized Water Reactor (PWR) and Small Modular Reactor (SMR) are included in the IRP. Two scenarios are evaluated: the reference scenario and the optimistic nuclear cost scenario. In the reference scenario, in terms of different technology type, the S-curve costs for PWR range from 90901 to 104553 ZAR/kW, and those for SMR range from 112477 to 113263 ZAR/kW. In the optimistic nuclear cost scenario, the learning curve of cost for SMR are used as shown in Figure 12, decreasing from 111,059 ZAR/kW in 2025 to 78253 ZAR/kW in 2040.

[2] S-curve costs is based on the overnight cost and reflects the phasing of project capital before commissioning of the first unit.

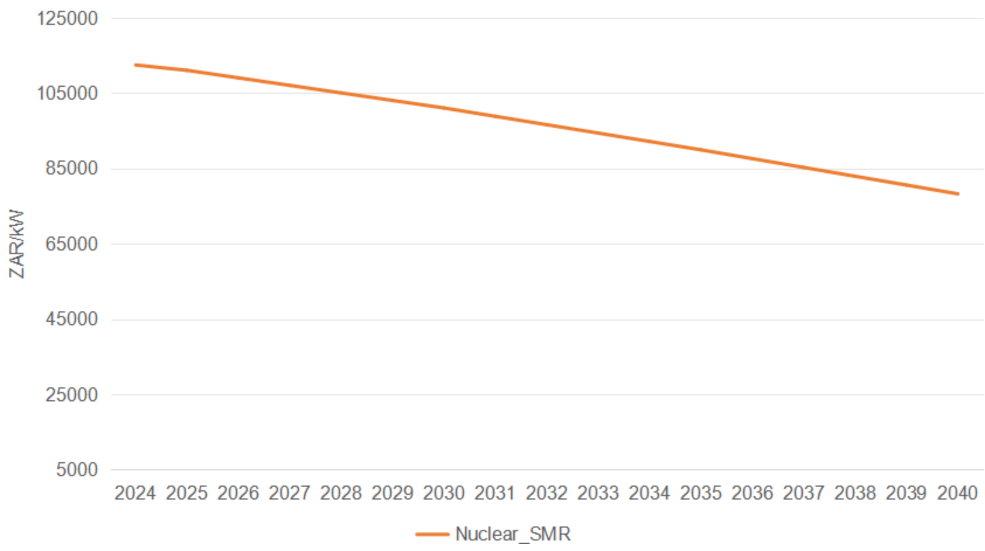

Figure 12. Learning curve of overnight cost for SMR

(3) VRE and BESS

Learning curves are incorporated into the model to illustrate the reduction in overnight costs for VRE sources and Battery Energy Storage Systems (BESS), as shown in Figure 13.

The S-curve cost of wind is projected to decline from 26,200 ZAR/kW in 2025 to 21,157 ZAR/kW by 2040. Similarly, the cost of photovoltaic (PV) is expected to decrease from 15,193 ZAR/kW in 2025 to 10,771 ZAR/kW in 2040. Two scenarios are presented for the cost of BESS. In the reference scenario, the cost is projected to decrease from 25,653 ZAR/kW in 2025 to 20,328 ZAR/kW by 2040. In contrast, the aggressive scenario anticipates a more significant reduction, with the cost dropping from 22,148 ZAR/kW in 2025 to 11,688 ZAR/kW in 2040.

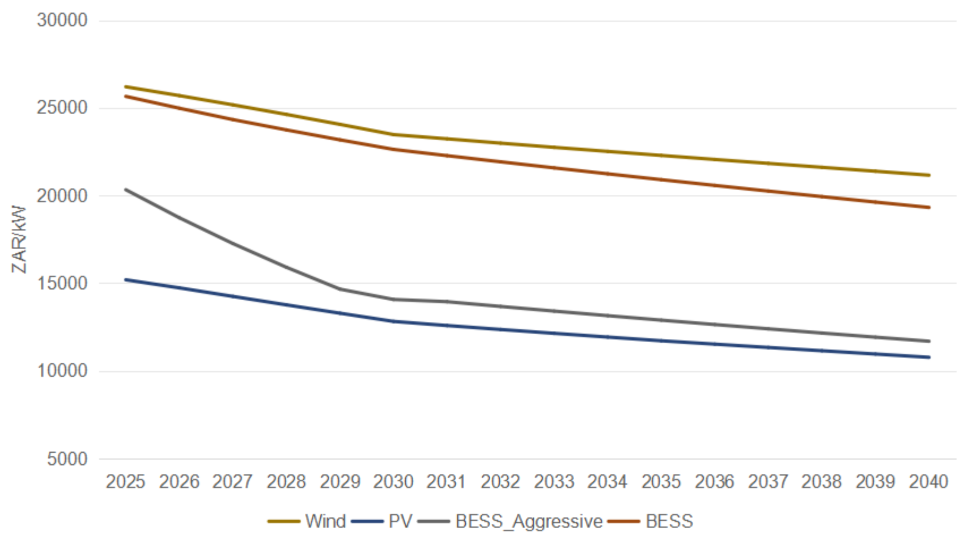

Figure 13. Overnight cost of wind, PV and BESS

2.5 Power Import

The import of power from the Hydro Cahora Bassa project in Mozambique, with a currently allocated capacity of 1GW, is considered in the IRP. The power import is represented in the model as a generator defined with the main properties of capacity, minimum stable level, and variable operation and maintenance (VO&M) charge, etc. The model also imposes constraints such as minimum output levels and maximum annual generation.

2.6 Grid Data

For the development of the IRP multi-node MT-ST model, the PSS/E models originally prepared for TDP is utilized as the basis for defining the power system topology. For each selected milestone year, relevant transmission system characteristics—including busbar definitions, transformers, and transmission lines, etc.—were extracted from the corresponding PSS/E models. These elements were then converted and imported into the PLEXOS to establish the nodal and transmission framework of the MT-ST model. This process enabled the representation of spatial generation and transmission constraints within the IRP modeling framework.

2.7 IRP Scenarios

The IRP creates 5 different scenarios to test specific government policy objectives, including:

- Reference Case: it provides an analysis of the system based on existing and planned policies over the planning horizon
- Gas at Risk Case: it is premised on the Reference Case except the 6 GW CCGT is not committed, assessing the impacts should the gas implementation be at risk
- Nuclear Case: it is premised on the Reference Case except including the nuclear technology and not allowing new gas build after 2030, exploring the implications of expanding the power system with a combination of cleaner generation technologies.
- Aggressive Battery Learning: it is premised on the Reference Case except applying more aggressive learning rates to reduce the capital cost of BESS, evaluating the potentials of developing BESS.
- Delayed Shutdown: it is premised on Reference Case except operation of coal-fired stations by an additional 10 years to 60-year life.

All scenarios are developed based on a consistent set of assumptions regarding electricity demand forecasts, existing and committed generation capacity, as well as economic and cost parameters, ensuring comparability across scenarios. The resulting pathways are then evaluated against the reference case to assess the extent to which they align with or diverge from the objectives outlined in the IRP and relevant policy frameworks.

3. Remarks & Observations

3.1 Demand Forecast

Electricity demand forecasting serves as a cornerstone of power system planning, providing the foundation for formulating a reliable, cost-effective and sustainable energy future. The Demand Projection Model in Support of IRP Update 2023 published in November, 2023 incorporates a structured methodology to electricity demand forecasting, where the inclusion of a dedicated forecasting framework reflects a commendable level of rigor and transparency in the planning process.

A notable strength of the IRP demand forecast lies in its attention to the multi-dimensional drivers of electricity demand, including population growth, economic development, and industrial transformation. These factors are critical for aligning forecasted demand with the structural changes underway in South Africa’s economy. Furthermore, the model's high temporal resolution (hourly) is essential to enable its integration into system modelling and flexibility studies. Besides, the IRP acknowledges the importance of considering historical load shedding events and metrics such as loss factor, which are particularly relevant in the South African historical context.

However, The Demand Projection Model in Support of IRP Update 2023 merely provides demand projections for a single-node model, which limits its ability to reflect regional differences in load development and network constraints. One notable improvement in IRP 2024 is the integration of a multi-node system model and the provision of spatially disaggregated demand projections. The full evaluation of the methodology awaits access to the updated report.

Besides, the demand forecasting framework would benefit from *a dynamic, adaptive approach*—such as incorporating annual updates and rolling forecasts—to enhance responsiveness to unforeseen economic fluctuations and policy shifts. Such a mechanism would further improve the robustness and credibility of long-term planning by ensuring that forecasts remain aligned with real-world developments.

3.2 Plant performance of Coal-fired stations

The Generation Recovery Plan (GRP) with the target of improving the EAF of coal plants has been well proposed and implemented in recent years. ESKOM provided both high and low EAF projections based on different outcomes of the GRP's implementation, with the high scenario assuming full recovery of the EAF under the GRP, and the low scenario assuming minimal recovery. The IRP recommends using a moderate EAF recovery scenario, reflecting partial recovery. We believe the EAF assumption in IRP is achievable through appropriate maintenance and technology upgradation in the future.

Given the dominant role of coal-fired generation in South Africa's current energy mix, the reliability of coal plants is critical to ensuring the security of the electricity supply. This importance is reflected in the IRP's modeling approach. A lower EAF necessitates the modeling of more frequent outages of coal units, which in turn increases modeling complexity, prolongs computation time, and may lead to convergence challenges within optimization process.

The IRP appropriately acknowledges the risks posed by low EAF for South Africa's power system stability, and provides alternative EAF trajectories to make it possible to evaluate system reliability under different availability assumptions. To enhance the transparency and applicability of the IRP results, it is recommended that further clarity be provided on the composition of the coal fleet included in the moderate EAF recovery scenario. Moreover, it is essential that *actual plant performance and availability improvements be closely monitored and periodically benchmarked*. These real-world performance trends should be fed back into future IRP updates to ensure that planning remains grounded in operational realities and reflects the evolving technical condition of the coal fleet.

3.3 Implementation of the Planned Generation Projects

The IRP encompasses different types of planned power sources: the Independent Power Producer Procurement Programme (IPPPP), committed private generation projects, committed Eskom projects, and rooftop PV systems. By 2030, these sources are projected to contribute 70% of South Africa's total capacity.

The existing power generation plans serve as a critical boundary for power system planning. Given the substantial proportion of these sources within the overall generation mix, it is suggested to closely monitor the implementation progress of these projects. Should any of these sources encounter delays in commissioning, it is essential to promptly update the planning outcomes to ensure that capacity targets and supply security are maintained.

3.4 Gas-Fired Plants

South Africa currently operates 6 OCGT units with a total installed capacity of 3.4 GW, and plans to add 6 GW of gas units by 2030. The IRP also forecasts additional gas power capacity to be installed annually from 2032 to 2042, indicating an increasingly significant role of gas in South Africa's energy mix.

Gas-fired generation is recognized for its high stability, excellent flexibility, and relatively low emissions. However, the development of gas-fired power faces several challenges in South Africa, including limited domestic gas supply, delayed infrastructure development, and high investment costs. To address these issues, in addition to fully explore both domestic and international gas resources, it is suggested to further study the optimized configuration of boilers, turbines, and generators to reduce the capital costs of gas-fired power plants.

Furthermore, given the uncertainty in natural gas prices, which will significantly affect the cost structure of gas generation, it is suggested that *a sensitivity analysis on gas prices* be conducted. This would help assess the impact of fluctuating gas prices on the gas-fired generation planning and ensure the robustness of long-term power planning.

