CHALMERS
UNIVERSITY OF TECHNOLOGY

Determining the Techno-Economic benefits of Energy storage in Solar PV Mini-grids

Study in rural regions of sub-Saharan Africa and India

Master's thesis in Sustainable Energy Systems

SHREYAS GOPAL SAVANUR

DEPARTMENT OF SPACE, EARTH AND ENVIRONMENT,
ENERGY TECHNOLOGY

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021
www.chalmers.se

DEPARTMENT OF SPACE, EARTH AND
ENVIRONMENT, ENERGY TECHNOLOGY
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021
www.chalmers.se

Determining the Techno-Economic benefits of Energy storage in Solar PV Mini-grids

Study in rural regions of sub-Saharan Africa and India

SHREYAS GOPAL SAVANUR

CHALMERS
UNIVERSITY OF TECHNOLOGY

Determining the Techno-Economic benefits of Energy storage in Solar PV Mini-grids
Study in rural regions of sub-Saharan Africa and India
SHREYAS GOPAL SAVANUR

Supervisor: Elias Hartvigsson, Department of Space, Earth and Environment
Examiner: Erik Ahlgren, Department of Space, Earth and Environment

Master's Thesis 2021
Department of Space, Earth and Environment
Division of Energy Technology
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: ……………………………………….

Printed by Chalmers Reproservice
Gothenburg, Sweden 2021

Determining the Techno-Economic benefits of Energy storage in Solar PV Mini-grids
Study in rural regions of sub-Saharan Africa and India
SHREYAS GOPAL SAVANUR
Department of Space, Earth and Environment
Chalmers University of Technology

Abstract

The aim of the study is to determine the technical benefit provided by the battery in a solar mini-grid. Mini-grids are used to increase electricity access to regions which lack access to the main grid. Existing literature on mini-grids in rural areas displayed the potential of electricity access. However, the lack of research in the battery utility in solar mini-grids in existing literature resulted in the aim of the thesis. The study was conducted with a focus on the technical and economic aspects.

The first step was to compare the effect the types of load profile has on the capacity on the battery. The next step was to compare the effect of battery in an economic perspective. An indicator called economic utility was found, which equates to the extra time required to get the investments back if the battery is installed in the system. This was calculated by comparing the investment costs and revenue from tariff, for a system with and without a battery.

A simulation model was used to represent the system. Three scenarios were created as an input to the simulation model. These scenarios represent different characteristics of load profiles, which captures the data from previous research in different regions. The scenarios also account for the change in solar insolation in different geographical regions and at different times of the year.

Results were extracted from the simulation model and economic utility was calculated. The results conclude that the solar insolation does not have a large impact on the battery capacity. However, the load profile has a profound impact on the battery requirement. Both the peak load demand and the total daily load was proportional to the battery requirement. The investment costs were found to not be directly dependant on the battery capacity but the economic utility was found to be proportional to the investment cost of the system.

Keywords: mini-grids, battery capacity, load profile, simulation model, solar insolation, peak load

Acknowledgements

I would like to thank my examiner, Erik Ahlgren and my supervisor, Elias Hartvigsson who have patiently guided me throughout the thesis. I would also like to thank Anton Bergman for giving me feedback to help me gain a different perspective. I could not have done any of this without the constant backing from my parents and family. I would also like to thank my friends who kept me motivated throughout the thesis.

Shreyas Gopal Savanur, August 2021

Contents

List of Figures ... 1
List of Tables ... 2
1 Introduction ... 3
1.1. Background ... 3
1.2. Aim ... 5
1.3. Research Questions ... 5
2 Theory ... 6
2.1. System Requirements ... 6
2.2. Constrained Equations ... 7
3 Methodology ... 9
3.1. Method ... 9
3.2. Literature Review ... 10
3.3. Simulation Model ... 11
3.4. Modelling Equations ... 11
3.5. Economic evaluation ... 13
3.6. Scenarios ... 14
3.7. Data Collection ... 16
4 Results ... 18
5 Analysis ... 21
5.1. Technical Ability ... 21
5.2. Economic Terms ... 23
6 Discussion ... 25
6.1. Method ... 25
6.3. Limitations ... 26
7 Conclusion ... 27
References ... 29
Appendices ... 31
Appendix A ... 31
Appendix A1 ... 31
Appendix A2 ... 31
Appendix A3 ... 32
Appendix B - Data collected for Scenario 2 ... 33
Appendix B1 ... 33

Appendix B2 33
Appendix B3 34
Appendix C- Data collected for Scenario 3 35
Appendix C1 35
Appendix C2 35
Appendix C3 36

List of Figures

Figure 1- Flowchart of the method 09
Figure 2- Relationship between supply and demand for Scenario 1 18
Figure 3- Relationship between supply and demand for Scenario 2 18
Figure 4- Relationship between supply and demand for Scenario 3 19

List of Tables

Table 1- Specification of Scenarios 15
Table 2- List of Variables and Constants used in modelling 16
Table 3- Comparison of Scenarios 20
Table 4- Results from model for all scenarios 37

1
Introduction

1.1. Background

About 1 billion people lack access to electricity with majority of that population living in Sub-Saharan Africa and Asia. Most of them live in rural areas which do not have access to the grid due to the geographical and economic restrictions in the region. Hence, off-grid systems are a possible solution for electrifying these regions [1].

Improvement in electricity access in rural areas directly corresponds to increased productivity in daily activities like local businesses, laundry, power tools and laboratories [2]. The effect of employing renewables can also be felt indirectly by reducing dependency on traditional fuels. These are a source of large amount of emissions and negatively impacts lives of the residents [3]. Also, it helps the community economically by driving it away from the price fluctuations of traditional fuels hence, developing other criteria like health, food, or entertainment. The reduced maintenance cost of the grid brings up the opportunity for rural business to strengthen the community and environment [4]. Overall improving the quality of life of the community.

The decrease in cost of photovoltaic cells have made solar mini-grids a viable option in rural regions. Also, the operating cost of generating electricity from solar is minimal compared to conventional sources of energy considering the transport cost of fuel to the region [5]. Energy storage is added to the system to manage the day and night variations from solar energy, which provides consistent supply of energy throughout the day. It also reduces curtailment of solar when there is no demand for electricity.

The type of storage depends on many factors among which variations from the energy source, duration of requirement, frequency of charge and discharge are predominant. Grid scale storage can be e.g. batteries, hydrogen storage, pumped hydro storage etc. which are chosen based on requirement of the grid. Batteries are the most common option for storage in such a mini-grid because of the diurnal nature of charge and discharge [6]. Also, batteries are used in the mini-grid to increase the availability of electricity throughout the day. It can also balance the electricity price as it reduces the peak power demand by storing excess renewable energy which can be discharged during hours of no renewable generation replacing the expensive, conventional source of generation. Storage also replaces traditional fuel generators which are used as backup to the main source of generation, hence reducing the carbon emission and reducing the operating costs that might have been incurred due to fuel usage [3]. The most important aspect for minimizing investment cost while employing a battery is the sizing (capacity) of the battery. Cost Optimization leads to minimal investment and better power quality and power reliability [4]. The nature of usage of the battery is a major factor to determine the size. The limited availability of financial resources for the off-grid systems means size of the battery should be meticulously designed to satisfy the demand and be economically reasonable.

Optimal sizing of the off-grid system is beneficial in reducing cost of system [7]. One of the hurdles in dimensioning the appropriate size of generation and storage needed, is the lack of accurate load profile data. Assessment of load profile data is essential for selecting the type of storage [8]. Mini-grids are usually designed with the combination of productive and household load profiles [2]. The amount of electricity used by productive consumers depends on the type of productive users for example workshops, agriculture, IT services. The amount of electricity required by productive users might be less than households, but they generate revenue to the region [9]. The capacity of mini-grid directly affects social, economic and environment of the region and the development is context dependent causing the complexity of designing/sizing a mini-grid [10]. Productive use is directly linked with the availability of electricity. However, the productive use also depends on other factors like production of goods close to the region or ease of access to transport.

Research on the mini-grids is being conducted in different contexts based on geographical region. It is interesting to look at different mini-grids being worked on because the capacity depends a lot on the context of the system. In India, rural mini-grids are a supplement to the main grid to increase the electricity access [11]. It is a combination of mini-grid and main grid, the requirement for storage is either limited or non-existent due to the reliance on the main grid for greater power reliability. Hence, the cost of the system is low because of the decreased investment in battery. As seen in mini-grids in a rural district in the state of Uttar Pradesh in India, the grants and funding acquired by non-governmental bodies boosts the growth of the project. Also, this creates a support for local productive users, which in turn increases the viability of the project [12]. However, these systems are reliant on the generation from the main grid which needs to have sufficient generation and transmission capacity and might emit greenhouse gases [11].

The revenue generated from the system is dependent on variables such as, load demand and tariff structure. The choice of tariff structure can strongly influence the long-term economic benefit of the system [7]. Generally, renewable energy-based systems use a time of use tariff or a demand tariff. Time of use tariff has one price in the daytime and lower price at nighttime based on Peak and low demands. Demand tariff uses real time electricity price and has a monthly peak demand cost for covering the capacity [13]. Another tariff that can be considered is a flat rate tariff, consisting of a fixed rate throughout the day, with a different tariff for different types of users (for example productive users and households have different tariff).

Current studies focus on the whole system with different energy sources, research on Solar mini-grids specifically are concerned with various methods to design the system. The environmental and social impacts are another area of focus. However, impact of adding battery to the system in economic and social terms are not easily answered. The economic impact of employing a battery in a solar mini-grid is a potential area of interest.

1.2. Aim

The aim of the thesis is to determine the benefit of employing a battery storage in a solar mini-grid system for different types of users, in terms of technical ability and economic gain. This includes changes brought about by the different load profiles with regards to using a power-based battery or an energy-based battery. Finally, the cost of the system is analyzed to determine the economic advantages of employing storage in the system.

