Master of Science in Mechanical Engineering

# A Framework to Decide Clustering of Solar Mini Grids

태양광 미니 그리드의 클러스터링을 결정하기 위한 프레임워크

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# A Framework to Decide Clustering of Solar Mini Grids

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# Abstract

Although solar mini grids provide cost benefits for electrification in certain niches compared to standalone systems or extension of a national grid, the unsubsidized electricity price from a typical solar mini grid is three to ten times higher than electricity price from a national grid. In addition, in typical solar mini grids a significant share of the possible electricity generation capacity is not utilized. One of the ways to increase the affordability of solar mini grids is, therefore, to increase the utilization of these electricity generation capacity through different methods. In this thesis, a concept of mini grid clustering, which is connecting two or more mini grids together, is proposed, particularly a framework to decide clustering of solar mini grids is presented.

Keyword: solar mini grid, solar mini grid clustering
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# Table of Contents

# Chapter 1. Introduction

## 1.1. Study Background

Enabling access to electricity to a household helps to improve quality of life [1,2]. For example, traditional biomass is a predominant source of energy where electricity is not accessible or sufficient [3]. Households with no access to modern energy such as electricity spend a significant amount of their time collecting and processing traditional energy resources. Households with access to modern energy can invest their resources in more productive activities that will help to improve their quality of life such as children going to school rather than collecting firewood. Access to modern energy also has health benefits [4]. The household air pollution due to burning of traditional energy resources in the household environment is one of the major causes of respiratory problems and numerous deaths each year in developing countries. Access to modern energy also helps to promote equality by reducing the household burden on women and children.

There are about a billion people without access to electricity and about three billion people without access to clean energy for cooking [5]. People without access to electricity are usually either remote, or poor, or both [6]. Moreover, electricity from conventional energy resources is polluting the environment, particularly, the emissions associated with conventional energy technologies are contributing to the increasing concentration of greenhouse gasses in the atmosphere which leads to global warming [7,8]. One of the solution to the problem is, therefore, the development of clean and affordable electricity technologies.

## 1.2. Purpose of Research

Solar mini grids convert the energy from the Sun into electrical energy through photovoltaic panels and either store it in the battery in the form of chemical energy for later use or directly transport it to end users in the form of electrical energy [9]. Although solar mini grids offer cost benefits in certain niches compared to other electrification modes such as standalone systems or extension of a national grid, their typical unsubsidized electricity price is three to ten times higher than the national grid electricity price values [10,11]. In addition, in typical solar mini grids a considerable share of the electricity generation capacity is not utilized. In typical cases, the unutilized amount of electricity generation capacity can exceed more than half of the possible electricity generation capacity. In this thesis, a concept of mini grid clustering is proposed, particularly a framework to decide clustering of solar mini grids is presented to reduce the cost of solar mini grids by increasing the utilization of the electricity generation capacity.

# Chapter 2. Energy from the Sun and Solar Mini Grids

## 2.1. Energy from the Sun

Any object emits energy to its surroundings in the form of electromagnetic waves due to its non-zero temperature [12]. This energy when emitted by a surface could be across different wavelengths and directions. The amount of energy emitted in a unit time, from a unit surface area, in a unit small wavelength interval around a given wavelength to a unit solid angle is called spectral directional emissive power. Integration of spectral directional emissive power over a hemisphere gives hemispherical spectral emissive power. Integration of hemispherical spectral emissive power with all wavelengths gives hemispherical total emissive power or in short emissive power.

A blackbody is an idealized type of body that absorbs all the electromagnetic waves that are incident on it [13]. A real body on the contrary absorbs a portion of the electromagnetic waves that are incident on it and reflects the remaining. Planck's law gives the functional relationship between hemispherical spectral emissive power, $E_{\lambda,b}(\lambda, T)$, and wavelength and temperature for a blackbody where $\lambda$ is wavelength, T is temperature, h is Planck constant, $c_o$ is speed of light, $k_B$ is Boltzmann constant.

$$E_{\lambda,b}(\lambda, T) = \frac{2\pi h c_o{}^2}{\lambda^5 (e^{\frac{hc_o}{\lambda k_B T}} - 1)} \quad (2.1)$$

Integrating the above equation across the entire wavelength range gives hemispherical total emissive power or in short emissive power which is given by the following formula where $\sigma$ is Stefan Boltzmann constant and T is temperature of the blackbody.

$$E_b = \sigma T^4 \quad (2.2)$$

The Sun can be modeled as a black body with a surface temperature of 5,778 K [14].

Solar energy per unit area per unit time is called irradiance. Solar irradiance at the Sun surface can be calculated to be 63MW/m$^2$ from the above formula. This value is the same in all directions around the Sun. By applying the law of conservation of energy on a volume between two concentric spheres around the Sun, it can be deduced that irradiance drops with an inverse square relationship with distance from the Sun center assuming that no energy is trapped in the volume. For instance, doubling the distance from the Sun center results in a four times drop in irradiance.

Irradiance at the top of the earth atmosphere perpendicular to Sun rays can also be calculated to be about 1377 W/m$^2$. This value, however, varies from time to time [9]. One is because of the changing separation distance between the Sun and the Earth. Since the Earth rotates around the Sun in an elliptical orbit, the distance between the Sun and Earth varies throughout the year attaining maximum and minimum distances at six months apart. Earth's closest distance to the Sun can fall anywhere between January 2 and January 6 in a given year. At this point in its orbit, the Earth is about 147.1 million km from the Sun. It is interesting to note that it is winter in the northern hemisphere when the Sun is closest to the Earth. Earth's farthest distance to the Sun is 152.1 million km away and happens during summer in the northern hemisphere. In addition to the change in Sun−Earth distance, the variation in the intensity of the Sun contributes to the variation for irradiance at the top of the Earth's atmosphere. The intensity of the Sun is found to fluctuate between maximum and minimum with an 11−year cycle called the solar cycle.

Taking into account the effects of Sun–Earth distance only (i.e. ignoring the effects of the solar cycle), the irradiance at the top of the atmosphere can be given by the following formula where n corresponds to the day of the year with n = 1 being January 1st [9]. The plot for the equation is given in the following figure plotted using MATLAB.

$$I_o = 1377 \ W/m^2 * (1 + 0.034cos(360n/365)) \quad (2.3)$$

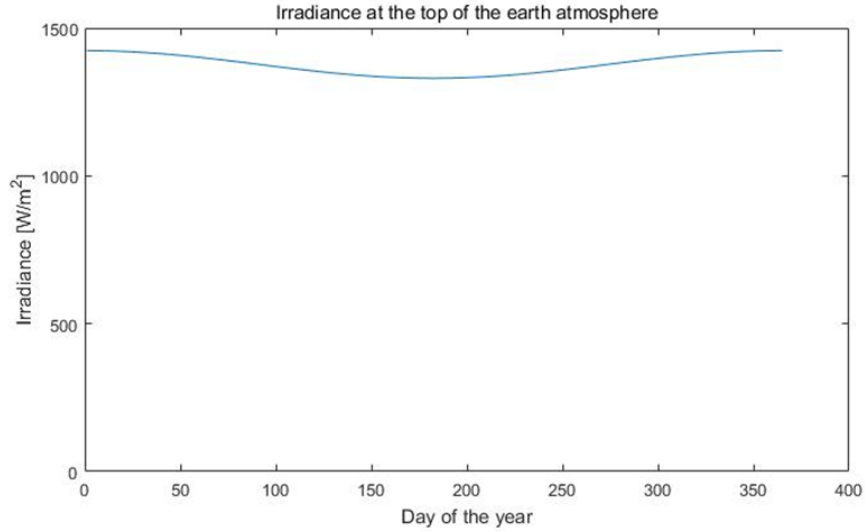Irradiance at the top of the earth atmosphere

Figure 2.1. Solar irradiance at the top of the Earth atmosphere

A number of factors determine the amount of solar irradiance on the Earth surface [9]. These include Earth's geometry, revolution and rotation, terrain, atmospheric attenuation due to scattering and absorption by gasses, aerosols, and clouds. The radiation that has reached the Earth's surface and striking the solar panel can be classified into three different types namely direct beam radiation, diffuse radiation and reflected radiation. All these three forms of radiation contribute to the energy generation in photovoltaic panels. Direct beam radiation is the radiation that passes in a straight line through the atmosphere to the Earth surface. As this beam passes through the atmosphere, it experiences attenuation. Diffuse radiation is the radiation that is

arriving on the solar panel that is scattered by molecules and aerosols in the atmosphere. Reflected radiation is the radiation arriving on the solar panel that is bounced off the ground or other surface in front of the panel.

It is important to note that the orientation of the solar panel directly determines the amount of energy it can generate. Typically, solar panels are oriented toward the south pole if their location is in the northern hemisphere and toward the north pole if their location is in the southern hemisphere. The angle the solar panel makes from a horizontal surface is typically the latitude angle of the location. In this way the maximum possible amount of energy is collected from a given area of a solar panel if the effect of clouds and shades are ignored. By changing the orientation of the solar panel with time of a day and/or year, the maximum possible amount of energy that can be collected can be increased even more. Accounting for all the effects, the optimum tilt angle for a solar panel for each country is presented in the following article [15].

