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A Study of Factors Impacting Grid Stability in the Nigerian Electricity Supply Industry

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ABSTRACT

Ensuring grid stability and optimizing demand response in power systems require an in-depth understanding of the interplay between feedstock availability, frequency governor control (FGC), and automatic voltage regulation (AVR). This study analyzes the impact of these factors on Nigerian power plants, revealing significant disparities in operational performance. Alaoji, Omotosho, and Trans-Amadi power plants recorded the highest feedstock unavailability, whereas Delta and Trans-Afam reported no such constraints. While Gbarain remained non-operational since 2022, Omotosho NIPP and Olorunsogo NIPP emerged as the leading contributors to FGC at 23%, followed by Kainji at 20%, with 62.5% of power plants providing no FGC support. AVR contributions were highest in Paras, Delta, and Jebba, whereas Omotosho NIPP, GPAL, and Sapele NIPP exhibited minimal impact. Regression analysis indicates that feedstock unavailability has a negligible effect on FGC but significantly influences AVR performance. Furthermore, an inverse relationship between FGC compliance and demand response suggests a potential trade-off between system controls, necessitating further investigation. Neither feedstock unavailability nor AVR exhibited a statistically significant impact on demand response. These findings underscore the need for a broader dataset and deeper exploration of interaction effects to refine strategies for enhancing grid stability and optimizing economic dispatch.

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INTRODUCTION

Feedstock management in power plants is critical for optimizing efficiency, ensuring safety, and reducing operational costs. Effective feedstock management systems integrate various functions such as supplier management, contract administration, and performance assessment, enabling comprehensive control over feedstock procurement, storage, and utilization.(Martinez-Valencia et al., 2021). In nuclear power plants, managing spent feedstock during the transition to decommissioning is crucial for maintaining safety and compliance with regulatory standards, as it involves transitioning spent feedstock to wet and dry storage systems, which significantly reduces radiation risks(Liu et al., 2020). The use of intelligent management and control systems, particularly in thermal power plants, enhances the automation and integration of feedstock management processes, leading to improved operational efficiency and reduced management costs(Al-Sinbol, 2017).

Fuel unavailability in power plants significantly impacts the power grid in sub-Saharan Africa, exacerbating existing challenges such as insufficient generation capacity, frequent power outages, and economic instability (Avila et al., 2017). When fuel shortages occur, power plants are forced to reduce or halt operations, leading to widespread electricity outages. These outages compel businesses and households to rely on backup diesel generators, which are more costly and less efficient than grid electricity, increasing consumer costs and fossil fuel

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consumption (Bawakyillenuo et al., 2018) The frequent use of diesel generators also results in higher greenhouse gas emissions, further straining the region's environmental sustainability goals (Baurzhan & Jenkins, 2017).

In Nigeria, there are twenty-seven (27) grid connected power plants as at 2023/Q4 consisting of nineteen (19) gas, four (4) hydro, two (2) steam, and two (2) gas/steam-powered plants. The plants' average available generation capacity during the quarter was 4,922.26MW(Nigeria Electricity Regulatory Commission, 2024). The thermal power plants alone contribute roughly 80 percent of the country's electricity generation. However, the nation faces several challenges in fully exploring the potential of the thermal power plants. One of major challenges is the unavailability of feedstock especially gas in the thermal plants. Data from The Nigerian Electricity Regulatory Commission (NERC) has shown that from May 2023 to April 2024, energy lost attributed to gas constraint was determined to be 2227 GWh.

Fuel unavailability in power plants poses significant challenges to maintaining stable frequency response and effective reactive power control in power grids(Shazon et al., 2022). Without reliable fuel supplies, power plants struggle to provide consistent real power, which is crucial for frequency regulation and reactive power compensation.

