

Effect of Solar Pv Plants on the Dispatchability of Power in the ZESCO System

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Abstract: This paper examines the impact of integrating solar photovoltaic (PV) plants into Zambia's national grid, with a particular focus on dispatchability within the ZESCO grid. The energy crisis due to climate change has forced Zambia to diversify its energy mix, which is currently dominated by hydropower at 86%. Variability in dispatchability, due in part to the integration of solar PV, presents a challenge to energy systems. Using DIgSILENT Power Factory software, this study performs both steady-state and transient stability analyses to determine transmission adequacy, voltage-frequency stability, and reserve requirements under increased penetration levels of solar photovoltaic (PV) energy. In fact, the results show that integrating solar PV near load centers reduces transmission line loading from hydropower stations, line losses, and improves voltage profiles along the network. However, ZESCO currently faces a shortfall in operating reserve, requiring an additional 82 MW for system regulation. With proper planning, the integration of solar PV will provide economic benefits that outweigh the costs; hence, it makes Zambia's energy system more resilient and diversified.

Keywords: variable renewable energy; power plant dispatchability; generation costs; battery energy storage system (BESS), intermittent, solar photo voltaic, DigSilent Power factory.

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I. INTRODUCTION

A. Climate Change and Energy Security Challenges

Like many other countries in the world, Zambia is threatened by climate change, which is manifesting through increased temperatures and changing rainfall patterns that have led to droughts and floods much more frequent than before [1]. These directly impact the country's electricity generation system, which predominantly relies on hydropower. By 2024, hydropower was projected to account for 86% of Zambia's electricity generation capacity of 3,705 MW, with coal, heavy fuel oil, and solar contributing the remaining 14% [2]. This shows a significant overreliance on hydropower and has made the energy sector significantly vulnerable: it especially struggles during low rainfall periods when hydro reservoirs are at a very reduced level due to low river-flows necessary for energy production. The current flows in rivers and reservoir levels are thereby impacting power generation/supply like the previous low-generating rainfall season of 2014/2015.

B. Energy Mix Diversification Initiatives

In addition to these challenges, and in pursuit of energy security, Zambia is also diversifying its energy mix; the major thrust being renewable sources, particularly solar PV and wind [4]. Grid integration studies project the contribution of solar PV to the generation mix will increase to 1,678 MW by 2026 and 2,083 MW by 2030 [5]. Such an increase in VRES is not so easy but offers opportunities alongside challenges to the prevailing power system. The key focus here is on dispatchability; that is the capability to control and modify generation output based on fluctuations in demand [6].

C. Solar PV Integration Challenges

The variable power output from solar PV generation due to its intermittent nature is induced by factors like day-to-day solar patterns, weather conditions, and shading effects which impact grid reliability and stability [7]. This is a great challenge to traditional electricity networks that are set up based on the ideology of having dispatchable (controllable) rotational synchronous machines. The disparate response of the interconnected electric grid to solar PV variability raises concerns about the active and reactive power

reliability of the system, which subsequently affects the general dispatchability of the interconnected electricity grid [8].

This research attempts to assess the impact of solar PV generation on the power dispatchability within the ZESCO framework, focusing on challenges and opportunities linked with the incorporation of solar PV into current dispatching strategies [9]. Moreover, it will present potential technological solutions and electricity generation costs related to those solutions in an effort to enhance dispatchability under conditions of solar PV variability, thus contributing to the current literature in the field of engineering and providing useful insights for various stakeholders in Zambia's energy sector [10].

II. BACKGROUND

A. Solar Resource Potential in Zambia

Zambia has high solar potential, with an average solar insolation of about 5.5 kWh/m²/day and around 3,000 sunshine hours per year [11]. Theoretically, based on its area of 752,618 km², Zambia can obtain annually 1.51×10^{10} GWh of solar energy; however, the practically obtainable amount depends on many factors such as land availability, seasonal variation, sunlight exposure, weather conditions and also the type of solar panels used. Despite this enormous potential, penetration of solar energy technologies is still relatively low in the country's energy mix [12].

B. Current Electricity Sector Challenges

The Zambian electricity sector is very affected by the overreliance on hydropower, which makes it susceptible to the effects of climate change [13]. Reduced river flow in the major rivers translates into reduced capacity to produce hydropower, thus necessitating the search for alternative energy sources. ZESCO's grid integration studies with several other partners indicate an energy profile that would be inadequate to meet the expected demand from both domestic and export customers between 2023 and 2027. The projected deficits are expected to range between 38.2 MW in 2023 and grow to 298.5 MW in 2027 [14].