3.5 Energy Storage and New Technologies

As the share of renewable energy continues to grow, energy storage becomes an essential technology for enhancing the flexibility and reliability of the power system. The IRP primarily considers two types of energy storage technologies, i.e., BESS and pumped storage. However, with the continuous advancements in technologies and declining costs, other emerged technologies (such as molten salt heat storage and compressed air energy storage) have been applied to demonstrations worldwide, offering superior performances and showing potential for commercial application. These emerging technologies provide additional options for South Africa's future energy storage development.

Incorporating a range of different energy storage technologies into the power mix can further enhance the flexibility, reliability, and cost-effectiveness of the power system. The IRP has conducted dedicated scenario to assess the impact of cost learning curves on BESS development. It is suggested to further expand the energy storage planning to *include a wider variety of storage technologies*, serving as complementary outcomes in addition to IRP.

3.6 Overnight Costs

The IRP model thoroughly evaluates the investment costs associated with various generation technologies, incorporating cost learning curves for wind, solar, and energy storage to forecast anticipated reductions in costs over time. The cost trends for some technologies are informed by the Electric Power Research Institute (EPRI) report titled "Supply-Side Cost and Performance Data for ESKOM Integrated Resource Planning". For pumped storage, cost is significantly affected by site-specific conditions, with the IRP referencing the Ingula Pumped Storage Scheme as a case study. The cost estimate for nuclear power is based on extensive research findings. Overall, these cost assessments are derived from credible sources.

China has established a comprehensive and mature industrial chain across coal, nuclear, wind, solar, and energy storage technologies. Driven by consistently high annual capacity additions, significant economies of scale in equipment manufacturing and deployment have been achieved, positioning China's power investment costs among the lowest globally. By comparison, South Africa's investment costs for similar generation technologies, as reflected in the IRP, are approximately twice those in China (as shown in Table 1[3]). This suggests notable potential for cost reduction in South Africa. To achieve this, South Africa could consider *improving trade policies to facilitate the import of competitive equipment and components, while also creating an enabling environment for developing a local manufacturing industry for renewable energy and other technologies*. Such efforts would not only help reduce capital costs over time but also contribute to job creation, technology transfer, and long-term industrial development.

Table 1. Overnight cost comparison between China and South Africa

Technology	Overnight costs in China (ZAR/kW)	Overnight costs in IRP model (ZAR/kW)
Coal	8,986 – 11,463	/

[3] The exchange rate is 1 CNY = 2.54 ZAR

Gas	5,234 – 5,318	12,336-16068
Nuclear	40,640 – 41,910	90,901 – 113,262
Onshore wind	7,620 – 11,430	26,647
Offshore wind	20,320 – 43,180	/
PV	7,112 – 8,890	15,715
BESS (4h)	9,144 - 10,160	26,972
Pumped Hydro	15,240 – 16,929	41,651

3.7 Power Import

The IRP includes the provisions for potential power imports from Mozambique's Cahora Bassa Hydroelectric Station. Given the currently limited scale of power imports, the modelling approach in the IRP remains relatively simplified, and the impact on overall system optimization is minimal.

Considering that interconnection with neighboring countries could be a crucial strategy for South Africa to ensure *a more diverse and reliable power supply*, the cross-border electricity interconnections may be expanded in the future. This may call for more detailed modeling of interconnection capacities, import costs, availability profiles, and associated transmission constraints to better reflect the role of regional cooperation in South Africa's power development strategy.

3.8 Grid Data

The coordination between the multi-nodal MT-ST model and the PSS/E model represents a promising technical advancement in aligning long-term generation planning with transmission development planning. By extracting node-level and transmission line data from PSS/E models developed for key horizon years in the TDP, and integrating them into the PLEXOS MT-ST framework, the model benefits from a delicately and spatially resolved transmission topology. This enables the MT-ST model to effectively simulate network congestion, assess regional generation adequacy, and evaluate location-specific operational constraints with improved accuracy. Such capabilities are especially valuable for identifying system stress points under high renewable penetration scenarios and for informing more robust and geographically targeted VRE developing mode and investment strategies.

3.9 Scenarios Analysis

The IRP's use of multiple scenarios provides a robust framework for testing the impacts of different policy directions and energy strategies. Each scenario is thoughtfully designed to explore distinct pathways that align with South Africa's energy transition goals. The Reference Case offers a clear baseline analysis, while the Gas at Risk Case and Nuclear Case explore uncertainties regarding gas power and opportunities regarding nuclear power, respectively. The Aggressive Battery Learning scenario highlights the potential of innovative BESS solutions, and the Delayed Shutdown scenario allows for a thorough understanding of the effects of extending the life of coal-fired plants.

These scenarios provide a wide view of potential future developments in the energy sector. The comparative approach allows for a meaningful assessment of the trade-offs and synergies between different policy options.

Looking ahead, it is suggested that *future iterations of the IRP may incorporate other promising scenarios* such as additional energy storage technology options, expanded regional interconnections, etc., to enhance planning adaptability.

III. SUMMARY

The draft IRP 2024 represents a comprehensive and forward-looking approach to addressing South Africa’s power system prospect, with an emphasis on balancing the transition to a low-carbon energy future while maintaining system reliability. The evaluation of the IRP model & methodology, input data & assumptions reveals several strengths that contribute to its credibility and usefulness in guiding South Africa’s energy transition.

1. Modeling & Methodology

The IRP employs a structured and well-integrated modeling framework, combining long-term capacity expansion with detailed dispatching analysis to optimize the future energy landscape. The IRP modeling approach integrates technical, economic, and policy considerations, ensuring that the plan not only optimizes the energy mix but also accounts for system security, cost-effectiveness, and long-term sustainability. The methodology effectively evaluates the trade-offs between various energy sources, including fossil fuels, renewables, and energy storage, supporting robust decision-making for a flexible and reliable power system. The sophisticated model reflects the technical team’s well understanding and expertise on the PLEXOS modeling.

A significant enhancement in this IRP 2024 lies in the introduction of a multi-node MT-ST model, which complements the LT planning results by incorporating PASA, MT and ST simulation to provide a more granular temporal and spatial resolution. This methodology improves the ability to capture system operation features, such as unit commitment behavior, transmission congestion and system adequacy. The coordination between the MT-ST model and PSS/E-derived network data also strengthens the alignment between generation expansion and grid development, promoting a more integrated system perspective.

To improve the robustness of the planning process, sensitivity analysis is suggested be conducted on key technical indicators that are difficult to be monetized in the cost-objective function. A multi-dimensional evaluation indicator system is also encouraged to determine the balanced and most-effective planning outcome. Furthermore, considering that the multi-node MT-ST model still has limitations on modelling system security constraints such as frequency and voltage stability and other dynamic security aspects, more coordination between different IRP volumes is recommended to emphasize the incorporation of updated system reliability constraints into the IRP process.

2. Input Data & Assumptions

The input data used in the IRP is derived from credible sources and established modeling tools, ensuring that key assumptions are based on realistic and reliable information. Critical factors such as electricity demand projections, existing and committed generation capacity, plant performance of coal-fired stations, and technological advancements are carefully considered. Transparent documentation of these assumptions enhances the credibility of the analysis and enables stakeholders to understand the drivers behind the projected outcomes. The use of multiple scenarios provides a more comprehensive view of possible development pathways, allowing greater flexibility in addressing future uncertainties.

Compared to China, South Africa faces higher investment cost across various generation technologies, indicating rooms for cost optimization. Gas-fired generation, in particular, is subject to volatility due to domestic gas availability and infrastructure constraints, which affect its economic competitiveness. Meanwhile, technological progress and cost reductions in energy storage are expanding the range of viable flexibility options. To ensure that the IRP remains responsive to market and technology developments, it is recommended to regularly review key input assumptions and maintain a rolling update of IRP.

PART B: REVIEW & INDEPENDENT ANALYSIS ON IRP RESULTS

I. REVIEW OF SCENARIO RESULTS FROM THE LT MODEL

The result review process is essential for evaluating the robustness and reliability of the IRP's outcomes. This section summarizes the generation capacity results across scenarios of the IRP and provides targeted recommendations for improvement. Specifically, for the Balanced Scenario recommended in the IRP, EPPEI conducted independent model calibration and simulation based on the LT and MT-ST models, providing more insights on South Africa's power transition pathway.

1. Overview of the IRP Model Results

In the IRP 2024 document and its public presentation, several scenarios are presented for the planning horizon up to 2050 to test specific planning objectives, including Reference Case, Gas at Risk Case, Nuclear Case, Aggressive Battery Learning, and Delayed Shutdown. The total system build capacity[4] of each scenario is presented in Figure 14, ranging from 113 GW to 136 GW.

The results of Gas at Risk and Nuclear Cases highlight notable benefits in terms of generation capacity diversity, lower system costs, and reduced carbon emissions, suggesting a potentially expanded role for gas and nuclear power in South Africa's future generation mix. However, both gas and nuclear development pathways are subject to considerable uncertainty. Gas-fired power is constrained by limited domestic reserves, lack of import infrastructure, and exposure to international price volatility. Nuclear power requires long development cycles, significant upfront capital investment and complex regulatory approvals.

[4] The results are sourced from a public presentation document provided by the IRP technical team. It is clarified that the results are derived directly from a multi-region LT model.

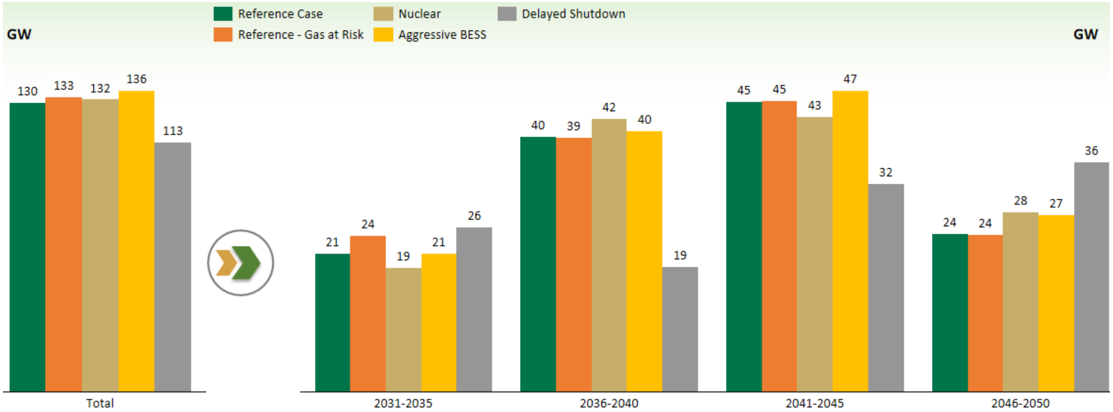

Figure 14. Total System Build Capacity for All Scenarios

To hedge against these uncertainties, the IRP includes the option of delaying the retirements of coal plants. This strategy would allow continued use of existing infrastructure, alleviating short to medium term capacity pressures. Plants selected for life extension would be required to comply with South Africa' Minimum Emission Standards (MES), necessitating environmental retrofits. IRP modeling indicates that, in terms of direct system-wide cost, this scenario is the most expensive among the alternatives.

Synthesizing insights from all the scenarios, a Balanced Scenario is proposed in IRP 2024. It presents a diversified pathway that includes renewable energy, natural gas, nuclear, coal and storage to mitigate supply risks and enhance system flexibility. In support of this strategy, the IRP also outlines several interventions to ensure supply security during the transition period.

Additionally, the IRP also provides more perspectives on the power generation development:

- it evaluates the flexibility of South Africa's future power system, highlighting a growing risk of supply shortfalls as the share of VRE increases;
- it discusses the 10-year TDP for the South African power system, outlining the methodology, assumptions, main results, implementation challenges and solutions;
- it introduces the power system operations appraisal to ensure continuous supply of power with an acceptable quality in accordance with the South African Grid Code, outlining the necessitation to conduct stability analysis on the power system under both normal conditions and contingencies.

