"A Technical Appraisal of Mini-Grids for the Rural Electrification of Developing Countries"

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Abstract

Rural electrification is a global problem that prevents economic and social equality to exist between people living in urban and remote areas of the world. To solve this a number of ideas are promoted including standalone systems, mini-grids and utility extension. Each solution has its own merits but the optimal decision to employ either will depend on local variables. This creates a need for a method of differentiating between the three main ideas in order to ensure sustainable development of rural communities. Through use of MATLAB this report demonstrates a method that can provide a comparison between these three options. To do this an optimisation based approach that aims to minimise the end cost that rural communities have to pay for electricity is demonstrated. This is achieved using particle swarm optimisation to minimise the cost of distributed generation equipment while maintaining power system supply. In doing this it will be shown how the output of a tilted solar collector can be ascertained using locally available resource. In addition to this, this report shows a method for the minimisation of network cable routing. This is done while maintaining power quality standards through the use of Esau-Williams heuristic. For evaluation between the different options levelized cost of energy and net present value is used as a baseline.

Contents

1.0 Introduction

As the industrialised world pushes the boundaries of technology, one and a half billion people live in the dark, unable to access electricity to perform the most basic of life-improving tasks. For many of these people the principle barriers are poverty and geography, living in rural community's too poor and too far from utility infrastructure for grid extension to be economically feasible. However, with the advent of lower cost renewable energy based, distributed generation sources, alternative solutions have been proposed. These include standalone home systems that serve a single household as well as mini-grids that can act as a source of centralised power generation and distribution for a community.

Mini-grids encompass all the main features of a utility grid such as generation, protection, control systems and loads. The main difference being that everything is conducted at the distribution level. This type of network architecture is illustrated by figure 1.1 below:

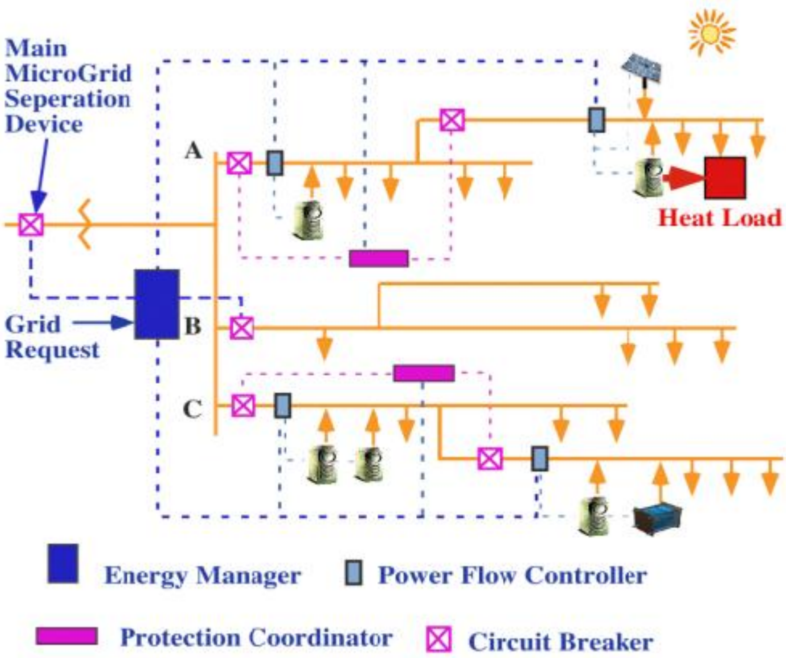


Figure 1.1 Mini-grid Network Architecture [1]

Mini-grids present a range of potential benefits that standalone systems aren't able to offer such as the larger generating capacities required for productive, poverty reducing, applications which can promote sustainable human development [6]. Uncertainties with resources demand and incomes however, damage the appetite for investors to support these projects given their potentially high capital cost. As well as this, the shear diversity between the needs and resources of each separate community means that a mini-grid will not present the most beneficial solution to each electrification project.

In order to promote sustainable rural development and encourage the use of mini-grids this project presents an optimisation based approach that can determine which electrification solution should be applied for a given case. To do this a methodology is designed to give insight into the viability of each strategy using local resource and demand information. In doing this, it will be demonstrated how particle swarm optimization (PSO) can be employed to determine generation sizing's for a renewable energy based power system. In addition, a heuristic method for computing near-optimal network topologies will also be explored with the aim of reducing the end cost of power distribution cable. Through MATLAB implementation it will be shown how this functionality can be used to compare the economic benefits of a Solar-PV/Diesel hybrid mini-grid to each alternative rural electrification solution.

1.1 Motivation

In the year 2000 the United Nations outlined the millennium development goals (MDG) with the aim of improving equality and standards of living for people worldwide. These goals outlined the problems faced by humans living in sub-standard conditions, they did not, however feature the solution: electricity [2]. The impact electricity has on a persons' socio-economic conditions cannot be overstated; it plays a vital role at improving every aspect of human life. The figure below shows the impact that electrification has on human development index (HDI), a measurement linked to education, poverty and health quality. Note that the countries with the lowest energy usage also have large rural populations.

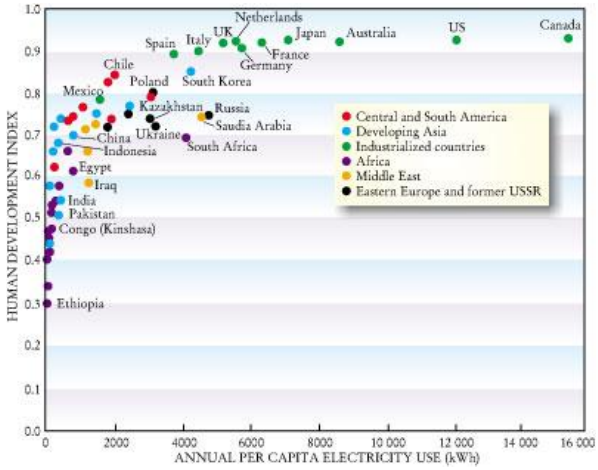


Figure 2.1. Human Development Index for Different Countries [3]

Each of the three HDI areas are heavily influenced by the use of electrical appliances. With respect to education, electrical lights can allow for children to study later into the night while computers can provide access to vital information [4]. Poverty reduction can be implemented through the automation of mundane tasks like water pumping, allowing more time to be spent on productivity [4]. As well as this Electricity can be used to power tools and small cottage industries, giving rural communities the chance to grow and compete economically [4].

Unfortunately electricity is not free, it is a commodity traded in high demand for substantial profit. Given that non-electrified rural communities represent some of the most impoverished and remote people in the world, utilities are unlikely to extend the national infrastructure to their areas. In attempt to gain access to some of the benefits of electricity, many rural communities rely on diesel generators as their primary source of energy. This is due to the historically low, initial capital cost of these sources compared to renewable alternatives as well as familiarity: it is a well-established technology. However this creates a reliance on fuel cost and availability and is likely to be a symptom of the poverty and poor education that people in these regions suffer from: they lack the funds necessary to save for a renewable solution and the education to realise diesel generators cost more on a lifetime basis.