C. Solar PV Development Initiatives

Zambia has therefore embarked on several on-grid solar PV power projects with various cooperating partners to address these challenges. These include Scaling Solar, the Alternative Renewable Energy Investment Program (AREIP), and Global Energy Transfer Feed-in Tariffs (GET FiT) [15]. The Scaling Solar Program, through the International Finance Corporation (IFC), commissioned the first utility-scale grid-connected solar PV projects in 2019. These were the 54 MW Bangweulu and 34 MW Ngonye plants, respectively [16]. The GET FiT program, too, is anticipated to commission an additional capacity of approximately 220 MW of solar and small hydro by the end of 2024 [17].

D. Synergies and Complementarities

Solar PV plants reach peak generation around midday, which coincides with one of the two daily demand peaks on the Zambian system [18]. This complementary relationship can assist in dispatch by allowing a shift from hydropower generation or imports to using PV generation during the midday peak, thus reducing the consumption of hydropower reservoirs [19]. In addition, solar PV integration on the Zambian grid will minimize line losses because proposed plants are located close to major load centers. Further,

summer peak solar generation occurs when reservoir levels are usually low hence creating natural complementarity between solar and hydro generation [20].

E. Conventional Power System and PV Integration Challenges

However, integration of variable renewable energy sources such as solar PV into the traditional power systems is challenging [21]. Conventional power systems are based on the assumption that electricity generation involves dispatchable fully rotational synchronous generators; hence, the influence of intermittent solar PV power on active and reactive power reliability impacts overall dispatchability in any interconnected power grid [22]. This study thus seeks to assess these impacts and identify solutions to enable reliable power dispatch within Zambia's changing energy context [23].

III. PROPOSED WORK

A. Research Objectives and Scope

The main purpose of this study is to assess the effect that the non-dispatchable nature of solar PV generation has on power dispatch in the Zambian Interconnected Power System [24]. The proposed study comprises several major components aimed at fully addressing this research objective. First, it shall be reviewed and quantified how the integration of solar PV into existing dispatch strategies affects spinning reserve requirements and potential generation curtailment issues have been covered. Hence, this part will lay down a base toward understanding operational impacts due to increased penetration of solar PV within the ZESCO system.

B. Power Flow and Transmission Adequacy Assessment

Second, the study will focus on investigating the effect of Solar PV Plants on ZESCO's power dispatchability; this will be based on the transmission line power flow and transmission adequacy [1]. In carrying out this investigation, DigSILENT Power Factory software will model the Zambia National Grid. This allows for an elaborate simulation and analysis of the power system under various scenarios of solar PV integration [2]. The model will be designed to incorporate both existing as well as proposed solar PV plants so that a proper evaluation is done regarding their cumulative impact on the grid. For this purpose, simulations are carried out for steady-state as well as transient stability conditions to check how rather the grid behaves towards the intermittence characteristic of solar PV generation [3].

C. Technological Solutions and Economic Analysis

Third, the proposed study will identify potential technological solutions and associated electricity generation costs to enable favorable dispatch regimes [4]. This will include a Battery Energy Storage System BESS exploration aimed at reducing the variability and intermittency solar PV plants introduce [5]. It will discuss the role of BESS in enhancing grid stability, reliability, and efficiency while also permitting higher renewable energy source penetration. Besides these, it will conduct a cost-benefit analysis to determine whether incorporating solar PV into ZESCO's grid is economically justified based on factors like transmission losses savings, avoided import costs, and solar PV generation costs plus any additional reserve requirements [6].

D. Methodology and Data Collection

The proposed work shall be implemented through a rigorous methodology comprising theoretical analysis of power systems, modeling and simulation with suitable software tools, field visits to operational and planned solar PV installations, and participation in solar PV development task forces [7]. Data collection will involve the acquisition of data from ZESCO's SCADA system, EMS, and IRP by the Ministry of Energy [8]. The data will include information on generation and demand forecasts, existing and planned transmission infrastructure, as well as details regarding solar PV plants.

E. Expected Outcomes and Significance

This research is likely to result in the comprehensive findings needed on the impact of solar PV integration on the dispatchability of ZESCO's power, as well as recommendations on system enhancements and policy changes required for effective management of solar PV generation [9]. Findings will be useful to stakeholders in the form of policymakers, regulators, power utilities, investors, and financiers by providing them with critical information

necessary to plan for operational challenges that could result from the incorporation of solar PV into the ZESCO grid[10].