2. Remarks

The IRP 2024 places a strong emphasis on energy security, focusing on system adequacy through the assessment of power supply gaps, peak load balancing, and reserve capacity. Upon on the IRP modeling results, both gas and nuclear power present significant opportunities for South Africa’s future power system. However, uncertainties associated with gas and nuclear development may introduce implicit system risks, such as the potential for unserved energy and security of supply concerns, especially in the power system with high penetration of VRE. .

In this context, coal plant life extension option presents strategic value as a contingency measure, despite its higher modeled costs. Acting as a form of system "insurance", it can enhance adequacy and resilience in the face of supply uncertainties.

To address these dynamics, the IRP recommends the Balanced Scenario as a viable pathway for South Africa’s energy transition. For the mid- to long-term period (2030–2050), where uncertainties are more pronounced, the IRP framework should remain flexible. In addition to delayed coal retirements, further exploration of alternative supply-side options is encouraged—particularly for the 2030–2038 period—to strike a balance between reliability, cost-effectiveness, and decarbonization goals.

II. INDEPENDENT ANALYSIS ON GENERATION MIX OF BALANCED SCENARIO PROPOSED IN IRP

In order to comprehensively assess the robustness of the proposed generation mix under the Balanced Scenario, EPPEI conducted an independent analysis using two complementary analytical approaches:

- **Trend Analysis** – Evaluation of capacity and generation patterns across key milestone years (2030, 2035, 2040, 2045) based on a simplified ST model derived from the received single-node LT model, aligned with the Balanced Scenario capacity mix for each year.
- **Focused Year Analysis** – In-depth assessment of the 2035 generation dispatch using the multi-node MT-ST model provided by the IRP technical team.

These two levels of analysis were designed to maximize the value of the available models and data. It is critical to note that the simplified ST model and the multi-node MT-ST model are built on different assumptions and configurations, and their results are not directly comparable. Instead, the aim of our analysis is to provide complementary insights that strengthen the IRP evaluation, identify potential challenges, and suggest opportunities for further optimization.

1. Trend Analysis

To assess the capacity and generation evolution under the IRP Balanced Scenario, EPPEI developed a simplified ST model based on the received single-node LT model, incorporating the proposed capacity mix from the IRP draft. This approach enables a more granular review of system performance across key milestone years.

Key Input & Assumptions

- The model covers full-year simulations (8,760 hours) for 2030, 2035, 2040, and 2045 with single-node.
- Installed capacities follow the Balanced Plan outlined in Table 1 of the IRP draft.
- In the absence of location-specific detail, new capacity is evenly distributed among extendable units of each technology type.

- The delayed shutdown of coal plants is not taken into account.

While this ST model differs from the full IRP multi-node MT-ST simulations in scope and spatial granularity, it is directly derived from the LT model. As such, it provides a coherent and valuable extension of the IRP's capacity planning logic and offers meaningful insights into temporal trends.

1.1 Capacity Mix

The installed capacity trajectory under the IRP Balanced Scenario reflects a clear transition toward a more renewable-based system. As shown in Figure 15, total installed capacity increases steadily until 2040, followed by a slight decline in 2045 due to planned decommissioning of coal and solar PV assets.

- By 2045, the total installed capacity reaches 138GW, comprising 44 GW wind, 37 GW solar, 12 GW coal, 20 GW gas, 6 GW nuclear, 9GW BESS and 3GW pumped storage.
- Three major VRE buildout phases are observed: 2026–2027, 2034–2035, and 2039–2042, each contributing over 5 GW of new VRE capacity annually
- The VRE share of total installed capacity rises from 20% in 2023 to 49% by 2035, and to 59% by 2045. The capacity of BESS also experiences significant growth.

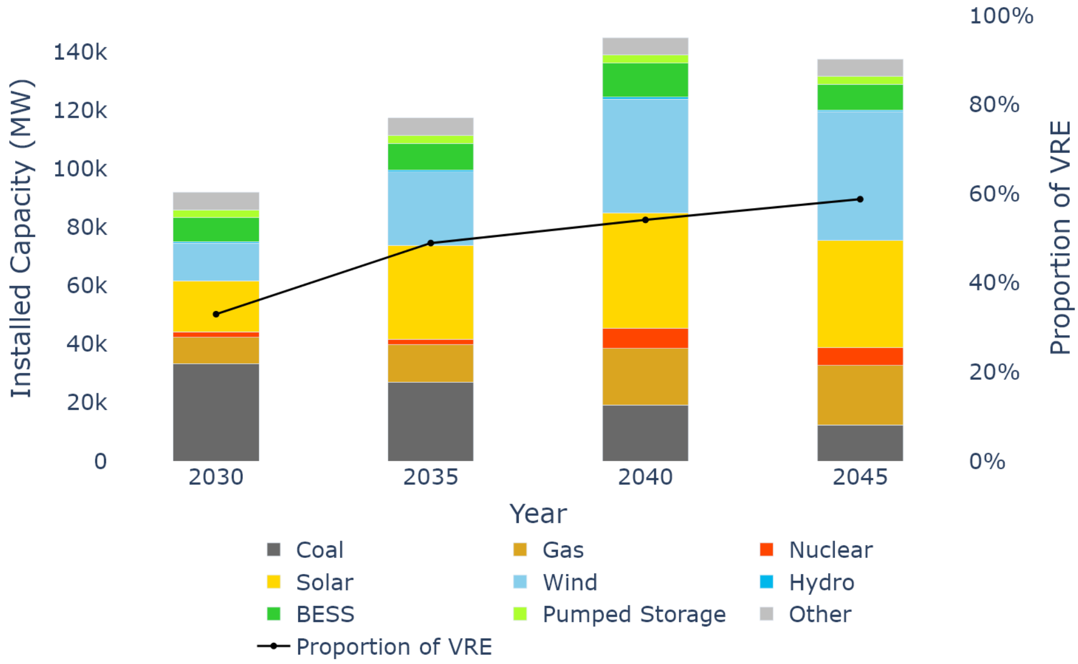

Figure 15. Capacity mix of the South Africa power system

1.2 Generation Mix

As illustrated in Figure 16, South Africa's power generation mix under the IRP Balanced Scenario undergoes a significant transformation, driven by the increasing penetration of VRE and the declining role of coal.

- By 2045, total generation reaches 388 TWh, representing a 72% increase compared to 2023. The breakdown includes 168 TWh wind, 75 TWh solar, 76 TWh coal, 25 TWh gas, and 41 TWh nuclear
- The generation share of VRE rises from 8% in 2023 to 63% by 2040.
- The rising contribution of VRE in both installed capacity and generation underscores a major structural shift toward decarbonization and sustainability. This trend also introduces increased variability and uncertainty on the supply side.

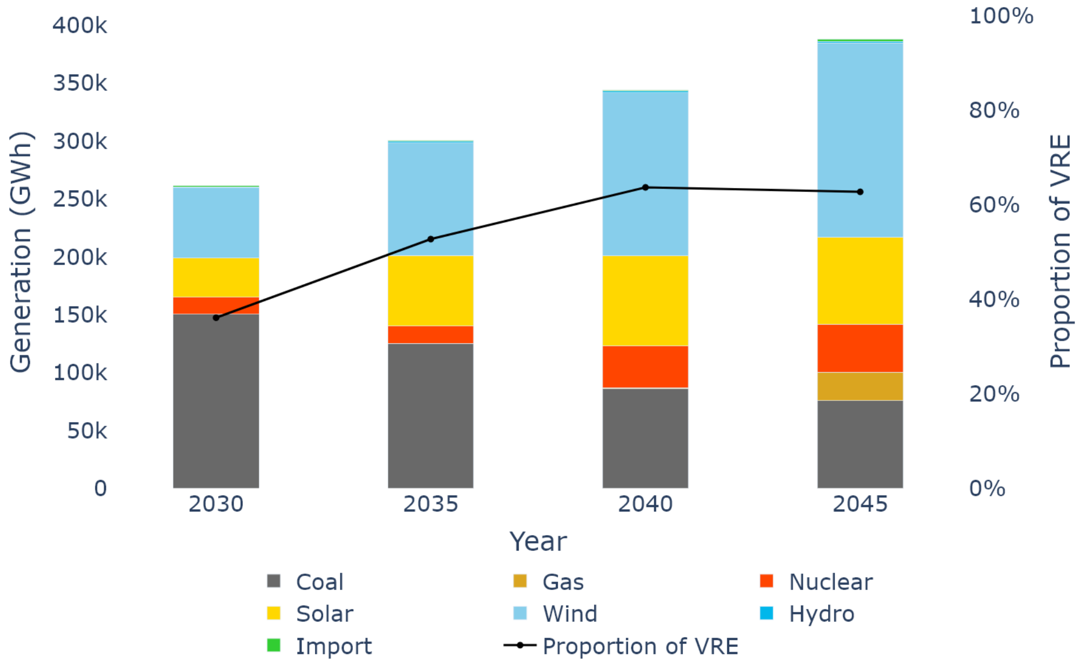

Figure 16. Generation mix of the South Africa power system

1.3 Load and Net Load Duration Curves

The load and net load duration curves are illustrated in Figure 17. It is indicated that the impact of VRE in 2040 is greater than in 2045, with the net load in 2040 experiencing a more pronounced decline compared to that in 2045. The minimum net load experiences a significant decline. By 2040, the minimum net load reaches -28 GW, with the difference between peak and minimum load amounting to 72 GW, indicating a high-level demand on flexibility.

The load and net load time series curves for 2045 are compared in Figure 18, providing a more direct illustration of VRE's impact. Negative value of net load indicates that there is absolute electricity surplus in the system, even when all other units are shut down. The electricity surplus is either absorbed by storage or curtailed. The time duration of negative load period will exceed 1,000h in 2040.