Irradiance and irradiation (insolation) are two different terms that are associated with solar energy. Irradiance as described previously is solar energy falling on a unit area per unit time. Its unit is therefore $W/m^2$. Integration of irradiance over a given period of time is called irradiation or insolation. To size the solar mini grid system, solar resource data in the form of irradiance or insolation at the location where the mini grid is intended to be built is needed. This data can be accessed online from different sources such as the one mentioned here [16]. The following figure shows yearly solar irradiance data on a one-meter square surface pointing toward the north pole with a tilt angle of the latitude of Mkalama, Tanzania.
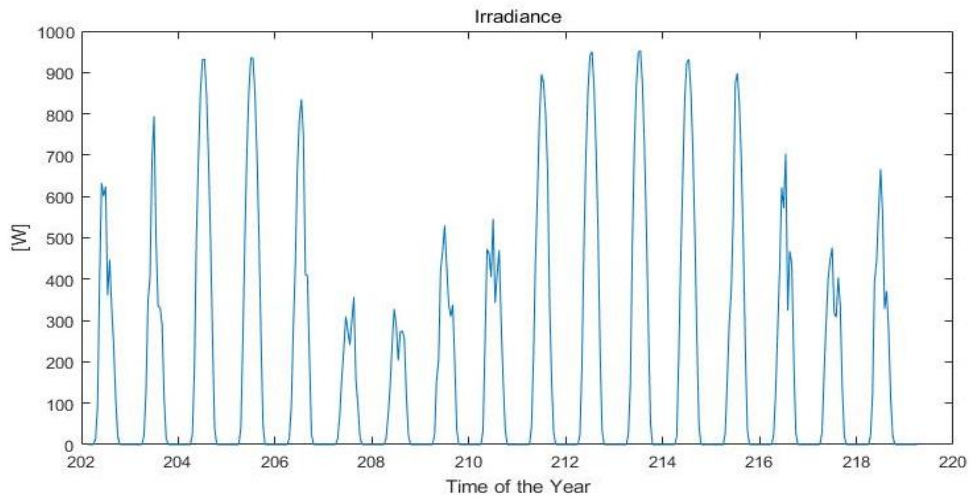
Figure 2.2. Solar irradiance data on a one−meter square surface
pointing toward the north pole with a tilt angle of the latitude of
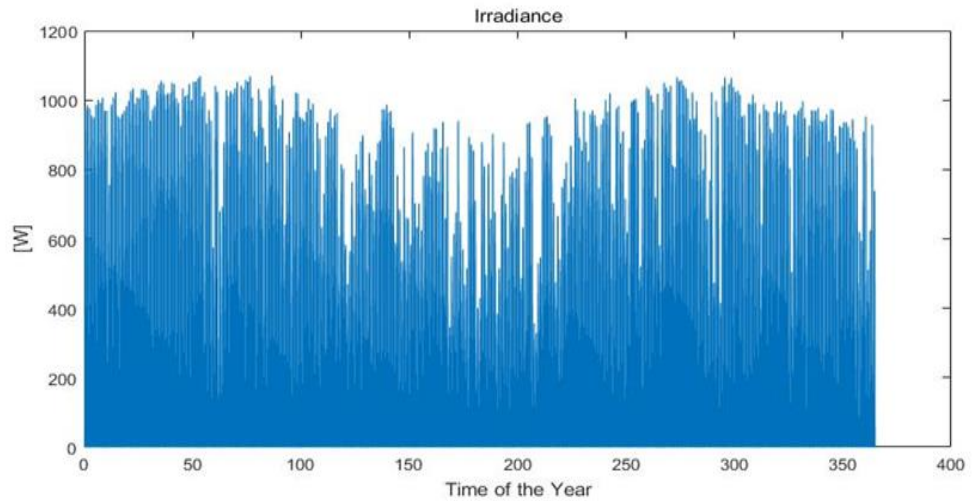Mkalama, Tanzania for the selected days in a year



Figure 2.3. Yearly solar irradiance data on a one−meter square
surface pointing toward the north pole with a tilt angle of the
latitude of Mkalama, Tanzania

## 2.2. Solar Mini Grids

The components of a typical solar mini grid can be divided into three subsystems: generation subsystem, distribution subsystem and end users (demand subsystem) [17]. The constituents of each subsystem are mentioned in the following table.

Table 1: Components of typical solar mini grid

| Generation subsystem | Distribution subsystem | Demand subsystem |
|---|---|---|
| PV Panels | Distribution lines | Meters |
| Energy management systems | Poles | Internal wiring |
| Batteries | Transformers | Grounding |
| Inverters | | Electrical devices |
| Electrical wiring | | |
| Racking | | |
| Powerhouse | | |

Photovoltaic panels convert the Sun radiation into electrical energy. Maximum power point tracker (MPPT) controls the operation of the photovoltaic panel and its interaction with the battery and the inverter. The battery converts the electrical energy and stores it in the form of chemical energy and back. The inverter converts the electrical energy from direct current type into alternating current type. Energy management systems include equipment which measure, monitor and control electrical loads including the charge controller, metering and monitoring devices. Distribution networks transport the electrical energy to end users. Distribution lines are supported by poles which are typically made of wood, metal, or concrete.
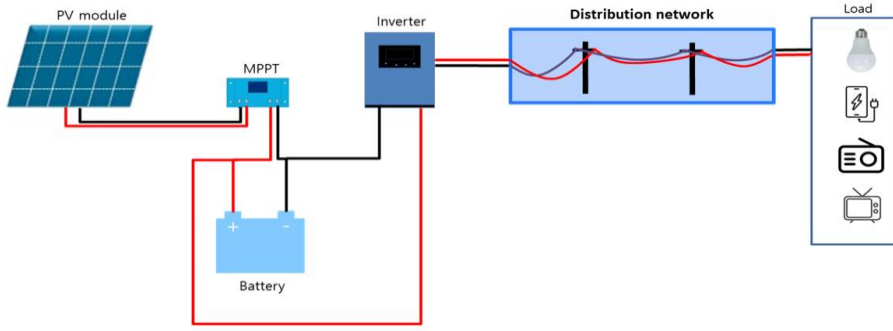
Figure 2.4. Schematic of a Solar Mini Grid

In the design of mini grids, cost minimization is one of the prime concerns. Cost effectiveness is defined as the ability to provide high reliability electric power at an affordable cost [18]. There are different types of costs used for evaluation during the design of mini grids including total cost, cost per connection, and levelized cost of electricity. The total cost is made up of the capital cost, operating and maintenance costs, and replacement costs. Future costs are adjusted to the present using a discount rate using the following formula where n is number of years to the future and r is the discount rate.

$$Cost_{present} = \frac{1}{(1+r)^n} \ Cost_{n^{th} \ year}$$
(2.4)

Cost per connection is the total cost divided by the number of households. Levelized cost of electricity is obtained by dividing the total cost adjusted to the present with the total energy sold to customers also adjusted to the present by the discount rate [19]. In this thesis, the levelized cost of electricity is the variable that is minimized during mini grid design because this is the cost which has the most direct effect on the electricity price.

$$LCOE = \frac{\sum_{t=1}^{n} \frac{C_t + M_t + R_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$
(2.5)

9

$C_t$: capital cost in the year t
$M_t$: operations and maintenance cost in the year t
$R_t$: replacement cost in the year t
$E_t$: electrical energy sold in the year t
$r$: discount rate
$n$: expected lifetime of a system

The levelized cost of electricity can also be thought of as a representation of the electricity sale price to recover all the investments with no profits or loss [20]. Therefore, in actual cases the electricity price will be the levelized cost of electricity plus some extra price that will become a profit. In this thesis, the cost structure of a mini grid is thought to constitute only the generation and distribution subsystems and the levelized cost of electricity is considered to be the electricity price. The total cost of the respective components obtained from numerous references is given in the following table [21,22,23,24].

Table 2: Cost of solar mini grid components

| Component | Capital cost [$] | O&M cost [$] |
|---|---|---|
| PV Panels | 610/kW | 0 |
| Energy management systems | 305/kW | 0 |
| Batteries | 270/kW | 0.003/yr/kWh |
| Inverters | 570/kW | 0 |
| Racking | 150/kW | 0 |
| Powerhouse | 50/kWh | 0 |
| Distribution network | 20,000/km | 160/yr/km |

Therefore, a cost structure for a typical solar mini grid can be given as follows taking into account a 5% discount rate, system lifetime of 25 years, and battery lifetime of 5 years.

$$Capital\ cost\ =\ 950*P\ +\ 550*B\ +630*I\ +\ 20{,}000*G$$
$$O\&M\ cost\ =\ 0.0423*B+2256*G$$
$$Replacement\ cost\ =\ 690*B$$

$$Total\ present\ cost\ =\ 950*P\ +\ 1240*B\ +630*I\ +\ 22{,}256*G$$
$$Total\ present\ energy\ consumption =\ 14.09*A \qquad (2.6)$$

$$LCOE\ =\ \frac{Total\ present\ cost}{Total\ present\ energy\ consumption}$$

$A:\ Annual\ energy\ consumption$
$B:\ Battery\ size$
$G:\ Grid\ length$
$I:\ Inverter\ size$
$P:\ PV\ size$

# Chapter 3. Modeling Components of Solar Mini Grid

## 3.1. Modeling Photovoltaic (PV) Panel and Maximum Power Point Tracker (MPPT)

Photovoltaic panels directly convert the energy from the Sun into electricity. The energy from the Sun is in the form of electromagnetic radiation and photovoltaic panels convert portions of this energy that is reaching them. The output from photovoltaic panels is direct current at different current and voltage values depending on the solar irradiance and external resistance. A photovoltaic panel can, therefore, be modeled as a black box.
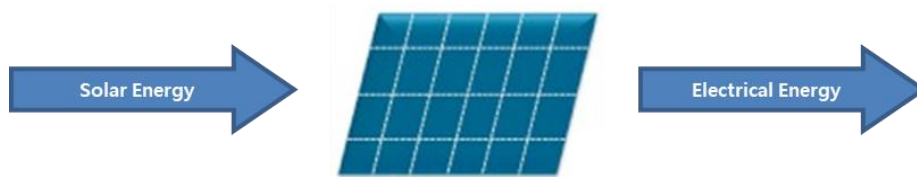


Figure 3.1. PV Panel

At a given solar irradiance value, the solar panel generates power that could vary from zero up to possible maximum depending on the external resistance that is connected to it. When the external resistance is zero (in other words when the positive and negative ends of the solar panel are connected without any resistor in between), the voltage drop is theoretically zero and the current is infinity. However, in reality there is always some resistance and the current has a finite value. This current is called short circuit current. On the other hand, when the positive and negative outputs of the solar panel are connected with a resistor with an infinite resistance (in practice when the positive and negative ends are unconnected and are free in space), the current is zero and the voltage is maximum and is called open circuit voltage.

In both cases, the power output from the solar panel is zero since power is a product of voltage and current. When the solar panel is connected with resistors with intermediate external resistances, its power output is non-zero. To extract maximum power possible for the given irradiance value, the solar panel should be operated at a specific voltage and current value. The maximum power point tracker (MPPT) allows the panel to operate at this specific point. The solar panel power output also changes with different irradiance values. The power output from the solar panel increases with increasing irradiance [9].