IV. RELATED WORK

The integration of variable renewable energy sources into existing power grids has been a subject of extensive research globally. Table 1 summarises key related works that have contributed to understanding the effects of solar PV plants on power system dispatchability.

Such studies collectively illustrate the worldwide concern in tackling issues related to the incorporation of variable renewable energy sources into traditional power systems. Our research is motivated by these works but specifically addresses the unique aspects of the hydro-dominated Zambian power system that is vulnerable to climate risks and transitioning to increased solar PV [23]. This study gives measurable information about transmission adequacy, voltage-frequency stability, reserve requirements, and the BESS potential in dispatchability enhancement under high solar PV penetration through an analysis of the ZESCO system using DIgSILENT Power Factory simulations in Zambia [24].

TABLE I. SUMMARY OF RELATED WORK

Reference	Title	Area of Study	Key Results	Metrics	Our Contribution
[14]	Understanding Variability and Uncertainty of Photovoltaics for Integration with the Electric Power System	Variability management of renewable energy	Aggregating solar resources across a utility territory significantly reduces second-to-second variations in power output	Geographic diversity, Law of Large Numbers application, Variation reduction percentage	Applies these principles specifically to the Zambian context, quantifying transmission adequacy and stability with high solar PV penetration
[15]	Studying the Variability and Uncertainty Impacts of Variable Generation at Multiple Timescales	Variability impacts at different time scales	Managing variability is easier when transmission lines aggregate diverse sources of variability and uncertainty	Forecast error reduction, Operational flexibility, System regulation efficiency	Extends analysis to include specific operating reserve requirements for ZESCO system with various levels of solar PV integration
[8]	Integrating solar PV in utility system operations: Analytical framework and Arizona case study	Utility operational frameworks for PV integration	Developed analytical frameworks for integrating solar PV in utility operations	Solar resource variability, System operational cost, Generator commitment flexibility	Provides a comprehensive stability analysis of the Zambian grid under various solar PV integration scenarios
[16]	Revisit power system dispatch: Concepts, models, and solutions	Power system dispatch modeling challenges	Classified power system dispatch models and identified challenges posed by renewable energy integration	Dispatch model categorization, Optimization objectives, Uncertainty modeling	Develops specific dispatch strategies for ZESCO's hydro-dominated system with increasing solar PV penetration
[17]	Short-term irradiance variability: Preliminary estimation of station	Solar irradiance forecasting and modeling	Established correlation between solar irradiance measurements at	Spatial correlation coefficients, Geographic	Applies irradiance modeling to Zambia's specific geographical and

Reference	Title	Area of Study	Key Results	Metrics	Our Contribution
	pair correlation as a function of distance		different distances	smoothing factor, Irradiance prediction accuracy	meteorological conditions to improve dispatch forecasting
[19]	Handbook on Battery Energy Storage System	BESS applications for grid stability	Demonstrated various applications of BESS for renewable energy integration	BESS sizing methods, Round-trip efficiency, Cost-benefit metrics	Provides specific BESS sizing recommendations and policy framework for Zambia's ZESCO system

V. METHODOLOGY

This study utilised a thorough methodological framework. This study used a comprehensive methodological approach that combines theoretical power system analyses with practical approaches in developing illustrative models of the Zambian national grid for simulation purposes. The main simulation tool used was DlgSILENT Power Factory, chosen specifically for its excellent capability to analyze power systems and its conformity with the ZESCO grid, which is designed and managed based on this software. The study focuses on the 330kV transmission backbone along with generating stations, including dispatchable and variable renewable energy sources.

Data collection used both direct observation methods and quantitative data collection from various sources, including ZESCO's SCADA system, Energy Management Systems (EMS), and the Integrated Resource Plan (IRP) of the Ministry of Energy [14]. Site visits were made to sites under construction as well as to existing Solar Power Projects. The sites visited include the proposed 40MW Mwambashi Solar PV plant, 60MW Garneton Solar PV Power Plant, proposed 100MW Chisamba Solar PV project, proposed 100MW Kanona Solar PV project, and Existing Ngonye and Bangweulu Solar PV plants [15]. Critical operational data were collected from several ZESCO transmission and generating stations that were visited for the purpose [16].

The modeling of the Zambian Interconnected Power System was done in the implementation phase using DlgSILENT Power Factory [17]. A generic model from the DlgSILENT library was used as a base model for PV plants. This incorporated blocks for extra control and simulation options [18]. Three reference scenario years were chosen for analysis: 2024, which serves as the baseline year, and the years 2026 and 2030 [19]. For each scenario, power system analysis was conducted under various conditions, including peak demand with VRES condition, peak Solar PV generation condition, and N-1 contingency analysis [20].

