Remote Microgrids for Energy Access in Indonesia—Part I: Scaling and Sustainability Challenges and A Technology Outlook

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Abstract: Although Indonesia’s electrification ratio reached 99.2% in 2020, it has shown stagnating electrification since 2018. This is because most of the remaining areas that need to be electrified are remote and have unique characteristics that hamper implementation of microgrids for providing energy access. Furthermore, not only the deployment but also the long-term sustainability of microgrids is crucial for ensuring continuity of energy access. This paper aims to investigate the scaling and sustainability challenges of remote microgrid development in Indonesia by analyzing microgrids in the Maluku and North Maluku provinces. This study is a two-part publication; the first part focuses on identifying challenges in Indonesia’s remote microgrid development, while the second part focuses on potential technology solutions. In the first part, an assessment of energy access within a multi-tier framework was conducted, which was then analyzed using a multi-dimensional (institutional, social, technical, economic, environmental, and policy) approach adapted from the literature. The framework was expanded by mapping the challenges onto specific phases of the microgrid development, which is intended to be helpful for the parties involved in specific phases. It is shown that the challenges related to unclear land status, lack of social engagement, preliminary survey, technical and practical knowledge, and O&M procedures—are the most prominent issues. Additionally, issues caused by electrical events and environmental conditions such as relatively humid and high-temperatures, and uncontrolled vegetation, rodents, insects, and lizards are often found. Furthermore, a high-level technological outlook to address some of these issues is presented.

Keywords: remote; microgrids; scaling and sustainability challenges; development phases; energy access; technology outlook

1. Introduction

As of 2019, there are 75.7 million Indonesian households with a 245.5 TWh total country electricity consumption throughout Indonesia’s archipelago [1]. These households are managed by “Perusahaan Listrik Negara” (PLN), a state-owned utility company that operates most of the generation, transmission, and distribution electrical systems in Indonesia. It was reported that 89% of the electricity is consumed in Java and Sumatra, which are the largest and most developed regions. In these regions, the consumption of the industrial sector is noticeably higher. In contrast, Maluku, Nusa Tenggara, and Papua regions (less-developed regions in the eastern part of Indonesia) only consume 2.3%
of the total electricity consumption. In these regions, the residential sector is the largest contributor to total electricity consumption. The report shows there is a huge electricity consumption gap between the regions in the western and the eastern part of Indonesia, especially in the regions with many islands and isolated areas.

Indonesia’s government uses system average interruption frequency (SAIFI: an indicator of the number of interruptions compared to the number of users throughout the year) and duration indexes (SAIDI: an indicator of the average duration of interruptions per user throughout the year), system losses, reserve margin, and electrification ratio to measure the accessibility and affordability of electricity [2]. Among these indicators, the government aimed for a 100% electrification ratio in 2020. This electrification has been progressing well, with a 10% increase from 88.3% in 2015 to 98.3% in 2018. However, the electrification rate is stagnating, with only a 0.9% increase since 2018, resulting in a 99.2% electrification ratio in 2020 [2]. This corresponds to about 590,000 households that are still unelectrified. Progress is stagnating because a lot of the remaining areas that need to be electrified are remote and isolated. Moreover, issues of unsynchronized customer databases between government bodies, unpredicted migration to electrified areas, and deviation in population forecasts make it difficult to keep track of the electrification progress [2,3]. Although a dedicated regulation to accelerate the electrification of remote and isolated areas has been established in the Ministry of Energy and Mineral Resource (MEMR) Regulation No. 38/2016, it is still difficult to provide electricity to these remote locations.

The remote and isolated areas are mostly located in the eastern part of Indonesia, which is indicated by the imparity of the electrification ratio, as shown in Figure 1. Although the electrification ratio in these areas (as in East Nusa Tenggara (NTT), Maluku, North Maluku (Malut), and Papua) is high, a household with a solar lantern is considered electrified by the national authorities [3]. This definition does not reflect whether access to electricity induces real improvement of welfare. On the other hand, energy access could be measured better using a multi-tier framework (MTF) that defines energy access attributes in terms of capacity, availability, reliability, quality, affordability, legality, and health and safety, as introduced by the Energy Sector Management Assistance Program (ESMAP) in [4]. The ESMAP is a partnership between the World Bank and 22 partners that support low and middle-income countries through sustainable energy solutions.

In this paper, energy access attributes from MTF are used to indicate access to electricity. MTF is used because it could measure electricity access with more elaborate attributes, which gives a more accurate illustration of how well electricity access improves people’s livelihood. This is important because it is not only about if electricity is accessible but more about how the electricity could make people’s lives better. Therefore, it is imperative to include these parameters as considerations in the electrification planning to assess and track multidimensional aspects of energy access, in line with the Sustainable Development Goal 7 (SDG 7), which aims to achieve universal access to affordable, reliable, sustainable, and modern energy by 2030 [5].

Figure 1. Indonesia provincial electrification ratio in 2020 (data from [6]).
Indonesia’s stagnating electrification rate since 2018 shows that rural electrification is more challenging, partially due to difficulties of logistics and infrastructure access [7]. Expanding the utility grid infrastructure requires significant investments, while utilizing small diesel generators (currently the most common solution in Indonesia) could lead to high fuel transportation, operation and maintenance (O&M) costs, and environmental issues. Furthermore, the low electricity consumption in these remote locations may not cover the capital and operational expenses of the electrification effort. Unless it is targeted electrification (included in a specific development program), providing electricity access will need more support and/or incentives to be provided.

As of now, the utilization of diesel generators (DiGs) and mobile gensets is being chosen by the government as a short-term solution to accelerate electrification in remote and isolated areas. To reduce operational costs, these DiGs are planned to be integrated with renewable energy (RE) sources once a promising source is identified [8]. These microgrids with RE sources are seen as promising solutions, since they could reduce or eliminate some of the aforementioned challenges of main grid extensions or DiGs. However, not only deployment of these microgrids at scale but also their maintenance will pose a challenge, since more sophisticated technologies are involved. There are cases of microgrid early failures, some of which are due to inappropriate design, unsuitable technology, and poor O&M, as reported in [9–11]. Therefore, it is important to understand the challenges in developing such remote microgrids in order to ensure effective implementation and to keep them functional throughout their lifetime.

This paper aims to identify the scaling and sustainability challenges of remote microgrid development in the Indonesian context and to present a high-level technology outlook to address some of these challenges towards improving energy access in Indonesia. This includes an assessment of energy access in the actual remote microgrids and the formulation of a practical framework of the identified challenges. In this study, remote microgrids in Maluku and North Maluku (MMU) were observed. Maluku and North Maluku are two provinces in the eastern part of Indonesia, which have many isolated microgrids that are still being developed. In the coming years, several remote microgrids will be developed and RE sources are planned for integration into many existing remote microgrids [8]. Therefore, due to the nature of remote areas in MMU, and the similarity of its development plan with this research objective, remote microgrids in MMU are considered suitable for this study.

2. Research Approach

This publication is divided into two parts: Part I focuses on identifying scaling and sustainability challenges of remote microgrid development in Indonesia. Part II focuses on potential technology solutions. A complete research approach is illustrated in Figure 2. Part I started with data collection on the actual condition of remote systems in MMU, which was then analyzed using a multi-tier framework. Sections 2.1 and 2.2 describe the data collection and multi-tier framework, respectively. This analysis was used to indicate which attributes of energy access (capacity, availability, reliability, quality, and/or affordability) are stunted in MMU. The results are presented in Section 3.1.

In parallel, a qualitative literature review on the condition of energy access in Indonesia from government reports as well as investigation reports published by nongovernment organizations was performed. Furthermore, literature reviews on the development of remote microgrids from various studies were conducted to identify their potential scaling and sustainability challenges. The literature review and a list of scaling and sustainability challenges were created and presented in Sections 3.2 and 3.3, respectively.
Finally, Part I synthesized the scaling and sustainability challenges that were identified in several remote microgrids development studies and investigated those that are relevant for Indonesia (based on the actual case in MMU). A framework was created to correlate the challenges, energy access attributes, and microgrid development phases. The formulation of the framework is described in Section 2.3. The results are presented at the beginning of Section 4, followed by a high-level technology outlook, which is elaborated in Sections 4.1–4.3.

