Chapter 12
Design and Implementation of Off-Grid Systems

12.1 Introduction

This chapter considers the design and implementation of off-grid systems. Mini-grid design is an exercise in design under constraints. The constraints most obviously include economic and technical issues, but often times social, political, legal, and environmental considerations influence the final design. Off-grid system design is almost always multi-objective. The systems are often deployed not only to provide electricity access but also to support development goals such as community resiliency and empowerment. Other off-grid systems are implemented to generate profit.

This chapter is primarily concerned with mini-grids. However, the same general concepts apply to off-grid systems serving single users. Stand-alone systems, such as those serving a single school or hospital, will have a more simplified distribution system than covered here.

Mini-grid design is not only design under constraints but also under considerable uncertainty in both the energy resources and load, as covered in Chap. 11. Compounding this challenge is that there is no universal approach to mini-grid design. Over the last several years, different organizations have developed guidelines or standards that can be used by mini-grid designers. However, the industry and technologies are evolving so swiftly that these documents are either presently being revised or are becoming outdated. This chapter is not intended to be a comprehensive off-grid design manual. Rather, it introduces the important concepts, considerations, and technical theory of mini-grid design.

There are several sources dedicated to the technical and nontechnical best practices of off-grid electrification. Many of these contain insightful case studies. The reader is directed in particular to references [1, 8, 9, 14].

H. Louie, *Off-Grid Electrical Systems in Developing Countries*,
https://doi.org/10.1007/978-3-319-91890-7_12

12.2 Mini-grid Life Cycle

We start by considering the life cycle of a mini-grid project. We take the perspective of an organization implementing mini-grids. This could be a for-profit company, a nonprofit organization, a governmental organization, or even an individual. Each will have their own priorities and definition of success, and so the following must be adjusted to fit a particular implementing organization.

From the initial decision to develop a mini-grid to the final decommissioning or expansion, the life cycle is composed of eight steps:

1. Prospecting and screening
2. Site assessment
3. Decision
4. Technical and commercial design
5. Pre-implementation
6. Implementation
7. Ongoing operation
8. Expansion or retirement

Before discussing each step in detail, we offer a comment on the general mindset one should have when implementing an off-grid project: never forget that off-grid communities are among the most underserved and at-risk in the world. These communities deserve better than to be treated as test grounds for electricity access projects. There are probably far more failed or unsustainable off-grid systems than there are those that are successful. Just as access to electricity can dramatically improve a community's outlook, a poorly planned project can ultimately cause more harm than good. The good news is that careful planning and diligence and guard against dramatic failure can provide the best opportunity for success.

12.2.1 Site Selection

The selection of the site for an off-grid system is the first and most important phase in the life cycle of a mini-grid. It includes steps 1 through 3 of the mini-grid life cycle. Each organization has its own site selection process, depending on its priorities and resources. Smaller organizations often use an informal approach. The location is selected based on a personal or organizational connection with a particular community. This approach does not scale well—a larger organization wanting to implement dozens or hundreds of mini-grids will use a more systematic approach.

In general, and from a techno-economic perspective, communities that are better candidates for sustainable mini-grids are those that have some or all of these characteristics:

- the national grid is located far away (20 km or more) with no credible plans for it to be extended to the community in the next several years;
- there are no other off-grid systems installed or planned to be installed;
- the estimated demand for electricity is high, and the planned uses are productive or improve the quality of life;
- one or more energy resources are suitable for electricity generation (see Chap. 11);
- there is sufficient ability and willingness to pay for electricity at a cost-reflective rate or a rate that aligns with the implementing organization’s ability to operate the mini-grid;
- the community is densely populated, which reduces distribution infrastructure costs;
- there is basic infrastructure, including roads and cellular network coverage;
- the community is politically stable;
- there is a low risk of theft and vandalism.

Other characteristics can be important, especially if the primary goal of the mini-grid is not commercial:

- access to electricity is a high-priority developmental goal for the community;
- access to electricity aligns with and supports other developmental goals, for example, health care and education;
- the community is able to organize itself to manage the mini-grid (if applicable).

12.2.2 Step 1: Prospecting and Screening

With so many communities without electricity access, a valid question is “Where to begin?” Resources are limited, and the success of a mini-grid largely depends on its location. The basic goal of this step is to develop a “short list” of communities where the mini-grid is believed to have best opportunity to be successful.

There may be thousands of off-grid communities in each country or region. They must be screened quickly and inexpensively. Secondary data from census or other data set that provides basic demographic information about communities can be used. These data are even more powerful when combined with the location of existing distribution lines, energy resources, and other geospatial data. Online tools are being developed to improve the screening process. An example is shown in Fig. 12.1 [11]. Screening is often done based on population density, distance to the national grid, and perhaps income. Other resources that can be consulted include Rural Electrification Authorities (see Chap. 3.6) and government electrification plans. The list of communities can be further reduced based on organizational convenience and priorities. These might include the distance from the implementing organization’s offices and cultural or language considerations. Additionally, grant-funded projects might be limited to specific regions or communities.

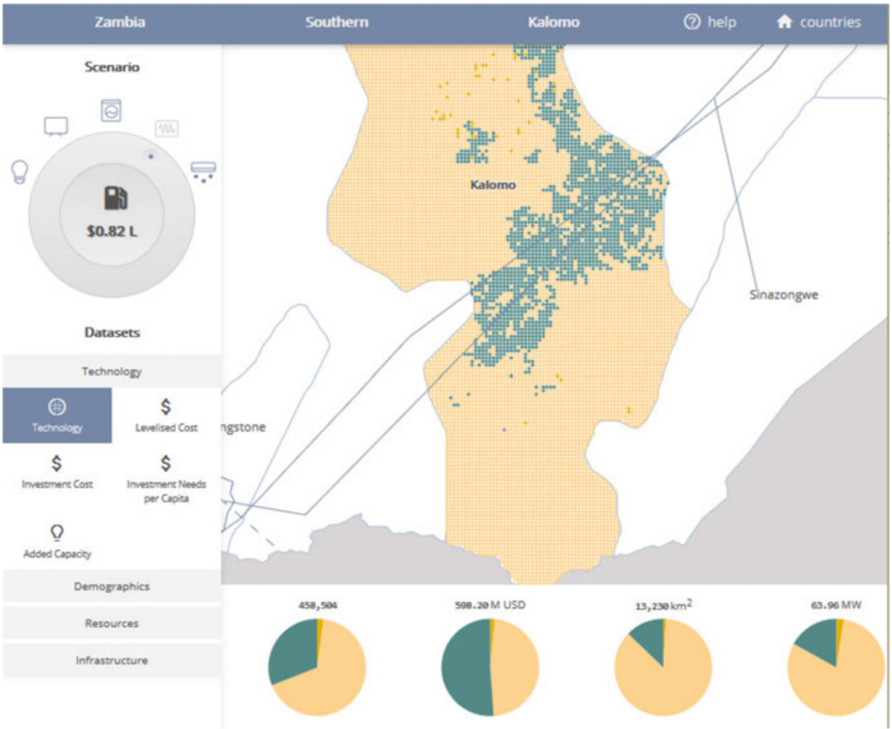

Fig. 12.1 Online screening tools combine demographic and geospatial data to visualize communities where off-grid solutions might be economically viable. Shown is a screenshot of the Electrification Pathways geospatial tool, which is part of the ENERGYDATA.INFO and World Bank Group Energy and Extractives Open Data and Analytics Initiative and created by the KTH University (courtesy of World Bank Group, KTH University, and the Energy Sector Management Assistance Program (ESMAP))

12.2.3 Step 2: Site Assessment

Once the list of communities is reduced to a manageable level, site visits are conducted. At this stage, the organization is investing considerable time and resources evaluating each site. The basic goal of the assessment is to gather primary data to support preliminary design and business modeling of the mini-grid. Typical activities include:

- observe the community firsthand;
- meet with local officials—this might involve governmental officers such as the District Commissioner, as well as traditional leaders such as chiefs, elders, or community groups;
- confirm that the secondary data used in the prospecting and screening step is reasonable;

- conduct surveys or focus groups to estimate present fuel consumption and predict future electric load and consumption patterns;
- check for cellular network coverage. This is important if the mini-grid will use mobile payments and/or remote data monitoring and control;
- identify existing and future local resources and economic activities;
- collect preliminary data for resource assessment;
- identify locations for mini-grid assets—generation equipment and facilities and distribution pathways—including discussion with landowners if land must be leased or purchased.

12.2.4 Step 3: Decision

The findings from the assessment trip can further reduce the list of candidate communities, and allow them to be prioritized. This might be done from a purely commercial perspective. Other tools such as PESTLE (Political, Economic, Social, Technology, Legal and Environmental) analysis and Risk Matrices can be useful in ranking the communities [17]. Depending on the implementing organization's resources, perhaps just one or two communities advance to the next step.

12.2.5 Step 4: Technical Design and Business Plan

Next, the system is designed and, if applicable, the business plan is developed. The technical and business plan should be guided by the targeted electricity access to tier (see Sect. 2.7). The technical design details are discussed later in this chapter. Associated with each design is an economic evaluation including capital and financing requirements, along with operation and maintenance costs. Systems intended to produce a profit or at least break even require a business plan. Most for-profit mini-grids use a metric known as average revenue per user (ARPU), which is the estimated or actual revenue associated with each connection over a period of time—typically 1 month. There might be a threshold ARPU below which the mini-grid is not deemed economically viable. Other financial targets can be similarly considered. The technical and commercial designs are interrelated and iterative. The process may involve further data collection from the site, for example, determining the routing for the distribution system or penstocks. If the mini-grid is found to be economically or technically impractical, then the next community on the priority list is considered.

12.2.6 Step 5: Pre-installation

After viable technical design and business plans have been completed or are nearly complete, pre-installation activities begin. This includes securing the required permits and approvals. This process may need to begin months in advance of a targeted installation date [13]. Many countries exempt mini-grids under a certain capacity, for example, 50 kW, from having to obtain a license or permit. Contracts with vendors, installers, and land owners are finalized. Be aware that importing materials can be a lengthy process.

Most mini-grids do not serve all households or potential customers in an area due to the high upfront connection costs. Therefore, the users need to be selected. Several factors are usually considered. For commercial mini-grids, the customer's expected ARPU and the cost to connect them are especially important. The mini-grid operator assumes a financial risk when connecting a customer. The connection costs are usually too high for the customer to pay upfront. Most operators build these costs into their tariff, essentially financing the connection with slightly higher rates over time. However, if the customer consumes very little energy, which is not uncommon, then the investment in the connection cost is never recuperated. It is therefore very important for the commercial success of a mini-grid to identify customers with high ARPU.

Community meetings and/or customer orientation like that shown in Fig. 12.2 occur during the pre-installation stage. The goal is to inform the community about the pending implementation. The electricity tariff is discussed, questions are answered, and feedback from the community is solicited. This often includes basic safety and technical topics including, for example, the typical cost of running various appliances.

12.2.7 Step 6: Installation

With proper planning, the installation of a mini-grid can occur quickly—often in just a matter of days for PV-powered mini-grids. Installation includes erecting poles or digging trenches for the distribution system and construction and outfitting the power house where the generation, controls, and battery storage (if needed) are located. The mini-grid should be commissioned before final payment is made to installers. Commissioning involves a series of tests and inspections to ensure the mini-grid has been installed properly. Standards such as IEC 62257 [5] offer guidance on commissioning. There is an unfortunate history of poorly installed or counterfeit components being used in many countries, as discussed in Chap. 14.

Fig. 12.2 Community meetings, like this one near Siavonga, Zambia, are important in introducing a project during the pre-installation stage (courtesy of A. Stewart)

12.2.8 Step 7: Ongoing Operation

After installation, the mini-grid begins serving its users. Some mini-grids, such as those powered by a PV array, require very little human intervention; others require daily or continuous oversight. A mini-grid using biomass gasification is one such example. Some mini-grids require administrative and customer support staff, for example, to collect payments. Maintenance should be performed routinely and as required. In some cases, local people can be trained to perform these tasks.

12.2.8.1 Step 8: Expansion or Retirement

Successful mini-grids can be expanded to supply more users or to generally improve the electricity access tier, for example, by increasing its availability. But when mini-grids are not successful, the operator might decide to relocate the major assets—the battery bank and PV array, for example—to another mini-grid, turn the asset over to the community or other organization, or fully retire and decommission the mini-grid. Retiring a mini-grid involves removing its assets, disposing them in an environmentally responsible way, and returning the land to its original condition. Retirement is not always a negative outcome. For example, a mini-grid might be retired because the national grid is finally extended to the community.

12.2.8.2 Modular Design

The desire to rapidly scale and reduce design and implementation costs has pushed some organizations toward using standardized or modular designs. For example, a robust portable structure like a shipping container is outfitted with the energy production components—PV array, batteries, and controllers—prior to being moved to the community.

12.3 Energy Conversion Technology Selection

The most commonly used energy conversion technologies in mini-grids are conventional or biomass gen sets, PV arrays, micro hydro power (MHP), and wind energy conversion systems (WECS). Each has its own advantages and disadvantages. When determining which to use, the designer should consider the characteristics that are important to the particular project. These typically include:

- Quality and availability of the energy resource;
- Fuel cost;
- Capital cost, including balance of system components such as batteries, inverters, conveyance systems, towers, and fuel storage;
- Lifespan of major components;
- Equipment availability, including replacement parts;
- Maintenance requirements;
- Human capital requirements—including technical and business skills;
- Environmental and land-use requirements;
- Design difficulty.

The first consideration should be the quality and availability of the energy resources. This involves estimating the capacity factor of the different technologies, as described in the last chapter. Economic characteristics are the next considered. For many organizations, especially those funded by grants, the upfront capital cost is critically important. However, the cost of fuel and maintenance over the life of the project can easily exceed the upfront cost. A metric such as the levelized cost of energy, which will be discussed in Sect. 12.8, is useful in making economic comparisons between different energy conversion technologies.

Next, characteristics affecting the ongoing operation of the energy conversion technology are considered. What is the expected lifespan of the components, and how long are they covered under the manufacturer's warranty? For example, a gen set might require a major overhaul after 3 years of operation, but a PV array might last 15 to 20 years. Are replacement parts readily available? Is it possible for routine maintenance to be performed without specialized tools and training?

The technical, organizational, and business skills needed to operate the system should be considered. For example, biomass gasification requires constant monitor-

Table 12.1 Energy conversion technology characteristics

	Gen Set	MHP	WECS	PV Array	Biogas	Gasification
Energy source availability	Available	Limited	Limited	Available	Available	Available
Cost of fuel	High	None	None	None	None–Medium	None–Medium
Capital cost	Low	Medium–High	Medium–High	Medium–High	Low	Medium
Cost of operation	High	Low	Low	Low	Low	Medium
Major component lifespan	Short	Long	Medium	PV-long, battery-short	Long	Medium
Availability of components	High	Medium	Low	High	High	Medium
Balance of system requirements	Low	High	High	High	Medium	Medium
Operation skill	Low–Medium	Low	Low	Low	Low	High
Environmental impact	High	Low/ Medium	Low	Low	Low/ Medium	Low/ Medium
Footprint	Low	Medium	Medium	Low/ Medium	Low	Low/ Medium
Design difficulty	Low	High	Medium	Low	Low	Medium

ing, but a MHP system with an electronic load controller (ELC) requires minimal human intervention. Often the workforce in a rural area will require some training to operate the system.

The environmental impact—including disposal of batteries and equipment—as well as land use should be considered. Conventional gen sets require little land, but noise, fuel spills, and exhaust emissions are a concern. WECSs and PV arrays require considerable land. MHP and biomass might disrupt the traditional use of resources.