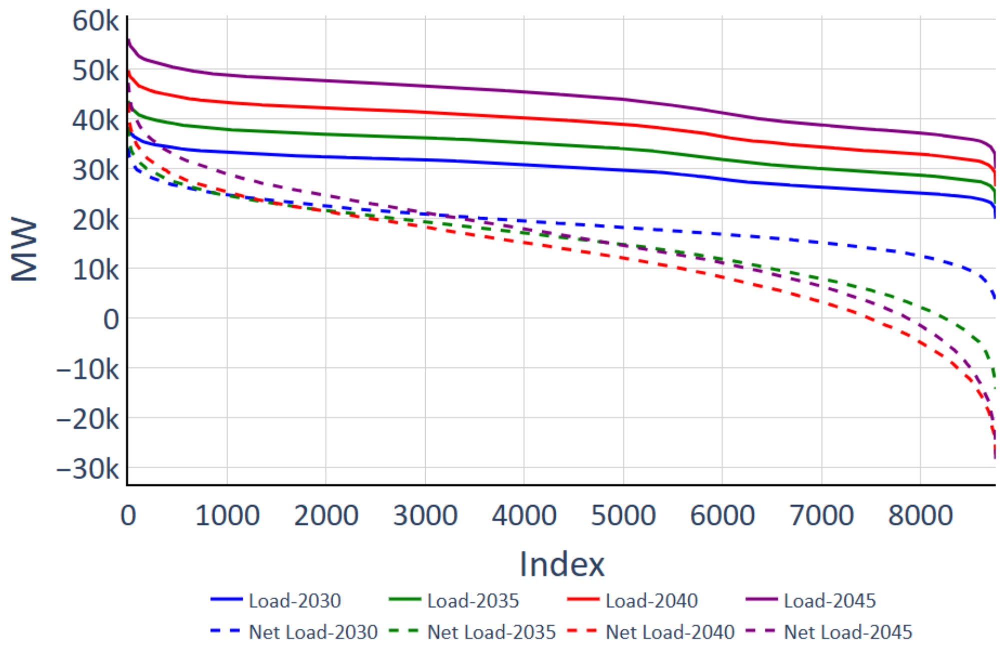

Figure 17. Load and Net Load Duration Curves

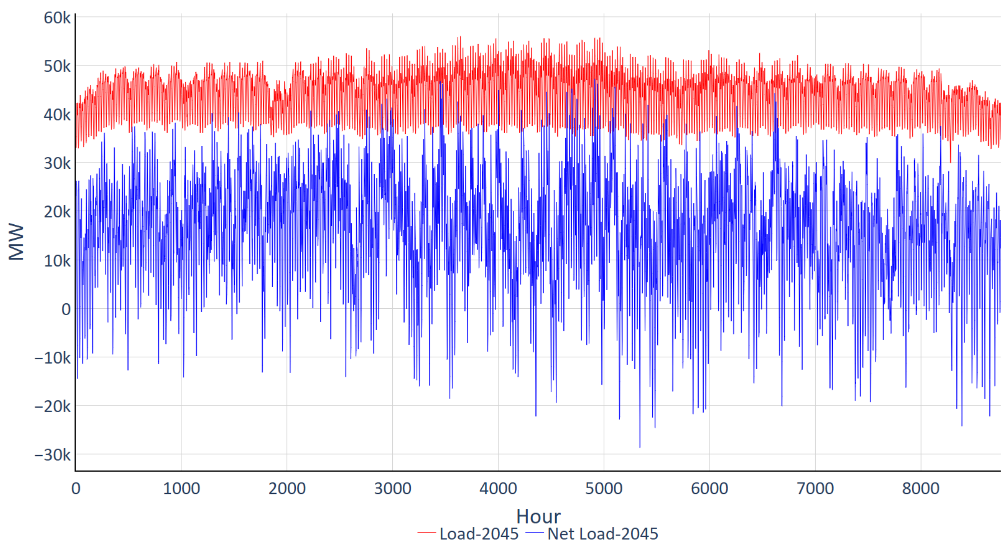

Figure 18. Load and Net Load Time Series Curves in 2045

1.4 Firm Capacity Ratio

Firm capacity refers to the capacity of stable and dispatchable power resources of the power system's generation fleet, typically including coal, gas, nuclear, and hydro. These sources are generally not subject to weather-related variability and can be reliably dispatched when needed. The firm capacity ratio is defined as the ratio of firm capacity generation to system load at each hour, serving as an important indicator of system adequacy. A higher ratio implies greater adequacy and reliability at a given time.

The cumulative distribution curve of the firm capacity ratio is depicted in Figure 19. Each point on the curve indicates the probability (y-axis) that the firm capacity ratio exceeds the corresponding value on the x-axis. Both the minimum and average firm capacity ratio declines over time . By 2045, the firm capacity ratio ranges from 19.8% to 90.0%, and only for 37% of the year's hours (3,241 hours), the firm capacity ratio surpasses 50%, suggesting a tighter adequacy margin as the system transitions toward higher shares of VRE.

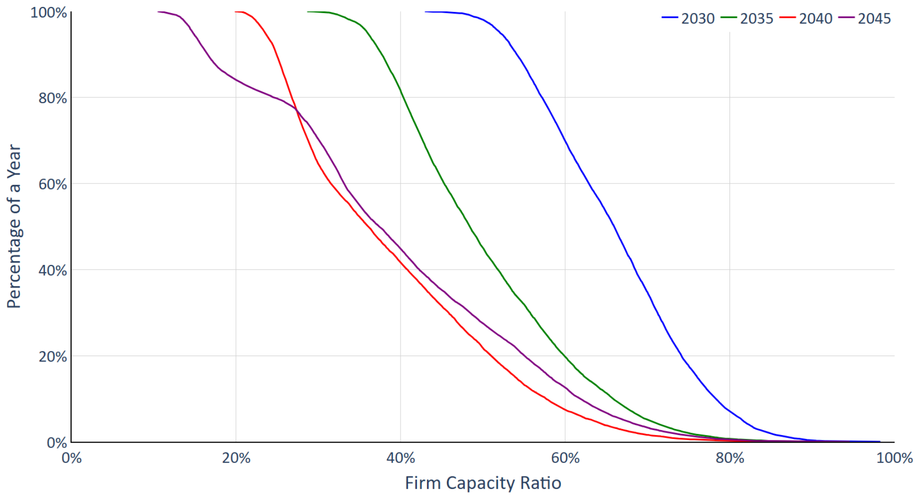

Figure 19. Cumulative Distribution Curve of Firm Capacity Ratio

1.5 Carbon Dioxide Emission

Carbon dioxide emission from coal and gas plants is depicted in Figure 20. Emission steadily decreases from 2030 to 2045. By 2045, emissions are approximately 50% lower than in 2030, indicating substantial decarbonization progress.

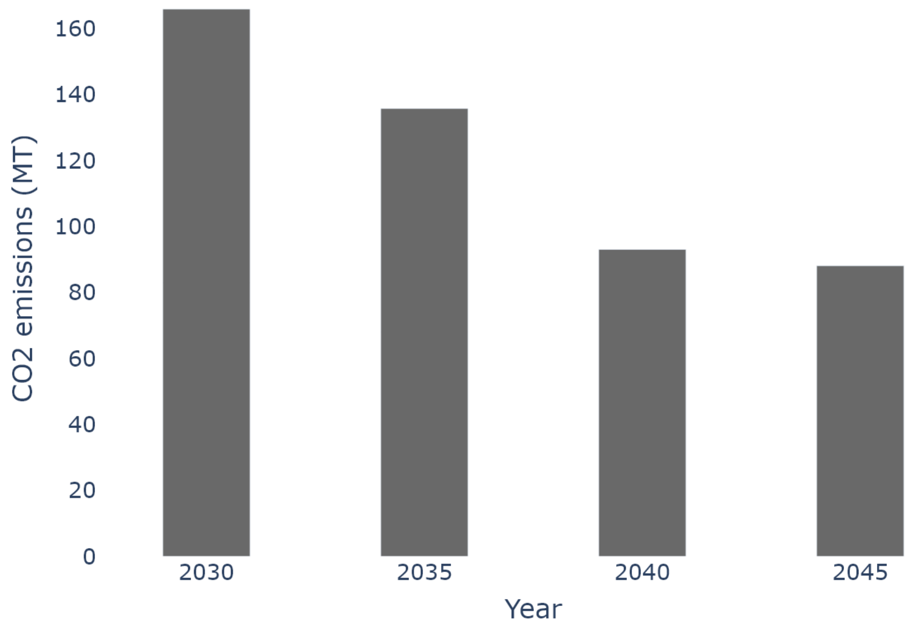

Figure 20. Carbon dioxide emission of power sector

2. Focused Year Analysis on 2035

The focused analysis centers on the year 2035, using the multi-node MT-ST model to evaluate system performance with greater spatial and temporal resolution.

Key Input & Assumptions

- The model simulates the full year of 2035, with the model configured in 52 steps of 1 week.
- The model adopts the 2035 transmission system derived from the PSS/E case. As such, the accuracy of the analysis is limited to that year's grid configuration.
- Installed capacities of power sources, batteries, and pumped storage align with the Balanced Scenario for 2035 as outlined in the IRP report. Unit-level capacities are proportionally scaled according to the original multi-node MT-ST model.
- The PASA, MT, and ST phases are executed sequentially, following PLEXOS's recommended modeling workflow.
- The stochastic analysis is conducted using the "Parallel Monte Carlo" method with samples of 200. Mean result from these simulations is reported.

- Several technical adjustments were made, including removal of commitment constraints on VRE units, disabling of dumped (unserved but not curtailed) energy options to better reflect system adequacy requirements, and other refinements to improve computational stability and output clarity.

2.1 Capacity Mix

The installed capacity for 2035 is depicted in Figure 21. Accounting for newly planned and decommissioned capacity, the total installed capacity and the proportion of VRE increase significantly compared to current levels, while the capacity of coal-fired plants decreases.

- Total installed capacity is 111GW, comprising 26 GW wind, 28 GW solar, 27 GW coal, 12 GW gas, 2 GW nuclear, 7GW BESS, and 3GW pumped storage.
- VRE capacity increases by approximately 46 GW from 2025, reflecting an average annual addition of 4 GW.
- The capacity share of VRE rises from 20% in 2023 to 49% by 2035. The capacity of BESS also experiences significant growth.

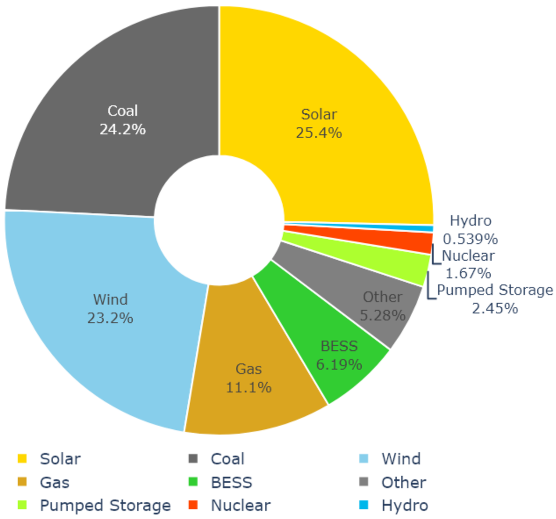

Figure 21. Capacity mix of the South Africa power system in 2035

2.2 Generation Mix

The generation mix of 2035 is shown in Figure 22. The total energy generation and the proportion of VRE grow significantly compared to current levels, while the generation of coal-fired plants declines.

- The total generation in 2035 reaches 309 TWh, consisting of 45 TWh wind, 47 TWh solar, 147 TWh coal, 41 TWh gas, and 15 TWh nuclear.
- The generation share of VRE reached 30% by 2035.

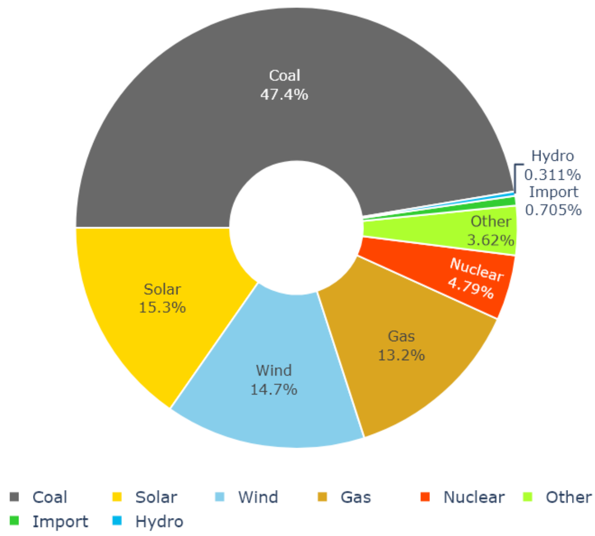

Figure 22. Generation mix of the South Africa power system in 2035

2.3 VRE Curtailment Ratio

The curtailed energy of wind and solar, along with the corresponding curtailment ratio, is depicted in Table . The total curtailed energy amounts to 36 TWh, with a VRE curtailment ratio of 28.5%, indicating that nearly one-third of the available wind and solar generation could not be utilized.