Furthermore, Part II discusses in more detail the actual cases that are reported in Part I and correlates the cases into the proposed framework. Additionally, potential technology solutions from various parts of the literature that are relevant to Indonesia’s context are presented in more detail in Part II.
2.1. Data Collection

To ensure the authenticity and accuracy of the data, a research collaboration with the state utility, PLN MMU Main Unit, was established. Primary data from actual remote microgrids were provided by PLN. Additionally, interviews and discussions with relevant stakeholders were also conducted to obtain a deeper understanding of the actual remote microgrids’ conditions and fill gaps in the available data. A qualitative review of various parts of the literature, i.e., government reports, national electricity development plans, previous investigation reports on Indonesia’s remote microgrids, was also performed.

2.2. Energy Access Assessment

MMU consists of several districts or villages that are supplied by one or more grids. Each generation system within the grids has several feeders to supply clusters of households. The households are divided into three customer types according to the maximum allowable power (R1: 900–2200 VA, R2: 3500–5500 VA, R3: ≥6600 VA, as in MEMR Regulation No. 3/2020). Ideally, the assessment is done using data per household. However, household data was not available, and estimations were done based on four types of data population, i.e., regency, grids/district/village, switchgear or feeder, and customer type. Data accuracy is better for the latter since, for instance, the regency average tends to overestimate the smallest electricity consumers and underestimate customers with higher electricity consumption.

The collected remote microgrid data was assessed based on the attributes introduced in MTF with adjustments for data availability. Except for the quality attribute, which has a large set of data, the assessed data are listed in the Appendix A (Tables A1–A4). The assessment was conducted almost exclusively on customers of PLN (there are a few non-PLN customers, but most customers are PLN’s); hence, it did not take into account households without electricity. The assessment parameters and the available data are listed in Table 1.

### Table 1. MTF matrix to assess energy access (adapted from [4]).

| Tier | Tier 0 | Tier 1 | Tier 2 | Tier 3 | Tier 4 | Tier 5 | Remarks | Available Data |
|------|--------|--------|--------|--------|--------|--------|---------|---------------|
| Capacity | 12 | 200 | 1000 | 3400 | 8200 | Min. value in Wh/day | Customer avg. (throughout 2020) |
| Availability | 4 | 4 | 7 | 16 | 23 | Min. h/day | District avg. (May 2021) |
| | 1 | 2 | 3 | 4 | 4 | Min. evening hours | Per feeder (Jan–May 2021) |
| Reliability | | | | | 14 | 3 with duration < 2 h | Per feeder (Jan–Jun 2021) |
| Quality | | | | | | Voltage within ±10% | Per feeder (Jan–Jun 2021) |
| Affordability | 1-year electricity cost < 5% of household income | | | | | | Regency avg. (Average of 2020) |

In this MTF, five energy attributes are analyzed, i.e., (1) the capacity attribute is used as the indicator of energy consumption per day; (2) availability indicates household access to electricity; (3) reliability is the maximum number of disruptions or blackouts per week; (4) quality is used to assess household voltage variation; and the energy access attribute of (5) affordability is used as the comparison between the 1-year electricity cost to household income. Each energy access attribute is divided into different tiers, with a higher tier representing better conditions of electricity access. The values of each tier are defined based on the possible electricity supply, for instance, Tier 1 can be met only by solar home systems (SHS) or small-scale isolated systems, while Tier 5 can be achieved by systems with diesel-based generation or linked to the national grid [4].
2.3. Formulation of Framework

The framework that was used in this study was adapted and synthesized from previous works on remote microgrids in various contexts. A multi-dimensional approach (institutional, social, technical, economic, environmental, policy) was used as the base list of potential scaling and sustainability challenges of remote microgrid development. These potential challenges were mapped into two dimensions:

- Operation and development phases (in which phase they occur)
- Energy access attributes (which attribute they affect)

Furthermore, the results from the qualitative literature review and the actual remote microgrid conditions from MMU’s MTF assessment were compared and incorporated into the initial framework. This was intended to complement any shortcomings from the literature and to construct a relevant and robust framework for remote microgrids in Indonesia.

2.4. Technology Outlook

The synthesized framework was used to indicate the correlation between microgrid development challenges and energy access attributes at each development phase. A high-level technology outlook was formulated to emphasize potential technology contributions in addressing specific challenges at certain development phases. A detailed discussion on technology outlook is presented in Part II of this publication.

3. Energy Access in Remote Area

3.1. Electricity Access in Eastern Indonesia: Case of Maluku and North Maluku

MMU consists of 104 grids, including 3 big grids and 101 microgrids. A big grid is defined as a grid with a peak load higher than 10 MW, which is planned to be interconnected with other grids, and/or there is a large power plant that will be built for the grid. On the other hand, microgrids are defined as grids with a peak load below 10 MW [8]. In this paper, the term PV is used to refer to a microgrid that is supplied only by PV and energy storage systems (ESS), while a PV hybrid refers to a microgrid with DiGs, a PV system, and ESS [12]. PV and PV hybrids can be connected to the big grid and referred as grid-connected, otherwise, they are considered off-grid. According to this definition, for the 104 grids that were assessed, 101 microgrids were off-grid and 1 of the big grids was currently off-grid (the planned power plant had not yet been operated), while the other 2 big grids were grid-connected.

In 2019, 62% of the generation capacity in MMU was from DiGs, which generated 81% of the total energy, and 35% of generation capacity was from gas engine generators [1]. However, due to the limited access to gas, some of those gas engine generators were still using diesel fuel instead of gas. MTF assessment was conducted on those 104 grids and the results are shown in Figure 3, which illustrate the condition of each energy access attribute of MMU. The figures present the level of each energy access attribute (x-axis) of the assessed population (y-axis). The assessed population for each attribute differs depending on the availability of data, as listed in Table 1.

Although the households had access to electricity, the results in Figure 3 show that it was still limited for a significant portion of the assessed population. In terms of the capacity attribute, 78% of households in MMU consumed less than 3400 Wh/day of electricity. This has not changed much from 2019, which corresponded to a consumption per capita of 948 Wh/day. The electricity consumption per capita of MMU was far less compared to the national electricity consumption per capita, which is 2507 Wh/day [13]. As for the availability attribute, 55% of the assessed population only had electricity for 7–16 h per day during the night. Moreover, the electricity tariff (affordability attribute) is still considered too high for 88% of the assessed population, which mainly work as farmers and laborers in the agriculture and retail sectors [14,15]. This limited energy access hinders the productive use of energy, and the benefits of electricity cannot be maximized. Therefore, improvements
are needed to ensure that implementation of microgrids is able to meet user needs, and could give real improvements to their prosperity.

![Diagram showing energy access in Maluku and North Maluku, Indonesia.](image)

**Figure 3.** MTF of energy access in Maluku and North Maluku, Indonesia.

On the other hand, Figure 3 also shows good quality and reliability attributes. Only 2% of the assessed population in MMU experienced voltage variations of ±10% from the nominal value. However, MEMR Regulation No. 04/2009 limits the voltage variation to a maximum of +5% and minimum of −10%—which are narrower limits than MTF. Consequently, there was an additional 6% of the assessed population that did not comply with this regulation. As for the reliability attribute, Figure 3 shows that only 5% of the assessed population in MMU experienced disruptions with a duration of more than 2 h/week (more information in Table A4). Although this number is considered good in MTF, it is significantly higher than the national SAIFI and SAIDI, which were 0.24 disruptions/user/week and 0.18 h/user/week in 2018 [8]. Although both quality and reliability attributes were considered good in the MTF assessment, the disparity between remote and urban areas was still apparent.

