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Evaluating microgrid business models for rural electrification: A novel framework and three cases in Southeast Asia

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Introduction

Since 1990, the Asia-Pacific region has moved more than 80 % of its population out of poverty (UNESCAP, U, 2018). However, the region remains a focal point for sustainable development research (Asian Development Bank, 2013). Linkages between economic development and electricity access have been incorporated into the region's responses to global challenges, with climate change and sustainability concerns chief among them (ACE, 2017). In the Asia-Pacific sub-region of Southeast Asia, the Association of Southeast Asian Nations (ASEAN) is home to the 10 ASEAN member economies.[1] ASEAN, has targeted universal electricity access among their many climate and energy targets (ACE, 2020). Roughly 50 % of the ASEAN population lives in rural environments, and today less than 10 % of the population remains without access to reliable & affordable electricity (ACE, 2023). Here, remain many unconnected communities with limited or no grid access and stranded energy services, with electrification rates extremely stratified depending on rural versus urban areas (IEA, 2022a).

Distributed energy systems (DES) generate and distribute electricity locally, rather than relying on a centralized power grid (IEA, 2022b). DES often utilise renewable energy sources such as solar, wind, and hydro power, and can be more cost-effective than traditional grid-based systems (NERC, 2017). These systems are crucial in providing electricity to communities underserved by centralized grids, for example in island or rural settings with poor grid infrastructure (IRENA, 2019a). DES can be implemented in a variety of ways, including using micro-grids - defined as a form of electricity network that is either partly or wholly isolated from the main electricity grid, and commonly delineated by their grid connected and off grid variants (Borghese et al., 2017). This is particularly relevant in ASEAN, where many rural communities still rely on expensive and environmentally damaging diesel generators. Bloomberg New Energy Finance recently estimated that more than 339 million people in South and Southeast Asia have no or limited electricity access, and that micro-grids would likely constitute 44 % of future connections (BNEF, 2022). More than 16,000 micro-grids have been installed to date in these regions, however many are reliant upon diesel, are not compatible or able to connect to the main grid and operate for a limited number of hours per day (ESMAP, 2019). In the terminology of the World Bank Energy Sector Management Assistance Program (ESMAP), these micro-grids constitute the 'first and second generation' of [micro-grids]" (ibid).

However, a third generation of renewable micro-grids – those which provide round the clock, reliable power - have begun to be installed in ASEAN, using a mix of micro hydro, solar and battery storage and micro-wind systems. Indeed, a recent report by the Alliance for Rural Electrification (ARE) (ARE, L, 2020, p. 1) argues that renewable micro-grids *"without ambiguity have significant environmental, practical, economic and socio-economic merits over grid expansion."* In ASEAN island nations this is particularly relevant, as geographical constraints have impacted grid-connection among rural communities. Renewable micro-grids can therefore enable 'reliable and affordable electricity access', achieving Sustainable Development Goal (SDG) 7 (Delina, 2023). However, to achieve this expansion of renewable micro-grids, the International Renewable Energy Agency (IRENA) argue that replicable business models which can attract finance (IRENA, 2019b), leverage local supply chains and empower communities to maintain and benefit from these systems (IRENA & SELCO, 2022), are now needed.

This need to rapidly expand renewable micro-grids (BNEF, 2022), and the often short lifespan of these projects, including in the ASEAN region (Derks & Romijn, 2019), suggest that new research on effective micro-grid business model design is needed. In this paper we explore this challenge, through a detailed study of the business models of rural micro-grid projects in three ASEAN nations; Vietnam, Malaysia, and the Philippines, using a mix of quantitative financial modelling and qualitative methods. Our aim is to characterise the core elements of these business models, providing insights about their successful features. We

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believe these general insights provide an important contribution to policy debates surrounding how renewable micro-grids can be expanded in remote areas. Moreover, we make a conceptual contribution to the energy and sustainable development literature, by proposing a 'micro-grid business models evaluation framework', which could be a useful tool for future scholars looking to study and compare these projects.

The paper is structured as follows. Literature review micro-grid business models section reviews the literature on micro-grid business models before proposing a novel evaluation framework. Methodology section outlines our mixed methods case study methodology, operationalising this framework. Results section outlines the results from our three micro-grid case studies. Discussion: developing business models for ASEAN rural electrification section discusses general principles for micro-grid business models their including policy implications. Conclusions section provides conclusions and recommendations for future research.

Literature review micro-grid business models

Business models are a holistic concept, which allow researchers and practitioners to neatly conceptualise the value that an organisation, project or firm creates, how this value is created through products and services and associated supply chains, how the organisation interfaces and engages with its customer base, and the financial model for capital expenditure, revenue creation and capture (Teece, 2010). More recently authors have also emphasised the importance of business model governance in managing and organising these processes (Brown, 2018). The business model perspective is, therefore, increasingly used in energy research to categorise, evaluate and problematise alternative approaches to providing energy services (Adams et al., 2021). This suggests that effective business models are of central importance for accelerating the energy transition (Bidmon & Knab, 2018).

The United Nations SDG 7 aims to ensure access to affordable, reliable, sustainable, and modern energy for all by 2030 (UNEP, 2017). To achieve this goal, innovative business models are being explored as a solution (Vanadzina et al., 2019). These models offer the potential for increased energy access, lower carbon emissions, and improved energy security, particularly in remote and rural areas where the cost of extending the main grid is prohibitive (IRENA, 2019a). Furthermore, electricity access helps promote wider sustainable development goals by enabling economic, health, education, and communication opportunities (IRENA & SELCO, 2022).

While the micro-grid engineering research literature is significant, there has been much less focus on the underlying business models for micro-grids (Gordijn & Akkermans, 2007). The handful of studies which adopt this approach, focus on cost optimal system design configurations in specific locations (Avilés et al., 2019; Sanz et al., 2014; Villa & Henao, 2022) or how techno-economic parameters interact with public policies (Hanna et al., 2017). A handful of studies identify different micro-grid business models (Jolly et al., 2012), developing typologies differentiated by whether they are grid connected or autarkic (Müller et al., 2011; Singh, 2016) their level of decentralisation and their payment and ownership structure (Asmus & Lawrence, 2016; Borghese et al., 2017; Falchetta et al., 2022; Napoli et al., 2014; Vanadzina et al., 2019; Yadav et al., 2019). Only Vanadzina et al., (2019) and Bâra and Oprea (2023) highlight the importance of 'community governance' in developing micro-grid business models, despite its emphasis in the wider energy access and development literature (Bhattacharyya, 2012; Derks & Romijn, 2019; Mandelli et al., 2016). Moreover, there remains a lack of standardisation to the study of micro-grid business models making comparisons between locations and contexts difficult.

This review of the limited micro-grid business model literature, highlights two gaps. Firstly, there presently exists no standardised framework for studies to compare different microgrid business models – which have been shown to vary significantly in off-grid systems (cf. Hanna et al., 2017; Vanadzina et al., 2019). Second, few of these studies provide recommendations for the effective design and implementation of microgrids using a business model lens (cf. Gordijn & Akkermans, 2007). We believe that a synthesis of these factors is needed to advance and standardise the evaluation and study of micro-grid business models in the rural electrification context – providing a template for the study and development of micro-grids in the future. In the following sections we outline our approach which combines Brown et al.'s (2019) five part qualitative framework for the analysis and comparison of different business models, with a simple technoeconomic analysis using the HOMER software (e.g., Veilleux et al., 2020). Here we review relevant literature from the micro-grid and energy access field to elucidate the important features and potential success factors for micro-grid business models, using Brown et al.'s (2019) five business model elements: value proposition; customer interface; supply chain; financial model; and business model governance.

Value proposition

Rural electrification programmes are primarily concerned with bringing power to communities previously without access, or improving their level of electrification, as embodied in the 0–5 World Bank Multi-Tier Framework (MTF) (The World Bank Group, 2015). The MTF provides a comprehensive approach to measuring and understanding energy access based on the level of electricity service available to households and businesses. This framework divides electricity access into five tiers, ranging from no access (Tier 0) to full access to reliable and high-quality electricity (Tier 5). Micro-grid projects usually involve an improvement in the MTF level as the core value proposition. However, this may be starting from a very low base and few islanded micro-grids are designed to offer a Tier 5 or grid parity level of electricity access (Narayan et al., 2019).

A second consideration is the extent to which electrification connotes full energy access. As demonstrated by Bhattacharyya (2012) most energy used by rural Indian households is for cooking and space heating. This problematises the sole focus on electrification, which Bhattacharyya (2012) argues dominates the energy access and development literature. Therefore, drawing on the research on clean cooking and heating programmes (Ekouevi & Tuntivate, 2012), study of micro-grid business models should consider how they enable other energy services or vectors (Lombardi et al., 2019).

A third consideration surrounds productive uses for electricity. As evidenced by Derks and Romijn (2019), rural electrification programmes too often focus on electricity access as an end in itself, emphasising electrification statistics, causing a 'fit and forget' mentality. Research has thus highlighted the importance of working with communities (often who have no cultural history of electricity use) to develop social and economic applications for electricity (Hartvigsson et al., 2021) through internet access, education programmes, agricultural and domestic labour mechanisation, and healthcare provision (IRENA & SELCO, 2022).

Customer interface

The customer interface concerns how a project engages with the host community and how ongoing interactions with the host communities are managed - with significant bearing on whether the project is successful in the long run (Mohn, 2013). Plutshack's (2014, 2020) research on rural electrification in India, highlights the importance of effective community engagement, and reflexivity towards local customs and cultural practices. IRENA and SELCO (2022) further outline how successful community engagement lies in recognizing the community as an integral part of the project and involving them in the design, planning, and operation of energy systems.