PROBLEM STATEMENT

The reliability and efficiency of power generation in sub-Saharan Africa, particularly in Nigeria, are significantly affected by the availability of feedstock, especially natural gas for thermal power plants. Despite contributing approximately 80% of Nigeria’s electricity generation, thermal power plants frequently experience operational disruptions due to fuel shortages. This limitation undermines the ability of power plants to provide stable frequency response and reactive power compensation, which are essential for maintaining grid stability. Data from the Nigerian Electricity Regulatory Commission (NERC) indicates that from May 2023 to April 2024, Nigeria lost 2,227 GWh of energy due to gas constraints. As a result, the nation has experienced multiple grid disturbances, with nine recorded in 2023 and twelve in 2024, further exacerbating the power supply challenges.

The current feedstock management practices in Nigerian power plants lack an integrated approach to supplier coordination, contract administration, and real-time performance assessment. Inefficient procurement and supply chain issues lead to inconsistent fuel availability, forcing power plants to operate below capacity or shut down entirely. Given the critical role of thermal power plants in the national energy mix, addressing fuel supply constraints is imperative to ensuring grid reliability and optimizing power generation. This research seeks to analyze the underlying causes of fuel shortages in Nigeria’s power sector, assess their impact on grid stability, and propose a comprehensive feedstock management framework that enhances operational efficiency and reduces power supply disruptions.

Hypothesis

Null Hypothesis (H_0):

Feedstock management inefficiencies and fuel shortages do not have a significant impact on the stability of Nigeria’s power grid, and optimizing feedstock management will not lead to improved power generation reliability.

Alternative Hypothesis (H_1):

Feedstock management inefficiencies and fuel shortages have a significant impact on the stability of Nigeria’s power grid, and optimizing feedstock management will lead to improved power generation reliability and reduced grid disturbances.

LITERATURE REVIEW

Rao et al (2023) proposed a nonlinear model predictive control (NMPC) method to minimize frequency deviations when the grid is affected by an unforeseen loss of multiple components, which can accurately model both nonlinear electric power flow physics and the primary and secondary frequency response of

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generator control mechanisms. However, simplified assumptions hinder accurate frequency response prediction (Rao et al., 2023)

A data-driven approach that utilizes an ensemble learning method to predict frequency response indices following power disturbances was presented in the work of Jawad et. al. (2023). The approach demonstrated impressive performance and exhibits balanced performance across all evaluated frequency response parameters. However, Conventional model-driven approaches lack speed and accuracy(Jawad et al., 2023).

Chi et. al (2022) analyzed the operation principle and control mode of various new energy resources in order to solve the above problems, the process and principle of power grid frequency response are studied and the evaluation index of frequency response capability was proposed. However, the work didn't consider the decline in inertia response and primary frequency modulation capabilities and sharp frequency drop experienced in East China Power Grid (Chi et al., 2022).

An overview of the changing trends in frequency response and frequency control strategies in the modern power grid under high renewable penetrations is provided in the work of Golpira et. al. (2020). A virtual inertia emulation through Energy Storage Systems (ESSs) is reviewed as a potential solution to the frequency instability issue. However, the work didn't consider challenges in procuring and rewarding fast frequency response services and decreased inertia and frequency instability in modern power grid.

Nigam et al. (2024) asserts that reactive power compensation is essential for improving power quality and reducing voltage drop in distribution systems. D-FACTS devices are used to manage reactive power and improve the performance of distribution system. However, the work didn't consider voltage instability and power quality issues in power plants. Furthermore, distributed generators also draw reactive power affecting voltage stability.

In the work of Potter et. al (2023), the authors proposed a reactive power market at the distribution level designed to meet the needs of decentralized and decarbonized grids, which uses variable payments to compensate DGs equipped with smart inverters, at an increased spatial and temporal granularity. In a similar work, the authors proposed the planning of static and dynamic reactors (TCR) to overcome the problems of over voltages in the transmission system of Rajasthan state of India. However, the work didn't consider Voltage limitations at grid nodes and Load flow limitations for adherence(Rauch & Brückl, 2023).

In this work, a detailed analysis of the effect of feedstock unavailability in power plants is examined. The plants' ability to provide frequency response and reactive power compensation during those periods is then evaluated. Finally, the effect of providing frequency response and reactive power compensation on demand response is analyzed using regression analysis. The rest of the paper is arranged as follows: section 1 provides an introduction, section II is the literature review, section III deals with methodology section IV presents the results and discussion and finally conclusion and recommendations are made in section V.