Lastly, the time, cost, and difficulty to design the system should be considered. Some systems like MHP must be custom-designed. On the other hand, PV array-powered mini-grids can be modularly constructed and mass manufactured.

Table 12.1 provides a rough ranking of the technologies in the various categories. Of course, these are highly site-specific. The decision of which technology to use can be obvious from this assessment. In other cases, it is worthwhile to consider several different energy conversion technologies separately or together in a hybrid system.

12.4 Design Approaches

We next discuss the design of the energy production components of off-grid systems. We focus on mini-grids in particular. The basic concepts also apply to stand-alone systems. Our primary focus is the electrical design. There are two basic approaches to designing a mini-grid: intuitive and numerical. There are several variations within each approach. The output of the design are the specifications of the energy conversion technologies, energy storage, controllers, and converters. The design of the distribution system is discussed separately in Sect. 12.7. The design of a mini-grid is iterative. Several designs are considered before a final design is selected. Each approach requires an estimation of the load and energy resources as described in the previous chapter.

12.5 Intuitive Approach

Intuitive design approaches have low input data requirements and allow the mini-grid to be designed using relatively simple calculations. The calculations can be based on "rules of thumb" or formalized standards, such as IEEE 1526 [6], IEEE 1013 [7], and IEC TS 62257 [5]. Intuitive approaches, however, provide limited insight and feedback as to how design choices affect the performance of the system, particularly its reliability. The final design may have lower reliability than needed, or higher reliability than necessary, wasting resources.

Through an example, we will produce a basic design which illustrates the fundamentals of an intuitive design approach. A complete design of the mini-grid would include specification of wire sizes, switches, protection equipment and grounding, physical layout, mechanical and civil design, and the distribution system. We stress that example is one of many possible intuitive approaches and do not suggest that it is optimal in any sense.

12.5.1 Project Overview

Assume that after screening and site assessment, the community of Mwase in the southern region of Zambia has been selected for a mini-grid implementation. Mwase is a fictional community. Its characteristics, however, are drawn from real off-grid communities.

The population of Mwase is approximately 3000 people. The nearest electrified town, Bona, is 23 km away. The road to Mwase is not well maintained and becomes impassable during the rainy season (roughly November to February). The people of Mwase primarily support themselves by fishing, raising livestock, and farming. It is anticipated that in addition to serving households, the mini-grid will supply a small number of businesses and a school located on the far side of town. One entrepreneur will start a barber shop/hair salon which will use a high-power blow dryer; another will sell refrigerated drinks from their shop. The households have indicated they will primarily use the electricity for lighting and watching television in the evening. In total, a mix of 24 households, businesses, and the school have been identified as users. These users are located along the main pathway through the town. The households to be connected to the mini-grid are arranged in two dense clusters along the pathway.

None of the users require a three-phase connection. Each will be supplied with a single-phase 230 V, 50 Hz connection, which matches that of the national grid. This means that the appliances readily available in the country can be used. A secure power house will be constructed.

The energy resource estimation showed that WECS, MHP, and biomass are not technically viable due to low availability of their respective resources. This leaves a gen set or a PV array as possible sources for the mini-grid. We will consider the preliminary design of the PV array system, assuming that the logistics of maintaining the fuel supply for a gen set are not practical.

12.5.2 Load Characterization

We begin by characterizing the aggregate load. A survey approach was used to estimate the load. At a minimum, an estimate of the average aggregate daily load and the aggregate peak load is needed. We will assume that the surveys were thorough enough so that a load profile can be produced, as shown in Fig. 12.3. This is inclusive of an assumed 6.5% loss in the distribution system. The daily aggregate average load is computed to be 7.875 kWh/day. The sum of the estimated peak load of the individual users is 4.11 kW. However, with 24 users, some of them businesses, we expect the aggregate peak to be lower because the coincidence factor will not be 1. We will assume a coincidence factor of 0.37, which is reasonable for this situation. The aggregate peak load is therefore $4.11 \times 0.37 = 1.54$ kW. The survey did not indicate if there will be seasonal variation to the load, so we shall assume it to be constant each month. The load growth is assumed to be 5% per year. We will design the system based on the projected load in 5 years. After 5 years the system may need to be upgraded. We will also plan on replacing the battery bank at this time. This brings the average and peak loads to 10.05 kWh/day and 1.94 kW, respectively. The pertinent load values are summarized in Table 12.2.

12.5.3 Architecture Selection

The next step is to determine the high-level architecture of the system. We are primarily concerned with identifying the components needed and how they are

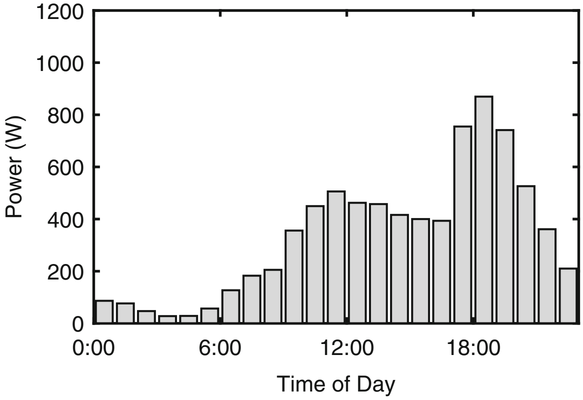

Fig. 12.3 Estimated load profile of Mwase

Table 12.2 Estimated load data

Parameter	Initial	After five years
Avg. daily load (kWh/Day)	7.875	10.05
Peak individual load (kW)	4.11	5.24
Coincidence factor	0.37	0.37
Peak aggregate load (kW)	1.52	1.94
Power factor	0.85	0.85

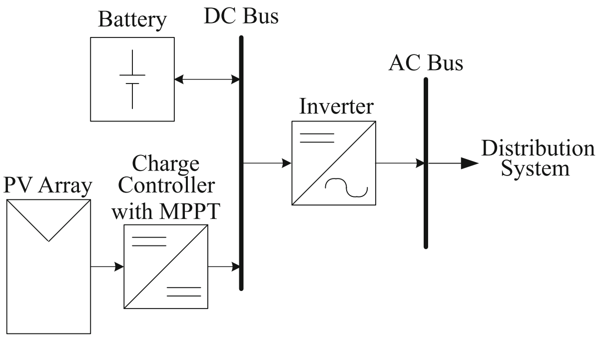

Fig. 12.4 Architecture of the Mwase mini-grid

interconnected. The reader may wish to review Chap. 4 for background information on mini-grid architecture. The architecture of the mini-grid is dictated by the energy conversion technology and the load. The only generation source is the PV array, and so the system is DC-coupled. The users require AC service, and so an inverter is needed. A battery bank will supply the load during evening hours. Because the system will be larger than a few hundred watts, a charge controller with maximum power point tracking (MPPT) will be included. A schematic of the mini-grid is shown in Fig. 12.4. The PV array will be installed on top of the power house, and the battery bank and all the DC components will be securely enclosed within.

12.5.4 Voltage Level Selection

The voltage at each bus is selected next. The AC bus voltage is already determined: 230 V at 50 Hz, single-phase. The DC bus voltage is set by the battery bank. Here we consider several factors:

- Nominal voltage of selected battery chemistry (see Chap. 8)
- Electrical distance between DC bus components
- Power capacity of the system
- Safety
- Compatibility with DC bus components

We will assume that the only large-capacity batteries easily available in the country are lead–acid. Therefore, the nominal voltage level will be an integer multiple of 2 V. The battery bank is in a secure area, and so both flooded and valve-regulated lead–acid are viable options. We will use AGM valve-regulated batteries because of the low maintenance requirements. The battery bank will be located in the power house near the PV array and inverter, and so we do not need to be concerned about excessive voltage drop or losses. However, the capacity of the PV array will be several kilowatts. To keep the wires from being too large, a higher voltage is preferred. To be compatible with most charge controllers and inverters, we should select either 12, 24, or 48 V. A common rule of thumb is to use 12 V for systems whose load is less than 1 kWh/day, 24 V for load between 1 and 4 kWh/day, and 48V when the load exceeds for 4 kWh/day. Exceptionally large systems might use 96 V or above. We therefore select a nominal 48 V DC bus voltage. With the DC bus voltage set, the current ratings of the charge controller and inverter can be calculated.

12.5.5 Inverter Selection

Recall from Chap. 9 that an inverter facilitates the flow of power from the DC bus to the AC bus. Inverter parameters that require specification by the designer are shown in Table 12.3. In general, the sum of the power ratings of the inverters and generators connected to the AC bus must be at least as large as the peak load. The minimum power rating of the inverter serving Mwase must therefore be 1.94 kW.

However, this value requires adjustment. We will apply a design margin to mitigate the possible underestimation of the peak load. The inverter will not be in a temperature-controlled environment. Most inverters are rated based on a certain ambient temperature, usually 25°C. If it is expected that the ambient temperature will consistently be higher than the rated temperature, then an inverter with a larger capacity is needed. We will select a high design margin of 0.20 to also account for the effect of temperature:

$$\textit{Inverter Power Requirement} = \textit{Peak Load} \times (1 + \textit{Design Margin})\,. \tag{12.1}$$

Table 12.3 Inverter specifications

Parameter	Requirement	Actual
Max. continuous output power	$>$ 2.33 kW	2.4 kW
Nominal input voltage	48 V	48 V
Nominal output voltage	230 V	230 V $\pm$ 2%
Output frequency	50 Hz	250 Hz $\pm$ 0.1%
Standby energy consumption	–	25 W
Max. DC current	$>$57.14 A	125 A
Efficiency	–	85% (assumed)
THD	$\leq$5%	5%
Phase	Single	Single
Bi-directional	No	No
LVD	Yes	Yes

The minimum required rating becomes $1.94 \times (1+0.20)$ =2.33 kW. Some inverters are rated in voltamps, not watts. In this case, the assumed power factor is used to convert the requirement to voltamps. For the Mwase system, we will assume a power factor of 0.85 so that the inverter rating in voltamps is $2.33/0.85 = 3.74$ kVA.

We next compute the maximum input current on the DC side of the inverter:

$$Max.\ Inverter\ DC\ Current = \frac{Required\ Inverter\ Power}{Nom.\ Battery\ Voltage \times Inverter\ Efficiency} \tag{12.2}$$

Inspection of Mwase's estimated load profile in Fig. 12.3 shows that for most hours the load is between 400 and 600 W. This is roughly 20 to 25% of the required inverter rating. Given the general shape of inverter efficiency curves shown in Sect. 9.9.5, we will assume the average efficiency of the inverter is 85%. This estimate could be improved by calculating the efficiency for each hour of the load profile using the selected inverter's efficiency curve and averaging the result. From (12.2), the maximum current on the DC side of the inverter is

$$Max.\ Inverter\ DC\ Current = \frac{2330}{48 \times 0.85} = 57.14\ \text{A}.$$

For convenience, we will round the maximum current up to 58 A.

There are a few other inverter parameters that we should specify. We are not sure if the appliances will tolerate high levels of distortion, so a modified sinewave inverter should not be used. We will only consider inverters whose total harmonic distortion (THD) does not exceed 5%. The users only need single-phase service. As discussed later, the distribution system could be three-phase. In this case each user would be supplied a line-to-neutral connection. However, the mini-grid is small enough that this complexity is not justified. Instead, we will use a single-phase inverter. The mini-grid's architecture is such that power will never flow from the AC bus to the DC bus, so the inverter need not be bi-directional. The battery bank needs protection from deep discharge. Therefore, the inverter must have a low-voltage disconnect (LVD) feature (see Sect. 10.3).

After considering several manufacturers and models of inverters, assume the selected model has the characteristics shown in the third column of Table 12.3.

There are a few other considerations worth noting. Most inverters have a “peak power” or “surge power” rating in addition to their continuous rating. This refers to the power that the inverter can supply for a short duration (often a few seconds to several minutes). Depending on the nature of the load, especially if the peak load is due to motor starting, the peak rating can be used instead of the continuous rating. For Mwase we will use the continuous rating, which is a more conservative approach. We also note the no-load power of the inverter is 25 W. Over the course of the day, the inverter will consume 600 Wh, which represents about 6% of the daily load. The load estimate can be increased to account for this in later iterations of the design. In the case that a single inverter is not capable of supplying the required peak power, multiple inverters can be connected in parallel. The inverters should be from the same manufacturer, and they should be capable of synchronizing with each other. If this is not possible, then separate AC buses can be created, with each inverter supplying power to its own AC bus and the subset of users connected to it.

12.5.6 Battery Bank Design

The battery bank is designed independently of the PV array. The following steps can generally be applied regardless of the energy conversion technology selected. Note the approach presented here is conservative, and it is possible that a smaller-capacity battery bank would be able to produce a similarly high reliability. However, without detailed knowledge of the actual load and given the inherent limitations of intuitive approaches, we cannot know this for certain.

The three most important factors affecting the design of the battery bank are (1) the nominal voltage of the DC bus, (2) the discharge current, and (3) the required reliability. The nominal voltage has already been specified. The discharge current is determined from the inverter input current. The reliability requirement is indirectly expressed as the “Days of Autonomy.” The Days of Autonomy is the number of days that the battery bank can supply the average load before being depleted, assuming it is not recharged during this period. This is an extreme scenario. It could occur if the PV array is damaged and the repair was delayed.

A system designed using more Days of Autonomy will have higher reliability than one with fewer. Increasing the Days of Autonomy increases the required battery bank capacity. However, the reliability does not necessarily proportionately scale with the Days of Autonomy. In other words, doubling the Days of Autonomy does not necessarily double the reliability. The specified Days of Autonomy is typically between 2 and 12. We will select just two Days of Autonomy to reduce costs.

It is convenient to specify the battery bank capacity requirement in terms of amphours. The average daily load required from the battery bank, in terms of amphours, is

$$Avg.\ Battery\ Load = \frac{Avg.\ Daily\ Load}{Inverter\ Efficiency \times Nominal\ Battery\ Voltage}. \tag{12.3}$$

For Mwase, this is

$$Avg.\ Battery\ Load = \frac{10,047}{0.85 \times 48} = 246.25 \text{ Ah}.$$

At a minimum, the battery bank must be capable of supplying the average battery load for the specified Days of Autonomy. This must be the case even at the end of the considered 5-year period. However, the battery bank's maximum capacity will naturally decrease over time. Most manufacturers define the maximum capacity at the end of life to be 80% of the initial capacity. The minimum-rated capacity of the battery bank is therefore

$$C_x = Days\ of\ Autonomy \times Avg.\ Battery\ Load \times \frac{1}{End\ of\ Life\ Rating} \tag{12.4}$$

where x is the discharge current the capacity is associated with, which will be discussed shortly.

The battery bank for Mwase must have a minimum capacity of

$$C_{\text{x}} = 2 \times 246.25 \times \frac{1}{0.80} = 615.63 \text{ Ah}.$$

From Sect. 8.5.3, we know that the capacity of a lead–acid battery varies with its discharge current. We must specify the discharge current x the capacity C_{x} is associated with. The discharge current varies throughout the day, but the capacity is defined at a single discharge current. Two reasonable options are to use the average inverter DC current or use the peak inverter DC current. The latter will yield a larger battery bank. We will take this more conservative approach. The minimum capacity is then 615.63 Ah when discharged at 58 A (C-rate of 58/615.63= 0.094, hour rate of 615.63/58 = 10.61 h). In other words, $C_{58} = 615.63$ Ah. In a very simple design approach, this is the capacity requirement of the battery bank. However, the designer may wish to consider other factors, in which case the following adjustments can be made:

First, recall that deeply discharging a battery can permanently degrade it. To prevent this, the state-of-charge (SoC) should not be zero even after a battery bank has supplied the average load for the specified days of autonomy. We select a maximum depth-of-discharge DoD_{max}, typically 0.50 to 0.80. In other words, we want the battery to still have 20 to 50% of its charge remaining after supplying the average load for the total Days of Autonomy. The capacity requirement is adjusted as

$$C'_{\text{x}} = C_{\text{x}} \times \frac{1}{DoD_{\text{max}}}. \tag{12.5}$$

It is stressed that this is the maximum depth-of-discharge. The battery should not be discharged this deeply on a daily basis. For the Mwase system

$$C'_{58} = C_{58} \times \frac{1}{0.8} = 769.49 \text{ Ah.}$$

We next check to see what daily DoD is consistent with the battery bank lasting the targeted number of years. For the Mwase system, the battery bank will be replaced every 5 years, corresponding to 5 × 365 =1825 cycles.