Supply chain

The supply chain for micro-grid projects includes design and technical installation of the system, the nature of the workforce, and how ongoing operations and maintenance (O&M) is managed. The two most common system configurations for rural micro-grids are solar photovoltaics, often paired with batteries; and micro-hydro plants (MHP), with micro wind or biomass-based systems less common (International Renewable Energy Agency, 2019). Systems may also be wholly or partially powered by diesel generators – historically the dominant means of powering off grid systems. However, development funding for rural electrification is increasingly geared towards renewables to mitigate climate change (IRENA, 2019a).

Micro-grids usually involve localised O&M of the power generation and distribution system, often with this responsibility fully delegated to host community (Vanadzina et al., 2019). This presents challenges in terms of access and logistics in reaching what are often very remote locations, as well as resupplying with spare parts (Azimoh et al., 2017). Much of the literature on rural electrification programmes therefore emphasises the importance of using local labour in developing and maintaining these systems (Mohn, 2013), and for generating buy in from host communities (Bautista et al., 2020).

Financial model

The financial model for micro-grid projects involves the capital cost of the system, the power consumption tariff (if present), how O&M costs are levied, depreciation, discounting and so on. These factors are captured in techno-economic analyses which use measurements or estimates of the production potential, to produce key indicators such as the net present cost (NPC) and, levelized cost of energy (LCOE) (Dhundhara et al., 2018; Veilleux et al., 2020). Micro-grids may involve metered power supply tariffs ($/kWh) common to grid connected areas, usage quotas, charge users only for O&M costs or be completely tariff free in their operation (Williams et al., 2015). An important further consideration is project financing and how this fits into the commercial and development policy landscape. Some have argued for an increased role for private finance in this space (Schmidt et al., 2013). However, others emphasise how rural electrification programmes in remote and poor communities, with their relatively high cost of providing power, necessitate a significant subsidy, either through public investment or Non Governmental Organisation (NGO)/philanthropic funding (Bhattacharyya et al., 2019; Williams et al., 2015). Understanding these factors is therefore of central importance in developing appropriate micro-grid business models.

Governance

Business model governance concerns who owns the system, how key relationships are structured, how decisions are made and by whom. Different actors ranging from public agencies, NGOs and private companies, alongside the host communities, may all have different roles. Again, research on rural electrification emphasises the importance of early involvement of the host communities in decision making and where possible community ownership and governance (Vanadzina et al., 2019). However, if poorly implemented and resourced, this may also lead to neglect of the system and its premature degradation (Derks & Romijn, 2019). These concepts are summarised in Table 1.

Methodology

The research methodology consisted of a mixed method evaluation of the business model of three rural micro-grids systems, using both qualitative and quantitative methods. These methods were followed by local stakeholder workshops to test and validate the findings and develop general recommendations for the effective design and development of microgrid business models, and the implications of this for rural electrification policy. The details of this methodology are set out below.

Table 1
Framework for evaluating micro-grid business models. Adapted from Richardson-Barlow et al. (2022).

Business model component	Considerations for rural micro-grids
Value proposition	• What level of electrification is offered? (MTF Tiers 1–5)—are there limits on daily consumption? Is power available at certain hours of the day? • What charge (if any) is there for power consumption? • What other services are included — i.e., support in power utilization, infrastructure works, training programmes?
Supply chain	• Who are the system designers? • Who are the equipment suppliers? • Who are the system installers? • Who undertakes maintenance? • How effective are these relationships?
Customer interface	• How is the community engaged during the planning process? • How is the ongoing relationship managed and by who?
Financial model	Technoeconomic analysis • What are the systems technical features? • What is the system power output (kWh) • What is the power demand profile/allocation (kWh) • What is the capital expenditure cost ($) • What is the operational expenditure cost ($) • What is the tariff structure (if any) for the ($/kWh) system? • Are there additional revenues e.g., from exported power? System funding • How is the capital cost of the system funded? • How are the operational costs of the system funded?
Governance	• Who owns the system? • How are key decisions taken? • What is the relationship between the funder/installer/owner and the host community?

Case study selection

Our aim was to explore examples of off-grid locations that had been, or were soon to be electrified through renewables, or where renewable micro-grids were being used in conjunction or as a replacement for diesel generators. The following requirements and specifications for the case study selection helped ensure effective access and appropriate examples:

- Small scale, renewable energy system <1MWp
- Off-grid or grid connected micro-grid arrangement
- Possibility of access for case study investigation (limited travel restrictions)
- Strong existing contacts to secure key interviewees
- Good availability of technical data
- Likely ongoing engagement through online workshops

Through engagement with regional partners, three illustrative case studies were put forward as meeting the above criteria, having the following characteristics, shown in Table 2.

Qualitative methods

This consisted primarily of case study visits and semi-structures interviews across the three case study locations, a combined 76 interviews in total, with 8 fully transcribed expert interviews and less formal interviews with 68 community stakeholders. These are summarised in the following sections.

Table 2
Case study characteristics and location details.

System type/stage	Case study
1. Micro-grid with renewables and centralized governance with project led by the national utility company	Standalone Solar Photovoltaic System at Rumah Panjang Tungan, Batang Rajang, Kapit Sarawak (Borneo), Malaysia
2. Micro-grid with renewables and decentralized governance with project led by the community	Timodos Micro Hydro Power Plant (MHP) Sitio Timodos, Brgy. Manobisa, Magpet Municipality, North Cotabato, Philippines
3. Without electricity access, about to have micro-grid installed by an NGO	Two sites were chosen in the Lang Son Province, Vietnam • Pa Mi village in the Chi Lang District • Lung Thuoc village in the Van Quan District

Expert interviews

To provide context and background to supplement case study interviews, 8 expert interviews were undertaken using video conference software (coded I#1- I#8). This included experts on the national, regional, and global electrification agenda, and the project leaders of the three case studies. Questions were centred on the challenges of rural electrification, the nature, successes and failures of government and NGO programmes, and the features of effective business models. These interviews were fully transcribed and coded using NVivo software. Details of these interviews are provided in Appendix 1.

Due to COVID-19 travel restrictions during 2021/2022, apart from the Malaysia case study, the research team was unable to conduct in-person interviews with the host communities. Therefore, we relied on our local contacts to gather this data. The local teams each made a visit to the case study community over several days. This included semi-structured interviews (details in Appendix 2) interspersed with documenting village life and the impact the electricity system has had on socio-economic dynamics in the community. These included a focus on elements of the business model and gathering data to support the techno-economic analysis. Here we relied on extensive field notes which were summarised by our case study partners, details of this are provided below.

Malaysia

The case study visit to Rumah Panjang by the research team took 3 days (28th February– 1st March 2022), involving 13 interviews with 2 officials, 5 project developers, 1 contractor and 5 villagers. The interviews lasted 3–4 h and involved a wider research team of 6 people. Interviews were recorded using extensive field notes with notes coded and analysed by the research team.

Philippines

The Timodos case study was undertaken in partnership with the NGO Yamog. with information taken from site visits conducted by Yamog between April 10th to June 15th, 2018. During the visit Yamog interviewed 36 villagers including 11 males and 24 females and the operations and management association, with a further focus group and interviews with 16 project stakeholders. Project stakeholders included members from the Timodos Tribal Micro-Hydropower Association (TTriMPA), Timodos Tribal Water and Sanitation Association (TTriWASA), Council of the Ancestral Domain Tribal (CADT) Municipality Local Government Unit (MLGU).

Vietnam

The Pa Mi village and Lung Thuoc case studies were developed using a site visit and interviews undertaken by the Lotus project, a UK based NGO, working in Vietnam. This included analysis of interviews from a visit in January 2019. This included two case study visits, with interviews with approximately 17 families in the villages, supplemented with an interview with the Chairman and Vice Chairman of the People's Committee of the local Chi Lang district.

Technoeconomic analysis

Techno-economic analysis assesses the viability of implementing off-grid power systems under alternative business models. The techno-economic analyses in this study are based on the site surveys and data/information gathering across the three case studies. A survey form was distributed to the system developers/installers at each of the case study locations, to determine the projects technical details. Details of the requested information are shown in Appendix 3.

The technical and economic input parameters were fed into the Hybrid Optimization of Multiple Energy Resources (HOMER) micro-grid software. HOMER's enhancement and sensitivity calculations make it simpler to assess the numerous conceivable system designs. HOMER mimics the operation of a system by making energy balance computations and presents a rundown of configurations, arranged by the net present cost that can be utilized to analyse the system. The economic evaluation criteria used by HOMER are further described in Appendix 4.

Policy workshops

The findings from the previous two phases were explored in four virtual stakeholder workshops. A table showing the timings of these different workshops is shown in Appendix 5. The first three workshops (February and March 2022) presented the findings from the data gathering phase with a focus on local stakeholders from each case study country. The workshops were used to disseminate the findings from the research, frame how rural electrification challenges are understood at the regional, national, and local level and discuss the potential of different business models and their policy implications. These workshops were therefore used to validate the assumptions from the interviews and test policy/business model recommendations with key stakeholders.

The fourth workshop was used to present findings from all three case studies, involving an international and ASEAN-wide group of stakeholders, including private and public stakeholders across the case study locations and keynotes from both ACE and International Renewable Energy Agency (IRENA). This online workshop took place on March 17th, 2022 and was hosted by SRI UiTM in Malaysia. Following presentations on the case studies, workshop participants were split into breakout groups to discuss justice components in their regions of expertise. This involved key stakeholders including representatives from the ASEAN Centre for Energy (ACE), NGOs and local, national, and regional government agencies and development banks.