### 3.2. Improving Energy Access with Renewable Resources

As stated in Section 3.1, the most common solution that is used to provide electricity access in Indonesia’s remote areas is DiGs. However, some problems might arise, i.e.,

1. Continuity of fuel supply, which might result in limited availability of electricity.
2. The requirement of regular maintenance and parts replacement, which could be difficult due to the long travel distance to the site.
3. High electricity generation costs due to fuel and transportation costs.
4. Environmental issues due to emissions, noise, and smell.

These problems with DiGs could be minimized by integrating RE sources such as PV systems (and ESS). A well-planned microgrid with renewable sources could significantly improve electricity availability, reliability, quality of supply, reduce energy costs, and lower carbon emissions. In terms of welfare, microgrids can enable access to education, improve
Moreover, compared to conventional DiGs, there is no fuel, and less frequent maintenance is required for the O&M of the PV system. Except for the main components, most daily maintenance activities could be done by the local operators (e.g., visual check, PV module cleaning, mowing). The sophisticated maintenance tasks should be conducted according to the manufacturer’s recommendations or by the manufacturer itself, which should be included in the warranty. Therefore, integrating a PV system to a microgrid with DiGs is expected to be beneficial in the long run.

Microgrids with RE sources seem to be a promising solution for rural electrification in Indonesia. However, designing, developing, and maintaining those microgrids has proven to encounter various challenges. In MMU, according to the internal investigation report of PLN MMU, together with its investigation partners (NZMATES and PT Syntek), the average operational period of all 15 small PV and PV hybrids is 4.3 years, with 8 and 2 years being the longest and the shortest. These investigation reports are based on actual site data from the operators’ logsheet and surveys of PLN and its investigation partners, which have not been published. The summary of these systems is listed in Table 2. Most of the failures were in the battery and inverter, which were caused by various reasons, e.g., incorrect sizing, improper operation environment, and unclear maintenance procedures. These are relevant to the findings in other locations reported in [9,10,21–24] regarding the lack of practical and technical knowledge and the lack of O&M standards. This condition shows that not only the scaling of microgrids, but also ensuring its sustainability, is challenging. The following Section 3.3 analyzes the scaling and sustainability challenges in developing remote microgrids based on the lessons learned from MMU and the literature on remote microgrid development in various locations.

Table 2. The operation status of the observed PV and PV hybrids in MMU.

| Designator | Year of Operation | Operational | System Condition | Possible Cause of Failure |
|------------|------------------|-------------|-------------------|--------------------------|
| Site 1     | 4                | No          | PV is significantly degraded, battery and inverter are out of service. | Demand doubled in 3 years. Undersized battery and no diesel backup resulted in a high depth of discharge (DoD). Battery removed without updating inverter setting. High battery temperature room. |
| Site 2     | 8                | No          | PV is significantly degraded and cracked. Inverter out of service due to burnt IGBT. Improper installation was found. Monitoring and communication device are out of service. Traces of animals were found inside electrical panels. | Needs further investigation. |
| Site 3     | 3                | No          | PV is degraded, battery and inverter are out of service. Uncovered cable trays. Trace of rodents’ bite on the cable insulation. Uncontrolled vegetation. | Significant load growth, broken battery, and issues in the control system. |
| Site 4     | 8                | Yes         | PV and inverter are in normal condition. Battery is degraded. | - |
| Site 5     | 5                | No          | PV is significantly degraded, battery and inverter are out of service. | Undersized battery and no diesel backup resulted in a high DoD. Battery removed without updating inverter setting. High battery temperature room. |
| Site 6     | 5                | No          | PV is significantly degraded, battery and inverter are out of service. | Poor array construction, MPPT failure, high battery DoD, and no diesel back-up. Battery removed without updating inverter setting. High battery temperature room. |
### Table 2. Cont.

| Designator | Year of Operation | Operational | System Condition | Possible Cause of Failure |
|------------|------------------|-------------|------------------|---------------------------|
| Site 7     | 3                | No          | PV significantly degraded, cracked, rusted, and accumulated dirt on the frame was found. The inverter cannot be operated and keep restarting. | Suspected as improper inverter commissioning. Battery removed without updating inverter setting. |
| Site 8     | 4                | No          | PV is significantly degraded, cracked, and broken. Inverter out of service. Uncontrolled vegetation and rusted electrical panels. | Undersized PV string cable. Fire in a combiner box was suspected due to improper installation. This resulted in insufficient battery recharge and eventually degrade the battery. |
| Site 9     | 3                | No          | Some PV is broken. Inverter and battery are in good condition. | Needs further investigation. |
| Site 10    | 3                | No          | Only 60% PV output. Inverter and battery are out of service. | Improper cable sizing resulted in a fire. High battery DoD and no diesel back-up. |
| Site 11    | 2                | No          | PV significantly degraded, battery and inverter are out of service. | Needs further investigation. |
| Site 12    | 3                | No          | PV is in good condition but partially covered by vegetation. Vegetation also growing on the inside of the inverter. Battery out of service. Rusted electrical panels. There is a huge opening below electrical panels at the incoming cable, which could be easily penetrated by animals. | Needs further investigation. |
| Site 13    | 6                | No          | Accumulated soiling and crack were found on PV panels. Inverter is out of service. The grounding cable is broken. Traces of animals inside electrical panels. | Needs further investigation. |
| Site 14    | 2                | No          | PV string voltage is normal. Vegetation growing on the inside of the inverter. Battery is out of service. Uncontrolled vegetation. Rusted electrical panels. Traces of animals and insects inside the powerhouse. | The operator needs to switch between PV and diesel manually. Due to the difficult and manual operation, the system is no longer operational. |
| Site 15    | 5                | Yes         | PV and inverter are in normal condition. | - |

### 3.3. Scaling and Sustainability Challenges

Improving energy access in remote and isolated areas is difficult due to its location’s characteristics, i.e., no proper infrastructure, geographically challenging in terms of access, far from main economic activity, far from the main grid, and low demand [17]. Several studies on remote microgrids have been conducted for different locations to identify their challenges. In this paper, the framework on scaling and sustainability challenges originating from the institutional, social, technical, economic, environmental, policy dimensions adapted from [21,24], as listed in Table 3, is used to identify and classify relevant scaling challenges of remote microgrids in Indonesia. This approach was used as the base framework and further improved with additional literature [10,17,22,23,25]. Based on the discussions with PLN and survey reports made by PT Syntek and NZMATES as investigation partners of PLN MMU, scaling and sustainability potential challenges in Table 3 are relevant for the cases in MMU. Specifically, So1, So2, Te1–Te4, En3, and En4 in Table 3 are most emphasized and will be the focus of the following discussion.

It is important to note that the electricity tariff for PLN customers is regulated by the government [26], meaning that the tariff for each customer group (R1, R2, and R3 as described in Section 2.2) is flat regardless of the location (urban or remote). Therefore, the electricity production cost does not influence people’s ability to pay but still affects the
In Section 4, the energy access attribute of affordability is defined, for both developers and users to distinguish its impact.