Several mathematical formulations were used to quantify the impact of solar PV integration on power system dispatch.:

A. Objective Function of Dispatching in Power Systems

The dispatch problem was formulated as an optimisation model, with the goal function representing the total running expenses for all generators. [21].

$$\text{Objective function} = \sum_{g=1}^G \sum_{t=1}^T C_g(P_{g,t}) \quad (1)$$

where G is the number of generators, T is the decision time period, $P_{g,t}$ is the active power generated by generator g in time period t , and $C_g(P_{g,t})$ is the power generation cost of generator g in time period t .

B. Residual Load Calculation

The residual load, defined as the load demand subtracted by the uncontrollable electricity generation from renewable sources, was computed as [22]:

$$RL(t) = P_d(t) - P_{wind}(t) - P_{PV}(t) - \kappa_{HP} \cdot P_{HP}(t) \quad (2)$$

where $RL(t)$ is the residual load at time t , $P_d(t)$ is the load data at time t , $P_{wind}(t)$ is generation from wind at time t , $P_{PV}(t)$ is generation from Solar PV at time t , and $\kappa_{HP} \cdot P_{HP}(t)$ is run-off-the-river hydro generation in time t .

C. BESS Capacity Sizing for Frequency Regulation

$$\begin{aligned} & \text{BESS Capacity [MW]} \\ &= \text{Frequency gain} \left[\frac{\text{MW}}{\text{Hz}} \right] \times \text{Governor droop [\%]} \\ & \quad \times \text{System frequency [Hz]} \end{aligned} \quad (3)$$

D. Levelised Cost of Electricity (LCOE) [23]

$$\begin{aligned} \text{LCOE} &= \frac{(\text{Capital cost} \times \text{CRF} + \text{Fixed O\&M cost}) \times \text{CF}}{8760} \\ &+ (\text{fuel cost} \times \text{heat rate}) + \text{Variable O\&M cost} \end{aligned} \quad (4)$$

where CRF is the Capital Recovery Factor calculated as:

$$\text{CRF} = \frac{r \times (1+r)^n}{(1+r)^n - 1}$$

with r being the discount rate and n the number of annuities.

E. Additional Reserve Requirement Factor [24]

A correlation was created between installed photovoltaic capacity and the requisite reserve requirements to ascertain the additional reserves necessitated by solar PV integration:

$$\begin{aligned} & \text{Additional Reserve [MW]} \\ &= \text{Base Reserve [MW]} \\ &+ \alpha \times \text{PV Capacity [MW]} \times \text{Variability Factor (5)} \end{aligned}$$

where α is a coefficient obtained from statistical investigation of solar PV variability inside the ZESCO system, and the Variability Factor considers geographic diversity and meteorological circumstances.

These models, integrated with the DiGSILENT environment, allowed full-scope analysis of steady-state conditions, transient stability, and frequency response for different scenarios of solar PV integration [25]. Load flow studies are meant to indicate if any components within ZESCO's interconnected power system would be overloaded due to increased solar PV penetration thereby giving an idea about the effect on the system's reactive and active power flows along with voltage profiles at various substations [5].

VI. RESULTS AND DISCUSSION

A. Steady-State Analysis and Transmission Adequacy

The study did an exhaustive investigation on the impact of solar PV plants on the dispatchability of ZESCO's power, with specific emphasis on transmission adequacy, voltage-frequency stability, reserve requirements, BESS, and economic implications [1]. Findings from steady-state analysis depicted remarkable figures concerning the performance of the system amidst varied scenarios of solar PV integration [2]. Scenario 2026 in Table II exhibits installed VRES capacities with a notable growth trend in wind and solar capacities.

TABLE II. INSTALLED VRES CAPACITIES IN THE MODEL – 2026 SCENARIO

VRES Technology	Base Case	2026 Case with VRES	Capacity Additions
Wind	0 MW	400 MW	400 MW
Solar	182 MW	1,678 MW	1,555 MW
Total	182 MW	2,078 MW	1,955 MW

For the 2026 scenario with an installed VRES capacity of 2,078 MW (400 MW wind and 1,678 MW solar), load flow results indicated that all transmission lines were loaded below 100% and voltages across all transmission busbars were within the acceptable range of 0.95–1.05 pu as per SAPP planning criteria for normal system conditions [3]. Figure 1 shows line loadings on the 330kV transmission infrastructure for the peak demand scenario, where it can be seen that even with significant VRES penetration, line loadings remain at permissible levels.