Over the past decade however, the cost of renewable energy, particularly solar-PV, has dropped remarkably as illustrated by figure 2.2:

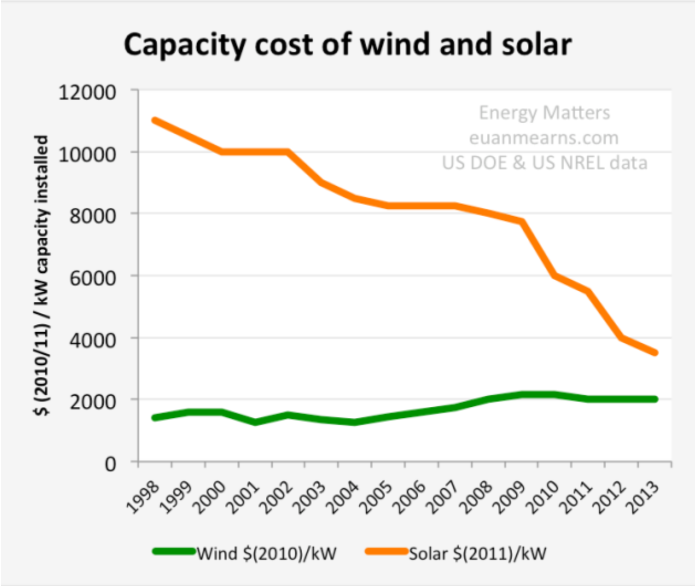


Figure 2.2 Cost of Wind and Solar per kW Capacity [5]

This reduction in renewable capital costs has led to an increase in interest and use of solar home systems for countries with suitable solar resources. Solar home systems can provide rural communities with a sustainable supply of electricity for a reasonable price, especially in countries such as India where subsidies for solar energy exist [6]. However the power provided by this solution is very small-scale, limited in its deployment for economic enhancing loads [7]. This ultimately limits potential for growth meaning that while a solar home system can provide some domestic benefits, it'll be difficult to solve the underlying issues of the MDG through implementation of this solution.

Mini-grids however do have the potential to provide the meaningful levels of power capacity necessary to promote economic and social development. This is because mini-grids benefit from the combined resources of multiple consumers, reducing the high capital barrier and potentially accessing the benefits that economies of scale can bring [8]. As well as this having a centralized generation source reduces the burden on the technical skills of a rural community as only a few members of the community would need to be trained to perform routine maintenance and this in turn could be conducted on a concentrated area rather than sporadic standalone systems.

Another advantage of mini-grids is the scalability of the system. Increasing generating capacity to meet growing demand can be easily achieved due to the modular nature of many renewable sources. One instance where this feature is apparent is the 132 kW hydro-based mini-grid located in the Baglung district of Nepal. This mini grid began as seven separate projects located within different villages along the Kalung River before becoming interconnected to form a regional grid. By accessing the untapped capacity of day time generation, small businesses were able to flourish, improving the economic growth and quality of life of the communities involved [9].

Mini-grids have great potential for increasing electricity access; however, they will not always represent the optimal solution for investors and consumers. Not all communities are going to be compact enough or require enough electricity to benefit from using a mini-grid and many may be better off using standalone solutions or waiting for grid extension as exemplified by [10].

This is partly due to the high capital costs associated with mini-grids compared to the use of a standalone. Given the poverty of rural communities, the cost of a mini-grid will be extremely difficult for them to support without significant contribution from either loans or investors. In order to justify to these bodies that paying this high expense has a long-term economic gain a tool is needed that can evaluate between the different options for rural electrification and determine their feasibility.

2.0 Background

2.1 Solar Resources

Any tool used for determining the feasibility of a renewable energy based power system must be able to accurately evaluate the local renewable resources. This is because these resources are inherently dependant on meteorological conditions such as sunlight and wind availability which is in turn related to both time and location. With respect to a solar PV based electrification project, the available power is directly related to the site's solar insolation, defined as the amount of solar energy that strikes an area over a given time period. Figure 2.1.1 below shows a map of the direct normal Irradiation throughout the world for an average year and day.

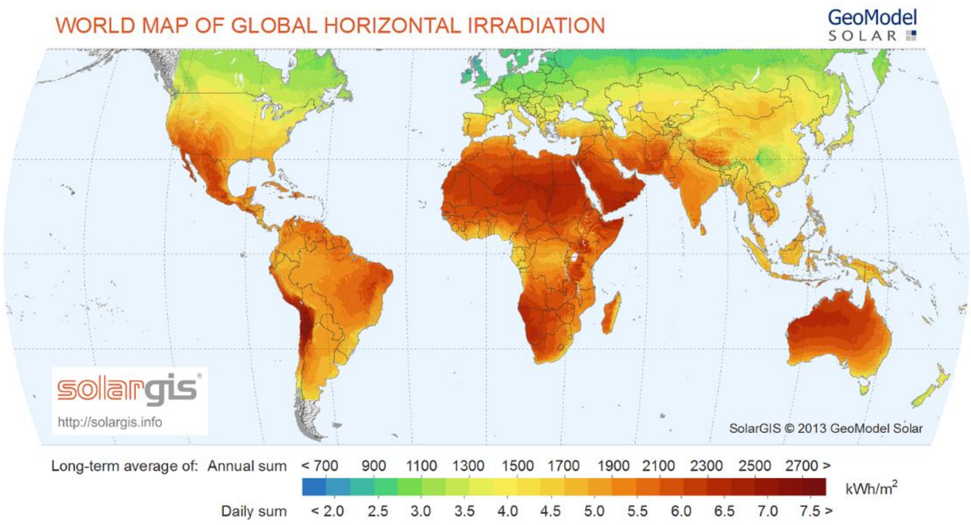


Figure 2.1.1 Solar Insolation map [12]

This variation between locations is due to the geometric relationship between a position on the ground and the sun over the course of a year. Due to the earth's tilt and resulting elliptical orbit around the sun, regions further from the equator suffer from greater seasonal variation in solar resource availability. This directly impacts the capacity factor of solar energy systems. The capacity factor is defined as the ratio of the amount of power actually produced by a source to the theoretical maximum output if it could operate at rated capacity all the time. This can be described using the energy output over the course of a year by using equation 2.1:

$$C_{fact} = \sum_{t=1}^{8760} \frac{E_{produced}(t)}{E_{theoretical}(t)} \quad [2.1]$$

Reducing the capacity factor of solar-PV, or indeed any power generation source, sours its ability to be a profitable and sustainable investment as it means that a larger generating capacity is required to fulfil the same energy demand. Figure 2.1.2 below shows how the difference in solar insolation between two regions, Glasgow and Palermo, can influence the payback period for a solar system.

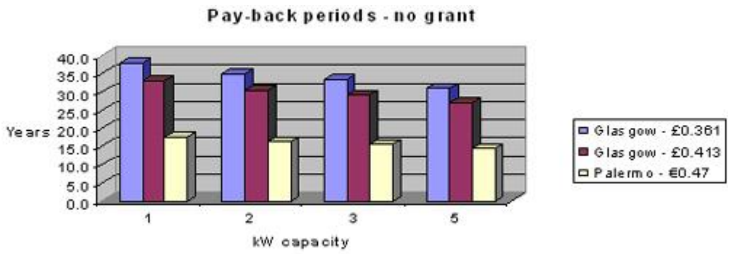


Figure 2.1.2 Pay Back Period for Solar Systems at Glasgow and Palermo [13]

While the yearly amount of solar insolation available a particular location is a relatively steady value, the variance in available power increases as the time interval between measurements decreases. This can be seen on figure 2.1.3 below:

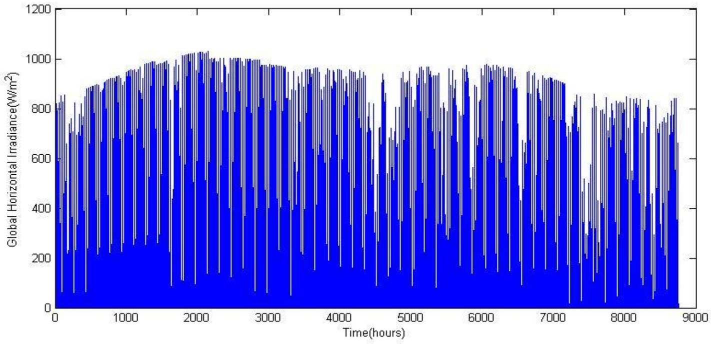


Figure 2.1.3 Hourly Variation in available irradiance at Pravaham

This high variance in the available solar irradiance is due to the change in the position of the sun throughout the course of the day which is turn dependant on what day of the year it is. Compounding this variation is the effect of weather conditions such as cloud cover which can negatively impact the available insolation by blocking much of the suns useful radiation. In order to get an accurate representation of the available resource at a given location it is thus vital to use local measurements or the system can risk being under or over-sized. This is an important stage in the design of any rural network as oversizing the generation can lead to unrecoverable capital costs while under sizing the equipment can cause frequent black outs due to inability to meet demand [14].

