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Technoeconomic Assessment of Microgrids in Myanmar*

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Abstract: *The electrification rate of Myanmar is the second-lowest in Asia, so its improvement is an urgent matter. Sustainable Development Goal 7 recognises the importance of energy access and calls for finding a way to realise the Government of Myanmar's goal to reach 100% electrification by 2030. To achieve this ambitious target, both centralised (main-grid extension) and decentralised approaches should be considered. In this study, we focused on distributed microgrids amongst electrification options. In Myanmar, as in other developing countries of the Association of Southeast Asian Nations (ASEAN), diesel generators are widely used as power sources of microgrids. Considering the global trend of renewable energy, especially opportunities available for solar photovoltaics (PVs), power sources should be selected carefully. When discussing possible power sources, cost-competitiveness is an important aspect. Therefore, we researched the question: How cost-competitive are microgrids powered by solar PVs compared to conventional diesel power source? We used the primary data collected through interviews and field surveys and calculated the levelised cost of electricity (LCOE) of microgrids. Our results show that solar PVs and batteries are cost-competitive compared with diesel in off-grid areas where diesel fuel prices are much higher than in urban areas. However, to improve efficiency, daytime use of electricity (e.g. productive use) needs to be promoted.*

***Keywords*:** Energy access; Rural electrification; Myanmar; LCOE; minigrid.
***JEL Classification*:** Q42; O22

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1. Introduction

Energy access is recognised globally as an urgent issue. This is evidenced by the United Nations Sustainable Development Goals (SDGs), adopted in 2015, which include SDG 7: Ensure access to affordable, reliable, sustainable and modern energy for all. That is, the way to achieve it is via renewable energy, not fossil-fuel-based energy.

Since the country started opening up to world trade, Myanmar’s growing economy has been receiving increasing attention in recent years. However, an electricity shortage hampers this economic growth. Only 35% of households had access to electricity as of 2016,[1] which was the second-lowest rate in Asia, after the Democratic People’s Republic of Korea. As 70% of the population in Myanmar lives in rural areas (Ministry of Immigration and Population, Department of Population, 2014), rural electrification is an urgent matter. In 2015, the Government of Myanmar set a target to achieve 100% electrification by 2030 (World Bank, 2014; IEA, 2017c), which matches SDG target 7.1: By 2030, ensure universal access to affordable, reliable and modern energy services. IEA (2017a) forecasted that renewable energy sources will cover over 60% of new access and that microgrid systems will be provided for almost half of new access cases.

This target seems very ambitious given the current low electrification rate. Achieving it means considering not only centralised approaches (main grid extension) but also decentralised ones. Main grid extension often prioritises urban or peri-urban areas, where demand is higher, while sparse rural areas are seen as less of a priority. In addition, electricity tariffs on the main grid in Myanmar are subsidised and kept very low. The tariff for the residential sector is 35–50 MK/kWh (0.026–0.036 US$/kWh)[2]. This makes it difficult for utilities to make necessary capital investments (ADB, 2016). It has been pointed out that the tariffs should be increased to a level adequate for new investments and operations (JICA et al., 2015).

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[1] IEA (2017a) reported that the national electrification rate was 59% in 2016, in urban areas 79%, and in rural areas 43%. IEA (2016), however, estimated the national electrification as 32% in the World Energy Outlook (WEO) 2016 database. This difference seems too big for a year. The Ministry of Electricity and Energy (2016) reported the share of grid-connected households as 35.87% in fiscal year 2016.

[2] Dollar–kyat exchange rate used is US$1 = MK1,370.71 (xe.com, 2017). Prices without notes are in 2017 US dollars.

When considering a decentralised approach, stand-alone systems such as solar lanterns and solar home systems (SHSs) are also options. They are easy to install, and their prices decreased from US$45 in 2009 to US$10 for more efficient LED lamps and mobile charging (ESMAP, 2017). However, the utilisation of SHSs is limited to household use and difficult to scale up. In Myanmar, SHSs were deployed in off-grid areas by the government (Greacen, 2015; Sovacool, 2013). In the current study, we focused on microgrids, which have a distributed power source and supply electricity to households. In the context of rural electrification in Myanmar, we use microgrids to mean only the isolated system from the main grid. Microgrids are scalable and can respond to the future growth of electric power demand (Greacen, 2017b). Various studies (Schnitzer et al., 2014; BNEF, 2017a) have reported the diffusion of microgrids all over the world.

As in other developing countries, diesel is a dominant power source of microgrids in Myanmar. Microgrids are electrified by diesel in 13,000 villages, by micro-hydropower in 2,400, by biomass gasifiers in 1,200, and by solar photovoltaics (PVs) in 150 (Greacen, 2017b). Installation of microgrids is easier because of their availability and lower initial investment costs. Moreover, flexibility is an advantage. A microgrid can be used as a backup power source for the main grid or for agricultural purposes. Most of diesel's costs come from the fuel itself. The price of diesel is highly volatile, and transportation costs are fairly high in off-grid areas where roads are not well developed. According to an interview with a local developer, the price of diesel fuel on a remote island in Myanmar was about 2,000 MK/L (about 1.46 US$/L) compared with 750 MK/L (about 0.55 US$/L) in Yangon in 2017. Diesel is considered to be relatively cheap because of its small initial investment; nevertheless, the case in rural areas should be investigated.

As mentioned, it is recognised internationally that electrification via clean energy sources is preferred over using fossil fuels. Amongst the different renewable energy sources, solar PVs have spread rapidly in recent years. The cost of PVs dropped 70% between 2010 and 2016 (IEA, 2017c). In relation to this price decline, installation has dramatically increased worldwide (IRENA, 2017b).

International donor organisations have been conducting projects with the Myanmar government to promote renewable-energy-based microgrids. While rural electrification is under the control of the Department of Rural Development (DRD) in the Ministry of Livestock, Fisheries and Rural Development, the main grid is under the Ministry of

Electricity and Energy. The DRD started the ‘60/20/20’ project under the National Electrification Project (NEP) funded by the World Bank. In this project, the DRD provided a subsidy to cover 60% of the costs and private companies and villagers invest 20% each. First, the private sector submitted project proposals to the DRD, including design, development, operation, and transfer to the villagers. Villagers organised a village electrification committee (VEC) or utilised an existing VEC. In Myanmar, committees are established to deal with village matters, for example water resources for agriculture (Takahashi, 2012). Members of the VEC are not elected but rather existing influential people often become members. The VEC makes decisions about energy-related topics, such as fuel procurement, tariffs, and the payment exemption of poor households. In addition, the VEC sometimes collects tariffs. The ‘60/20/20’ project includes capacity building of the VEC to prepare for the transfer of the microgrids from the developers after they have been operational for a few years. Eight of 40 project proposals were selected in the first year (i.e. 2016). Most of the selected microgrid projects were under construction as of May 2017. Their solar PV capacity ranged from 10 kW to 110 kW. Companies have also supplied LED lamps for households and street lights in villages. Tariffs are set by the companies and reviewed by the DRD.

