CIGRE 2025 International Symposium
Palais des Congrès de Montréal, Québec, Canada
September 29 to October 3, 2025

10820
C5 ELECTRICITY MARKETS & REGULATIONS
PS1 System Enhancement, Markets and Regulation

Optimising South Africa's Power Grid: An Analysis of Demand Response and BESS Integration

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SUMMARY

South Africa's energy landscape is currently strained due to an aging power generation fleet and financial constraints, leading to frequent load shedding. This study explores how integrating Demand Response (DR) and Battery Energy Storage Systems (BESS) can enhance grid resilience and economic efficiency. Using the PLEXOS techno-economic tool, the research models South Africa's 2027 power system to determine the optimal use of BESS and assess the impact of varying levels of DR and BESS capacity.

The findings reveal that BESS revenue is maximized when 50% of its capacity is allocated to ancillary services and 50% to energy arbitrage, indicating a need for a balanced operational strategy. A flexible revenue-generating range exists between 30% and 65% allocation to ancillary services.

Three scenarios were modelled: Low, Moderate, and High penetration of DR and BESS. The results show that increasing DR and BESS integration significantly improves energy reliability. Specifically, it leads to an 80% reduction in unserved energy and its associated costs and a 42% decrease in the use of costly Open-Cycle Gas Turbines (OCGT). These findings underscore the tangible economic benefits and operational flexibility gained from strategic investments in DR and BESS, positioning them as key enablers for a resilient and cost-effective energy future for South Africa.

KEYWORDS

Demand response, Plexos modelling, flexibility services, energy markets, open cycle gas turbine, battery energy storage systems

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1 Introduction

The global energy landscape is undergoing a profound transformation, characterised by an increasing emphasis on sustainability, efficiency, and grid resilience. Within this dynamic context, DR has emerged as a pivotal strategy to balance energy supply and demand, reduce peak loads, and integrate renewable resources effectively. As the energy sector evolves, it is imperative to comprehensively understand the opportunities and barriers associated with the adoption of DR solutions for both domestic and non-domestic customers [1], [3].

The power utility in South Africa (SA), Eskom, has experienced demand-supply challenges on the electricity network, resulting in the implementation of unavoidable load shedding nationally. Reasons for the constrained network include an aging generation fleet and a lack of funds for maintenance and spares due to low tariffs, resulting in breakdowns of the generating units at power plants. This results in a declining energy availability factor, causing an increase in the frequency and severity of load shedding [3], [4].

This study explores the operational and economic role of BESS within South Africa's 2027 integrated power system under different levels of DR and BESS deployment. It evaluates the optimal allocation of BESS capacity between ancillary services and energy arbitrage to maximise revenue, starting with a baseline BESS capacity of 493 MW and minimal DR. A series of scenarios were developed by varying the proportion of BESS capacity allocated to reserves from 5% to 100% to identify the revenue-maximising reserve share. The analysis uses the PLEXOS techno-economic simulation tool to capture generation dynamics, storage behaviour, and DR participation. DR modelling includes residential, commercial, industrial, mining, and agricultural loads, enabling a comprehensive assessment of BESS contributions under evolving grid conditions.

The results provide a BESS dispatch strategy that enhances economic value, reduces energy curtailment, and maintains grid reliability. The analysis highlights that higher DR levels influence both the economic contribution and operational prioritisation of BESS within the power system. The analysis of total revenue shows that BESS revenue is maximised when 50% of capacity is allocated to ancillary services, with diminishing returns observed beyond this point. Revenue remains relatively stable between 30% and 65%, indicating operational flexibility within this range.

2 Demand response potential in the South African electricity market

Major cities in South Africa are increasingly adopting DR initiatives to manage electricity consumption better, reduce peak demand, and alleviate grid congestion-related power cuts. Demand response initiatives have been effective in enhancing overall energy efficiency. Additionally, these programs have been effective in the integration of renewable energy sources. However, there are still some challenges to overcome to support DR initiatives. Such challenges include the development of infrastructure requirements for implementing these initiatives [10].

Eskom is providing the complement of energy for bilateral trades entered between new renewable energy (RE) producers and customers. This means that Eskom is providing power throughout the day to cover the difference between the customer's actual load and the actual power generated by the RE facilities associated with the bilateral contract. Eskom balances the system in real time using its own resources and does not charge market participants for the additional cost of managing imbalances. This includes municipalities and their own customers, to whom Eskom provides full supply contracts.