To achieve an accurate representation of solar panel output this project therefore uses hourly measurements of global horizontal, I_{gh}, and diffuse, I_{bh}, irradiance made available by the Indian meteorological services at [15].

The suns radiation is made up of two components: direct and diffuse. Direct or beam radiation is the most useful component of the sun's rays as this is radiation that is travelling through the atmosphere and striking the collector surface directly [16]. The amount of direct radiation that strikes the surface depends on the angle of incidence between the collectors' surface normal and the direction of incoming radiation as shown by figure 2.1.4 below:

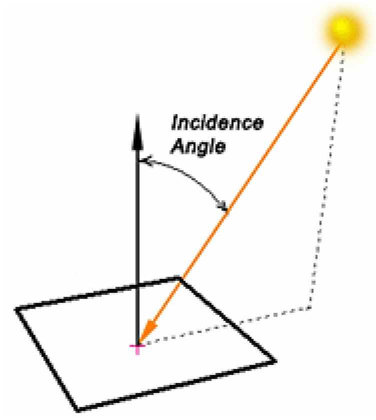


Figure 2.1.4 Angle of Incidence representation [17]

The diffuse component however is made up of radiation that is scattered by the earth's atmosphere, reducing the concentration of power that reaches the collector. The sum of these two components makes up the total available, or global, irradiance that can be harnessed by the solar panels, I_{gh}. To calculate the direct horizontal component, I_{dh}, from the data provided by [15], equation 2.2 must be used:

$$Idh = Igh - Ibh \quad [2.2]$$

This provides the irradiance that is available on a solar collector that is horizontal, lying flat on the ground. In order to maximize the amount of solar energy captured over the course of a year however, the array must be tilted towards the direction of the sun as this reduces the angle of incidence, maximizing the radiation that is captured [16]. While solar trackers exist that allow the surface to point directly at the position of the sun throughout the course of the day, this project assumed a fixed tilt for the solar collector year round. For fixed tilt collectors the rule of thumb for panel orientation is to tilt it at an angle, β_{surf}, which is equal to the latitude of the location. Calculating the irradiance incident on a tilted collector and the resulting output power at every hour of the year is discussed further in section 3.2.

2.2 Hybrid Based Networks

While renewable power presents major advantages in lower running cost due to the constantly replenishing and free energy source, the clear downside of the technology is the intermittency of the resource profile. To circumvent this battery storage is often used to time-shift the generation profile of resources to match the community demand. Battery storage technology is currently very expensive however and presents a major cost for a renewable energy system, estimated by [10] as accounting for approximately 11% of mini-grid system cost. In addition to this, prolonged periods of low resource availability mean that the mini-grid will require a much larger generating capacity in order to provide the additional power required to charge these storage devices [18]. This can drive the capital costs of the generation system into unrecoverable levels by making the system unpayable for end consumers, ultimately damaging project sustainability.

This is where a hybrid system that incorporates multiple sources of generation can become a better approach. Hybridization of generation is one of the main advantages of mini-grids as it allows the inclusion of multiple sources of generation that a single consumer would be unable to afford, manage or maintain on their own. Example architecture of a hybrid mini grid is shown below on figure 2.2.1:

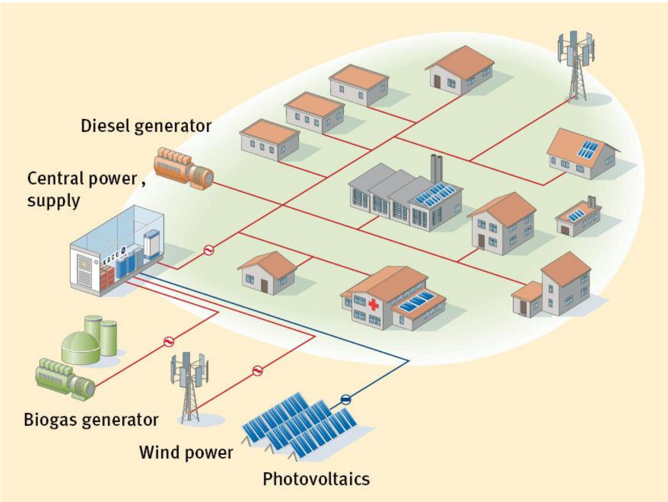


Figure 2.2.1 Hybrid mini-grid [19]

Hybridization of a power system reduces the likelihood that there will be no avenues of power available when it is required, increasing the reliability of the network while also being able to reduce life time costs through reduced reliance on battery storage [18].

However the inclusion of multiple generation sources can require more complex control systems to maintain system reliability. This means that maintenance personnel will require more technical knowledge to maintain a system which can be quite difficult in very remote regions [20]. One example of this is in the case of a wind-PV-diesel hybrid mini-grid in Vanua Levu in Fiji. In this instance the lack of community technical skills saw the proportion of power supplied from renewable sources reduce from 60% to 15% over the course of 4 years and ultimately the system had to be reconfigured to be diesel only [20].

2.3 Optimal Generation sizing

Sizing of generation equipment is an important topic in the design of rural hybrid mini-grids due to severe need to minimise the cost of generation for the impoverished consumers. There exist a number of methods for achieving this goal as well as software applications such as HOMER that are able to extrapolate results. However, in order to gain a greater understanding of the optimization process and allow full control over the source code, this project implements Particle Swarm Optimization (PSO) to ascertain the optimal generation mix of PV and conventional sources. PSO consists of a set number, swarm, of particles moving through a search space in which every location is a potential solution to the objective function that requires optimization [21]. An example of this is shown below on figure 2.3.1:

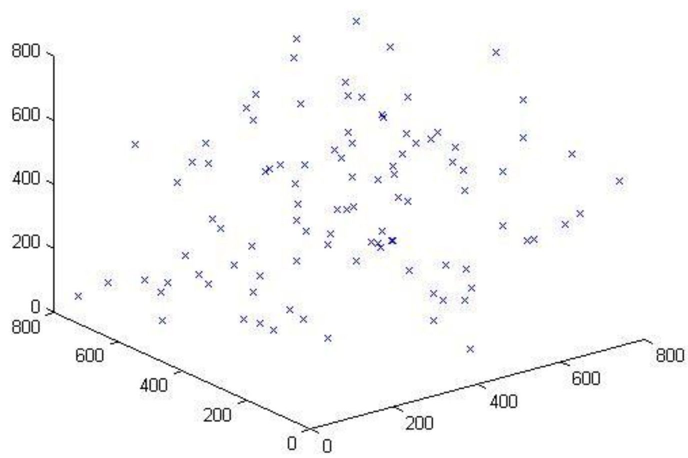


Figure 2.3.1 PSO Example

In order to find the global minimum or maximum within this search space each particle tracks the location of its personal best known solution, P_{best}, and the best known solution that any particle within the swarm has managed to find, G_{best}. Upon every iteration of this technique the objective function is evaluated for each particle, i, and their current positions, X, in each dimension, j, are updated according to their current location and the answer to the velocity vector equation as shown below:

$$V_{ij}(t+1) = V_{ij}(t) + C_1\, R_1 \left(Pbest_{ij}(t) - X_{ij}(t)\right) + C_2\, R_2 \left(Gbest_{ij}(t) - X_{ij}(t)\right) \; [\mathbf{2.3}]$$

The correction coefficients C1 and C2 describe the cognitive and social capacity of the particles respectively, essentially how much the particle wants to move in the area of its personal best solution and how much the particle wants to move toward to best known location within the swarm. It is this communication between individual particles and the overall swarm that allows for convergence to occur. R1 and R2 are random numbers between 0 and 1 that add a random element into the movement of the particles. Positions are updated on each iteration of the technique according to equation 2.4:

$$X_{ij}(t+1) = X_{ij}(t) + V_{ij}(t+1) \; [\mathbf{2.4}]$$

PSO has a number of advantages over other optimization techniques for this problem due to its speed and relatively simple procedure: it updates a particles position in each dimension of the search space based using easy to understand relationships [21]. As well as this, the ability to consider new generation sources by simply adding a new dimension to the problem makes it very useful for hybrid mini-grid generation sizing. Moreover PSO is also very good when problems require constraints, allowing pre-programmed user commands to dictate the boundaries of the feasible search space [21]. How this optimisation technique can be applied to find the generation size of a mini-grid is discussed in section 3.4.