METHODOLOGY

The methodology is divided into three aspects: data collection, data mining and analysis.

A. Data Collection

Data from National Control Center (NCC) from August-September 2024 was utilized for this analysis. The data provided information on the following:

1. Data on feedstock unavailability by power plants: This data was obtained from the daily situation room meetings amongst all licensees in the Nigeria Electricity Supply Industry.
2. Data on FGC compliance by Power plants: This is a daily compliance data submitted by NCC to NERC.
3. Data on AVR compliance by power plants: This is a daily compliance data submitted by NCC to NERC.

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4. Data on demand response. This is computed by evaluating plants that their actual generation greater than their declaration. This data is calculated daily. It is given by equation 1

$$Demand\ Response\ (DR) = Plant's\ Declaration - Plant's\ Average\ Generation \quad (1)$$

B. Data Mining

The data obtained in section 3A was processed to enable the analysis outlined in the objectives. Data for the months of May-July 2024 were extracted being the timeframe considered for the work. Power DBI software was used to extract instances of feedstock unavailability from the daily situation room reports from NCC. Furthermore, data on FGC and AVR compliance was also obtained using Power DBI. Finally, data on plant's declaration and average generation for the day was also extracted. Equation 1 was used to determine the demand response.

C. Analysis

Regression analysis was used for the analysis to determine the relationship between feedstock unavailability and compliance with the provision of Free Governor Control (FGC) and Automatic Voltage Regulation (AVR). The regression model has the general format given in equation 2.

$$y = \beta_0 + \beta_1 . x_1 \quad (2)$$

Where y is the provision of Automatic Voltage Regulation (AVR), x_1 is the feedstock unavailability in days, β_0 is the intercept and β_1 is the slope. The intercept is the estimated provision of AVR when feedstock unavailability is 0 days the slope tells us how the provision of AVR changes as feedstock unavailability increases by 1 day. Furthermore, a regression analysis of feedstock unavailability and compliance with the provision of Free Governor Control (FGC) using equation 3.

$$z = \alpha_0 + \alpha_1 . x_1 \quad (3)$$

Where z is the provision of free governor control, x_1 is the feedstock unavailability in days, α_0 is the intercept and α_1 is the slope. The intercept is the estimated provision of FGC when feedstock unavailability is 0 days the slope tells us how the provision of FGC changes as feedstock unavailability increases by 1 day. Finally, the effect of these factors i.e. FGC and AVR and fuel unavailability on demand response was analyzed and provided.

RESULTS AND ANALYSIS

A. ANALYSIS OF FUEL UNAVAILABILITY

Analysis has shown that there were 468 instances (days) of fuel unavailability across the thirty-two (32) power plants for the period under review as shown in table 1.

Table 1: GenCos percentage of Plant's Units on FGC and Unavailability of Feedstock

S/N	Power Station	% On FGC	UNAVAILABILITY OF FEEDSTOCK(Days)
1	AFAM III FAST POWER	0%	0
2	TRANS AFAM POWER	0%	0
3	AFAM VI	0%	4
4	ALAOJI NIPP	0%	58
5	DELTA	0%	0
6	EGBIN	0%	0
7	GBARAIN	0%	0
8	GEREGU GAS	9.52%	12
9	GEREGU NIPP	0%	6
10	IBOM	33.33%	16
11	IHOVBOR	10.34%	33
12	JEBBA	0%	0
13	KAINJI	62.50%	0

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S/N	Power Station	% On FGC	UNAVAILABILITY OF FEEDSTOCK(Days)
14	ODUKPANI	54.29%	9
15	OKPAI	21.21%	46
16	OMOKU	0%	20
17	AZURA IPP	100%	10
18	OLORUNSOGO GAS	85.71%	25
19	OLORUNSOGO NIPP	0%	14
20	OMOTOSHO GAS	87.50%	19
21	OMOTOSHO NIPP	0%	55
22	PARAS	0%	0
23	SAPELE NIPP	10.34%	38
24	SAPELE STEAM	0%	15
25	SHIRORO	27.27%	0
26	TRANS-AMADI	0%	54
27	RIVERS IPP	0%	34
28	DADINKOWA	0%	0
29	ZUNGERU	0%	0
30	TAOPEX ENERGY	0%	0
31	MEPP	0%	0
32	GPAL	0%	0