Table 2. VRE Curtailment in 2035

VRE Curtailed	VRE Curtailment Ratio
36 TWh	28.5%

To identify the cause of high VRE curtailment, we run the multi-node MT-ST model with the transmission detail in PLEXOS set to "regional," which excludes transmission lines and transformers within regions and only accounts for inter-regional transmission constraints. Under this configuration, the VRE curtailment ratio dropped sharply to 0.4%, indicating that transmission congestion is likely the primary driver of VRE curtailment. Through a detailed analysis of congestion issues, it is evident that the primary cause of congestion is the insufficient transformer capacity. As the IRP workflow addresses transmission planning in Phase 2, this issue may be resolved through more detailed and targeted transmission expansion strategies in that phase.

2.4 Capacity Factor

The capacity factors of power sources are presented in Table , indicating the varying levels of utilization and operational characteristics of different technologies in the system.

- Nuclear and coal exhibit significantly higher capacity factors, reflecting their baseload generation roles.
- CCGT units operate at a moderate capacity factor, indicating a combination of baseload and mid-merit dispatch.
- OCGT units, in contrast, show lower capacity factor, consistent with their role as peaking resources and providers of system flexibility.
- Wind and solar remain relatively lower capacity factors, consistent with their variable characteristics.

Table 3. Capacity factor of power sources in 2035

Power Source	Capacity factor
Coal	62.0%
Gas CCGT	51.4%
Gas OCGT	20.0%
Nuclear	91.1%
Solar	19.1%
Wind	20.1%
Hydro	18.3%

2.5 Load and Net Load Duration Curves

The load and net load duration curve and time series curve are presented in Figure 23 and Figure 24. By 2035, the minimum net load reaches -2 GW, compared to a minimum load of 23 GW. The net load exhibits a range of 40 GW, nearly double the 21 GW range of the gross load. This widening gap underscores the growing need for system flexibility, primarily driven by the high penetration of VRE.

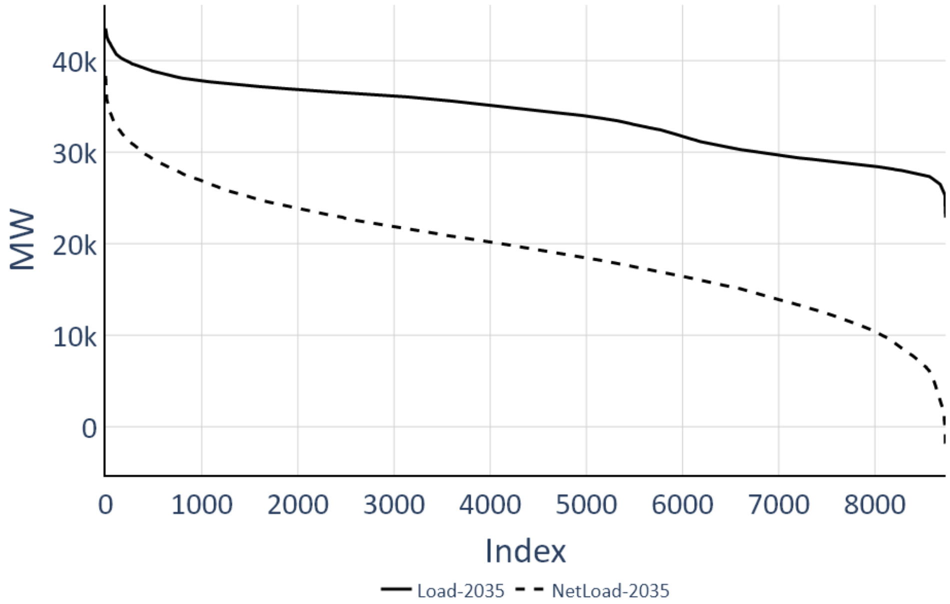

Figure 23. Load and Net Load Duration Curves

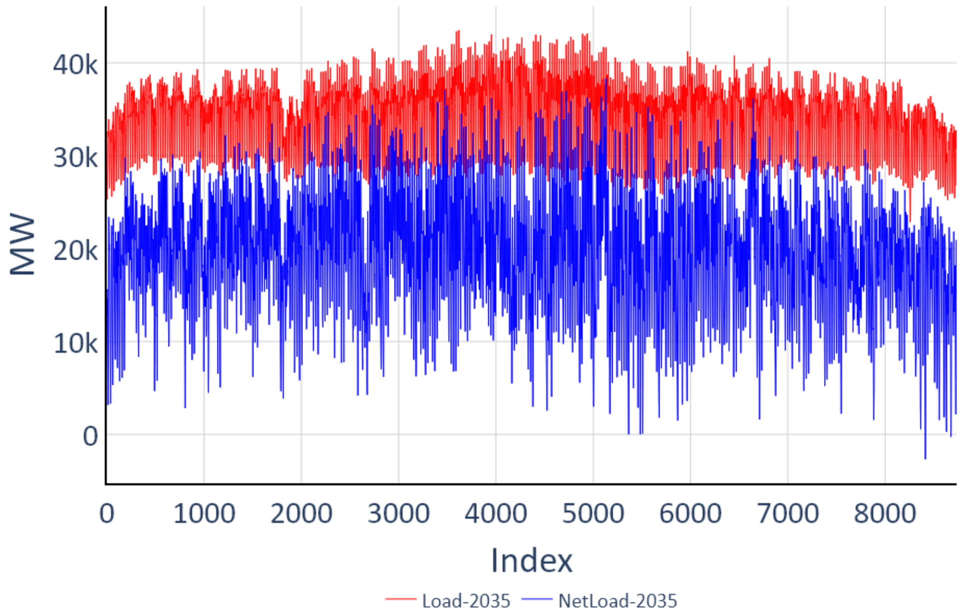

Figure 24. Load and Net Load Time Series Curve

2.6 Firm Capacity Ratio

The cumulative distribution curve of the firm capacity ratio is shown in Figure 25. In 2035, the firm capacity ratio ranges between 39% and 100%, implying that instantaneous VRE generation can account for up to 61% of system demand. Notably, for 95% of the year's hours, the firm capacity ratio exceeds 50%, indicating a seemingly strong level of system adequacy. However, this result may be overly optimistic, primarily due to the significant curtailment of

VRE observed in the simulations. If curtailment were reduced, the firm capacity ratio would likely decline, revealing greater reliance on VRE production.

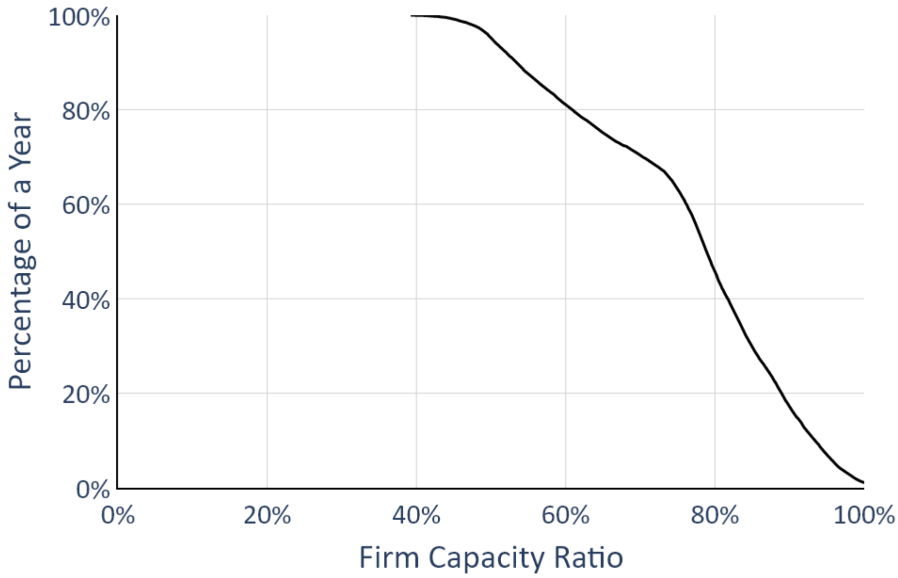

Figure 25. Cumulative Distribution Curve of Firm Capacity Ratio in 2035

2.7 System Operation Result

The cumulative power output for a typical week in 2035 is presented in Figure 26, which visually complements the previous capacity factor analysis.

- Coal and nuclear serve as the baseload source, providing a stable foundation for the system.
- Wind and solar contribute a substantial share to the generation mix, but their inherent variability results in frequent ramping of gas units and active cycling of storage systems to maintain system balance and flexibility.
- Significant wind and solar curtailment can also be intuitively observed.

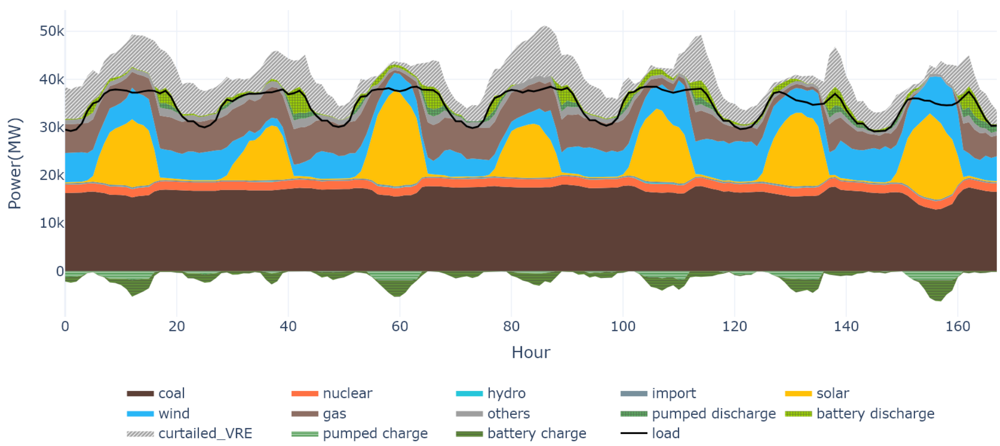

Figure 26. Power output cumulative graph for a typical week in 2035

3. Remarks & Observations

(1) South Africa's IRP Supports a Significant Green Transition

Under the IRP capacity expansion plan, South Africa is positioned to achieve a major transformation toward a greener power system. By 2035, the installed VRE capacity is projected to grow from 12 GW in 2023 to 54 GW, raising its share from 20% to 49%. The successful implementation of this plan is expected to substantially reduce carbon emissions from the power sector, thereby supporting South Africa's broader goal of building a low-carbon and climate-resilient economy and society.

The large-scale deployment of VRE should be strategically coordinated with the development of dispatchable generation, flexible resources, and a resilient power grid. These components work in concert to ensure system stability and reliability, creating a cohesive and robust energy transition framework.

(2) Coal, Gas, and Nuclear: Distinct Role and Development Consideration

According to our independent analysis based on the multi-node MT-ST model, by 2035 nuclear and coal units primarily serve as baseload source, while CCGT units act as a combination of baseload and mid-merit dispatch, and OCGT units serve as peaking resources and providers of system flexibility. The following recommendations are proposed for the development and optimization of these power sources.

Coal Plant. Given the current state of South Africa's coal fleet, it is critical to closely monitor the operational status of individual units, particularly identifying and supervising those with the lowest EAF over time. Premature decommissioning of coal plants should be avoided until viable baseload alternatives are fully in place. Instead, emphasis should be placed on improving reliability through plant performance upgrades. For units that remain in good condition, retrofits to enhance both reliability and operational flexibility—such as advanced controls or improved ramping capabilities—could restore capacity and better support VRE integration and peak demand management. In parallel, clean energy transition measures, including carbon capture, utilization and storage (CCUS), and biomass co-firing, should be explored to reduce emissions and align with climate targets.