The Asian Development Bank (ADB) funded 12 distributed solar PV ‘grid-ready’ microgrids in fiscal year 2016 (ADB, 2018). The selected developer installed the system in the village, which was funded 80% by ADB and 20% by the VEC. LED lamps and street lights were also installed as part of the projects (Doshi, 2017). ADB set tariffs at MK1,500 per household per month (about US$1.1). ADB also requested that half of the VEC members be women. An operator, who is employed by the developer/owner of the microgrid, visits the village once a week. The operator’s jobs are conducting basic maintenance, charging prepaid cards for meters, and keeping a payment record. Some higher-income households own TVs, DVD players, and satellite TV antennas. The levelised cost of electricity (LCOE) of those projects was 0.20–0.26 US$/kWh, but it excluded battery replacement (ADB, 2017). One supplier to these projects estimated that the lead-acid battery life would be 2–3 years. Battery replacement should be considered if the LCOE is compared against other generation types.

The Japan International Cooperation System (JICS) installed microgrids in Shan and Chin states using ¥994 million in grant aid from the Government of Japan. Of the total 31 projects, 27 had been handed over by September 2016. The microgrids were powered by solar PV or micro-hydropower. Capacities ranged from 0.1 kW to 10 kW for micro-hydropower and from 1.2 kW to 20 kW for solar PV. The DRC and VEC coordinated the tariff setting (JICS, 2015; 2016).

As with other developing countries, collecting well organised data is difficult, except for projects by donor organisations. Other challenges include unclear definition of terms and limited comparability of the data from other institutions. To spread the use of renewable-based microgrids, it is important to find out how cost-competitive they are against conventional diesel-based microgrids.

Our research question was: How cost-competitive are microgrids powered by solar PVs compared with a conventional diesel power source? In our analysis we compared the LCOE for solar-PV-based microgrids and traditional diesel-based microgrids in Myanmar. First, we assumed two load cases: (1) basic usage only at night based on the interview survey data, which is similar to current microgrids in Myanmar; and (2) a more developed case that includes productive uses during the daytime. Second, we calculated the required system capacity to fulfil the assumed load for each case. Finally, we calculated the LCOE values and compared them.

2. Cost of Microgrids and Solar Photovoltaic Integration

We reviewed studies about the electrification and energy situation in Myanmar, as well as about distributed microgrids and their technologies.

Microgrids are spreading rapidly as a way of rural electrification because they have multiple uses – for lighting and mobile charging as well as entertainment (e.g. TVs and DVD players) and for productive uses (Schnitzer et al., 2014). Moreover, they provide electricity to social welfare facilities such as hospitals and schools. Energy companies are interested in this field, as are large well-known technology companies. Microsoft and Facebook founded the Microgrid Investment Accelerator and raised US$50 million (BNEF, 2017a). In member states of the Association of Southeast Asian Nations (ASEAN), the investment opportunities may be large (Phoumin and Kimura, 2016).

Providing electricity in rural areas previously focused on conventional solutions such as main grid extension and diesel-powered microgrids. The Sustainable Engineering Lab

(2014) estimated the total investment for electrification using both grid extension and off-grid programmes, but only assumed diesel-powered microgrids and SHSs as off-grid electrification.

Myanmar also ratified the Paris Agreement (UNFCCC, 2018). In their Intended Nationally Determined Contribution (INDC), the country stated an indicative goal in the energy sector as ‘Rural electrification through the use of at least 30% renewable sources as to generate electricity supplies’ though afforestation and/or reforestation is stated as the main action (Republic of the Union of Myanmar, 2015). Myanmar has plentiful renewable energy resources, not only solar radiation but also hydropower. The country’s maximum solar power potential was an estimated 40 TWh/year, and the capacity potential of micro- and mini-hydropower about 230 MW and of large hydropower about 100,000 MW (ADB, 2016). Not only large-scale generation but also microgrid power sources use these technologies (Del Barrio Alvarez, 2018).

However, studies about renewable energy in Myanmar are lacking. ACE (2016) reported the LCOE values of renewable energy types of solar PVs, biomass, and hydropower for Indonesia, the Lao People’s Democratic Republic, Malaysia, Thailand, Viet Nam, and Myanmar. They assessed 64 renewable energy projects, of which only two were in Myanmar and hydropower based. No solar PV project in Myanmar was included.

Moreover, the microgrids situation is similar in other developing countries. Blum, Wakeling, and Schmidt (2013) analysed the case in Indonesia, and we used their analysis method in the current study.

Microgrids powered by renewable energy, especially solar PVs, are considered expensive. Sasaki et al. (2015) estimated the cost for rural electrification via microgrids based on assumed load projection using the HOMER software for microgrid design and optimisation. They assumed three types of microgrids, powered by (1) a combination of solar PVs and biomass, (2) micro-hydropower, and (3) diesel generators. Win, Jin, and Yoon (2017) compared diesel generators and a hybrid system that comprised solar PVs, batteries, and a diesel generator. Kim and Jung (2018) compared different energy sources: diesel generators, solar PVs, lead-acid batteries, lithium ion batteries (LIBs), and various combinations of such.

The above studies are valuable to understand the possibilities for microgrids in Myanmar, but possible decline in the future cost should be also considered. Solar PV costs are expected to decrease continuously and will be one of the cheapest means to produce electricity (BNEF, 2017b). Lithium ion batteries (LIBs) were following the same track (Kittner, Lill, and Kammen, 2017; Kittner, Gheewala, and Kammen, 2016). When discussing microgrids powered by solar PVs, storage technology is imperative. As in many other developing countries, solar PV microgrids in Myanmar utilise lead-acid batteries for storage. However, LIBs have a longer cycle life in deeper discharge usages with higher round-trip efficiency than lead-acid batteries (IRENA, 2017a). When using batteries in microgrids, the assumed charging/discharging cycle is quite frequent, at least once per day. LIBs would be a better solution in many ways, but higher costs are a barrier to installation. The situation seems to be changing, however. It was forecasted that future prices would fall to around 124.24 US$/kWh for lithium-ion electric energy storage battery packs in 2020 (Kittner, Lill, and Kammen, 2017), 135 US$/kWh for LIB packs (Schmidt et al., 2017), and 120–380 US$/kWh in 2035 for installation cost (IRENA, 2016). Developers in Myanmar have also started to consider the installation of LIBs in their microgrids in the near future. Therefore, we calculated the LCOE values for microgrids not only with diesel generators and/or solar PVs with lead-acid batteries, but also of configurations with LIBs based on their projected costs.