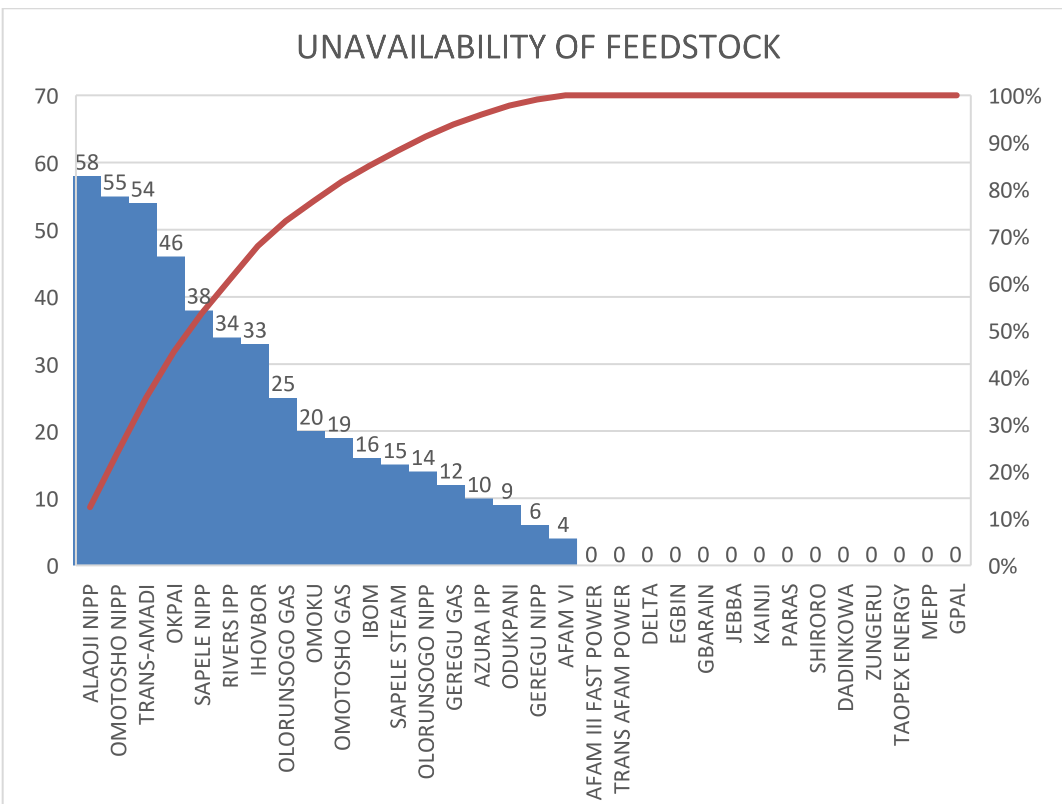

Figure 1: Unavailability of Feedstock

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The analysis shows that Alaoji, Omotosho and Tans-Amadi power plants had the highest number of feedstock unavailability for the period under review. While Delta, Trans-Afam, Afam III Fast power, Jebba, Kainji, Paras, Shiroro, Dandin Kowa, Zungeru, Taopex MEPP, GPAL and Gbarain had no case of feedstock unavailability. Its worth noting that Gbarain hasn't been in operational since 2022 as such no feedstock is expected in the plant.

B. ANALYSIS OF FGC COMPLAINCE

The analysis was conducted for thirty-two (32) plants. Data from August-September 2024 from NCC was utilize on the compliance of GenCos to provision of FGC.