1.3. Research Questions

- How does different load profiles affect the capacity (kWh) of storage in a cost optimal system?

- What advantages do the batteries provide to the system in monetary terms?

2
Theory

2.1. System Requirements

The capacity of storage depends on the amount of electricity needed by the system. The electricity usage of households and productive users are varying. Productive users are the customers using the energy for income generating activity, revenue of the system largely depends on these users. The productive users can be differentiated by the utilities used and the type of function they perform e.g. Flour mills, workshops, shops, small scale manufacturing, water pumping etc. The daily load profiles of both productive users and households are combined. Since, accurate annual load profiles are not readily available, generated daily load is a realistic demand for the region. The loads are calculated by assuming individual application in terms of power (kW) and each is multiplied with the number of hours it runs to get the energy (kWh), the sum of this is the total energy consumed.

Eq. 1
$$E_{load} = \sum_{x=0}^{n} (P_x * t_x)$$

Eq. 1 represents E_{load}, the total load on the system (kWh) and P_x is the power consumed (kW) by x application and t_x is the number of hours x is running. The storage should be charged when there is excess generation from solar PVs during the day and discharged when there is lesser generation from solar PVs compared to demand and during the times there is no generation from solar PVs (Eq. 2). In Eq. 2, Cap_{bat} is the capacity of battery which depends on total load E_{load} (kWh) and energy generated E_{Gen} (kWh). The capacity of storage should be sized so it can satisfy the demand during the night and during lower solar generation depending on the load profile. This enhances the power reliability of the system by supplying the demand during all times.

Eq. 2
$$Cap_{bat} \geq E_{load} - E_{Gen}$$

Load varies with respect to the type of users and generation varies with geographical location and number of PVs installed, the capacity of battery also varies. The investment cost depends on the capacity of storage required, so the costs will change with load profile. The results for different loads are compared with each other. As seen in Eq. 3, $CAPEX_{bat}$ is the capital cost for installing the battery and $OPEX_{bat}$ is the operation cost involved in using a battery, sum of which will yield the total cost of the battery.

Eq. 3
$$Total\ Cost_{bat} = CAPEX_{bat} + OPEX_{bat}$$

2.2. Constrained Equations

The geographic boundaries are mostly theoretically determined, however economic and technological specifications (such as type of storage, size of PV) are open ended. In the equations below, each technology is treated independently rather than as a whole system. Specification of each technology is constrained to theoretically understand the specifications of the technology.

The capacity of PV's installed in the system (Cap_{PV}) is determined by finding the total daily load over the whole day from the hourly load profile ($Load_{hr}$) and multiplying the power loss (δ) incurred when producing solar energy.

$$Cap_{\ PV} = \sum Load_{hr} * \ \delta$$

Battery capacity is found by multiplying the load at time t ($Load\ (t)$) and the number of hours the battery can be discharged without charging again (*Hours of Autonomy*), this is divided by the depth of discharge of the battery (*DoD*) and temperature factor of the battery (Δ).

$$Total\ Cap_{batt}(kWh) = \frac{Load(t) * hours\ of\ autonomy}{DoD * \ \Delta}$$

The battery will be charged using the excess solar energy generated after the load at that point in time is supplied. This means that the generation from solar (Gen_{PV}) should be greater than the load at time t ($Load(t)$), to charge the battery.

$$Gen_{PV}(t) > Load(t)$$

The maximum limit while charging will be the maximum State of Charge ($SOC(t)$) limit (usually 100) [14].

$$SOC(t) \leq 100 \qquad [14]$$

The battery is discharged when the load is greater than generated solar energy at time t. The battery can also be discharged in cases where the increase in load between two steps is very large, which would require a battery optimized for power. During high load event and zero or low solar generation, the battery is discharged.

$$Load\ (t) > Gen_{PV}(t)$$

The battery has an electrical limitation for the lower limit of State of Charge, so the battery should not be discharged below the limit (*CClimit*).

$$SOC \geq CClimit \qquad [14]$$

State of Charge at every time step is calculated to see if the battery is getting charged or discharged. If the generation is greater than load, the State of Charge will be greater than the previous time step i.e. battery is getting charged. On the contrary, if the load is greater than the generation means the State of Charge decreases compared to the previous time step i.e. battery is getting discharged.

$$SOC(t) = SOC(t-1) - [-Load(t) + E_{Gen}(t)] \qquad [14]$$

The intention of installing PV and batteries together is to supply the load demand at every point in time thereby increasing power reliability. The solar generation and capacity of the battery ($Cap_{Disbatt}(t)$) should be equal to the load at time t.

$$Load\ (t) = Gen_{PV}(t) + Cap_{Disbatt}(t)$$

3
Methodology

3.1. Method

The research questions are addressed by studying the existing system and technologies and then forming a methodology to answer the questions. The method devised to answer the research questions is described in this section. The objective is to find the benefits of having storage in a solar mini-grid in terms of the impact it has on the customers. The method can be split into two parts, first of which deals with the technical ability of the grid which includes deciding the battery and PV capacity. The other part deals with the economic part of the system, where the investment cost, electricity tariffs are found.

The structure of the method is illustrated in Figure , Details of each step is explained in the corresponding section. The objective is already described in section 1.2 and 1.3 above. The method was developed following the literature review with the objective to find the benefits of having storage in a solar mini-grid in terms of the impact it has on the customers. The benefits being investigated are in economic in nature. Different scenarios are used to observe the change in behavior of the results.

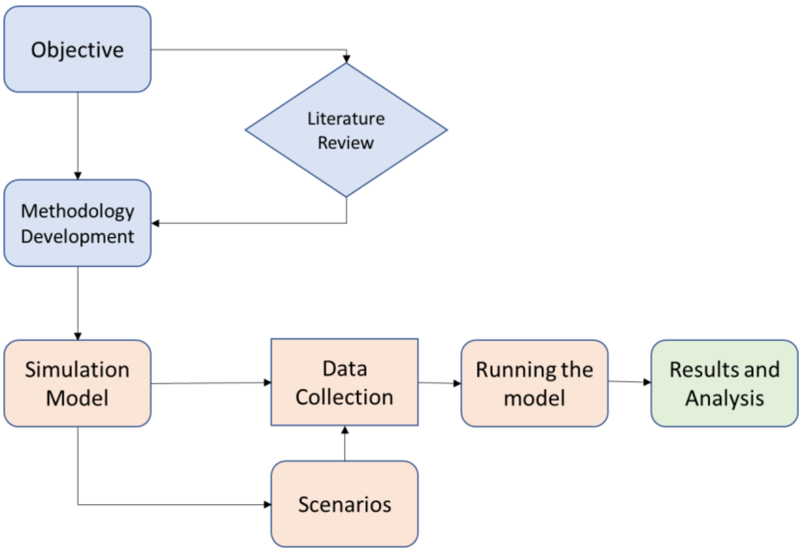


Figure 1- Flowchart of the method

3.2. Literature Review

In order to formulate a plan to answer the research questions the systems being used in present day in rural regions needs to be understood. This includes the utility of batteries in mini-grids and the planning of size of generation and battery in the mini-grids. Research and development of mini-grid systems have been conducted for many years now, but mini-grids in the rural regions is relatively new (source). The advantages of having a mini-grid and battery storage has been individually studied numerous times. However, the study of using a battery in the mini-grid is not well documented. Commonly used methods for grid optimization were studied to observe the trend in research.

A multi-objective approach focusing both on technology and economy where the microgrids are modeled for a battery-PV system considering the technical factors based on battery life and economic factors like payback. Focus on the state of charge (SoC) and state of health (SoH) of the battery to indicate the lifetime. Total cost of the system is calculated using the capacity of generation and the unit cost of each technology. Also, the tariff system that can help the investment are considered while sizing. The focus on taking advantage of the tariff system is another plus using this method. However, it doesn't have an economical limitation and the tariff systems considered might not be appropriate for an upcoming mini-grid [15].

Another multi-objective model, a bus injection model can be used for sizing of energy storage. First step is to find the total installed capacity and second is to find the optimal size of storage. Many scenarios are computed in this approach, with one scenario solved at a time to reduce the computation load [16].

Optimum size of generation and storage required are found by finding the lowest Net Present Cost (NPC) using specialized tool to find an optimal sizing model, called HOMER (Hybrid Optimization Model for Electric Renewables). Since, Technical data was available easily to satisfy the purpose, it is a good approach to find the optimal sizes. However, it is hard to find all the technical details of a larger system, which involves many assumptions causing inaccuracies [5].

For regions where the load profile data is not available readily, LoadProGen is used to generate the possible load profiles of the region to decide the optimal grid size. Then different combinations of PV-Battery sizes are simulated to satisfy the loads, the lowest Net Present Cost is chosen as the optimal solution. However, it is a single objective approach [8].

When optimizing the net Present Value, a rather complicated method considering all the economic variables using different tariff for household and business consumers. A Mixed Integer Linear Program is used to carry out such optimization [7]. The profitability of the off-grid system is determined by optimizing the NPV, Economic utility, LCOE using a multi-objective approach. A single objective method can also be considered which can be more relevant to the required objective, with revenue and CAPEX as the output function [17].

To investigate the size as well as the timing this method considers the amount of energy bought and sold as the objective. Using a function for cost consisting of stored energy, market price of electricity and battery size and a decision variable is computed by the amount of energy that should be charged and discharged from the battery with limits set to not overcharge or over discharge the battery [18].

3.3. Simulation Model

A model is planned to be used to evaluate the behavior of the system with the change in input, so the detail of each element can be limited to parameters that will change the behavior of the output. The system is planned to be designed using a simulation model of the mini-grid using a programming software, GAMS. The developed model is a tool to evaluate the advantage of having a storage in a PV mini-grid system. The ideology considered for modelling is –

1. Defining the problem
2. Choosing system boundaries
3. Simplifying the problem by making assumptions and excluding certain variables
4. Calculation
5. Interpreting the result.
6. Repeat step 2-5 with modified inputs

The required results are planned to be extracted from the model by the means of the iterative process. The system has many variables that might be important for the operation of the system but might not have a large impact on the characteristics of the current objective.