Gas Plant. A reasonable gas capacity is necessary, particularly for responding to extreme weather conditions (such as multi-day periods of low wind speeds and reduced sunlight) or unexpected large plant shutdowns that require extended repair times. Gas-fired plants can also provide essential support at weak grid nodes. Given South Africa's limited natural gas resources, it is important to carefully evaluate the type of gas-fired plants.

While OCGT units offer faster start-up times, CCGT can also provide adequate flexibility for load following needs if designed appropriately and integrated with energy storage. Furthermore, CCGT is generally more efficient and cost-effective over the long term due to its higher fuel efficiency and lower operating costs. In China, where gas resources are also limited, CCGT units are the dominant configuration. Unless there is clear evidence that OCGT is significantly more cost-effective than CCGT in South Africa, it is recommended to prioritize CCGT for new gas-fired power plants.

Nuclear Power. Although the development of nuclear power is a long-term undertaking, it remains a vital strategy for a power system facing a shortage of firm baseload capacity. Accordingly, early-stage preparation and feasibility assessments for new nuclear capacity are recommended. Should overnight costs decline, nuclear power may emerge as a competitive option, especially in the context of carbon reduction commitments and long-term security.

(3) Emphasizing coordinated planning for large-scale VRE development and integration.

The Balanced Scenario indicates significant fluctuations in the short-term deployment of solar PV and wind capacity. For instance, a gradual increase in PV capacity is planned from 2025-2027, followed by no additions in 2028 and only limited additions appear in 2029. This uneven rollout is largely due to the IRP's consideration of already committed or soon-to-be constructed projects in the near term. While this reflects the realities of current project pipelines, it may lead to integration bottlenecks and hinder investment continuity if not accompanied by a forward-looking infrastructure development plan.

Moreover, from 2030 to 2042, the IRP proposes sustained annual additions of 800~2,000 MW of PV and 2,000~3,500 MW of wind, peaking in some years at levels comparable to South Africa's entire current VRE fleet. Integrating this scale of VRE could poses significant risks to system adequacy, flexibility and stability. Our independent analysis on indicates that:

- VRE curtailment rate arises to nearly 30% by 2035 due to transmission congestions, especially transformer capacity insufficiency;

- reduced firm capacity and sharper net load ramps raise more requirements for system adequacy and flexibility in the future;
- rising instantaneous shares of VRE (more than 60% by 2035) are expected to weaken system frequency, voltage and dynamic stability, requiring close operational attention and proactive mitigation measures.

While these challenges cannot be fully captured by production cost models such as PLEXOS, the LT and MT-ST models can help flag high-risk periods for further investigation. It is commendable that the IRP has already started integrating grid constraints through a multi-node model and plans to expand technical depth in Phases 2 and 3 through more detailed transmission and operational studies. To further strengthen this approach, it is recommended to:

- integrate generation and transmission planning as a concurrent, iterative process under the IRP;
- conduct a dedicated study on large-scale VRE development, integration, and transmission to clarify regional development pathways, identify operational risks, and propose comprehensive solutions in advance.

(4) Enhancing Efforts on Energy Storage Study and Application.

Considering the uncertainties in generation and grid development, such as accelerated VRE deployment, delayed gas and nuclear power deployment, and delayed transmission expansion, the energy storage technologies could provide more controllable and predictable solutions to enhance system flexibility. While the IRP currently includes battery storage and pumped hydro, advancements in technology and cost reductions are making other storage options—such as compressed air energy storage and molten salt thermal storage—more attractive. These energy storage technologies may address VRE integration challenges across different temporal (seconds to seasons) and spatial (local to inter-regional) dimensions, providing an alternative to mitigate risks associated with gas and nuclear power development uncertainties.

Considering the above factors, a dedicated study on energy storage development is suggested to be conducted, which aims to evaluate the full potential and value of different types of energy storage, optimize the combined deployment, and address cost-effectiveness and reliability challenges in large-scale VRE systems.

(5) Improving Grid Codes and Promoting Innovative Power Technologies for High VRE Penetration

To ensure security and stability of the power system under high VRE penetration, it is crucial to modernize the grid code framework and adopt advanced power technologies. Key recommendations include:

- developing comprehensive grid connection standards that not only regulates power flow, short circuit, voltage and frequency stability, but also address active power fluctuations, voltage and frequency adaptability, fault ride-through capability, and active-reactive power control of renewable energy sources etc.
- conducting in-depth studies on advanced power technologies to mitigate challenges posed by the large-scale VRE integration, including fluctuation and intermittency of VRE generation, low inertia, and reduced short-circuit capacity associated with IBRs.

A robust grid code defines clear responsibilities between generation and grid assets and is essential for maintaining power system security as traditional baseload generators are displaced. Research and demonstration of innovative solutions—such as multi-energy complementary baseload sources, grid-forming inverters, and advanced transmission technologies—should also be encouraged to support the seamless integration of VRE.

III. SUMMARY

The results from the IRP modeling demonstrate a promising energy future, where VRE such as solar and wind are making great progress to support green transition. The emphasis on peaking capacity and flexibility, including the use of gas power and storage, ensures the system can respond to the VRE fluctuation. Additionally, the incorporation of gas and nuclear are addressing challenges related to coal power phasing-down. By integrating diverse energy sources and technologies, the IRP creates a pathway that supports both the reliability of the system and the country’s long-term sustainability goals.

Based on the models provided by the IRP technical team, EPPEI conducted an independent two-stage analysis to provide additional technical insights for the IRP's proposed Balanced Scenario. The results highlight a significant green transition in South Africa’s power system over the long term with the increasing penetration of VRE, alongside the gas, nuclear, coal and storage as firm power capacity and flexibility which play key supporting role. By 2035, VRE’s share in power generation is expected to increase from 8% to 30%, but projected curtailment could reach 30% due to transmission congestion. Furthermore, decreasing firm capacity and sharper net load ramps raise requirements for system adequacy and flexibility. In addition, rising instantaneous VRE shares (over 60% by 2035) are expected to introduce risks to system frequency, voltage and dynamic stability, requiring close operational attention and proactive mitigation measures. These findings underscore the need for systematic planning, along with advancements in generation, grid, and storage technologies and standards to ensure the success of high VRE penetration transition.

PART C: ACTIONABLE SUGGESTIONS & INSIGHTS

I. ACTIONABLE SUGGESTIONS FOR NEXT STEPS

IRP 2024 reflects South Africa's strong commitment to a secure and sustainable energy future, underpinned by an ambitious transition toward high shares of renewable energy. This pathway not only safeguards long-term power supply security but also reinforces the country's decarbonization agenda in alignment with global climate goals.

To realize a resilient and low-carbon power system with high VRE penetration, additional efforts will be essential—including the adoption of pragmatic implementation measures, the development of robust and enabling policy frameworks, and the undertaking of comprehensive technical studies to support long-term system sustainability and operational reliability.

1. Key Technical and Policy Recommendations

- **Strengthen coordination between generation and transmission planning:** Transmission constraints significantly affect the deliverability of new generation, especially for VRE located far from load centers. It is essential that transmission planning is closely coordinated with generation planning to avoid bottlenecks and ensure grid readiness. To this end, we recommend strengthening SANEDI's role as the lead institution for integrated power system planning. This will facilitate better alignment of development strategies across planning cycles and enhance overall planning efficiency. A closed-loop planning framework, linking long-term modelling, technical validation, and implementation monitoring, should also be established to ensure better planning coordination and support broader infrastructure strategies.
- **Enhance coal-fired power flexibility and reliability:** Despite the declining long-term role of coal, the existing coal fleet remains critical for ensuring system dispatchability and stability. Selective retrofitting of coal units is recommended to improve ramping capabilities, enhance start/stop flexibility, and meet environmental standards. Partially retired units may be repurposed as strategic reserve, converted into synchronous condensers, or hybridized with long-duration storage technologies (e.g., Carnot batteries), to retain system support capabilities during emergencies. Furthermore, considering that achieving the assumed EAF levels is critical for maintaining energy security in South Africa, the IRP should incorporate

EAF as a binding reliability target to ensure alignment between planning targets and operational reliability.

- **Optimize gas-fired power development:** Given South Africa's limited domestic gas supply and infrastructure, the development of gas generation should be carefully optimized. More efficient CCGT plants are recommended to be prioritized over OCGTs. Hybrid configurations (e.g., CCGT + BESS) can replicate the fast-ramping capability of OCGTs while improving efficiency and lowering operating cost. Besides, innovative baseload solutions (e.g., VRE + storage + CCGT) could be explored to enhance system stability and mitigate gas supply risks.
- **Facilitate VRE deployment, integration and transmission:** The scale of planned VRE development requires a stronger system-level coordination, supported by advanced technology upgrade and enabling investment environment. International collaboration can play a key role by offering competitive financing and innovative technologies. South Africa could also explore integrated development models—such as co-locating VRE with thermal plants (e.g., on brownfield sites), or building large-scale clean energy bases with dedicated transmission corridors from resource-rich zones to load centers. These approaches can enhance system efficiency and reliability while leveraging economies of scale to reduce overall costs. In addition, showcasing advanced power technologies, equipment, standards, and codes will also play a critical role in accelerating the large-scale development and deployment of VRE.
- **Diversify energy storage portfolios:** Realizing the full value of energy storage requires targeted policy support that ensures investor returns while promoting operational effectiveness. Storage assets should be compensated for services such as frequency regulation, reserve provision, and load shifting. A diversified storage portfolio—spanning various technologies, durations, and locations—will be essential to enhance system resilience, support VRE integration, and improve overall system flexibility.
- **Promote regional integration:** South Africa acts as a regional energy hub which contributes to broader energy security and integration across the Southern African Development Community. This can be strengthened by supporting development from hydro options in the region and investment on cross-border interconnections, to enhance energy security, diversity and advance the transition.

- **Advance power market reform:** Continued power market reform is essential to support South Africa's energy transition. The long-term goal should be to build a more competitive, transparent, and flexible market framework. Dynamic pricing mechanisms that reflect real-time system conditions and facilitate greater participation are critical to effectively integrate high shares of VRE and attract broader participation.

2. Proposed Supporting Studies

- **IRP Transmission and System Stability Studies (IRP Phase 2 and 3).** The transition from dispatchable generation to high-penetration VRE poses major challenges for power system stability and operability. While IRP Phase 1 addresses generation adequacy, it is limited in evaluating system stability under high VRE penetration. Phase 2 and 3 are designed to bridge this gap: Phase 2 identifies grid constraints, which need to feed back into generation planning in Phase 1; Phase 3 assesses the stability and operability of the proposed generation-transmission mix and offers mitigation strategies. Advancing the development of Phases 2 & 3, and enhancing iteration and coordination across all phases, is critical to ensuring a secure, balanced, and implementable energy transition.
- **Coal Plants Power Retrofitting and Functional Transition Study.** For technically sound coal-fired units, pilot projects could be initiated to test flexibility retrofitting measures (e.g., ramping, cycling, minimum load reduction) alongside emissions improvements. Moreover, decommissioned units may be converted into strategic emergency power reserves, serving as backup during extreme weather events, grid outages, or gas supply disruptions—thus maintaining system controllability. All retrofitting and transition strategies should meet a binding constraint on the targeted EAF.
- **Gas-fired Generation Dedicated Study.** Gas-fired power offers low-carbon, flexible capacity and is a strategic bridge in South Africa's energy transition. However, development is constrained by limited domestic gas supply and underdeveloped infrastructure. A comprehensive technical and economic assessment is needed to evaluate the future role of gas, considering fuel price volatility, currency fluctuation, technology choices (OCGT vs. CCGT), spatial deployment, and compatibility with VRE integration and coal retirements. This study would be helpful to guide gas power investment planning and system integration strategies.

