



FACULTY OF ENGINEERING AND TECHNOLOGY

DEPARTMENT OF ELECTRICAL ENGINEERING

FINAL YEAR PROJECT REPORT

**RESEARCH TITLE: ANALYSIS OF GRID RELIABILITY IMPACT ON THE ENERGY
PRODUCTION AND ECONOMIC PERFORMANCE OF THE BUSITEMA SOLAR PV
PLANT: CASE STUDY 4 MW BUSITEMA GRID-TIED SOLAR PLANT.**

BY

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This report is submitted to the faculty of engineering and technology in partial fulfillment of the requirement for the award of the BSc. Electrical engineering at Busitema University.

MAY, 2025

DECLARATION

I, **IGOE THEOPISTER** declare that this report is my original work and has not been submitted elsewhere for academic credit. I affirm that all information presented is accurate to the best of my knowledge.

IGOE THEOPISTER

A handwritten signature in blue ink, appearing to read 'Igoe', with a stylized flourish extending to the right.

DATE: 15th JULY 2025

APPROVAL

This report has been submitted by **IGOE THEOPISTER** in partial fulfillment of the requirements for the degree of **Bachelor of Science in Electrical Engineering** at Busitema University. This report has been reviewed and approved by my supervisors.

Mr. Kilama George

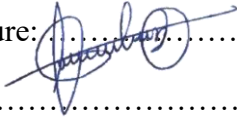
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DEDICATION

I would like to dedicate this report to my family members, friends and relatives for their unwavering support and encouragement.

ACKNOWLEDGMENT

I express my sincere gratitude to my supervisors, Eng. Butime Eric and Mr. Kilama George, for their guidance and support throughout the preparation of this report. I also thank my project partner, Muwanguzi Mildred Lynda as well as my friends, colleagues, and family for their encouragement and assistance. Lastly, I am grateful to God for sustaining me during this period.

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ACRONYMS

AC	Alternating current
BESS	Battery Energy Storage System
BMS	Battery Management System
DERs	Distributed energy Systems
DC	Direct current
ERA	Electricity Regulatory System
IEEE	Institute of Electrical and Electronics Engineers
kVA	Kilo volt ampere.
kVAR	Kilo Volt Ampere Reactive
kWh	kilowatt hour
kWp	kilowatt power
MPPT	Maximum Power Point Tracker
MW	Megawatts
NPV	Net Present Value
PCS	power conditioning systems
PHS	Pumped Hydro System
PV	Photovoltaic
SoC	state of charge

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ABSTRACT

This study investigates the effects of grid reliability on the energy production and economic performance of the 4 MW Busitema Solar Photovoltaic (PV) Plant in Uganda.

Despite the increasing deployment of Grid-tied solar PV systems, frequent grid outages and voltage fluctuations in Uganda's power infrastructure pose significant challenges to their performance.

The research was conducted over a four-month period from November 2024 to March 2025, during which half-hourly solar generation data and grid conditions were analyzed. Results revealed a total of 360,556 kWh of unutilized solar energy due to 2,520 minutes (42 hours) of grid outages, translating into financial losses of approximately UGX 14.6 million (USD 3,980.49).

To mitigate these losses, three technical solutions were evaluated: Battery Energy Storage Systems (BESS), Pumped Hydro Storage (PHS), and hybrid inverter systems capable of islanding mode operation.

Technical simulations using MATLAB and cost-benefit analyses showed that while PHS had a negative Net Present Value due to high capital investment, both BESS and hybrid inverter systems presented financially viable options, with the hybrid inverter achieving the shortest payback period.

The study concludes that addressing grid reliability through smart storage and control technologies is essential for maximizing the potential of solar PV plants and achieving energy sustainability goals in Uganda. Recommendations include adopting BESS as the primary mitigation strategy and developing predictive outage management tools to enhance system resilience.