2.4 DC Transmission

While almost all power distribution is currently conducted using AC transmission systems, in recent years there has been a growth in the interest of DC distribution networks [11]. Within the context of a rural mini grid DC distribution networks present a range of benefits that could help to improve the implementation of the project. Particularly one of the key advantages of DC distribution is due to the reduced converter stages associated with distributed generation sources such as Solar-PV and wind turbines. For instance, Solar-PV produces a DC output so in order to transmit captured power across an AC network an inverter stage is required. Removing this requirement for power inversion removes both the cost of the device as well as its associated losses. This in turn could allow for more consumers and appliances to be served using the same generation equipment and for lower cost. In addition to this DC transmission also presents advantages in terms of line losses due to the removal of reactive power which has the added benefit of reducing system complexity [22].

Although appliances used in the industrial world are built for AC distribution networks, many of these appliances are actually DC in nature [11]. Examples of this include LED lights, device chargers and personal computers. This means that these devices also require converter stages which introduce further inefficiency's to power distribution [11]. Removal of these stages could again allow for more of the generating capacity to be used. For instance the amount of light that an LED is capable of outputting with the same input power is much higher for DC systems than for AC as shown on figure 2.4.1:

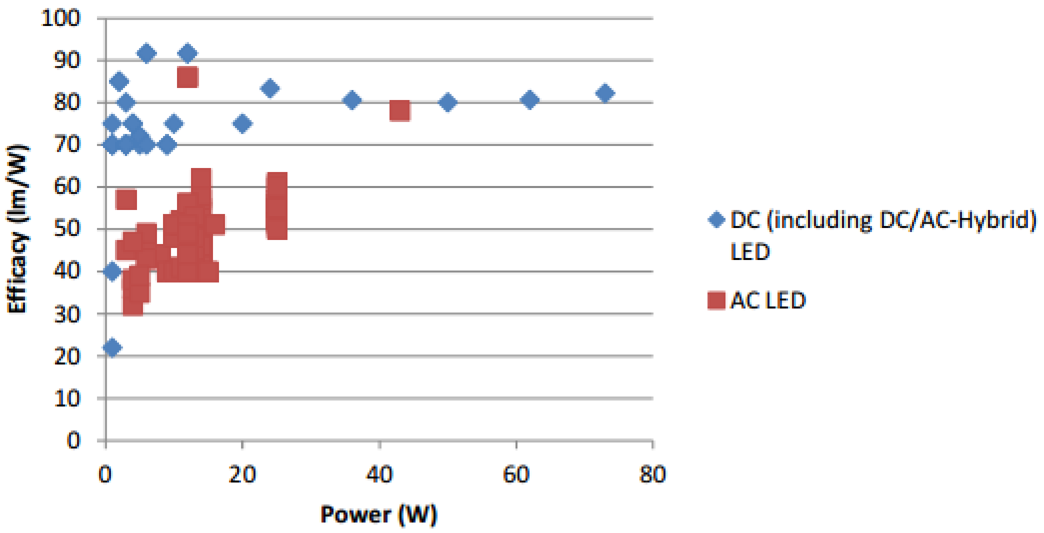


Figure 2.4.1 Efficacy of LED Lights in AC and DC Systems [23]

Due to low demand of DC household appliances in the developed world however, the cost of more productive DC devices such as motors and refrigerators can be much higher compared to their AC counterparts [23]. This in turn limits the ability of low income rural communities to afford them and access the economic benefits. Inability to purchase these devices will limit the growth of the network and this can affect sustainability as consumers become dissatisfied due to being unable to gain access to new appliances.

Another problem for DC transmission is the voltage levels that a rural DC mini-grid can utilise are very low: typically 12 and 24 Volts. This limits the potential for transmission to very short distances and low power appliances due to the large current and subsequent voltage drops. One company called "Mera Gao Power" currently installs these low voltage DC networks for lighting and mobile phone charging in the Uttar Pradesh region of India

[24]. Despite the limitations of DC networks the company has achieved much success with their business model, attaining pay back periods of less than 3 years [24]. This illustrates that while a DC mini-grid could be a detriment to a community seeking productive uses of electricity, it can be suitable for those without that requirement. In addition a DC mini-grid could also act as a transitional phase in an electrification strategy, providing power for low end uses at lower risk of capital while viability of future energy uses is evaluated.

2.5 Minimizing Distribution System Cost

Regardless of wither AC or DC transmission is used, power distribution networks can be very expensive to build and maintain, estimated at accounting for up to 16% of a mini-grids' initial capital [10]. In order to minimize the cost of the distribution network, the topology of the conductor layout must be optimized. To do this requires that each consumer is connected to the generation source using as little power cable as possible. This represents a well-known computer-science problem called a minimum spanning tree (MST). An MST is defined as a tree which connects each node within a graph together through paths with a combined length that is less than that achievable through any other tree [25]. An example of this is shown below on figure 2.5.1:

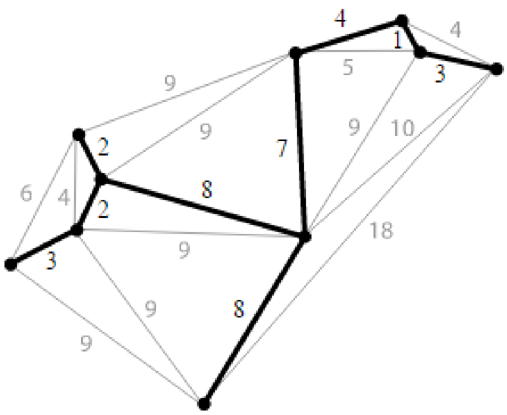


Figure 2.5.1 Minimum spanning Tree for a directed graph [25]

An MST allows the evaluation of the least cost path for conductor cabling. However because this is a power network, there is an additional constraint on the problem in the form of voltage regulation and cable current rating. Depending on the consumers demand profile, they will draw a different amount of current at different times of the day. Because conductor cables contain a resistive element there will be a voltage drop between nodes according to ohms law which in turn causes the voltage to depreciate the further away from the source consumers are located. Adequate voltage regulation is a requirement of any power distribution network due the adverse effect voltage deviations can have on consumer appliances. This is no less true in a mini-grid, especially when it is considered that they might lack the fund to replace damage caused by grid instability.

To prevent poor voltage regulation the MST produced must therefore obey the capacity constraints of voltage regulation and current rating while also connecting each node to the source. Adding these constraints to an MST causes the problem to become a capacitated minimum spanning tree (CMST), the optimal solution to which is NP-Hard [26]. This means that while it is possible to find the optimal solution for low numbers of consumers by simply checking every combination, as more consumers are added to the problem, the time taken to calculate an optimal solution tends to infinity.