The current status quo of demand response from a South African perspective can be summarised as follows [4]:

- DR has the potential to provide substantial demand reductions, improve energy efficiency, and support the sustainable integration of renewable energy.
- Current DR programs are limited to energy-intensive users and should be expanded to include residential, commercial, and small to medium industrial sectors.
- Effective implementation of DR requires addressing economic factors, policy landscapes, and technical considerations.
- Different sectors (industrial, commercial, residential) exhibit unique energy consumption patterns and require tailored DR strategies.
- The draft Integrated Resource Plan (IRP) outlined additional capacity plans for solar PV, wind, etc. This plan must be augmented to include DR initiatives for a holistic approach in dealing with the current electricity challenges in SA.
- The demand is expected to grow at a faster rate than previously forecasted; thus, there is an increasing need for the implementation of DR within the SA context.
- Hot water demand load from geysers exceeds all residential appliances in middle- and high-income households. This presents an opportunity for SA to implement DR measures to make demand more flexible.
- In the industrial sector, the bulk of the energy consumed is in process heating. Thus, DR has the potential to be implemented in that space.
- Electricity distributors or metropolitan municipalities in South Africa have begun with the installation of smart meters, partnering with aggregators to test DR programs, raising awareness about DR, control of geysers remotely, partnerships with institutions of higher learning to develop innovative DR solutions, and incentivising DR. The City of Cape Town municipality has issued a Request-for-Proposal (RFP) for demand response aggregators, a move towards increasing the implementation of DR.

The South African electricity market is undergoing a just energy transition. The current status quo and dynamics are continuously changing to adapt to this energy transformation.

3 Demand response and BESS modelling using the PLEXOS tool

3.1 Methodology

This study investigates the operational and economic implications of BESS in the South African integrated power system under varying demand response levels and installed BESS capacities.

The study begins by assessing the most economic use case for BESS operation based on revenue generated from the combination of BESS for ancillary services and energy arbitrage. The assessment is based on the South African integrated power system for the year 2027, assuming minimal DR initiatives are introduced. The system includes a baseline BESS capacity of 493 MW. The financial benefit of BESS contribution to ancillary services is compared against the benefit of deploying BESS for energy arbitrage. We determine the optimal allocation of BESS capacity between ancillary services provision and energy arbitrage. This baseline model provides a reference for comparative evaluation under various DR and BESS utilization scenarios.

A series of reserve allocation scenarios are explored, these scenarios allocate between 5% and 100% of the total BESS capacity to reserves, in increments of 5%. Each scenario simulates how much of the BESS capacity is allocated to ancillary services, assuming the remaining capacity is reserved for energy arbitrage. The reserve allocations were calculated as

$$Reserve\ Capacity\ (MW) = Installed\ Capacity (MW) \text{ x Reserve Share}(\%) \quad (1)$$

These values are used to:

- Identify thresholds where reserving additional capacity yields diminishing marginal benefits
- Evaluate trade-offs between meeting power system reserve requirements and the economic opportunity of energy arbitrage
- Determine the optimal reserve allocation level for BESS under different operational strategies.

The power system is modelled using a techno-economic simulation tool (PLEXOS) that incorporates generation, load, storage dynamics, and DR to capture both operational and economic impacts. The ancillary services and energy arbitrage capabilities of BESS are explicitly modelled to capture trade-offs. The modelled DR load includes identified potential geyser loads for the residential, commercial, industrial and mining sectors in South Africa. Potential residential and agricultural pump loads are also included.

3.2 Use cases and Scenarios

Three scenarios are constructed to assess the impact of varying DR penetration and installed BESS for a combination of reserve provision and energy arbitrage:

- Scenario 1 (base case): Low DR penetration + low BESS
- Scenario 2: Moderate DR penetration + moderate BESS

- Scenario 3: High DR penetration + high BESS

To ensure consistency across scenarios, a fixed optimal allocation strategy is adopted, wherein 50% of the BESS capacity is dedicated to ancillary services and the remaining 50% to energy arbitrage. Accordingly, each scenario examines the effectiveness of this balanced utilization in optimizing overall system performance.