We consult a chart such as Fig. 8.16 provided by a battery's manufacturer to determine the daily DoD that corresponds to 1825 cycles. This will vary, perhaps appreciably, for each battery considered. For the AGM battery in the Fig. 8.16, the DoD corresponding to 1825 cycles is 40%.

We then check what the average daily DoD is when the capacity is C'_x

$$DoD_{\text{daily}} = 100 \times \frac{Avg.\ Battery\ Load}{C'_x} \qquad (12.6)$$

which for the Mwase system is

$$DoD_{\text{daily}} = 100 \times \frac{246.25}{769.49} = 32\%.$$

This is less than the targeted DoD of 40%, and so we expect the battery bank to last at least 1825 cycles. Should we find that DoD_{daily} exceeds the targeted value, then we increase the capacity requirement according to

$$C'_x = \frac{Avg.\ Battery\ Load}{End\ of\ Life\ Rating} \times \frac{100}{DoD\ for\ Required\ Number\ of\ Cycles}. \qquad (12.7)$$

The required battery bank capacity can be further adjusted by a design margin to account for the effects of temperature, load estimation error, and losses not modeled elsewhere by applying a design margin:

$$C''_x = C'_x \times (1 + Battery\ Design\ Margin)\,. \qquad (12.8)$$

We will apply a design margin of 7.5% bringing the total required capacity to

$$C''_{58} = 769.49 \times (1.0 + 0.075) = 827.21 \text{ Ah}$$

at a discharge rate of 58A (C-rate of 58/827.21 = 0.07C, hour rate of 827.21/58 = 14.25 h). The battery bank requirements are summarized in Table 12.4. A summary of the battery capacity calculations is provided in Table 12.5.

Table 12.4 Battery bank specifications

Parameter	Bank requirement	Bank actual (5 strings, 8/string)	Battery actual
Battery type	AGM	AGM	AGM
Nominal voltage	48 V	48 V	6 V
Capacity	827.21 Ah (0.07C)	≈ 1000 Ah (0.07C)	≈ 200 Ah (0.07C)
Min. cycles at 40% DoD	1825	1825	1825
Max. bulk current	–	220 A	20% of C_{20} (44 A)
Absorption set-point	–	57.60V	7.20
Float set-point	–	54.00 V	6.75 V
Cut-off voltage	–	42 V	1.75 V/cell

Table 12.5 Battery charge capacity design summary

Quantity	Value	Computed from	Equation
Avg. Battery Load	246.25 Ah	Load estimate, inverter efficiency and battery bank nominal voltage	(12.3)
C_x	615.63 Ah	Avg. battery load, days of autonomy and end of life rating	(12.4)
C'_x	769.49 Ah	C_x, maximum depth-of-discharge OR	(12.5)
	–	Avg. battery load, end of life rating, and depth-of-discharge for required number of cycles	(12.7)
C''_x	827.21 Ah	C'_x and design margin	(12.8)

Table 12.6 Battery charge capacity

Hour-rate	10 hr (19A, 0.1C)	20 hr (11A, 0.05C)	48 hr (4.8A, 0.021C)	72 hr (2.96A, 0.014C)	100 hr (2.35A, 0.01C)
Capacity	190Ah	220Ah	228Ah	231Ah	235Ah

12.5.6.1 Battery Bank Configuration

We have determined the requirements of the battery bank and now must select the individual battery and the configuration of the bank. We will assume that the particular battery considered has characteristics in the last column of Table 12.4 and whose capacity is described in Table 12.6. These data are typically found in the battery's specification sheet provided by the manufacturer.

The number of batteries in series is computed from

$$\textit{Number of Series Batteries} = \frac{\textit{Battery Bank Nominal Voltage}}{\textit{Battery Nominal Voltage}} \tag{12.9}$$

The given battery has a nominal voltage of 6 V. Therefore, each string will have 48/6 = 8 series-connected batteries.

Next, we determine the number of parallel strings that will be needed to supply the required current. The capacity requirement of the battery bank is 827.21 Ah at a discharge of 58 A. This corresponds to a C-rate of 0.07C and an hour rate of 14.25 h. Although the capacity at the 14.25 hour rate is not provided by the manufacturer, we can approximate it as being somewhat above the 10-hour rate but below the 20-hour rate. We will use 200Ah. This estimate could be somewhat improved using the Peukert equation as discussed in Sect. 8.5.3.6. The number of strings required is found from

$$\textit{Number of Battery Strings} = \frac{\textit{Required Battery Bank Capacity}}{\textit{Battery Capacity}}. \tag{12.10}$$

Using a capacity of 200 Ah, 827.21/200 = 4.13 strings are needed, which we round up to 5 strings. With this design, each string supplies 58/5 = 11.6 A during the peak load.

The battery bank therefore has 5 strings of 8 batteries, for a total of 40 batteries. This arrangement is shown in Fig 12.5. We note that it would also be reasonable to use four strings instead of five. Recall that we conservatively used the maximum discharge current to determine the discharge rate. If we used the average discharge current instead, we would find that four strings would be viable. This would reduce the material cost of the battery bank cost by 20%. It also results in fewer batteries

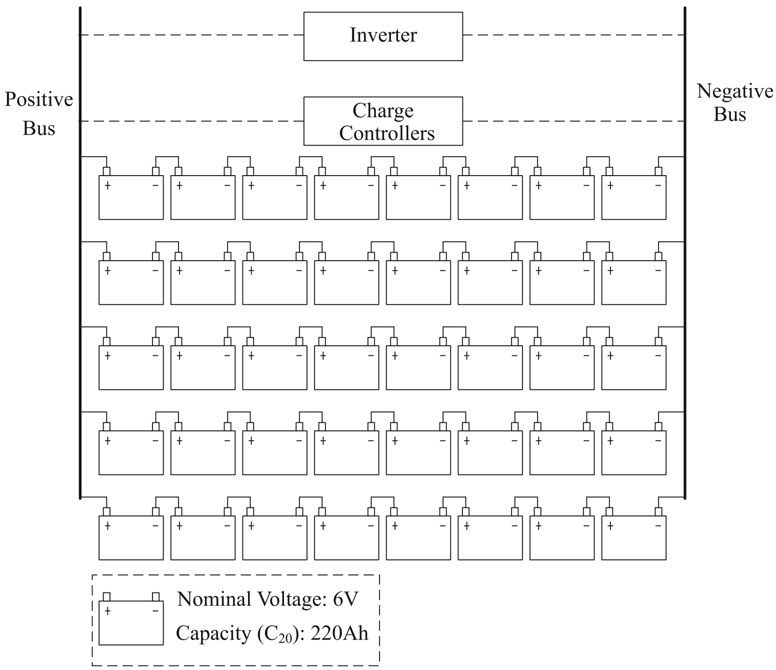

Fig. 12.5 Battery bank configuration for the Mwase system

Table 12.7 Average daily insolation by month

	Month (kWh/m^2/day)												
Tilt	1	2	3	4	5	6	7	8	9	10	11	12	Avg.
Latitude -15°	5.51	5.61	5.69	5.76	5.36	**4.90**	5.15	5.99	6.51	6.78	6.19	5.54	5.79
Latitude	**5.08**	5.39	5.77	6.31	6.40	6.01	6.20	6.87	6.85	6.64	5.76	5.09	6.06
Latitude +15°	4.47	4.94	5.54	6.46	6.89	6.58	6.78	7.23	6.76	6.15	5.08	**4.44**	5.94

placed in parallel, which is desirable from a safety perspective. Nonetheless, because this is a first iteration design, we will proceed using five strings.

From Table 12.4, the battery's cut-off voltage is 1.75 V/cell. Recall that this is the terminal voltage during discharge (not the open-circuit voltage) that corresponds to a zero SoC. Since there are 24 series-connected cells in a 48 V bank, the bank's cut-off voltage is 42 V. The LVD on the inverter should be set to at least this voltage. However, since the $DoD_{\max}$ is 80%, not 100%, it is prudent to slightly increase this to, for example, 43 V.

The characteristics of the battery bank are shown in the third column of Table 12.4. To briefly summarize, the average daily battery load 5 years after installation is 246.25 Ah for a 48 V battery bank. The first iteration of the design produced by the intuitive approach calls for a battery bank rated at 1000 Ah at 0.07C. The battery bank has enough capacity to supply the average load for at least 2 days without recharging, to a depth-of-discharge of less than 80%, even after 5 years of operation.

12.5.7 Energy Source Design

The guiding principle of energy source design is that the source should be capable of supplying enough energy to supply the expected average load accounting for generation and storage losses. The system is designed around the month with the lowest capacity factor. Chapter 11 explains how the capacity factor is estimated for different energy conversion technologies. If the load has a seasonal component, then designs are produced for each month or season, and the design with the largest energy source rating is used.

The average daily insolation by month for Mwase was found by consulting a solar database. The data are provided in Table 12.7 for three different array tilts.

12.5.7.1 Tilt Selection

The tilt of PV array is selected by comparing the insolation data in Table 12.7. The month with the lowest insolation for each tilt is highlighted in bold. We select the tilt that corresponds to the largest of these three values. That is, we select the tilt with the greatest minimum monthly insolation. In this case it corresponds to an array tilted at the latitude, whose minimum insolation occurs in January with 5.08 kWh/m^2/day.

12.5.7.2 Capacity Factor

From (11.13), we know that the capacity factor is related to the insolation as

$$Capacity\ Factor = \frac{\bar{I}}{24} \tag{12.11}$$

where $\bar{I}$ is the average insolation. For Mwase during January, the average capacity factor is 5.08/24 = 0.21. The daily energy production potential for a PV array rated at $P_{\text{PV,rated}}$ is

$$E_{\text{PV}} = 24 \times Capacity\ Factor \times P_{\text{PV,rated}}. \tag{12.12}$$

Therefore, if all losses are ignored, the PV array must be rated at no less than

$$P_{\text{PV,rated}} = \frac{Avg.\ Daily\ Load}{24 \times Capacity\ Factor \times Inverter\ Efficiency}. \tag{12.13}$$

For Mwase, this corresponds to

$$P_{\text{PV,rated}} = \frac{10.05}{24 \times 0.21 \times 0.85} = 2.33\ \text{kW}.$$

This represents an idealized case. A higher rating is needed to account for losses.

12.5.7.3 Generation and Storage Losses

The actual usable energy production from a PV array will be less than E_{PV}. This is due to a number of factors:

- Array shading, including dust (see Sect. 7.12)
- Wire and connection resistive losses
- Parasitic losses (stand-by consumption of controllers, monitors, data acquisition systems, and other devices)
- Module mismatch (caused by PV strings or modules having different maximum power points)
- Array degradation over time (aging)

The production is also affected by coincidence of the load and the irradiance. Recall that during the absorption charging stage, the power to the battery bank is intentionally limited. If the load is also low during this time, the PV array production will be reduced (throttled). Further, any energy stored incurs losses associated with the battery (see Sect. 8.5.4).

It is difficult to estimate the generation and storage losses. Typical ranges are shown in Table 12.8. Whether it is prudent to select a value toward the low end

Table 12.8 Typical generation and storage losses

Type	Low (%)	High (%)
Shading	0	40
Wire and connection loss	0	10
Parasitic loss	1	10
Module mismatch	0	5
Aging	0	15
Coulombic effect	5	25

or high end of the range, or even exceeding it, depends on the particular local conditions. For example, the soil and wind conditions can inform whether the losses due to dust are closer to 20% or 0%. Use of oversized cables, high-quality batteries, and efficient charge controllers and monitoring equipment can make loss estimates toward the lower end of the range plausible. Note that these losses are associated with the production and storage of energy, not its distribution. Distribution and inverter losses have already been accounted for.

Estimates are made for each type of loss, and the results are summed to determine the total loss K_L. It is obvious that $0 \le K_L \le 100$.

The required PV array rating is therefore

$$P'_{\text{PV,rated}} = \frac{P_{\text{PV,rated}}}{1 - K_L/100}. \tag{12.14}$$

We note that $P'_{\text{PV,rated}}$ will always be greater than $P_{\text{PV,rated}}$ when losses are considered. For Mwase, we will assume a loss of 22% so that

$$P'_{\text{PV,rated}} = \frac{2.33}{1 - 0.22} = 2.98\ \text{kW}.$$

12.5.7.4 Temperature Effects

As discussed in Chap. 7.10, the power output of a PV module decreases with temperature. The temperature of a PV cell during the daytime is usually much higher than the ambient air temperature. A reasonable range of operating temperatures is between 30°C and 60°C. Given a typical temperature power coefficient α_p of −0.5 % per degree Celsius (or Kelvin) above 25°C, the presumed power output of the PV array should be reduced by 2.5% to 17.5%. A value within this range can be selected based on an informal assessment of the climate (warmer locations warrant more severe reduction). However, more accurate estimation can be made using the specification of the PV array and temperature data. The required rating becomes

$$P''_{\text{PV,rated}} = 100 \times \frac{P'_{\text{PV,rated}}}{100 - \textit{Temperature Related Reduction}}. \tag{12.15}$$

Table 12.9 PV array requirements and actual values

Parameter	Array requirement	Array actual (5 strings, 3/string)	Module actual
Maximum power	4.71 kW	5.25 kW	0.350 kW
Optimum operating voltage (V^*)	–	115.62 V	38.54 V
Optimum operating current (I^*)	–	45.40 A	9.08 A
Open-circuit voltage (V_{OC}), STC	$\leq$ 150 V	142.29 V	47.43 V
Short-circuit current (I_{SC}),STC	$\leq$ 60 A	47.45 A	9.49 A
Short-circuit current temp. coeff. (α_i)	–	0.04 %/K	0.04 %/K
Open-circuit temp. coeff. (α_V)	–	-0.29 %/K	-0.29 %/K
Max. power temp. coeff. (α_P)	–	-0.38 %/K	-0.38 %/K
NOCT	–	45°C	45°C

Assume that the PV modules to be used in Mwase have electrical characteristics provided in the last column of Table 12.9. The average ambient daytime temperature in January is 25°C. With this information the temperature de-rating is calculated as described in Sect. 7.10 and is found to be 9.5%. The required rating of the PV array is

$$P''_{\mathrm{PV,rated}} = 100 \times \frac{2.98}{100 - 9.5} = 3.29 \text{ kW}.$$

12.5.7.5 Design Margin

The reliability of the mini-grid can be improved by sizing the PV array such that its energy production capability somewhat exceeds the energy supplied by the battery bank to the load each day. The PV array will be able to supply additional energy to the battery bank in case it is deeply discharged or if the insolation is below average for several consecutive days.

The PV array design margin, K_{PV}, generally ranges from 0.1 to 0.2 (10 to 20%) for systems with non-critical loads or with consistent average daily load and consistent insolation. Systems with higher reliability requirements or with inconsistent load or insolation should use higher values, perhaps up to 0.4.