Results

For each case, we first describe case study location and details of the data gathered, before examining the business model including the project's techno-economic parameters.

Malaysia case study– Sarawak Energy Berhad (SEB)

In the Malaysian case study, we partnered with the local utility SEB and Tenaga Nasional Berhad Energy Services (TNBES) to secure a community based solar off-grid system located at the remote Rumah Panjang (longhouse) Tungan Batang Rajang (Fig. 1) inhabited by an Iban community. The 28.12 kW solar PV (Fig. 2) and battery system was commissioned on November 2021, with 60 % of the electricity consumption in Rumah Panjang supplied by the battery and 40 % by the solar PV. The capacity of the battery is 218.3 kWh, which is entirely charged by the solar panels, with autonomous operation for 3.1 days when fully charged. Other components include indoor wiring schemes complete with light bulbs (5 units/ house) and power sockets (4 units/ house) and an individual smart meter at each door for community

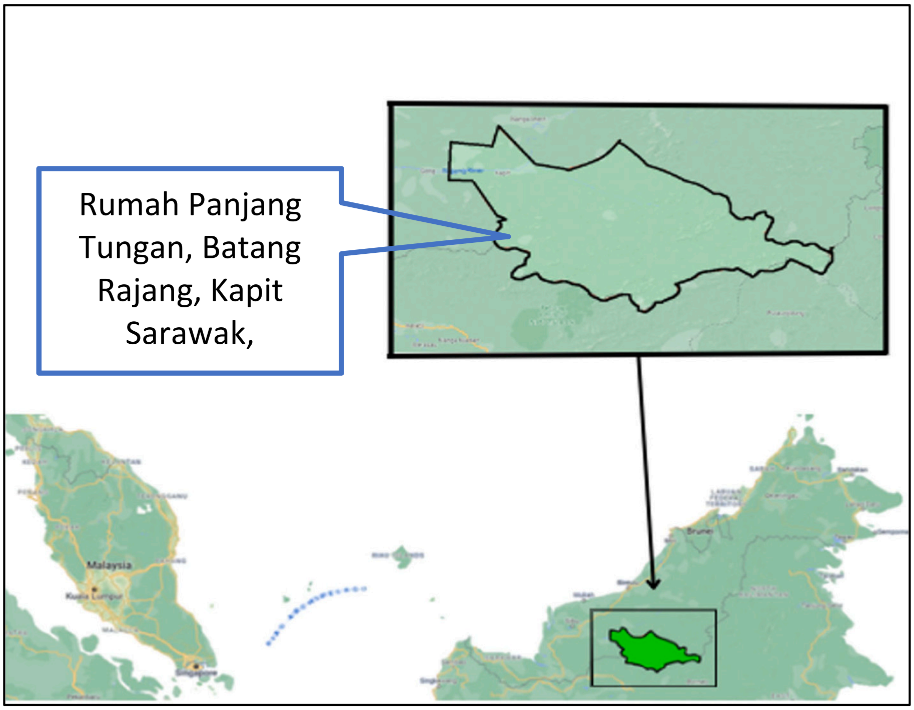

Fig. 1. Location of standalone solar photovoltaic system at Rumah Panjang Tungan, Batang Rajang, Kapit Sarawak.

Fig. 2. Components of the solar PV system at Rumah Panjang Tungan.

members to monitor their energy consumption.

Sarawak Alternative Rural Electrification Scheme (SARES)—as in the case reported in this study—is a fast-track solution to provide remote households with standalone solar or micro hydro systems in partnership with remote communities in Sarawak. This initiative is being led by the state owned Sarawak Energy Berhad (SEB) utility.

Value proposition

SARES provides a basic MTF Tier 3 level of electricity supply. "*They get 3 kWh of electricity per day 6 p.m from to 6 a.m.. If they run out of power, they can request more.*" (I#8). However, the micro-grid incorporates features to temporarily boost the supply capacity for celebration events or community ceremonies. These include extra allocation for the head of village with 4kWh and common area with 10kWh of additional energy every 24 h. Under well managed conditions, it takes 1 to 2 h for the solar system to recharge the batteries. If weather conditions are cloudy for consecutive days, the battery storage is sufficient for up to 3 days on regular consumption patterns.

The system has several key benefits to the previous intermittent diesel generator. Firstly, the electricity is cheaper, where previously, the community had to pay about USD $23 per household for purchasing diesel and face additional O&M costs. In addition, the community no longer needs to travel to the nearest town Kapit to buy diesel. "*It takes more than an hour by car to get to Kapit, but only twenty minutes by boat*" (I#8). The community can now use basic electrical appliances such as washing machines, TV, refrigerator etc., and access a Wi-Fi, internet connection. The community now use mobile phones to connect with the outside world, improving the education of the village children, allowing them to study at night, and access tuition through online classes. The system has also improved knowledge and skills in the village adult population on electricity, energy management, solar power, and environmental conservation.

Customer interface

In implementing the project, SEB met and briefed the residents early on, to discuss the project locations, and implementation "*To install solar panels, discussions need to be held and approval needs to be obtained from the residents of the longhouse*." (I#8), as they would have to collectively agree on an area in the village to erect the solar power station. The engagement started with a meeting between the SARES team, the head of the village and the contractor. During the installation, the contractor also stayed in the Rumah Panjang longhouse, where together they cleared the vegetation to build the powerhouse. The community members mentioned that this involvement engendered a sense of belonging towards the area and project. In terms of the ongoing relationship, the SARES and SEB team are in contact with the head/committee of the village. The SEB team undertakes a periodical visit to the site every 6 months to monitor the solar system production and load consumption, provided there are no major issues.

Supply chain

The contractor for the project installation, Eco Green, is a Sarawak-based company, with the contract awarded via a competitive bidding process. The community are trained to operate, monitor, and maintain the system, by SEB after completion and handover, while major technical issues are handled by the SARES team. To ensure effective implementation, SARES provide equipment that is utility-grade and in compliance with international technical and safety standards. The interviews also mentioned SARES face challenges in securing local, competent, and reliable contractors.

In implementing the SARES project, SEB faces several challenges and issues, especially access to the site's remote, rural locations with rugged terrain. Moreover, finding construction materials was also often a challenge "*Longhouse construction has been planned, but there are insufficient materials to complete it.*" (I#8). According to SEB, most of their sites can be accessed via land - off-road (logging roads). However, the physical off-road conditions can be a challenge for the transportation of the equipment (especially which involves a sensitive warranty, e.g., for a battery). Therefore, our case study site required mobilisation via river. These logistical issues can result in burdensome project costs and safety issues for the workforce.

Financial model

The technoeconomic analysis assumed 3 kWh energy usage, per home, per day (18:00–06:00) with an annual load estimated by HOMER for the 28 houses of 20,435kWh, or 55.99kWh day, based on the electrical consumption of the appliances within the residences. The schematic model is shown in Fig. 3a. A sample of 1 week energy dispatch from all components at the optimum case appears in Fig. 3b. The figure demonstrates that solar PV system produced excess electricity during the day. The battery allows excess electricity produced by solar PV to be stored and accessed at night or during cloudy days when the system is not producing energy.

The project was wholly funded by Sarawak Government and developed by Sarawak Energy. The system is tariff free, with the only fee/tariff collected voluntarily for O&M purposes by the community. Table 3 shows the Capital Expenditure (CAPEX), expected operational expenditure (OPEX), simulated Net Present Cost (NPC) and levelized cost of energy (LCOE) of the Batang Rajang system, using a 10 % discount rate for a system lifetime of 25 years. For comparison we show the average SEB Residential Tariff Rate (RTR), highlighting a 2300 % discrepancy between the LCOE and the RTR. This indicates significant above market rate subsidy is required to sustain the financial model for the off-grid system.

Governance

After agreeing to the micro-grid installation, the community undertook a ritual and festival activity to aquire spiritural blessing and find the appropriate location to place the solar and powerhouse system. "*The houses were built collaboratively by the community, who raised a significant amount of money for the [solar] project.*" (I#8). Typically, off-grid standalone SARES systems are handed over to the village community to own, operate and maintain with Sarawak Energy providing support on technical issues. Basic operation of SARES system is maintained by the community with the support from Sarawak Energy. Meanwhile, major operational costs are borne by the local government. There is a contractor defect liability period that last for 12 months, whereafter maintenance is managed by Sarawak Energy with funding from the Sarawak government. A collaborative effort is therefore crucial to ensure the smooth and timely implementation of these electrification projects. Interviewees mentioned without proper awareness, the system may be wrongly or not effectively used, leading to damage of the equipment - especially the battery bank. This provided a need for the system's governance to assimilate into the community's traditions and culture.

Philippines - Yamog Renewable Energy Development Group

For the Philippines case study, the team partnered with Yamog Renewable Energy Development Group, Inc., an NGO that has been working with rural, indigenous populations to improve socio-economic and environmental well-being in Mindanao, Philippines since 1993. The case study chosen by Yamog, was the 23 kW Timodos MHP commissioned in 2016 and located at Sitio Timodos, Brgy. Manobisa, Magpet Municipality, North Cotabato (Fig. 4). The use of the Mabato River for the MHP system which traverses Sitio Timodos, was decided by the residents of Timodos in keeping with the participatory development approach of Yamog.