- Ancillary services: fast-response markets with high operational reliability requirements
- Energy arbitrage: buying low-cost electricity during off-peak hours and selling during high-price periods

The simulation identifies the optimal BESS dispatch strategy in each scenario to maximize system-wide economic value, minimize curtailment, and support grid reliability. The trade-off analysis reveals how increasing DR capabilities affect the economic value and preferred utilization mode of BESS.

3.3 Assumptions

3.3.1 Energy system mix across DR and BESS scenarios

This study assumes a fixed generation portfolio across the scenarios to assess the impact of varying DR and BESS integration on the existing energy resource mix. Figure 1 shows the assumed installed capacities across all scenarios.

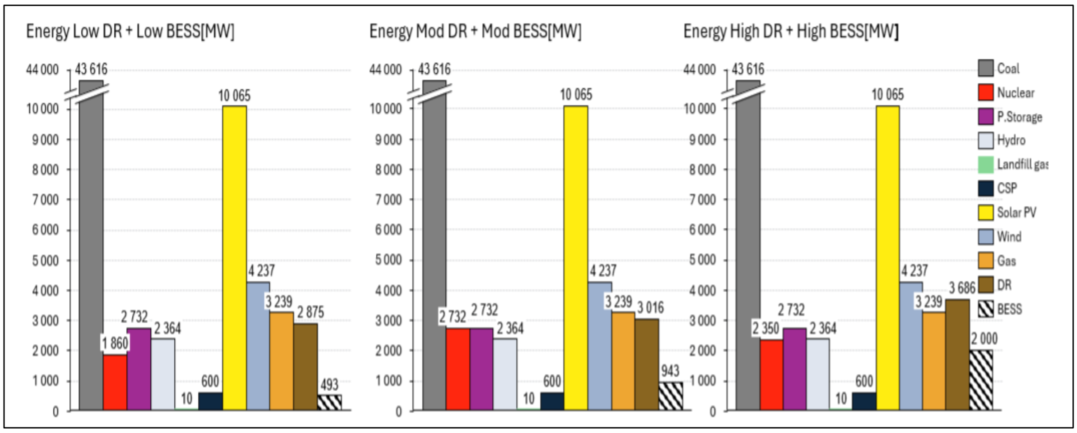

***Figure 1*: Installed Capacity per scenario**

3.3.2 Potential demand response

Figure 2 illustrates the average 24-hour load profiles assumed for each month from January to December 2019 across various end uses, including residential geysers, industrial geysers, residential pool pumps, commercial geysers, agricultural pumps, and mining geysers. These load shapes served as the foundational basis for constructing and evaluating the different DR scenarios analysed in the study [10].