6. references

- Battery Energy Storage Systems (BESS): How They Work, Key Components, Benefits, and Future Trends*. (n.d.). Retrieved May 30, 2025, from <https://www.delfos.energy/blog-posts/battery-energy-storage-systems-bess-how-they-work-key-components-benefits-and-future-trends>
- Chayawatto, N., ... S. S.-15 th I., & 2005, undefined. (n.d.). Islanding effects due to voltage conditions of grid disconnecting. *Researchgate.Net* N Chayawatto, S Stakulcharoen, N Ruangrotsin, K Kirtikara, C Jivacate, D Chenvidhya 15 Th International Photovoltaic Science Engineering Conference, 2005 •researchgate.Net. Retrieved May 30, 2025, from https://www.researchgate.net/profile/Krissanapong-Kirtikara/publication/228408582_Islanding_Effects_Due_to_Voltage_Conditions_of_Grid_Disconnecting/links/54f4598a0cf2f9e34f098758/Islanding-Effects-Due-to-Voltage-Conditions-of-Grid-Disconnecting.pdf
- de Oliveira, F. M., Oliveira da Silva, S. A., Durand, F. R., Sampaio, L. P., Bacon, V. D., & Campanhol, L. B. G. (2016). Grid-tied photovoltaic system based on PSO MPPT technique with active power line conditioning. *IET Power Electronics*, 9(6), 1180–1191. <https://doi.org/10.1049/IET-PEL.2015.0655>;SUBPAGE:STRING:ABSTRACT;WEBSITE:WEBSITE:IETRESEARCH;JOURNAL:JOURNAL:17554543;WGROU:STRING:PUBLICATION
- Difference Between Grid-Tied PV Inverter And Regular Inverter*. (n.d.). Retrieved May 30, 2025, from <https://www.chintglobal.com/global/en/about-us/news-center/blog/difference-between-grid-tied-pv-inverter-and-regular-inverter.html>
- Four Essential Parts of a Solar Energy System | The Solar Addict*. (n.d.). Retrieved May 31, 2025, from <https://thesolaraddict.com/four-key-components-solar-energy-system/>
- Gawhade, P., & Ojha, A. (2021). Recent advances in synchronization techniques for grid-tied PV system: A review. *Energy Reports*, 7, 6581–6599. <https://doi.org/10.1016/J.EGYR.2021.09.006>
- Generation Tariffs – Electricity Regulatory Authority*. (n.d.). Retrieved May 30, 2025, from <https://www.era.go.ug/generation-tariffs/>
- GRID CONNECTED PV SYSTEMS WITH BATTERY ENERGY STORAGE SYSTEMS DESIGN GUIDELINES Acknowledgement They represent latest industry BEST PRACTICE for Design of Grid Connected PV Systems with Battery Energy Storage Systems*. (2020).
- Grid-Tied Solar System: Everything You Want to Know | HUAWEI Smart PV Global*. (n.d.). Retrieved May 31, 2025, from <https://solar.huawei.com/en/blog/2024/grid-tied-solar-system/>

- Installed Capacity – Electricity Regulatory Authority*. (n.d.). Retrieved May 30, 2025, from <https://www.era.go.ug/installed-capacity/>
- Kouro, S., Leon, J. I., Vinnikov, D., & Franquelo, L. G. (2015). Grid-connected photovoltaic systems: An overview of recent research and emerging PV converter technology. *IEEE Industrial Electronics Magazine*, 9(1), 47–61. <https://doi.org/10.1109/MIE.2014.2376976>
- Maghami, M. R., Pasupuleti, J., & Ekanayake, J. (2024). Energy storage and demand response as hybrid mitigation technique for photovoltaic grid connection: Challenges and future trends. *Journal of Energy Storage*, 88, 111680. <https://doi.org/10.1016/J.EST.2024.111680>
- Mirzapour, O., Rui, X., & Sahraei-Ardakani, M. (2024). Grid-enhancing technologies: Progress, challenges, and future research directions. *Electric Power Systems Research*, 230. <https://doi.org/10.1016/j.epsr.2024.110304>
- Momoh, O. (2022). *Impact of power quality on PV performance of grid connected systems*. 299.
- Oller, G. M. (2020). *Anàlisi de viabilitat de salts hidràulics reversibles tancats de capacitat mitjana i petita per emmagatzematge d'energia*. <https://upcommons.upc.edu/handle/2117/333831>
- Rai, B., Dhungyel, M., Tenzin, K., ... P. T.-... on S. and, & 2017, undefined. (n.d.). Investigation of Performance and Power Quality of Grid-Connected Solar PV System. *Researchgate.Net* B Rai, MP Dhungyel, K Tenzin, P Tshering, T Lhendup *International Conference on Sustainable and Renewable Energy, 2017*•*researchgate.Net*. Retrieved May 30, 2025, from https://www.researchgate.net/profile/Tshewang-Lhendup-3/publication/319702387_Investigation_of_Performance_and_Power_Quality_of_Grid-Connected_Solar_PV_System/links/59ba4c270f7e9bc4ca40b874/Investigation-of-Performance-and-Power-Quality-of-Grid-Connected-Solar-PV-System.pdf
- Reliability Explainer | Federal Energy Regulatory Commission*. (n.d.). Retrieved June 4, 2025, from <https://www.ferc.gov/reliability-explainer>
- Reports – Uganda Electricity Transmission Company Limited*. (n.d.). Retrieved June 4, 2025, from <https://uetcl.go.ug/reports/>
- Solar Grid Tie Inverter Working Principle | inverter.com*. (n.d.). Retrieved June 4, 2025, from <https://www.inverter.com/solar-grid-tie-inverter-working-principle>
- Understanding Power System Islanding*. (n.d.). Retrieved May 30, 2025, from <https://blog.hubbell.com/en/hubbellpowersystems/power-system-islanding>
- UNSD, WHO, IEA, IRENA, W. B. (2021). the Energy Progress Report 2022. *Iea*, 1–273.

Visser, L. R., Schuurmans, E. M. B., AlSkaif, T. A., Fidler, H. A., van Voorden, A. M., & van Sark, W. G. J. H. M. (2022). Regulation strategies for mitigating voltage fluctuations induced by photovoltaic solar systems in an urban low voltage grid. *International Journal of Electrical Power & Energy Systems*, 137, 107695.
<https://doi.org/10.1016/J.IJEPES.2021.107695>

What is Hybrid Inverter? Understanding Its Role in Energy | BENY New Energy. (n.d.). Retrieved May 30, 2025, from <https://www.beny.com/what-is-hybrid-inverter/>

What Is Pumped Hydro Storage, and How Does It Work? (n.d.). Retrieved May 30, 2025, from <https://blog.yesenergy.com/yeblog/what-is-pumped-hydro-storage-and-how-does-it-work>