TECHNO-ECONOMIC ANALYSIS OF TRANSITIONING OFF-GRID PHOTOVOLTAIC (PV) SYSTEMS TO ON-GRID OPERATION IN RURAL SARAWAK

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MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

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DECLARATION

I declare that this thesis entitled "Techno-Economic Analysis of Transitioning Off-Grid Photovoltaic Systems to On-Grid Operation in Rural Sarawak" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature	:...
Name	: Amy Chin Swin Yee
Date	: 24/02/2026

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality as a partial fulfillment of Master of Science in Electrical Engineering.

Signature : ....

Supervisor Name : Professor Ir. Dr. Gan Chin Kim

Date : 24 / 2 / 2026

DEDICATION

To my beloved mother and father.

ABSTRACT

In recent years, rural electrification in Malaysia, particularly in Sarawak, has experienced significant development driven by both off-grid and grid-based solutions. To overcome the challenges of remote locations, rugged terrain, and low population densities, off-grid photovoltaic (PV) systems have been deployed under initiatives such as the Sarawak Alternative Rural Electrification Scheme (SARES) to provide basic electricity access. However, with the continued expansion of the main grid into interior regions, many areas previously served by standalone PV systems are gradually being integrated into the grid network. Despite this, these off-grid solar systems are often unconnected to the grid due to concerns about their potential impact on grid operations and performance under varying conditions. This thesis presents a comprehensive strategy for the technical and economic assessment of the implications of transitioning from off-grid to on-grid electricity supply in rural areas. The developed methodology is based on real-world case studies of two rural sites in Sarawak, selected based on key parameters such as distribution voltage level (33kV and 11kV), installed PV capacity, and population density. From a technical perspective, the study involved network modeling and power flow simulations using DIgSILENT PowerFactory software to analyse voltage behaviour and power losses under various load and PV penetration scenarios. Simulation results show that 33kV networks experience lower voltage rise and better stability due to lower current flow per unit of power delivered. In contrast, 11kV feeders demonstrated potential voltage excursions beyond ±5% of nominal voltage, especially under conditions of light loading and high PV injection, highlighting the need for careful voltage regulation planning. In terms of economics, the study compared the annualised cost per household for off-grid solar systems with that of grid extension under various conditions, including scenarios with and without road access. Findings indicate that grid extension is more cost-effective in areas with existing infrastructure and high load density. However, in remote and sparsely populated areas, off-grid systems remain the more financially viable option due to the high costs of grid extension and maintenance. The results of this study confirm that voltage levels, load density and accessibility are critical in determining the most appropriate electrification approach. This developed strategy enables technical and economic evaluation of rural electrification options, supporting informed decision-making for utilities and policymakers. In conclusion, coordinated technical planning combined with structured cost analysis is essential to facilitate a smooth, efficient and sustainable transition from off-grid to on-grid systems for remote rural areas in Malaysia.