Table 3. Multi-dimensional scaling and sustainability challenges in remote microgrid development that are relevant for Indonesia.

| No. | Potential Challenges                                      | Possible Impacts                                                                                                                                                                                                 | Reference         |
|-----|----------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------|
|     | Institutional                                            |                                                                                                                                                                                                               |                   |
| In1 | Misalignment between central and local institutions     | Development does not reflect users’ needs, lack of local participation, contradicting development plan, abandonment of off-grid PV or off-grid PV hybrids.                                                    | [22–25]          |
| In2 | Unclear responsibility allocation                        | Overlapping tasks between stakeholders, lack of coordination, communities do not assume ownership and responsibility. These lead to a limited budget for O&M, replacement, and other variable expenses.          | [10,21–24]       |
| In3 | Unstable and weak enforcement of formal authority        | Difficulties in conducting warranty claims, not binding penalties, unrealized incentives, connections over regulations.                                                                                      | [10,23,24]       |
|     | Social                                                   |                                                                                                                                                                                                               |                   |
| So1 | Lack of social engagement and technology awareness      | Low social acceptance, insecurity (vandalism/theft), wasteful energy consumption.                                                                                                                                | [21–25]          |
| So2 | Unclear land status                                      | Disputes, insufficient area, incompatible land-use, difficult permit.                                                                                                                                              | [22]              |
|     | Technical                                                |                                                                                                                                                                                                               |                   |
| Te1 | Lack of practical and technical knowledge and inadequate preliminary survey | Incorrect load characterization, incorrect equipment sizing, high system losses, shorter system lifetime. High mismatch of supply/demand resulting in curtailment or energy deficit. | [9,21,24]       |
| Te2 | Lack of local skilled personnel or expert know-how      | Use of uncertified or low-quality materials, incorrect use of components, poor quality assurance and implementation. Extra cost for foreign technical experts.                                                                 | [10,11,21–24]   |
| Te3 | Lack of O&M standards                                    | Incorrect or inefficient O&M practices, lack of measurement tools for troubleshooting, longer time required for corrective maintenance, shorter component lifetime.                                           | [10,21–24]      |
| Te4 | Power quality issues                                     | Increasing losses, false trips, equipment communication error.                                                                                                                                                  | PLN MMU investigation report |
|     | Economic                                                 |                                                                                                                                                                                                               |                   |
| Ec1 | Lack of financial framework                             | Lack of attractive business models, uncertain investment.                                                                                                                                                         | [17,21,24]       |
| Ec2 | High initial investment and replacement costs, lack of financial support | High electricity production costs; this leads to an unattractive return since the tariff is regulated and most likely to be lower than the production cost.                                                     | [17,21–25]      |
| Ec3 | Lack of productive energy use of energy                 | Electricity does not increase the users’ income, lack of revenue generation due to low demand.                                                                                                                | [17,21,27]      |
In the social challenges category (So), land disputes (So2) were apparent during the planning, design, and implementation phases—especially once land acquisition was started. The disputed lands were usually the ones that were inherited from ancestors by many generations after; after decades it was difficult to trace to whom the lands were inherited. Some heirs might have been deceased, and due to the lack of administrative knowledge, the lands were inherited without proper legal documentation. This resulted in overlapping claims of ownership. Even after disputes were legally resolved, the risk of vandalism (So1) was still high due to protracted conflicts. For example, cracked PV modules were found due to rocks thrown by people. This could be triggered by jealousy or may just be irresponsible actions.

In terms of technical challenges (Te), the lack of a preliminary survey (Te1) resulted in the incorrect prediction of load growth and high supply/load mismatch. In one case, there was a significant increase in demand after the microgrid was deployed, which could not be met by the microgrid. This overloaded the microgrid and resulted in early failures and reduced availability, especially with respect to the battery system. In contrast, there were also cases of oversized DiGs. According to [8], the targeted margin between peak load and total generation capacity for off-grid microgrids is 30%. However, when the load grows more slowly than predicted, inefficient operation of DiGs due to oversizing is unavoidable. In such cases, DiGs are sometimes relocated to a location with a higher demand, but not necessarily an optimal load match.

Lack of practical knowledge (Te1) was also apparent, especially regarding implementation. Initial installation was most likely in compliance with a certain standard since it was installed by experts or experienced contractors. However, after the microgrid was handed over for operation, ensuring that the appointed operator has the required skill for performing proper repairs is difficult. There were improper installations found, e.g., a miniature circuit breaker (MCB) was not mounted properly after replacement. There was also issues with messy cabling and uncovered cable lines, which increase the risk of damaged insulation due to rodent bites, scratches, or other external factors.
Lack of local skilled personnel (Te2) is also related to Te1. The installation that did not conform to standards happened because the installation and repair were not performed or supervised by skilled personnel. Furthermore, skilled personnel are also important for adjusting the microgrid settings whenever a modification is done to the microgrid, especially for the inverter, which is responsible for controlling the charging and discharging of the battery system. There was a case where several batteries were broken and removed from the battery string. However, the battery inverter setting was not adjusted, and the battery inverter was still set to the capacity of the initial number of batteries. This increased the risk of cascading failure to the other batteries in the bank.

Furthermore, the lack of O&M standards and procedures (Te3) are most often found in microgrids with a PV and in PV hybrids in MMU. Some cases resulted in low energy yields (due to accumulated soiling and shading from uncontrolled vegetation), unavailable parts for replacement, and early equipment failures. As of now, the cause of early failures was difficult to trace, except for the ones with visible marks from rodents, bugs, and lizards. These untraced causes were presumed mainly to be due to electrical events (under-voltage, unbalance voltage, under frequency), as recorded in some of the fault logs. This shows that there are insufficiently understood and investigated possibilities of power quality issues (Te4) that can disrupt the microgrids. On the other hand, early failure of equipment could also be caused by low-quality materials and components, and/or incorrect design and installation. Nevertheless, with proper O&M procedures, there is a higher chance to prevent or minimize early failures.

Te3 could also result in uncontrolled vegetation and rodent, bug, or lizard problems (En3), because without appropriate procedures, substantial O&M activities could be missed or neglected. Many PV systems in MMU and other remote microgrids in Indonesia were built near a farm, forest, or other plantation, which are the natural habitats of many living creatures. Traces of rodents, bugs, and lizards such as eggs, dirt, bite marks, and carcasses, were found within equipment enclosures. The heat from the equipment was suspected to be the cause that drew the attention of the animals to reside within the enclosure. Unwanted foreign material in the equipment increases the risk of unintended resistive connection or electrical shorts, which could lead to fire or equipment failure.

The relatively humid and high-temperature conditions (En4) could increase the risk of rust to equipment that is not properly plated or laminated, which potentially induces losses and leads to failure. Rust was found within the PV frame, mounting, combiner box, and distribution panel. Furthermore, the environmental conditions of microgrids that are located on islands or coastal areas tend to have a high level of salt pollutants, which could accelerate the rusting process. It is important to ensure that the environmental conditions of the equipment comply with the manufacturer’s requirements—especially for batteries and inverters. These components have a specific operating temperature range and humidity conditions, which may require a dedicated air conditioning system. However, in most cases, it was found that there was no proper control on the room conditions, which resulted in a higher degradation rate of the component. Anecdotal experience indicates that high-quality microgrid equipment designed to operate in Global North climate conditions and deployed in hot and humid conditions in South Asia will experience early failures. This is related to Te2 and Te3, since understanding the importance of operating conditions is inseparable from the good practice of installation and O&M.

In MMU, there are 15 microgrids that are integrated with various sizes of PV systems, ranging from 75 to 600 kWp. Although the potential benefits of these 15 small PV and PV hybrids could not be maximized due to the aforementioned issues, microgrids with RE sources are still a promising option to improve energy access in these remote areas, as long as they are adequately designed and implemented and have a clear O&M procedure. As shown in Figure 3 of the MMU’s MTF assessment, more than half of the assessed population only have electricity during the night; the cost is still considered too high (>5% household income) for 88% of the assessed population, and the electricity consumption of 78% of the assessed population is less than 3400 Wh/day. The small PV systems within the microgrids
were supposed to complement or replace the DiG supply during the day; hence, these energy access attributes (availability, affordability, and capacity) could be improved.

To ensure the sustainability and scaling of future remote microgrids, the identified challenges in Table 3 should be addressed properly. Therefore, these scaling and sustainability challenges are classified based on the affected energy access attributes to make them more practical. Furthermore, it is also categorized based on the microgrid development phases, in order to segregate the potential challenges at each phase and make it easier to formulate distinctive strategies in addressing such challenges. The aforementioned framework is elaborated in Section 4.

4. Framework for Assessment of Energy Access

In Indonesia, some of the remote microgrids are owned by private companies, either to fulfill their own energy needs or as a corporate social responsibility program. There are also a few microgrids that are funded by non-government organizations or from foreign grants. However, most remote microgrids are owned by the government—mostly under PLN and MEMR—which were planned, designed, implemented, and operated by either of the two. Developers and contractors might be involved if the project was tendered, but the initial planning and O&M are mainly conducted by PLN.