- **VRE Development, Integration and Transmission Study.** With South Africa's growing reliance on VRE, the power system faces rising challenges in flexibility and stability. VRE's variability and the use of inverter-based technologies weaken the system's dynamic response, while the spatial mismatch between resource locations and load centers calls for targeted transmission expansion. Accordingly, dedicated studies are needed to assess system flexibility requirements, advanced integration technologies, and optimized transmission corridors. In addition, assessing the cost-effectiveness of VRE integration and the design of green electricity and certificate mechanisms is essential to unlock investment and promote market-based development. To navigate these complexities and support the development of renewables, conducting systematic VRE study is essential to develop reasonable and feasible strategies.
- **Cross-Technology Energy Storage Portfolio Study.** Given uncertainties in gas and nuclear development and the rise of VRE, modular and scalable storage solutions are increasingly critical. A cross-technology portfolio study is recommended to develop a roadmap for energy storage in South Africa, including timelines, deployment scales, technology pathways, pilot demonstrations, etc. This would help reduce reliance on conventional generation, improve flexibility and strengthen investor confidence.
- **Multi-Energy Complementary Baseload Power Source Study.** VRE sources are inherently intermittent and have much lower capacity credit compared to traditional baseload sources. While gas and nuclear are taken as transitional baseload options, their development both face considerable uncertainties in South Africa. Given the country's exceptional wind and solar resources, an alternative pathway lies in developing a new form of baseload power through multi-energy complementarity mode, i.e., combining wind and solar as primary sources, firmed by diverse storage systems and supplemented by limited gas capacity for extreme scenarios. Such a study could offer a viable solution beyond coal life extension to hedge against delays or risks in gas and nuclear development.
- **Cross-Border Power Interconnection Study.** Neighboring countries offer significant untapped hydropower potential. Enhancing cross-border interconnections via SAPP could reduce South Africa's dependence on coal and diversify its power mix. A prerequisite is to first secure domestic generation adequacy. Once met, importing hydropower could serve as a low-carbon, dispatchable resource. A study on assessing technical,

economic, and institutional pathways for expanding regional integration is helpful to enhance South Africa's leadership in continental energy cooperation.

- **Exploring the application of Artificial Intelligence in IRP Modeling and Analysis.** AI can play a transformative role across the IRP process. In data handling, AI can automate cleaning, identify anomalies, and detect trends across vast, diverse datasets. During modeling, AI algorithms can assist with parameter tuning, sensitivity analysis, and scenario optimization, reducing manual effort and improving model robustness. Post modeling, AI tools can be used to efficiently extract large volumes of results, helping to reduce inaccuracies and human error.

  In long-term, AI-based forecasting and adaptive learning can enhance planning agility and enable more dynamic, real-time decision-making. Embedding AI into the IRP framework could significantly improve the responsiveness, precision, and transparency of power system planning—particularly given increasing data complexity and renewable variability.

II. INSIGHTS FROM CHINA'S EXPERIENCES

1. South Africa's Effective Actions

Since the release of the IRP 2019, South Africa has implemented a series of measures to promote the development of its power sector, including but not limited to:

- establishing the Presidential Climate Commission (PCC),
- implementing the Energy Action Plan (EAP) aimed at reducing emissions and ensuring energy security,
- repairing coal units' availability,
- lifting licensing restrictions on distributed generation,
- addressing ESKOM's debt crisis,
- procuring additional generation capacity through the IPPPP.

We highly commend South Africa's efforts aiming to reduce load shedding and ensure energy security. Recently, the performance of several key coal power plants has improved significantly, with a noticeable reduction in unplanned outages and a rebound trend in the EAF. At the same time, South Africa continues to demonstrate strong commitment to harnessing its abundant wind and solar resources, with publishing a series of practical measures to accelerate VRE development, such as increased investment in generation capacity and streamlined project approval processes. Additionally, the Balanced Scenario outlined in IRP 2024 promotes large-scale deployment of wind and solar, reflecting a well-aligned strategy for advancing a just and sustainable energy transition.

2. China's Experiences

South Africa's energy landscape—characterized by abundant coal, limited oil and gas resources, a high share of coal-fired power, and accelerating growth of renewables—closely mirrors China's past and ongoing power sector transition. In pursuit of its climate goals to peak carbon emissions by 2030 and achieve carbon neutrality by 2060, China is rapidly scaling up wind and solar deployment. While advancing a green and sustainable energy system, China remains firmly committed to ensuring power system security, reliability and affordability. This has led to the strategic development of “new-type power system”, a transformative framework guiding China’s power system transition.

In 2023, entrusted by the Chinese central government, EPPEI has prepared a National Bluebook on New-type Power System Development, developing a roadmap for transitioning to a new-type power system that integrates large-scale VRE, and laying out a staged implementation plan through 2060. Based on these experiences, EPPEI offers several insights that may benefit to South Africa’s power system transition:

- **Strengthening VRE planning and utilization framework.** Prioritize the planning and development of a well-structured VRE supply and consumption system. This can involve integrating centralized and distributed VRE sources with advanced, high-efficiency thermal power as backup, supported by a robust and flexible transmission network. To ensure effective implementation of the planning, continuous monitoring and early warning mechanisms for key VRE development and consumption indicators (such as installed capacity, production generation, and curtailment rates) can be established. This approach would enable adaptive adjustments and a closed-loop management system for the implementation of the planning.
- **Developing a modernized dispatching and operation system.** Enhancing forecasting accuracy for VRE generation and overall system power output is essential for maintaining grid stability. Establishing a digital and smart dispatching and operation support system can help improve real-time power prediction, grid management and operational efficiency. Strengthening coordinated operations among wind, solar, hydro, thermal, nuclear and storage resources across different regions can further enhance system flexibility, while also facilitating the rapid expansion of distributed intelligent grids.
- **Establishing innovating standards and regulatory frameworks for the power system.** A holistic system of power system standards can support the transition toward a power system with high penetration of VRE. This includes establishing comprehensive standards across generation, transmission, distribution, consumption, and storage. Regulatory frameworks can be adapted to address power system security, market operations, and emerging technologies, ensuring the coordinated development of all sectors within the power industry.

- **Accelerating technological innovation and deployment of key equipment.** Advancing innovation across generation, grid infrastructure, consumption, and storage can enhance power system resilience and efficiency. Promoting large-scale deployment of key technologies—including clean and efficient generation, advanced flexible transmission and distribution, system stability solutions, and emerging storage and hydrogen technologies—can support a secure and reliable energy transition.
- **Enhancing policy and market mechanisms to support reform.** Expanding electricity market reforms with finer time granularity and diversified trading mechanisms can improve market efficiency and resource allocation. A balanced approach combining regulated oversight with market liberalization can enhance efficiency and competition in the power sector. Introducing more competitive elements while maintaining essential regulatory functions will help optimize resource allocation, encourage investment, and improve overall system performance.
- **Demonstrating flagship projects to drive large-scale implementation.** Leading large-scale demonstration projects can play a pivotal role in validating innovative technologies, market mechanisms, and operational strategies. These projects serve as benchmarks for broader adoption, mitigating risks associated with new approaches and expediting South Africa's transition toward a more sustainable and resilient power system.

EPPEI BRIEF INTRODUCTION

China Electric Power Planning & Engineering Institute (EPPEI) is a national-level high-end consulting institution with over 70 years of proven track record. EPPEI assists government authorities to navigate the clean energy transition by translating long-term energy targets into actionable plans. EPPEI also creates values for its industry partners by innovating technical solutions and formulating forward-looking strategies.

EPPEI has a knowledge-intensive consulting team and provides services to government departments, financial institutions, and energy & power enterprises on development strategy, power system modelling & planning study, flagship engineering projects consulting, etc. EPPEI has approximately 500 professional analysts and engineers with expertise ranging from conventional energy to renewable energy, including more than 190 Ph.D.-level experts and 240 Master-Level experts. Years of hands-on experience navigating planning studies and actual projects allow us to assist authorities in translating high-level targets into feasible actions.

EPPEI supports Chinese central government on research for the National Five-Year-Plan on Energy and Power Development. We effectively address the rapid growth and geographically imbalanced distribution of VRE and power demand, enhance VRE development and integration, and ensure safety and stability of national power grid. Entrusted by Chinese government, EPPEI has conducted a series of national-level planning studies including but not limited to:

- 13th, 14th Five-Year Plan for National Energy Development
- 13th, 14th Five-Year Plan for National Power Development
- National Energy Technology Innovation Development Plan
- Smart Grid Development and Planning
- Monitoring and Evaluating System for VRE Consumption and Utilization in National, Provincial and Local level

EPPEI helps enterprises and financial institutions to keep track of new opportunities in the evolving energy landscape. With a strong engineering background and a high-caliber expert team, EPPEI has presided over the engineering and implementation of many flagship projects in China, including but not limited to:

- Multi-gigawatt Hybrid Renewable Energy Bases Planning in China
- National Grid Interconnection Planning Research
- West-to-East power transmission corridors
- Planning and consulting for almost all UHVDC/UHVAC projects in China

EPPEI has also been entrusted by governments and grid operators in many countries to conduct Oversea Power System Planning & Modelling Studies. Using internationally recognized simulation methodologies and tools, EPPEI assists these governments in formulating tailored power system development roadmaps, and provides forward-looking solutions to address challenges related to the renewability, affordability & sustainability of their power systems. Our main overseas planning and modeling study including but not limited to:

- Power System Development Planning Study, entrusted by Ministry of Energy, Uzbekistan
- Clean Energy Development & Transmission Planning Study, entrusted by Ministry of Energy and Mine, LAOs
- Multi-Energy Complementarity Solutions Study, entrusted by Ministry of Mines and Energy, Cambodia
- The Grid Analysis of Azerbaijan Transmission Network, entrusted by Ministry of Energy, Azerbaijan
- Power System Planning Study Collaboration, entrusted by PLN, National Power Corporation of Indonesia
- System Impact Study of Renewable Energy, entrusted by NGCP, National Grid Corporation of Philippines
- Power Grid Optimization & Energy Application Study, entrusted by State Grid Brazil Holding

EPPEI is equipped with a comprehensive suite of power system modeling software (PLEXOS, PSS/E, PSCAD/EMTDC, DIgSILENT/PowerFactory, Dymola, etc.), enabling us to develop high-fidelity models that fully capture the long-, mid-, and short-term dynamics of modern grids with high penetration of IBRs. This model-based approach provides both accuracy and confidence for system operators, planners, and project developers.

Our extensive power system modeling capabilities have been utilized and validated across numerous planning studies and flagship projects in China and abroad. With extensive expertise and rich experience on energy and power sector, EPPEI is committed to continually supporting the successful implementation of South Africa's long-term energy targets.