The PV array requirement after accounting for the design margin is

$$P'''_{\mathrm{PV,rated}} = \frac{P''_{\mathrm{PV,rated}}}{1 - K_{\mathrm{PV}}}. \tag{12.16}$$

January is in the middle of Mwase's rainy season. It is commonly overcast for several days in a row. Therefore we use a higher design margin of 0.3, so that

$$P'''_{\mathrm{PV,rated}} = \frac{3.29}{1 - 0.3} = 4.71 \text{ kW}.$$

Table 12.10 PV array capacity design summary

Quantity	Value	Computed from	Equation
$P_{\mathrm{PV,rated}}$	2.33 kW	Avg. daily load, capacity factor, and inverter efficiency	(12.13)
$P'_{\mathrm{PV,rated}}$	2.98 kW	$P_{\mathrm{PV,rated}}$, generation and storage losses	(12.14)
$P''_{\mathrm{PV,rated}}$	3.29 kW	$P'_{\mathrm{PV,rated}}$, temperature and temperature coefficient	(12.15)
$P'''_{\mathrm{PV,rated}}$	4.71 kW	$P''_{\mathrm{PV,rated}}$, design margin	(12.16)

Table 12.11 Charge controller parameters

Parameter	Required	Actual
Nominal battery voltage	48 V	4 8V
Power	5250 W	3500 W
Max. short-circuit current	>59.31 A	60 A
Max. input open-circuit voltage	>148.48 V	150 V
Max. charge current	–	60 A
MPPT	Yes	Yes
3-stage algorithm	Yes	Yes

This is the final required capacity of the PV array. A summary of the PV array capacity calculations is provided in Table 12.10. We can produce a preliminary design of the PV array, but before it is finalized, it must be checked for compatibility with the charge controller. Assume the charge controller being considered has parameters in the last column of Table 12.11.

The number of PV modules needed is found from

$$\textit{Number of Array Strings} = \frac{P'''_{\mathrm{PV,rated}}}{\textit{Module Rating}} \tag{12.17}$$

and then rounding up. For the Mwase system

$$\textit{Number of Array Strings} = \frac{4.71}{0.35} = 13.46$$

meaning that at least 14 PV modules are needed. Now we have to determine how they are arranged. We generally try to minimize the number of strings required so that the string voltage is increased. This reduces losses and wiring complexity. From the last column in Table 12.9, the open-circuit voltage per module is 47.43 V. The maximum number that we can place in series is limited by the charge controller. From Table 12.11, the charge controller is rated at 150 V. This means that the input voltage from the PV array cannot exceed 150 V. Therefore at most three modules ($150/47.43 = 3.16$) are placed in series. When three are placed in series, the open-circuit voltage under Standard Test Conditions is $3 \times 47.43 = 142.29$ V. While this is below the maximum voltage allowed for the charge controller, it is close enough that we should consider the effects of temperature.

Recall that the open-circuit voltage of a PV array increases when the temperature is low. The module's open-circuit voltage temperature coefficient α_{V} is used to determine the open-circuit voltage at the minimum operating temperature. This likely occurs early in the morning. We will assume this to be 10°C in Mwase. From (7.20) in Sect. 7.8, the open-circuit voltage is

$$\begin{aligned} V_{OC}(T_C) &= V_{OC}(25^\circ\text{ C})\left(1 + \frac{\alpha_V}{100} \times (T_C - 25)\right) \\ &= 142.29((1 - 0.0029 \times (10 - 25)) \\ &= 148.48\text{ V}. \end{aligned}$$

This is below the charge controller's maximum voltage of 150 V. If it were found to be above 150 V, then either the number of modules of per string would be limited to two (but the number of strings increased) or different modules (or charge controller) would be necessary.

Each string must have the same number of modules connected in series. Therefore, we can use 15 modules arranged in 5 strings, yielding a rated power of $15 \times 0.35 = 5.25$ kW. Note that if four strings are used, the capacity of the array is 4.20 kW, which is somewhat less than the required 4.71 kW. Using four strings instead of five would lower the cost of the system but would also decrease the reliability.

We must also check that the short-circuit current of the module does not exceed the current rating of the charge controller. Based on the modules' electrical characteristics in Table 12.9, the short-circuit current of the array is $9.49 \times 5 = 47.45$ A. However, remember that the short-circuit current is proportional to the irradiance. In especially sunny areas, the irradiance can exceed the Standard Test Condition value of 1000 W/m^2. To account for this, the short-circuit current is theoretically increased by 25% so that it is 59.31 A. The short-circuit current rating of the charge controller is 60 A. This requirement is nearly at the limit, but it assumes extreme conditions.

12.5.8 Charge Controller Selection

The last major system component to be specified is the charge controller. The major parameters that must be specified are in Table 12.11. The parameters of the selected charge controller are in the last column. The charger satisfies the voltage and current constraints, but not the power constraint. We can either select a larger charge controller or use two in parallel. We will consider two in parallel. One controller will have three strings and the other two. The PV array and charge controllers in this configuration are shown in Fig. 12.6. Note that this also reduces the maximum short-circuit current that each charge controller could be exposed to.

We next check that the current supplied by the charge controller does not exceed the maximum current recommended by the battery's manufacturer. Per the battery specifications, the maximum charging current is 20% of the C_{20} rating, which equals 44 A. The battery bank has five strings, and so the maximum battery bank charging current is $44 \times 5 = 220$ A. The maximum charging current per charge controller

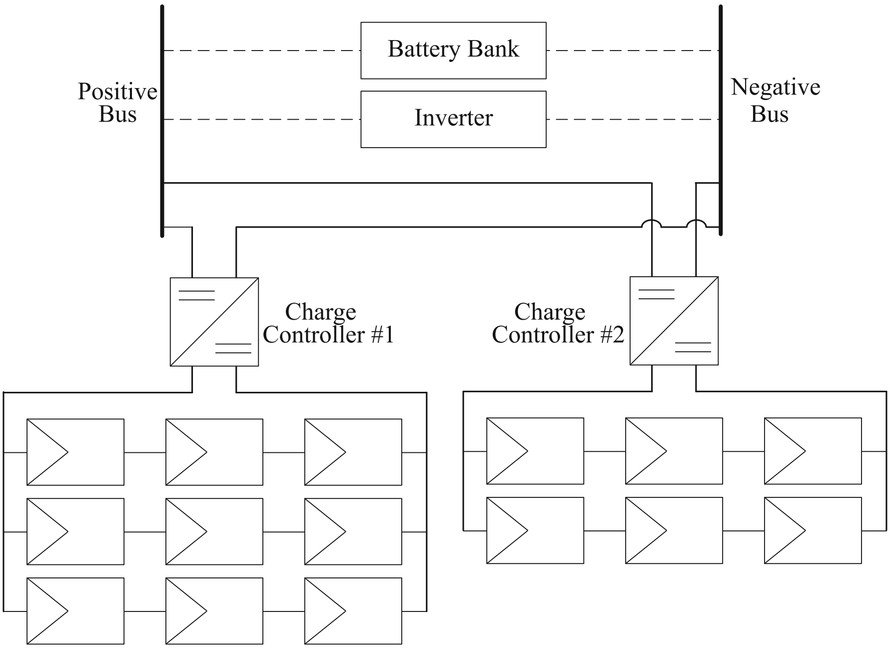

Fig. 12.6 PV array and charge controller configuration for Mwase

is 60 A (120 A total), and so we are not concerned with exceeding the battery bank charging current limit.

There are few other parameters that should be specified. Due to the size of the PV array, the additional cost of using a charge controller with MPPT functionality is justified. To prolong the lifespan of the battery bank, we should select a charge controller that uses a three-stage charging algorithm. The charge controller's absorption and float voltage set-points are set according to the battery manufacturer's specifications.

This completes one iteration of an intuitive design process. This design serves as a starting point for economic and other analyses. Based on the results of these analyses, new designs will be produced using different inputs—for example, serving additional or fewer users—or changing assumptions and specifications such as the Days of Autonomy.

12.5.9 Cost Estimate

We will briefly consider the implementation cost of the proposed design. The material costs will vary widely from one country to the next and from one vendor to the next. Table 12.12 gives an indication of costs that might be considered typical

Table 12.12 Component cost

Item	Each (US$)	No.	Total (US$)
PV module (350 W)	580	15	8700
Battery (220Ah)	204	40	8160
Inverter (2.4kW)	1275	1	1275
Charge controller (150V/60A)	600	2	1200
		Total	US$19,335

Table 12.13 Other costs for Mwase

Item	Each (US$)	No.	Total (US$)
PV mounting rack	1200	1	1200
Battery monitor	290	1	290
Other BoS components	2000	1	2000
Installation (labor and travel)	1800	1	1800
Power house construction	2000	1	2000
		Total	US$7290

in Zambia in 2016, inclusive of the value-added tax. Additional costs are shown Table 12.13. Balance of system (BoS) components typically include power house wiring, outlets, switches, circuit breakers, grounding rods, and surge arrestors. The total estimated cost is US$19, 335 + US$7290 = US$26,625. This excludes the cost of the distribution system and any costs associated with the site assessment and engineering of the system. If this cost is too high, then alterations to the design can be made. For example, the number of battery bank or PV module strings can be reduced. If the cost remains too high, then the system can be designed to serve fewer users or to supply electricity at a lower access tier.

12.6 Numerical Approach

An alternative to an intuitive approach is a numerical approach. Numerical approaches can be applied to simple systems, but they are particularly useful in designing hybrid systems with complex control.

The numerical design approach relies on a computer program to guide the design of the mini-grid. Most are simulation-based. That is, they simulate the operation of a mini-grid over a period of time and provide the user with a summary of the results. The programs do not design the mini-grid. They are better thought of as aides or tools assisting the designer. The programs require engineering judgment at both ends of the process—defining the technical and economic environment in which the mini-grid will operate and interpreting the results provided by the program.

Numerical approaches allow the designer to make better-informed decisions than intuitive approaches. The programs can provide the designer with information regarding the reliability and cost and other technical and economic information. However, the programs have heavier input data requirements than intuitive approaches. For example, a simulation might require the hourly or daily variability of the load to be specified. If the input data provided by the user has a wide range of uncertainty, as it often does, then so does the output of the simulation. There is no guarantee that the actual mini-grid will perform as simulated, especially if the load or resource is substantially higher or lower than input into the program. The designer should always keep this mind. Despite this caveat, computer-aided simulation can be very beneficial when the user understands the limitations and capabilities of the program. Uncertainty in input data can be guarded against by simulating many load and resource scenarios, for example, high, medium, and low projections. The design that best balances cost and risk is selected. Computer-aided design programs are continually improving and will likely play an increasing role in mini-grid design in the future.

There are a few commercial-grade computer programs that can assist in mini-grid design [15]. Among the most popular are HOMER (see Figs. 12.7 and 12.8) and RetScreen [4, 12]. There are at least a dozen other programs developed by universities, but these tend not to be well-supported.

Most computer-aided tools use a time-based simulation of the mini-grid. This means that the program simulates the operation of the mini-grid at discrete time steps over a period of time. The simulation period is usually 1 year but can be longer or shorter. Most programs use a time step of 1 h. A power flow model, like that developed in the previous chapter, is used to simulate the operation and control of the mini-grid at each time step. The different programs might use slightly different models, but the general approach is similar.

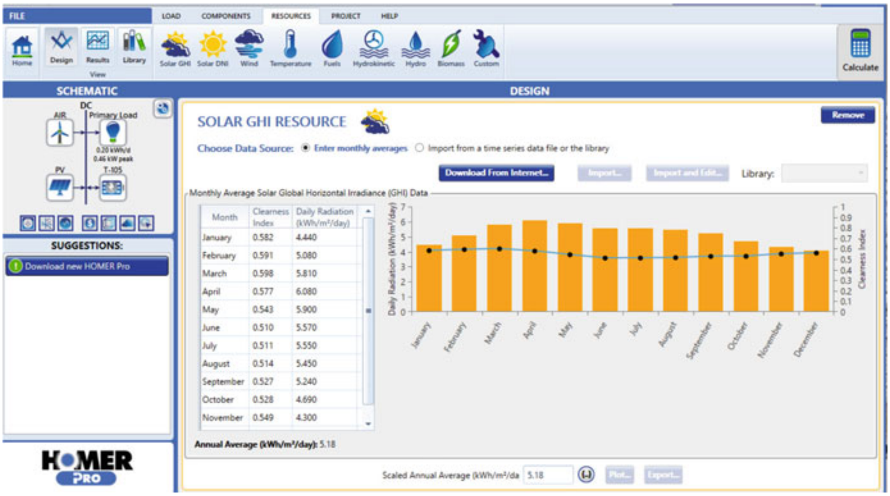

Fig. 12.7 The solar resource input screen from HOMER (courtesy of HOMER Energy)

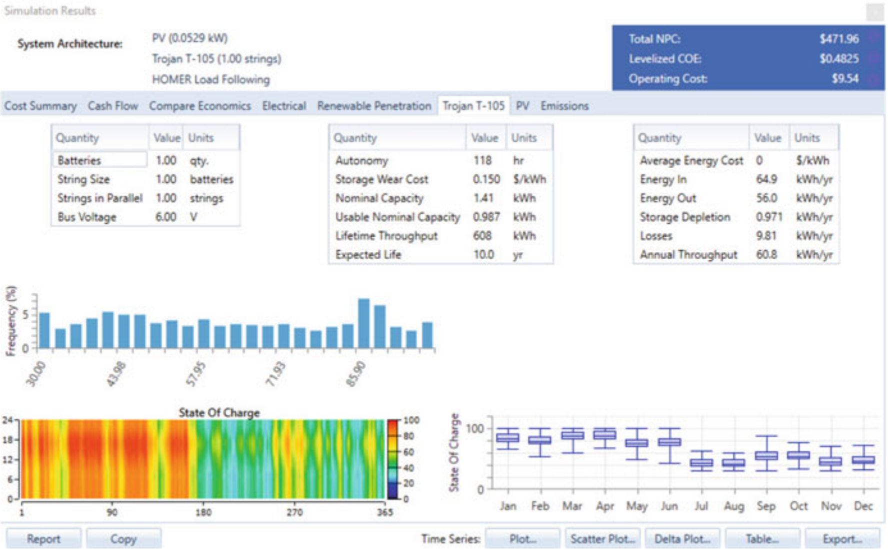

Fig. 12.8 The simulation result screen from HOMER (courtesy of HOMER Energy)

12.7 Distribution System Design

We next consider the distribution system of a mini-grid. The distribution system encompasses the wires, transformers, switches, protection equipment, poles, civil structures, and other components between the AC or DC bus and the users' meter or distribution panel. We will focus on the electrical design of distribution. The reader should consult references such as [16] for information related to other aspects of distribution systems.

The basic purpose of a distribution system is to facilitate the transfer of power from the mini-grid's generators to the user. Its design should be consistent with the targeted electricity access tier (see Sect. 2.7) of the mini-grid as a whole. Especially relevant are the capacity, reliability, safety, and quality (voltage drop) attributes. The distribution system can cost as much or more than the combined cost of the mini-grid's energy conversion, storage, and control components. The distribution system is also known as the reticulation system.

The principles governing the sizing of the conductors, namely, the voltage drop and thermal limits, and the effect of the nominal voltage discussed in Chap. 3 are also relevant to mini-grid distribution design. They are not repeated in this chapter. The economic calculations are also equally applicable, although many mini-grids are not large enough to warrant substations or medium-voltage lines. The reader may wish to review Chap. 3 before continuing. The distribution lines are usually at the same voltage as provided to the user and generally do not exceed 415 V.

A distribution system is characterized by its:

- Voltage type: AC or DC
- Method: overhead or underground
- Topology: hub-and-spoke or trunk-and-branch
- Type: single-phase, split-phase, or three-phase

The following sections discuss these characteristics.

12.7.1 Distribution Voltage Type

A distribution system can be designed to operate with AC or DC voltage. Presently, AC distribution is the de facto approach for larger mini-grid systems, particularly those above 1 kilowatt in capacity. At lower capacities some systems will use AC distribution, and others will use DC distribution.