In this section, a framework for assessing energy access in each development phase of a microgrid is formulated. The synthesized framework aims to answer the practical question of, "Which attribute of energy access is potentially compromised in each development phase?". The correlation between challenges and development phases is shown in Table 4 with the designators (In, So, Te, Ec, En, and Po), referred to in Table 3. The sub-phases of each microgrid development phase are adapted from [28–30]. The energy access attribute that is affected is indicated in the table as capacity and availability (CA), reliability and quality (RQ), affordability for developers (Ad), and affordability for users (Au).

### Table 4. Potential scaling and sustainability challenges and the impact on the energy access attributes at each development phase. Challenges: institutional (In), social (So), technical (Te), economic (Ec), environment (En), policy (Po); Energy access attributes: capacity and availability (CA), reliability and quality (RQ), affordability for developers (Ad), and affordability for users (Au).
Practically, Table 4 shows the expected challenges (first column) at each development phase (table header) and the energy access attributes that will be affected (the table content). By using this framework, the reader could indicate the potential challenges at each development phase and formulate the most efficient strategy according to the energy access attributes that are prioritized. For instance, the system planner should expect challenges that are marked by energy access attributes within Table 4 under the planning phase. Then, the system planner should appoint personnel that are relevant to each challenge’s dimension to address the challenges. Ideally, all expected challenges should be dealt with completely, but in the case of limited budgets and time, the effort on dealing with the challenges can be adjusted according to the prioritized energy access attributes and mandates from stakeholders. Therefore, each challenge can be dealt with effectively. The implementation of this framework could help to ensure the scaling and sustainability of the remote microgrids.

Based on the MTF introduced in [4], affordability involves relating the electricity tariff with the user’s income. However, since the electricity tariff is regulated by the government (same tariff within the same customer type), this MTF’s definition of affordability may not cover the issues faced by developers. Therefore, the definition of the MTF’s affordability attribute is adjusted and divided into Ad and Au to distinguish the impacts on developers. Ad is defined as a tariff that is attractive for developers, whereas Au is defined as the users’ ability to pay. Consequently, Ad is highly affected in the planning, design, and implementation phases, because these phases determine the capital and operational expenses as well as the required tariff to obtain the desired return. In contrast, Au is considered to not be directly affected in those phases. For instance, in the condition of oversized supply or slower than predicted demand growth, there is a possibility that the required revenue will not be achieved (Ad); hence, lowering the developer’s return. However, this does not affect the tariff since it is regulated, and hence does not affect Au. On the other hand, Au is correlated to the users’ productive use of energy and how it could increase the users’ income to meet the payment rate.

As shown in Table 4, MTF attributes of capacity, availability, and affordability for developers are mostly affected due to challenges in the planning phases, while reliability, quality, and affordability of users are mostly affected in the design, implementation, and O&M phase. The correlation between challenges, development phases, and energy access attributes in Table 4 is constructed based on the authors’ reflections and experiences from actual cases in Indonesia. The authors invite other researchers to test and apply the framework in other contexts and contribute to making a more comprehensive and robust framework. Adjustments might be required to fit site-specific conditions.

4.1. Planning

In Indonesia, PLN conducts microgrid planning based on many criteria; among others is demand projection, forecasted from indicators such as economic growth, population, electrification ratio, inflation, prospective customers, grid losses, and load factors. The limited amount of data is one of the difficulties faced by PLN in creating an accurate load forecast. In load forecasting, data such as population, income, livelihood, and people’s needs are required. These data are mainly produced by Badan Pusat Statistik, which is responsible for conducting statistical surveys, including censuses. However, the census is conducted only once a decade (according to government regulations No. 6 and 7, year 1960) and the data for the years in between are approximated, introducing uncertainty in reflecting the current demand. This is related to the challenges of Te1 and So1, which could also lead to So2. Moreover, the unsynchronized databases between government bodies, unpredicted migration, and uncertainty of prospective customers [2,3] could also increase the level of error in demand projections.

In the case of a large-scale grid-connected system, the types of demand are more varied (industry, social, etc.) but are also more manageable and easier to predict based on the available historical data and registration process to connect. This registration
process, which states the needed power for the new load, is required by PLN so they can adjust the system planning. Additionally, since the load change compared to the available generation capacity in large-scale systems is relatively less significant than in remote microgrids, implementing an effective control system is mainly used instead of highly over-sizing the system. There are more advanced control systems that could perform real-time adjustment of reserve margins for available power plants according to demand (as in the cases discussed in [31,32]). Therefore, load forecasting might not be as critical as in remote microgrids because the demand growth could be anticipated efficiently. In contrast, in the case of remote microgrids—as in MMU—load forecasting is critical and more difficult because of the limited generation and storage capacities and the unpredicted behavior of the people after the electrification.

In 2019, a difference of 16.3% and −20.2% between the forecasted and realized electricity consumption was reported in Maluku and North Maluku, respectively [1,33]. This shows an accumulated forecasting error resulting from many estimated input values. In many cases, including in MMU, a comprehensive survey at the household level to obtain more accurate assumptions for load forecasting was not feasible because it would require too much time and cost. As an alternative, a study by [34] proposed a bottom-up, stochastic load profile construction method that takes into account the peak and average loads, energy demand, load factor, coincidence factor, and typical off-grid appliances. The load profile is constructed by first classifying the typical loads into five tiers (based on MTF) and constructing a year load profile using the proposed mathematical model, which incorporates randomness into each day. The constructed load profile from the proposed method could be used to improve the demand forecast, since it also quantifies the yearly energy consumption. Although it uses historical data, not primary data from surveys, this could still give a better accuracy since more parameters are used to approximate the actual household conditions. Other methods to increase the accuracy of load forecasting are briefly elaborated in Part II of this publication. Additionally, shortcomings in load prediction could be partially alleviated in the design phase by using a modular, scalable approach. Both more accurate load forecasting and modularity in design could address future issues of supply/demand mismatch by minimizing the mismatch and enabling efficient capacity adjustment/augmentation of the supply system. This solution could be used to prevent the issues in Site 1 and 3 shown in Table 2, regarding rapid load growth.

In terms of the solar resource assessment for off-grid PV or off-grid PV hybrids, secondary data from Meteonorm, Solaris, and/or Solcast are commonly used. This data is an approximation based on a certain algorithm. Different data sources might use different references and different algorithms—hence the produced data are different. It is difficult to justify which data source is more reliable and accurate for cases in Indonesia, since most of the microgrid projects are still in the development phase or in early operation years (actual data for comparison is not yet sufficient). To improve the confidence level of the data input, it is better to use data that is directly measured from the site or within the same region. Measurement of the important parameters can be realized by using a simple, low-power, and portable weather station with a pyranometer, anemometer, logging devices, and communication component, that can be installed within PLN’s work area. Considering that the data would also be useful for many other applications, collaboration with nearby universities, non-government organizations, industries, and/or other government bodies could be an option.

4.2. Design and Implementation

The national grid code was published in MEMR Regulation No. 04/2009 and No. 20/2020, covering the operation limit, scheduling, and dispatch for each region. However, this regulation acts as a general guideline and needs to be complemented according to the grid, load condition, technology used, and energy management strategy. In collaboration with partners, MEMR also published several guidelines for designing microgrids with renewable sources. One of them is a product from a collaboration with Deutsche
Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, which is a PV hybrid design guideline that covers the assessment of the existing grid, step-by-step design procedure, technology selection, and control system that was published in 2020 [35]. The design procedure consists of the topology selection, operation scheme definition, system sizing, technology selection, and land assessment. The system sizing method is formulated in such a way that it can be implemented with widely used calculation tools, (e.g., MS Excel), hence simplifications of assumptions were made for the one-year load profile, system losses, peak sun hour correction factor, and power factor. Although these simplified assumptions have a certain degree of error (especially the sun hour correction factor, which is highly dependent on region), the design results are considered sufficient for the preliminary study. However, adjustments on detailed assumptions such as system losses, equipment degradation, and customized energy management systems are still required for detailed design and further implementation. These design adjustments require sufficient technical knowledge, which is related to Te1.

