Demonstrating the Value of Generating and Sharing Data on Off-Grid Energy Systems: A Case Study from Malawi

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***Abstract*— To achieve electricity access in sub-Saharan Africa, off-grid Distributed Energy Resource Systems, such as microgrids, are required. Sustainability of these systems requires improved business models and efficient maintenance and operations frameworks. However, a lack of technical and economic data from the existing installation base hampers the necessary learning and innovation. This paper describes a case study deployment of DER systems in Malawi, demonstrating the application and benefits of high levels of instrumentation and monitoring. A proposed classification of minimum, preferred and desirable levels of data gathering and sharing is offered as a key recommendation for future DER system deployments in Malawi.**

Keywords—Microgrids, Off-Grid, DER, SDG7, Electricity Access, Rural Electrification, Remote Monitoring, Malawi

I. INTRODUCTION

Access to modern and reliable energy is crucial for economic development and the achievement of the United Nations Sustainable Development Goals (SDGs) [1]. SDG7 specifically aims to ensure access to affordable, reliable, sustainable, and modern energy for all [2]. However, sub-Saharan Africa remains the region with the lowest access to electricity, with an estimated 580 million people lacking access to electricity, according to the International Energy Agency (IEA) [3].

In this context, Distributed Energy Resource (DER) systems have emerged as a promising solution to provide energy access in sub-Saharan Africa [3] [4]. Commonly deployed types of DER are minigrids, microgrids and energy hubs; all types of small-scale electricity systems that can operate independently or in parallel with the main grid, using a combination of renewable energy sources, energy storage systems, and smart control systems [5]. These DER can provide reliable and affordable electricity to remote and off-grid communities, enabling productive use of energy (PUE), improving health and education outcomes, and supporting small and medium enterprises [6]. However, there is a lack of comprehensive information available on the in-field performance of DER in Malawi, including generation, storage, and demand data [7] [8]. Commercially available power electronics, which are often used as the control hub of off-grid DER, have built-in remote monitoring systems [9]. However, these systems have limitations, particularly in terms of environmental data and the full potential generation output, as they only monitor utilised generation.

The lack of in-field performance data presents a significant challenge to scaling up off-grid DER, as it limits the ability of stakeholders to learn from existing projects, improve system design and operation, and develop standardised services and performance metrics. This paper presents a case study of microgrid and energy hub deployment in Malawi, building the case for increased investment in data gathering and sharing in the off-grid sector. Section II provides an overview of the case-study project and the data gathering framework, Section III provides details on the way the data has been used and shared, Section IV discusses implications for the off-grid sector and Section V provides conclusions and recommendations.

II. CASE STUDY: EASE PROJECT

The Rural Energy Access through Social Enterprise and Decentralisation (EASE) project focuses primarily on SDG7 progress in Malawi and runs from October 2018 to March 2024 with funding from the Scottish Government [10]. The EASE project deployed four solar DER systems in Dedza and Balaka districts, providing electricity for domestic and productive use in rural villages. Two village microgrids target domestic and small business connections and the other two take an energy hub approach. The energy hubs have co-located agricultural (irrigation and cold storage), or educational (school building) loads, plus small set of additional domestic and small business customers. The village microgrids have a much more extensive distribution network, connecting greater numbers of domestic and small business customers. Data capture to enable learning and dissemination has been a core feature of the project [11].

A. System Data

The systems installed through EASE have central generation systems with solar photovoltaic (PV) panels, Lithium-ion battery storage and power electronics, usually housed in a shipping container. A robust outdoor router with local cellular network connection provides an Internet uplink. The inverter/charger control hubs (SMA, Victron or Growatt) have integrated remote monitoring, allowing cloud-based access and storage of system data (generation output, aggregate energy consumption, battery state of charge). This data can be logged at minutely intervals and archived on a daily or weekly basis. A key gap in the data provided by these systems is the potential generation output of the system. Only the *utilised* generation is logged (e.g. the generation output that is used to meet connected electrical load and/or used to charge battery storage), described in this paper as the microgrid power generation (MG). The full generation potential of the installed system under local weather conditions is therefore not logged and, without custom monitoring systems, remains unknown.