The maximum power output from a solar panel can be modeled with the following formula where $Y_{PV}$ is PV power output under standard test conditions and it is a PV rating given by the manufacturer, $f_{pv}$ is PV derating factor to account for reduced output in real-world operating conditions such as due to dust covering etc., $G_T$ is the solar radiation incident on the PV array, and $G_{T,STC}$ is the incident radiation at standard test conditions which is $1\ kW/m^2$ [25].

$$PV_{output} = Y_{PV}\ f_{pv}\frac{G_T}{G_{T,STC}} \quad (3.1)$$

Accounting for the inefficiency associated with the MPPT, the power output from the maximum power point tracker can be modeled with the following equation where $P_{out}$ is the power out from the MPPT, and $\eta_{mppt}$ is its efficiency.

$$P_{out} = \eta_{mppt}Y_{PV}\ f_{pv}\frac{G_T}{G_{T,STC}} \quad (3.2)$$

## 3.2. Modeling Electrochemical Energy Storage Device

Energy generated from the Sun through photovoltaic panels is variable and may not always match the demand. Therefore, energy storage devices could be one of the solutions to balance the electricity demand and supply. In this thesis, electrochemical batteries are considered. Electrochemical batteries convert electrical energy into chemical energy and store it and convert the stored chemical energy back to electrical energy when needed. In this thesis electrochemical batteries are modeled as a combination of energy conversion unit and energy storage unit as shown in the figure below [26]. The energy conversion unit converts the electrical energy into chemical energy for storage. The energy storage unit stores the converted chemical energy.
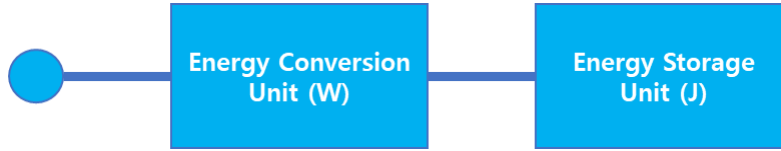


Figure 3.2. Energy Storage Device Model

The energy conversion unit is modeled with the following equation where $P_{in}$ is the power in to the energy conversion unit, $P_{out}$ is power out from the energy conversion unit, and $\eta_C$ is energy conversion unit efficiency.

$$P_{out} = \eta_C P_{in} \quad (3.3)$$

The energy storage unit is modeled with the following formula where E is the energy stored in the battery, $P_s$ is power in or out from the storage unit and is also referred to as charge/discharge rate, Q is energy lost due to self−discharge, k is a constant signifying % of energy lost per unit time.

$$\frac{dE}{dt} = P_s - \frac{dQ}{dt} = P_{in} - kE \qquad (3.4)$$

For a unit step time step, t, the above equation can be rewritten as

$$\Delta E = E_2 - E_1 = P_s \Delta t - kE\Delta t \quad (3.5)$$

Therefore, the combined electrochemical battery model becomes,

$$\frac{dE}{dt} = \eta_C P_{in} - kE$$

$$\Delta E = E_2 - E_1 = \eta_C P_{in}\Delta t - kE\Delta t$$

$$E_2 = E_1 + \eta_C P_{in}\Delta t - kE\Delta t \qquad (3.6)$$

Round−trip efficiency ($\eta_B$) is the percentage of the energy put into storage that is later retrieved. Power conversion efficiency of the battery can be given by the square root of the roundtrip efficiency assuming that the conversion efficiency is the same for charging and discharging.

$$\eta_C = \sqrt{\eta_B} \qquad (3.7)$$

The typical k values for lithium ion and lead acid batteries is given in the following table.

Table 3: Typical self−discharge rates for lithium ion and lead acid batteries

| Battery type | k |
|---|---|
| Lithium ion | 1.5–2% per month |
| Lead acid | 5% per month |

The energy stored is utilized within a day or few days in typical solar mini grids. Therefore, the value of k is very small and

is ignored in the analysis in this thesis.

Charge capacity of a battery is a measure of charge stored and is typically represented in units of Ah. State of charge (SOC) is a ratio of the amount of charge presently stored to the nominal rated capacity. Common way to measure battery SOC is to measure the voltage and compare it to the voltage at fully charged state. Energy capacity which is a related concept with charge capacity and typically represented in Wh is a measure of the energy stored by the battery. Energy capacity is the product of charge capacity and voltage difference between the battery electrodes. Depth of Discharge (DOD) is a fraction of energy that can be withdrawn from the battery without causing irreparable damage to the battery.

Table 4: Depth of discharge for typical lithium ion and lead acid batteries

| Battery type | Depth of discharge |
|---|---|
| Lithium ion | 80% to 95% |
| Lead acid | 50% |

Connecting batteries in series increases the voltage, but the charge capacity stays the same. Connecting batteries in parallel increases the charge capacity, but the voltage stays the same. In both cases, the energy capacity doubles.
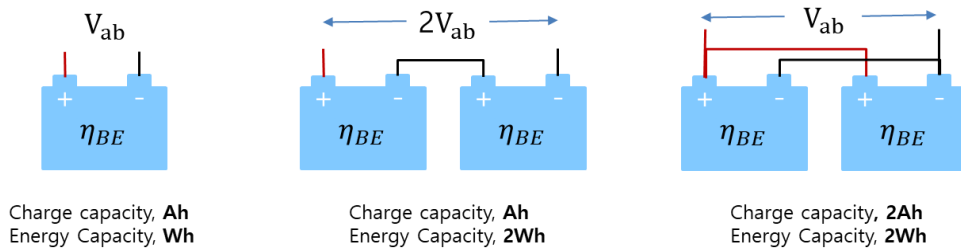


Figure 3.3. Batteries in Series and Parallel

Battery capacity decreases with increasing charge or discharge rates. This fact is represented in what is called the Peukert's law for lead acid batteries where $C_{eff}$ is effective capacity (in ampere hours) at discharge rate I (in amperes), and H is the rated discharge time (in hours) and C is the rated capacity at that discharge rate (in ampere hours), and k is the Peukert constant.

$$C_{effective} \; = \; C(\frac{C}{IH})^{k-1}$$
(3.8)

For example, for the 12V US AGM 31 battery with 100 Ah at discharge rate of 5A, the capacity of the battery at different discharge rates can be modeled with the above equation and Peukert constant of 1.15 [27]. The resulting curve and actual data points are shown in the figure below.
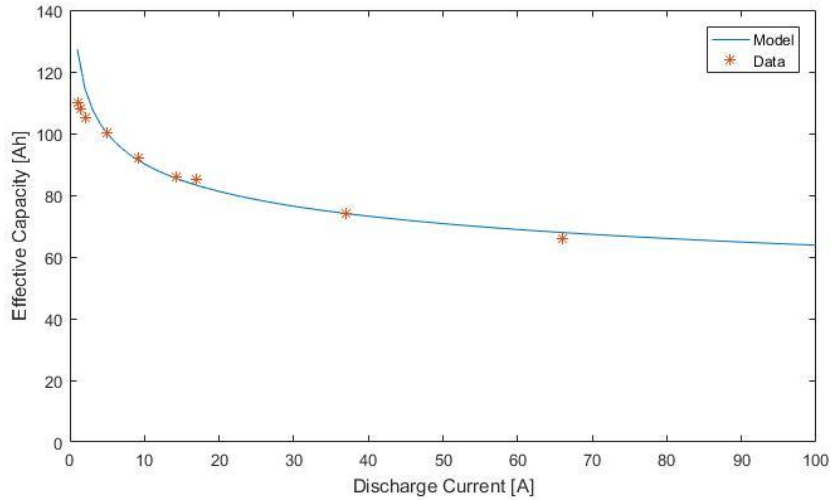


Figure 3.4. Charge capacity with different charge or discharge rates

The same graph in terms of energy capacity vs discharge power is presented in the following figure.
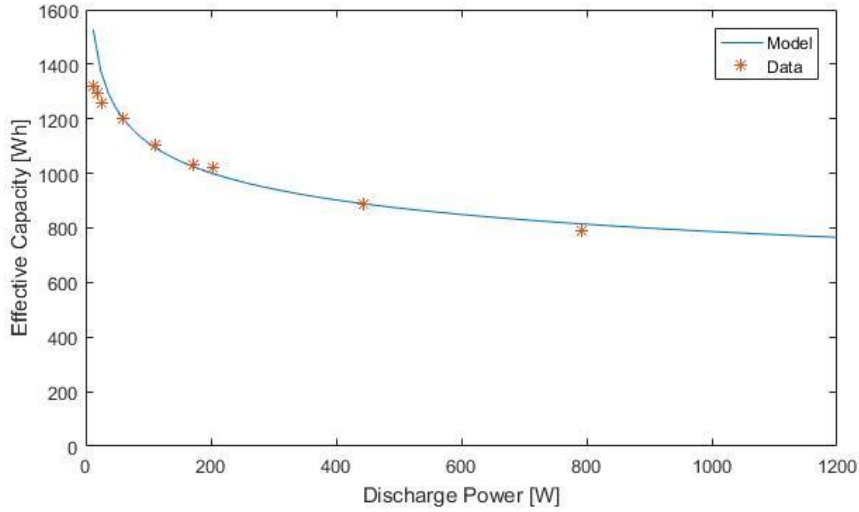
Figure 3.5. Energy capacity with different charge or discharge rates

The following figure shows the charge/discharge power distribution for a year for a typical solar mini grid with a battery capacity of 5.3 kWh. It can be noted that most of the charge or discharge happens at smaller rates within the range −200 W to 200 W. Therefore, ignoring the effect of capacity change due to charge/discharge rate is a reasonable assumption to get a fairly accurate estimate of the battery size at a reasonable computational cost. The battery capacity will be higher than the company capacity rating in cases of very slow charge/discharge rate and lower than company capacity rating in cases of fast charging or discharging.
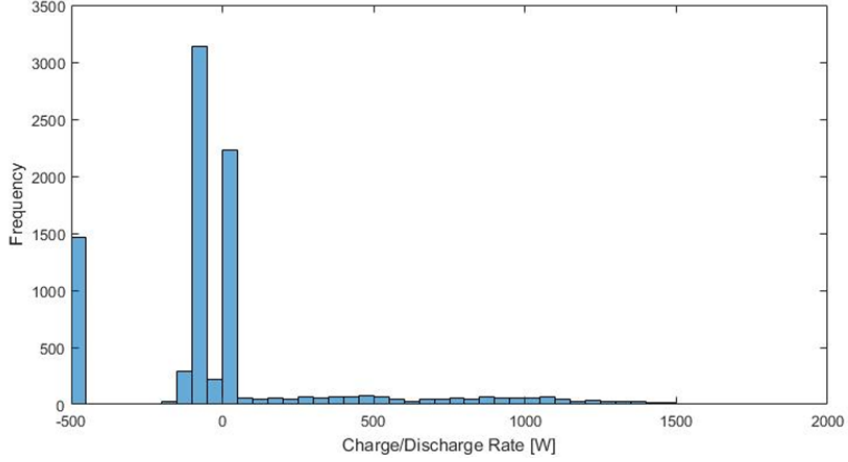
Figure 3.6. Charge/discharge rates for typical solar mini grid