Difficulties in selecting suitable technologies are also a challenge in designing remote microgrids in Indonesia. Manufacturers have produced various technologies that can be used for remote microgrids, but choosing the one that suits the microgrid requirements and future planning requires more understanding of technology implementation, which is related to the challenges of Te2. One of the cases that occurred in Indonesia was using a single point connection to interconnect the battery and PV systems to the distribution line. Although this simplified things for the local operator, it made the microgrid unscalable and frail. Once the demand grew, the capacity of PV and battery could not be increased since it was limited by the rating of the single point of connection. Another possibility is that of a single string of battery systems for the whole system. This results in a higher chance of disruption, especially when the operation of the whole microgrid depends on the battery system. Once this single inverter fails or needs to be disconnected for maintenance, the whole microgrid has to stop. To address these issues, choosing/designing the system to have high adaptability, e.g., a modular and scalable, flexible energy management system, broad operating range, and adjustable and more autonomous operation could alleviate some of these challenges.

A certain degree of redundancy is important to avoid a single point of failure and to make the system more robust. Similar to the previous section, this could also be addressed by implementing a modular design. A failure in one of the components will only partially reduce the electricity generation. Moreover, to a certain extent of modularity, this could simplify the troubleshooting process. Although physical space is still required for future additional equipment, it is considered to be more cost-efficient compared to highly oversizing the system.

Component suitability also applies to environmental challenges such as En3 and En4. Due to the relatively high-humidity environment, special treatment and installation methods might be needed to minimize the possibility of rust and to prevent foreign material from entering the equipment. Closing gaps or openings by a tight component sealing might impair the ventilation and heat transfer, which could result in a higher component degradation rate. Therefore, it is important to ensure the required operating condition is still in compliance with the manufacturer’s requirements. Choosing technology with a broad environment operating range and adding a proper air conditioning system is also important to prevent the equipment from degrading faster than designed. Additionally, the use of components that are suitable for a high-temperature operation range may also be needed. Although the more adaptable technology is most likely to require more cost and time during commissioning, it may perform significantly better in terms of long-term sustainability and even total life-cycle cost. These solutions, for example, could prevent the issues in Site 1, 5, 8, and 10 shown in Table 2, regarding high-temperature battery room and component sizing.
4.3. Operation and Maintenance

In Indonesia, it is easier to find or train local operators to manage remote microgrids with DiGs as the main supply compared to those with RE sources. This is because DiG technology is already mature, and the required knowledge is easier to transfer. As documented by PLN’s DiG operators, most of the disruptions are from mechanical parts, e.g., the piston, bearing, cylinder, or crankshaft, which are visible and easy to understand. Moreover, electrical disruptions are usually related to the battery, injector, or motor starter, which are relatively well-understood by the locals. Adding to that, PLN also has periodic skill improvement training for operators with clear instruction materials.

In contrast, O&M becomes more challenging in the case of microgrids with RE sources. Finding or training skilled operators becomes more difficult because the comprehensive O&M training materials and their procedures are currently still under development (related to Te3). Moreover, equipment such as inverters, energy management systems, and monitoring systems are also more technically sophisticated. Operators could do minimum O&M activities, such as visual checks and reading operation parameters from the equipment’s built-in display or monitor (if available), but further activities such as adjusting setpoints, downloading data, and troubleshooting are often difficult to carry out (related to Te2). For instance, if a warning is displayed by the equipment, corrective action might require a long time since the operator needs to contact the manufacturer and wait for a response. In some cases, preliminary measurements might be needed, which could also be a problem since the required skill and measurement equipment might not be available. Additionally, without a clear O&M procedure, early failure indicators due to high humidity and foreign material entering the equipment, such as early traces of rust, and rodent, insect, and lizard remains (related to En3 and En4), could not be identified, lowering the chances of failure prevention. In the case of MMU, providing skilled personnel with an appropriate and clear O&M is still very challenging. This jeopardizes the operation of remote microgrids with RE.

The aforementioned challenges could be addressed by ensuring a proper training program and preparing an elaborate O&M document during system handover after commissioning is finished. The O&M document has to be made according to applicable standards and the manufacturer’s recommendations. This, for instance, could help to prevent the issues in Sites 5–7 shown in Table 2 in relation to updating the inverters’ settings. Additionally, to prevent early failure, robust online remote monitoring should be implemented to acquire the operation parameters, components’ state of health, and to log important environmental conditions. These would be useful for both early identification of failure and to record historical data for future use (troubleshooting, project planning, scientific studies, etc.). Further discussion on online monitoring is presented in Part II of this publication. In addition to that, the implementation of equipment with high-level automation is also important for minimizing human intervention, covering the lack of skilled personnel, and for remotes challenges. This high-level automation could ease the work of the operators so that they could focus more on simpler O&M activities such as module cleaning, mowing, and visual checks. This also minimizes human errors and improves the reliability of the system. As an example, this could prevent the issue at Site 14 shown in Table 2, related to the manual operation of switching between PV and diesel generators.

Apart from the technical aspects, it is also important to ensure clear responsibility allocation in O&M for each stakeholder to avoid overlapping (or worse, abandonment) of tasks. This could help to ensure that remote microgrids have a sufficient O&M budget for both annual and incidental expenses. However, even with a clear responsibility allocation, there are still possibilities of neglect of duty; hence, enforcement of formal authority is also required. Therefore, not only the availability of skilled personnel with a proper O&M procedure, but also high-level automation equipment, and clear responsibility allocation among stakeholders are critical to support the sustainability of remote microgrids with RE.
5. Conclusions

This paper used MTF to evaluate the attributes of energy access in remote microgrids in MMU, Indonesia. The assessment is performed specifically for the systems that already have access to electricity. The assessment showed relatively good results in capacity, availability, reliability, and quality attributes, in contrast to the affordability attribute; the tariff is still considered too high for 88% of the assessed population. These energy access attributes could be improved by implementing remote microgrids with RE. However, based on the 15 PVs and PV hybrids that were analyzed, their average operational period is 4.3 years with 8 and 2 years being the longest and the shortest. This gives bad precedents for the scaling of microgrids with RE. The analysis showed that the prominent challenges are related to unclear land status, lack of social engagement, and uncertainty in load profile estimation, technical knowledge, and O&M procedures—especially for remote microgrids with RE sources. Additionally, due to the tropical environment conditions, a higher risk of failure caused by humidity, high-temperature, uncontrolled vegetation, rodents, insects, and lizards are also apparent. These challenges hampered the scaling of remote microgrids with RE sources and stunted the energy access attributes of capacity, availability, and affordability as shown in MMU.

A framework that correlates these challenges, development phases, and energy attributes was proposed. This framework is aimed at providing a practical view of expected challenges in each development phase of remote microgrids and helping relevant stakeholders to formulate appropriate strategies. The proposed framework is primarily based on the authors’ experiences, field data, and studies of specific MMU cases; hence, further adjustment and substantiation of the framework might be required for application to other energy access contexts. To this end, the authors invite other researchers and stakeholders to apply and test the framework in other contexts, towards creating a robust and relevant framework for scaling and sustainability of remote microgrids as an important contributor to achieving universal energy access.

It should be pointed out that some of the identified social, economic, or environmental challenges could, to an extent, be alleviated by technological solutions. Social acceptance and non-optimal utilization could be improved by ensuring quality and reliability of the supply and utilizing demand management; highly efficient, productive energy use appliances could contribute to increasing affordability for both end-users and developers; materials, components, and cooling methods suitable for high-temperature, high humidity environments would address some of the environmental issues, etc. This requires a transdisciplinary approach and new methods of collaboration among scientists of different disciplines.

Finally, this Part I identified the scaling and sustainability challenges of remote microgrid development in Indonesia based on the cases in MMU and other locations from the literature. Furthermore, a high-level technology outlook was presented to give recommendations for future works on addressing some of the identified challenges. However, the depth of understanding of each identified challenge and the proposed technology solutions was limited by data availability. Considering the data from actual remote sites is inadequate for more detailed and comprehensive analysis, further study and on-site measurements are still required to acquire a complete picture of these challenges and to identify suitable technology needs for further technology development.