Value proposition

Yamog aim to ensure electricity access to remote low-income communities that are currently not being served by government funded electrification programmes:

> "*We have what we call electric cooperatives or quasi government institutions [which] are supposed to be extending electricity to these areas... But …they couldn't … meet the quota.*"
>
> (I#7)

> "*We have … successfully provided… 26 community scale …household lighting… or energy [systems] in off grid areas. Especially in communities that are suffering from extreme poverty.*"
>
> (I#7)

The Timodos MHP is a community driven off-grid system initially for electrification of 87 indigenous households belonging to the Manobo tribe, who were given access for household and community lighting in 2016. The MHP is a run-of-river type off-grid system to supply electricity expanded to 115 households as of 2022. The MHP is also designed to energize post-harvest facilities (like corn mills, hammer mills, coffee huller, and abaca stripping machines) to boost agricultural production and family incomes; and battery charging and for other activities that are driven by electricity, including the elementary school (Fig. 5).

Customer interface

The project was initiated by the community through the Barangay (village) office, requesting that Yamog assist in the development of the project. Yamog view community participation as essential in the delivery of their projects and have refined this process over almost three decades:

> "*We encourage the communities to participate in the entire project cycle from the identification of the project up to the monitoring and evaluation... So people we organize them.*"
>
> (I#7)

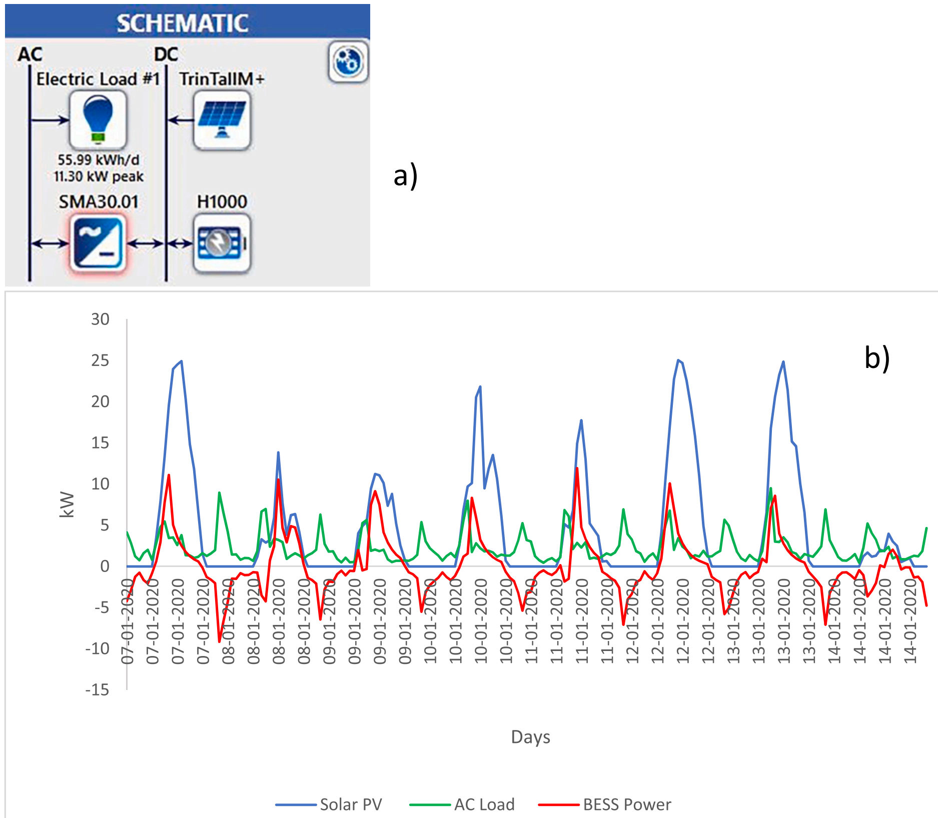

Fig. 3. (a) Schematic diagram and (b) one week energy dispatch for Solar PV system in Batang Rajang, Sarawak.

Table 3
Financial details of Batang Rajang project.

CAPEX	OPEX	OPEX/kWh	NPC	LCOE	Tariff	SEB RTR	LCOE: RTR
$316 k	$6066	$0.30/kWh	$425 k	$1.61 /kWh	N/A	$0.07 /kWh	2300 %

> *"We don't just go in and introduce micro hydropower…. We would appreciate it very much if people come to us and discuss their problems with us and we try to help them in terms of defining what appropriate renewable energy system they should be doing in their communities"*
> (I#7)

Supply chain

The Timodos project was developed by Yamog who did most of the engineering, including technical design of all civil works and selection of appropriate electro-mechanical components. However, as much as possible, Yamog seek to develop a local supply chains and skills:

> *"We are not only providing the hardware like the micro hydropower technology … We are also providing the 'software', meaning generating and encouraging more people empowerment…, people participation because for us, that's the only way, that these projects can be sustained."*
> (I#7)

While the more technical work involves paid labour, a substantial component of the lower skilled work is provided by the villagers, through a cultural practice known as "pintakassi":

> *"when it comes to, you know, unskilled labour. The community was more than willing to give the share you know, like hauling or the materials digging… They call it locally as 'pintakassi' locally with collective communal labour. We're happy because the cultural practice is still alive"*
> (I#7)

Financial model

Fig. 6 shows the schematic design of the Timodos MHP, and the annual hydropower output is dependent on the stream flow of the Mabato River. HOMER was employed to simulate the stream flow, utilizing the technical parameters supplied by Yamog. These parameters encompassed the micro hydropower plant's nominal capacity of 23 kW, a design head of 13.53 m, and an annual average flow rate of 350 l/s. The time series analysis for annual hydropower stream flow, as illustrated in Fig. 6, was simulated using HOMER based on the geographical information for North Cotabato provided in the HOMER. Utilizing this location data, HOMER simulates both the quantity and timing of streamflow by considering local precipitation and temperature patterns that influence the water cycle. The climate data selected for simulation are sourced from the NASA database resources integrated into HOMER. The hydropower output (in kW) is then calculated through a standard formula relating output power to stream flow within the HOMER platform.

Table 4 shows the CAPEX, expected OPEX, simulated NPC and LCOE of the Timodos MHP system, using a 10 % discount rate for a system lifetime of 25 years, assuming an annual operating & maintenance cost of 60,000 Philippine Peso (PHP) and replacement cost of 164,000 PHP for the flat bed and 200,000 PHP for logistics. For comparison we show the Manila Electric Company (MERALCO) average RTR, highlighting a 685 % discrepancy between the LCOE and the RTR. This indicates significant above market rate subsidy is required to sustain the financial model.

Yamog's capital funding relies largely on foreign development funding, to plug the gaps where the Philippine government deems

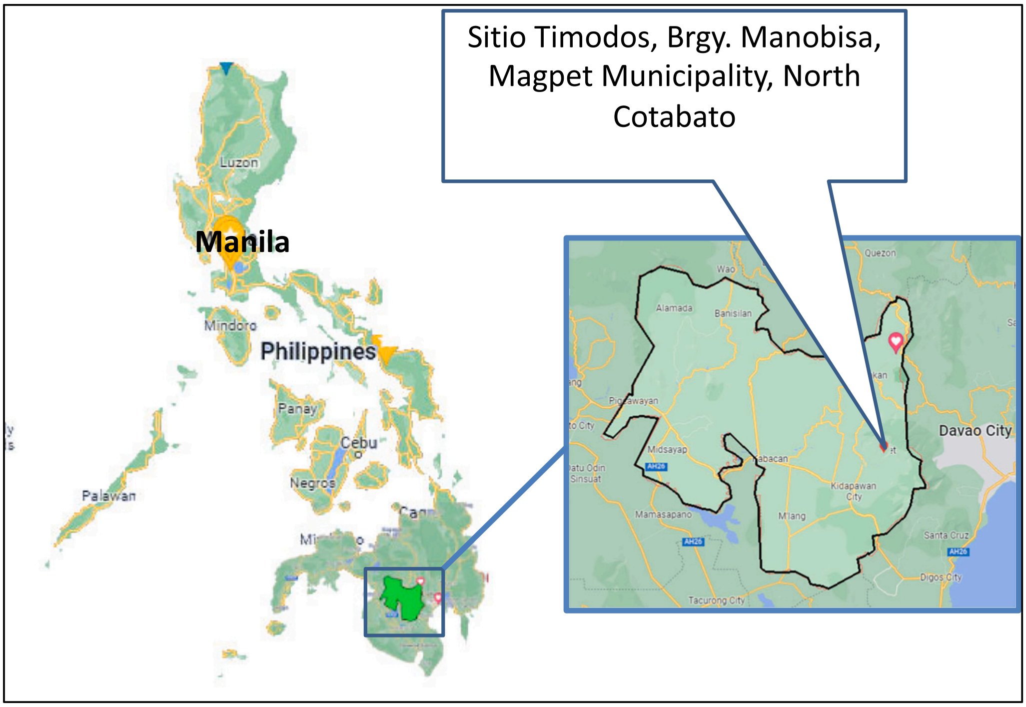

Fig. 4. Timodos Micro Hydro Power Plant, Brgy. Manobisa, Magpet Municipality, North Cotabato, Philippines.