Therefore, the combined simplified electrochemical battery model for a time step size of t becomes,

$$E_2 = E_1 + \sqrt{\eta_B} P_{in} \Delta t \qquad (3.9)$$

## 3.3. Modeling Inverter

Inverters convert the electrical energy from direct current (DC) type into alternating type (AC) type. Inverters can be modeled as a black box characterized by their energy conversion efficiency of $\eta_{in}$. The energy conversion efficiency of inverters could vary depending on the input power. However, for simplicity reasons the efficiency is assumed to be constant.

$$P_{out} = \eta_{in} P_{in} \qquad (3.10)$$

$P_{in}$: power in to the inverter
$P_{out}$: power out from the inverter
$\eta_{in}$: energy/power conversion efficiency

1 9

## 3.4. Modeling Distribution Networks

The distribution network is composed of the electrical wires to transport the electricity and the poles to support the electrical wires. The electrical wire can be modeled as a resistor and inductor connected in series as shown in the following figure [31].
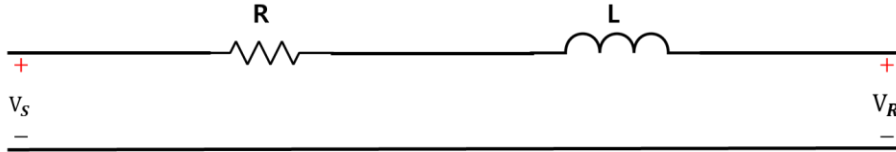


Figure 3.7. Distribution network model

The resistance of a given conductor can be calculated from material property called resistivity and geometry of the conductor as shown in the following equation where is resistivity of the material, d is length and A is the cross−sectional area of the conductor. Therefore, a conductor with a larger cross−sectional area has a lower resistance and increasing a conductor length increases the resistance.

$$R = \rho \frac{d}{A} \qquad (3.11)$$

Inductive reactance is due to an indicator nature of the electricity grid and can be characterized by a parameter called inductance (L). Inductive reactance can be calculated by the following formula where is frequency in radians per second, and L is inductance.

$$X = \omega L \qquad (3.12)$$

Calculating the total impedance for the combination of resistor and indicator has similar rules to the combination rules for resistors.

$$Z_{line} = \rho \frac{d}{A} + j\omega L \qquad (3.13)$$

The voltage drop along a conductor is given by Ohm's law where V is a voltage drop, I is a current and $Z_{line}$ is an impedance of the conductor. There is, therefore, energy loss along a grid line due to resistance and inductive reactance.

$$V_S - V_R = I Z_{line} \qquad (3.14)$$

The electric distribution system should be designed to minimize the cost. Using conductors with higher cross sectional area increases the cost and the need for a stronger supporting structure. Using conductors with smaller cross sectional area increases the voltage drop and wastage of energy as heat. The power loss due to resistance of the distribution network is assumed to be 2% and the change in total distribution system cost due to different wire thicknesses is assumed to be zero.

Designing the distribution network can be regarded as the Euclidean Minimum Spanning Tree problem. Euclidean Minimum Spanning Tree is a minimum spanning tree of a set of n points in the plane, where the weight of the edge between each pair of points is the Euclidean distance between those two points. The following figure shows the code flow for the Euclidean Minimum Spanning Tree algorithm.
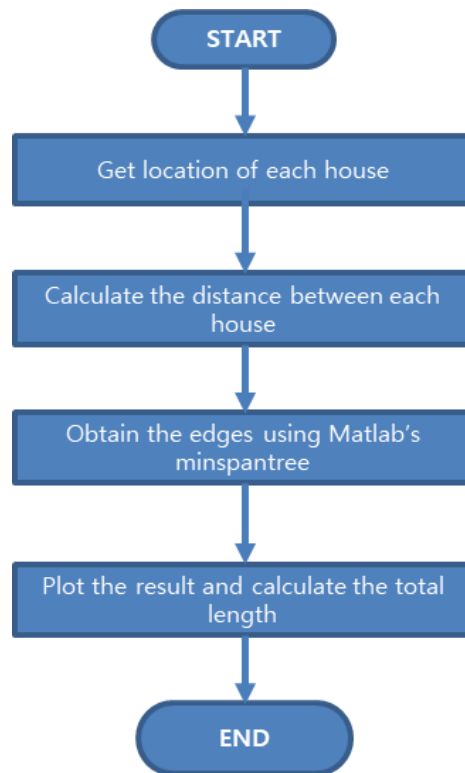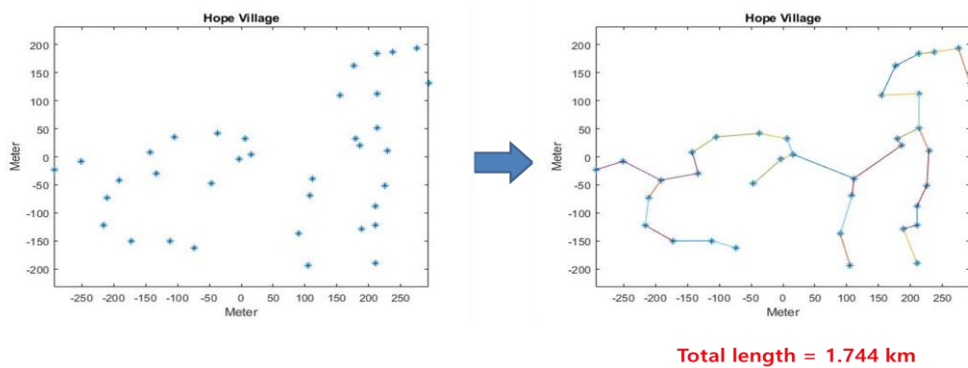
Figure 3.8. Code flow for the Euclidean Minimum Spanning Tree algorithm
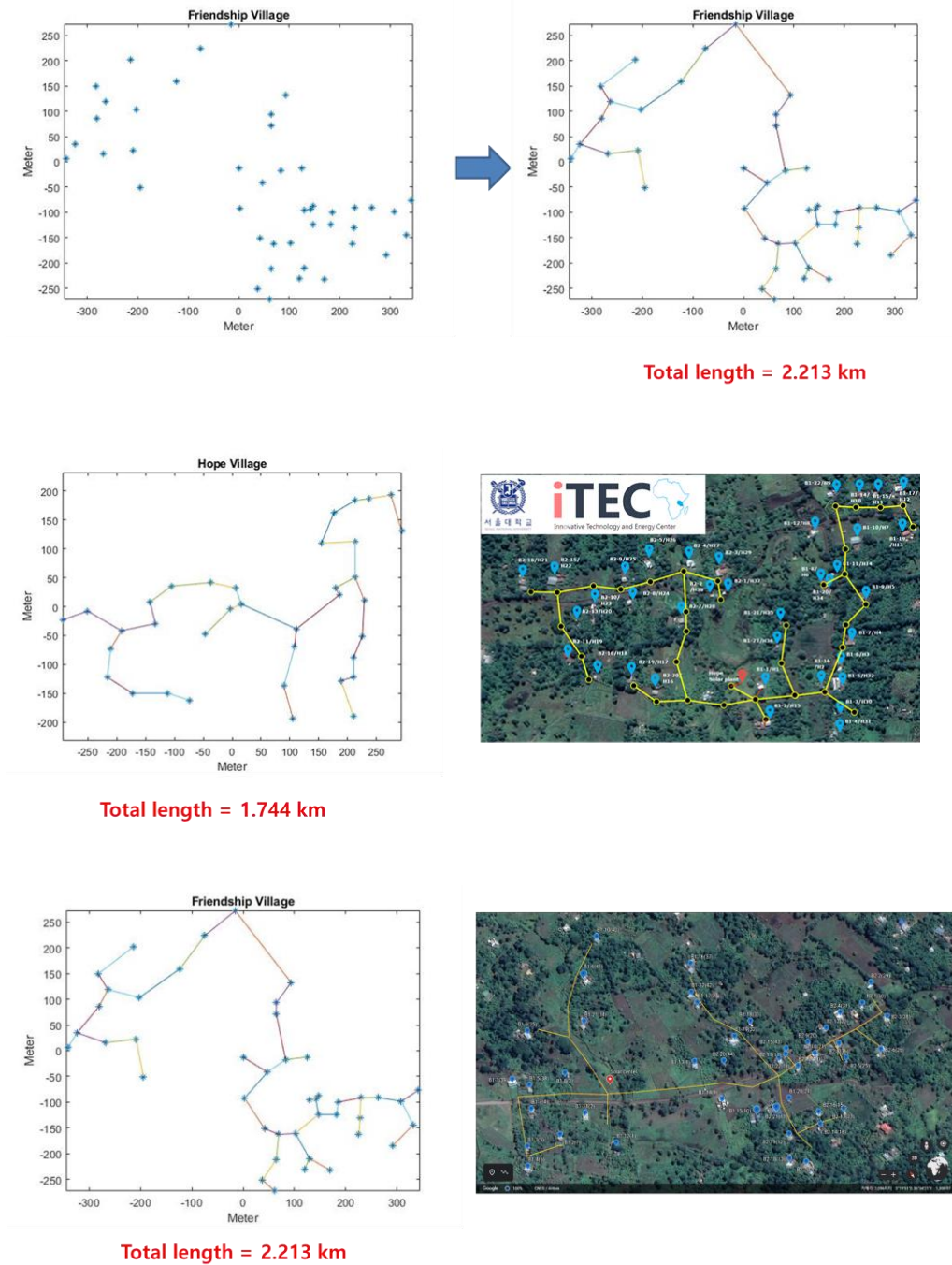


Total length = 1.744 km

Figure 3.9. The above code is used to generate the grid line for the Hope and Friendship Mini Grids located in Mkalama, Tanzania. The dots represent the location of houses. The third and fourth plots compare the generated network with the actual grid.