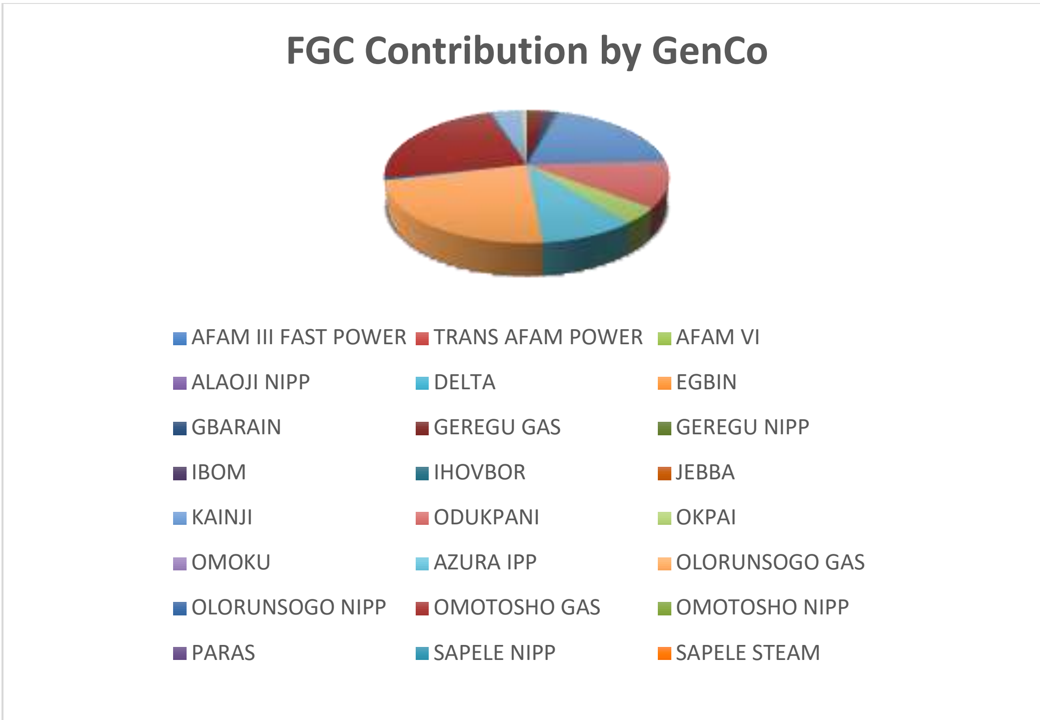

Figure 2: FGC Contribution by GenCos

The highest contribution to FGC on the grid for the period were recorded by Omotosho NIPP, Olorunsogo NIPP both 23% each closely followed by Kainji with 20%. Twenty (20) GenCos had no contribution for FGC which translates to 62.5% of the total plants.

C. ANALYSIS OF AVR COMPLAINCE

The analysis was conducted for thirty-two (32) plants. Data from August-September 2024 from NCC was utilize on the compliance of GenCos to provision of AVR.

Table 2: GenCos percentage of Plant's Units on AVR and Unavailability of Feedstock.

S/N	Power Station	% On AVR	UNAVAILABILITY OF FEEDSTOCK(Days)
1	AFAM III FAST POWER	19%	0
2	TRANS AFAM POWER	15%	0
3	AFAM VI	72%	4

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S/N	Power Station	% On AVR	UNAVAILABILITY OF FEEDSTOCK(Days)
4	ALAOJI NIPP	8%	58
5	DELTA	42%	0
6	EGBIN	68%	0
7	GBARAIN	9%	0
8	GEREGU GAS	59%	12
9	GEREGU NIPP	56%	6
10	IBOM	45%	16
11	IHOVBOR	12%	33
12	JEBBA	82%	0
13	KAINJI	61%	0
14	ODUKPANI	52%	9
15	OKPAI	60%	46
16	OMOKU	58%	20
17	AZURA IPP	58%	10
18	OLORUNSOGO GAS	66%	25
19	OLORUNSOGO NIPP	12%	14
20	OMOTOSHO GAS	61%	19
21	OMOTOSHO NIPP	0%	55
22	PARAS	100%	0
23	SAPELE NIPP	5%	38
24	SAPELE STEAM	17%	15
25	SHIRORO	69%	0
26	TRANS-AMADI	11%	54
27	RIVERS IPP	84%	34
28	DADINKOWA	100%	0
29	ZUNGERU	76%	0
30	TAOPEX ENERGY	26%	0
31	MEPP	50%	0
32	GPAL	4%	0