B. *Customer Data*

All customer connections have pay-as-you-go (PAYG) smart meters that can disconnect customers when their balance runs low, as well as setting power limits to protect the system from misuse. The village microgrids utilize a SteamaCo smart meter system [12] for managing payments and monitoring energy use. Meters at the customer point of connection communicate via radio (LoRa) to a core unit which connects the microgrid to the SteamaCo cloud platform (via its own GPRS/SMS uplink). This system allows customer management through an online interface and detailed analysis of near real-time data on revenue, demand, and smart meter uptime. The energy hub systems utilize Conlog [13] pre-paid meters that are token based and do not provide remote access or time-series logging of consumption. This makes the meters easier to deploy and manage, but data from the payment system only provides a longer term, aggregated view of customer revenue and demand (monthly at best), and detailed load profiles cannot be obtained.

C. *Custom Data*

In addition to these commercially available solutions, custom-built monitoring was deployed to capture weather data and battery temperatures. Weather data includes: ultraviolet (UV) index, solar irradiance (SI), module temperature (MT), ambient temperature (AT), relative humidity (RH), wind speed (WS), wind gust (WG), atmospheric pressure (AP), dewpoint temperature (DT), rainfall rate (RR), and wind direction (WD). A control treatment solar PV plant (120Wp) was also installed to mitigate for the partial data on generation output provided by standard system monitoring (as highlighted in Section II A). This independent small PV system located next to the main PV array had a flexible load configured so that all possible PV generation was utilised and logged. This is described as the control treatment power generation (CG).

III. APPLICATIONS

1) *Data for Maintenance, Operation and Planning*

In general, remote monitoring of DER systems, particularly in off-grid remote locations, is acknowledged as providing sustainability benefits [14] [15]. Most commercial suppliers of inverter/chargers designed to be the control hub of microgrids and other types of DER systems provide a free to use, cloud-based remote monitoring service. The service is positioned as a monitor, manage and optimise tool that allows system performance to be observed in real-time, providing early warning of faults or technical issues. With remote access, maintenance actions can be enacted without a site visit and loads managed in response to available generation. These services have been of significant value to the EASE microgrids, informing maintenance, operation, and planning procedures, as well as business modelling and future system sizing and design.

An example is provided by one of the microgrids that experienced significant downtime resulting in customer blackouts (Fig. 1). Remote access to the system data not only supported troubleshooting, pinpointing the cause as smart-meter issues arising from poor mobile reception, but also has helped track the impact on both customer satisfaction and microgrid income. While fault frequency is expected to reduce with improving mobile signal and increased smart meter product upgrades, it has been a crucial management task to track and monitor downtime in the short-term.

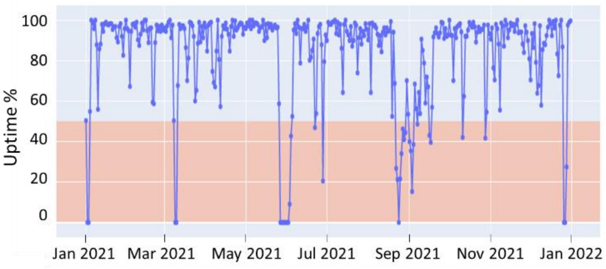

Figure 1: Microgrid System Downtime

The monitoring of battery health has also provided valuable insights into the technical performance of microgrids, as well as the impact of weather conditions on battery performance, thereby testing design assumptions. Fig. 2 shows the typical daily energy balance for one of the microgrids, revealing batteries fully charged by mid-morning, indicating excess capacity for daytime uses. Meanwhile battery capacity reached recommended depth of discharge by early morning, indicating no capacity for night-time residential customers. Analysis of this resulted in a tariff offering of a 75% discount to incentivise daytime use and increase utilisation rate.

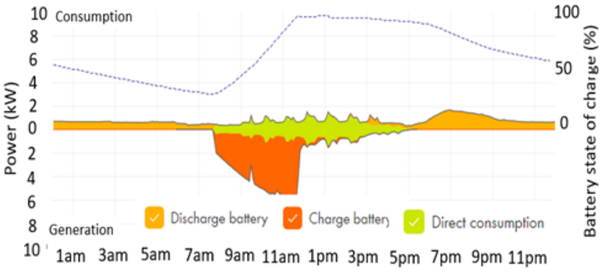

Figure 2: Typical daily battery state of charge

For the energy hub with integrated cold room, system monitoring quickly helped identify an issue with the power consumption of the refrigeration system. A temperature sensor fault meant continuous operation of the cooling unit, resulting in batteries discharging fully overnight (Fig. 3– battery daily average state of charge shown by blue line, range shown by blue shaded area.). This data also exposed an oversight by commissioning engineers where the minimum battery state of charge had been set at 5% instead of the planned 20%. Without remote monitoring, damage to the batteries could have been extensive. Similarly, monitoring battery temperatures has informed optimisation of the AC units, ensuring the storage is kept at appropriate temperatures for extended life-span and hence improved system technical and economic sustainability.