3. Methodology and Data

We estimated costs and load assumptions based on three field surveys (February, March, and October 2017) and on the literature. We interviewed developers at Yangon Technological University and collaborated with Mitasu Consultants Group in Yangon on questionnaires and follow-up. Survey results were anonymised (Appendix 1); thus, cost data were averaged.

3.1.Levelised cost of electricity calculation

The LCOE for different power sources of microgrids were calculated (**Error! Reference source not found.**1). The LCOE formula has been presented in many publications (e.g. IEA and NEA, 2015). The calculation of the LCOE for solar PVs combined with batteries followed that described in Pawel (2014). The denominator of the LCOE formula is the net present value of electricity in the project period. We used the amount of sold electricity (in kWh) for the denominator, assuming that it equals the load and that generation of electricity always covers the load. We did not use the amount of produced electricity because of obvious electricity loss in the daytime, not consumed or charged to batteries.

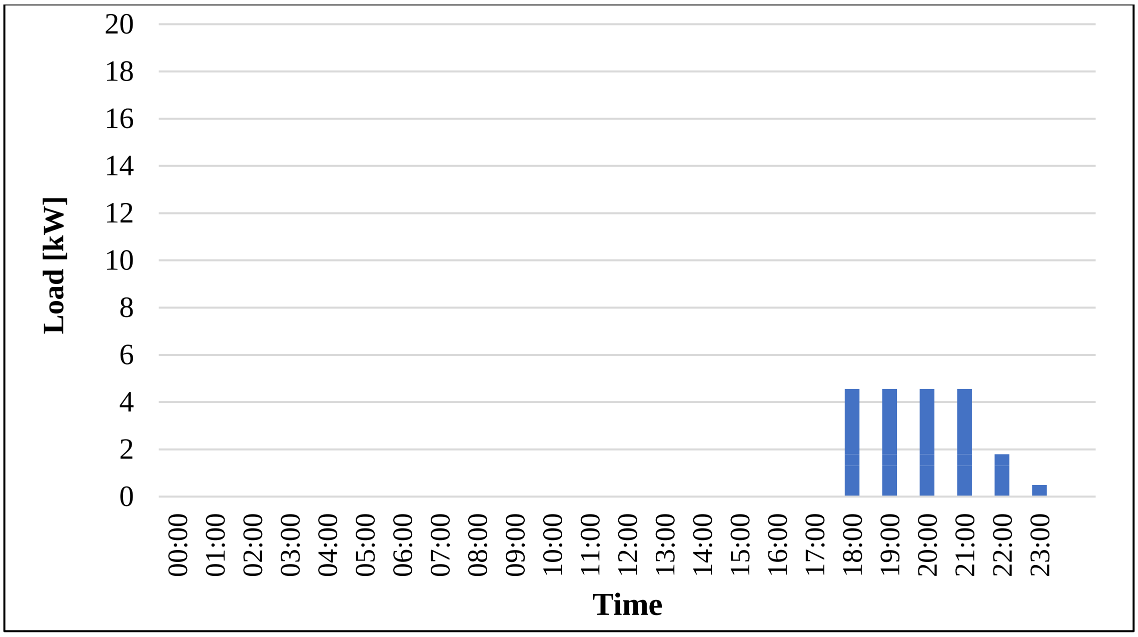
3.2.Load assumption

Two load scenarios are assumed. Because of limited power consumption data for off-grid areas, our assumption was based on cumulative power consumption of appliances, for which households provided data in a survey done by one of the developers. The number of households per village was assumed to be 100, which is similar to the typical number of households for interviewees' microgrids.

Scenario A is a lower load case only for basic uses such as LED lights and TVs. The assumption was that each household has three LED lights (two indoors and one outdoors), and three out of four households have a TV. The assumed load was 20.5 kWh/day, only at night, as shown in Figure 1.

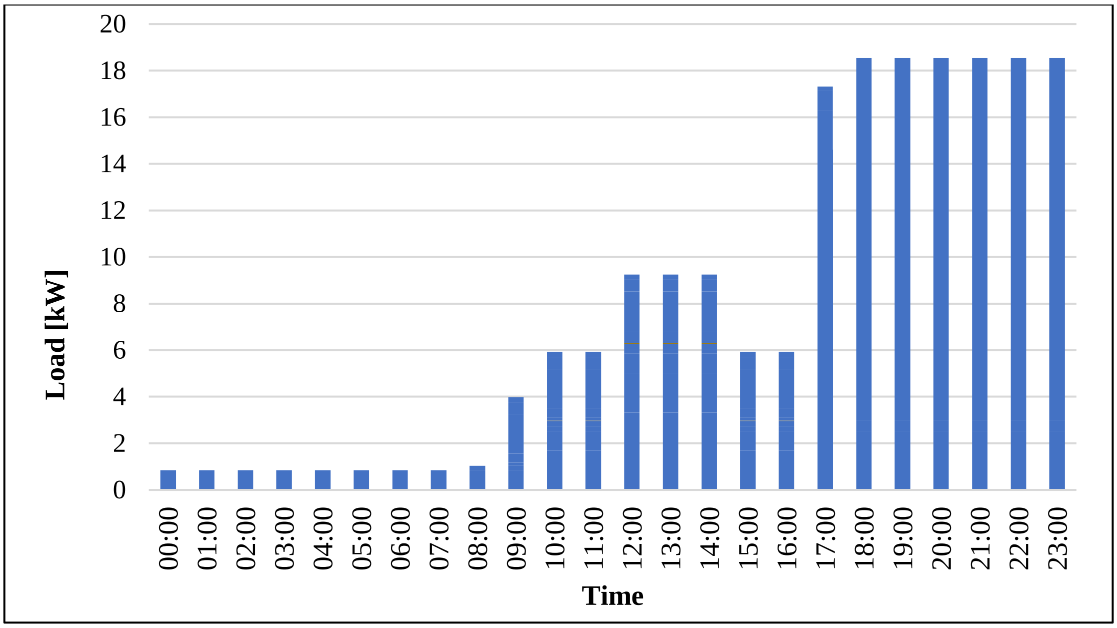
Scenario B is a higher load case, meant for both household use at night and productive use during the daytime. Household use was assumed based on the appliances that households wish to have in the future from a feasibility study undertaken by one of the developers. Productive use was assumed to be the total number of small businesses that the developers stated were in their microgrids. Each load from productive use was taken from the literature (Blum, Wakeling, and Schmidt, 2013; Aye, 2015). The assumed load was 192 kWh/day, which comprised 61 kWh from 06:00 to 18:00 and 131 kWh from 18:00 to 06:00, the profile of which is shown in Figure 2. The detailed load assumptions are outlined in Appendix 2. Detailed Load Assumption.