Fig. 5. From left to right and top to bottom: Diversion Weir/Intake, Headrace Canal, and Penstock. Source: YAMOG.

electrification too expensive:

"Well, it's simply very expensive... They [government] don't usually go to these areas because they said there are no roads ... So of course. We will go… In our projects, we rely mostly on or mainly I would say on funding from foreign sources." (I#7)

The Timodos MHP project was funded through MISEREOR (an NGO from Germany) and KZE-Germany (German Government). The O&M costs are taken from the tariff collection from the households, with a tariff of 90 PHP per kWh per household was collected every month for the first year of operation. The tariff was then updated to 120 PHP per

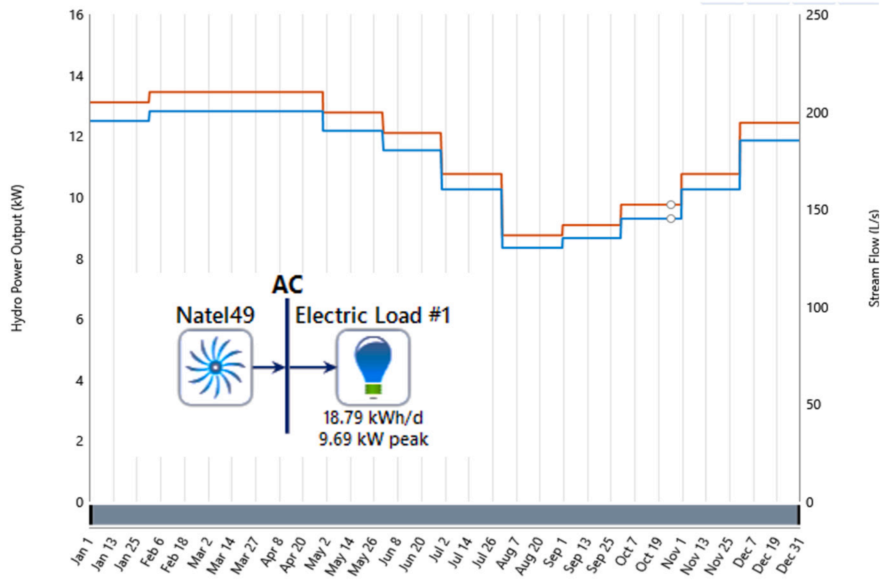

Fig. 6. Schematic diagram and Annual hydropower output and stream flow in Timodos micro hydropower for Timodos MHP.

Table 4
Financial details of Timodos MHP system.

CAPEX	OPEX	OPEX/kWh	NPC	LCOE	Tariff	MERALCO RTR	LCOE: RTR
$121 k	$1100	0.01/kWh	$140 k	$1.57 /kWh	N/A	$0.20 /kWh	685 %

household per month for the first 20 kWh (2018). An additional 10 PHP per kWh is then collected for household exceeding 20 kWh. For the households, this tariff was seen as reasonable and would cover the annual O&M cost and parts replacement cost of the plant. As verified by Yamog, these low prices are necessary to limit the costs to the community:

> *"so very, very cheap, so that's why this kind of electricity is very affordable and right rightly so because it's a very poor communities. Indigenous communities that have very limited sources of income."* (I#7)

Governance

The management of the Timodos MHP is through the creation the Timodos Tribal Micro-Hydropower Association (TTriMPA). The Timodos MHP was turned over to this association through a donation certificate. The association is a duly registered entity with the department of labour and employment (DOLE). The role of the association includes 1) management, 2) tariff collection, 3) reporting and 4) O&M of all MHP equipment. All 87 household-beneficiaries have successfully organized themselves into one energy-users association via the TTriMPA. Yamog describe how the community accepted the responsibility of taking care of the sustainable operation and maintenance of the MHP, including the protection of the Timodos watershed which is crucial to the sustainability of the MHP:

> *"We have organized the community in what we call an 'energy users association'…[the] TTriMPA. So within this organization they … with our help… also set up an O&M team. The organization has a board of directors… which set the policies… with regard to how the system should be used, how it should be taken care of etc."* (I#7)

Vietnam - the Lotus Project

Founded in 2017 the Lotus project is a small interdisciplinary NGO, focussed on the rural development of remote and ethnic minority communities in Vietnam. By providing support to villages in rural underserved regions of Vietnam, the Lotus Project has created a rural development model (RDM), which the founders hope can be replicated to empower rural communities and improve their quality of life and local economies. In 2018 the Lotus project team identified their first case study locations in Northeast Vietnam in the Lang Son Province, Pa Mi village in the Chi Lang District, and Lung Thuoc village, both in the Van Quan District. While the Lotus team planned to undertake a second visit to install a solar micro-grid in each village during the spring of 2022, the ongoing COVID-19 pandemic has delayed this. Therefore, at the time of writing both projects remain in the pre-install phase (Fig. 7). The following sections provide a detailed description of each case, with data drawn from a report from Lotus project's visit in 2019.[2]

Lung Thuoc -Van Quan District

Lung Thuoc village (Fig. 8) is occupied by 7 families who live in wooden shacks without any access to electricity. The villagers lead a very harsh life engaging in subsistence agriculture and raising livestock for personal use. The houses don't have any air sealing and get very cold during the winter months due to air drafts. All the cooking is done indoors using firewood and this leads to very poor indoor air quality.

Pa Mi- Chi Lang District

Pa Mi, (Fig. 9) a small, isolated village occupied by 10 families, who live in very similar conditions as Lung Thuoc but have some access to electricity, thanks to a small hydroelectric generator which lives in a bucket wedged between some stones on the nearby spring. The generator provides enough electricity to light 2–3 bulbs per household and is out of commission for 5 months a year during which the spring floods due to rains.

[2] Lotus Project Vietnam Trip Report: January 2019: https://www.lotus-project.org/.

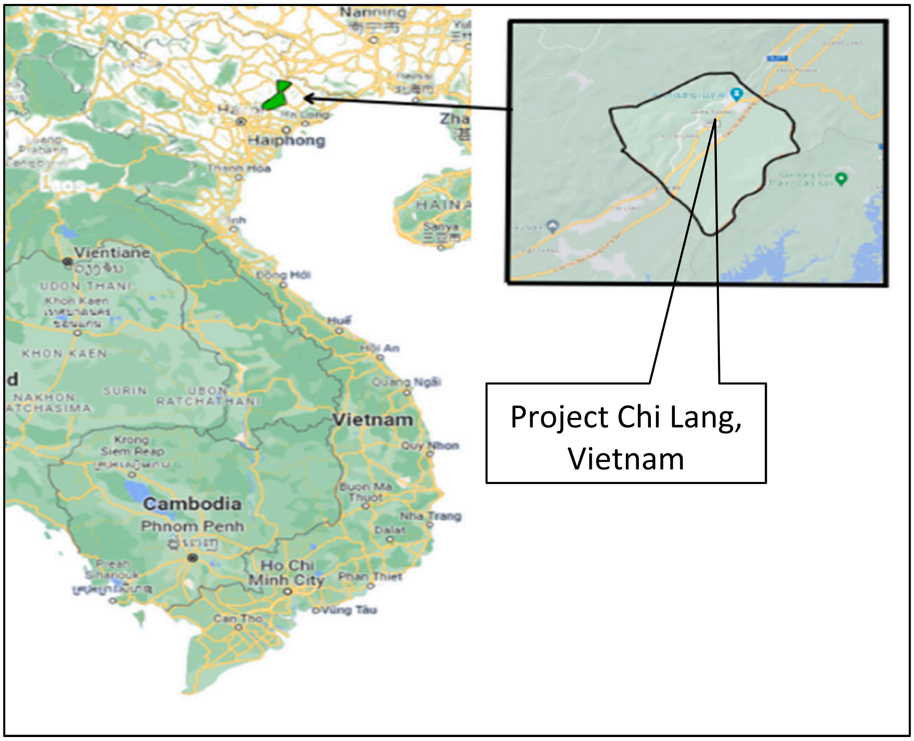

Fig. 7. Lotus project locations.

Fig. 8. Lung Thuoc Village.

Fig. 9. Pa Mi Village.

At the time of writing Lotus have only completed detailed design and feasibility on their first two projects. Therefore, the following sections findings are caveated by this early stage of development.

Value proposition

Lotus' core focus is on ensuring and improving electricity access as a key first step in the community's development journey. In the Pa Mi and Lung Thoc cases, this will involve moving to a MTF Tier 2/3 connection from an MTF Tier 1 and Tier 0 connection respectively, with each home expected to have around 4.24 kWh of reliable safe power for at least half the day. The proposal is that the villagers will not be charged initially, although a tariff would likely be introduced in future years. A critical feature of the Lotus project RDM is that they secure substantial funding for ongoing community economic development and technology transfer:

"Our aim is not just to visit them, provide them with some solar panels and then leave, but it's more of becoming…long term partners so that we can ensure that impact actually happens" (I#4)

This includes training programs, commercialisation, and micro-finance initiatives. However, clearly evaluating the impact of these programs is impossible given the pre-electrification phase of the two projects.

Customer interface

Lotus main interface for the projects are local government officials who work with the respective villages:

"They usually have someone who they are assigned to us, to… support our efforts with the villages and that person then connects us to the village leader." (I#4)

Lotus expressed that this ongoing connection is crucial for long term sustainability, especially as their main team is based in Europe. However, much of the technical monitoring of the system can be done remotely. Eventually, Lotus plan to become obsolete after approximately 5 years of engaging with the community.

Supply chain

Lotus plan to use a Vietnamese solar install company for the micro-grid installations, who are specialists in this type of off-grid system with storage. However, this organisation was not local to the area, and the role of the community in the installation phase appeared to be limited. The system design, financial modelling and monitoring are done in house by the Lotus team, although it is noteworthy that several members of this team are based in Vietnam. Lotus plan to provide some basic O&M training to some of the villagers who would undertake basic tasks such as cleaning the system etc. Indeed, their local capacity building proposals seemed to focus more on the uses of the electricity system, rather than viewing the micro-grid and power generation as potential sources of economic development in their own right.