3.4. Modelling Equations

The constrained equations in section 2.3 can be used each if individual technologies are used. However, using these equations for modelling the whole system would hinder the flexibility of the system. Using the constrained equations as the foundation, the following model is created.

Inequalities are used so that the optimal solution can be chosen by the model from the various time steps. The input data required for the model is the daily load profile and daily solar generation. The minimum time step taken is one hour considering the average usage over the whole hour i.e. the variations in load (such as peaks) are accounted for. The objective function of the model is minimization of investment cost. However, the objective of the study is to find the advantage of having a storage in the system which is achieved by finding the optimal size of battery and system cost.

The idea behind deciding the size of PV's that are installed is that the size of PV should be greater than the total daily load multiplied by the power loss in the PV (which is taken as a constant number). The size of PV installed is used to find the hourly generation from solar. In order to model the solar capacity without restricting the size, the following equation was written down. Solar is the only source of energy in the mini-grid, so it is the primary energy producer which is considered for balancing the load in the system. Energy generation depends on the size of PV's installed and the hourly solar profile for the geographical region.

$$Gen_{PV}(t) < Cap_{PV}(t) * ProfilePV(t)$$

The equation limits the hourly generation from the PV ($Gen_{PV}(t)$) with the product of production profile at time t ($ProfilePV(t)$) and the capacity of the PV ($Cap_{PV}(t)$). The production profile is read from the input file which has hourly solar production from a 1kW PV, which gives hourly production in terms of kW produced per 1 kW installed.

A storage technology is needed to shift the energy produced during the peak production hours to the hours where the solar production is zero or lesser than the load. Storage becomes ever so important in such a system where there is a single source of production. Furthermore, the size of the storage needs to be designed in such a way that it improves the power reliability and keeps the cost to a minimum. Battery is the storage technology being employed in said mini-grid.

The size of batteries depends on the load and the number of hours the battery should be run without charging again.

$$bat_{lvl}(t) < \; maxcap_{bat}$$

The battery level at any point in time ($bat_{lvl}(t)$) should not exceed the maximum battery capacity ($maxcap_{bat}$).

$$bat_{lvl}(t+1) \; = \; bat_{lvl}(t) \; + \; cap_{bat}(t)$$

The capacity of the battery at the next time step ($bat_{lvl}(t+1)$) is sum of battery capacity at the current time step ($bat_{lvl}(t)$) and change in battery level ($cap_{bat}(t)$) i.e. charging or discharging. If the battery is charged, the capacity of battery increases and if it is discharged, the capacity decreases. The change in battery level at each time step, can be positive (charge) or negative (discharge).

The lower limit for battery capacity is constrained by limiting the capacity of battery at any time to be greater than the minimum capacity of the battery. The minimum capacity of the battery ($bat_{lvl}(t)$) is found by the least value of depth of discharge of the battery (DOD) multiplied by the maximum capacity of the battery ($maxcap_{bat}$).

$$bat_{lvl}(t) \; > \; maxcap_{bat} \; * \; (1 \; - \; DOD)$$

The energy capacity in the battery at any time t is found by finding the difference in charging and discharging and the energy in the battery at the previous hour.

$$Load\ (t) < Gen_{PV}\ (t) - cap_{bat}(t)$$

The load ($Load(t)$) should always be lower than the difference between production in PV ($Gen_{PV}(t)$) and the change in battery level at each time step ($cap_{bat}(t)$). This equation helps in deciding the capacity of PV required and the charge and discharge condition.

$$inv_{total} = cap_{PV} * inv_{PV} + maxcap_{bat} * inv_{bat}$$

Investment cost is the objective function of the model, which means the inequalities are changed with respect to minimising the investment cost. Investment cost of the system (inv_{total}) is calculated for a power and energy optimised battery separately by changing the investment cost of the battery accordingly. The price of power and energy battery is explained in 3.7. Data Collection section.

3.5. Economic evaluation

The model calculates the parameters required for the system from the perspective of the electricity grid such as the total cost of the system and the battery sizing. However, to determine the benefit of the battery in monetary terms economic calculations were conducted with the perspective of electricity consumers.

1. **Revenue from tariffs**
   A flat rate tariff is considered as mentioned in chapter which contains a fixed price each for commercial and household loads throughout the day. The revenue is calculated per hour of electricity used multiplied with the fixed tariffs. The total revenue is the sum of hourly household and commercial use, which is extrapolated over the whole year.

2. **Economic Utility of the battery**
   The investment cost and revenue generated over the whole year is compared. This indicates the extra time in years required to recover the investment cost of investing in a battery i.e. comparison of the investment made in the system and the corresponding change in revenue with and without a battery. The Economic Utility is an indicator to show the economic benefit of the battery [19].

$$Economic\ utility\ in\ years = \frac{inv\ cost\ (with\ battery - without\ battery)}{Revenue\ (with\ battery - without\ battery)}$$

There are two types of batteries considered for finding the investment costs. The two batteries are based on the usage i.e. energy or power battery. The loads influence the choice of energy or power battery. The longer duration requires larger energy storage capacity due to the evening household loads. Alternatively, the higher power requirement of commercial load might require the batteries to charge/discharge larger power output. However, the investigation in the model is purely economic in terms of power or energy battery investment. The investment cost is calculated for either an energy battery per kWh energy required or for a power battery per kW peak required.

3.6. Scenarios

The various scenarios are created to observe the behavior of the batteries for different types of load profiles. The load profile data for the rural regions is less readily available. Hence, the data sets used are realistic load data based on characteristic of the loads in different regions. The load profiles consist of a combination of household and commercial loads and the resulting load profiles are created using the NREL microgrid Load Profile Explorer [20]. Another distinction made in the scenarios is the timing of PV availability. The different solar generations are due to the geographical changes. The impact of change in solar insolation throughout the year on the sizing of battery is also investigated.

1. **Scenario 1**

The load profile created in this scenario consists of a steady load during the day with multiple small peaks as seen in Appendix A1. The day time peaks, 12:00 and 14:00 are a result of commercial loads and the evening peak at 21:00 is caused by household load. This scenario is created with Zambia as the reference for the loads [21]. Where 200 households are considered with 40% each of low- and medium-income household and 20% of high-income household. Since, agriculture was found to be primary occupation, milling and water pumps were the primary commercial loads. There is also consideration for a school, a clinic, few small shops and street lights in the commercial load. The daily load profile can be seen in Appendix A1.

Daily solar generation received in this region is almost 12 hours (from 06:00 – 18:00) throughout the year. The peak load corresponds to the peak solar generation (11:00 – 12:00). The impact of change in PV generation is compared by comparing the different solar insolation during the year. The solar insolation at the start and end of the year is lower compared (0.3 - 0.4) to the middle of the year (0.7) as seen in Appendix A2.

2. **Scenario 2**

The load profile created in this scenario consists of an evening peak due to the household load as seen in
Appendix B1. The day time commercial loads are in steady and peaks at 13 kW in the middle of the day. The household load of 20 kW in the evening is the peak demand in this case. This scenario is created with Niger as the reference for the loads [22]. In this scenario 300 households are considered with equally distributed low, medium and high-income households. Similar to scenario 1, agriculture is the primary occupation. Hence, the commercial loads are considered similar to the above case. The daily load profile can be seen in
Appendix B1.

Daily solar generation received in this region is almost 12 hours (from 07:00 – 19:00) throughout the year. The peak load does not correlate with the peak solar generation which leads to the potential for charging the battery. The impact of change in PV generation is compared by comparing the different solar insolation during the year. The solar insolation at the start and end of the year is higher compared (0.8 - 0.9) to the middle of the year (0.6) as seen in Appendix B2.

3. **Scenario 3**

The load profile for this scenario has a constant demand comparable to the peak throughout the day and an evening peak Appendix C1. There is day time peak of 9 kW at 09:00 due to the commercial loads and the evening peak of 11 kW at 21:00 caused by household load. This scenario is created with India as the reference for the loads [23]. Where 100 households are considered with 24% low-income, 18% high-income household and majority of 58% of medium-income household. Here, workshops and milling were primary commercial loads. The daily load profile can be seen in Appendix C1.

Daily solar generation received in this region is about 11 hours throughout the year. The impact of change in PV generation is compared by comparing the different solar insolation during the year. The solar insolation at the start and end of the year is higher compared (0.7) to the middle of the year (0.6) as seen in Appendix C2.

The basis of the scenario is to model different load profiles and check the results based on the behaviour of the load profiles. The unique characteristics of the load profiles are also mentioned in Table 1.

Table 1- Specification of Scenarios

Scenario Number	**1**	**2**	**3**
Region	Zambia	Niger	India
Peak Load	Commercial	Household	Combination of Household and Commercial
Distribution of load	Load is evenly distributed 09:00-18:00	Peak – evening household load, load is not evenly distributed throughout the day. Commercial and household loads are comparable during the day	Peak- evening, but the load is constantly high from 09:00 - 22:00
Unique Characteristic of Load Profile	Varying Peaks	Low demand with high peak	Constant demand with single peak
Peak Load and time of occurrence	12 kW at 10-11 am	16 kW at 21 pm	11 kW at 21 pm
Load Profile Reference	Figure 5	Figure 8	Figure 11

Data used in the scenarios is a combination of variables and constants as seen in Table 2. The variables define the unique characteristics of each scenario, some of which are determined by the model.

Table 2- List of Variables and Constants used in modelling

Variables	**Constants**
Daily load	Cost of PV
Solar generation	Cost of batteries (power and energy)
Size of batteries	
Capacity of installed PV	

3.7. Data Collection

The model is a general tool which gives a result for the required output parameters depending on the changing input parameters. The change in input parameters are the indicators to provide the different results. Two parameters are changed to create the different scenarios, the daily load profile and the solar generation data. The data is found after meticulous literature review along with using ready-made tools to create some data sets and using databases for different geographical regions.