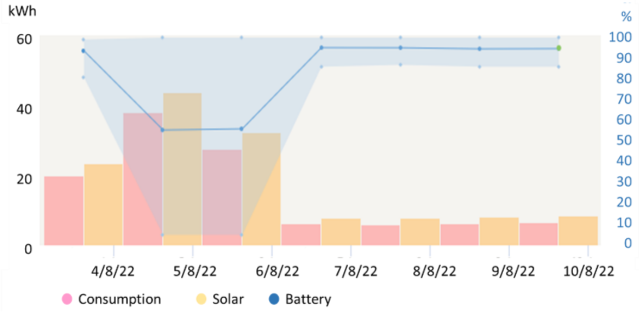

Figure 3: Energy System Performance Snapshot

2) *Data for Customer Management and Tariff Design*

The data provided by system monitoring provides a useful view of total, aggregated, load on the system. However, this provides only limited insight into customer behaviour. The aggregated load profile includes appliances at the generation hub (AC units, ICT equipment, room lighting, etc), making disaggregating customer load profiles challenging. Smart meter data allows analysis of consumption patterns for individual customers that can be used to build up statistical profiles (Fig. 4) and cluster customers into segments using a range of demographic metrics (Fig. 5) – an essential aspect of electricity network planning [16] [17].

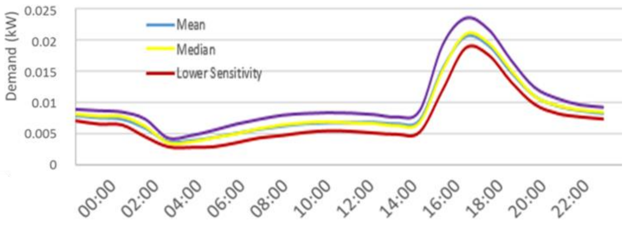

Figure 4: Microgrid Aggregate Load Profiles

The EASE project used this data to identify high and low consumption users across residential, business, and social institution customers, adapting tariff offerings to accommodate the needs of all.

The SteamaCo platform used on the microgrids and the Conlog meters used at the energy hubs have different strengths and weaknesses. The SteamaCo smart meters offer a more innovative and flexible solution with remote switching and data logging, allowing for real-time monitoring and troubleshooting of the microgrid. In terms of data granularity, the SteamaCo platform provides more detailed and frequent data compared to the Conlog meters, which have a lower sampling frequency and offer less detailed data on customer behaviour. On the other hand, the Conlog meters are more reliable and easier to install, as they do not require a cellular network connection. They also provide a more straightforward solution for metering and billing, which may be beneficial for certain DER applications in areas with poor cellular network coverage.

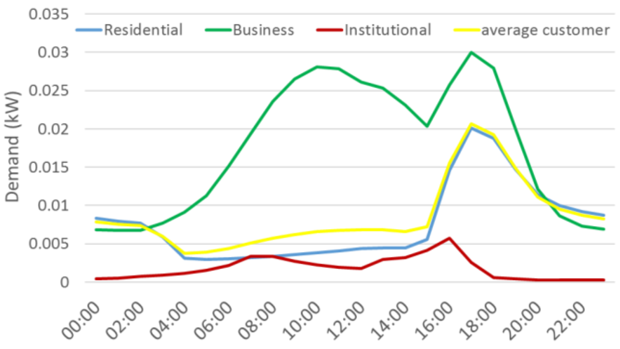

Figure 5: Microgrid Demand Profiles by Customer Class

Although at the moment payments are facilitated through site agents, both platforms can accommodate customers buying top-up with their mobile phones, which is a convenient and accessible feature. Both metering systems provide data that allows analysis of Average Revenue Per User (ARPU) (Fig. 6).