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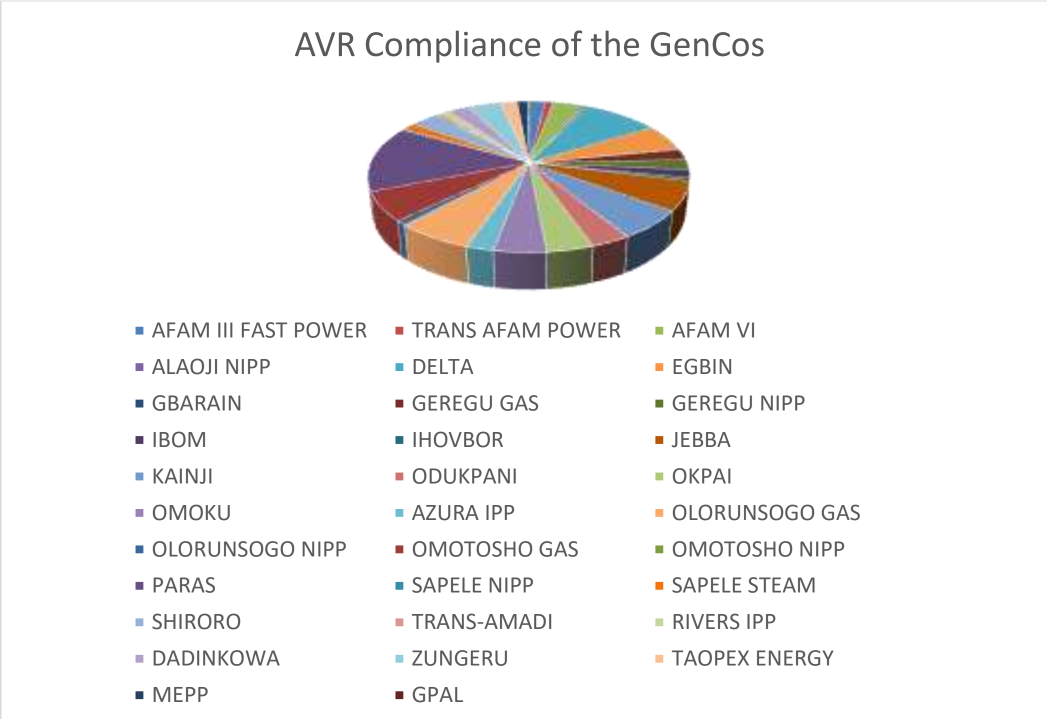

Figure 3: AVR Contribution by GenCos

The highest contributors to AVR are Paras, Delta and Jebba with 14.12%, 9.14% and 6.21% respectively. While the lowest contributors are Omotosho NIPP, GPAL and Sapele NIPP with 0%, 0.15%, 0.26% contribution respectively.

D. REGRESSION ANALYSIS

In this section, the regression analysis of the effect of feedstock unavailability on both FGC and AVR is presented.

i. Feedstock Unavailability and FGC

The slope and intercept provide important information about the relationship between the independent variable (predictor) and the dependent variable (outcome). The intercept is the estimated value of the provision of free governor control when feedstock unavailability is 0 days which was found to be 15.625. This means that, when no feedstock unavailability is present, the expected provision of free governor control is 15.265%.

Similarly, the slope is the change in the provision of free governor control for each additional day of feedstock unavailability. A slope of 0.02889 indicates that for every additional day of feedstock unavailability, the provision of free governor control increases by 0.02889%. This is a very small and insignificant increase.