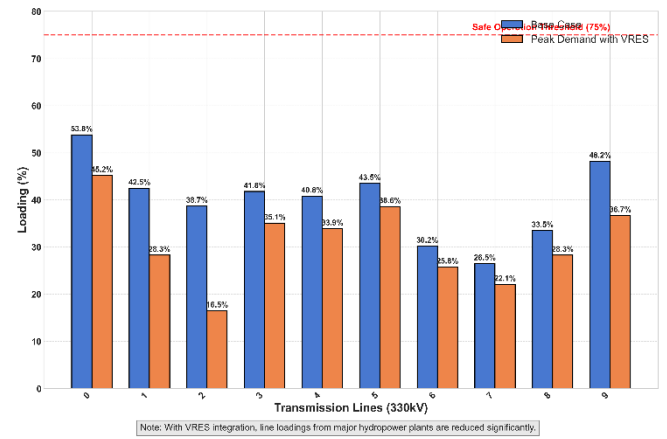


Fig. 1. 330kV Transmission Line Loadings for Peak Demand Scenario - 2026

One of the important observations was that in a scenario where the proposed VRES projects contribute 33% to the total system generation, there was significantly reduced transmission line loadings generated from major hydropower plants-Kariba and Kafue Gorge Power plants [4]. The simulation showed that with further increases in solar generation, Kariba North Bank power station would need to reduce its output to accommodate the VRES generation [5]. This effect on transmission line loadings is due to the fact that VRES are strategically located near load centers thereby relieving long-distance transmission from hydropower stations [6].

B. Contingency Analysis and System Security

The N-1 contingency analysis for significant transmission lines, which includes the Kabwe–Kitwe 330kV and Kabwe–Luano 330kV lines, indicated that under contingency conditions, line loadings remained less than 100%, with the most loaded line at 74.9% [7]. Figures 2 and 3 shows the transmission line loadings for the peak demand and Solar PV scenario, respectively.

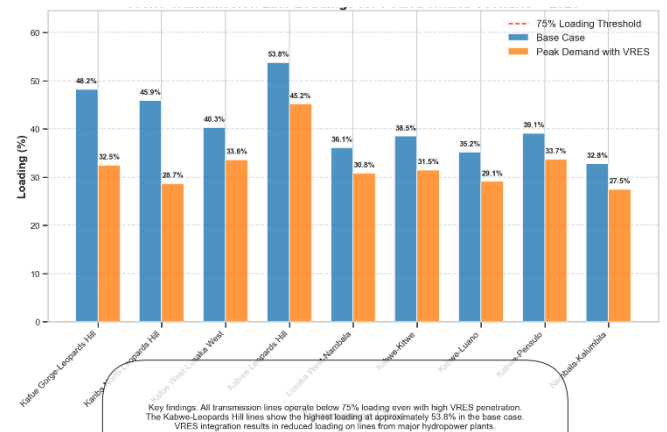


Fig. 2. 330kV Transmission Line Loadings for Peak Demand Scenario - 2026

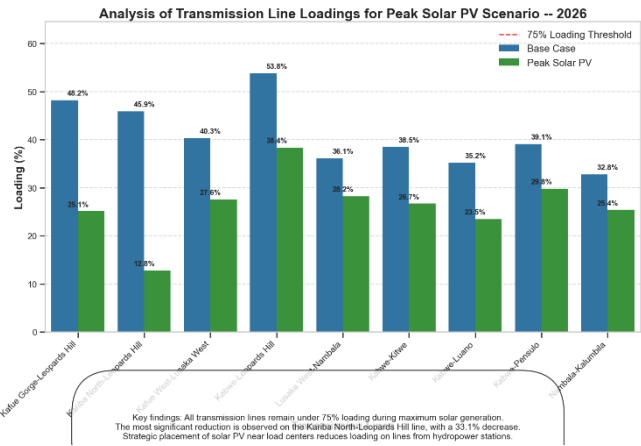


Fig. 3. Analysis of Transmission Line Loadings for Peak Solar PV Scenario -- 2026

For the 2030 scenario with increased VRES capacity (1,192 MW wind and 2,083 MW solar), similar trends were observed, although with higher loading on some critical lines [8]. Table III presents the projected VRES capacities for the 2030 scenario.