Figure 1: Load Scenario A: Night only



kW = kilowatt.
Source: Authors' assumption.

Figure 2: Load Scenario B: Day and night



kW = kilowatt.
Source: Authors' assumption.

3.3.Cases for calculation

For power source, we compared diesel and solar PVs. Solar PVs need some kind of backup because systems are isolated from the main grid. We assumed two types of backups: batteries only and a combination of batteries and diesel generators. The following system configurations are assumed:

- Power source
  - Diesel: conventional diesel generator
  - PV + Battery: solar PVs backed up by batteries
  - PV + Battery + Diesel: hybrid systems of solar PVs backed up by batteries and a diesel generator

As explained, the fuel price differs greatly by area. One of the interviewees explained that the price around their site was about 2,000 MK/L (about 1.46 US$/L) and it was 750 MK/L (about 0.55 US$/L) in Yangon. On that basis, we assumed two fuel prices to cover a relatively cheap area and the highest priced area:

- Fuel price (FP)
  - International price for diesel fuel costs
  - International price multiplied by 2.7 (= 2,000/750), representing the ratio between urban and off-grid rural areas

For batteries, the current dominant technology is valve-regulated lead-acid batteries and LIBs are expected to replace them in the near future. When LIBs eventually come into use because of their lower cost, the cost of solar PVs is also expected to decrease. Therefore, we set the current cost scenario assuming lead-acid batteries and the future cost scenario assuming LIB technologies:

- Equipment costs
  - Current cost (lead-acid batteries): average price for PVs and lead-acid batteries based on our surveys
  - Future cost (LIBs): PV costs decreased to the SunShot 2020 cost target price for residential-scale solar, set by the SunShot initiative under the US Department of Energy's Solar Energy Technologies Office (Woodhouse et al., 2016) and costs of LIBs decreased to 124.24 US$/kWh in 2020 (Kittner, Gheewaka, and Kammen, 2017)

Based on the assumptions above, we set 12 cases for calculation (see Table 1 for each case and its capacity and Table 2 for common assumptions). Each capacity was set to cover loads and will be explained in detail later.

Table 1: Scenario Types and Their Capacities

		Capacity for load scenario A: night only	Capacity for load scenario B: day & night
Diesel	FP × 1	(1a) Diesel 5 kVA	(1b) Diesel 20 kVA
	FP × 2.7	(2a) Diesel 5 kVA	(2b) Diesel 20 kVA
PV + Battery	Current – Lead-acid batteries	(3a) PV 7.9 kW Battery 39.5 kWh	(3b) PV 81.1 kW Battery 252.5 kWh
	Future – LIBs	(4a) PV 7.4 kW Battery 22.5 kWh	(4b) PV 76.9 kW Battery 143.5 kWh
PV + Battery + Diesel	FP × 1	(5a) PV 3.9 kW Battery 23.0 kWh Diesel 3.9 kVA	(5b) PV 33.5 kW Battery 91.6 kWh Diesel 33.5 kVA
	FP × 2.7	(6a) PV 3.9 kW Battery 23.0 kWh Diesel 3.9 kVA	(6b) PV 33.5 kW Battery 91.6 kWh Diesel 33.5 kVA

FP = fuel price, kVA = kilovolt-ampere, kW = kilowatt, kWh = kilowatt-hour, LIB = lithium ion battery, PV = photovoltaic.
Source: Authors' assumption.

Table 2: General Assumptions for Calculations

	Value	Source
Discount rate	10%	ACE (2016)
Project term	20 years	Our assumption
Number of households in a village	100	Simplified number based on survey
Loss of distribution	4%	Blum, Wakeling, and Schmidt (2013)

Source: Authors.

3.4.Microgrid powered by diesel generator

As explained, we assumed two diesel fuel price cases: (i) international fuel price (FP × 1), which represents urban areas, and (ii) international fuel price multiplied by 2.7 (FP × 2.7) for rural areas. The international fuel price is based on forecasting by the United States Energy Information Administration (2015).

Table 3 lists the assumptions with respect to a microgrid powered by a diesel generator. We assumed the diesel generator could follow the load and adjust its output.

Table 3: Assumptions for Diesel-powered Microgrids

	Value	Source
Efficiency	26%	Blum, Wakeling, and Schmidt (2013)
Operating hours	(Load: night only) 6 hours/day (Load: day & night) 24 hours/day	Survey by the authors
Capital expenditure (CAPEX)		
Cost of equipment	259 US$/kW	Survey by the authors
Cost of engineering	241 US$/kW	Lazard (2014)
O&M cost	2.6 US cents/kWh	Dobermann (2016)
Replacement	None	Lifetime: 20 years (IRENA and ACE, 2016)

kW = kilowatt, kWh = kilowatt-hour, O&M = operation and maintenance.
Source: Authors.

3.5. Microgrid powered by solar photovoltaics with batteries

We chose crystalline polysilicon as the PV technology because it is the dominant technology in small-scale, residential applications. Isolated solar PV microgrids need storage to accommodate the load at night. The current dominant storage technology is lead-acid batteries, but developers have begun to think about installing LIBs because they are cheaper. Assuming the rapid cost reduction of solar PVs and LIBs continues, we set two cost cases.

The current cost case assumes the use of lead-acid batteries, and prices are averaged numbers based on our surveys. For the specification, we assumed that the highest class of lead-acid batteries are installed in Myanmar. Our assumption of the current installation costs for solar PV systems was 2,178 US$/kW, which is based on the averaged results of interviews. It is similar to the price in ASEAN Member States, i.e. 2,576 US$/kW (ACE, 2016). The assumptions are summarised in Table 4.

The future cost case assumes LIBs and their price will decrease to 124.24 US$/kWh in 2020 (Kittner, Lill, and Kammen, 2017), and PV cost will decrease to the SunShot 2020 target price at the residential scale (Woodhouse et al., 2016).