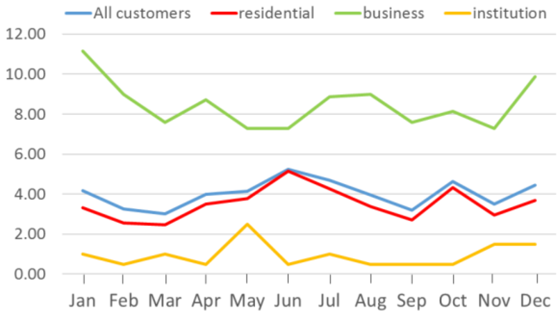

Figure 6: Monthly Average Revenue per User (ARPU) (USD)

ARPU provides insights into the actual Willingness To Pay (WTP) of rural customers. This can differ significantly from that indicated in initial feasibility assessments. For the first EASE microgrid, the tariff was designed based on community surveys; however, on implementation it was deemed too high by the community, resulting in complaints and subsequent negotiations to find an acceptable tariff.

3) *Data for Advanced Research*

The installed weather station, additional temperature monitoring and solar PV control treatment plant have been used to support a range of research projects. The example presented here focussed on predicting microgrid generation output based on weather conditions and the partial generation data provided by standard system monitoring. In this work, the CG dataset was used to 1) identify the weather parameters with most correlation to power generation and 2) to establish the section of the MG dataset representing the full output potential of the microgrid generation plant. The latter was then used to build a model that could forecast the potential MG power for the whole day.

A sample of correlation results between the CG dataset and the MG dataset for January 2022 on an hourly basis is depicted in Fig.7. There is a statistically significant correlation (over 0.91) between CG and MG datasets from 05:00 to 09:00 and from 17:00 to 18:00. Based on these results, MG data from high correlation periods were utilised to build and train a machine-learning-based prediction model. A simple linear regression (LR) model was employed as in [18] with a set of the top 5 correlating weather parameters chosen as inputs and historical microgrid data as target outputs [19] [20].

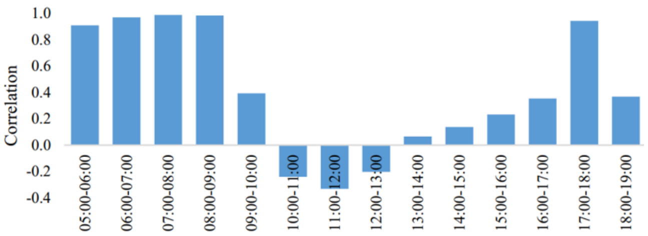

Figure 7: Hourly correlation between control treatment solar PV plant and microgrid power generation outputs

Fig.8 shows that the measured and the predicted microgrid power generation outputs closely match throughout the morning (up to around 10:00) on partly cloudy and mostly clear days, with more potential power generation remaining unrecorded for the rest of the day. This matching is substantially longer in overcast/rainy and cloudy conditions, suggesting that the power generated is only just enough to sustain the load and battery bank.

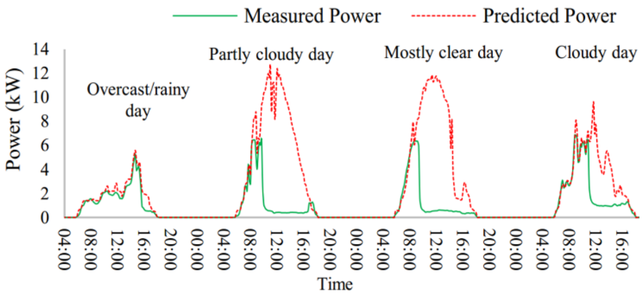

Figure 8 Microgrid power generation profiles (measured and predicted)

The lost potential energy yield was then estimated by evaluating and comparing the area under each power generation profile. Fig. 9 depicts the recorded and predicted daily energy production for January 2022 as a sample result. These figures reveal daily average energy yields of 20.44 kWh and 56.17 kWh for the recorded and predicted, respectively. These values translate to monthly energy yields of 634 kWh and 1,741 kWh for the recorded and predicted, representing an unused potential energy yield of 64%.

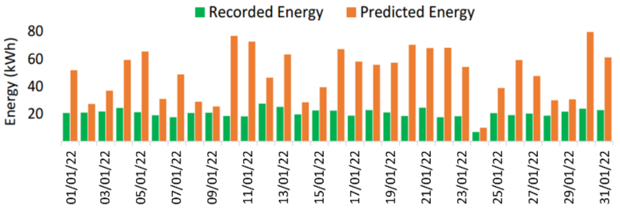

Figure 9: Recorded and Predicted Daily Energy Yields

4) *Platforms for Data Sharing*

Data acquisition, analysis, and sharing are critical for solar microgrid developers to understand the technical, economic, and social impact performance of microgrids, ultimately informing business strategies for scaling microgrid operations. The lack of data sharing platforms has been identified as a significant barrier to the acceleration of microgrids [21], preventing the exchange of knowledge and best practices, hindering the improvement of technical design and business models, and hampering informed policymaking. Therefore, the development and use of data visualisation platforms can help overcome these barriers, improving the sustainability and scalability of microgrids in developing countries.