Financial model

Lotus' projects are funded by a combination of government grants, corporate social responsibly (CSR) funding and philanthropic donations from individuals. Details of the financial model for each site are described below.

Pa-Mi Project. The planned Pa-Mi hybrid system consists of solar PV with capacity of 4.8 kW and diesel generator with capacity of 12 kW, with demand estimated about 18.8 kWh/day. Fig. 10 (a) shows the schematic diagram the project, where solar PV is prioritised with the diesel genset and batteries as a backup. The modelling suggests Pa-Mi will have a high peak of energy usage but lower solar PV available in the months of June, July, August and September. Fig. 10 (b) presents one week sample of energy dispatch in July indicates that in the event of insufficient solar energy, diesel and battery will compensate to ensure continuous supply to users.

Table 5 shows the CAPEX, expected OPEX, simulated NPC and LCOE of the Chi Lang Solar PV Project, using a 10 % discount rate for a system lifetime of 25 years. For comparison we show the Vietnamese EVN average RTR, highlighting a 930 % discrepancy between the LCOE and the RTR. This indicates significant above market rate subsidy is required to sustain the financial model.

Lung Thuoc Project. The off-grid Lung Thuoc hybrid system consists of solar PV with capacity of 3.4 kW and diesel generator with capacity 11.0 kW, with demand estimated at 18.8 kWh/day. Fig. 11 (a) shows the schematic diagram of Lung Thuoc Solar project. Meanwhile, Fig. 11(b) shows the one-week energy dispatch for the PV.

Table 6 shows the CAPEX, expected OPEX, simulated NPC and LCOE of the Lung Thuoc project, using a 10 % discount for a system lifetime of 25 years. For comparison we show the Vietnamese EVN average RTR, highlighting a 710 % discrepancy between the LCOE and the RTR. This indicates significant above market rate subsidy is required to sustain the financial model.

Lotus adopts a blended approach to financing their micro-grid systems, using a combination of philanthropic donations and government

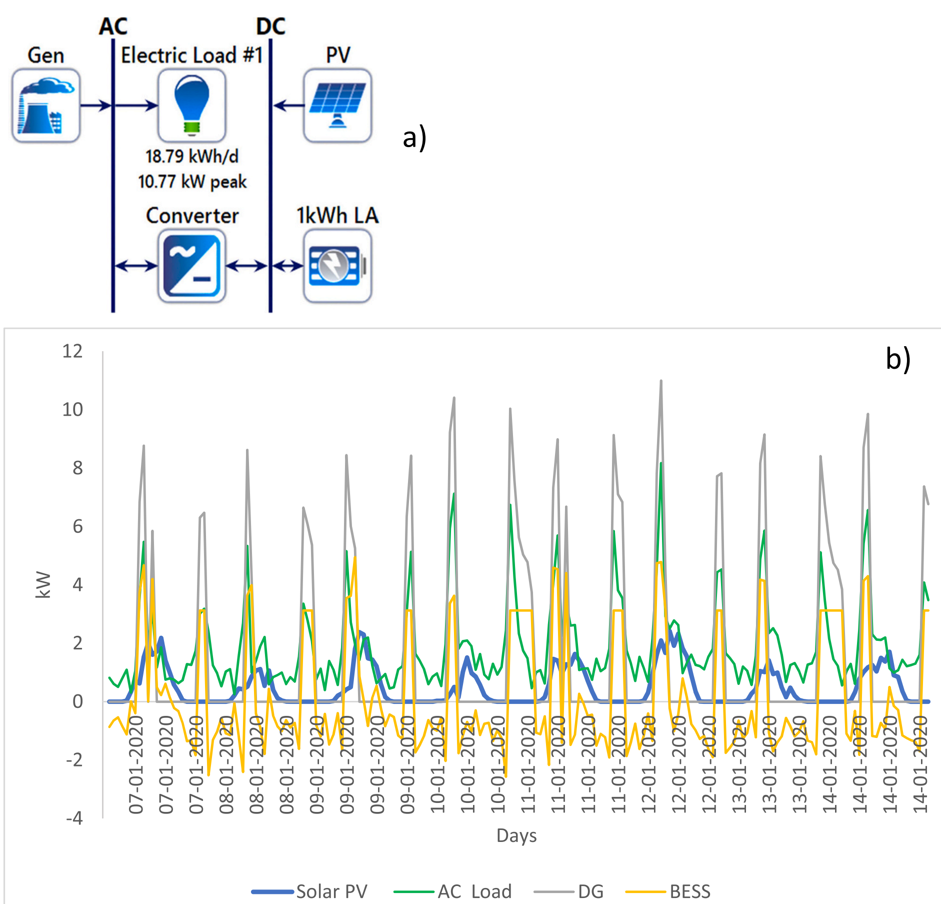

Fig. 10. (a) Schematic diagram and (b) One week energy dispatch for solar PV system in Chi Lang.

Table 5
Financial details for Chi lang project.

CAPEX	OPEX	OPEX/kWh	NPC	LCOE	Tariff	EVN RTR	LCOE: RTR
USD $30,097	$3937	$0.48/kWh	$90,865	$1.03 USD/kWh	N/A	0.1 USD/kWh	930 %

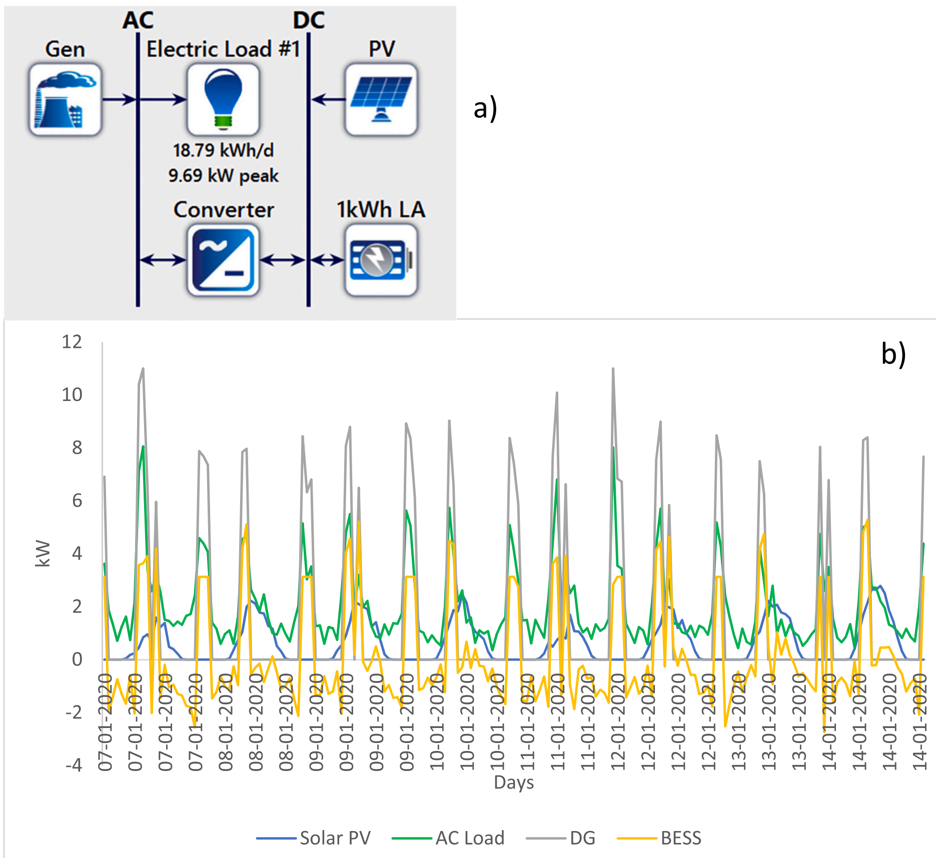

Fig. 11. (a) Schematic diagram and (b) One week energy dispatch for solar PV system in Van Quan.

Table 6
Financial details of Lung Thuoc project.

CAPEX	OPEX	OPEX/kWh	NPC	LCOE	Tariff	EVN RTR	LCOE: RTR
USD $22,714	$3796	$0.46/kWh	$71,780	$0.81 USD/kWh	N/A	0.1 USD/kWh	710 %

grants - with a significant contribution from a social media crowd-funding campaign. After an initial "tariff free" period, the ongoing O&M costs are to be supported from revenues from electricity sales. Importantly, a large share of the capital budget is set aside for "R&D funding" for the rural development model, including funding for training and commercialisation interventions in later phases of the project. This relative emphasis on these ongoing investments in the community's skills and development, are noteworthy in comparison to other rural electrification programmes which devote most of their funding to the project's initial capital costs.

Governance

The ownership of the system if based on *"a three-party agreement into place between Lotus project, the …village and the local authority to manage the system"* (I#4). Lotus described how this shared ownership model was important to the sustainability of the projects, as there is a risk that if villagers encountered periods of extreme hardship, there is a danger that they could sell on the systems components. Lotus saw the long-term role of the local government as critical to the sustainable management of the system, and therefore this partnership with villagers would be critical in managing the system over the long term:

> *"It's not really like sustainable or effective in that matter, like for us … Westerners, Europeans going to remote village in Vietnam and just kind of trying to make decisions for them… So even if it's if it's our advice or something like that, it should always come from the local authority or someone within the village."* (I#4).

A summary of the three business models in the respective countries is shown in Table 7.