While a CMST is an NP-hard problem it is possible to find near optimal solutions using techniques such as the one employed in this project called Esau-Williams Heuristic. This exchanges accuracy in the final result for enhanced computational speed, providing a practical method for determining the expected topology and cost of the mini-grids distribution lines. While other methods such as Prim's algorithm exist for finding near optimal solutions, Esau-Williams Heuristic is used due to its tendency to provide better results than other techniques [26]. In addition its relatively simple procedure allows more time to be spent programming constraints.

The procedure for Esau-Williams involves connecting each node to the source and then iteratively calculating the trade-off function. The trade-off function calculates the new connection between two nodes that minimises the total length of line required by the network. Following this the constraints are evaluated to determine whether or not the connection is valid. This implementation of this method is discussed further in section 3.3.

2.6 Evaluation

Determining wither a mini-grid is the best solution for rural electrification will depend on its comparison to the other alternatives. In order to evaluate this, the levelized cost of energy (LCoE) of each approach can be calculated. LCoE defines the minimum unit cost of energy that the end consumers must pay in order for the project to be a break-even investment over the course of its lifetime [27]. This can be calculated according to the following equation:

$$LCoE = \frac{\sum_{n=1}^{n=20} \frac{C_n + M_n + F_n}{(1+r)^n}}{\sum_{n=1}^{n=20} \frac{D_n}{(1+r)^n}} \quad [2.5]$$

Where: Cn is the capital cost in year n

Mn is the maintenance cost in year n

Fn is the fuel cost in year n

Dn is the annual demand in year n

r is the discount ratio

The discount rate is a percentage used to evaluate future expenses and incomes in terms of today’s money [27]. Essentially this is considering the time value of money. What this means is that money invested today is worth more than money received in the future, and similarly for expenses. This is due to both inflation and the potential earnings that money could of produced had it been invested in something else [27].

Lifetime of components can vary depending on quality, environment and the manner in which they are used. For instance while a diesel generator may last for longer than 8 years when properly maintained by a professional technician, in a rural setting without trained support the lifetime can be reduced to as little as 5 years [28]. Similarly the lifetime of a battery bank will vary depending on the temperature in which it is kept as well as the depth of discharge (DoD) that it is regularly reduced to as shown on the figure below:

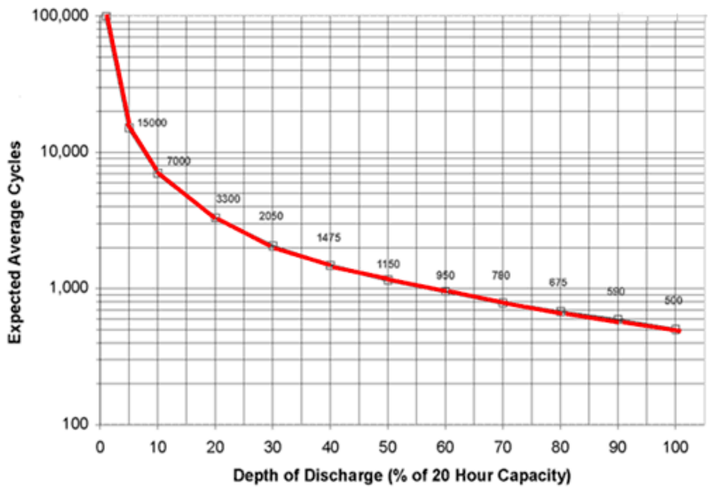


Figure 4.4.2 Impact of DoD on Battery Life Cycles [29]

In order to take into account the cost of replacing these components there lifetime needs to be estimated and the resulting cost evaluated in terms of today's money. Net Present Value (NPV) allows the evaluation of the economic gains and losses of the project over the course of its lifespan by taking into account the cash flows of each year, discounted in order to gain a value in today's monetary terms [27]. This is calculated as shown below:

$$NPV = \int_{n=1}^{n=20} \frac{Cin_n - Cout_n}{(1+r)^n}$$

Where: Cin_n is the cash flowing into the project in year n

$Cout_n$ is the cash flowing out of the project in year n

3.0 Methodology

3.1 Measuring the demand of a rural area

In order to implement a rural electrification project, the communities demand profile must first be ascertained. Measuring the Demand profile of the local area is a critical step in the design stages of implementing any rural electrification strategy. It is important to know when and where power is going to be required in order to appropriately size generation as well as conductors. In addition reliably predicting growth in demand can allow for reduction in costs for future upgrades to the system. This can be undertaken by measures such as oversizing conductors as well as balance of system devices to avoid paying for completely new components later in the projects lifetime [14].

Forecasting the demand of a community that has never had access to electricity will be a difficult task however some guidelines that can be followed at this stage could include:

- Investigate similar Electrified villages
- Identify any opportunities for productive loads
- Identify the types of energy use that exists already e.g. kerosene lamps.
- Organise community meetings
- Identify any local commerce that would benefit from electricity
- Identify potential seasonal variations in appliance use e.g. air conditioning

In order to model the parameters of the mini grid this project incorporates a GUI that uses the *'uitab'* feature of MATLAB to create separate tabs for user input and program outputs. For the Network Demand profile tab the user is able to input the power requirements of each consumer for every hour of the day as shown below:

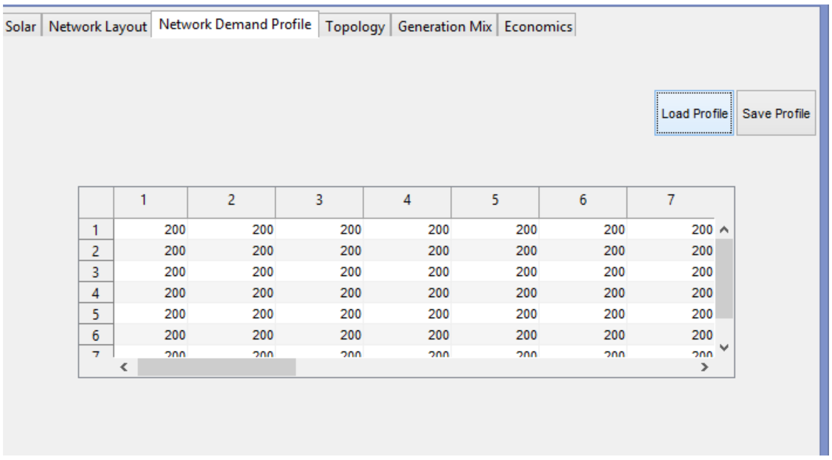


Figure 3.1.1 Network Demand Profile Tab

The user is also able to save the community demand to an excel file so that it can be plotted or loaded for later simulations. Currently this implementation does not allow the modelling of seasonal or daily variations in consumer demand.

3.2 Measuring the Locally available Resources

The choice of generation mix for a hybrid mini grid is determined based on the local renewable and conventional resources as well as the cost of each component. This report will consider the use of a Solar PV-diesel hybrid generation mix and therefore the amount of power that is available for use is determined by the available solar insolation at the given site and the availability of fuel.