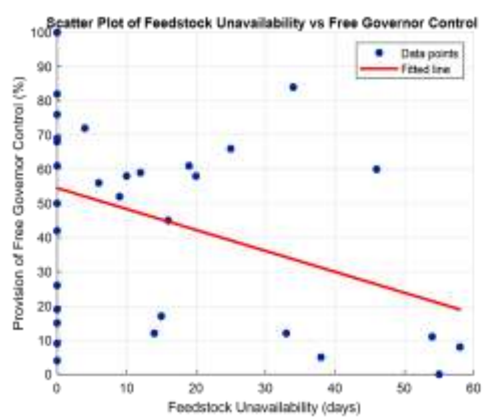

Figure 4: Scatter Plot of Feedstock Unavailability vs FGC

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A p-value of 0.921 means that the relationship between feedstock unavailability and the provision of free governor control is statistically insignificant. This indicates that feedstock unavailability is not a meaningful predictor of free governor control in this case. The p-value for the slope (0.921) is far above the typical significance threshold of 0.05.

The t-statistic measures how many standard errors the coefficient is from zero. A low t-value, like 0.10042, supports the conclusion that the coefficient for feedstock unavailability is not significantly different from zero. The R-squared value indicates the proportion of variance in the dependent variable (provision of free governor control) that is explained by the independent variable (feedstock unavailability). An R-squared value of 0.000336 (close to 0) means that only 0.0336% of the variability in the provision of free governor control is explained by feedstock unavailability. This suggests that the model does not fit the data well.

The adjusted R-squared accounts for the number of predictors in the model. A negative adjusted R-squared value indicates that the model is worse than a simple horizontal line (a constant model). This reinforces the idea that feedstock unavailability has almost no explanatory power for predicting free governor control.

ii. Feedstock Unavailability and AVR

The intercept for the estimated provision of AVR when feedstock unavailability was found to 54.488% while the slope which indicates how the provision of AVR changes as feedstock unavailability increases by 1 day was evaluated at -0.61245 indicates that for every additional day of feedstock unavailability, the provision of AVR decreases by 0.61245%. This is a significant negative relationship, meaning that as feedstock unavailability increases, the provision of AVR tends to decline.

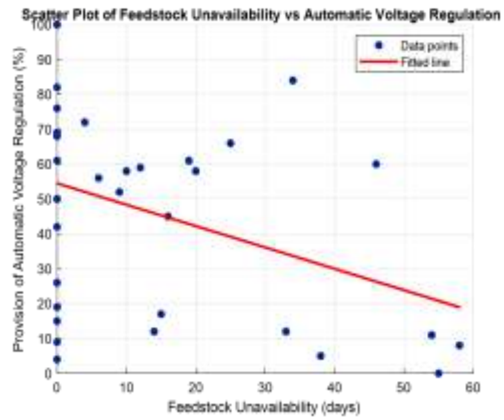

Figure 5: Scatter Plot of Feedstock Unavailability vs AVR

The p-value was for the slope was found to be 0.03146, which is below the common significance level of 0.05 which indicates that there is statistical significance for the relationship between feedstock unavailability and the provision of AVR. We can reject the null hypothesis (which suggests no relationship) and conclude that feedstock unavailability significantly affects AVR provision. A t-value of -2.2568 is large enough to indicate that the slope is significantly different from 0, supporting the conclusion that feedstock unavailability has a real effect on AVR.

An R-squared of 0.145 means that 14.5% of the variability in the provision of AVR is explained by feedstock unavailability. This suggests that while there is a significant relationship, feedstock unavailability is not a very strong predictor of AVR on its own (as 85.5% of the variability is still unexplained). The adjusted R-squared accounts for the number of predictors in the model. An adjusted R-squared of 0.117 suggests a slightly lower explanatory power than R-squared, but still in line with a small positive effect of the independent variable.