Table 4: Assumptions for Solar PVs and Batteries

	Current cost	Future cost
PVs		
Capacity factor	18%[1] (World Bank & ESMAP, 2017)	
Degradation rate	1% (Authors' assumption)	0.2% (Woodhouse et al., 2016)
CAPEX	2,707 US$/kW (average number from survey by the authors)	1,600 US$/kW (Woodhouse et al., 2016)
O&M cost	1% of CAPEX (ACE, 2016) with inverter replacement	10 US$/kW without inverter replacement; inverter lifetime is assumed 30 years
Batteries	Lead-acid batteries (current price)	LIBs (forecasted price)
Round-trip efficiency	90% (HOPPECKE Batterien GmbH & Co. KG, 2016)	95% (IRENA, 2017a)
Depth of discharge[2]	60% (HOPPECKE Batterien GmbH & Co. KG, 2016)	100% (IRENA, 2017a)
CAPEX	286 US$/kWh[3] (Off-Grid Europe GmbH, 2017)	124.24 US$/kWh[4] (Kittner et al., 2017)
O&M cost	0 US$/kW (Lazard, 2017)	0.04 US$/kWh (Lazard, 2017)
Replacement[5]	Every 7 years	Only in the 11th year

CAPEX = capital expenditure, kW = kilowatt, kWh = kilowatt-hour, LIB = lithium ion battery, O&M = operation and maintenance, PV = photovoltaic.

Notes:

Limitations: For simplicity, the self-discharge of the lead-acid battery and the relationship between the available capacity and discharge time were not considered.

1 Calculated from 4.32kWh/kW daily in Nay Pyi Taw

2 Depth of discharge was set to minimise total costs including Capex and replacement cost within the operation range

3 Dollar-euro exchange rate is US$1 = €1.15880 (XE.com, 2017)

4 In 2015 US$

5 Calculated from life cycle

Source: See literature cited in cells.

3.6. Microgrid powered by a combination of solar photovoltaic system with batteries and a diesel generator

A hybrid system comprising solar PVs, batteries, and a diesel generator was installed at many sites in Myanmar. Since the capacities of solar and diesel systems differed from site to site, we assumed the capacity to be the same, following the configuration of Blum, Wakeling, and Schmidt (2013). The load during the daytime was covered by the solar PVs, and excess generation was used to charge the batteries. At night, diesel powered the first three hours and the batteries were discharged for the rest of the night. The capacities are shown in Table 1. The batteries were assumed to be made of lead acid, and other assumptions aligned with those of the current cost in Table 4.

4. Levelised Cost of Electricity for Solar-Photovoltaic-Based Microgrids

The LCOE was calculated for each case in scenario A: night only (Figure 3) and scenario B: both day and night (Figure 4). A diesel generator may not be an affordable option in rural areas because the fuel costs in such areas would be much higher than in urban areas. Case (1) represents the fuel cost in urban areas and case (2) in rural areas. Most of the diesel LCOE is from the fuel cost; hence, the LCOE is estimated as proportional to the fuel price. We calculated two cases (1 and 2) of diesel prices and roughly presumed the LCOE in other areas, even though fuel price differs by area, distance from the distribution centre, and means of transportation. In addition to these domestic conditions, the international fuel price itself is very volatile.

The LCOE of the combination of solar PVs and lead-acid batteries, represented in case 3a, is 0.68 US$/kWh, which is relatively expensive. When loads occur only at night, the electricity generated by solar PVs during the daytime needs to be stored. The system needs enough battery capacity to meet the demand, whereas the capacity of solar PVs is relatively low. The current battery price is still high, even for lead-acid batteries; hence, batteries need to be used more efficiently.

The LCOE of solar PV + LIB, represented in case 4a, indicates it is the cheapest amongst the cases. The longer cycle life of LIBs meant fewer replacements were required (only once in the project period in contrast to twice for lead-acid batteries). The capital expenditure (CAPEX) of batteries occupies a smaller portion of the LCOE than in case (3a), lead-acid batteries.

It is not necessarily appropriate to suggest that the LCOE is cheaper after combining solar PVs, batteries, and a diesel generator. Each component’s capacity was set following the configuration of Blum, Wakeling, and Schmidt (2013), but the optimal combination should be investigated further. The system capacities of cases 5a and 6a and of cases 5b and 6b were the same in each load scenario (Table 1); thus, the levelised costs from solar

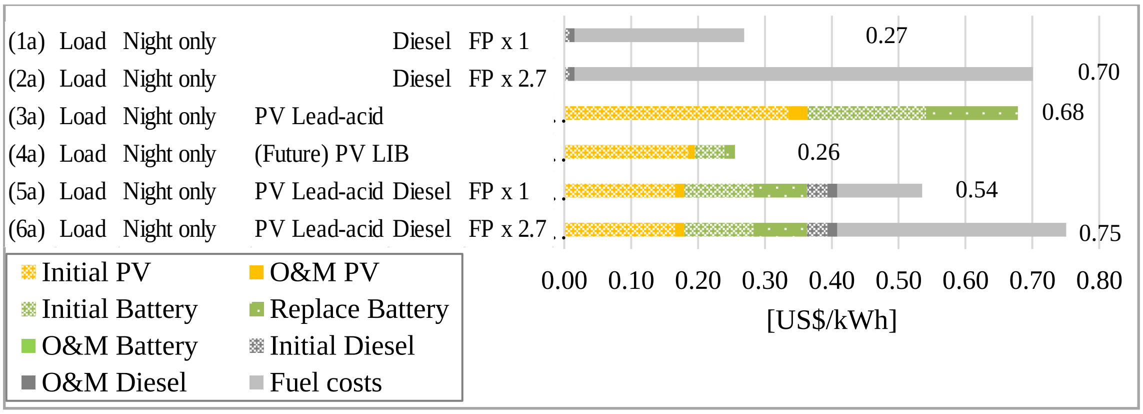
PVs and batteries were the same in cases 5a and 6a and in 5b and 6b. The differences in LCOE came from fuel costs.

When the load became bigger and increased continuously both in the daytime and at night, the LCOE generally became cheaper, as compared with Figure 3 and 4.

However, the differences per load scenario of the diesel power source, represented by cases 1a and 1b and by cases 2a and 2b, are very small. This is because we assumed that diesel generators can adjust their output following the load.