3.2.1 Incident Radiation on a Tilted Surface

In order to calculate the output power of a tilted solar panel the amount of direct and diffuse radiation it captures must first be ascertained. The amount of direct radiation that a tilted surface is able to collect is described using equation 3.1 shown below:

$$Idb = \frac{I_{dh}\cos(\theta_i)}{sin(\beta sol)} \quad [\mathbf{3.1}]$$

Where I_{dh} is the direct radiation available to a horizontal surface and θ_i is the angle of incidence between the sun's ray and the collector's surface normal vector. β_{sol} is the solar elevation angle, used to describe the height of the sun in the sky relative to horizontal plane [15]. Figure 3.2.1 below illustrates the angles related to irradiance capture discussed in this section:

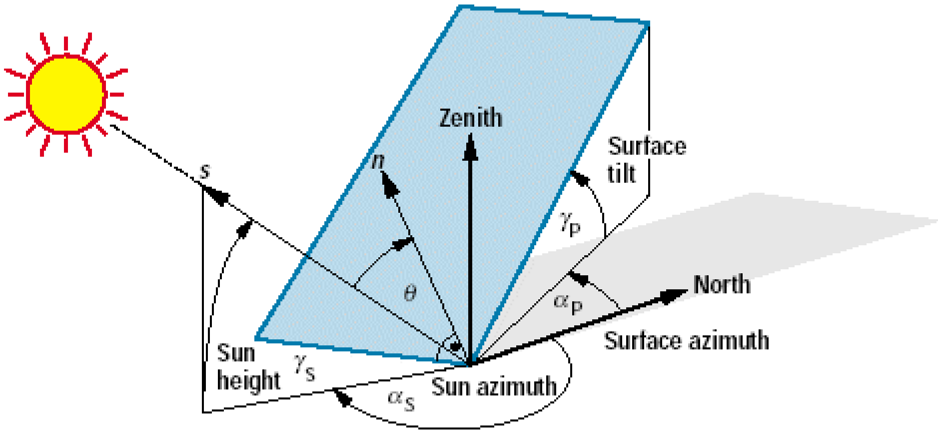


Figure 3.2.1 Solar Angles [30]

In order to calculate the angle of incidence for every hour of the year the suns position relative to the collector must be ascertained. The position of the sun in the sky at any point in time is dependent on which day of the year it is and the current time of the day. Due to variations in the earth's orbit over the course of a year and the use of standardized time zones, the true solar time, Ts, varies from the actual local time measured by a watch according to the equation 3.2 [15]:

$$\mathrm{Ts} = \mathrm{Tm} + 4\frac{\mathrm{Ldiff} + \mathrm{Et}}{60} + \mathrm{Ds}\ [\mathbf{3.2}]$$

Where Tm is the local meridian time, L_{diff} is the Difference in longitude between the local meridian and the location in question. In addition Ds is used to accommodate daylight savings. The equation of time, E_t, is used to incorporate the fact that the earth follows an elliptical orbit around the sun. This in turn means that the earth will be closer or further away from the sun depending on the time of year and this in turn has an impact on the suns position in the sky. This can be calculated for each day of the year using the relationship shown below:

$$Et = 9.87\sin(1.978n - 160.22) - 7.53\cos(0.989n - 80.11) - 1.5\sin(0.989n - 80.11) \ [\mathbf{3.3}]$$

Where n is the day number of the year. The answer to this equation varies over the course of the year according to the graph shown below on figure 3.2.2:

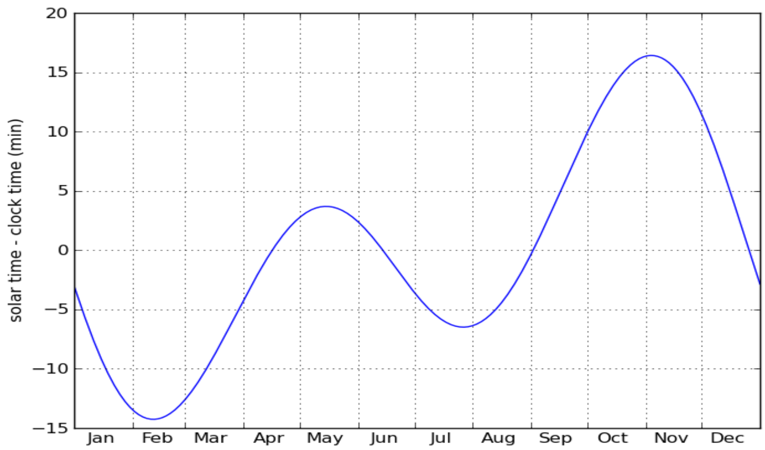


Figure.3.2.2 Answer to the equation of time [31]

Once the true solar time is calculated the hour angle, ω, can be ascertained. The hour angle is used to relate the apparent motion of the sun across the sky due to the earth's daily rotation into an angular quantity. Given that there are 24 hours in a day and the earth completes a full, 360°, revolution in that time, the hour angle changes by 15 degrees over the course of a single hour as described using the equation shown below.

$$\omega = 15 \times (12 - Ts) \ [\mathbf{3.4}]$$

The height of the sun in the sky changes according due to the earth's natural tilt. This is characterised by the declination angle, $\theta_{d,}$ and this responsible for creating the seasons. The declination angle varies between +23.5° and -23.5° over the course of a year dependant entirely on the day number, n, as shown by equation 4.6 [x].

$$\theta_d = 23.45 \times \sin(280.1 + 0.9863n) \ [\mathbf{3.5}]$$

At its maximum the northern hemisphere is tilted towards to the sun increasing the height of the sun in the sky as well as the path the sun needs to travel during the course of a day. This is why during summer the amount of hours of sunlight are increased and conversely in winter are decreased. This variation is characterised as shown on the diagram below:

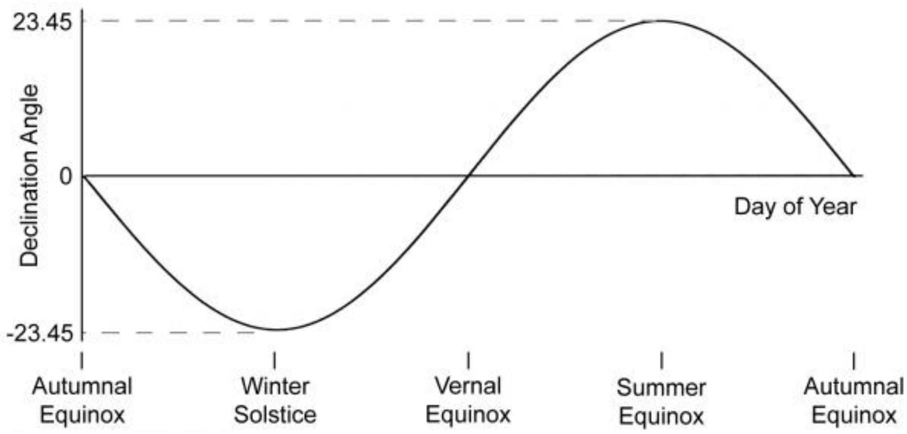


Figure 3.2.3 Variation in declination angle throughout the course of a year [32]

The elevation angle, $\beta_{sol,}$ depends on the distance from the equator, the local latitude, the declination angle as well as the hour angle as shown by equation 3.6.

$$\beta \text{sol} = \sin^{-1}\left(\cos(\text{Lati})\cos(\theta_d)\cos(\omega) + \sin(\text{Lati})\sin(\theta_d)\right) \; [\mathbf{3.6}]$$

The solar azimuth angle, θ_Z, is used to describe the horizontal movement of the sun through the sky over the course of a day. This is related to the hour angle, the declination angle as well as the elevation of the sun as shown on equation 3.7:

$$\theta_Z = \sin^{-1}\left(\frac{\sin(\omega)\cos(\theta_d)}{\cos(\beta \text{sol})}\right) \; [\mathbf{3.7}]$$

Once these angles have been calculated the angle of incidence can be evaluated. The angle of incidence takes into account the tilt of the collector, the height of the sun, and the azimuth of the sun relative to the direction the collector is facing as shown in equation 3.8. Different conventions exist on defining azimuth angle however this report takes due south to be equivalent to 0^{o} with angles east being negative and angles west being positive. In order to prevent the equation from producing a negative irradiance output it is assumed that when the sun is east of the surface normal vector the azimuth angle ranges from -90 to 0 and conversely from south to west is 0 to +90.

$$\theta_i = \cos^{-1}\left(\sin(\beta \text{sol})\cos(\beta \text{surf}) - \cos(\beta \text{sol})\sin(\beta \text{surf})\cos(\theta_Z)\right) \; [\mathbf{3.8}]$$