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Appendix A

Table A1. Per capita gross regional domestic product (GRDP) by regency/municipality (in thousands rupiahs) [36].

| Regency/Municipality | Area (PLN) | No Regency/Municipality | Area (PLN) |
|----------------------|------------|--------------------------|------------|
| Maluku Tenggara Barat | 23,901     | 1 Maluku Tenggara Barat | 19,024     |
| Maluku Tenggara     | 32,547     | 2 Halmahera Barat       | 55,403     |
| Maluku Tengah       | 23,303     | 3 Sula Islands           | 23,964     |
| Buru                 | 16,419     | 4 Halmahera Selatan      | 36,438     |
| Kepulauan Aru        | 36,051     | 5 Halmahera Utara        | 29,005     |
| Seram Bagian Barat   | 17,623     | 6 Halmahera Timur        | 36,605     |
| Seram Bagian Timur   | 25,075     | 7 Morotai Island         | 2304       |
| Maluku Barat Daya   | 2276       | 8 Taliabu Island         | 27,917     |
| Buru Selatan         | 22,104     | 9 Ternate                | 44,287     |
| Ambon                | 29,682     | 10 Tidore Islands        | 29,083     |
| Tual                 | 32,095     | Total of Reg./Mun.       | 2558       |
| Total of Reg./Mun.   | 25,255     | Total of Reg./Mun.       | 33,284     |

* very preliminary figures.

Table A2. Maluku and North Maluku household electricity consumption throughout the year 2020 (PLN data).

| No | Unit         | Consumption in a Year (kWh) | Number of Customers | Avg. Consumption Per Day (Wh/Day) |
|----|--------------|----------------------------|---------------------|----------------------------------|
| 1  | Ambon        | 221,464,531                | 181,336             | 3346                             |
| 2  | Masohi       | 86,594,525                 | 92,127              | 2575                             |
| 3  | Ternate      | 171,483,183                | 123,920             | 3791                             |
| 4  | Sofifi       | 73,410,625                 | 74,530              | 2699                             |
| 5  | Tual         | 52,735,515                 | 43,364              | 3332                             |
| 6  | Tobelo       | 58,886,518                 | 58,279              | 2768                             |
| 7  | Saumlaki     | 28,563,816                 | 34,038              | 2299                             |
### Table A2. Cont.

| No | Unit      | Consumption in a Year (kWh) | Number of Customers | Avg. Consumption Per Day (Wh/Day) |
|----|-----------|-----------------------------|---------------------|-----------------------------------|
|    |           | R2: 3500–5500 VA            |                     |                                   |
| 1  | Ambon     | 12,266,222                  | 2825                | 11,896                            |
| 2  | Masohi    | 1,849,961                   | 507                 | 9997                              |
| 3  | Ternate   | 12,223,466                  | 2599                | 12,885                            |
| 4  | Sofifi    | 1,876,204                   | 932                 | 5515                              |
| 5  | Tual      | 3,044,693                   | 738                 | 11,303                            |
| 6  | Tobelo    | 2,487,704                   | 804                 | 8477                              |
| 7  | Saumlaki  | 1,585,478                   | 718                 | 6050                              |
|    |           | R3: ≥6600 VA                |                     |                                   |
| 1  | Ambon     | 8,571,497                   | 481                 | 48,822                            |
| 2  | Masohi    | 826,950                     | 46                  | 49,253                            |
| 3  | Ternate   | 3,328,643                   | 257                 | 35,485                            |
| 4  | Sofifi    | 986,646                     | 73                  | 37,029                            |

### Table A3. Maluku and North Maluku system sizes in May 2021 (PLN data). The ones in grey are microgrids with PV (and battery) systems.

| No  | System | Availability (Hours) | Installed Capacity (MW) | Peak Load (MW) | No  | System | Availability (Hours) | Installed Capacity (MW) | Peak Load (MW) |
|-----|--------|----------------------|-------------------------|----------------|-----|--------|----------------------|-------------------------|----------------|
| 1   | Amb1   | 24                   | 0.89                    | 0.56           | 47  | Sau3   | 12                   | 0.2                      | 0.04           |
| 2   | Amb2   | 12                   | 0.63                    | 0.43           | 48  | Sau4   | 12                   | 1.25                     | 0.39           |
| 3   | Amb3   | 12                   | 0.65                    | 0.18           | 49  | Sau5   | 24                   | 7.6                      | 3.99           |
| 4   | Amb4   | 24                   | 2.15                    | 1.35           | 50  | Sau6   | 12                   | 2                        | 0.57           |
| 5   | Amb5   | 12                   | 1.67                    | 0.93           | 51  | Sau7   | 12                   | 1.45                     | 0.72           |
| 6   | Amb6   | 12                   | 0.77                    | 0.31           | 52  | Sau8   | 12                   | 1.18                     | 0.23           |
| 7   | Amb7   | 12                   | 0.2                     | 0.19           | 53  | Sau9   | 12                   | 1.1                      | 0.3            |
| 8   | Amb8   | 12                   | 1                      | 0.31           | 54  | Sau10  | 12                   | 0.79                    | 0.21           |
| 9   | Amb9   | 12                   | 0.11                    | 0.02           | 55  | Sau11  | 12                   | 1.3                      | 0.48           |
| 10  | Amb10  | 12                   | 0.14                    | 0.08           | 56  | Sau12  | 24                   | 2.5                      | 1.27           |
| 11  | Amb11  | 12                   | 0.1                     | 0.05           | 57  | Sau13  | 24                   | 2.31                     | 0.76           |
| 12  | Amb12  | 12                   | 0.19                    | 0.14           | 58  | Sau1   | 24                   | 0.35                     | 0.22           |
| 13  | Amb13  | 12                   | 0.02                    | 0.01           | 59  | Sau2   | 24                   | 0.91                     | 0              |
| 14  | Amb14  | 24                   | 2.2                     | 1              | 60  | Sau3   | 24                   | 0.65                     | 0.33           |
| 15  | Amb15  | 24                   | 1.34                    | 0.26           | 61  | Sau4   | 24                   | 1.89                     | 0.77           |
| 16  | Amb16  | 6                    | 0.14                    | 0.11           | 62  | Sau5   | 12                   | 0.7                       | 0.09          |
| 17  | Amb17  | 12                   | 2.83                    | 1.21           | 63  | Sau6   | 12                   | 0                        | 0              |
| 18  | Amb18  | 24                   | 4.31                    | 1.52           | 64  | Sau7   | 24                   | 1.45                     | 0.4            |
| 19  | Amb19  | 24                   | 5.33                    | 2.74           | 65  | Sau8   | 24                   | 3.05                     | 1.37           |
| 20  | Amb20  | 24                   | 166.51                  | 56.36          | 66  | Sau9   | 24                   | 3.1                      | 1.2           |
| 21  | Amb21  | 24                   | 7.06                    | 1.21           | 67  | Sau10  | 24                   | 7.78                     | 4.33           |
| 22  | Amb22  | 24                   | 1.5                     | 0.56           | 68  | Sau11  | 24                   | 4                        | 2.05           |
| 23  | Amb23  | 24                   | 12.48                   | 4.99           | 69  | Sau12  | 24                   | 6.8                      | 6.06           |

| 24  | Mas1   | 24                   | 1.68                    | 0.48           | 70  | Sau13  | 24                   | 3.05                     | 0              |
Table A3. Cont.