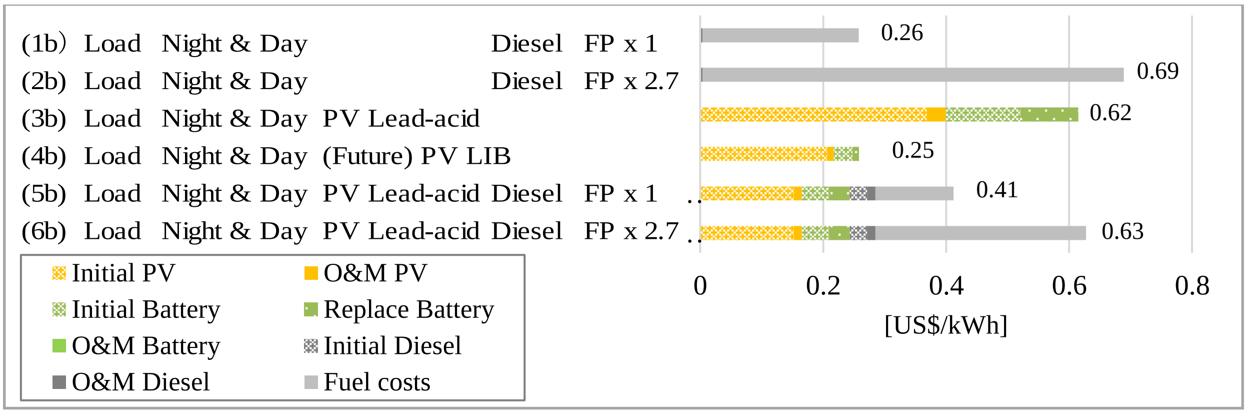
The LCOE of solar PV + lead-acid battery became cheaper when there were loads during the daytime and at night, as in cases 3a and 3b, respectively. As explained above, an absence of load in the daytime requires a higher capacity of batteries and a lower capacity of solar PVs. Daytime loads reduce inefficiency of system configuration. The LCOE of solar PV + LIB in cases 4a and 4b only differed slightly, because the battery price was low enough that the capacity difference between PVs and batteries is small.

Figure 3: Calculation Results of LCOE: Load scenario A (night only)



FP = fuel price, LCOE = levelised cost of electricity, kWh = kilowatt-hour, LIB = lithium ion battery, O&M = operation and maintenance, PV = photovoltaic.
Source: Authors' calculation.

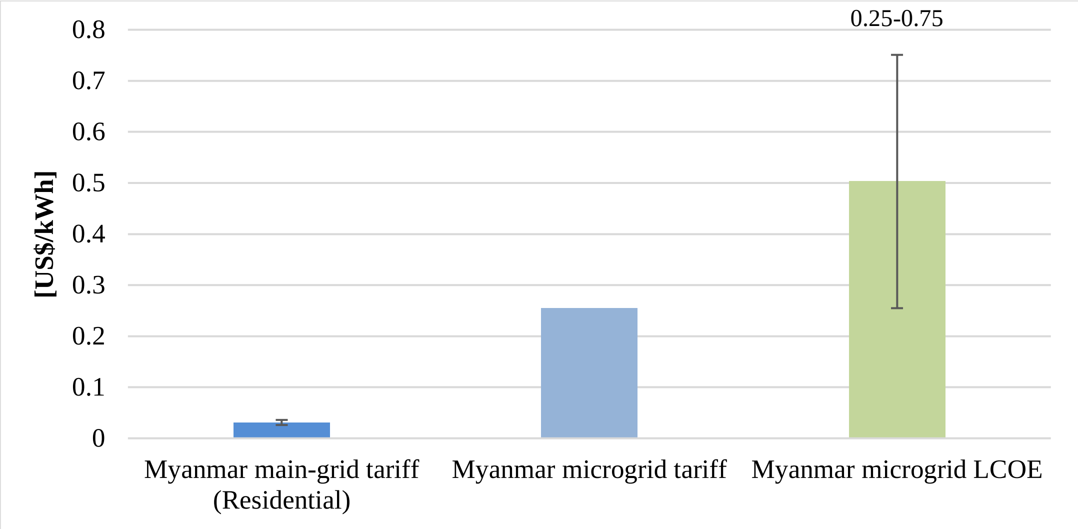
Figure 4: Calculation Results of LCOE: Load scenario B (night and day)



FP = fuel price, LCOE = levelised cost of electricity, kWh = kilowatt-hour, LIB = lithium ion battery, O&M = operation and maintenance, PV = photovoltaic.
Source: Authors' calculation.

We observed that the LCOE values of hybrid systems of solar PVs, batteries, and a diesel generator were lower when there were loads during the daytime for cases 5a and 5b and for cases 6a and 6b. Because the solar PVs covered the loads in the daytime, system use was more efficient in cases 5b and 6b than in cases 5a and 6a. Capacities of each equipment (solar PV, batteries, and diesel generator) increased in cases 5b and 6b, but the LCOE proportion of batteries declined from 34% in case 5a to 19% in case 5b and from 25% in case 6a to 12% in case 6b. In contrast, the proportion of fuel costs increased from 46% in case 6a to 55% in case 6b and from 24% in case 5a to 31% in case 5b because the fuel price of case 6 was higher than that of case 5. Our results were generally in alignment with the results of previous studies (Skat, 2017; Kim and Jung, 2018). The LCOE calculation results for diesel were a little off range, but they depended highly on the fuel price during the project period. Therefore, we think the differences were due to the source of fuel price forecasting.

Figure 5: Comparison of Tariffs and LCOE Values



LCOE = levelised cost of electricity.
Source: Myanmar main-grid tariff: ADB (2016); Myanmar microgrid tariff: authors' survey; Myanmar microgrid LCOE: authors' calculation.

Figure 5 shows a comparison of residential tariffs on the main grid, one of the tariffs of the hybrid system microgrid, and our LCOE calculation results from cases 1–6. The microgrid tariff was subsidised by the government under the '60/20/20' project and became profitable for developers. It seems difficult to keep tariffs at a payable level without subsidies. The main-grid tariff for residential customers was 0.026–0.036 US$/kWh (ADB, 2016) and was heavily subsidised. It is nearly 10 times higher than the microgrid tariff.

5. Discussion

The LCOE values of microgrids powered by solar PVs and batteries in Myanmar are still high, but lower than those of diesel power sources depending on fuel price – and these systems are expected to be one of the cheapest power sources in the near future in combination with LIBs. This leads to a narrowing of the gap between the microgrid tariff and the LCOE of microgrids. If the LCOE of microgrids decreases to the level of the current subsidised microgrid tariff, a subsidy will no longer be necessary.

However, the gap between tariffs of microgrids and the main grid is a different issue. The gap is so huge that improving it in the short term seems difficult. The main-grid tariff should be increased enough to cover power generation costs, operation and maintenance costs for existing transmission/distribution lines and power plants, and new development costs (JICA, NEWJEC, and Kansai Electric Power, 2015). The government plans to increase the main-grid tariff, but Frontier Myanmar Research (2017) reported a delay in these plans in November 2017.

The tariff gap expands the inequality between grid-connected urban and microgrid rural areas (Dapice, 2014). People in urban areas can enjoy electricity from the grid at cheap prices including the subsidy (although frequent blackouts/brownouts are a problem) and also can get diesel fuel cheaper. In contrast, people in rural areas have to pay more for diesel fuel and for electricity. Subsidies to main-grid electricity are regressive. Electricity for people in rural areas should be subsidised, so it stands to reason that subsidies to CAPEX of microgrids under the '60/20/20' project should also. However, the problem of the urban poor is outside the scope of this research.