The advantages of using AC distribution are:

- maturity: large-scale AC systems have been in widespread use for over a century, and engineers, electricians, and inspectors are familiar with their design and use;
- availability of components: AC appliances, generators, protection equipment, meters, and other components are widely available, mass-produced, and inexpensive;
- voltage transformation: voltage levels can be increased for distribution using inexpensive transformers, reducing losses; however, the limited geographic scope of most mini-grids can make this relatively unimportant;
- compatibility with rotating machines: most large motors require three-phase AC supply;
- standards and codes: there are established international quality standards[1] and local codes for the design, installation, and maintenance of AC systems.

The advantages of using DC distribution are:

- compatibility with solar power and batteries: PV modules and batteries are inherently DC;
- compatibility with electronic devices: devices such as mobile phones, laptops, televisions, and LED lights use DC internally; direct supply of DC can eliminate or simplify their power supplies;
- reduced distribution line impedance: the reactive component of a distribution line's series impedance can be ignored, reducing the voltage drop and power loss along the line;

[1] At the time of writing, both the IEEE and IEC are working on standards for low-voltage DC mini-grids.

- measurement and metering: measuring the power flow and energy consumption of DC systems is easier than in AC systems because there is no phase angle between the voltage and current.

To improve efficiency, a rule of thumb is to minimize the number of conversions (AC/DC, DC/AC, AC/AC, and DC/DC) between the generation and load. AC loads should be supplied by AC generation using an AC distribution system and vice versa for DC loads. However, it is not difficult to imagine scenarios where this is not possible. When the choice of AC or DC distribution is not obvious, it is reasonable to default to using AC. However, DC should be considered if any of the following conditions are true: the majority of the energy produced is from a DC source (PV module or DC generator); the geographic reach of the distribution system is limited, perhaps no more than 1 kilometer from the point of generation; the load is primarily or entirely LED lighting which can be more efficaciously powered by DC.

12.7.2 Distribution Method

AC or DC distribution lines can be strung overhead or buried underground. Local codes might dictate which method is required, but in many cases it is left to the designer. Burying distribution lines involves digging trenches along the distribution path and then burying the cables, as seen in Fig. 12.9. Overhead lines require installing poles and stringing cables between them. Overhead lines seem to be more common, primarily due to economic reasons.

12.7.2.1 Underground Lines

The advantages of underground lines include:

- protection from sun exposure, rain, vandalism, and aboveground animals;
- discouragement of theft and tampering as it is more difficult to access the lines; however, tampering and theft is less noticeable;
- preservation of community aesthetics;
- elimination of the need for poles, which reduces material, design, and maintenance costs.

The disadvantages include:

- locating faults and troubleshooting the system are more challenging as visual inspection is impossible;
- accessing the cables to connect new users is more difficult;
- the conductors must be protected against burrowing animals, insects, and moisture by using conduit or specialized insulation that prevents moisture intrusion and is resistant to corrosion and fungi;
- burying cables is not practical in areas with rocky terrain.

Fig. 12.9 Trenches being dug for underground distribution (courtesy of PowerGen)

The cables must be buried deep enough to avoid being exposed or disturbed by erosion, people, animals, and vehicles. A minimum of 0.5 m is often recommended. Burying cables underneath earthen roads should be avoided. If this cannot be avoided, then the cables should be buried at a sufficient depth to avoid damage should the road be re-graded. Buried distribution lines cannot be easily moved or re-routed, so the distribution paths must be carefully planned and sized based on anticipated future load growth.

12.7.2.2 Overhead Lines

Overhead lines are strung from pole tops, as seen in Figs. 12.10 and 12.11. The poles add material cost and require some labor, in particular if vegetation needs to be cleared or pruned. The poles must be of sufficient height to discourage tampering and to avoid accidental contact with people or vehicles. This is especially important when the cables span a road. Sometimes the cables can be strung from existing trees, but this requires diligent maintenance and inspection.

The conductors might or might not be insulated. Uninsulated conductors require additional safety precautions to protect against accidental contact. If insulated conductors are used, they must be capable of safe and reliable operation in the exposed outdoor environment. It is important that the insulation is resistant to ultraviolet rays.

Fig. 12.10 An overhead low-voltage distribution line being installed (courtesy of PowerGen)

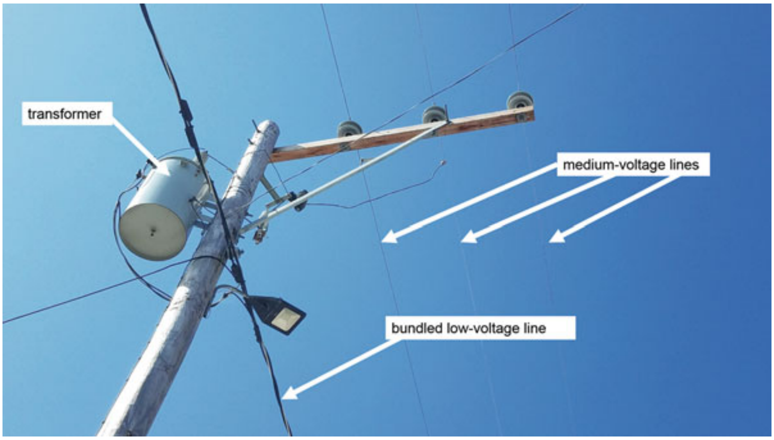

Fig. 12.11 The medium-voltage (22.8 kV) overhead lines in this mini-grid are uninsulated. The low-voltage, split-phase wires from the transformer are bundled and insulated (courtesy of Sigora Haiti)

The added weight of the insulation means that the poles must be placed closer together. Some developers have found success using aerial bundled conductor (ABC) cable. In ABC cable, each phase is separately insulated and bundled around a usually bare neutral conductor. Although the ABC cable itself is more expensive and heavier than uninsulated alternatives, it tends to be safer and easier to install, and it makes electricity theft more difficult.

12.7.3 Distribution Topology

The distribution topology is concerned with the physical routing of the distribution lines. Figure 12.12 shows the two types of distribution topology in use in mini-grids:

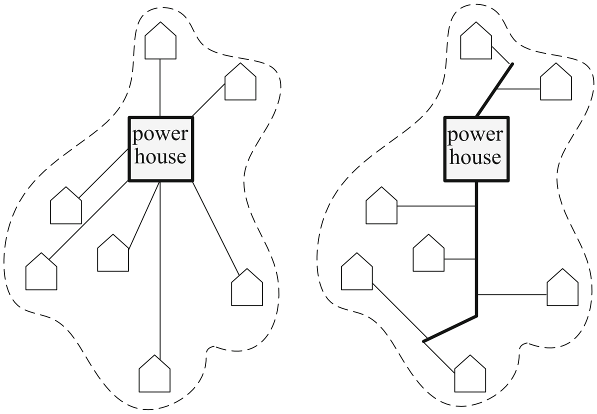

Fig. 12.12 Example distribution system layout of the same users with a hub-and-spoke (left) and a trunk-and-branch (right) topologies

hub-and-spoke and trunk-and-branch (also known as a "radial" topology). In each there is a single path from the power house to the user. This is different than in some grid-connected systems which use "meshed" topologies.

In a hub-and-spoke topology, individual lines are run to each customer. In a trunk-and-branch topology, high ampacity trunk lines are tapped by smaller "branch" lines serving an individual or small group of users. The trunk-and-branch topology tends to be less expensive, especially if the users are located far from the power house along the same direction. In the hub-and-spoke topology, each user has a dedicated line. This can prove to be less expensive if the users are close to and surrounding the power house. The hub-and-spoke approach is less complicated to design. Further, the meters can be centrally and securely located in the power house, rather than in the users' premises. This can reduce meter tampering. It might also encourage users to watch for illegal connections on their lines, knowing that they will be billed for any stolen electricity.

12.7.4 AC Distribution Configuration

There are four basic AC distribution line configurations, as shown in Fig. 12.13. Deciding which configuration to use depends on the user requirements as well as economic considerations. Large industrial, agricultural, or commercial users might require three-phase service to operate motors, pumps, and other equipment. These users must be supplied with either a three-phase delta or wye connection. Most users, particularly households, only require single-phase service. A three-phase distribution configuration can still be used to supply these users, as shown in Fig. 12.13. When split-phase systems are used, they are usually in countries where the nominal voltage is 120 V.

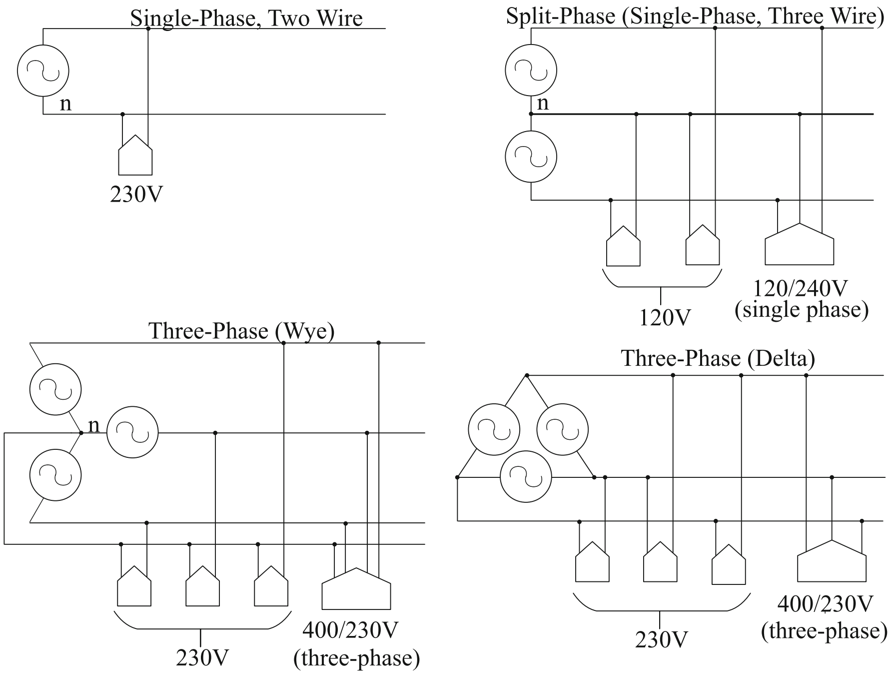

Fig. 12.13 Distribution system types

The generator and inverter might limit the configuration that can be used. For example, single-phase generators and inverters cannot distribute three-phase electricity (but in some cases three single-phase inverters can be arranged to supply three-phase power). Regardless of what configuration is used, at a minimum, each user should have access to the nominal voltage used in that country's national grid, typically 230 V or 120 V.

12.7.4.1 Single-Phase, Two-Wire

This configuration supplies each user with two wires: one phase wire and one neutral wire. This configuration requires the least design work and is conceptually simple, but it is more expensive and results in greater losses when compared to other configurations. It is especially suitable for a hub-and-spoke topology.

A simple circuit model of a single-phase, two-wire configuration is shown in Fig. 12.14. In this model, the users are located at the end of the line. Each wire is modeled as an impedance $Z_\mathrm{w} = R_\mathrm{w} + \mathrm{j}X_\mathrm{w}$. The wires are identical in length, material, and cross-sectional area. Therefore, the phase and neutral wires have the same impedance. We will assume that there are H households with identical loads whose impedance is Z_L. The loads are connected in parallel across the phase and

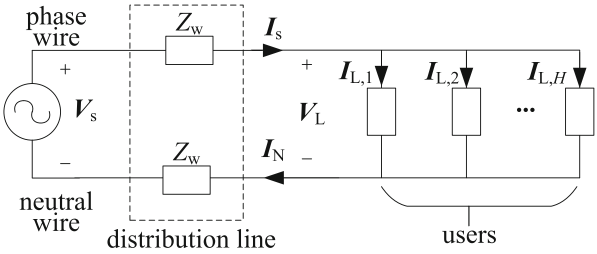

Fig. 12.14 Equivalent circuit of a single-phase, two-wire distribution system

neutral wires. They each therefore are supplied the same voltage $\boldsymbol{V}_{\mathrm{L}}$. With the voltage and load of each household the same, the current must also be the same

$$\boldsymbol{I}_{\mathrm{L},1} = \boldsymbol{I}_{\mathrm{L},2} = \cdots = \boldsymbol{I}_{\mathrm{L},H} = \boldsymbol{I}_{\mathrm{L}} \tag{12.18}$$

where $\boldsymbol{I}_{\mathrm{L}}$ is the current to each household.

At the sending end of the line, the wires are connected to either the AC bus, a single-phase distribution transformer or the line and neutral of three-phase wye distribution line. Whatever the configuration, we designate the voltage at the sending-end $\boldsymbol{V}_{\mathrm{s}}$. Let the current in the phase wire be $\boldsymbol{I}_{\mathrm{s}}$ and the neutral wire be $\boldsymbol{I}_{\mathrm{N}}$. Applying Kirchhoff's Current Law to the top and bottom nodes at the end of the line in Fig. 12.14

$$\boldsymbol{I}_{\mathrm{s}} = \sum_{h=1}^{H} \boldsymbol{I}_{\mathrm{L},h} = \boldsymbol{I}_{\mathrm{L}} H = \boldsymbol{I}_{\mathrm{N}}. \tag{12.19}$$

The current through the phase wire is equal to the sum of the currents to each household. This current returns to the source on the neutral wire. Applying Kirchhoff's Voltage Law to this circuit shows

$$\boldsymbol{V}_{\mathrm{s}} = \boldsymbol{I}_{\mathrm{s}} Z_{\mathrm{w}} + \boldsymbol{V}_{\mathrm{L}} + \boldsymbol{I}_{\mathrm{N}} Z_{\mathrm{w}} = 2\boldsymbol{I}_{\mathrm{s}} Z_{\mathrm{w}} + \boldsymbol{V}_{\mathrm{L}}. \tag{12.20}$$

Recall from Chap. 3 that the voltage drop along a line is the magnitude of the difference between sending-end and receiving-end voltage. In this circuit, the receiving-end voltage is at the end of the line ($\boldsymbol{V}_{\mathrm{L}}$) where the households are located. To ensure that the houses will receive suitable voltage, the drop should be no more than 5 to 10% of the sending-end voltage. For a single-phase, two-wire configuration, the voltage drop is therefore

$$V_{\mathrm{drop}} = |\boldsymbol{V}_{\mathrm{s}} - \boldsymbol{V}_{\mathrm{L}}| = 2|\boldsymbol{I}_{\mathrm{s}} Z_{\mathrm{w}}| = 2|\boldsymbol{I}_{\mathrm{L}}|H|Z_{\mathrm{w}}|. \tag{12.21}$$

We see that the voltage drop increases in proportion to number of households served as well the current supplied to each household. Half of the voltage drop is caused by the phase wire and half by the neutral wire. Equivalently, the total voltage drop is twice of that along the phase or neutral wire. There is also power loss along each wire. The total power loss is

$$P_{\mathrm{Loss}} = |\boldsymbol{I}_{\mathrm{s}}|^2 R_{\mathrm{w}} + |\boldsymbol{I}_{\mathrm{N}}|^2 R_{\mathrm{w}} = 2|\boldsymbol{I}_{\mathrm{s}}|^2 R_{\mathrm{w}} = 2|\boldsymbol{I}_{\mathrm{L}}|^2 H^2 R_{\mathrm{w}} \tag{12.22}$$

showing that the losses increase with the square of the number of households and current supplied to each household.