ANALISIS TEKNO-EKONOMI PERALIHAN SISTEM FOTOVOLTAIK TIDAK TERSAMBUNG GRID KEPADA SISTEM GRID DI LUAR BANDAR SARAWAK

ABSTRAK

Kebelakangan ini, usaha electrifikasi luar bandar di Malaysia, khususnya di Sarawak, telah mengalami perkembangan pesat yang didorong oleh perlaksanaan kaedah luar grid and grid. Bagi mengatasi cabaran berkaitan lokasi terpencil, bentuk muka bumi yang bercabar, dan kepadatan penduduk yang rendah, sistem fotovolta (PV) berdiri sendiri telah dilaksanakan di bawah inisiatif seperti Skim Elektrifikasi Luar Bandar Alternatif Sarawak (SARES) bagi membekalkan elektrik asas kepada komuniti terpencil. Walau bagaimanapun, dengan perkembangan progresif rangkaian grid ke kawasan pedalaman, kawasan yang sebelum ini dilayani oleh sistem PV berdiri sendiri kini secara beransur-ansur beralih ke grid. Namun begitu, sistem PV berdiri sendiri ini sering tidak disambungkan ke grid kerana kebimbingan terhadap potensi kesannya terhadap operasi dan prestasi grid. Tesis ini membentangkan satu strategi komprehensif untuk penilaian teknikal dan ekonomi terhadap implikasi peralihan daripada bekalkan electrik luar grid kepada sistem grid di kawasan luar bandar. Kaedah kajian ini berdasarkan kajian kes sebenar di dua lokasi luar bandar di Sarawak, yang dipilih berdasarkan parameter utama sperti tahap voltage pengagihan (33kV dan 11kV), kapasiti PV yang dipasang, dan kepadatan penduduk. Dari aspek teknikal, kajian ini melibatkan pemodelan rangkaian dan simulasi aliran kuasa menggunakan DIgSILENT PowerFactory bagi menganalisis tingkah laku voltan dan kerugian tenaga di bawah pelbagai senario beban dan penembusan PV. Hasil simulasi menunjukkan bahawa rangkaian 33kV mengalami kenaikan voltan yang lebih rendah dan kestabilan yang lebih baik daripada rangkaian 11kV kerana aliran arus yang lebih rendah bagi setiap unit kuasa yang dihantar. Sebaliknya, rangkaian 11kV menunjukkan kemungkinan berlakunya voltan melebihi had yang ditetapkan oleh Kod Grid Negeri Sarawak, terutamanya di bawah keadaan penembusan PV yang tinggi dan beban yang ringan. Penemuan ini menekankan kepentingan penilaian profil voltan, kapasiti pengumpan dan keadaan aliran kuasa semasa merancang proses peralihan. Dari aspek ekonomi, kajian ini membandingkan kos tahunan setiap isi rumah antara sistem solar berdiri sendiri dengan sambungan grid di bawah pelbagai keadaan, termasuk senario dengan dan tanpa akses jalan. Dapatan kajian menunjukkan bahawa sambungan grid lebih menjimatkan di kawasan yang mempunyai infrastruktur sedia ada dan kepadatan beban yang tinggi. Walau bagaimanapun, di kawasan terpencil dan berpenduduk jarang, sistem PV berdiri sendiri kekal sebagai pilihan yang lebih berdaya saing dari segi kewangan berikutan kos sambungan dan penyelenggaraan grid yang tinggi. Hasil kajian ini mengesahkan bahawa tahap voltan, ketumpatan beban dan penyediaan infrastruktur jalan adalah faktor kritikal dalam menentukan pendekatan elektrifikasi yang paling sesuai. Strategi yang dibangunkan ini boleh berfungsi sebagai alat sokongan keputusan yang praktikal bagi perancang utiliti dalam projek electrifikasi luar bandar. Kesimpulannya, perancangan teknikal yang diselaras dan disokong oleh penilaian ekonomi yang berstruktur adalah penting bagi memastikan peraliran yang lancar, cekap dan mampan daripada sistem PV berdiri sendiri kepada sistem sambungan grid di kawasan luar bandar.

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LIST OF ABBREVIATIONS

DER	-	Distributed Energy Resource
SARES	-	Sarawak Alternative Rural Electrification Scheme
RES	-	Rural Electrification Scheme
PV	-	Photovoltaics
ADMD	-	After Diversity Maximum Demand
ABC		Aerial Bundled Cables
SFC		System Fault Ceiling
LV	-	Low Voltage
HV	-	High Voltage
LT	-	Low Tension
HH	-	Households
FRT	-	Fault Ride-Through
O&M	-	Operation and Maintenance
NPC	-	Net Present Cost
CRF	-	Capital Recovery Factor

LIST OF SYMBOLS

Ip	-	Short-Circuit Surge Current
Ik’’	-	Initial Symmetrical Short-Circuit Current
Ik	-	Uninterrupted Short-Circuit Current
p.u.	-	Per Unit
km	-	Kilometer (length)
kV	-	Kilovolt
kVA	-	Kilovolt-ampere (Apparent Power)
kW	-	Kilowatt (Real Power)
kA	-	Kiloampere
%	-	Percentage
kWh	-	Kilowatt-hour (Energy)
W/m^2	-	Watt per square meter (solar irradiation)

LIST OF PUBLICATIONS

The following is the publication related to the work on this dissertation/master project/project paper:

S. Y. A. Chin, C. K. Gan and C. W. Ajan, "Impact of PV Penetration on Grid Transition in Sarawak's Remote Villages," *2024 IEEE Sustainable Power and Energy Conference (iSPEC)*, Kuching, Sarawak, Malaysia, 2024, pp. 1-5, doi: 10.1109/iSPEC59716.2024.10892467.