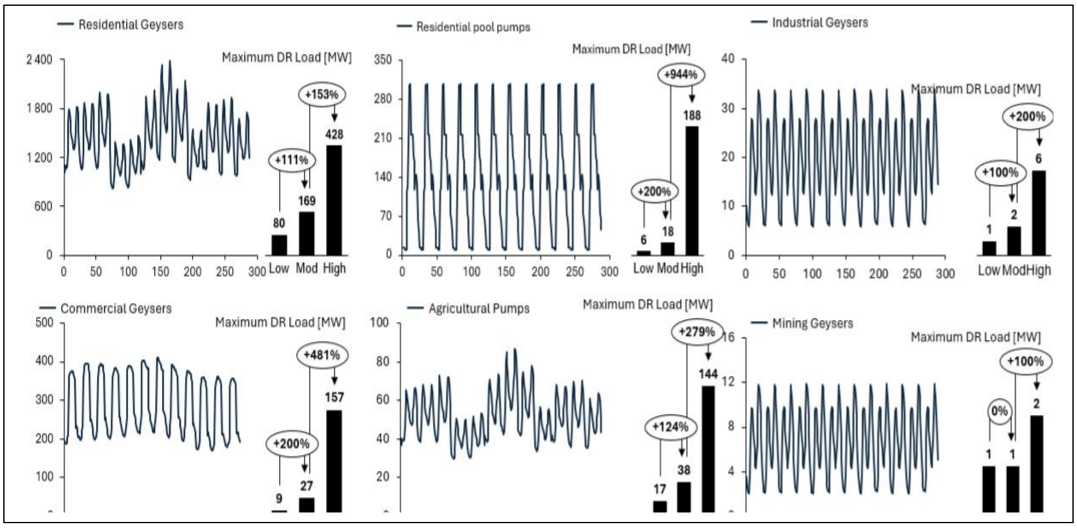

Figure 2: DR penetration scenarios per end-use and profiles

3.4 Results and Analysis

3.4.1 Analysis of total revenue vs ancillary services provision

Figure 3 illustrates the total revenue generated under varying levels of BESS allocation to ancillary services provision, ranging from 5% to 100%. The results show a non-linear relationship between ancillary services provision and total revenue, highlighting an optimal balance point at 50% provision. Revenue begins to gradually decline beyond the 50% allocation mark, indicating diminishing returns from prioritising ancillary services over arbitrage. Allocation at extreme ends suggests underutilisation of the dual revenue-generating potential of BESS. Between 30% and 65%, the revenue remains relatively stable and high, suggesting some flexibility in operation strategy while avoiding significant revenue loss.

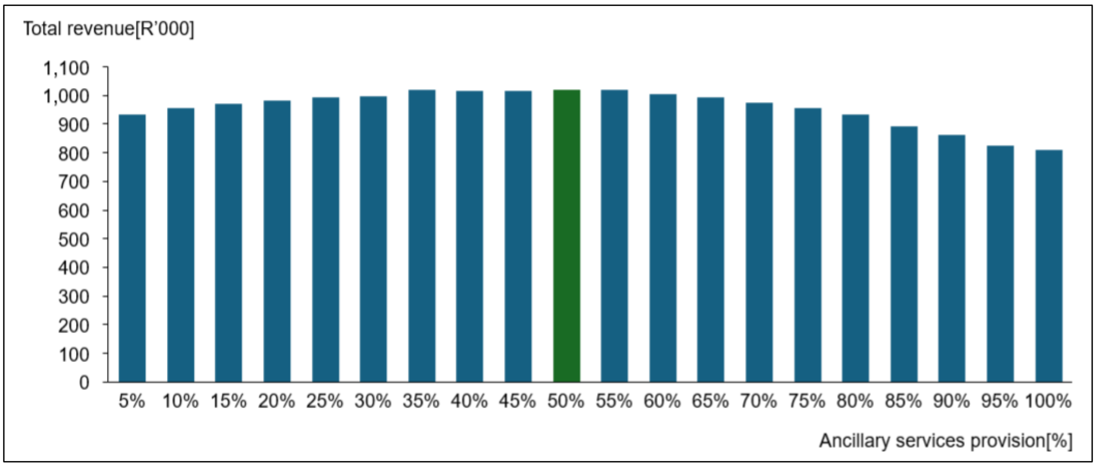

Figure 3: BESS total revenue (energy arbitrage + ancillary services)

3.4.2 OCGT Capacity Factors and Cost

Figure 4 presents the OCGT utilisation and associated cost. The capacity factor decreases by 41% from 1% to 0.6% due to increased penetration of BESS and DR. Similarly, the cost of utilising the OCGT reduces by 42%.