# Chapter 4. Load Profile

A load profile is a graph of the variation in the electrical load in units of power versus time. The area under a load profile curve gives the total energy consumed over the selected period of time. The load profile information is used to appropriately size components of the solar mini grid. The smart meters installed at each house generate the load profile of the house. A load profile can be represented as a vector for computation purposes. A load vector is a vector representation of a load profile. The load vector can be divided into hour, minute, or second or other convenient time steps. The time steps are usually equally spaced. The elements of the load vector are, therefore, the energy consumed in a unit time step. A smaller time step gives better accuracy but at a higher computational cost. The load vectors are based on one−hour time steps in this thesis. For example, a daily load profile can be divided into 24 element load vectors each area representing the energy consumed in one hour. A load vector can be a row or column vector.

$$Time \; vector \; = \; [t_1, t_2, \ldots, t_k, \ldots, t_n]$$

$$Time \; step = \Delta t \; = t_2 \; - \; t_1 = \ldots = t_k - t_{k-1} = \ldots = t_n - t_{n-1}$$

$$Load \; vector \; = \; [a_1, a_2, \ldots, a_k, \ldots, a_n]$$

$$\sum_{k=1}^{n} = t_k = total \; time$$

$$\sum_{k=1}^{n} = a_k = total \; load \tag{4.1}$$

The power consumed over each time step can be calculated by dividing the elements of the load vector with the respective time step. The power vector is important in devices where the energy addition or extraction rate has a limit such as in batteries and inverters. The maximum element in a power vector during a specified time period is called peak demand and it is measured in

units of power.

$$Time\ step = \Delta t\ = t_2\ -\ t_1 =...= t_k - t_{k-1} =...= t_n - t_{n-1}$$

$$Power\ vector = [\frac{a_1}{\Delta t}, \frac{a_2}{\Delta t}, ...., \frac{a_k}{\Delta t}, ...., \frac{a_n}{\Delta t}] =\ [p_1, p_2, ...., p_k, ...., p_n]$$

$$Peak\ demand = max\{p_1, p_2, ...., p_k, ...., p_n\} \qquad (4.2)$$

The household energy consumption is typically for lighting, cooking, and powering electronic devices and appliances. The following table shows the typical electrical power consumption ranges for technologies that have a potential to improve the quality of life of a household [28].

Table 5: Power consumption for different household appliances

| Electrical device | Power consumption [W] |
|---|---|
| LED lamp | 7−10 |
| Incandescent lamp | 40−100 |
| Phone | 2−7 |
| Radio | 1−5 |
| Television | 17−150 |
| Microwave | 600−1700 |
| Cooking stove | 2150 |
| Refrigerator | 100−200 |
| Washing machine | 400−1400 |

According to the international energy agency (IEA) the typical shape of load profile for a household in rural areas is as shown in the figure below [29]. It can be noted that the demand is very low after midnight, about one−eighth of the peak demand. The demand increases during the day to about three eighth of the peak demand. The demand peaks during the evening and starts to decrease for the rest of the night.
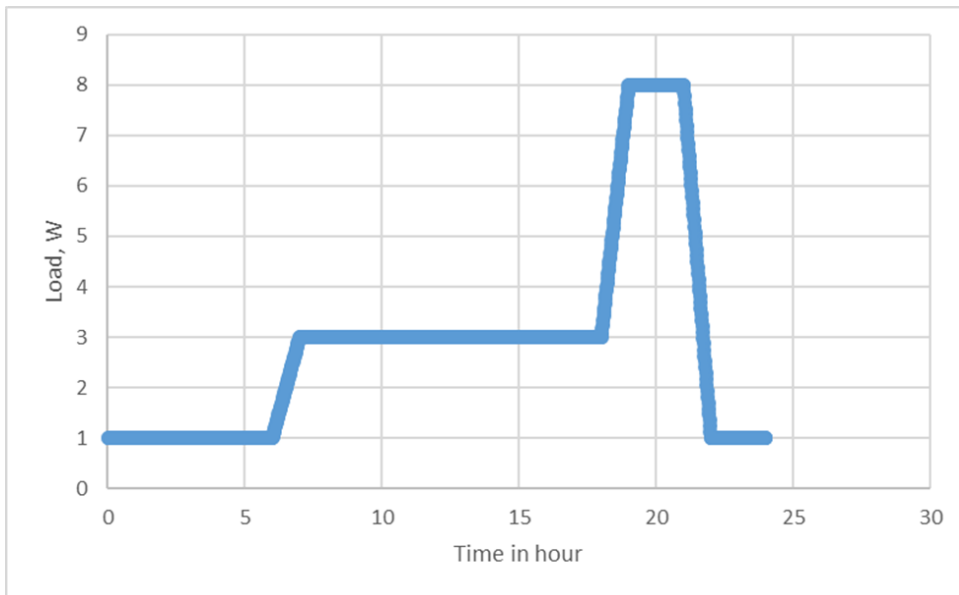


Figure 4.1. Typical shape of load profile for a household in rural areas

# Chapter 5. System Sizing

Solar panels convert the energy from the Sun into electrical energy. The MPPT keeps the power output from the solar panels at its maximum. The electricity after the MPPT is either sent to the end users if there is any demand and/or it is stored in the battery [9]. In some cases, the electricity generated is not sufficient or not present at all to supply the demand. In such cases, energy stored in the battery is used. In some other cases, the energy generated from the solar panel is more than the electricity demand and the available battery space for storing it. In such cases the extra energy that is generated is wasted. This energy is wasted purely because there is no demand or battery space to store it rather than the inefficiency associated with the energy conversion, storage or transport devices.
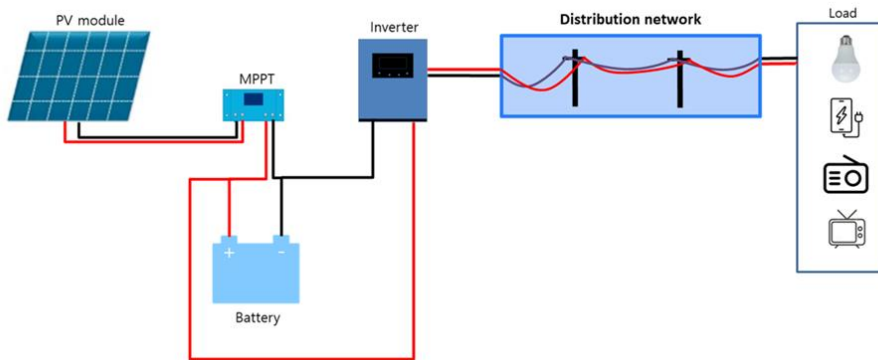


Figure 5.1. Schematic of Solar Mini Grid

The energy conversion efficiency associated with the energy conversion, transport and storage devices is captured in the device efficiency. The typical energy conversion efficiency of a solar mini grid components is presented in the following table.

Table 6: Energy efficiency of solar mini grid components

| Component | Efficiency |
|---|---|
| PV derating factor | 0.90 |
| MPPT efficiency | 0.95 |
| Battery round trip efficiency | 0.92 |
| Battery round trip efficiency | 0.96 |
| Battery round trip efficiency | 0.96 |
| Inverter efficiency | 0.95 |
| Distribution network efficiency | 0.98 |

Energy is transported at the speed of light in electrical wires [30]. Therefore, the energy generated at the solar panel is transported to the end user almost instantaneously in cases where it is not stored in the battery. Therefore, the energy transport in electrical wires has a very small characteristic time. The energy from the Sun or the electricity demand, on the other hand, does not fluctuate in such order very short of time. The characteristic time for electricity generation or demand change is much larger than the characteristic time the energy takes to travel to the end users. In this thesis, the energy from the Sun and the electricity demand are modeled as a step function with a step size of one hour.

The components of a mini grid should be sized optimally so that the system meets the required electricity demand at a minimum cost possible [31]. In this thesis, the levelized cost of electricity is the variable that is minimized in sizing of components with the constraints being solar irradiance and electricity demand. The energy balance is performed in such a way that the electricity demand in one hour is balanced by the energy generated from the solar panel in one hour or from energy stored in the battery. Time resolutions smaller than one hour could provide better accuracy but

at a higher computational cost. Based on the fact in the previous paragraph, a time resolution of one hour will give fairly accurate results with a reasonable computational cost.

The code flow to size mini grids is given in the following figure. It starts with solar irradiance and electricity consumption data as inputs. Initially the battery size is set very large to the level that it can power the yearly demand without being charged from the solar panel. In this case the PV size is zero. The battery size that is utilized is obtained by subtracting the full battery size to the lowest battery charge recorded during operation and dividing the result by the depth of discharge of the battery. The levelized cost of electricity (LCOE) is then calculated and saved. In the next step in the loop, the solar panel size is increased by a small amount and the corresponding battery size is calculated. The loop continues until sufficient PV and battery sizes are obtained. The combination that gives the minimum LCOE is then chosen.

The size of the MPPT can be obtained by multiplying the power output from the solar panel by a certain scaling factor to accommodate situations that could be beyond estimated. The typical scaling factor is 1.2. The size of the inverter is also found using a similar way. It is obtained by multiplying the maximum power the inverter is expected to face in its lifetime by a scaling factor. The scaling factor used in this thesis is 1.2 again. The grid sizing is performed independently of the solar irradiance and electricity demand.
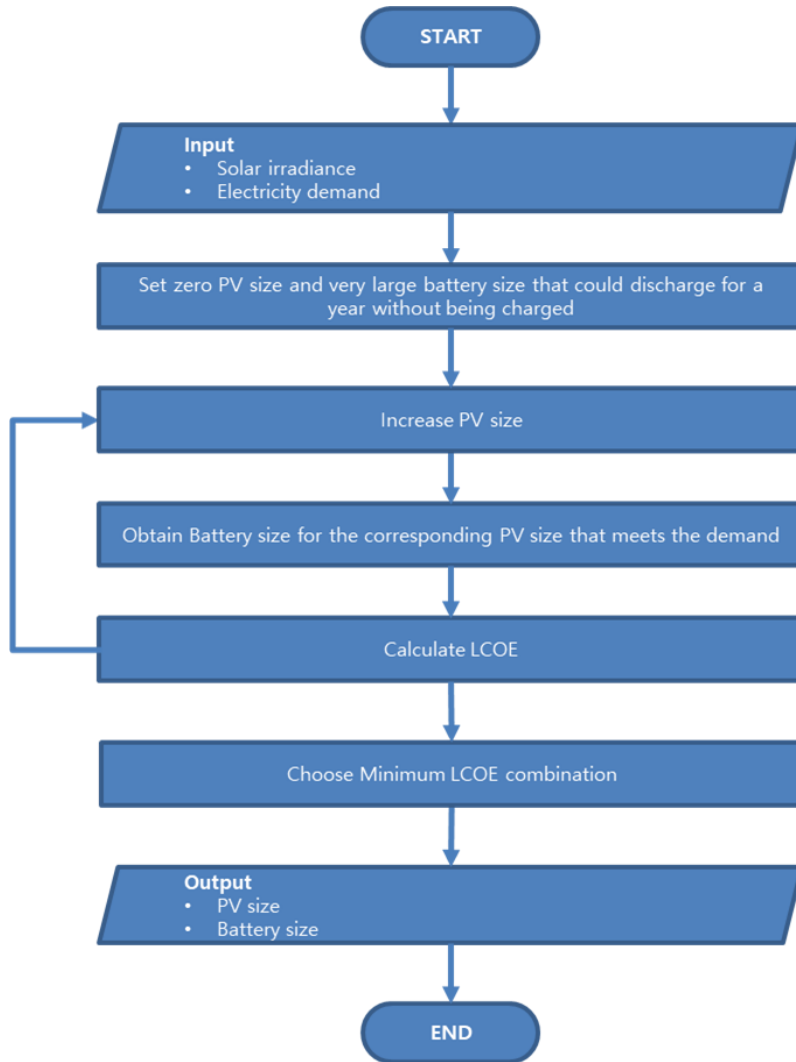
Figure 5.2. Code flow to size mini grids

$$Generation: \ PV_{gen}(i) \ = \ DF * ME * PV_{gen} * \frac{Irradiance(i)}{1000}$$

$$Charging/Discharging: \ SOC(i)$$
$$= \ SOC(i-1) \ + \ \{PV_{gen}(i) - \frac{Demand(i)}{IE * DN}\} * \sqrt{BE}$$