With this established it is possible to calculate the angle of incidence for a location with a given longitude, latitude and a fixed tilt angle for every hour of the year. This can be implemented in MATLAB as shown on figure 3.2.4:

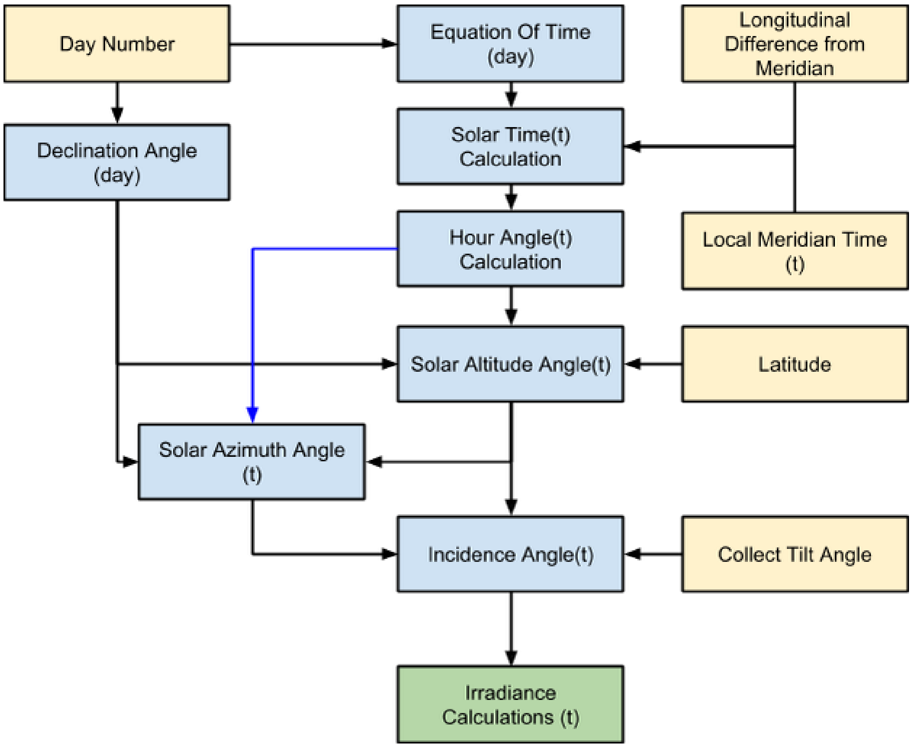


Figure 3.2.4 Incidence Angle Program Progression

This program works by using a *'for loop'* to iterate through all 8760 hours of the year. In order to increment the number of days a counter variable is used to mark when 24 hours have been calculated and increment the day number of the year variable. Yellow boxes show user inputs while blue boxes perform the functions that return angles required to make each successive calculation until the incidence angle for that hour is calculated. Once the angle of incidence for a point in time is known, the total amount of incident radiation striking the surface of the collector can be calculated.

While the beam radiation can be calculated straightforwardly by using equation 3.1, the diffuse component needs to take into account the fact that the scattered radiation is not spread evenly throughout the sky, its anisotropic [15]. This means that the diffuse solar radiation is concentrated at certain locations. There are number of models that can be used to calculate this however this project uses the relationship shown below:

$$I_{sb} = \mathrm{Ifh(t)}\left(\frac{1+\cos(90-\mathrm{Bsurf})}{2}\right)\left(1+\left(1-\left(\frac{\mathrm{Ifh(t)}^2}{\mathrm{Igh(t)}^2}\right)\right)\left(\sin\left(\frac{\mathrm{Bsurf}}{2}\right)\right)\left(1+\left(1-\left(\frac{\mathrm{Ifh(t)}^2}{\mathrm{Igh(t)}^2}\right)\right)\right)\left((\cos(\theta i))^2\right)\left((\sin(90-\mathrm{Bsol}))^3\right)\right) \quad \textbf{[3.9]}$$

This relationship allows the effects of horizon brightening and circumsolar activity to be taken into account [15]. Circumsolar activity describes how much of the diffuse radiation is located close to the region of sky that the sun occupies while horizon brightening is the affect that much of the diffuse radiation will be located between the sun and the horizon [33]. In addition to the diffuse radiation present in the sky there is also a small amount of diffuse radiation reflected from other surfaces onto the solar collector. This presents a very small portion of the total irradiance however it is still included and calculated using equation 3.10

$$I_{rb} = 0.5\left[1 - cos\left(90 - \beta_f\right)\right](Idh + Ifh)r$$

Where: Irb is the reflected diffuse component

Bsurf is the tilt of the collected

Ifh is the horizontal diffuse irradiation

With these equations in mind the program is able to calculate the total irradiance incident on the surface for each hour of the year. It is able to do this by reading in locally available resource data stored within an excel file. It will then split the diffuse and direct horizontal up according to equation 2.1. Using the solar angles calculated for that hour the program will then calculate the value of each radiation component to find the total radiation incident on the surface. The operation of this part of the program can be described using figure 3.2.5:

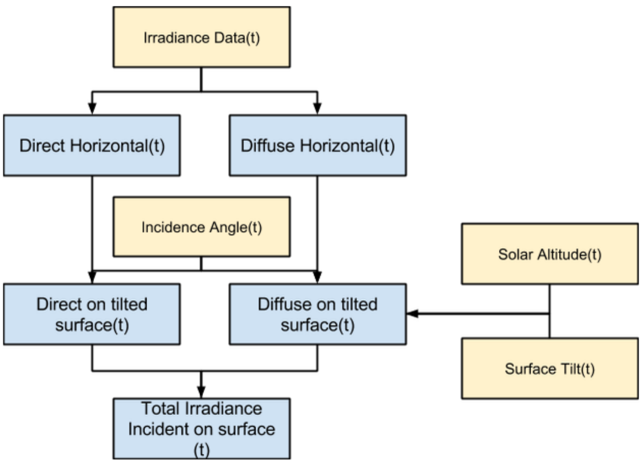


Figure 3.2.5 Calculation of Irradiance on Tilted Surface

3.2.2 Power Output of a Single Module

The power output of a solar panel depends on the ratio of incident radiation to power output under irradiance at standard testing conditions (STC), 1000w/m^2. In addition to this the operating temperature of the cell also affects the output power as shown by figure 3.2.6.

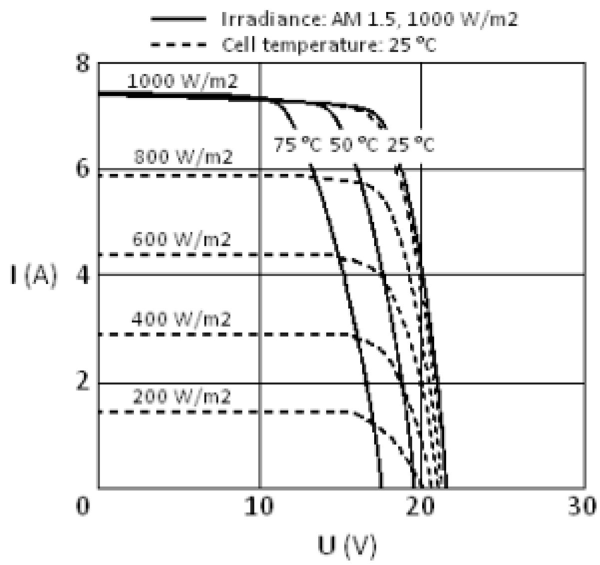


Figure 3.2.6 Output Characteristics of a solar cell for different temperatures [34]

Figure 3.2.6 shows the influence that operating temperature can have on solar cell output power. This variation is characterized by the temperature coefficient, k, of a solar cell and varies between different panel models [34]. In order to take this variation in output into account the current operating temperature of the cell can be calculated according to the following equation:

$$T_{cell} = T_{amb} + \frac{NOCT - 20}{800} \times I_{tot} \quad [\mathbf{3.11}]$$