CHAPTER 1

INTRODUCTION

1.1 Background

In 2015, the United Nations General Assembly (UN-GA) launched the Sustainable Development Agenda 2030 (Agenda 2030), calling on the global community to collectively work toward achieving sustainable development for all by the year 2030 (UN, 2015). One of the key components of this agenda is Sustainable Development Goal (SDG) 7, which aims to ensure universal access to affordable, reliable, sustainable, and modern energy. According to the 2025 Tracking SDG 7 Report, global electrification efforts have made significant progress, with access rising to 92% worldwide (World Bank, 2025). However, as countries approach universal access, the remaining unelectrified populations represent the most difficult and costly groups to reach. These "last mile" communities are typically located in remote, sparsely populated, and geographically complex areas. Many are situated in mountainous regions, along river valleys, or spread across widely dispersed settlements, which makes grid extension both technically difficult and economically costly.

In response to these challenges, Distributed Energy Resources (DERs), particularly those based on renewable energy technologies such as small hydro, solar, and wind, have gained widespread attention within the energy sector. DERs can be deployed either as grid-connected systems at the distribution level or as standalone configurations. For instance, Shah et al. (2018) claimed DERs as one of the most viable solutions for electricity generation in remote and inaccessible areas.

Across the ASEAN region, countries have made substantial progress toward full electrification, with most achieving nationwide 100% coverage. However, a few countries like Cambodia and Myanmar continue to face challenges in reaching the remaining unelectrified communities (ACE, 2024). Although Malaysia is officially reported to have reached full electrification, regional disparities persist, particularly in East Malaysia. In Sarawak, electrification challenges remain due to its vast land area, mountainous interior, and widely scattered rural settlements.

To accelerate progress, the Sarawak government introduced the Rural Power Master Plan alongside the launch of the SDGs, targeting full electrification by 2025. As part of this effort, the Sarawak Alternative Rural Electrification Scheme (SARES) was launched in March 2016 to complement existing initiatives such as the Rural Electrification Scheme (RES), the Hybrid Scheme, and the Rural Power Supply Scheme (RPSS). SARES utilises standalone solar battery systems to deliver 24-hour electricity to remote communities located far from the grid. Through the implementation of these combined efforts, the electricity coverage in rural Sarawak has achieved about 96.5% throughout Sarawak in early 2022 as compared with 2009 when rural electricity coverage was only at 56% (Sarawak Energy, 2022).

Despite these achievements, SARES systems are still considered as the temporary electrification solution (Sarawak Energy, 2021). From the utility's perspective, grid extension remains the preferred long-term approach for delivering a stable and scalable electricity supply to rural communities. The concern arises that once the grid reaches these remote villages, the existing DER systems, particularly standalone solar PV with batteries are expected to be disconnected and abandoned due to potential grid interconnection challenges and operational risks. This situation not only results in underutilised assets but also represents a missed opportunity to harness the grid-support potential of DERs.

Grid-connected PV systems are capable of providing multiple grid-support services that could be highly beneficial in rural networks. The integration of PV help stabilise voltage through reactive power control and improve power quality by mitigating issues such as unbalanced loading, harmonics, and voltage flicker. Additionally, it can enhance local grid resilience by supporting the network during disturbances. While these capabilities are widely discussed in the context of urban or suburban networks, their potential contribution within rural electrification, particularly in communities transitioning from off-grid to on-grid supply, remains largely underexplored. Most rural electrification efforts globally have focused on standalone PV systems rather than examining their potential secondary role once the main grid arrives. This gap highlights the need for a structured evaluation of how existing solar-battery systems can be repurposed or integrated into the grid to provide technical and economic benefits.