Discussion: developing business models for ASEAN rural electrification

Rural electrification remains a challenge in the three ASEAN nations we studied. Malaysia is one of the more globally integrated of ASEAN's regional economies, and while peninsular Malaysia enjoys near 100 %

Table 7
Summary of business models across four three case studies.

Case	Value proposition	Customer interface	Supply chain	Financial model	Governance
Malaysia SARES - Tungan Batang Rajang, Kapit, Sarawak	• MTF level 3/4 – 3kWh/day • Power is provided for free, O&M costs are collected voluntarily • SARES provide some behind the meter services and basic O&M training • Eventually, SARES aim to bring grid access	• Public utility identifies unconnected areas and contacts community leaders • Ongoing relationship is with community leader	• Off grid PV and battery system • SARES design and install the system • Equipment is largely imported from China and Europe • Sarawak supply chain for some parts although limited role for local labour • Some roles for locals in basic O&M	• System is funded via public utility • Major O&M costs are covered by SARES, basic O&M covered by donation • No tariff is charged • No export	• System is owned by the community • SARES take major decisions during design and development, this changes to community leaders after construction • Regular 6 monthly visits with SARES and the community.
Philippines Yamog - The Parina MHP, Apayao province	• MTF level 3–200 W max usage • Power is provided for free, although there is a flat rate annual charge for O&M • Significant focus on productive end uses as well as capacity building and financial management of the system	• Community is engaged via large informal gatherings to create an Energy Users Association • Energy Users Association nominate a System Manager who engages with the villagers	• Typically, MHP systems, off grid • Yamog design the system with input from locals • Equipment suppliers are largely foreign with some local supply chain • Locals are heavily involved in installation and O&M	• System is funded via Aid funding mostly • O&M costs are covered by flat rate charge from each villager • No tariff is charged • No export	• System is 100 % community owned • Key decisions are taken by Energy Users Association and system manager • Yamog aim to develop a federation of projects
Vietnam Lotus - Lang Son Province	• MTF level 2/3 - ~500 Wh/household • Power is initially free, with plans to introduce a tariff structure in years 2/3 • Main emphasis is on productive uses of energy & capacity building via RDM	• Lotus undertakes case study visits to interview villagers and understand their needs • Ongoing relationship is largely with local government officials	• Off grid PV and battery system • Lotus design and install the system • Equipment is largely imported from China and Europe • Lotus use Vietnamese supply chain for some parts although limited role for local labour • Some roles for locals in basic O&M	• System is funded via philanthropy, government grant and crowdfunding • O&M will be covered by a small tariff from year 2 • No other tariff is charged • Large share of funding developed to R&D and economic development under RDM	• System ownership is shared between the community and the local government • Key decisions are taken between 3 actors, Lotus, the community, and the local government • Lotus 5-year RDM has a structure that aims for Lotus to cease involvement after 5 years

electrification, it still has energy access challenges on the island of Borneo. In line with its 2017–2040 Renewable energy roadmap, the government of Philippines is committed to pursue a Total Electrification Programme (TEP) in a mission to provide electricity to all off-grid areas. In the Philippines, the MHPs are supporting the government's rural electrification program targeting 100 % barangay (or village) electrification to harness the power of water to produce electricity. By 2016, 99 % of the Vietnamese population used electricity as their main source of lighting, up from just 14 % in 1993. However, as of 2014, there were still almost 550,000 Vietnamese households without access to the National Grid, with around 80 % of the total population residing in rural areas (US Aid, 2014). These factors suggest renewable micro-grids will pay an important role in the region meeting SDG 7 objectives.

In the following sections, we elucidate the factors which drive the relative success or failure of DES micro-grids in our case studies, with a focus on the techno-economic parameters, the chosen business model, and its governance.

Value proposition

Firstly, we observed varying degrees of electricity access. While the Vietnam case had the lowest level of access (MTF 2/3), with ~0.5kWh/day available per household, the Sarawak system was designed to provide constant power with a per household allowance of 3kWh/day. However, both improved on zero access in one Vietnam case and a lower MTF tier level in the previous Sarawak system. In addition, all three examples involved some form of free power provision with the Philippine and Sarawak systems without a unit charge altogether. Instead, each took a different approach to O&M costs, with the Philippine case having a flat annual rate, the Sarawak system covering basic O&M by a voluntary donation, and the Vietnam example planning a basic tariff to cover O&M. These findings highlight the radically different business models that DES micro-grids can enable, as their power production is close to zero marginal cost (Rifkin, 2014).

Further, all three business models involved services beyond the electricity connection. While the utility led SARES Sarawak model only involved some basic O&M training and behind the meter services, both the Lotus and Yamog cases placed huge emphasis on capacity building and developing productive uses of energy. This involved support in developing new agricultural processes, improved educational outcomes as well and providing training for system and financial management. Lotus project takes these principles furthest, with a 5-year plan for economic development in their host communities as part of their RDM. Indeed 68 % of their proposed funding model is dedicated to these activities.

Indeed, this emphasis on capacity building is highlighted by IRENA and SELCO foundation (2022), focussed on 5 areas forming the ecosystem necessary for linking electricity services with people's livelihoods. Namely, technology innovation; financing solutions; backward and forward linkages (market access); training and capacity building; and policy. Much like our three ASEAN NGO examples, SELCO have undertaken extensive work in India to develop this ecosystem, with solutions tailored to the local context (Sahni et al., 2023). These findings suggest that NGOs such as Yamog, Lotus and SELCO may be better placed to develop this broader social value proposition, over a longer period than a traditional electricity utility, who are naturally more focussed on the engineering dimensions.

Customer interface

The importance of community engagement was emphasised across all case study examples, although this was embodied in different ways in each example. Unlike a traditional utility: consumer relationship, none of the host communities had pre-existing relationships with an electricity supplier, nor a tradition of email or even postal communication. This meant that the customer interface was largely via in person interactions, or via informal mobile phone contact thereafter. For example, Yamog in the Philippines set up a local energy users association, with a system manager who appoints a team to maintain the system. Lotus in Vietnam, undertake interviews with the host community and then work closely with local government officials. While the SARES approach is naturally more top-down, they too undertake extensive community engagement, and are in contact with the head/committee of the village with a periodical visit to the site every 6 months. In each case, the importance of ongoing personal relationships, with local stakeholders was evident. Community engagement therefore requires a flexible approach; a clear understanding of the local socioeconomic and cultural characteristics; and tailoring of promotional tools, materials, and channels (Plutshack, 2020).

Supply chain

We also observed heterogeneity in the technical features of the micro grid systems and the associated supply chains. In the Philippines, the MHP was built using local labour including from women in the installation phase, in what Yamog described as 'collective community labour' or 'Pintakasi' (Bautista et al., 2020). Many of the Philippine MHP parts were imported from Indonesia. By contrast the Vietnamese and Malaysian examples were PV & battery systems, with both using domestic companies for installation, although presenting less opportunities for using local, low skilled labour. This was also true of the system components, which tended to be imported from Europe or China. In general PV systems tend to be more capital intensive than MHP systems, where a greater share of the CAPEX cost goes towards labour (Lema et al., 2018).

The rural electrification literature emphasises the importance of developing local supply chains and the upskilling and use of labour from within the community where possible (Williams et al., 2015). For example, IRENA and SELCO prioritise developing local technical skills training, such as in installation, maintenance and repair of system components, to ensure their long-term sustainability in remote contexts (IRENA & SELCO, 2022). We further emphasise the support of local and regional technology suppliers in experimentation and innovation phases.

A key success factor for system longevity also appears to be in developing co-dependency between the O&M of the system, and productive uses of energy, particularly where they generate an income for the community. Several of the expert interviewees (I#1–3) described examples where no links had been built and the micro-grid would be neglected and underutilised – citing an example of a refrigeration system which had been disconnected and used for general storage (I#3).

Financial model

None of our case studies involved standard $/kWh tariff to which the vast majority of grid connected users would be accustomed. As outlined in the MTF (The World Bank Group, 2015), the provision of power for 'free' is often seen as a sub-optimal outcome in development literature, due to the potential of a 'free rider' effect. However, we found little evidence of this type of profligacy. While all involved some form of contribution for O&M, the communities seemed to see inherent value in the system. These findings suggest that the host communities place other, non-financial value on the micro-grid, which may be difficult to quantify through 'willingness to pay' type evaluations (Adams et al., 2021).

A further finding was the high LCOE of energy in all our case study locations. Our modelling showed LCOE's ranging from 685 %-2300 % higher than the typical national residential tariff rate (RTR). Thus, electrifying remote locations remains a costly endeavour, despite the recent falls in the cost of solar PV and battery technology. Given that these projects are primarily targeting development objectives, it is hard to see how unsubsidised private investors could expect a return, whilst ensuring communities receive affordable power (Bhattacharyya et al., 2019). This contradicts research which promotes private financing of electricity access projects in the global south (e.g., Schmidt et al., 2013; Williams et al., 2015).

From a funding perspective, the DES examined in the Philippines and Vietnam have similar models—an NGO facilitates philanthropic funding to increase electricity access, providing free or subsidised power. However, we expect there are limits to what an NGO funded can accomplish. Malaysia's 100 % electrification programme is primarily state funded, despite including off-grid approaches. While Yamog, and Lotus secure substantial funding for these projects, they are unlikely to attract sufficient capital to achieve scale. Thus, achieving full electricity access is likely to require state funding for full electrification of the "last mile" using off grid systems.