The model is using an hourly time step for daily loads and solar generation data, a set of data for time steps 1 to 24 is used. The input data are entered into the program as parameters, external data sets can also be assigned to the parameters. The depth of discharge is a value from 0 to 1 used to indicate the maximum amount of energy that can be discharged from the battery at a time. Usually for grid scale batteries the value is 0.8 [24].

The load profile data is generated using a tool [20] which was developed for generating hourly load profiles based on different household and commercial load specifically in the sub-Saharan Africa region. The percentage of low, medium and large income households and the various commercial users (like water pumping, milling, small shops, clinics, schools, street lights) are the inputs required for the tool to generate load profiles.

All households are assumed to have appliances with the same rating but the time of use and the number of appliances depends on whether it is a small, medium or large household. The assumed appliances are lights, radio, mobile chargers, television, DVD players, iron, refrigerator. The usage of appliance according to the type of household is set in the tool [20]. The tool also accounts for the difference in hourly usage of each appliance with respect to the type of household. Finally, the tool adds the hourly loads of all households to generate the overall household load.

Commercial loads in the tool are the productive users of the mini-grid. The load from commercial consumers are calculated by the per unit wattage and the operating hours, multiplied with the number of commercial users. The commercial users consist of – water pumping operation, milling operation, small shops, Schools, medical clinics and street lights. Since, the tool only has limited types of consumers other consumers were substituted with the present users, for example the Indian load profile contains IT shops and workshops which were assumed to be 0.5 times and 3 times the consumption of 1 milling operation present in the tool by comparing the energy used [21],[22],[23]. The tool produces an overall hourly commercial load profile by adding all the consumers. Ultimately, the tool generates the overall hourly load profile by adding the household and commercial loads.

The data set used for solar generation data is taken from an online database, Renewable Ninja [25], [26], [27]. This provides solar generation data per 1 kW of PV installed, for the specified geographical location. The data contains 1kW PV capacity with a system loss of 0.1 and an angular tilt of 35 degrees, with no tracking technology used in the panels. It provides hourly generation data over the whole year, specifically 2019. The data for three regions is extracted throughout the year, after which three days are selected with high, low and medium generation of solar. The behavior of requirement of battery and PV generation can be found.

There are two types of batteries that can be employed in the system, a power-based battery and an energy-based battery. The size of the batteries is decided by the model itself, the input to the model however is the battery cost. The cost of an energy battery is taken as 200 $/kWh and the cost of a power-based battery as 1600 $/kW [28]. The batteries used in the model are 4-hour batteries meaning the battery can store energy (kWh) up to rated power (kW) times 4 hours [28]. The cost of power battery is converted in $/kWh by dividing the $/kW by 4 hours, taking the cost of power-based battery to be 400 $/kWh.

The hourly price for electricity is taken as a flat rate per hour, having one tariff for household and one for commercial consumers. The tariff for commercial users is greater than for households. The tariff for commercial loads is set at 0.5 $/kWh [29]. The electricity price paid by the households is considered to be lower than (half) the commercial consumers, and is taken to be 0.2 $/kWh. The price is equated considering the current system [30] and future system with complete renewable production [29].

4

Results

The model is simulated for all scenarios and results are compared. The behaviour of change is displayed in the results section and the explanation for the behaviour is elaborated in the analysis section. Battery capacity is calculated at three different periods of the year based on solar generation from PV. The investment cost of the system is calculated with the resulting solar and battery capacity. The results also compare the cost for power and energy-based battery for each scenario. Economic utility is used as an indicator for comparing the economic benefits [19].

The following plots are extracted from the model. The plots show the behavior of PV generation (in purple) and the load profile (in red), based on which the battery behavior (in blue) is also determined. The PV and battery capacity are determined by the model, with the load profiles as the input. The plots below show the system with the largest battery capacity in each scenario. Specifications of all results is found in Table 4.

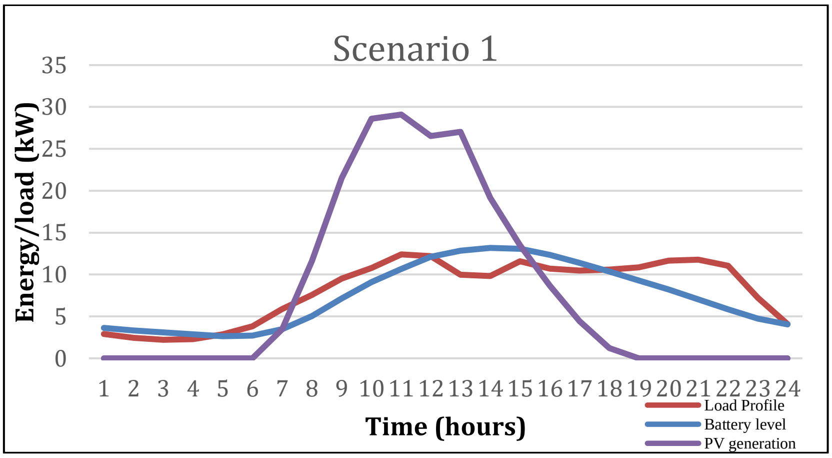


Figure 2- Relationship between supply and demand for Scenario 1

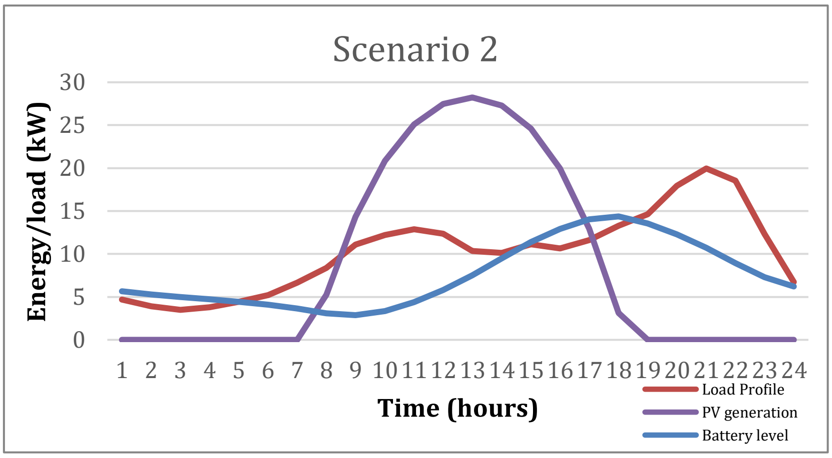


Figure 3- Relationship between supply and demand for Scenario 2

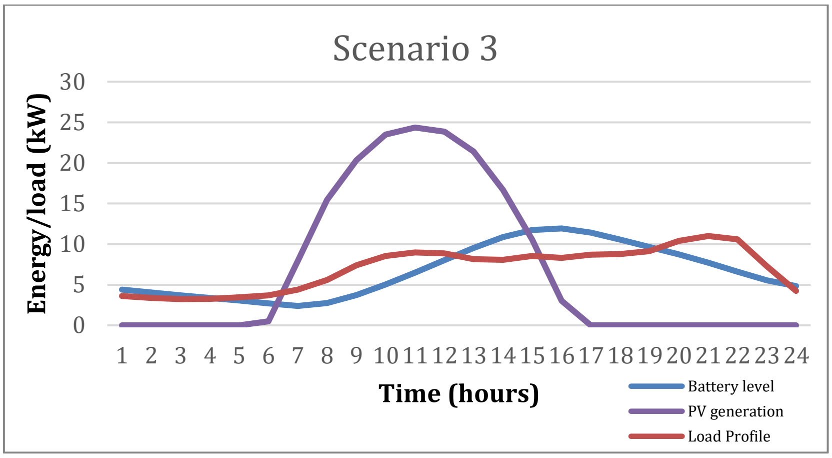


Figure 4- Relationship between supply and demand for Scenario 3

The change in battery sizing with respect to load profile can be seen in Figure 2, Figure 3, Figure 44. Load profiles for Scenario 1 has a constant load of ~10 kW with three peaks of 12 kW at different times of the day as seen in Appendix A1, corresponding battery capacity is 132 kWh. Scenario 2 has a high peak of 18 kW in the evening and a base load of ~ 9 kW as seen in Appendix B1, which requires a battery of 144 kWh. Scenario 3 has a fairly constant demand of 9 kW during the day and a small peak (compared to the other scenarios) of 11 kW in the evening as seen in Appendix C1, this scenario requires a battery of 119 kWh. Since the base load of all three scenarios are similar, it can be seen that peak load changes the size of battery. The case with the highest peak load, Scenario 2 requires the largest battery size. The case with smallest peak i.e. Scenario 3 has the smallest battery requirement.

In Table 3 the results are compared with each other in terms of Battery size (kWh), PV capacity (kW), Investment cost of Energy and Power battery ($), revenue ($/year) and economic utility for Energy and Power battery. The technical details of the system such as battery and PV capacity are used to find how the load demand affects the optimal capacity of storage. The economic details such as investment cost, revenue and economic utility provide results in monetary terms.

Table 3- Comparison of Scenarios

	Scenario 1	Scenario 2	Scenario 3
Unique Charecterstic of Load Profile	Varying Peaks	Low demand with high peak	Constant demand with single peak
Peak load (kW)	12	16	11
Load per day (kWh/day)	195	247	168
PV Capacity (kW)	65	35	33
Revenue generated with a battery ($/ year)	29k	33k	27k
Revenue generated without a battery ($/ year)	19k	19k	14k
Investment cost for system with Energy battery ($)	111k	74k	67k
Investment cost for system with Power battery ($)	138k	103k	91k
Investment cost for system without battery ($)	85k	45k	43k
Economic utility Energy battery (years)	2.7	2	1.8
Economic utility Power battery (years)	5.3	4	3.6
Battery Size (kWh)	132	144	120

5
Analysis

This section brings the research questions back into focus by analysing the impact of optimal sizing of battery in a mini-grid system. The relationship between inputs (i.e. Load profiles) and results are compared with a focus on battery sizing to analyse the benefit a battery provides to the energy system. The benefits are analysed in two parts, technical ability based on the power reliability and the economic terms based on the investment cost and the economic utility.