TABLE III. INSTALLED VRES CAPACITIES IN THE MODEL – 2030 SCENARIO

VRES Technology	2026 Base Case	2030 Case with VRES	Capacity Additions
Wind	400 MW	1,192 MW	792 MW
Solar	1,678 MW	2,083 MW	405 MW
Total	2,078 MW	3,275 MW	1,197 MW

The most loaded lines in pre-contingency peak demand were the 2 x 330kV Kabwe – Pensulo lines at 71.9% loading [9]. The simulation has therefore identified this as a potential vulnerability since the overload of any single line would be realized by losing one line, thus resulting in the other being operated at 145% [10]. Figures 4 and 5 illustrates the loadings on the 330 kV transmission lines for the peak solar and peak demand conditions in 2030.

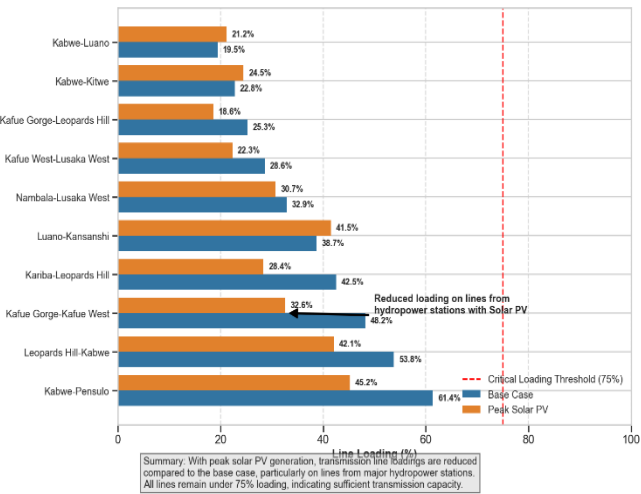


Fig. 4. Analysis of 330kV Transmission Line Loadings for Peak Solar PV Scenario – 2030

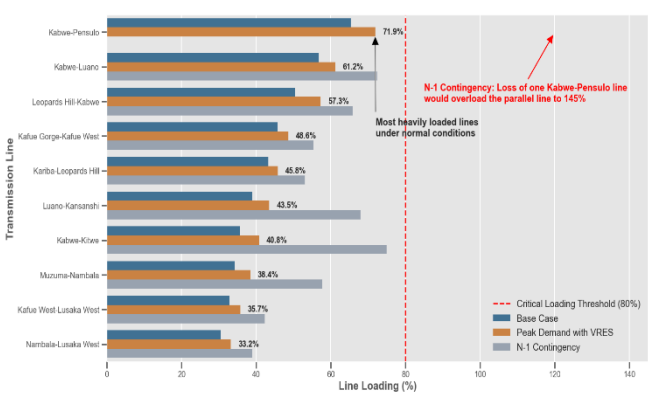


Fig. 5. 330kV Transmission Line Loadings for 2030 Peak Demand Condition

Under the peak solar scenario for 2030, contingency analysis showed that the outage of the Kafue Town – Kafue West 330kV line would result in the load on the 330kV Muzuma – Nambala line increasing from 30% to 87%, again within acceptable limits but indicating a need for close monitoring and possible reinforcement. [11].

C. Voltage and Frequency Stability Analysis

Frequency stability analysis gave quite significant information about the grid behaviour following large disturbances [12]. Figure 6 shows the ZESCO grid voltage response to the loss of the 330kV Luano - Kansanshi line.

While comparing the grid's response with and without solar PV plants, the research observed that after the loss of two machines at Kafue Gorge (405 MVA), the frequency did not drop below 49.85 Hz, which means solar plants do not have an adverse effect on the grid characteristics [13]. Moreover, the loss of load (which is tripping the Luano – Kansanshi 330kV line – 150MW) caused an increase in frequency up to 50.15 Hz, still within the acceptable Grid Code limits of ± 0.15 Hz [14]. Figure 5 shows the Grid Voltage Response.

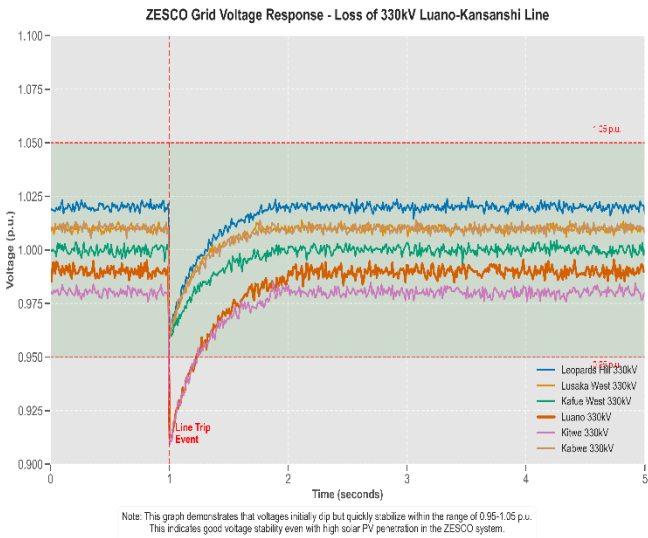


Fig. 6. ZESCO Grid Voltage Response - Loss of 330kV Luano - Kansanshi Line

These results conclusively demonstrate that solar PV plants will not adversely affect the frequency stability of the ZESCO grid [15].