Therefore, a strategy approach is essential to examine the technical performance and economic viability of reusing existing solar battery systems in grid-connected settings. Such an approach could help maximise the long-term value of rural DER investments while mitigating any adverse impacts on the stability and reliability of the broader power distribution system.

1.2 Research Motivation

The Sarawak government has been supplying rural villages with standalone solar battery systems since 2016. With the continued grid expansion into these areas, many of these villages are expected to be connected to the main grid. To prevent grid interference by other sources, the existing solar battery systems typically be disconnected from the load, leaving them unused despite still being in good condition. Re-utilise and re-purpose these solar battery systems to function within the grid-connected environment can be a good alternative. However, the uncertain impacts of these solar battery systems on the grid's performance need to be disclosed justifying local power utilities the benefit of transitioning off-grid to on-grid systems.

This research is motivated by the need to address this knowledge gap. It aims to develop a comprehensive strategy for transitioning from off-grid to on-grid systems, focusing on the technical and economic feasibility of reusing existing distributed energy resources in rural areas. By evaluating how these systems can be effectively integrated without compromising grid performance, the study provides valuable insights and justification for local power utilities and policymakers to support informed decision-making in rural electrification planning.

1.3 Problem Statement

To date, more than 428 villages in interior Sarawak are benefiting from the SARES, which provides off-grid solar battery systems to remote communities. However, with the ongoing expansion of the RES grid lines into these areas, there is potential for many of these villages, including those already equipped with standalone solar systems to be connected to the main grid. In such cases, the previously installed off-grid solar systems risk being left unused, despite many of them still operating in good condition. Additionally, due to the limited energy usage of 2kWh and the villagers returning mainly during festival seasons or major events while being away on weekdays for work in town, the systems are frequently underutilised. Chong et al. (2020) revealed that the average energy utilisation rate of the SARES system ranged between 55% and 66% in Long Bedian and Katibas areas.

Apart from that, the research regarding the feasibility of off-grid DER as compared with grid connection is still considered lacking in the context of rural electrification in Sarawak. It is commonly understood that longer distribution lines result in higher electricity losses and greater voltage drops. Extending the grid to rural areas typically incurs significantly higher costs compared to urban regions, due to low population density, lower energy demand, and the need for long-distance distribution lines across challenging terrain. Off-grid systems on the other hand can bypass these issues but they may involve high operational costs, especially the limited lifespan of key components such as inverter and batteries. Given these trade-offs, a comprehensive techno-economic assessment is necessary to determine whether rural villages should be connected to the grid or continue operating in off-grid mode.

Conventional grid systems are designed for centralised power flow with electricity flowing from the generation to the load. The bi-directional flow of electricity by distributed energy resources is not in the initial plan of grid construction. This presents operational challenges for utility companies, particularly in maintaining voltage quality and system reliability in response to dynamic DER behaviour.

While various research studies have examined DER integration in either off-grid or on-grid contexts for rural electrification, limited research has focused on the transitional phase between these modes, specifically how off-grid DERs can support grid operations once connected. Most research efforts, such as those by Mamaghani et al. (2016), Chambon et al. (2020), and Ali F et al. (2021) have primarily focused on the standalone feasibility or grid connectivity, with little emphasis on the potential for DERs to provide ancillary services or technical support to the main grid during or after integration.

1.4 Research Hypothesis and Research Questions

i. Solar battery systems can be utilised to improve the reliability and resilience of the rural electricity grid.

ii. The integration of solar battery systems can provide grid support including electricity loss reduction, voltage profile improvement, load factor improvement, etc.

The research questions to be addressed throughout the research include: -

i) What applications can standalone solar battery systems offer after grid arrival?

ii) How do standalone solar battery systems impact the utility grid once grid-connected?

iii) Will it be reliable and feasible to use standalone solar battery systems to provide electricity supply to rural villagers compared to the conventional rural method?

1.5 Research Objectives

This research aims to propose comprehensive strategies for evaluating the transition from off-grid solar systems to on-grid electricity supply in rural Sarawak. The research objectives are:

i) To evaluate the technical performance of SARES standalone solar systems after their transition from off-grid operation to connection with the on-grid supply.