5.1. Technical Ability

Technical ability includes the capacity of battery and PV employed to increase the power reliability of the mini-grid system. Power reliability can be defined as the ability of the electricity system to provide electricity without interruption. Since this is a solar mini-grid system, the power reliability during the day depends mostly on the solar insolation of that geographical region along with the capacity of solar PV installed. The introduction of battery into the mini-grid boosts the power reliability by providing electricity to the system during the night and the hours of low solar insolation. Hence, optimal size of battery is crucial factor in a solar mini-grid.

The model determines the optimal size of battery and solar PV in each scenario. Characteristics of the load profile influences the output. The time of year signifies the change in solar insolation, thereby changing the capacity of PV and therefore, the size of battery. The results extracted from the model for all scenarios can be seen in Table 4. The two major inputs investigated for battery sizing is analyzed below-

1. **Load Profile**

   The current trends of research were found to have little to do with observing the influence of different types of load profiles with the size of battery required in a mini-grid. The timing and occurrence of peak load and the energy requirement during the hours of no renewable generation were found to have a profound impact on the size of the battery. The load profiles created in the scenarios characterize the realistic behavior of the loads over the course of the day. The usage of electricity can be different in different geographical region, which inspired the creation of different scenarios.

   Peak load is found to have a direct impact on the size of battery, which can be seen in Table 3. Greater the peak load, greater the power requirement of the battery. Change in peak load is proportionally to the battery size. The peak load in the Scenario 2 has the largest battery of 144 kWh and scenario 3 has the smallest battery of 112 kWh, which corresponds to the highest and smallest peak load of 16 kW and 11 kW respectively. The scenario 1 has an intermediate peak load of 12 kW resulting in a battery of 132 kWh.

The occurrence and duration of the peak load is also expected to have an impact on the sizing of the battery. The single high evening peak demand (16 kW) in Scenario 2 requires a larger battery than multiple small peaks. Multiple short peaks throughout the day in Scenario 1 results in an intermediate battery size due to the time of occurrence of the peaks and a relatively lower power demand (12 kW) compared to Scenario 2. Likewise, the constant load with a relatively small peak (11 kW) requires the smallest battery.

Finally, overall load is found to be proportional to the battery sizing as seen in Table 3. Scenario 2, having the highest load per day, 247 kWh/day requires the largest battery i.e. 144kWh among the three scenarios. Correspondingly, the lowest load per day, 168 kWh/day in Scenario 3 requires the smallest battery, 120 kWh. The behavior is further supported by Scenario 1 which has an intermediate load, 195kWh/day and intermediate battery size, 132kWh. Hence, relationship between load profile and size of the battery is confirmed to be proportional.

2. PV generation

The other input being investigated in the model is the change in solar insolation in different geographical locations as well as different periods of the year. The varying solar insolation in different regions results in varying periods of solar generation as well as varying peak generation. Whereas, seasonal changes in the same region leads to increase or decrease of peak generation capacity.

The PV capacity decided by the model does not directly influence the size of the battery as seen in Table 4. The largest battery size i.e. Scenario 2 is hypothesized to need a higher PV capacity. However, this does not correlate to the output of the model which corresponds to a 35 kW capacity of PV, compared to a 65 kW requirement from the system in Scenario 1. The PV capacity correlates directly with the load profile. The peak demand in the morning and the need for charging the battery for evening peak causes the need for a higher capacity of PV generation.

The battery size is calculated by the time of occurrence of peak load and the PV generation. This is seen by comparing the battery requirement at different time of the year across all the three scenarios. In scenario 1, PV generation at the start and end of the year is lower compared to the middle of the year as seen in Appendix A2, the PV capacity at these times of the year is found to be higher (from Table 4). Since, the evening load (beyond 16:00) is when a battery is required the largest PV capacity does not correspond to the largest battery. On the contrary, Scenario 2 has the largest PV generation at the start and end of the year compared to the middle. This case has a night peak load of 16 kW, the result proves that the battery is dependent on load profile as the largest battery size does not correspond to the largest PV capacity (Appendix A2). Scenario 3 has a relatively constant load throughout the day, battery is required to compliment PV generation during the evening/ night. The case with larger solar generation i.e. ends of the year (as seen in Appendix C2) results in the largest battery.

5.2. Economic Terms

While the technical ability of the system helps decide the size of battery and capacity of PV installed, the economic constraints of rural regions also needs to be accounted for. The model was designed with the focus on finding the size of the battery, however the objective function of the model was to minimize the investment cost of the system. Since rural regions lack large investment potential, it is important to minimize the investment cost. The cost of PV and battery together is considered as the investment cost of the system. Different investment costs are used for power and energy battery.

The scenarios have different battery and PV sizing making a direct comparison of the investment cost impractical. This prompts the use of economic utility to make a direct comparison which includes the revenue generated from the system in each scenario.

1. **Investment Cost**

Comparing all the scenarios with respect to the investment cost shows Scenario 1 requires the largest investment for both energy and power battery. Scenario 1 has the second largest battery size of 132 kWh and the most PV capacity required, 65 kW among the three. The scenario with the least investment cost is the one with the least battery and PV capacity, 120 kWh and 33 kW respectively. The investment in an energy and power battery for this scenario is 67k $ and 91k $ both of which is lower compared to other scenarios. Scenario 2, which has the highest battery requirement of 144 kWh has a lower investment cost than Scenario 1. However, the PV capacity in Scenario 1 (65 kW) is almost twice as large as Scenario 2 (35 kW).

2. **Economic Utility**

The relationship between battery size and economics of the system is not directly correlated. Economic utility compares the revenue generated over the whole year with the difference between investment cost of the system with battery and system without battery. The economic utility indicates the extra time (in years) needed to recover the investment cost if a battery is used in the system compared to a battery not being used in the system. The benefit of using a battery can be seen if the economic utility is relatively lower.

The economic utility is found to be highest for Scenario 1, having 2.7 years for energy battery and 5.3 years for power battery compared to a battery size of 132 kWh. The largest battery size of the three in Scenario 2, 144 kWh has a lower economic utility of 2 years for an energy battery and 4 years for a power battery. The smallest battery was found to have the lowest economic utility of 1.8 years for an energy battery and 3.6 years for a power battery. It can be seen that there is no direct relationship between battery size and economic utility.

The economic utility is directly related to the usage of the battery. Comparing the economic utility and the investment made in the system and the corresponding change in revenue with and without a battery shows the proportional relationship between them. The highest investment cost was found to be in Scenario 1 which also corresponds to the highest economic utility. The change in revenue between battery and without battery is significantly lower from 19k $ to 29k $. The change in revenue for Scenario 2, was higher than the previous scenario both of which had the same revenue without a battery of 19k $ but changed to 33k $ after the battery was introduced into the system. The economic utility was found to be 2 years for an energy battery and 4 years for a power battery. The final scenario has a similar economic utility as Scenario 2 with 1.8 years for an energy battery and 3.6 years for a power battery. The change in revenue is also comparable to Scenario 2 increasing from 14k $ to 27k $, also having the lowest investment cost among the three. The economic utility is directly proportional to the investment cost of the system and inversely related to the change in revenue generated with and without a battery.

6
Discussion

This section precedes the conclusion of the report by contextualising the result with respect to the objective. The accuracy of this approach and the possibility of modifying the approach in the future are discussed in this section. General discussion about the growth in the rural regions is also included.

6.1. Method

The choice of modelling the mini-grid as a linear program to find the size and investment cost of the system is a result of the literature review. Past research on the topic of solar mini-grids and mini-grids in rural areas focus on different ways to model the load profiles and tariffs as well as different types of energy sources that can be used in the mini-grid. Furthermore, different methods of modelling a mini-grid with a focus on optimizing the existing grid was considered in section 3.3. Simulation Model. The research suggested that the change in load profiles will affect the need for a storage, more importantly the time of use of storage with respect to the load profile will determine the size of the storage. Loads which exceeded the hourly generation from the installed energy capacity would also benefit from a storage source that would complement the generation at times of high-power demand.

The size of battery required in the solar mini-grid system from section 5.1. Technical Ability can be seen to agree with the literature. The size of battery was directly related to the type of load profile. The scenario with the larger loads required larger batteries to increase the power reliability. Since, all the peak load occurs at times when there is no solar production, the battery did not need to compliment the solar production during the day. However, the scenario with the largest peak demand also corresponds to the largest battery size. The different types of battery are only investigated with respect to the investment costs for power and energy type battery. This can be improved further by investigating the use of only power battery and only energy battery and finding the change in utility for the different scenarios.

The technical ability of the min grid system is found by the capacity of PV and battery using the model. The model is a single objective model to minimise the investment cost of the system, which focuses on the monetary benefit that can be achieved for a power reliable system. This model overlooks the power loss incurred by transmission because the distance is considered to be insignificant. Also, since the aim was to find the sensitivity of the results by changing the input, certain criteria like power loss, transmission loss, and even maintenance costs were overlooked as it is insignificant to the purpose.

6.2. Scenarios

In 3.6. were constructed using data from literature and a micro grid tool [20]. This was a method used in the research to extract different types of load profiles to evaluate the behavior of the system. This lacks accurate data, which is hard to find for a rural region due to the lack of existing grids and low power reliability. The focus of the report is to find the benefit of storage by observing the behavior of changing input, so accuracy was a secondary objective. The results extracted can be helpful only to predict the nature of storage required compared to the load profile, which can be improved by using interview or metered load profiles.