| No  | System | No System Availability (Hours) | Installed Capacity (MW) | Peak Load (MW) | No System Availability (Hours) | Installed Capacity (MW) | Peak Load (MW) |
|-----|--------|--------------------------------|-------------------------|---------------|--------------------------------|-------------------------|---------------|
| 25  | Mas2   | 12                             | 1.87                    | 0.53          | 71                             | Sof14                   | 24            | 6.5           | 3.78          |
| 26  | Mas3   | 12                             | 0.52                    | 0.24          | 72                             | Sof15                   | 24            | 0.48          | 0.28          |
| 27  | Mas4   | 12                             | 2.14                    | 0.63          | 73                             | Ter1                    | 12            | 0.12          | 0.02          |
| 28  | Mas5   | 24                             | 0.61                    | 0.15          | 74                             | Ter2                    | 12            | 0.32          | 0.11          |
| 29  | Mas6   | 12                             | 0.36                    | 0.16          | 75                             | Ter3                    | 24            | 15.05         | 4.85          |
| 30  | Mas7   | 12                             | 1.14                    | 0.57          | 76                             | Ter4                    | 24            | 5.75          | 3.62          |
| 31  | Mas8   | 24                             | 2.26                    | 0             | 77                             | Ter5                    | 12            | 2.29          | 0.61          |
| 32  | Mas9   | 24                             | 1.87                    | 0.72          | 78                             | Ter6                    | 24            | 0.3           | 0.14          |
| 33  | Mas10  | 12                             | 2.03                    | 0.74          | 79                             | Ter7                    | 24            | 0.85          | 0.21          |
| 34  | Mas11  | 12                             | 0.35                    | 0.2           | 80                             | Ter8                    | 24            | 1.7           | 0.58          |
| 35  | Mas12  | 12                             | 0.72                    | 0.24          | 81                             | Ter9                    | 12            | 1.2           | 0.46          |
| 36  | Mas13  | 12                             | 0.04                    | 0.03          | 82                             | Ter10                   | 12            | 2.4           | 1.08          |
| 37  | Mas14  | 12                             | 0.4                     | 0.23          | 83                             | Ter11                   | 12            | 0.81          | 0.37          |
| 38  | Mas15  | 12                             | 0.1                     | 0.01          | 84                             | Ter12                   | 12            | 1.47          | 0.74          |
| 39  | Mas16  | 6                              | 0.1                     | 0             | 85                             | Ter13                   | 24            | 6.4           | 1.35          |
| 40  | Mas17  | 24                             | 8.46                    | 3.36          | 86                             | Ter14                   | 12            | 0.8           | 0.27          |
| 41  | Mas18  | 24                             | 7.7                     | 2.74          | 87                             | Ter15                   | 12            | 1.49          | 0.75          |
| 42  | Mas19  | 24                             | 24.32                   | 7.27          | 88                             | Ter16                   | 24            | 64.24         | 38.02         |
| 43  | Mas20  | 24                             | 3.92                    | 1.68          | 89                             | Tob1                    | 12            | 0.6           | 0.36          |
| 44  | Mas21  | 24                             | 7.2                     | 2.8           | 90                             | Tob2                    | 12            | 0.5           | 0.35          |
| 45  | Sau1   | 12                             | 1                       | 0.1           | 91                             | Tob3                    | 12            | 0.15          | 0.02          |
| 46  | Sau2   | 12                             | 0.04                    | 0.01          | 92                             | Tob4                    | 12            | 0.15          | 0.05          |
| 93  | Tob5   | 12                             | 0.23                    | 0.05          | 99                             | Tob11                   | 24            | 28.18         | 12.30         |
| 94  | Tob6   | 12                             | 0.25                    | 0.13          | 100                            | Tu1                     | 24            | 14.12         | 5.25          |
| 95  | Tob7   | 12                             | 0.06                    | 0.02          | 101                            | Tu2                     | 24            | 42.52         | 10.50         |
| 96  | Tob8   | 12                             | 0.5                     | 0.17          | 102                            | Tu3                     | 24            | 4.57          | 3.03          |
| 97  | Tob9   | 24                             | 7.7                     | 3.75          | 103                            | Tu4                     | 12            | 0.78          | 0.07          |
| 98  | Tob10  | 12                             | 2.45                    | 0.72          | 104                            | Tu5                     | 12            | 0.52          | 0.18          |

Table A4. Maluku and North Maluku feeder disruption report in 2021. Total feeders: 203. (PLN data).

| No | PLN Service Unit | Number of Disruptions | Number of Feeders with Disruption Longer than 2 h |
|----|------------------|-----------------------|-----------------------------------------------|
|    |                  | Jan | Feb | Mar | Apr | May | Total |                              |
| 1  | Amb1             | 3   | 5   | 6   | 7   | 23  | 44    | 1                              |
| 2  | Amb2             | 0   | 0   | 0   | 0   | 0   | 0     | 1                              |
| 3  | Amb3             | 12  | 13  | 16  | 14  | 20  | 75    | 7                              |
| 4  | Amb4             | 0   | 0   | 0   | 0   | 0   | 0     | 0                              |
| 5  | Amb5             | 0   | 0   | 0   | 2   | 0   | 2     | 0                              |
| 6  | Amb6             | 0   | 0   | 0   | 0   | 0   | 0     | 0                              |
| 7  | Amb7             | 1   | 0   | 0   | 1   | 0   | 2     | 0                              |
| 8  | Amb8             | 1   | 2   | 1   | 1   | 2   | 7     | 0                              |
| 9  | Amb9             | 0   | 1   | 1   | 0   | 0   | 2     | 0                              |
| 10 | Amb10            | 1   | 2   | 1   | 3   | 2   | 9     | 0                              |
| 11 | Amb11            | 0   | 0   | 0   | 0   | 2   | 2     | 0                              |
| 12 | Ter1             | 5   | 4   | 3   | 5   | 2   | 19    | 0                              |
| 13 | Ter2             | 0   | 1   | 2   | 0   | 1   | 4     | 0                              |
| 14 | Ter3             | 3   | 3   | 2   | 2   | 1   | 11    | 0                              |
| 15 | Ter4             | 4   | 3   | 0   | 0   | 2   | 9     | 0                              |
### Table A4. Cont.

| No | PLN Service Unit | Number of Disruptions | Number of Feeders with Disruption Longer than 2 h |
|----|------------------|-----------------------|-----------------------------------------------|
|    |                  | Jan | Feb | Mar | Apr | May | Total |                                    |
| 16 | Ter5             | 2   | 3   | 1   | 2   | 0   | 8     |                                    |
| 17 | Ter6             | 2   | 2   | 1   | 1   | 0   | 6     |                                    |
| 18 | Ter7             | 2   | 2   | 1   | 1   | 0   | 6     |                                    |
| 19 | Ter8             | 2   | 1   | 1   | 1   | 0   | 5     |                                    |
| 20 | Tua1             | 0   | 0   | 0   | 0   | 0   | 0     |                                    |
| 21 | Tua2             | 4   | 4   | 10  | 5   | 1   | 24    |                                    |
| 22 | Tua3             | 1   | 2   | 3   | 0   | 2   | 8     |                                    |
| 23 | Mas1             | 7   | 2   | 6   | 4   | 6   | 25    |                                    |
| 24 | Mas2             | 3   | 1   | 1   | 1   | 1   | 7     |                                    |
| 25 | Mas3             | 4   | 3   | 5   | 4   | 2   | 18    |                                    |
| 26 | Mas4             | 7   | 6   | 9   | 8   | 2   | 32    |                                    |
| 27 | Mas5             | 1   | 2   | 1   | 0   | 1   | 5     |                                    |
| 28 | Sof1             | 1   | 1   | 1   | 2   | 1   | 6     |                                    |
| 29 | Sof2             | 3   | 5   | 5   | 2   | 2   | 17    |                                    |
| 30 | Sof3             | 1   | 0   | 0   | 0   | 0   | 1     |                                    |
| 31 | Sof4             | 5   | 3   | 9   | 1   | 2   | 20    |                                    |
| 32 | Tob1             | 2   | 3   | 5   | 5   | 5   | 20    |                                    |
| 33 | Tob2             | 0   | 1   | 0   | 0   | 1   | 2     |                                    |
| 34 | Sau1             | 3   | 1   | 2   | 3   | 3   | 12    |                                    |
| 35 | Sau2             | 0   | 2   | 1   | 0   | 1   | 4     |                                    |

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