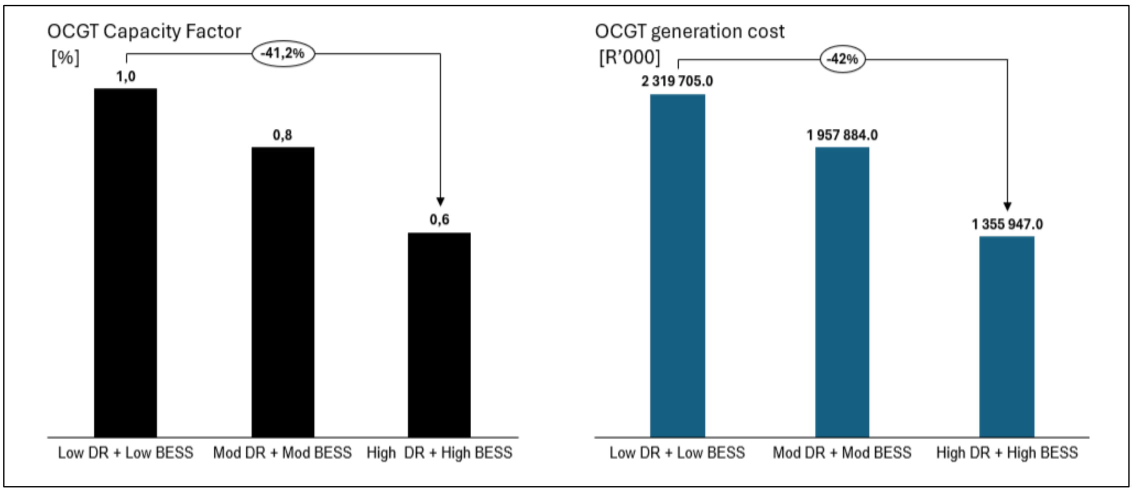

***Figure 4**: OCGT capacity factors and cost*

3.4.2 Unserved Energy Volumes and Cost

Figure 5 shows unserved energy volumes and the associated cost of unserved energy (COUE). Unserved energy volumes reduce by approximately 80% from 36 GWh to 7 GWh due to increased penetration of BESS and DR. Likewise, the cost of unserved energy reduces by approximately 80%.

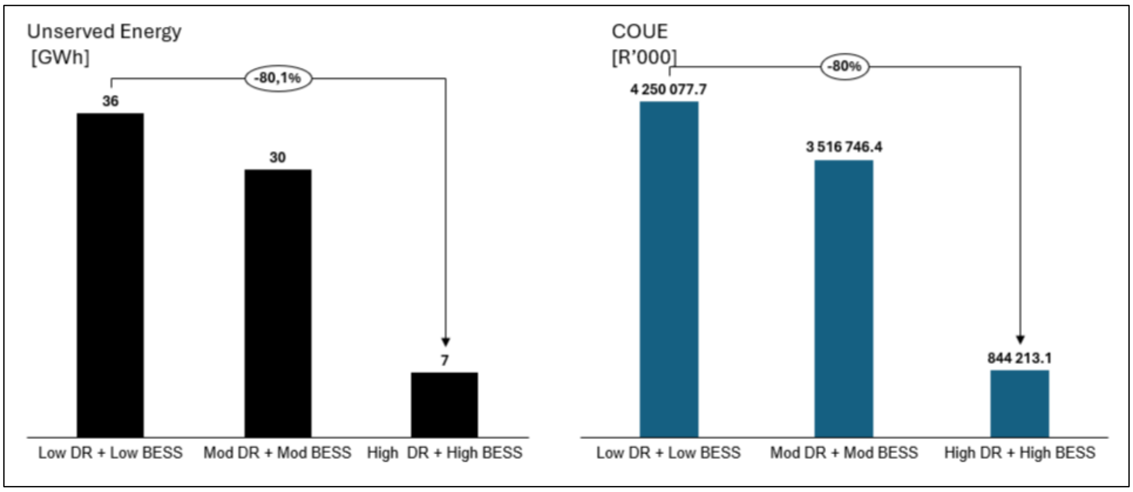

***Figure 5**: Unserved Energy and cost*

4 Conclusions

The integration of higher levels of DR and BESS leads to substantial improvements in energy reliability and system flexibility for the South African power system. This study found that total revenue is maximized when the 4-hour BESS capacity, which contributes to ancillary services (instantaneous, 10-minute, and regulation), is allocated 50% to these services and the remainder to energy arbitrage. The BESS model accounted for an 85% charging efficiency and technical constraints, such as a maximum of one cycle per day.

The DR considered was limited to controllable, load-shifting resources. When combined with scaled BESS integration, this approach offers tangible economic benefits. The results demonstrate a significant 80% reduction in unserved energy volumes and their associated costs and a 42% decrease in generation costs from OCGT. These findings support strategic investments in BESS and DR to lower system costs, reduce reliance on carbon-intensive peaking generation, and enhance South Africa's energy security and resilience.

5 Recommendations

Based on the detailed findings of the study, the following recommendations are proposed to enhance South Africa's energy security and economic efficiency:

It is recommended that policymakers and system planners prioritize strategic investments in both BESS and DR. For BESS, a balanced operational strategy is crucial to leveraging its dual revenue potential from ancillary services and energy arbitrage.

Concurrently, national DR programs should be expanded beyond their current limitation to energy-intensive users to include the residential, commercial, and industrial sectors. Efforts should target high-potential loads like hot water geysers and industrial process heating, using tailored strategies that account for each sector's unique energy consumption patterns. To facilitate this, the IRP must be augmented to include DR initiatives formally.

This combined investment is justified by the significant outcomes observed, including an 80% reduction in unserved energy and a 42% decrease in costly OCGT generation.

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