12.7.4.2 Split-Phase

Split-phase is also known as "single-phase, three-wire." It is more efficient and has a lower-voltage drop and losses than the single-phase configuration. The simplified circuit model of the split-phase circuit serving H households is shown in Fig. 12.15. There are two phase wires and one neutral. Each wire has the same impedance. The circuit is supplied by two voltage sources with equal magnitude but are out of phase by 180° so that

$$\boldsymbol{V}_{\mathrm{s,even}} = -\boldsymbol{V}_{\mathrm{s,odd}}. \tag{12.23}$$

Some gen sets are internally wired for split-phase distribution. Split-phase inverters are also commercially available, but they most often are rated at 120 V line-to-neutral (240 line-to-line). Single-phase generators and inverters can supply a split-phase distribution system by using a "center-tapped" transformer.

We will assume that there are an even number of households H, each with identical power consumption. Although users can be connected between both phase wires, we omit these connections for clarity. It does not change the general

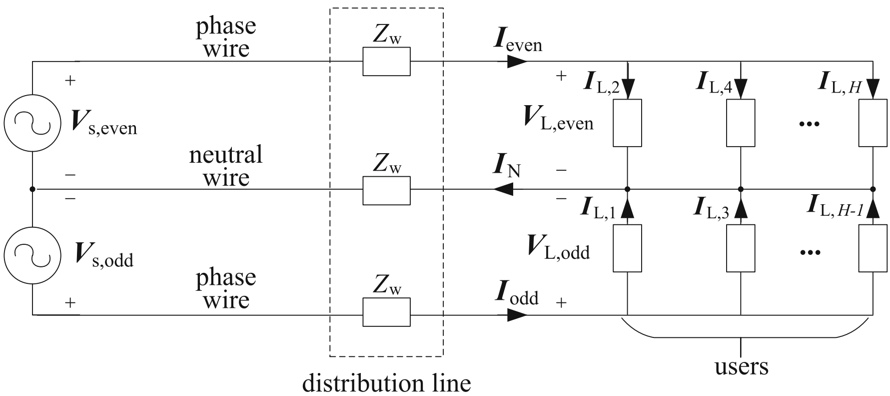

Fig. 12.15 Equivalent circuit of a split-phase (single-phase three-wire) distribution system

results. These connections supply twice the phase-to-neutral voltage and are used in countries where the line-to-neutral voltage is 120 V. They provide access to 240 V supply which is used in high-power appliances.

The households with even indices are connected in parallel and so have the same voltage and current; similarly, the households with odd indices are in parallel and have the same voltage and current.

Let the current to and the voltage at even-indexed households be $\boldsymbol{I}_{\mathrm{L,even}}$ and $\boldsymbol{V}_{\mathrm{L,even}}$, and $\boldsymbol{I}_{\mathrm{L,odd}}$ and $\boldsymbol{V}_{\mathrm{L,odd}}$ for odd-indexed households. The current through each phase wire is the sum of the current to the households it serves

$$\boldsymbol{I}_{\mathrm{even}} = \sum_{h:\mathrm{even}} \boldsymbol{I}_{\mathrm{L},h} = \frac{H}{2}\boldsymbol{I}_{\mathrm{L,even}} \tag{12.24}$$

$$\boldsymbol{I}_{\mathrm{odd}} = \sum_{h:\mathrm{odd}} \boldsymbol{I}_{\mathrm{L},h} = \frac{H}{2}\boldsymbol{I}_{\mathrm{L,odd}}. \tag{12.25}$$

By Kirchhoff's Current Law, the neutral current is the sum of the current to the even- and the odd-indexed households:

$$\boldsymbol{I}_{\mathrm{N}} = \boldsymbol{I}_{\mathrm{even}} + \boldsymbol{I}_{\mathrm{odd}}. \tag{12.26}$$

Importantly, this shows us that the neutral current is the sum of the phase wire currents.

Applying Kirchhoff's Voltage Law to this circuit shows

$$\boldsymbol{V}_{\mathrm{s,even}} = \boldsymbol{I}_{\mathrm{even}} Z_{\mathrm{w}} + \boldsymbol{V}_{\mathrm{L,even}} + \boldsymbol{I}_{\mathrm{N}} Z_{\mathrm{w}} \tag{12.27}$$

$$\boldsymbol{V}_{\mathrm{s,odd}} = \boldsymbol{I}_{\mathrm{odd}} Z_{\mathrm{w}} + \boldsymbol{V}_{\mathrm{L,odd}} + \boldsymbol{I}_{\mathrm{N}} Z_{\mathrm{w}}. \tag{12.28}$$

Adding (12.28) and (12.27) yields

$$\boldsymbol{V}_{\mathrm{s,even}} + \boldsymbol{V}_{\mathrm{s,odd}} = \left(\boldsymbol{I}_{\mathrm{even}} + \boldsymbol{I}_{\mathrm{odd}}\right) Z_{\mathrm{w}} + \boldsymbol{V}_{\mathrm{L,even}} + \boldsymbol{V}_{\mathrm{L,odd}} + 2\boldsymbol{I}_{\mathrm{N}} Z_{\mathrm{w}}. \tag{12.29}$$

Substituting (12.23) and (12.26) into (12.29) yields

$$0 = 3\boldsymbol{I}_{\mathrm{N}} Z_{\mathrm{w}} + \boldsymbol{V}_{\mathrm{L,even}} + \boldsymbol{V}_{\mathrm{L,odd}}. \tag{12.30}$$

We can express the voltage at the households as

$$\boldsymbol{V}_{\mathrm{L,even}} = \boldsymbol{I}_{\mathrm{even}} Z_{\mathrm{eq,even}} \tag{12.31}$$

$$\boldsymbol{V}_{\mathrm{L,odd}} = \boldsymbol{I}_{\mathrm{odd}} Z_{\mathrm{eq,odd}} \tag{12.32}$$

where $Z_{\mathrm{eq,even}}$ and $Z_{\mathrm{eq,odd}}$ are the equivalent impedances of the even- and odd-indexed households. These impedances are equal because each house consumes the same power, are supplied with current of the same magnitude, and there are an equal number of even- and odd-indexed houses.

Substituting (12.31) and (12.32) into (12.30) yields

$$0 = 3\boldsymbol{I}_{\mathrm{N}} Z_{\mathrm{w}} + \boldsymbol{I}_{\mathrm{even}} Z_{\mathrm{eq,even}} + \boldsymbol{I}_{\mathrm{odd}} Z_{\mathrm{eq,odd}} \tag{12.33}$$

$$0 = 3\boldsymbol{I}_{\mathrm{N}} Z_{\mathrm{w}} + 2\boldsymbol{I}_{\mathrm{N}} Z_{\mathrm{eq,even}} \tag{12.34}$$

$$0 = \boldsymbol{I}_{\mathrm{N}} \left(3Z_{\mathrm{w}} + 2Z_{\mathrm{eq,even}}\right) \tag{12.35}$$

which is only practically possible if $\boldsymbol{I}_{\mathrm{N}} = 0$. In other words, when the loads are balanced in a split-phase system, the current in the neutral wire is zero. From (12.26), the current through each phase is equal in magnitude but opposite in phase:

$$\boldsymbol{I}_{\mathrm{odd}} = -\boldsymbol{I}_{\mathrm{even}}. \tag{12.36}$$

We generically express the magnitude of the current and voltage to each household as $|\boldsymbol{I}_{\mathrm{L}}|$ and $|\boldsymbol{V}_{\mathrm{L}}|$.

The voltage drop along the line for the odd-indexed households is

$$V_{\mathrm{drop}} = |\boldsymbol{V}_{\mathrm{s,odd}} - \boldsymbol{V}_{\mathrm{L,odd}}| \tag{12.37}$$

Using (12.28) and (12.25)

$$V_{\mathrm{drop}} = |\left(\boldsymbol{I}_{\mathrm{odd}} Z_{\mathrm{w}} + \boldsymbol{V}_{\mathrm{L,odd}} + \boldsymbol{I}_{\mathrm{N}} Z_{\mathrm{w}}\right) - \boldsymbol{V}_{\mathrm{L,odd}}| \tag{12.38}$$

$$= |\boldsymbol{I}_{\mathrm{odd}} Z_{\mathrm{w}} + \boldsymbol{I}_{\mathrm{N}} Z_{\mathrm{w}}| \tag{12.39}$$

$$= |\boldsymbol{I}_{\mathrm{odd}} Z_{\mathrm{w}}| = \frac{H}{2} |\boldsymbol{I}_{\mathrm{L}}||Z_{\mathrm{w}}|. \tag{12.40}$$

This assumes that the system is balanced so that $\boldsymbol{I}_{\mathrm{N}} = 0$ A as shown previously.

It can be shown that the voltage drop for the even-indexed households is same. The total power loss is calculated considering only the phase wires since the neutral current is zero:

$$P_{\mathrm{loss}} = |\boldsymbol{I}_{\mathrm{s,odd}}|^2 R_{\mathrm{w}} + |\boldsymbol{I}_{\mathrm{s,even}}|^2 R_{\mathrm{w}} = 2\left(\frac{H}{2}|I_{\mathrm{L}}|\right)^2 R_{\mathrm{w}}. \tag{12.41}$$

Comparing (12.21) and (12.22) with (12.40) and (12.41), we see the advantage of using split-phase: the voltage drop and power losses are one-fourth that of a single-phase configuration. This is caused by each phase wire carrying half the current of the phase wire in the single-phase configuration, and, because there is no neutral current, there is no voltage drop or power loss associated with the neutral wire.

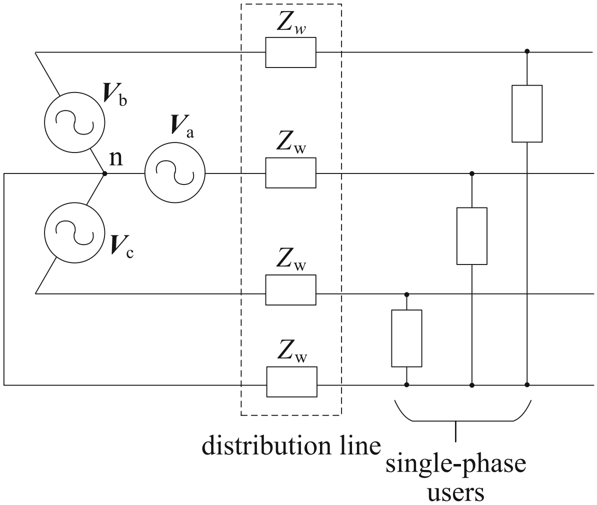

Fig. 12.16 Three-phase wye-connected system

12.7.4.3 Three-Phase Configuration

Higher-capacity systems generally use three-phase distribution. There are two common ways that a three-phase distribution system can be configured: as a wye or delta. Three-phase systems are well covered in other texts [2, 3], and so we only present a short overview here.

Three-phase distribution requires three-phase generators or inverters. In a wye-connected system, a total of four wires are used: three-phase wires and a neutral wire. A circuit model for a three-phase, four-wire configuration is shown in Fig. 12.16. Users can be supplied three-phase or single-phase service. Single-phase users are connected between the phase and neutral wires as in a single-phase two-wire configuration. If the loads are balanced, then there is no neutral current. Center-tapped transformers can be used to supply some users with a split-phase service, if needed.

Delta-connected systems are also known as "three-wire" systems because they do not use a neutral conductor. A circuit model for the three-phase, three-wire configuration is show in Fig. 12.17. Single-phase users are connected phase-to-phase; three-phase users are connected to all three phases.

A wye configuration is the most efficient of the four distribution configurations. Less current is needed than in a delta connection to provide same power because the line–line voltage is $\sqrt{3}$ times greater. This reduces the voltage drop and losses along the conductors. Users should be connected to balance the load as nearly as possible on all phases. When this is not done, the voltage drops and power loss increases.

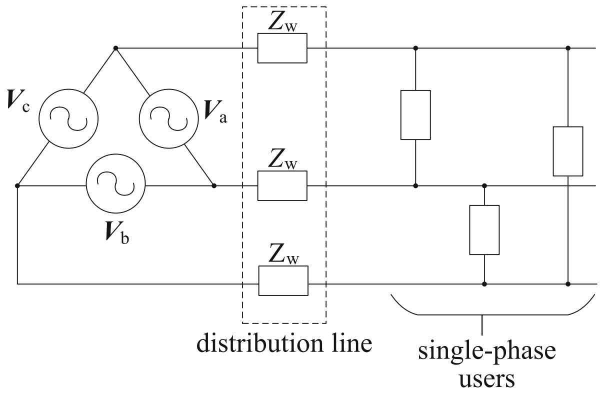

Fig. 12.17 Three-phase delta-connected system

Table 12.14 Distribution configuration summary

Configuration	Voltage drop	Power loss
Single-phase, two-wire	$2H\lvert\boldsymbol{I}_L\rvert\lvert Z_w\rvert$	$2\,(H\lvert\boldsymbol{I}_L\rvert)^2\,R_w$
Split-phase (single-phase, three-wire)	$\frac{1}{2}H\lvert\boldsymbol{I}_L\rvert\lvert Z_w\rvert$	$\frac{1}{2}\,(H\lvert\boldsymbol{I}_L\rvert)^2\,R_w$
Three-phase, wye (four-wire)	$\frac{1}{3}H\lvert\boldsymbol{I}_L\rvert\lvert Z_w\rvert$	$\frac{1}{3}\,(H\lvert\boldsymbol{I}_L\rvert)^2\,R_w$
Three-phase, delta (three-wire)	$H\lvert\boldsymbol{I}_L\rvert\lvert Z_w\rvert$	$(H\lvert\boldsymbol{I}_L\rvert)^2\,R_w$

12.7.4.4 Distribution Configuration Comparison

For a given conductor size and total user load, the voltage drop and power loss will be different depending on the distribution configuration used, as shown in Table 12.14. From this table we see that, for example, the power loss associated with a three-phase delta configuration is twice that of a split-phase configuration but half that of a single-phase configuration. The split-phase configuration has one-fourth the voltage drop and power loss of the single-phase configuration.

Interpreted in another way, the split-phase system can use conductors with four times the resistance and have the same voltage drop and power loss as a single-phase system. Since resistance is inversely proportional to cross-sectional area, the split-phase configuration can use conductors whose cross-sectional area is one-fourth that of the single-phase configuration. However, the split-phase configuration requires three conductors, not two. The total cross-sectional area relative to a single-phase configuration is $(0.25 \times 3)/2 = 0.375$. The material costs of the conductor should therefore be approximately 37.5% of the single-phase configuration. Table 12.15 shows the conductor area and cost for each configuration relative to the single-phase configuration. We see that the three-phase wye configuration requires the least total area of conductors—just 33% of the single-phase configuration.

Table 12.15 Distribution configuration conductor comparison summary

Configuration	No. of conductors	Area per conductor	Total area	Conductor cost relative to single-phase, two-wire
Single-phase, two-wire	2	1.0	2.0	1.0
Single-phase, three-wire (split-phase)	3	0.250	0.75	0.375
Three-phase, four-wire (wye)	4	0.167	0.667	0.333
Three-phase, three-wire (delta)	3	0.50	1.5	0.75

12.7.4.5 Imbalanced Load

The results in the last section are based on the assumption that each user consumes the exact same power. That is, the load is balanced. In practice this is almost never the case, especially in smaller-capacity mini-grids with a limited number of users. An imbalance erodes some of the benefits of split-phase and three-phase (delta and wye) configurations. When the load is imbalanced, the neutral current is no longer zero in the split-phase and three-phase wye configurations. There is now a voltage drop and power loss associated with the neutral current. The severity of the effect depends on the magnitude of the imbalance. The voltage drop and power loss for the unbalanced loads can be calculated through AC circuit analysis but can be tedious to do by hand. The voltage drop and power loss in split-phase and wye-connected configurations might increase by 50%, but this still is an improvement of a single-phase configuration. Delta-connected systems are less affected by imbalance.