Investment costs for a battery and solar PV is on a decline in the past few years, hence making these a plausible option. The lower electricity prices from the mini-grid is an added benefit along with greater power reliability. Since, there is no comparison of this system with an existing system the exact monetary benefit of the system as a whole is not evaluated. However, the data extracted for the scenarios have very little power reliability or non-existent grid with only few diesel generators and kerosene gas lamps. Considering these systems as the basis of study the comparison to the existing system will be illogical. Furthermore, the aim was to find the benefit of the battery in a mini-grid system.

The patterns of study suggest that the energy demand by any grid would only increase in the future. This means that increasing the power reliability will lead to change in the activities of the rural population, which would further increase the energy demand. This means that the load profiles will be significantly different with that increased power reliability. Eventually increase the capacity of storage required. Thereby using accurate data to find the results will be both expensive (in the case of metering) and time consuming. Hence, results from Table 4 can be used as a stepping stone to predict the behavior of the system where a battery is needed.

The size of the battery is important to satisfy different types of load demands. The battery capacity needed for different loads is dependent on the peak load demand and the energy demand during hours of no PV generation. The battery provides technical benefits to the system by increasing power reliability. The load demand is directly proportional to the size of battery required in the system. This shows the change in behaviour of the battery sizing with varying loads.

6.3. Limitations

Since, limited economic resources are available for the rural regions there is a need for cost minimisation. The investment cost is observed to be proportional to the capacity of both battery and solar PV. The size of battery and solar PV is not always correlated, so economic utility is used for monetary assessment of the existing options. The increased usage of the grid relates to faster economic utility. Which means that the weightage of the relationship between investment cost and usage of electricity is crucial in making investments in the system. The economic benefits between all the scenarios is evaluated on a relative scale.

The chosen method shows that the battery will increase the power reliability of the system. The size of the battery is largely dependent on the load profile. It also displays that the increased usage of the battery is economically beneficial in terms of investment.

7
Conclusion

The aim of the thesis was to determine the technical and economic advantage of employing batteries in a solar mini-grid system. The specific effect of batteries in the system was to be analysed and compared in the context of usage of electricity from the batteries. The study includes generating load profiles from previous research data. The technical and economic ability of the batteries were determined.

The capacity of the battery is dependent on the use of electricity from consumers i.e. load profiles have a major impact on deciding the size of batteries being used in the system. The peak load had a direct impact on the capacity with the size of batteries increasing with larger peak loads. Also, multiple peak loads require a battery with larger capacity than single peak load. Further supporting the impact of load profile on the battery is the total daily load. The total daily load also had a proportional effect on the capacity of the battery. The load profiles have a profound impact on the battery sizing.

The economic effect of the battery on the grid was also calculated. The increased investments on the whole system does not correspond directly to the increased size of battery in the grid. The largest investments were found in a system with large PV capacity with a medium battery size, and the system with the largest battery had the second largest investment cost. However, the usage of battery was found by comparing the revenues generated by electricity tariffs on the system, which shows the use of battery significantly increases the revenues as seen in Scenario 2 and 3. Economic utility further compares the investment made on the batteries with the revenues generated showing the systems with higher usage of the batteries require lesser time to get the investment back from revenue alone. The economic utility shows that the usage of battery in the system has a larger impact than the investments made on the battery.

The technical and economic evaluation of batteries in the solar mini-grid shows that the usage of the battery is predominant while making investments in the battery. The capacity of the battery depends on the loads in the grid. The investments made on battery also depends on the usage of the battery to get back the investments faster. The increased availability of electricity that is a product of using a battery in turn dominates the need for the battery.

References

[1] E. Hartvigsson and E. O. Ahlgren, "Comparison of load profiles in a mini-grid: Assessment of performance metrics using measured and interview-based data," *Energy Sustain. Dev.*, vol. 43, pp. 186–195, 2018, doi: 10.1016/j.esd.2018.01.009.

[2] J. M. Ngowi, L. Bångens, and E. O. Ahlgren, "Benefits and challenges to productive use of off-grid rural electrification: The case of mini-hydropower in Bulongwa-Tanzania," *Energy Sustain. Dev.*, vol. 53, pp. 97–103, 2019, doi: 10.1016/j.esd.2019.10.001.

[3] P. Sandwell, N. Ekins-Daukes, and J. Nelson, "What are the greatest opportunities for PV to contribute to rural development?," *Energy Procedia*, vol. 130, pp. 139–146, 2017, doi: 10.1016/j.egypro.2017.09.416.

[4] C. Spataru and P. Bouffaron, *Off-Grid Energy Storage*. Elsevier Inc., 2016.

[5] L. J. Olatomiwa, S. Mekhilef, and A. S. N. Huda, "Optimal sizing of hybrid energy system for a remote telecom tower: A case study in Nigeria," *2014 IEEE Conf. Energy Conversion, CENCON 2014*, pp. 243–247, 2014, doi: 10.1109/CENCON.2014.6967509.

[6] T. Bowen, I. Chernyakhovskiy, and P. Denholm, "Grid-Scale Battery Storage: Frequently Asked Questions," *Nrel*, no. 2013, pp. 1–8, 2018, [Online]. Available: www.greeningthegrid.org.

[7] O. Talent and H. Du, "Optimal sizing and energy scheduling of photovoltaic-battery systems under different tariff structures," *Renew. Energy*, vol. 129, pp. 513–526, 2018, doi: 10.1016/j.renene.2018.06.016.

[8] S. Mandelli, C. Brivio, E. Colombo, and M. Merlo, "Effect of load profile uncertainty on the optimum sizing of off-grid PV systems for rural electrification," *Sustain. Energy Technol. Assessments*, vol. 18, pp. 34–47, 2016, doi: 10.1016/j.seta.2016.09.010.

[9] E. Hartvigsson, J. Ehnberg, E. O. Ahlgren, and S. Molander, "Linking household and productive use of electricity with mini-grid dimensioning and operation," *Energy Sustain. Dev.*, vol. 60, pp. 82–89, 2021, doi: 10.1016/j.esd.2020.12.004.

[10] E. Hartvigsson, E. O. Ahlgren, and S. Molander, "Tackling complexity and problem formulation in rural electrification through conceptual modelling in system dynamics," *Syst. Res. Behav. Sci.*, vol. 37, no. 1, pp. 141–153, 2020, doi: 10.1002/sres.2611.

[11] S. D. Comello, S. J. Reichelstein, A. Sahoo, and T. S. Schmidt, "Enabling Mini-Grid Development in Rural India," *World Dev.*, vol. 93, pp. 94–107, 2017, doi: 10.1016/j.worlddev.2016.12.029.

[12] S. C. Bhattacharyya, D. Palit, G. K. Sarangi, V. Srivastava, and P. Sharma, "Solar PV mini-grids versus large-scale embedded PV generation: A case study of Uttar Pradesh (India)," *Energy Policy*, vol. 128, no. January, pp. 36–44, 2019, doi: 10.1016/j.enpol.2018.12.040.

[13] M. Ansarin, Y. Ghiassi-Farrokhfal, W. Ketter, and J. Collins, "The economic consequences of electricity tariff design in a renewable energy era," *Appl. Energy*, vol. 275, no. June, p. 115317, 2020, doi: 10.1016/j.apenergy.2020.115317.

[14] A. Holmberg and O. Petterson, "Design of a Techno-Economic Optimization Tool for Solar Home Systems in Namibia," 2016.

[15] S. Bandyopadhyay, G. R. C. Mouli, Z. Qin, L. R. Elizondo, and P. Bauer, "Techno-Economical Model Based Optimal Sizing of PV-Battery Systems for Microgrids," *IEEE Trans. Sustain. Energy*, vol. 11, no. 3, pp. 1657–1668, 2020, doi: 10.1109/TSTE.2019.2936129.

[16] M. Bucciarelli, S. Paoletti, and A. Vicino, "Optimal sizing of energy storage systems under uncertain demand and generation," *Appl. Energy*, vol. 225, no. May, pp. 611–621, 2018, doi: 10.1016/j.apenergy.2018.03.153.

[17] D. Fioriti, S. Pintus, G. Lutzemberger, and D. Poli, "Economic multi-objective approach to design off-grid microgrids: A support for business decision making," *Renew. Energy*, vol. 159, pp. 693–704, 2020, doi: 10.1016/j.renene.2020.05.154.

[18] J. J. Kelly and P. G. Leahy, "Optimal investment timing and sizing for battery energy storage systems," *J. Energy Storage*, vol. 28, no. September 2019, p. 101272, 2020, doi: 10.1016/j.est.2020.101272.

[19] M. Kojima, X. Zhou, J. J. Han, J. de Wit, R. Bacon, and C. Trimble, "Who Uses Electricity in Sub-Saharan Africa? Findings from Household Surveys," *Who Uses Electr. Sub-Saharan Africa? Find. from Househ. Surv.*, no. August, 2016, doi: 10.1596/1813-9450-7789.

[20] X. Li, J. Salasovich, and T. Reber, "Microgrid Load Profile Explorer." .

[21] M. Bhatia and N. Angelou, "Beyond Connections," *Beyond Connect.*, 2015, doi: 10.1596/24368.

[22] R. Bhandari, V. Sessa, and R. Adamou, "Rural electrification in Africa – A willingness to pay assessment in Niger," *Renew. Energy*, vol. 161, pp. 20–29, 2020, doi: 10.1016/j.renene.2020.06.151.