(5.1)

$DF:$ $PV$ $Derating$ $factor$
$ME:$ $MPPT$ $efficiency$
$BE:$ $Battery$ $efficiency$
$IE:$ $Inverter$ $efficiency$
$DOD:$ $Depth$ $of$ $discharge$
$DN:$ $Distribution$ $network$ $efficiency$

The typical load profile for rural households in rural areas is presented in the previous section. In this section, the component sizing based on the load profile is investigated, particularly the effect of peak power while keeping the load shape the same. It can be noted that the PV, battery, inverter, and MPPT sizes increase linearly with the peak power. The distribution system cost is assumed not to be affected by the peak power.
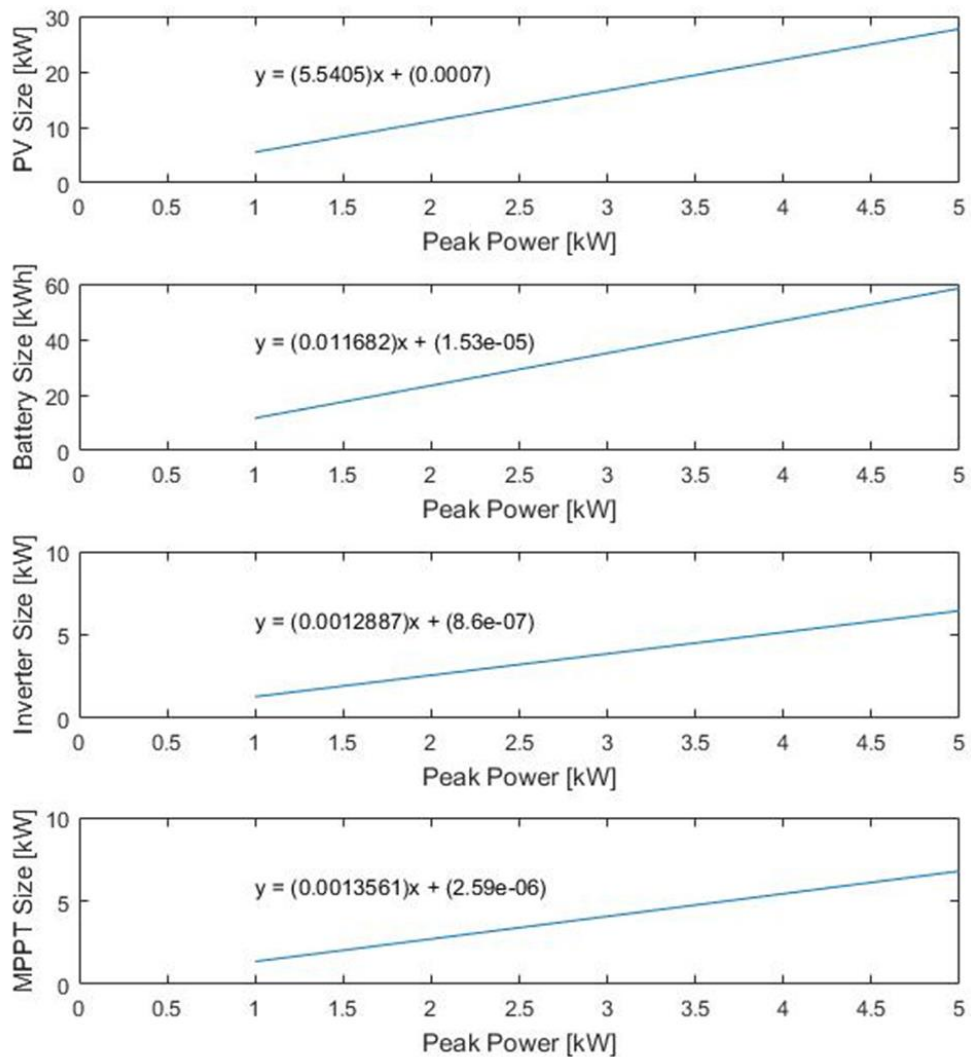


Figure 5.3. Effect of Peak Power

A share of component costs for the above load profile with peak power from 1kW to 10kW and grid length of 2.5 km is given below. The total LCOE is composed from the generation and distribution part. It can be noted that as the peak power increases the cost becomes more dominated by the generation part. Since the grid length is constant the LCOE share from it is constant.
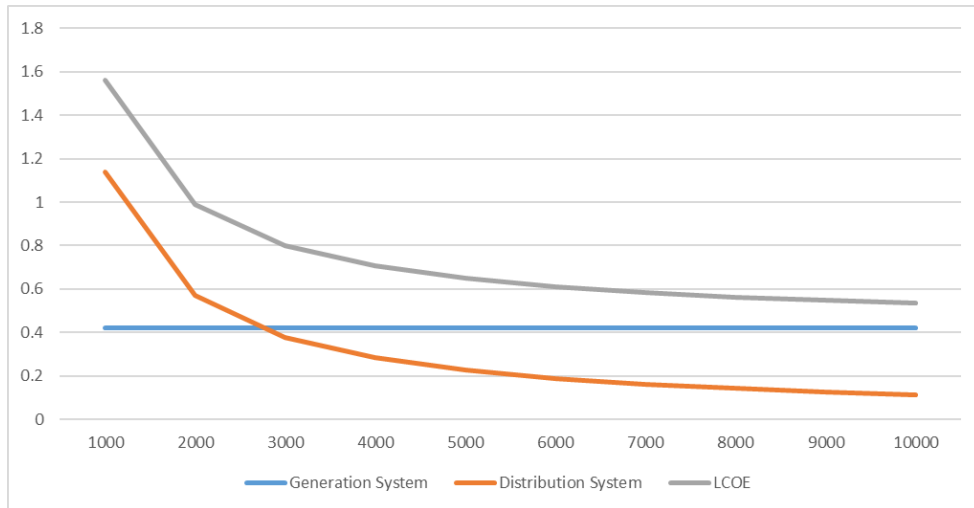


Figure 5.4. LCOE share of mini grids for generation and distribution system at different peak powers

Different load shapes have an effect on the size of components of the solar mini grid. A load profile similar to the Sun irradiance at the surface of the solar panel yields the theoretical minimum cost because there is no unutilized energy and storage cost. On the other hand, if all the load is shifted to the night with the same load profile, there will be battery discharge during the day and the PV size is larger than the previous case to compensate for the energy loss at the battery. It can also be noted that there is no curtailment.

Peak Load = 420 W

Daily Load= 2.28 kWhr

PV Size = **493 W**

Battery Size = **0 Wh**
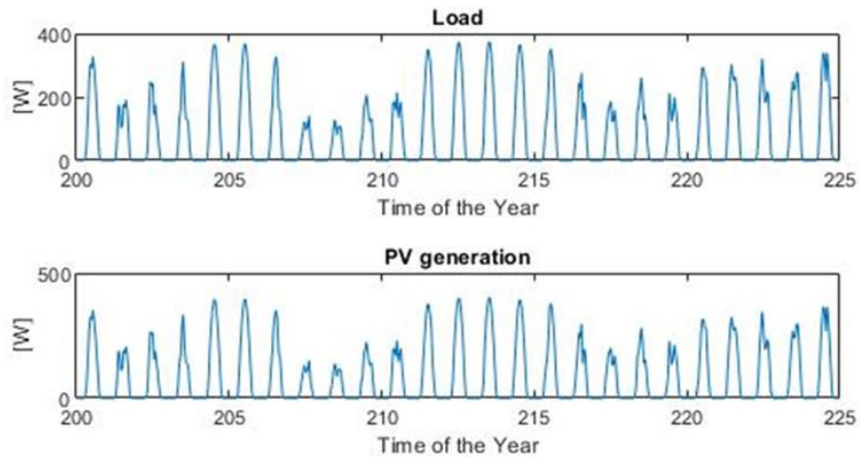
Inverter Size = 540 W

MPPT Size = 570 W



Figure 5.5. A load profile similar to the Sun irradiance

Peak Load = 420 W

Daily Load= 2.28 kWhr

PV Size = **536 W**

Battery Size = **8774 Wh**

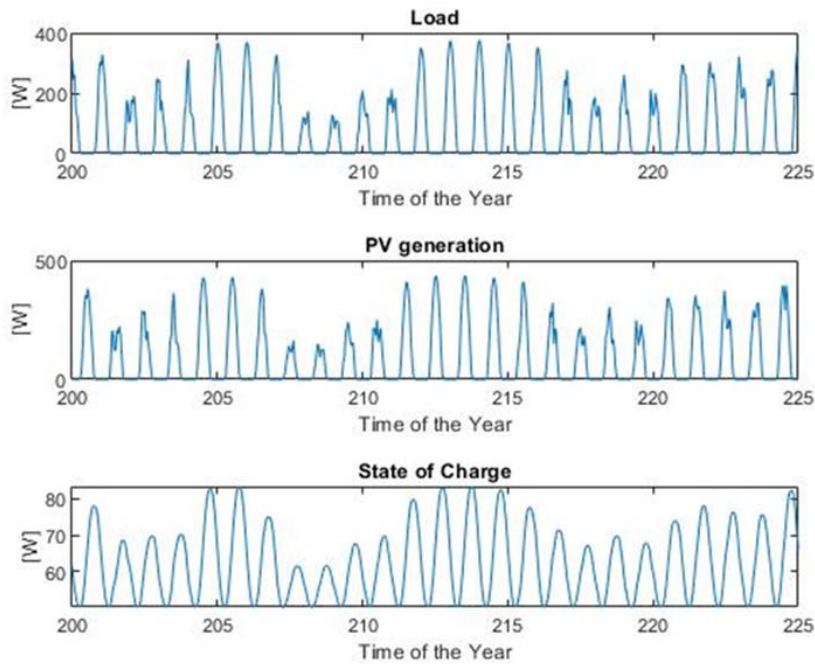Inverter Size = 540 W

MPPT Size = 570 W

Figure 5.6. A load profile similar to the Sun irradiance but shifted to the night

A load profile "similar" with the solar irradiance requires the least storage capacity. Such load profiles enable the energy generated not to encounter the inefficiency associated with the battery. Therefore, the need for smaller storage capacity and increased efficiency leads to lower LCOE. We can take advantage of this gain through load shifting – making the demand more "similar" with solar irradiance.