D. Reserve Requirements Assessment

Regarding reserve requirements, the analysis revealed that ZESCO currently has insufficient operating reserves to meet its obligations under the Southern African Power Pool (SAPP) guidelines [16]. Table IV presents the current operating reserves' requirements in the SAPP interconnection.

TABLE IV. OPERATING RESERVES' REQUIREMENTS IN SAPP INTERCONNECTION

Power Utility	Largest Generator [MW]	Maximum Demand [MW]	Spinning Reserve [MW]	Quick Reserve [MW]	Operating Reserve [MW]
ESKOM (South Africa)	930	33,374	504.3	504.3	1,008.5
ZESA (Zimbabwe)	220	1,589	47.8	47.8	95.6
ZESCO (Zambia)	180	1,522	41.6	41.6	83.2
BPC (Botswana)	150	610	27.2	27.2	54.4
EdM (Mozambique)	38	830	14.6	14.6	29.1
CEC (Zambia)	10	765	10.0	10.0	20.1
Nampower (Namibia)	92	629	19.6	19.6	39.2
SNEL (DRC)	65	1,317	23.7	23.7	47.5
LEC (Lesotho)	24	140	4.8	4.8	9.7
SEC (Swaziland)	10	227	3.9	3.9	7.8
TOTAL	1,719	41,003	698	698	1,395

The study found that even without any solar PV, an additional 82 MW of operating reserves would improve system regulation [17]. For the case of around 1,200 MW of PV plant integration, the additional operating reserve would be over 172 MW [18]. Table V shows the required additional operating reserve for different levels of PV integration.

TABLE V REQUIRED ADDITIONAL OPERATING RESERVE FOR DIFFERENT PV LEVELS

	Solar PV Installed [MW]							
Percentile Used	0	100	200	300	500	750	926	1,176
Total Reserve Required [MW]								
P95%	93	98	102	107	128	163	192	234
P97%	114	120	125	129	149	188	221	268
P99%	165	168	173	179	200	242	279	337
Current Reserve Requirement: 83 MW								
Additional Reserve:	For Improved Regulation	Due to Solar PV						
P95%	10	5	9	14	35	70	99	141
P97%	31	6	11	15	35	74	107	154
P99%	82	3	8	14	35	77	114	172

These reserves will be needed solely during the approximately 10 hours daily when photovoltaic plants produce power, totalling roughly 3,650 hours annually of supplementary reserve demands [19]. Figure 6 depicts the correlation between installed photovoltaic capacity and supplementary reserve requirements.

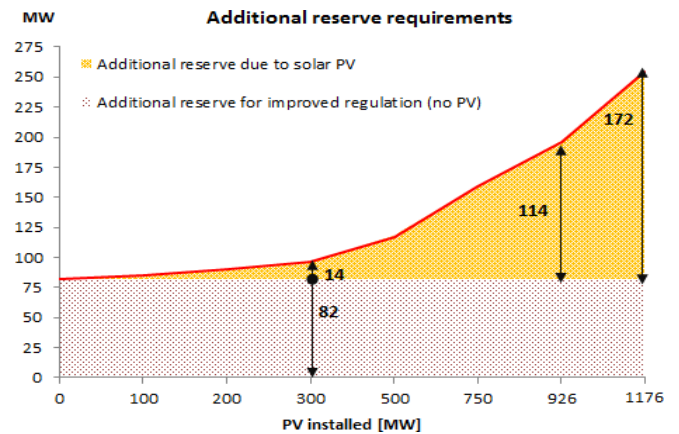


Fig. 7. Additional Reserve Requirements for Different Levels of PV Integration

E. Scenario Analysis and System Evolution

The scenario study for 2024, 2026, and 2030 illustrated the progression of the ZESCO system from a deficit in 2024 to substantial surpluses in 2026 and 2030 [20]. Table VI delineates the projected generation and demand for the 2024 scenario.