Table 3: Summary of Performance metrics for AVR and FGC

	Slope	Intercept	P-Value	t-statistic	R-squared
FGC	0.02889	15.625	0.921	0.10042	0.000336
AVR	-0.61245	54.488	0.0315	-2.2568	0.145

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iii. Feedstock Unavailability FGC, AVR and Demand Response

A Multiple Linear Regression analysis was carried out to examine how Feedstock Unavailability, Compliance with Free Governor Control, and Automatic Voltage Control influence a plant's ability to provide Demand Response. Approximately 19.5% of the variability in Demand Response is explained by the three predictors in the model this implies that the model has a low explanatory power, indicating that other factors not included in the model may significantly influence Demand Response. Furthermore, with an adjusted R-squared of 0.1091, about 10.9% of the variability is explained. This implies that adjusted value is lower than R-squared, further emphasizing the limited explanatory power of the model.

With a p-value of 0.103, which is greater than the common significance level of 0.05, the overall model is not statistically significant, suggesting that, collectively, the predictors do not reliably explain variations in Demand Response

Table 4: Summary of Performance metrics for Demand Response against Fuel Unavailability AVR and FGC

Predictor	**Estimate**	**Standard Error (SE)**	**t-Statistic**	**p-Value**
Feedstock Unavailability	-0.034016	0.22275	-0.15271	0.87972
FGC	-0.29701	0.13396	-2.2172	0.034902
AVR	-0.11074	0.14201	-0.77982	0.44204

For the analysis of Feedstock Unavailability against demand response an estimate of -0.034016 was obtained this means that for each additional unit increase in Feedstock Unavailability, Demand Response is expected to decrease by 0.034016 units, holding other factors constant. A p-Value of 0.87972 was obtained which is not statistically significant ($p > 0.05$). This demonstrates that Feedstock Unavailability does not have a significant impact on Demand Response in this model.

An estimate of -0.29701 was observed for the regression analysis of Demand Response with FGC this implies that for each additional unit increase in FGC, Demand Response is expected to decrease by 0.29701 units, holding other factors constant. The p-Value 0.034902 observed is statistically significant at the 0.05 level. This implies that FGC has a significant negative effect on Demand Response.

For the analysis of AVR with Demand Response an Estimate of -0.11074 was observed which implies that for each additional unit increase in AVR, Demand Response is expected to decrease by 0.11074 units, holding other factors constant. Similarly, a p-Value 0.44204 was observed which is not statistically significant ($p > 0.05$). This implies that AVR does not have a significant impact on Demand Response in this model.

The analysis indicates that FGC negatively affects Demand Response. As such higher compliance with free governor control is associated with a decrease in the plant's ability to provide demand response. The analysis further shows that Feedstock Unavailability and AVR have no significant effect on Demand Response.

CONCLUSION

The analysis shows that Alaoji, Omotosho and Tans-Amadi power plants had the highest number of feedstock unavailability for the period under review. While Delta, Trans-Afam, Afam III Fast power, Jebba, Kainji, Paras, Shiroro, Dandin Kowa, Zungeru, Taopex MEPP, GPAL and Gbarain had no case of feedstock unavailability. Its worth noting that Gbarain hasn't been in operational since 2022 as such no feedstock is expected in the plant. The highest contribution to FGC on the grid for the period were recorded by Omotosho NIPP, Olorunsogo NIPP both 23% each closely followed by Kainji with 20%. Twenty (20) GenCos had no contribution for FGC which translates to 62.5% of the total plants.

The highest contributors to AVR are Paras, Delta and Jebba with 14.12%, 9.14% and 6.21% respectively. While the lowest contributors

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are Omotosho NIPP, GPAL and Sapele NIPP with 0%, 0.15%, 0.26% contribution respectively. Regression analysis shows that feedstock unavailability has almost no explanatory power for predicting FGC, while it shows a significant relationship with AVR.

Finally, the regression analysis of demand response against fuel unavailability, AVR and FGC indicates that FGC negatively affects Demand Response. As such higher compliance with free governor control is associated with a decrease in the plant's ability to provide demand response. The analysis further shows that Feedstock Unavailability and AVR have no significant effect on Demand Response. Further works should include an investigation on why increased compliance correlates with reduced demand response which might be due to operational constraints or trade-offs in system controls. The data size might also need to be increase statistical power to detect smaller effects. Furthermore, investigation of interactions between predictors might reveal hidden effects.

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