Strathclyde University has developed a data visualisation platform utilising EASE primary microgrid data that enables easy monitoring and evaluation of data to understand microgrid performance [22]. Technical indicators are mostly gathered via the Sunny portal API and include PV generation, consumption, battery temperature, system downtime, and system efficiency. Carbon savings are calculated following the UNFCCC methodology for mini-grids [23]. Demand indicators include revenue, monthly demand and hourly load profiles, which show energy use for single customer segments and the whole microgrid. Social impact indicators are taken from analysis of enumerator surveys and show customer responses to questions on the impact of the microgrid on their quality of life. The platform offers a detailed description of each indicator and an option to download the data as a spreadsheet. The data analysis presented through the tool aims to deepen the understanding of the microgrid's performance and help remove barriers to scaling up of microgrids and other decentralised renewable energy infrastructure. The findings also contribute to the business and operational planning concerned with future microgrids deployed as part of the EASE project.

IV. IMPLICATIONS FOR OFF-GRID ENERGY ACCESS IN MALAWI

The learning from the EASE project highlights the importance of investing in high levels of data capture and sharing to support the scale-up of the off-grid sector in Malawi. The benefits are presented from two perspectives. Firstly, quality system monitoring and demand data offers improved sustainability, which in turn leads to more efficient and cost-effective operation of microgrids. Secondly, increased instrumentation opens up new research potential and opportunities for innovation. Minimum, preferred and desirable data gathering and sharing levels are suggested here for off—grid energy projects in Malawi.

A. Mimimum Data

As a minimum requirement, the native system data monitoring included within most commercial inverter/charger offerings must be used effectively. The additional expense of providing Internet access to a site for remote monitoring is usually a small proportion of overall project costs. Using the EASE example of system downtime, the native system monitoring enabled the quantification of the impact of downtime on microgrid financials and customer satisfaction, and informed robust mitigation strategies. Prioritizing minimum data gathering means microgrid operators can improve maintenance and operations to enhance customer satisfaction and profitability.

B. Preferred Data

Load profiles and customer segment demand are of particular value and relevance to microgrid operators in Malawi. Insight into the electricity use of previously unconnected communities is rare, and understanding daily and seasonal demand, along with load growth over time, is essential for optimising future microgrid technical and business designs. Along with promoting data sharing of pilot load profiles, further research comparing measured load profiles of specific customer segments to baseline survey responses will provide greater accuracy in predicting customer segment demand. Continuous assessment of WTP is crucial to finding optimal tariff levels that ensure customer satisfaction and sustainable levels of electricity consumption, thereby avoiding further impoverishment of communities.

C. Desirable Data

In addition to native system monitoring and smart meter data, adding further instrumentation to microgrid deployments opens the door for local research and innovation. The EASE project has demonstrated the value of recording site specific weather parameters and solar PV output, along with battery temperature monitoring and PUE specific monitoring. The associated research project provided valuable insight on unused generation capacity and methods for forecasting PV generation output based on local weather parameters. The design of instrumentation at this level is difficult to standardize and should be determined in collaboration with local research institutions.

V. CONCLUSIONS AND RECOMMENDATIONS FOR THE SECTOR

The market for off-grid DER systems in Malawi, e.g. solar microgrids, is nascent with significant growth potential. Currently, there is no proven sustainable business model for DER developers in the country and the lack of economic, demand, and operational data are challenges stymying the sector. Detailed monitoring of electrical grids is not a novel concept; however, in this context it appears to be rare and undervalued. Further action research involving pilot projects is needed to grow local capacity in 1) deploying and operating systems that generate high quality data, and 2) developing evidence-based business models that reduce the risk to investors. However, pilot projects are only of value where they place a strong focus on data sharing. The lack of data sharing platforms and standardised data collection practices remains a barrier to accelerating DER deployment in Malawi. The development of shared platforms that promote data accessibility and analysis should be a priority for DER developers, policymakers, and researchers. Such platforms will enable better coordination of DER deployment, facilitate knowledge-sharing, and lead to more informed decision-making

In conclusion, this study calls for increased investment in data acquisition and analysis for off-grid energy systems in Malawi. In particular, government and donor subsidized programs should mainstream data capture and sharing when funding pilot projects; adopting a minimum, preferred and desirable data capture framework similar to that described in this paper. These findings and recommendations are applicable to energy access programs across SSA. Through improved data sharing and analysis, policymakers, academics and practitioners can better understand the needs of rural communities and design more effective off-grid energy access programs that deliver on SDG7 targets and improve the quality of life for underserved populations.