Reliability is an important parameter in mini grid design. It can be defined as the ratio of time with electricity to total period of time. Electricity blackouts could occur due to component malfunctioning or weather conditions. In this section, component malfunctioning is ignored and all the components of the mini grid are assumed to operate during the entire lifetime of the system.

The following code calculates the reliability of the solar mini grid for a given solar irradiance and electricity demand, PV and

battery sizes. If the electricity generated by the PV and the available energy from the battery is less than the demand, the supply is less than demand. In this case, the reliability of the system is less than one. The battery will be fully discharged by the end of the process. In the second scenario, if the electricity generated by the PV is greater than the demand, however, the electricity generated by the PV and the available energy from the battery is less than the demand, the demand can be satisfied by the supply, therefore, the reliability in this time slot is one. The battery will not be fully discharged. In the third scenario, if energy generated from the PV is greater than the demand, the battery will be charged from the leftover charge and the demand is satisfied. In this timeslot the reliability is one.
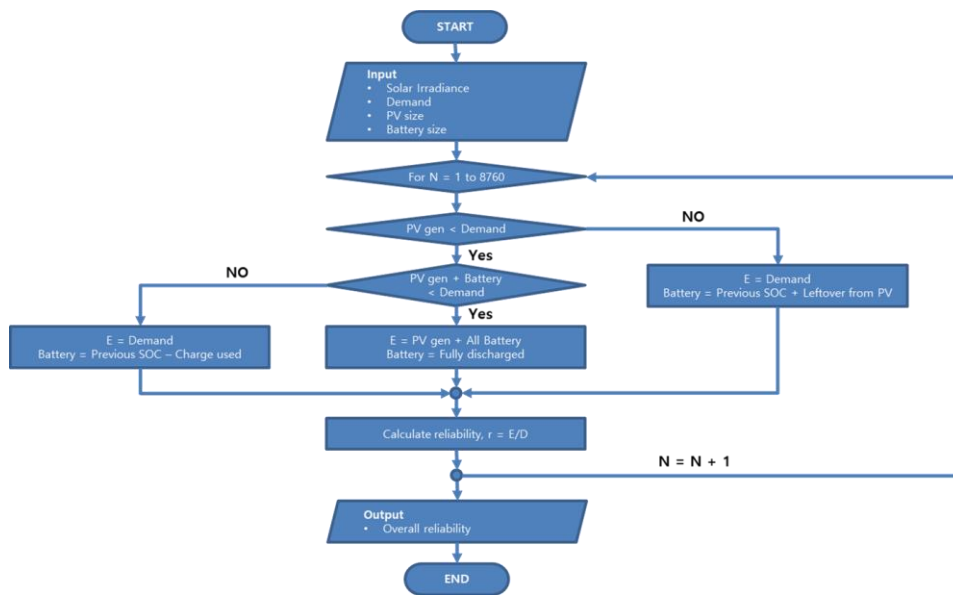


Figure 5.6. Code flow to calculate the reliability of the solar mini grid

The following code plots the reliability vs LCOE curve given the solar irradiance electricity demand data.
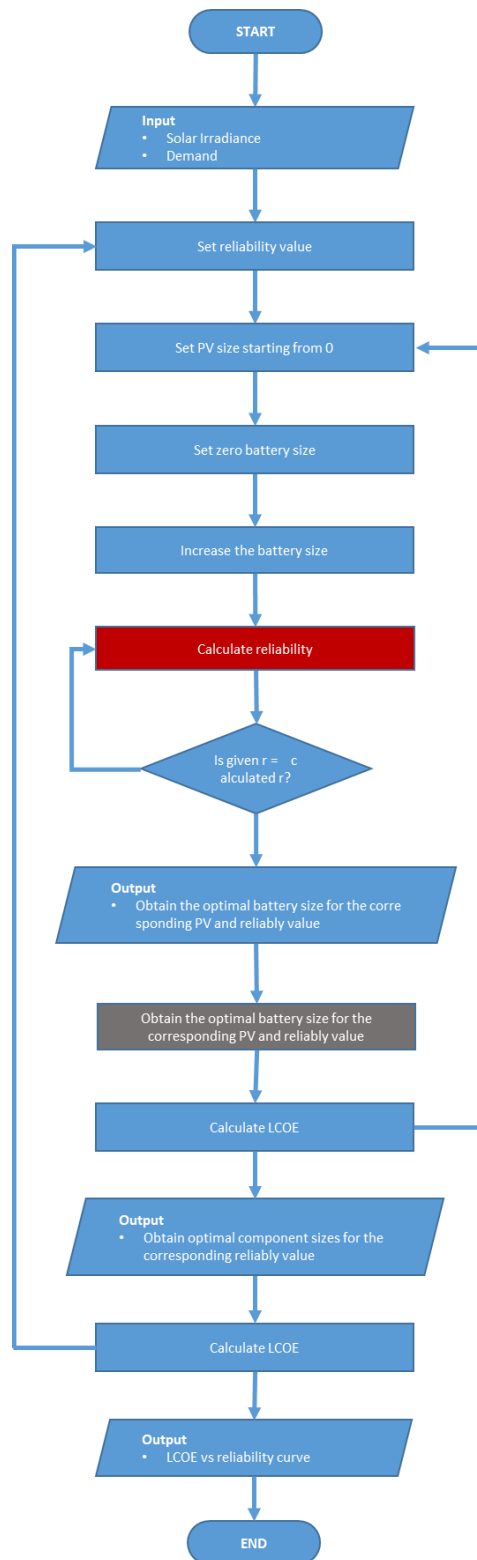
Figure 5.7. Code to generate reliability vs LCOE curve

The following plot shows reliability value for a load profile given in chapter four with peak power of 1.3 kW. As the size of PV and battery increases, so does the reliability. However, it can be noted that after a certain point, the reliability saturates at one. For the plot below a PV size of 7.2 kW and battery size of 15.2 kWh gives a reliability value of one at the minimum cost possible.
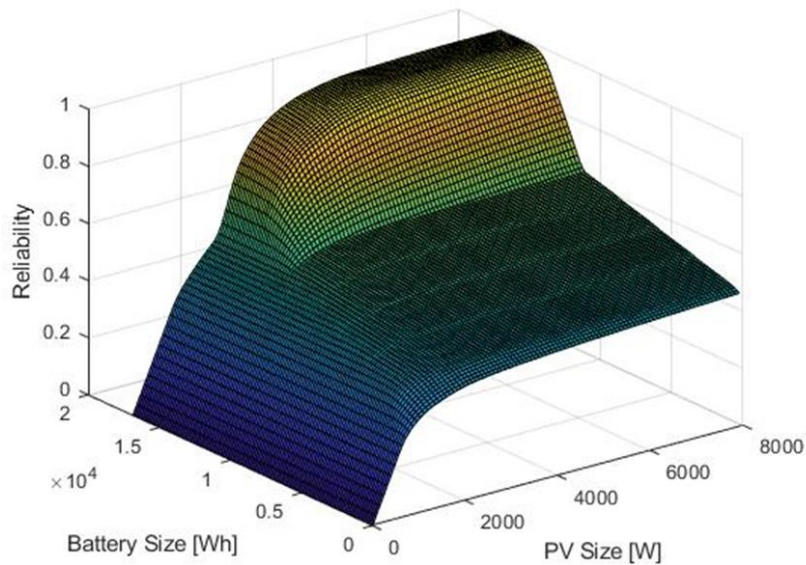


Figure 5.8. Reliability for a load profile given in chapter four

The same type of graph can be plotted for a different load profile. The following plot shows the reliability value for a constant demand of 500 W for different battery and PV sizes. A PV size of 7.0 kW and battery size of 14.3 kWh gives a reliability value of one at the minimum cost possible.
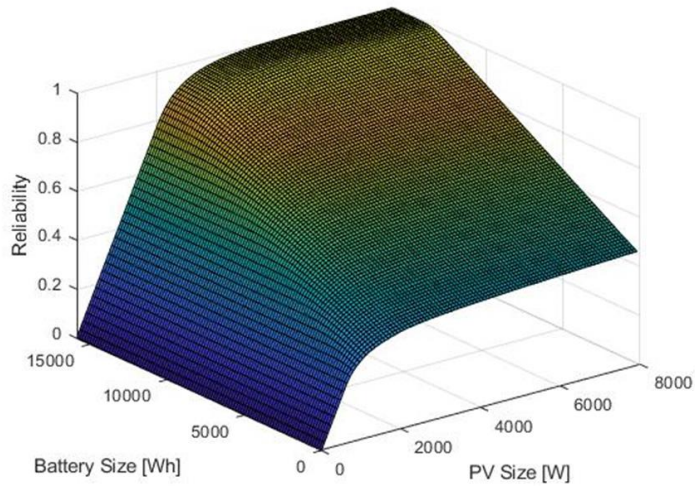
Figure 5.9. Reliability for a constant load