The main-grid tariff is sometimes erroneously referred to as a standard of electricity tariff, as one interviewee pointed out. The microgrid sites under the government were selected in areas where the main grid will not extend within 10 years. The government would review proposals including tariffs and reject them if the imposed tariffs were too high. However, one interviewee said that a project had faced pressures to cut tariffs, not only from villagers but also from local officials. Because there is no legal standard for tariffs, people compared the main-grid tariff to that of the microgrid. They deemed the latter too expensive, when in fact it is the main-grid tariff that is too cheap. Education not only for villagers but also for local officials is anticipated. This is a big risk for private companies if they cannot make use of the tariff to cover the development and operating costs and to earn reasonable profits from projects. Companies thus hesitate to enter the microgrid business.

Decreasing price trend and economy of scale are effective in lowering microgrids' LCOE. It is important for microgrids' operations to ensure a certain size load (known as anchor customers), for example telecom towers and agricultural machinery (Tenenbaum et al., 2014; Mukherjee and Symington, 2018). Telecom towers do not always exist near off-grid villages. It is reasonable to start a business in a profitable place with more certainty and then to expand. However, the main industry in most off-grid villages is agriculture. Using agricultural machinery (e.g. crop drier) instead of diesel machinery would serve a dual purpose: anchor customers for a microgrid and cleaner power source for those pieces of machinery (Bouille et al., 2012).

If villagers using diesel for electric power were to simply replace their power source with solar PVs and batteries, running a microgrid business would be easier. Their willingness to pay is not for the main-grid tariff but for the level of diesel fuel, which is relatively high. In addition, they often have already made productive use of electricity, for example oxygen pumps for fish cultivation. However, if the electricity from developers' microgrids is generally the first modern energy for villagers, the situation is more difficult.

Developers need to begin by encouraging villagers to start businesses that use electricity, but most have engineering backgrounds and are not professional consultants for entrepreneurs. It would be useful to provide a support programme for villagers to start a new business and to easily access financial packages for small businesses, such as a two-step loan for small and medium-sized enterprises (SMEs). These also are used by productive end users of microgrids (Vaghela, 2017).

Because the main industry in off-grid areas is agriculture, villagers' income is very seasonal. All the microgrids in our survey set monthly payments. Therefore, seasonal income affects the collection of tariffs (Siteur and Granfelt, 2017). Payment variations should be offered, for example one or a few payments in harvest season or two-tier amounts (paying more in the harvest season and less in the seeding season). Karlan and Appel (2011) discussed a similar approach with respect to the payment of fertiliser.

Cost versus quality should be discussed further. In this study, we assumed the price reductions in solar PV system cost and LIB cost would continue and referred to the SunShot 2020 cost target for PV systems (Woodhouse et al., 2016) and forecasting of LIB price (Kittner, Lill, and Kammen, 2017) in the near-future case. However, there is a known trade-off between efficiency and manufacturing cost (Woodhouse et al., 2016), which is known more in developing countries as 'cheap and nasty'. A regulatory framework is needed to ensure the quality of electrical products (Baring–Gould et al., 2016; Greacen, 2017a). In rural areas in Myanmar, the image of solar PV products as 'nasty' has already surfaced. Our interviews with international donor organisations revealed that people in off-grid villages preferred electrification via micro-hydropower to solar PVs because of this bad image. It is important to maintain the level of quality while reducing costs.

6. Conclusions

We conclude with our major findings and mention some limitations. Our results show that the combination of solar PV and batteries is cost-competitive against diesel generators as a power source of microgrids. In the near future, the cost of solar PV and batteries are expected to decrease even further to be more competitive.

In addition to cost reduction of systems, growth of demand is also important for business sustainability of microgrids. Expanding daytime use of electricity is key. This could be done by expanding productive use, which is a strong option, but microgrid operators are not entrepreneurs. The government is highly encouraged to provide a support programme for entrepreneurs (e.g. education, finance).

To reduce inequality between urban and rural areas, subsidies for the CAPEX of renewable energy sources could have potential. In urban areas, the electricity tariff of the main grid is subsidised for residential customers and diesel fuel is cheaper. In rural areas, however, people do not have access to electricity and need to buy more expensive diesel fuel. Solar PV requires a high initial investment, which is a barrier for poorer people, so a subsidy would be effective, though it should be designed carefully in terms of financial resources and not distort the market.

Our results are limited to simplified calculations but show the current market situation of microgrids powered by solar PVs in Myanmar and the needed policy reforms. Our survey process revealed many barriers to deployment of microgrids powered by renewable energy, for example regulatory, financial, and educational (Anbumozhi and Tuan, 2015). To accelerate rural electrification through microgrids, these barriers must be overcome. Barrier analysis is one of the possibilities for further research. In addition, detailed analysis of the LCOE is also needed. Because our results are limited to solar PV technologies, other renewable sources such as micro-hydropower and biomass gasification should be discussed as well.

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Appendix 1. Survey Details

Because the survey data included confidential information from companies, it was anonymised (see the table below for survey details). The numbers acquired from the surveys were averaged and used in the levelised cost of electricity (LCOE) calculation. The interviews (survey 1) were conducted based on the Questionnaire for Supplier/Developer of Solar Home Systems (SHSs)/Solar Microgrids (Appendix 1.1) and the questionnaires (survey 2) used the form in Appendix 1.2.

Survey details

Survey 1	
Date	2–3 February 2017
Venue	Yangon Technological University
Method	Semi-structured interview
Interviewer	The authors
Number of interviewees (companies)	7
Survey 2	
Date	April to July 2017
Method	Questionnaire
Surveyor	Mitasu Consultants Group
Number of interviewees (companies)	2
Survey 3	
Date	19–24 October 2017
Method	Open interview
Interviewer	The authors
Number of interviewees (companies)	4

Source: Authors.