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REFERENCES

[1] United Nations Department of Economic and Social Affairs, "The Sustainable Development Goals Report," 2018.

[2] IEA, IRENA, UNSD and the World Bank, "Tracking SDG 7 – The Energy Progress Report," ESMAP, 2022.

[3] International Energy Agency, "Africa Energy Outlook," Paris, 2022.

[4] World Bank, November 2022. [Online]. Available: https://www.worldbank.org/en/news/press-release/2022/11/09/world-bank-group-announces-major-initiative-to-electrify-sub-saharan-africa-with-distributed-renewable-energy. [Accessed May 2023].

[5] S. C. Bhattacharyya and D. Palit, Mini-Grids for Rural Electrification of Developing Countries: Analysis and Case Studies from South Asia, Swtizerland: Springer, 2014.

[6] REN21, "Renewables 2018 Global Status Report," Paris, 2018.

[7] K. N. D. O. Mavuto H. Banda, "Performance evaluation of 830 kWp grid-connected photovoltaic power plant at Kamuzu International Airport-Malawi," *Energy for Sustainable Development,* vol. 51, pp. 50-55, 2019.

[8] A. Eales, E. Banda, G. Taulo, W. Coley and D. Frame, "Deploying Solar Microgrids in Malawi: Lessons Learned and Implications for the Malawian Microgrid Ecosystem," University of Strathclyde, Glasgow, 2022.

[9] Regen Power, [Online]. Available: https://regenpower.com/remote-monitoring-of-a-rooftop-solar-system-performance/. [Accessed May 2023].

[10] The University of Strathclyde, [Online]. Available: https://ease.eee.strath.ac.uk/about/. [Accessed May 2023].

[11] The Scottish Government, "Scottish Government International Development Programme: End of Year Report," Edinburgh, 2021.

[12] SteamaCo, [Online]. Available: https://steama.co/off-grid-smart-metering-platform. [Accessed May 2023].

[13] Conlog, [Online]. Available: https://conlog.com/about/. [Accessed May 2023].

[14] P. Dauenhauer, D. Frame, S. Strachan, M. Dolan, M. Mafuta, D. Chakraverty and J. Henrikson, "Remote Monitoring of Off-Grid Renewable Energy: Case Studies in rural Malawi, Zambia, and

Gambia," in *IEEE Global Humanitarian Technology Conference (GHTC)*, 2013.

[15] P. D. T. C. Million Mafuta, "Small Scale Rollout of PV Systems in Chikwawa District, Malawi: Remote Monitoring System Effectiveness," *Journal of Solar Energy,* 2017.

[16] British Electricity Board, "Report on statistical method for calculating demands and voltage regulation on L.V. radial distribution systems, A.C.E. report No. 49," 1981.

[17] P. H. S. W. D. McQueen, "Monte Carlo simulation of residential electricity demand for forecasting maximum demand on distribution networks," *IEEE Transactions on Power Systems,* vol. 19, pp. 1685-1689, 2004.

[18] C.-Y. P. e. al., "Inverter Efficiency Analysis Model Based on Solar Power Estimation Using Solar Radiation," *Processes,* vol. 8, p. 1–19, 2020.

[19] Z. C. a. Q. Z. W. Ma, "Ultra-Short-Term Forecasting of Photo-Voltaic Power via RBF Neural Network," *Electronics,* vol. 9, pp. 1-19, 2020.

[20] H. Z. X. L. a. X. G. P. Jia, "Short-Term Photovoltaic Power Forecasting Based on VMD and ISSA-GRU," *IEEE Access,* vol. 9, p. 105939–105950, 2021.

[21] J. T. Lee, J. Freitas, I. L. Ferrall, D. M. Kammen and D. S. Callaway, "Review and Perspectives on Data Sharing and Privacy in Expanding Electricity Access," *Proceedings of the IEEE,* vol. 107, 2019.

[22] The University of Strathclyde, [Online]. Available: https://malawi-microgrids.herokuapp.com/. [Accessed May 2023].