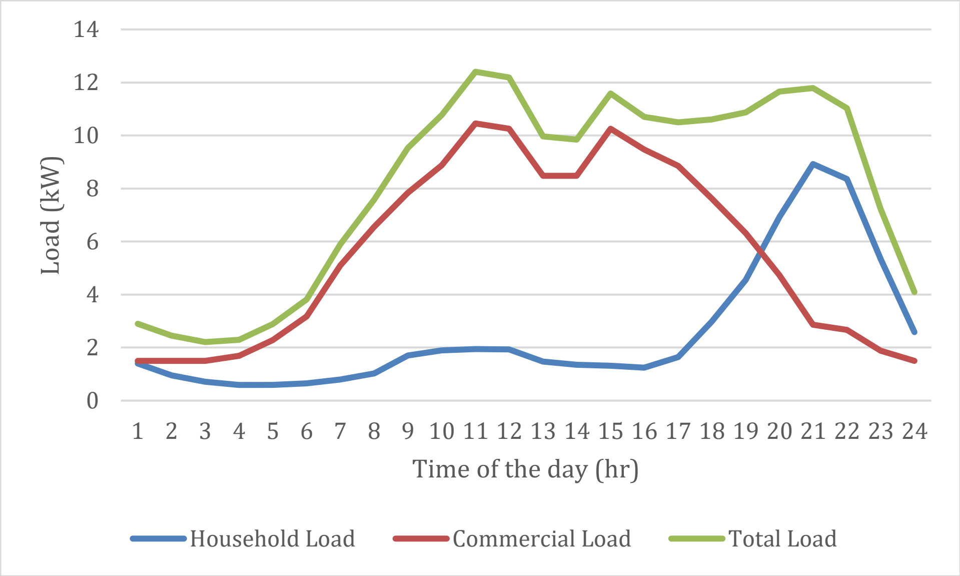
[23] S. Agarwal, N. Bali, and J. Urpelainen, "Rural Electrification in India: Customer behaviour and demand,"

Rockefeller Found., no. February, pp. 55–71, 2019.
[24] G. Rancilio *et al.*, "Modeling a large-scale battery energy storage system for power grid application analysis," *Energies*, vol. 12, no. 17, 2019, doi: 10.3390/en12173312.
[25] "Solar generation data," 2019. www.renewables.ninja.
[26] I. Staffell and S. Pfenninger, "Using bias-corrected reanalysis to simulate current and future wind power output," *Energy*, vol. 114, pp. 1224–1239, 2016, doi: 10.1016/j.energy.2016.08.068.
[27] S. Pfenninger and I. Staffell, "Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data," *Energy*, vol. 114, pp. 1251–1265, 2016, doi: 10.1016/j.energy.2016.08.060.
[28] W. Cole, A. W. Frazier, W. Cole, and A. W. Frazier, "Cost Projections for Utility-Scale Battery Storage : 2020 Update Cost Projections for Utility-Scale Battery Storage : 2020 Update," *Nat. Renew. Energy Lab.*, no. June, 2020.
[29] Power for All, "Mini-grids costs can be reduced by 60% by 2030," no. September, pp. 1–2, 2016.
[30] T. Review, "In the matter of Application by the TANZANIA ELECTRIC SUPPLY COMPANY LTD For Tariff Review Application," vol. 19, no. February 2016, pp. 1–11, 2017.

Appendices

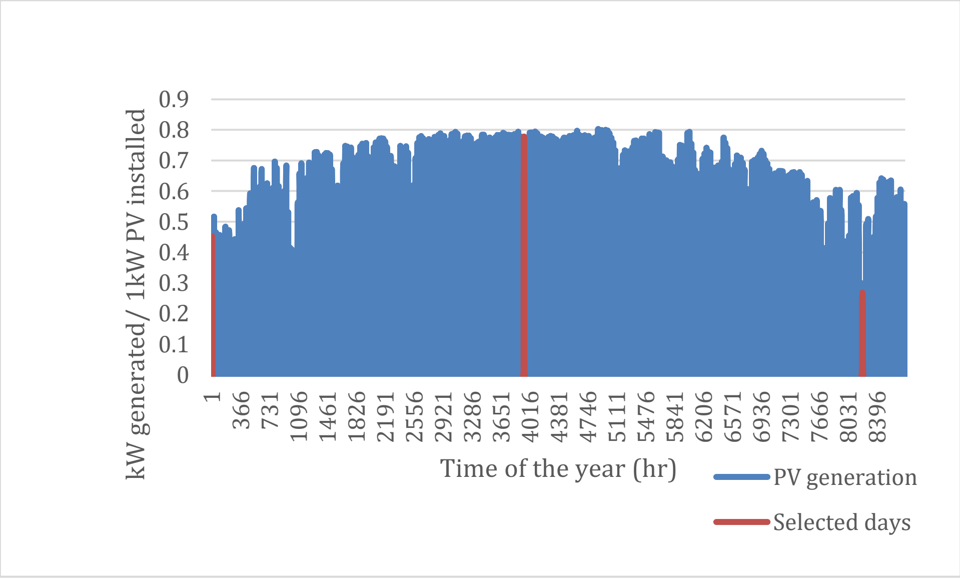
Appendix A - Data collected for Scenario 1

Appendix A1



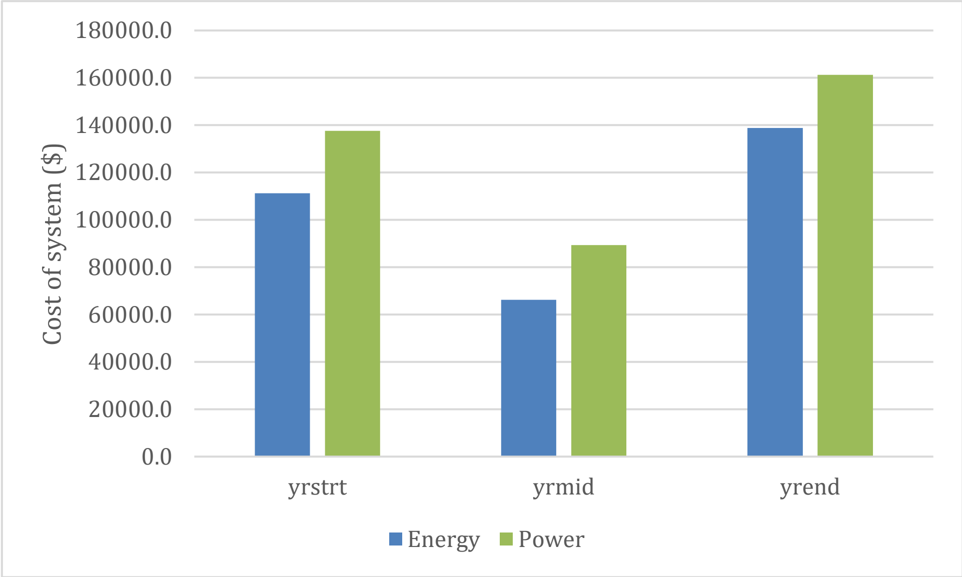
Appendix A1 shows the daily load profile created from data in scenario 1, The blue line represents the Household load, red line represents the commercial load and the green line represents the sum of both the loads.

Appendix A2



Appendix A2 shows the solar generation profile for a typical year in Zambia when 1 kW PV is installed. The red lines represent the days considered for calculation in Scenario 1.

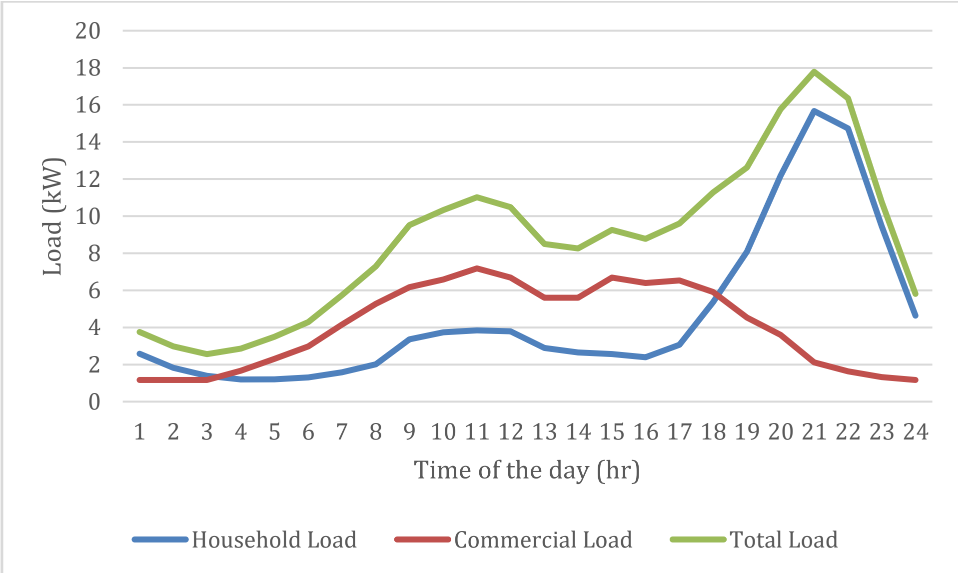
Appendix A3



Appendix A3 shows the comparison between investment cost of the system at the three days selected from Appendix A2. The blue line represents the investment cost for a system having an energy battery and green line represents that of a power battery.