12.7.4.6 Location of Load

The circuit models in Figs. 12.15–12.17 assumed the users were lumped at the end of the line. More than likely, the users are spread along the line. When this is the case, the voltage drop and power losses are reduced. This scenario is explored in the following example.

Example 12.1 Consider the split-phase circuit in Fig. 12.18 where $H = 40$. Twenty users are located at the midpoint of the line and 20 are at the end. The impedance of each wire is $Z_w = 0.14 + j0.01\ \Omega$. The sending-end line-neutral voltage is 120 V, and the magnitude of the current to each house is 3A. Compute the voltage drop for the users at the midpoint and end of the line and the total power loss.

(continued)

Solution Due to symmetry, we only need to consider the users connected to one of the phases. We will arbitrarily consider the odd-indexed customers. The current magnitude in the segment of the wire between the source and the midpoint is

$$|\boldsymbol{I}_{\text{odd}}| = |\boldsymbol{I}_{\text{L}}|\frac{H}{2} = 3\frac{40}{2} = 60 \text{ A}.$$

The impedance of this segment is half the total impedance of the phase wire. The voltage drop across the segment 1 is

$$V_{\text{drop,mid}} = V_{\text{drop},1} = |\boldsymbol{I}_{\text{odd}}|\frac{|Z_{\text{w}}|}{2} = 60\frac{0.14}{2} = 4.21 \text{ V}.$$

This corresponds to a 4.21/120 = 3.51% voltage drop. The associated power loss is the magnitude of the current squared multiplied by the resistance:

$$P_{\text{loss},1} = (|\boldsymbol{I}_{\text{odd}}|)^2 \frac{R_{\text{w}}}{2} = (60)^2 \frac{0.14}{2} = 252.0 \text{ W}.$$

Only half of the current continues to segment 2. The voltage drop is therefore

$$V_{\text{drop},2} = \frac{|\boldsymbol{I}_{\text{odd}}|}{2}\frac{|Z_{\text{w}}|}{2} = \left(\frac{60}{2}\right)\left(\frac{0.14}{2}\right) = 2.11 \text{ V}$$

The total voltage drop at the end of the line is

$$V_{\text{drop,end}} = V_{\text{drop},1} + V_{\text{drop},2} = 6.32 \text{ V}$$

which corresponds to a 6.32/120 = 5.26% voltage drop. The power loss of segment 2 is

$$P_{\text{loss},2} = \left(\frac{|I_{\text{odd}}|}{2}\right)^2 \frac{R_{\text{w}}}{2} = 30^2 \times \frac{0.14}{2} = 63 \text{ W}.$$

The total power loss, considering both the even and odd phase wires, is twice that of the one of the phases:

$$P_{\text{loss,total}} = 2 \times \left(P_{\text{loss},1} + V_{\text{loss},2}\right) = 630 \text{ W}.$$

We note that the voltage drop associated with the segment between the midpoint and end of the line is one-half of those associated with the first segment of the line, and the power loss is one-fourth.

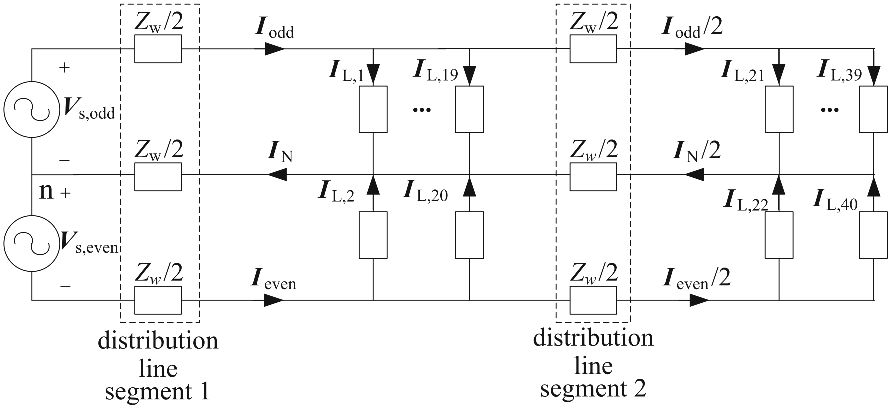

Fig. 12.18 A split-phase system with loads at the midpoint and the end of the line

In general, as the load is distributed across the line, the voltage drop at the end of the line and the total power loss decrease. It can be shown that if the load is uniformly spread along the line, then the voltage drop is one-half of the case when the loads are located at the end, and the power loss is reduced to one-third. It turns out that these reductions are independent of the configuration, as long as the loads are balanced. Keep in mind, it is always more advantageous to have the load closer to the power house than farther away.

12.7.5 Estimating Voltage Drop and Power Losses

We now return to Mwase and consider the design of the distribution system. Since the location of the users and the power house is known, the path for the distribution system can be determined. The users are all located on one side of the power house, and so a radial (trunk-and-branch) topology is selected. It is good practice for the path of the distribution line to be as short and as straight as possible. The lines will also be overhead in order to reduce costs. The planned distribution system for Mwase is shown in Fig. 12.19. The nodes correspond to certain landmarks in Mwase. The landmarks are used to measure the length of the different line segments. The segment lengths are given in the second column of Table 12.16.

As previously described, a single-phase distribution system will be used. The supply voltage is 230 V, and so we will consider a single-phase two-wire design. We must decide what size and type of wire to use. For mechanical reasons, we will use an uninsulated ASCR conductor with spacing of 0.30 m. We will consider two different sizes with characteristics shown in Table 12.17. We will start with the 13 mm^2 wire, the smaller of the two. Its ampacity is far above the peak current of the mini-grid, and so we continue in estimating the voltage drop and power loss.

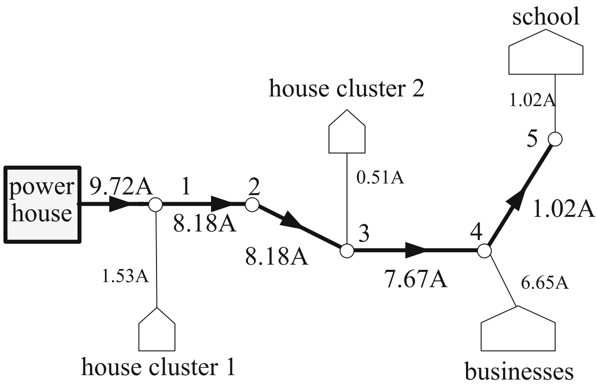

Fig. 12.19 Distribution line path and segment and node current for Mwase

Table 12.16 Distribution system calculation table

Node	Length (km)	Estimated coincident peak load (W)	Estimated load current $\lvert \boldsymbol{I}_{L,n} \rvert$ (A)	Segment $\lvert Z_{w,n} \rvert$ (Ω)	Segment $\lvert \boldsymbol{I}_s \rvert$ (A)	Segment voltage drop (V)	Segment power loss (W)
5	0.15	200	1.02	0.34	1.02	0.70	0.71
4	0.10	1300	6.65	0.23	7.67	3.49	26.49
3	0.08	100	0.51	0.18	8.18	2.97	24.11
2	0.05	0	0	0.11	8.18	1.86	15.07
1	0.05	300	1.53	0.11	9.72	2.21	21.25
					Totals	11.22	87.63

Table 12.17 Distribution wire characteristics

Cross-section (mm^2)	Resistance (Ohms/km)	Reactance (Ohms/km)	Ampacity (A)
13	2.25	0.31	105
21	1.40	0.31	140

A rough estimate of the voltage drop and losses can be made by assuming the entire load is located at the end of the distribution line and applying the equations in Table 12.14 for a single-phase, two-wire system. However, since we have rough plan of the distribution line, we will use a more accurate method.

We begin by grouping all users near each node together. The surveys are used to estimate each node's contribution to the aggregate peak load, which we have rounded to 1.9 kW. These values are shown in the third column of Table 12.16. We make the simplifying assumptions that the current supplied to the users at each node n can be approximated as

$$\lvert \boldsymbol{I}_{L,n} \rvert = \frac{P_{L,n}}{PF_{L,n} \times \lvert \boldsymbol{V}_s \rvert} \tag{12.42}$$

where $P_{\mathrm{L},n}$ is the real power associated with all users connected to the node n and $PF_{\mathrm{L},n}$ is the power factor of the users at node n. The PF is assumed to be 0.85 for all nodes. The node current computed from (12.42) is an approximation because the voltage at each node is not exactly $\boldsymbol{V}_{\mathrm{s}}$ due to the voltage drop. This approximation usually does not significantly alter the result. The calculated values are shown in fourth column of Table 12.16.

The magnitude of the impedance for each segment $|Z_{\mathrm{w},n}|$ is computed, taking into account each segment's length. The resulting values are shown in the fifth column of Table 12.16.

The current in each segment is calculated by applying Kirchhoff's Current Law at each node, starting with the node at the end of the line. For example, the current in the segment between node 4 and 5 must be equal to the load current of the school at node 5 (1.02 A). The current in the segment from node 3 to node 4 must be the sum of the current in the segment between node 4 and 5 and the current to businesses at node 4 (6.65 A), for a total of 1.02 + 6.65 = 7.67 A. The calculation proceeds in this manner until the total current that supplied the line (9.72 A) is determined.

Once again, starting at the node 5, the voltage drop and power loss are computed. The voltage drop and power loss equation is found from Table 12.14 for the distribution configuration considered. In this case, the equations for the single-phase configuration are used. The results are shown in the last two columns of Table 12.16. After this is done for all segments, the voltage drop and power losses are totaled. In this case, the percent voltage drop at the end of the line (node 5) is $11.22/230 = 0.0488$ or 4.88%. Note that if the approximation was made that the entire load was lumped at the end of the line, then the voltage drop would be 22.08 V (9.6%). The total power loss is 4.6% of the peak load, which is somewhat less than our initial estimate of 6.5% used in the design of the battery and PV array. This is close enough to not warrant revising the design. If the voltage drop or power loss are too large, then the process is repeated using the next larger-size wire. It is left to the reader to compute the voltage drop and losses if the 21 mm^2 wire is used.

12.8 Economic Considerations

Associated with each proposed technical design is an economic analysis. This is required to compare different designs and to understand trade-offs during the design phase. The economic analysis can be presented in several ways: levelized cost of energy (LCOE), yearly cash flow, total life cycle costs, and annualized maintenance, operating, and replacement costs. The last three are covered in most business economics textbooks. We will briefly discuss the LCOE.

Energy economists and power system planners use the (LCOE) to express the cost of supplying each unit of energy. A system with a lower LCOE is able to supply energy at a lower cost than one with a higher LCOE. The basic premise of computing the LCOE is straightforward: divide the lifetime cost of a system by its lifetime energy production, yielding a figure whose units are cost per unit energy:

In practice, the LCOE is computed before the system is operational, so its lifetime costs and energy production must be estimated. The LCOE is particularly useful in comparing the economics of systems that have unequal lifetimes, capacities, and costs. As you might suspect, the LCOE depends heavily on the energy conversion technology used. For context, the LCOE for utility-scale power plants in the United States ranges from about US$0.05 to US$0.15 per kilowatthour. It is usually much larger for small-scale off-grid systems.

12.8.1 Simplified LCOE

The lifetime cost of an off-grid system includes jurisdiction-dependent factors such as insurance and taxes paid on revenue and real estate. We will skip over these factors and consider the *simplified LCOE* (sLCOE), which approximates the LCOE while using a conceptually simple cost model. The sLCOE includes many of the key elements of LCOE:

- capital costs
- fuel costs
- operation and maintenance cost.

Any complete cost estimation would have to include the localized factors mentioned above.

12.8.1.1 Capital Cost

The overnight capital cost is the cost of bringing the system to a commercially operable state, assuming the cost is incurred (and the system was commercially operable) overnight. The overnight capital costs typically include costs of not only equipment but also land, buildings, construction labor, permitting, and other nonrecurring costs.

The overnight capital cost can be expressed as K dollars per kilowatt capacity of the system. The overnight capital cost is converted to an annuity extending over the lifetime Y years of the system as

$$Cap = \frac{K}{\frac{(1+i)^Y - 1}{i(1+i)^Y}} \tag{12.43}$$

where i is the interest rate, so that Cap is the total capital cost per kilowatt of capacity per year. Note the similarity between (12.43) and (3.31) from Chap. 3.

12.8.1.2 Fuel Cost

The fuel cost per kilowatthour of energy produced are computed as

$$Fuel = \frac{p_\mathrm{f} \times h}{1 \times 10^6} \tag{12.44}$$

where p_f is the price of fuel in $/MMBTU and h is the heat rate of the power plant in BTU per kilowatthour. Fuel prices are commonly quoted in MMBTU, where each "M" is "thousand" in Roman numerals. The "MM" is interpreted as one thousand thousands or one million. Hence, the scaling by 10^6 in the denominator of (12.44) is needed. For renewable mini-grids, the fuel costs are zero (an exception is biomass, where the feedstock might have an associated cost).

12.8.1.3 Operations and Maintenance Costs

Operations and maintenance costs are split into fixed and variable costs. Fixed costs O_f are incurred regardless of the energy produced and are associated with the capacity of the system. It is expressed as dollars per kilowatt of capacity per year. Variable costs O_v are based on the amount of energy produced and expressed as dollars per kilowatthour.

12.8.1.4 sLCOE Calculation

The sLCOE is computed as

$$sLCOE = \frac{Cap + O_\mathrm{f}}{E_\mathrm{annual}} + Fuel + O_\mathrm{v} \tag{12.45}$$

where E_annual is the average annual energy production per kilowatt of capacity. The annual production, rather than lifetime production, is used to be consistent with the units of the capital and fixed operation costs.

All else being equal, a design that results in the lower sLCOE is the more economically favorable. The sLCOE also has very useful commercial interpretation: it is the minimum cost that can be charged for electricity per kilowatthour without losing money. The sLCOE for off-grid systems is typically much higher than for the grid, which is often subsidized. It is common for the sLOCE to exceed US$1/kWh for mini-grids.

Table 12.18 Mwase sLCOE parameters

Parameter	Value
Lifespan	15 (years)
Interest rate	5%
Overnight capital cost	18465 (US$); 3920 (US$/kW)
Annual production	3668.3 (kWh); 778.8 (kWh/kW)
Fuel price	0 ($/MMBTU)
Heat rate	N/A (BTU/kWh)
Fixed OM	2132 (US$/year); 452.7 (US$/kW/year)
Variable OM	0 (US$/kWh)

12.8.1.5 sLOCE Example

We now compute the sLCOE of the Mwase system using the costs in Tables 12.12 and 12.13. We will assume an interest rate of 5%. The lifespan of the system is taken as 15 years. However, the system was designed for the batteries to be replaced every 5 years. To represent this, we will model the battery replacement as a fixed operating cost whose annual value is one-fifth of the cost of the battery (US$8160/5 = US$1632/year). We will assume that other fixed operating costs include routine maintenance every 6 months, for an annual cost of US$500. The capital cost excluding the battery is US$18,465. There are no fuel costs or variable operation and maintenance costs. We do not know if the load will continue to grow at 5% after the fifth year. We will assume that the average annual production during the 15-year lifespan of the system is equal to the consumption at during the fifth year (10.05 kWh/day = 3668.3 kWh/year). These parameters are summarized in Table 12.18. Recall that the capacity of the system is 4.71 kW, which is used in computing the cost per capacity values.

The sLCOE is found by first computing the overnight capital cost in the form of an annuity from (12.43):

$$Cap = \frac{3920}{\frac{(1+0.05)^{15}-1}{0.05(1+0.05)^{15}}} = \text{US\$411.1/kW}.$$

Now applying (12.45)

$$sLCOE = \frac{411.1 + 452.7}{778.8} + 0 + 0 = \text{US\$0.973/kWh}.$$

This sets the break-even price for the Mwase system considering the energy production system. The analysis could be further expanded to include distribution cost, which would further increase the break-even price. If this price is deemed too high, it can be lowered by decreasing the size of the system components, but this may reduce the reliability of the system.