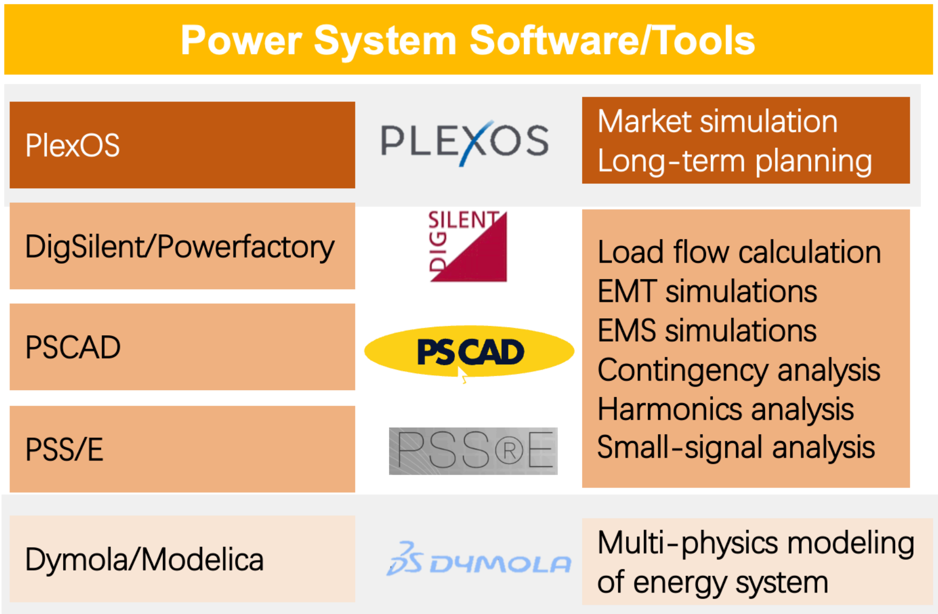

Figure 27. Power system modeling and simulation tools equipped by EPPEI

ANNEXURES I: DATA, MODEL & DOCUMENT USED FOR REVIEW

The input received by EPPEI to conduct IRP technical review includes raw data, PLEXOS model, and IRP Document.

TABLE AI-1. Data, model and report files provided by IRP technical team

Category	File name
Raw data	Eskom Fleet Continued Operation.pptx
	Eskom Gx shutdown plan.xlsx
	Emission retrofits for ISEP full compliance_Sep24_v0 ... .xlsx
	Heat Rates.xlsx
	Eskom Gx Data_Peer Review.xlsx
	Supply_Side Cost and Performance Data for Eskom Integrated Resource Planning_ 2023_2024 Update.pdf
	Fixed+Operations Costs.xlsx
	New Technologies (MS Excel & PDF)
	Eskom Gx Data_Peer Review.xlsx
	Ancillary Services Technical Requirements 2024-2028 rev 1.pdf
PLEXOS model	LT model: IRP 2024_Nov2024.xml & Input folder (containing 31 csv files)
	Multi-node MT-ST model: IRP 2024 MT-ST Model_Nov2024.xml & Input folder (containing 37 csv files)
Report	A copy of IRP report

1. Raw Data

The raw data contains 10 data files, for each a brief Introduction was provided from IRP technical team as follows:

- Supply_Side Cost and Performance

This report is specifically prepared for South Africa and provides detailed information on generic technology costs and performance characteristics. IRP technical team has used this report for coal, gas (turbines and engines), wind solar PV, CSP and storage options (BESS and hydro pumped storage). Nuclear costs were provided by the Nuclear Branch of the Department of Minerals and Energy in South Africa.

- Ancillary Services Technical Requirements

This is a five-year view of different categories of reserve requirements. In the LT model, a total for operational reserves is used. It is increased in proportion with growth of the peak demand.

- Emission Retrofits for ISEP Full Compliance

This file provides additional outages for the delayed shutdown scenario. Delayed shutdown refers to operation of coal fired station beyond their 50-year life of plant by an additional ten years.

- Eskom Fleet Continued Operation/ Eskom Gx shutdown plan

These contain identical information except that Eskom Fleet Continued Operation refers to coal fired station and Koeberg nuclear plant. They provide specific dates on when the individual units of the different stations are expected to be shut down in line with 50-years life of plant.

- Eskom Gx Data_Peer Review

This file contains existing coal fired station capacities, performance related data (planned, unplanned and other outages), ramp rates, thermal efficiencies and different buckets of operation and maintenance costs.

- Fixed+Operations Costs

This file is based on the data in file number 5 above and provides calculations of these costs in PLEXOS format.

- Gx_Fleet_50_&_60 year_Total Capex

This file provides additional costs to for the 60-year life of plant used in the Delayed Shut Down scenario

- Heat Rates

This provides calculations of heat rates base on thermal efficiencies information provided in file number 5 above.

- New Technologies

This provides calculations of new technology cost S-curves and other calculations based on quoted sources of information, economic parameters from appropriate countries used in escalation of costs to relevant years.

2. Model

The PLEXOS LT model consist one .xml model file and 31 csv input data files, and the MT-ST model consist one .xml model file and 37 csv input data files. The input data mainly includes:

- Demand forecast data
- Existing, committed and future power generation project capacity
- Plant performance parameters of coal-fired stations
- Fuel contract price and quantity
- Power production profiles of wind, solar PV and CSP generation
- Newbuild, maintenance and operation cost of power sources and BESS

3. IRP Document

The IRP document received by EPPEI is a copy document for undergoing South Africa internal process. The document illustrates:

- IRP context, review methodology
- Input assumptions
- Analysis of scenarios and modelling results
- Summary of the analysis
- Overall observations
- Proposed interventions
- Three Annexures on power system flexibility, power system grid planning, and power system operations appraisal

ANNEXURES II: INPUT REVIEW COMMENTS & RESPONSES

1. Raw Data

TABLE AII-1. Raw Data Summary for Shutdown plan of power units

Category	Summary and Comment
Files	File 1: Eskom Fleet Continued Operation.pptx File 2: Eskom Gx shutdown plan.xlsx File 3: Emission retrofits for ISEP full compliance_Sep24_v0 ... .xlsx
Representation in the PLEXOS model	Property -- Units, Data form.
Comments from EPPEI	The plants Sere, Port Rex, and Acacia are not included in the PLEXOS model. There are minor discrepancies between the files and the PLEXOS model for the plants Ankerlig, Vanderkloof, and Kendal. The delayed shutdown dates in File 3 do not match those in the PLEXOS model.
Response from IRP technical team	Sere is a wind generator and is included in the main transmission substation (MTS) where it is connected in the model. Port Rex and Acacia are fuel oil fired OCGT and do not generate capacity and energy for the system. They provide grid support services and black start capability. There are typically several iterations of the file submitted by Eskom generation thus minor discrepancies in dates occur. However, variations are usually a number of days at most a month. The date as modelled remain consistent across scenarios and between LT and MT/ST models.

TABLE AII-2. Raw Data Summary for Heat Rates

Category	Summary and Comment
Files	File 1: Heat Rates.xlsx File 2: Eskom Gx Data Peer Review.xlsx
Representation in the PLEXOS model	property -- Heat Rate Base, Heat Rate Incr.
Comments from EPPEI	For some plants, the fuel price properties are not set up, which results in the heat rate being ineffective in the model calculations.
Response from IRP technical team	Consideration for heat rate curve increases run times in the LT and thus was modelled as 'Simplest' in PLEXOS. A 'Detailed' heat rate modeling is done in ST/MT.

TABLE AII-3. Raw Data Summary for Costs

Category	Summary and Comment
Files	File 1: Supply_Side Cost and Performance Data for Eskom Integrated Resource Planning_ 2023_2024 Update.pdf File 2: Fixed+Operations Costs.xlsx File 3: New Technologies.xlsx.
Representation in the PLEXOS model	Property -- Build cost, VO&M Charge, FO&M Charge
Comments from EPPEI	The VO&M and FO&M costs in File 2 are different from the costs in the PLEXOS model. Some of the VO&M and FO&M costs are set only from 2022 to 2031.
Response from IRP technical team	Eskom generation provides a 10-year view for generator costs and PLEXOS perpetuates the last year's costs. The costs provided are in Rand billion, these were converted to per R/kW and R/MWh. This is what has been reflected in the model.

TABLE AII-4. Raw Data Summary for Other parameters of the ESKOM units

Category	Summary and Comment
Files	File 1: Eskom Gx Data_Peer Review.xlsx File 2: Ancillary Services Technical Requirements 2024-2028 rev 1.pdf
Representation in the PLEXOS model	Property -- Max Capacity, Forced Outage Rate, Maintenance Rate, Max Ramp Up, Max Ramp Down, Min Provision (Reserve).
Comments from EPPEI	The capacity in File 1 does not match the capacity in the model. The properties of Forced Outage Rate, Maintenance Rate, Max Ramp Up, and Max Ramp Down could not be found the data in File 1. The reserve requirement in File 2 is not consistent with that in the model.
Response from IRP technical team	Different units in the same stations sometimes have different capacities, and these are then averaged as 'Max capacities'. Do note that the averages reported by PLEXOS may differ particularly where there is decommissioning depending on the month of decommissioning. Also note that different submissions from Eskom Generation may have different values for the same stations as seen in the 'Capacity sheet' versus 'Fleet parameters'. Forced outages combine UCLF and OCLF and the data is in the sheet. Maintenance is referred to as PCLF in the sheet.

2. Model

TABLE AII-5. Communications between EPPEI and IRP technical team on the model review

	Clarification and Suggestion on the PLEXOS Model by the EPPEI	Comments and responses from the IRP technical team
1	The economic life of new BESSs is set as 20 years (for lithium batteries	The BESS costs and performance characteristics have been adjusted for

	the average physical life is typically around 10 years).	20-year life with augmentation reflected in the overnight costs
2	The models for the BESS in the categories of Eskom BESS 1~2, Battery Storage, ESIPPPP 1~3 is simplified (only Units, Capacity, and Max Power are defined), which may lead to an overestimation of their flexibility. It is suggested to be modeled similarly to the BESS in the New BESS category.	The over simplification has been noted in the LT. The ST model does consider the limitation on the BESS system in terms of availability and efficiency.
3	Unlike other CSP plants, the variables are not set for the REDSTONE_RBP3.5. What's the consideration?	This CSP plant has had several delays during construction and was thus excluded by mistake in the LT model. However, the ST model does include this capacity. The impact on the outcomes of the LT plan would be very minimally impacted
4	What is the meaning and function of the plants in the Risk Mitigation category.	This is capacity that was specified by the System Operator for specific operation of between 5h30 am and 21h00 pm. The consideration of the different technologies that form hybrid capacity contracted are not explicitly modelled. This could be considered in the future as details these combinations become available.
5	Fuel price properties are not set for Gas plant Ankerlig and Gourikwa. But for Avon and Dedisa, fuel prices are set. What's the consideration?	For Ankerlig and Gourikwa the fuel price is specified in the VOM as is the consideration for other Eskom plant. Avon and Dedisa are IPPS that have a minimum capacity factor of 1% per semester for fuel cycling.
6	No capacity expansion property is set in the new gas plant Gas	This is just a place holder as the port in this location is no longer considered for

	CCGT_Durban. It will not be optimized in the model and result.	LNG import. This option will be deleted in future iterations.
7	The plants GOODH_RBP6 and NGONY_RBP6 do not have "units" property set. They will not be represented in the model and result.	These plants had won preferred bidder status and failed to reach financial close. They are thus not part of the committed options. They may however have been considered as part of the private projects in different names.
8	Based on the properties set in the model, it seems that Tubatse is modeled as a battery, but it belongs to the pumped storage category. What's the consideration?	PLEXOS is unable to optimize the storage capacity of a pumped storage scheme in the optimization. It is thus modelled as battery option due to similar characteristics. As storage capacity for existing pumped storage is known (number of hours), the flaw in the PLEXOS does impact it.
9	The plant Acacia_PV only has variables set, but no properties are defined for the generator. It will not be represented in the model and result.	The only 'Acacia' in the model is the Rooftop PV_Acacia. This has been considered in the model and appears in the results.
10	For the profile settings of PP Pierterboth_PV, PP Rabbit_PV, PP Camden_Wind, and others, they are currently only set to the 'Temp Out' scenario. This might lead to an increased capacity factor for these accounts in other scenarios.	There were no profiles for these three options at the time has no files associated with them. The intention was to exclude them. However, inadvertently the three options accounting just over 200 MW are seen to have 100% availability. This is an error. The impact of this to the outcomes of the study must be quantified. It our view that it will be negligible on the basis that although 100% available they do not generate at 100% all the time for all the years in the study period.