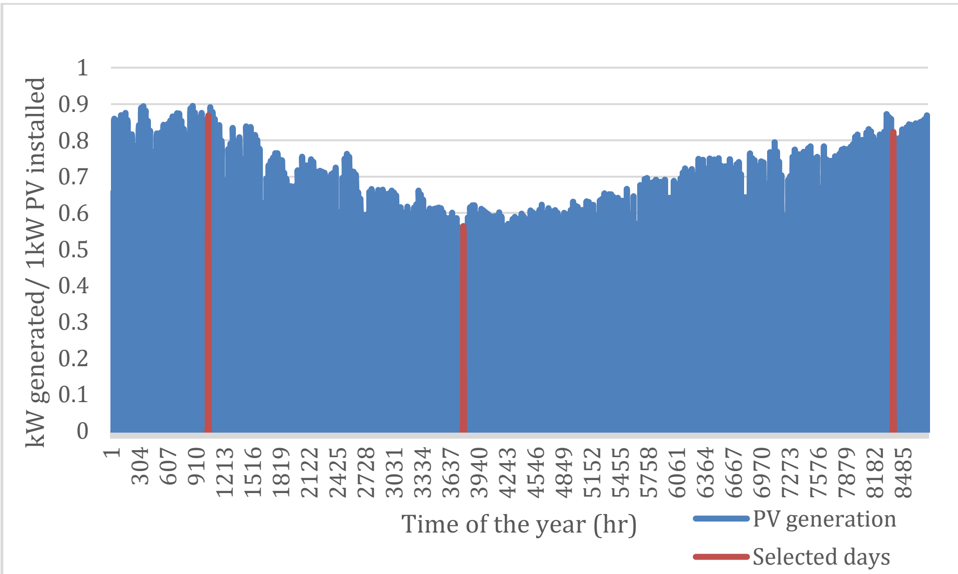
Appendix B - Data collected for Scenario 2

Appendix B1



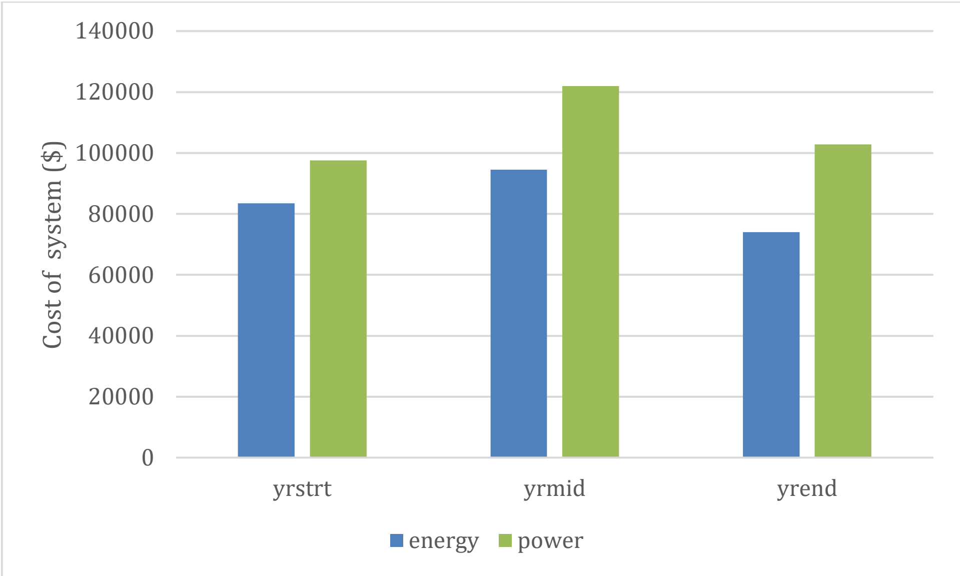
Appendix B1 shows the daily load profile created from data in scenario 2, The blue line represents the Household load, red line represents the commercial load and the green line represents the sum of both the loads.

Appendix B2



Appendix B2 shows the solar generation profile for a typical year in Tanzania when 1 kW PV is installed. The red lines represent the days considered for calculation in Scenario 2.

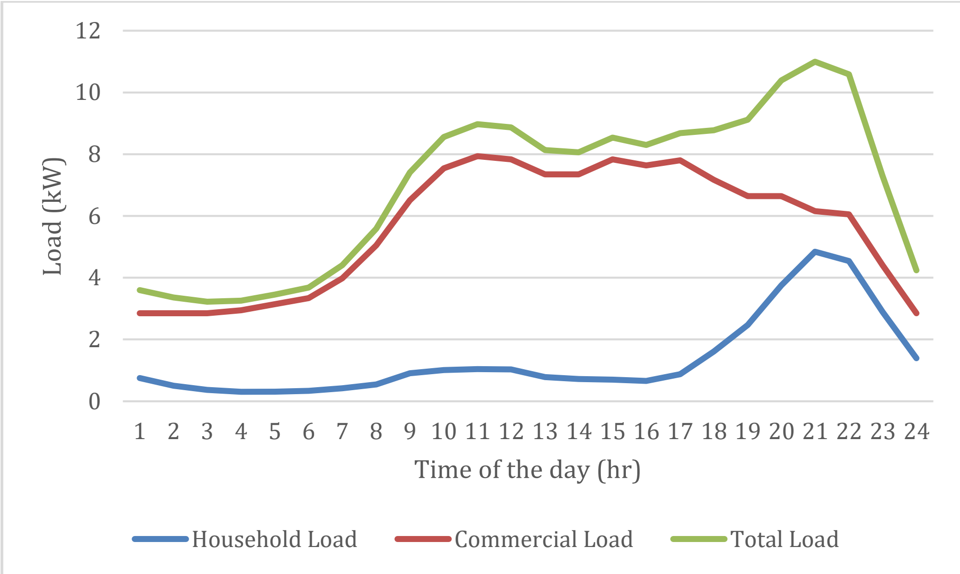
Appendix B3



Appendix B3 shows the comparison between investment cost of the system at the three days selected from Appendix B2. The blue line represents the investment cost for a system having an energy battery and green line represents that of a power battery.

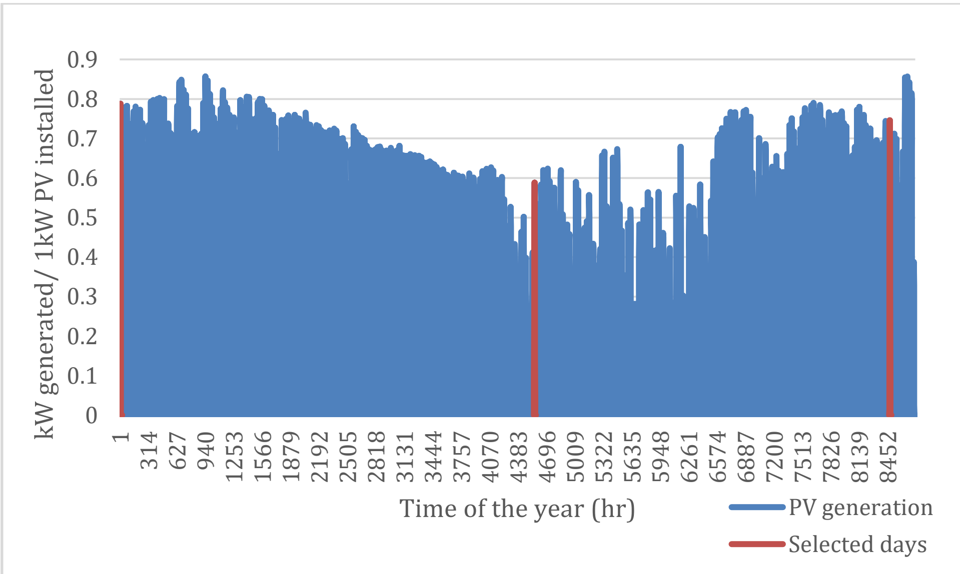
Appendix C- Data collected for Scenario 3

Appendix C1



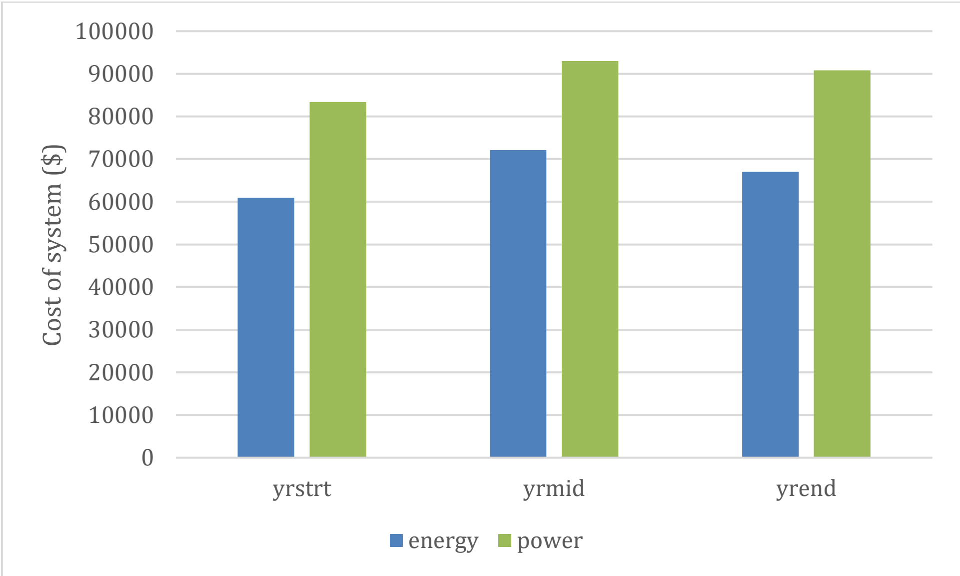
Appendix C1 shows the daily load profile created from data in scenario 2, The blue line represents the Household load, red line represents the commercial load and the green line represents the sum of both the loads.

Appendix C2



Appendix C2 shows the solar generation profile for a typical year in India when 1 kW PV is installed. The red lines represent the days considered for calculation in Scenario 3.

Appendix C3



Appendix C3 shows the comparison between investment cost of the system at the three days selected from Appendix C2. The blue line represents the investment cost for a system having an energy battery and green line represents that of a power battery.

Appendix D – Compilation of results from the model

Table 4- Results from model for all scenarios

Load Profile	Time of the year	Battery size (kWh)	PV capacity (kW)	Total Investment cost for energy battery ($)	Total Investment cost for power battery ($)
Scenario 1	Start	132	64	111k	138k
	Middle	116	33	66k	89k
	End	112	88	139k	161k
Scenario 2	Start	140	31	83k	97k
	Middle	137	51	94k	122k
	End	144	34	74k	103k
Scenario 3	Start	112	29	61k	83k
	Middle	104	39	72k	93k
	End	119	33	67k	91k

Case with the largest battery
Case with the highest investment cost
Case with the largest battery and highest investment cost