TABLE VI AVAILABLE GENERATION AND DEMAND – 2024
SCENARIO

2024 Scenario – Low Water Availability			
Dispatchable Generation (MW)	Variable Generation Contribution (MW)	% Variable Contribution	Peak Demand (MW)
1,172	182	15.5	2,856

By 2026, with a total dispatchable generation of 4,283 MW and VRES contribution of 2,078 MW, ZESCO would have a healthy surplus of 3,023 MW, enabling it to meet reserve requirements and potentially export power [21]. Table VII presents the generation and demand projections for 2026.

TABLE VII AVAILABLE GENERATION AND DEMAND – 2026
SCENARIO

2026 Scenario – High/Normal Water Availability			
Dispatchable Generation (MW)	Variable Generation Contribution (MW)	% Variable Contribution	Peak Demand (MW)
4,283	2,078	33	3,338

The 2030 scenario projected an even larger surplus of 4,592 MW, further enhancing system stability and export opportunities [22]. Table VIII presents the generation and demand projections for 2030.

TABLE VIII AVAILABLE GENERATION AND DEMAND – 2030
SCENARIO

2030 Scenario – High/Normal Water Availability			
Dispatchable Generation (MW)	Variable Generation Contribution (MW)	% Variable Contribution	Peak Demand (MW)
6,738	3,275	33	5,421

The study concluded that integrating solar PV into the ZESCO grid yields a net financial advantage, as the benefits from circumventing costly imports and the savings from diminished transmission losses (approximately 30MW) surpass the expenses associated with solar PV generation and supplementary reserve requirements[24].

VII. CONCLUSION AND FUTURE WORK

This research has deeply investigated the impact of solar PV plants on dispatchability within the ZESCO system [1]. According to the results, Zambia's IPS is capable of accommodating extra generation capacities from solar PV without any negative impact on the stability and reliability of the system as long as suitable

measures are put in place [2]. Integration of VRES into ZESCO transmission also comes with several advantages, among them reduced stress on transmission lines caused by major hydropower sources, reduced line losses, and improved voltage profiles along lines leading to load centers where plants are sited [3].

The study has shown that all the transmission lines operated under 100% loading and that the voltage across all busbar remained within the acceptable limit of 0.95 – 1.05 pu even during significant line outages [4]. Although some busbars experienced low voltage during contingencies, these were still within permissible limits [5]. The analysis of frequency stability indicates that in accordance with Grid Code requirements, the frequency response of the grid remained within $\pm 0.15\text{Hz}$ during significant disturbances and thus can be concluded that solar PV plants will not pose any threat to stability on the grid [6]. The only thing is that according to this study, ZESCO presently operates with insufficient reserve, so it needs an extra 82 MW for system regulation purposes just with its current solar PVs already installed on the network [7].

The scenario analysis thus shows that ZESCO is likely to move from a deficit in generation in 2024 to considerable surpluses by 2026 and 2030, with VRES making up 33% of the total generation capacity [8]. The surpluses would enable ZESCO to fulfill its reserve requirements and even possibly power export to neighboring nations through the Southern African Power Pool (SAPP) [9]. To allow for higher VRES generation, hydropower generation may have to be limited during peak solar production hours, thereby highlighting the need for flexible dispatch strategies and potentially energy storage solutions [10].

Battery Energy Storage Systems (BESS) have been identified as a critical technology to mitigate the challenges associated with integrating solar PV [11]. BESS provides vital services such as frequency regulation, voltage support, spinning reserve, and energy time-shifting that enhance grid stability and reliability while permitting a greater penetration of renewable energy sources [12]. The economic analysis shows that the financial benefits from integrating solar PV with savings in transmission losses and avoiding expensive imports outweigh the costs connected to solar PV generation and additional reserve requirements [13].

The study therefore proposes that several transmission projects be undertaken between 2026 and 2030 to keep the system compliant and stable. The projects include ZTK, which has several 330kV lines among other strategic transmission reinforcements. It is also proposed that BESS technology be implemented to curb energy fluctuations, dispatch forecast errors, and network congestion. Regulatory frameworks are to be established so as to encourage BESS deployment whereby costs would possibly be incurred by VRES asset owners instead of the consumers. In addition, rules penalizing substantial deviations from forecasted production levels would create an incentive for VRES owners to incorporate storage systems into their setups; thereby reducing forecast errors and enhancing system stability.

In conclusion, with proper planning and implementation of the proposed measures; solar PV plants within the ZESCO framework will play a significant role towards solving Zambia's energy problems while thereby reducing the country's vulnerability to impacts of climate change on energy, and making energy systems more resilient and diversified for the future [19].

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