12.9 Cost and Reliability Trade-Off

As is often the case in engineering, there is a trade-off between the reliability of an off-grid system and its cost. There are several ways to improve reliability: increasing the Days of Autonomy or design margin when specifying components, adding redundancy, or using a hybrid architecture to diversify the energy sources. These tend to increase the capital and perhaps the operating cost of the system. This trade-off is perhaps the most important to understand of mini-grid design. An example of a cost-versus-reliability curve is shown in Fig. 12.20. Here the cost refers to the capital cost of the energy production system (conversion technology, storage, and controllers), not the distribution system.

The curve, which will be somewhat different for each mini-grid, shows that it becomes increasingly more expensive to increase reliability. For example, increasing the reliability from 98.5% to 99.5% might increase the energy production capital cost by 40%. Whether or not this additional outlay is worth it depends on the context of a particular project.

There a tendency to over-design off-grid systems. That is, making them more reliable than needed. However, it must be acknowledged that the goal of many off-grid systems is to provide life-improving electricity access, and this can be accomplished at somewhat low reliability. A target of 95% is typical. The budget saved by not installing a system with higher reliability can be used to install additional systems, having a wider impact.

The designer should also be mindful of the impact that low reliability has on the LCOE. Certain costs are fixed. When the reliability is low, less energy is supplied and the revenue decreases. This causes the LCOE to increase because the fixed cost are spread over a smaller amount of production [18].

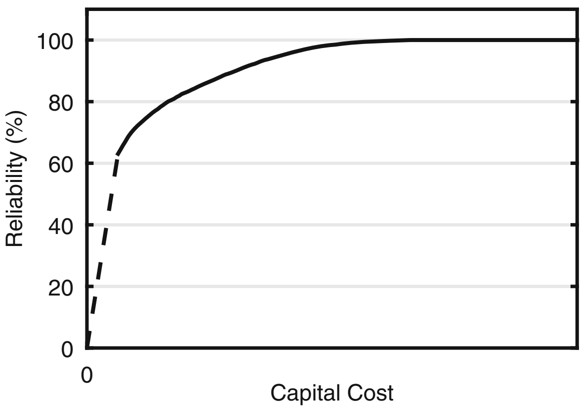

Fig. 12.20 Example relationship between the capital cost of the energy production system and reliability of an off-grid system

12.10 Example Systems

We conclude this chapter by briefly discussing three real-world off-grid systems.

12.10.1 Môle-Saint-Nicolas Mini-Grid: Sigora Haiti

In 2015, Sigora Haiti implemented a hybrid solar–diesel mini-grid in Môle-Saint-Nicolas, Haiti. Môle-Saint-Nicolas is located on Haiti's northwestern coast. The grid presently supplies a mix of 1,100 households, businesses, and social institutions. Household users are supplied with a 120 V, 60 Hz connection rated at 15 A. Images from Môle-Saint-Nicolas are shown in Figs. 12.21, 12.22, 12.23. Additional technical details are summarized in Table 12.19.

Sigora Haiti uses a proprietary multifunctional meter. The meter allows users to prepay for electricity. Credits can be purchased in small amount through the local

Fig. 12.21 Two 100 kW gen sets used in the Môle-Saint-Nicolas mini-grid (courtesy of Sigora Haiti)

Fig. 12.22 A 200 kW PV array is used in the Môle-Saint-Nicolas mini-grid (courtesy of Sigora Haiti)

Fig. 12.23 Street lights are also powered by the Môle-Saint-Nicolas mini-grid (courtesy of Sigora Haiti)

Table 12.19 Môle-Saint-Nicolas system details

Year commissioned	2015
Users (present)	1,100 (5,500 people)
Users (future)	Eight additional towns
Energy sources	Solar (200 kW), Diesel (200 kW)
Peak load	70 kW (evening)
Energy storage (future)	130 kW, 630 kWh, lithium–ion
Low-voltage distribution	AC, 120/240 V, split-phase
Medium-voltage distribution	24 km (total), 22.8 kV, #2 ASCR, overhead, three-phase, radial

network of Sigora vendors, online and directly by mobile money payments. The maximum power that can be drawn by the user can be set via the meter's software.

Although many mini-grids are designed to serve a single community, the Môle-Saint-Nicolas mini-grid was designed at the outset to rapidly scale. In total, nine towns will be served, representing a significant increase over the present load. Sigora Haiti has designed the energy production system to evolve and scale as additional towns are added.

At present, there are two identical 100 kW diesel gen sets and a 200 kW PV array. Although this may seem like excessive capacity given the peak load of 70 kW, it allows Sigora Haiti to serve additional towns as the mini-grid is extended. A 630 kWh lithium–ion battery bank with 130 kW bi-directional converter will be added in the near future. In the interim, the gen sets are operated using a load-following scheme. The PV array is AC coupled using grid-tied string inverters. The inverters are not capable of forming the AC bus voltage, and so one gen set must be online at all times. Once installed, the battery bank will allow the utilization of the PV array to increase and dramatically reduce the use of the gen sets.

The Môle-Saint-Nicolas mini-grid has achieved a high level of reliability, in excess of 99.5%. This is remarkable given the prevalence of tropic storms and hurricanes in the region.

Table 12.20 Ighombwe system details

Year commissioned	2016
Users	50
Energy source	Solar (3.18 kW, 12 × 265 W panels)
Energy storage	24 V, 18 kWh lead–acid (12 batteries at 2 V, 750 Ah)
Low-voltage distribution	AC, 230 V, underground, single-phase, hub-and-spoke

Fig. 12.24 The PV array of the Ighombwe mini-grid with the batteries, inverters and meters securely located in the housing below (courtesy of PowerGen)

12.10.2 Ighombwe Mini-Grid: PowerGen

The Ighombwe mini-grid was implemented by PowerGen in 2016. Ighombwe is a farming community in central Tanzania. The Ighombwe site was chosen because it is one of the largest villages in the district with no national grid power, and the businesses served by the mini-grid are tightly clustered. Existing infrastructure was another consideration. There is a well-maintained road nearby. The grid was entirely self-funded by PowerGen, a Kenyan company. The technical details are provided in Table 12.20, and an image of the energy production equipment is in Fig. 12.24.

12.10.3 Filibaba–LiChi's Community Solutions and KiloWatts for Humanity

The Filibaba energy kiosk was implemented in 2015 by the nonprofit organizations KiloWatts for Humanity (USA) and LiChi's Community Solutions (Zambia) [10]. The energy kiosk is funded by a grant from IEEE Smart Village. Filibaba is a farming community located in the Copperbelt province of Zambia. Filibaba was selected in particular because LiChi's Community Solutions had previously been active in the community. The kiosk is shown in Figs. 12.25 and 12.26 with technical specifications in Table 12.21.

Fig. 12.25 The energy kiosk in Filibaba, Zambia (courtesy of KiloWatts for Humanity)

Fig. 12.26 The Filibaba energy kiosk sells groceries including refrigerated food and beverages (courtesy of KiloWatts for Humanity)

The kiosk is operated as a social enterprise. The kiosk recharges mobile phones and batteries and sells groceries and sundries. Frozen food and cold beverages are sold from a refrigerator inside the kiosk. Filibaba is a sparsely populated community. It was deemed not cost-effective to install a distribution system. Instead, small solar home systems were made available to the community for purchase. Financing was provided so that the solar home systems, each of which cost about US$35, could be paid off over several months. In addition, two nearby houses and a church were provided a wired connection.

Table 12.21 Filibaba system details

Year commissioned	2016
Users	4
Energy source	Solar (1.8 kW, 6 × 300 W panels)
Energy storage	24 V, 10.56 kWh lead–acid (4 batteries at 12 V, 220 Ah)

12.11 Summary

This chapter discussed the implementation and technical design of mini-grids. The mini-grid life cycle consists of eight steps, starting with prospecting and screening and ending with expansion or retirement. Early in the design phase, the different energy conversion technologies are compared against several objectives, constraints, and other considerations.

The technical design can proceed in two ways: using an intuitive approach, guided perhaps by rules of thumb, standards, and best practices. This approach can be used with limited information. Becoming more popular is the numerical or computer-aided approach. This approach uses computer simulations to evaluate and possibly identify feasible designs that are optimized in some sense—typically economic.

The design of the distribution system was discussed. There are several options that should be considered: AC or DC, overhead or underground, and hub-and-spoke or trunk-and-branch topology. The configuration can be single-phase, split-phase, three-phase wye, and three-phase delta. Hybrid configurations are also possible. The design should consider the targeted access tier, the user requirements, the load, the location of the users, and the cost of implementation.

The economics of each design are important. There are several ways of evaluating a mini-grid for economic viability. One important metric is the levelized cost of energy (LCOE), which shows the cost of providing each unit of energy over the lifetime of the project considering operation and capital costs. Ultimately the design of a mini-grid requires balancing the economic considerations with the technical. With the input data often very uncertain, there is almost never a single "best" design.

Problems

12.1 Design the battery bank for the users in Table 12.22. The characteristics of the available batteries are provided in Tables 12.23 and 12.24. Provide details of the battery selected, and the number of strings and batteries per string needed, if applicable.

12.2 Design the PV array for the users in Table 12.22. The characteristics of the available PV modules are provided in Table 12.25. Provide details of the module

Table 12.22 Standalone system details

User	Community center	Maternity ward	Restaurant	School
Avg. daily load (kWh)	0.68	0.40	0.56	2.36
Inverter efficiency (%)	0.85	0.83	0.78	0.82
Peak DC current @ 12 V	13.0	12.5	20.8	11.0
End of life rating	0.8	0.8	0.9	0.8
Days of autonomy	1.5	6	2	2
Maximum DoD	0.90	0.85	0.80	0.85
Cycles required	2000	1000	1500	2000
Battery design margin	0.08	0.10	0.15	0.05
Insolation kWh/m^2/day	4.3	5.2	5.5	5.1
Generation and storage loss(%)	18	18	25	32
Temperature reduction (%)	8	10	14	17
PV design margin	0.09	0.20	0.12	0.05
Minimum operating temp. (Celsius)	5	10	10	10

Table 12.23 Battery characteristics

Parameter	Battery A	Battery B	Battery C	Battery D	Battery E
Type	Flooded	Flooded	Flooded	AGM	AGM
Nominal voltage (V)	2	6	12	2	12
DoD for 1000 cycles	0.70	0.70	0.50	0.70	0.70
DoD for 1500 cycles	0.45	0.45	0.25	0.48	0.48
DoD for 2000 cycles	0.25	0.25	–	0.35	0.35

Table 12.24 Battery charge capacity

Hour-rate	10 hr	20 hr	50 hr	100 hr
Battery A	955 Ah	1124 Ah	1338 Ah	1452 Ah
Battery B	268 Ah	315 Ah	375 Ah	419 Ah
Battery C	72 Ah	85 Ah	95 Ah	106 Ah
Battery D	1040 Ah	1150 Ah	1200 Ah	1275 Ah
Battery E	189 Ah	210 Ah	218 Ah	230 Ah

Table 12.25 PV module characteristics

Parameter	Module A	Module B	Module C	Module D
Maximum power (W)	50	80	190	300
Open-circuit voltage, STC (V)	22.5	22.3	43.2	45.5
Short-circuit current, STC (A)	2	4.96	5.98	8.56
Open-circuit voltage temp. coeff.	−0.34%/K	−0.34%/K	−0.34%/K	−0.34%/K

selected, and the number of strings and modules per string needed, if applicable. Assume the maximum input voltage and current of the charge controller is 75 V and 15 A, respectively.

Table 12.26 Community parameters

Parameter	Initial
Avg. daily load (kWh/Day)	25
Peak load (kW)	38
Battery bank voltage (V)	48
Inverter efficiency (%)	81
Inverter design margin	1.05
End of life rating	0.80
Days of autonomy	3
Maximum DoD	0.90
Cycles required	2000
Battery design margin	0.05
Generation & storage loss (%)	30
Temperature reduction (%)	8.75
PV design margin	0.05
Minimum operating temp.	10

Table 12.27 WECS capacity factor by month

	Month (kWh/m^2/day)											
	1	2	3	4	5	6	7	8	9	10	11	12
Capacity factor	0.25	0.29	0.40	0.18	0.34	0.36	0.38	0.10	0.24	0.39	0.22	0.34

12.3 Repeat the design for Mwase using a coincidence factor of 0.80. Specify the requirements for the inverter, battery bank, and charge controller. Compare this to the design when the coincidence factor is 0.37.

12.4 Repeat the design of the battery bank for Mwase using Battery D whose characteristics are in Tables 12.23 and 12.24.

12.5 Repeat the design for Mwase, but assume the average daily worst-month insolation is 5.5 kWh/m^2/day. Specify the required PV array capacity. Provide details of the number of strings and modules per string needed, if applicable.

12.6 Design an off-grid system for a community whose characteristics are in Table 12.26. Assume the average daily worst-month insolation is 5.2 kWh/m^2/day. Select the PV modules and batteries from Tables 12.25 and 12.23. Assume the maximum input voltage and current of the charge controller is 250 V and 60 A, respectively. Assume the selected inverter has a maximum rating of 5000 W and is able to be synchronized with other generators.

12.7 Design a DC-coupled wind-powered mini-grid for Mwase using the monthly capacity factors in Table 12.27. Determine the required rating of the WECS and rectifier. Assume each WEC is rated at 1 kW. Use a design margin of 0.5; assume the generation and storage losses are 15%. There is no temperature-related reduction.

12.8 Assume that there is viable hydro resource near Mwase. The effective head is 32 m and the maximum flow rate that can be used is 10 l/s. The combined efficiency of the turbine and generator is 82%. Determine the required power rating of the MHP system and the required flow rate if the system is AC coupled without batteries. Draw the architecture of the system. Include the rating of the electronic load controller.

12.9 Consider a 1 km single-phase, two-wire distribution line. The line serves 30 households. Ten households are located at 0.33 km down the distribution line; another ten are located at 0.67 km down the line, and the rest are located at the end of the line. Compute the voltage drop at each location along the line and the total power loss. Assume the impedance of the line is $Z_w = 0.4 + j0.3\Omega$, the current to each customer is 1.25 A, and the sending-end voltage is 230 V.

12.10 Compute the voltage drop and power loss for the Mwase system if a split-phase distribution system is used. Assume the loads are evenly balanced.

12.11 Compute the voltage drop and power loss for the Mwase system if the 21 mm^2 wire is used, as described in Table 12.17.

12.12 Compute the sLCOE of an diesel-based internal combustion engine used in an off-grid system with the parameters found in Table 12.28.

12.13 Consider a biomass gasification system serving 400 houses. Each house consumes 300 Wh of electricity per day. The gasification system is 60% efficient, and the combined efficiency of the engine and generator is 33.3%. The energy content of the dry husk feedstock is 12.6 MJ/kg, which costs US$25 per metric ton. The peak power demand is 20 kW. The overnight capital cost is US$1200/kW, and the distribution infrastructure and user premise costs total US$5000. The interest rate is 10%. The fixed operation and maintenance costs are $500 per month. There are no variable operation and maintenance costs. The lifespan of the system is 15 years. Compute the sLCOE associated with this system.

Table 12.28 System parameters

Parameter	Value
Lifespan (years)	8
Interest rate (%)	5%
K ($/kW)	400
Annual production (kWh/kW)	7884
Fuel price ($/MMBTU)	29
Heat rate (BTU/kWh)	11,500
Fixed OM ($/kW-year)	15
Variable OM ($/kWh)	0.007

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