Governance

Our case studies showed a mix of governance models, with some more state led and centrally coordinated such as SARES and others, such as Yamog - more bottom up in their development. Lotus involves an NGO, but is largely developed by foreign/external actors, with Lotus based in the UK and Vietnam's major cities. In each example, the ownership of the system would be transferred to the community after the development period. Yamog also included developing a community governance model, in a similar manner to an energy co-operative, which planned to create a federation of community MHP groups, to aid knowledge sharing and troubleshooting within the network.

Based on interviews with experts and officials in Vietnam, Lotus' believe a state-NGO model is serving communities quite well. NGOs are building community-based DES projects, incorporating communities in the process and sustainment of these projects as well as building economic development benefits into the projects themselves. The state, on the other hand, is bringing power and access to larger communities, providing infrastructure, and leading the general delivery model that incorporates local government for long-term management. Consequently, this marriage between publicly funded NGO and state-driven management of these DES projects, could result in an effective partnership between state and civil society utilizing complementary skill sets if designed correctly.

Conclusions

This paper has examined the challenges of developing effective and sustainable business models for renewable micro-grids, towards achieving rural electrification objectives. In doing so the paper makes two key contributions. First, via three case studies, in Malaysia, the Philippines and Vietnam we have explored the design features of these business models, using a novel business model evaluation framework, which we test and verify through three case studies. Second, we provide recommendations for the features of effective micro-grid business models.

Current studies on micro-grid business models lack a unified framework to aid comparison between different models and approaches. We therefore propose a novel framework (Table 1) which could be used in future studies. This includes a focus on the *value proposition* to the host community including incorporation of the World Bank MTF on electrification, evaluating the *customer interface* for engaging the host community; how *supply chains* are organized and involve local workers; examining the *financial model* pairing simple technoeconomic analysis tools such as HOMER, with understanding of how the project is financed; and finally the project *governance* in terms of who owns the system, how key relationships are structured, how decisions are made and by whom.

The paper presents generalisable recommendations for the design and implementation of rural micro-grids, and further recommends the adoption of this framework for future studies in this field, as summarised below. Building on this framework we outline likely successful features of micro-grid business models as follows:

- **Value proposition:** Improvement of the level of electricity access i.e., MTF Tiers 3 and above, should be paired with a focus on productive uses of electricity. Moreover, business models should also consider other energy vectors such as space heating/cooling and cooking in their design.
- **Customer interface:** Successful business models should engage with communities from the earliest stages and be sensitive to the local context and cultural practices. This should also involve developing an ongoing relationship between project developers and host communities to ensure system longevity.
- **Supply chain:** Working with a local labour force improves the economic development potential of electrification projects and creates local buy in. Moreover, by pairing electricity access with its productive uses, virtuous circles are created which provide strong incentives for the host community to ensure effective O&M of micro-grids.
- **Financial model:** Renewable micro-grids may often not involve a traditional electricity tariff, and in our examples have LCOEs well above the typical national residential tariff rate. This suggests that last mile electrification requires extensive subsidy and financial support, likely beyond what NGOs can achieve alone.
- **Governance:** Community involvement and stewardship is essential for micro-grid projects where ownership and responsibility is often transferred after projects are completed. Our research has shown that developing effective partnerships between NGOs, communities and local government actors are key to ensuring effective governance over the long term.

This multi-country research has unpacked challenges of developing sustainable business models for renewable micro-grids, towards achieving rural electrification goals. The study offers valuable insights and recommendations for the design and execution of rural micro-grids, while advocating for the widespread application of a business model framework in further research in this area. Moreover, this research contributes to advancing the understanding and development of effective and sustainable business models for renewable micro-grids, towards fostering further rural electrification and broader energy access objectives.

The study has several limitations. These mostly relate to the challenges of accessing the case study locations during the COVID-19 pandemic, and therefore the main research team being unable to visit the sites. Secondly, we have a relatively small sample of 3 case studies. Further studies are needed to test the utility and validity of the business models evaluation framework, to support its refinement and applicability.

CRediT authorship contribution statement

Donal Brown: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. **Nofri Dahlan:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft. **Clare Richardson-Barlow:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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Appendix 1. Recorded and transcribed interviews

Interview code	Country	Organisation	Interview date
I#1	Indonesia	GIZ Indonesia	22/02/2022
I#2	International	IRENA	22/02/2022
I#3	Indonesia	Inovasi Dinamika Pratama	24/02/2022
I#4	Vietnam	Lotus Project	28/02/2022
I#5	International	United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP): Energy Division	3/2/2022
I#6	Vietnam	Hanoi University of Science and Technology	3/3/2022
I#7	Philippines	Yamog Renewable Energy Development Group, Inc.	10/3/2022
I#8	Malaysia	Sarawak Alternative Rural Electrification Scheme (SARES)	1/3/2022

Appendix 2. Unrecorded interviews

Interview location	Details	Date
Malaysia	Iban Community (n = 5)	28/2/22–1/3/22
	Sarawak Alternative Rural Electrification Scheme (SARES) Team (n = 2)	28/2/22–1/3/22
	Sarawak Energy Berhad (SEB) (n = 2)	15/12/21 & 07/2/22
	Tenaga Nasional Berhad (TNB)	20/1/22
	Tenaga Nasional Berhad Energy Services (TNBES) (n = 1)	04/3/22
	Department of Orang Asli Development (JAKAO) (n = 2)	08/3/22

(*continued on next page*)

(*continued*)

Interview location	Details	Date
Philippines	n = 36 interviews (11 males and 24 females) for Sitio Timodos, (Yamog)	4/04/2018–15/06/2018
Vietnam	n = 17 interviews conducted with Villagers from Chi Lang district (Lotus project)	January 2019
	n = 2 Chairman and Vice Chairman of the People's Committee of the local Chi Lang district	

Appendix 3. HOMER input information

Vietnam – Pa Mi, Chi Lang	As for annual average of solar irradiance received in this area is 4.23 kWh/m^2/day with a 1.088 cloud clearness index.
Vietnam – Lung Thoc Sarawak	A similar annual average of solar irradiance as Chi Lang is used in the simulation. The standalone solar photovoltaic (PV) system at Rumah Panjang Tungan comprises of components such as below: • Solar PV Capacity: 28.12 kW (76 panels × 370 W) • Battery: 218.3 kWh (96 units x 1250AH)-Lead Acid (Gel type) • Inverters: 3 units (2 units × 10 kW, 1 unit × 6 kW) • Battery Inverters • Solar charge controller • Monitoring system • System integrator • Electrical distribution system
Philippines	• The system has a capacity of 23 kW with the head of 15 m and flow rate of 350 cubic meter per second comprises of components such as below. • Diversion Weir/Intake (concrete and steel construction, steel sluice gate to control the inflow, gravel trap, spillway and PVC pipe for flushing) • Headrace Canal - Hollow block with steel reinforcement and 306 m total length - A Concrete slab cover is included throughout the length with several cleaning access along the length • Forebay and Penstock (reinforced concrete, spillway, flushing pipe, fine trash-rack, 0.4 m diameter X 56 m length mild steel penstock, expansion joint in all anchor block) • Turbine, Generator and Controller (cross flow turbine, flat belt transmission, 3 phase generator, electronic load controller with dummy load)

Appendix 4. HOMER input information and economic evaluation criteria

Input information:

- Site location – location of the off-grid system
- Configuration/ technical information of the off-grid renewable energy system - In the design of hybrid renewable energy system (HRES), there are several components can be considered. For example, the hybrid system may consist of a Photovoltaic (PV) system as the source of energy together with the batteries and diesel generators as the backup.
- Solar Radiation/temperature - Solar radiation data for the case studies are obtained from NASA Surface Meteorology and Solar Energy Database that available in HOMER software
- Capital investment and source of capital
- Incentives from the government (e.g., public grant, subsidies, tax incentives, etc.)
- System components cost (fuel price, operational & maintenance, replacement, logistics)
- Site's load demand – Hourly average daily load profile of the community/villagers
- User tariff information – the tariff imposed to the consumers
- Main grid information – if the system is connected to the grid, the main grid information may require

The economic performance of the micro-grid systems were evaluated by the Net Present Cost (NPC) and Levelized Cost of Energy (LCOE). A brief description for both indicator; NPC and LCOE, are expressed as follows:

a) Net Present Cost (NPC)

In HOMER, the life cycle cost f is represented by the total net present cost (NPC). It comprises of capital cost, replacement costs, O&M cost and fuel costs. The NPC is defined as the existing value of all components that are connected in the plant minus the present value of all the revenues that it receives over the lifetime and mathematically expressed as:

$$C_{NPC} = \frac{C_{TAC}}{CRF(i, n)}$$

where C_{NPC} is the Net Present Cost (NPC), C_{TAC} is the total annualized cost ($/year) and CRF represents the capital recovery factor of annual interest rate (i) and the year of cash flow (n). CRF formulation can be expressed as below:

$$CRF(i, n) = \frac{i(1+i)^n}{(1+i)^n - 1}$$

b) Levelized Cost of Energy (LCOE)

The levelized cost of energy (LCOE) is the average cost per kWh of electricity generation by the system. HOMER used following equation to compute COE.

$$COE = \frac{C_{TAC}}{E_S}$$

where E_s is the total annual energy supplied to the load in kWh.

Appendix 5. Workshop details

Workshop	Key participants	Date
Vietnam Workshop	Lotus Project & Hanoi University of Science and Technology	3rd March 2022
Philippines Workshop	De La Salle University and Yamog Renewable Energy Development Group	10th March 2022
Malaysia Workshop	Solar Research Institute and SARES Project	11th March 2022
ASEAN Workshop	International Audience, hosted by ASEAN Centre for Energy and SRI UiTM in Malaysia	March 17th 2022

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