Appendix 1.1 Questionnaire for Survey 1

Questionnaire for Supplier/Developer of Solar Home Systems (SHSs)/Solar Minigrids

General questions (if you do not have a name card, please fill in)

1. Name of company:
2. Address:
3. E-mail:
4. Phone/mobile:
   (if this information is not on the website of your company, please fill in)
5. Owner(s) of the company:
6. Number of staff:
7. Year company was established:

Your business field

8. What kind of products do you sell?
   - ☐ Solar lanterns
   - ☐ Solar-powered pumps
   - ☐ Solar home systems
   - ☐ Solar minigrid/microgrid systems (capacity kW ~ kW)
   - ☐ Solar modules
   - ☐ Inverters
   - ☐ Mounting systems
   - ☐ Batteries
   - ☐ Others ( )

9. What kind of services do you provide?
   - ☐ Engineering (design, preparation of permit documents, project management)
   - ☐ Procurement
   - ☐ Construction
   - ☐ Operation of minigrids
   - ☐ Maintenance
   - ☐ Manufacturing of ( )

10. When did you start businesses related to solar lantern/solar home systems (SHSs)/minigrids?
    ( )

11. Did you have any experience in the energy business before entering the (SHS)/minigrid business?
    ( )

12. Does your company provide any other business products/services?
    ( )

13. How many minigrids have you built? Or how many SHSs have you sold?
    ( )

14. How many minigrid projects are you working on (pipeline)?
    (   )

15. Do you sell second-hand components?   Yes/No
    If yes, from where do you procure them?
    (   )

16. In which country are the products made?
    i. Solar modules
    (   )

    ii. Inverters
    (   )

    iii. Mounting systems
    (   )

    iv. Batteries
    (   )

    v. Others in question 8
    (   )

17. From whom do you buy the components?
    i. Solar modules
       ☐ Maker
       ☐ Distributor
       ☐ Other (   )
    ii. Inverters
       ☐ Maker
       ☐ Distributor
       ☐ Other (   )
    iii. Mounting systems
       ☐ Maker
       ☐ Distributor
       ☐ Other (   )
    iv. Batteries
       ☐ Maker
       ☐ Distributor
       ☐ Other (   )
    v. Others in question 8
       ☐ Maker
       ☐ Distributor
       ☐ Other (   )

18. For about how much do you sell products to your customers?

i. Solar modules

About (   ) kyat <100/1,000 units (circle the number nearest to the units your consumers typically purchase)

About (   ) kyat >100/1,000 units

ii. Inverters

(   ) kW: About (   ) kyat

If there are other inverters, which you sell?

(   ) kW: About (   ) kyat

iii. Mounting systems

About (   ) kyat/kW

iv. Batteries

(   ) W: About (   ) kyat/unit

or About (   ) kyat/W

v. Systems as a whole

About (   ) kyat/kW (Including construction costs   Yes/No)

vi. Others in question 8

(   )

19. To whom do you sell the components?

☐ End users
☐ Distributors
☐ Developers
☐ Independent power producers
☐ Others (   )

20. How much do you pay for electricity at the office?

i. Do you connect to the national grid? If yes, how much is the tariff?

(   ) kyat/month

If you know, (   ) kyat/kWh

ii. Do you have a backup generator? If yes, what is its power source?

Diesel/Solar/Other (   )

21. What do you think is the barrier to your business?

(Please answer freely, e.g., revenue collection risks, the potential for theft, and central grid extension.)

*For minigrid suppliers/developers, please continue to the next page.

For Minigrid Suppliers/Developers

Your track record information

1. Where is this minigrid? (GPS coordinates or address)
   ( )

2. What is the installed capacity?
   ( ) kW

3. What is the power source?
   1. Solar 2. Hydro 3. Diesel 4. Combination of ( ) 5. Other
   ( )

4. Who owns this minigrid?
   - ☐ Community
   - ☐ Distributor
   - ☐ Developer
   - ☐ Independent power producer
   - ☐ Other ( )

5. How long did it take to construct?
   ( )

6. About how much was the investment cost?
   i. Equipment ( ) kyat
   ii. Construction ( ) kyat
   iii. Other ( ) ( ) kyat

7. Please write the contact info for the minigrid operator, if possible.
   ( )

8. What is the tariff for the minigrid's electricity?
   ( ) kyat/kWh or month (Please circle the appropriate option.)

9. If any, what kind of complaints do you receive from customers?

Appendix 1.2: Questionnaire for Survey 2

Project Summary		
PV capacity		**kW**
Battery capacity		**kWh or Ah**
Diesel capacity		**kW**
Number of households		

Cost Breakdown			
Item	**Quantity**	**Unit Price (USD)**	**Cost (USD)**
Primary Components			
PV modules			
Inverters			
PV array rack			
Batteries (if any)			
Diesel generator (if any)			
Transportation to site			
Distribution to Households			
Lamps			
Prepayment meters			
Accessories			
Internal wiring			
Distribution cables			
Streetlight			
LED street lightbulb			
Lamppost			
Cables			
Installation			
Site preparation			
Primary component installation			
Household distribution installation			
Others			
Studies and surveys			
Training			
Trials (Pretesting)			
Grand TOTAL			

Appendix 2. Detailed Load Assumptions

Table A2.1: Load Assumptions for Scenario A

Electrical appliance	Power consumption	Quantity per household	Hours of use
Lamp inside (3W × 2, 7W × 1)	13 W	1 set	18:00–23:00
Lamp outside (streetlight)	5 W	1	18:00–24:00
TV	147 W*	0.75 (3 HHs/4 HHs)	1 hour at night
Total daily electricity consumption			20.5 kWh/day

HH = household, W = watt.
Source: Authors' assumption.
Assumptions without notes are based on the survey by the authors.

Table A2.2: Load Assumption for Scenario B

Electrical appliance	Power consumption	Quantity per household	Hours of use
Lamp inside	5 W	5	18:00–23:00
Lamp outside (streetlight)	5 W	1	18:00–24:00
TV	147 W[a]	1	1 hour at night
Rice cooker	584 W[a]	0.5	0.5 at night[a]
Refrigerator	84 W[a]	0.1	24
Fan	58 W[a]	0.6	2.86 in the daytime[a]
Iron	1,000 W[a]	0.5	0.27 in the daytime[a]
Water pump	146 W[a]	0.15[c]	0.88 in the daytime[a]
Computer	130 W[a]	0.03[c]	4.34 in the daytime[a]
Printer	30 W	0.01[c]	2 in the daytime[b]
Grinder	120 W[b]	0.03 (3 carpenters per village[c])	9:00–17:00
Drilling machine	350 W[b]	0.03	9:00–17:00
Circular saw	1500 W[b]	0.03	9:00–17:00
Planer	450 W[b]	0.03	9:00–17:00
Sewing machine	120 W[b]	0.01	9:00–17:00
Total daily electricity consumption			227 kWh/day (daytime: 96, night-time: 131)

kWh = kilowatt-hour, W = watt.
Sources:
[a] M.P. Aye (2015), Deliverable Report for MECON Project Task 1.2 Baseline Energy Consumption of MECON Household in Myanmar. Retrieved from http://www.meconproject.com/wp-content/uploads/report/[Task 1.2-Energy baseline] Myanmar country report.pdf
[b] N.U. Blum, R.S. Wakeling, and T.S Schmidt (2013), Rural Electrification through Village Grids: Assessing the Cost Competitiveness of Isolated Renewable Energy Technologies in Indonesia. *Renewable and Sustainable Energy Reviews*, 22, pp.482–96. https://doi.org/10.1016/j.rser.2013.01.049
[c] Survey by the authors.

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