The same plot with a load profile similar to the solar irradiance is shown below. A PV size of 1.52 kW and battery size of 0 kWh gives a reliability value of one at the minimum cost possible.
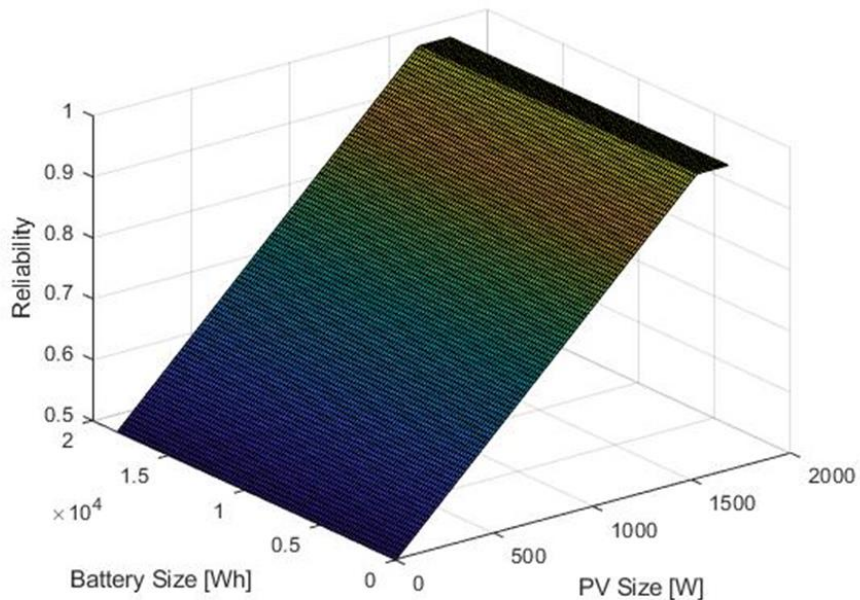


Figure 5.9. Reliability for a load profile similar with Sun irradiance

The following plot shows the LCOE vs reliability curve for a generation system. As can be noted as the reliability increases the

cost also increases. There is a sharp increase in reliability values
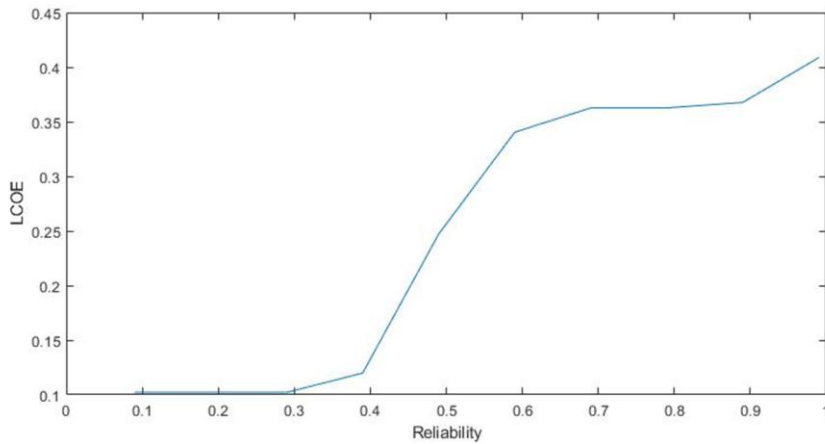between 0.4 and 0.6.
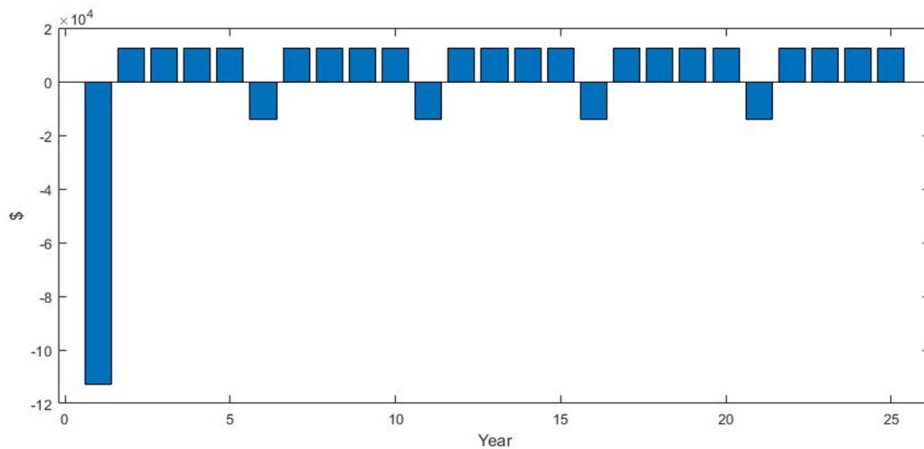


Figure 5.10. LCOE vs reliability curve



Figure 5.11. The above graph shows the typical investment-profit
versus time graph of a solar battery mini grid. Investment in the
first year and gain in two to five years can be noted. Investment in
the sixth year to replace the battery can also be noted.

# Chapter 6. Mini Grid Clustering

Mini grid clustering is defined as connecting two or more mini-grids together. Mini grid clustering may lead to improved mini grid performance such as improved affordability, reliability, system efficiency, resiliency, availability of productive power etc. A mini grid becomes more affordable when the electricity price is reduced, more reliable when the total electricity black out durations are reduced, more efficient when the energy wasted is lowered, and more resilient when it can recover quicker from any disasters that could happen to it.

Two or more mini grids can be connected through a controller in between the mini grids. Current always flows from a higher voltage to a lower voltage. By creating a small voltage difference, the direction of current flow can be controlled. In addition, for mini grids that operate based on alternating current, the phase should be matched between the mini grids so that the energy waste is minimized [32].

The primary determinant for clustering is whether clustering enables a reduction in electricity price, particularly levelized cost of electricity or LCOE. Electricity price can be decomposed into LCOE and an extra price above the LCOE which will accumulate to become a profit for the electricity provider. Therefore, LCOE has a direct impact on the electricity price.

Let Li be the independent mini grid LCOE for the $i^{th}$ mini grids and are defined as follows.

$$L_i = \frac{C_i}{E_i} \qquad (6.1)$$

Let's say X amount of extra money is spent for clustering and Y amount of extra energy is utilized as a result. The new LCOE $L_c$ will become

$$L_c = \frac{X + \sum_{i=1}^{n} C_i}{Y + \sum_{i=1}^{n} E_i}$$ (6.2)

All X, Y, $C_i$, and $E_i$ should be discounted to the present when calculating the $L_i$. Therefore clustering is advantageous for the $i^{t,i}$ solar mini grid if the new levelized cost of electricity, $L_c$ is below $L_i$. That is:

$$L_c \leq L_i$$ (6.3)

The extra cost for clustering comes from the construction and operation of the electricity line to connect the mini grids and from controllers employed to match the current flow. In addition, in typical solar mini grids, solar mini grids with the load profile similar to the one given in chapter 4, more than half of the possible electricity generation capacity is not utilized merely because there is no electricity demand when there is a possible electricity generation capacity. Therefore, connecting two or more mini grids together may enable this extra energy to be transported to the other mini grid and be utilized as a result to lower the levelized cost of electricity.

**For example**
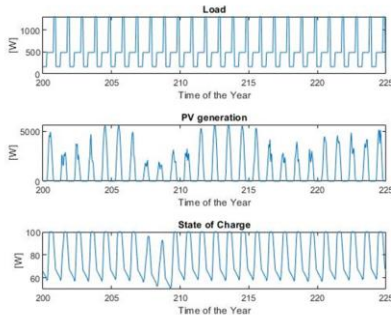


Peak Load = 1.3kW

PV Size = 7kW

Battery size = 18.8kWh

**LCOE = 1.05$/kWh**

% of PV generation wasted = 57%

If all the electricity generated were utilized, the LCOE would have been
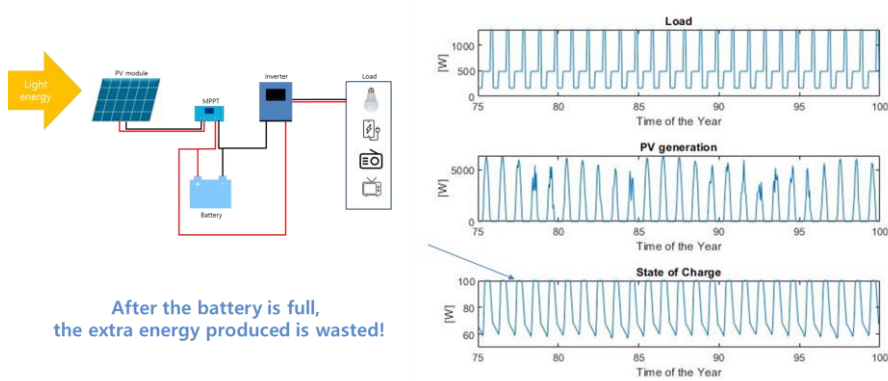
**LCOE = 0.44$/kWh** (58% ⬇)

Figure 6.1. More than 50 percent of the electricity generated is not utilized in typical solar mini grids

In addition, since the probability that two or more mini grids collapsing together at the same time is lower than collapsing at two different times, connecting the mini grids together could enhance the reliability and resiliency of the whole system. Mini grid clustering also enables availability of a more productive power. As mini grids are connected, the available maximum power also increases, which in turn increases the possible number of productive machines that can be incorporated to the mini grid that can be operated. Therefore, mini grid clustering enables electricity for productive uses or income-generating activities. Typical technologies for productive uses include irrigation pumps, refrigerators, crop harvesters, grain millers, sewing machines.

Aggregate load profile is the sum of individual load profiles. The aggregate load profile is usually similar with household load profile as the consumption pattern of households tends to be similar. A parameter called coincidence factor characterizes the diversity of individual loads [33]. Coincidence factor (CF) is calculated as the ratio of the peak aggregate load to the sum of the individual peak loads.

$$CF = \frac{P_{peak,agg}}{\sum_{k=1}^{N} P_{peak,k}} \quad (6.4)$$

It can be noted that coincidence factor decreases with increasing number of connected houses as the probability that these individual loads picking at the same time becomes smaller and smaller. Therefore, it can be noted that more diverse loads lead to low coincidence factor which in turn is more desirable as it leads to smaller mini grid component sizes.

# Chapter 7. Conclusion

A framework to decide clustering of mini grids is developed. Clustering becomes more desirable as the loads are diversified. clustering is advantageous for a given solar mini grid if the new levelized cost of electricity after clustering is below independent mini grid levelized cost of electricity. Mini grid clustering also enables availability of a more productive power and improved reliability and resiliency.

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# 초록

태양광 미니 그리드는 독립형 시스템이나 국가 그리드 확장에 비해 특정 틈새에서 비용 편익을 제공하지만, 일반적인 태양광 미니 그리드의 무보조 전기 가격은 국가 그리드의 전기 가격보다 3배에서 10배 높다. 또한 일반적인 태양광 미니 그리드에서 발전 용량의 상당 부분이 활용되지 않는다. 미활용 전력량이 가능한 발전 용량의 50% 이상에 도달하는 경우도 있다. 따라서, 태양광 미니 그리드의 경제성을 높이는 방법 중 하나는 다양한 방법을 통해 전력의 활용도를 높이는 것이다. 본 논문에서는 미니 그리드 클러스터링 개념을 제안하며, 특히 태양광 미니 그리드의 클러스터링을 결정하는 프레임워크를 제시한다.