Where I_{tot} is total incident radiation, T_{amb} is the ambient temperature of the location and NOCT defines the nominal operating cell temperature, the temperature of the cell under NOCT testing conditions. These conditions are 800w/m^2 of irradiance and an ambient temperature of 20^{o}C [34]. Using the cell temperature obtained from equation 3.11 and the amount of incident solar irradiance, the power output of a solar cell can be ascertained by using equation 3.12:

$$P_{out(t)} = P_{stc} \frac{I_{tot}}{1000} \left(1 - k(T_{cell} - 25) \right) [\mathbf{3.12}]$$

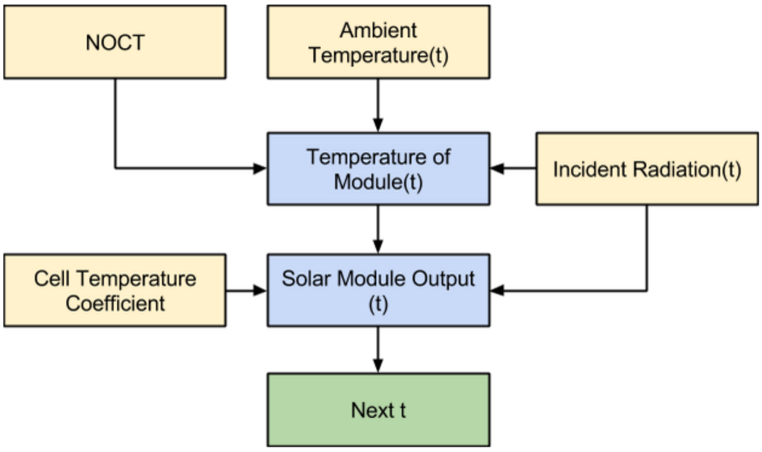


Figure 3.2.7 Flow Diagram of Output Power Calculator

The figure above shows the final operation of this stage of the program in which the power output is calculated. Following this the program will continue to loop for every hour and day of the year until the output of a single solar panel is calculated for the full period. At this point the output can be plotted on the GUI and saved to an excel file for future use. The solar data is also ready to be used for ascertaining the optimal generation mix as discussed in section 3.4.

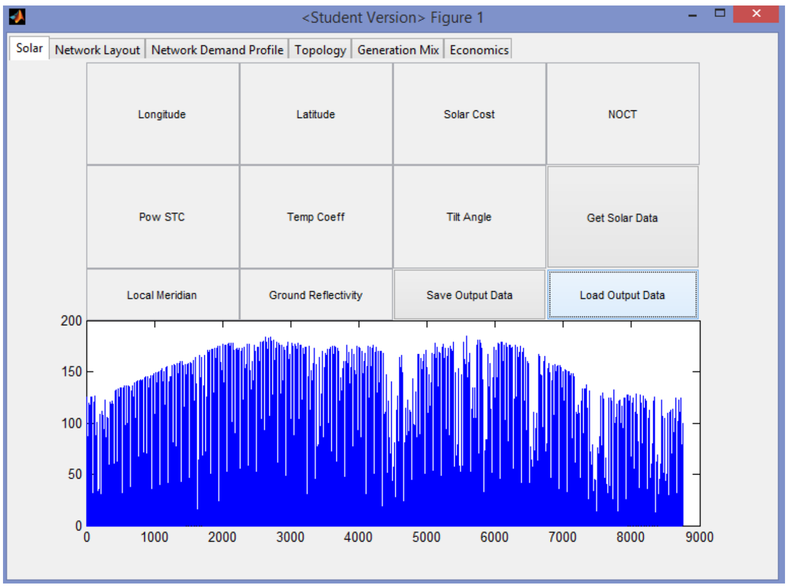


Figure 3.2.8 Solar GUI Tab

The GUI allows the user to input a number of different solar parameters that are key to determining the output as shown above. Currently the file location for the local insolation and temperature data must be altered manually if the output of a solar cell at a new location is to be appraised.

3.3 Creating an Infrastructure

This part of the report will present a method that can be used to minimise the cost of distribution network through optimization of network topology. Esau-Williams heuristic is used to find a near optimal solution for the capacitated minimum spanning tree problem that this task presents. The approach presented in this section only applies to DC mini-grids however the results can be used an approximation for equivalent AC networks if it is assumed that the line reactance is negligible and that all loads operate at unity power factor.

3.3.1 User Inputs

Before the program is able to implement Esau-Williams heuristic a lot of information is required about both the system parameters as well as the consumer loads. Firstly it is important that the locations of consumer loads are established. The program enables this by allowing users to specify the number of consumer locations, or nodes, within the network and creates an input table for x-y coordinates on the user interface. The user can also choose the scale for the network in order to increase the relative distance that values of x and y represent. The Layout of the rural community can then be plotted as shown on figure 4.3.1:

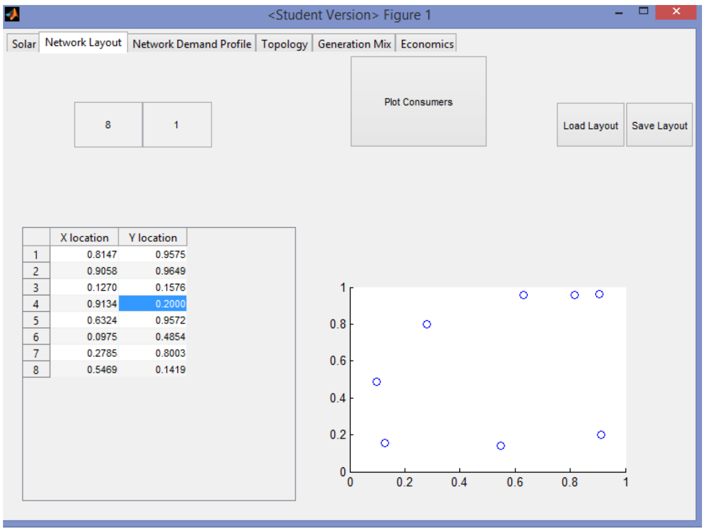


Figure 3.3.1 GUI Network Layout Editor Tab

In order to function the program also needs information on the amount of power that each individual node is consuming at each hour of the day. This data is entered into the network demand profile tab as discussed in section 3.1 and retrieved using two '*for loops*' that assign demand profiles to their respective nodes. All the relative information for each node is stored within a multi-dimensional array. The topology Tab on the user interface also allows the user to enter network specific information related to nominal voltage, line cost, current rating and resistance as shown below on figure 3.3.2:

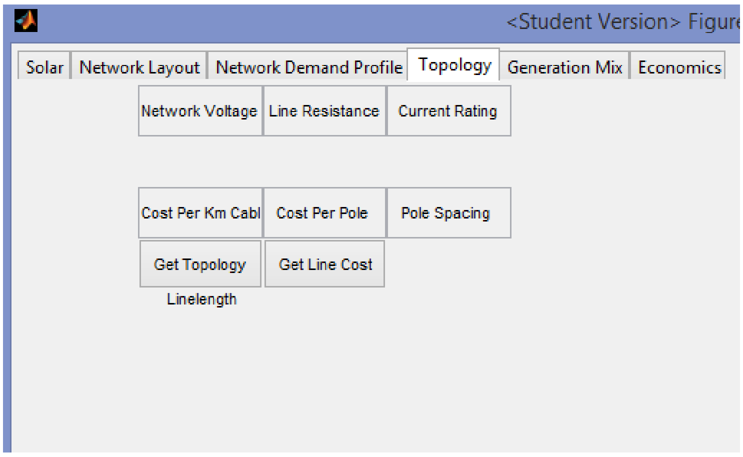


Figure 3.3.2 Topology Tab

Currently the program only allows one type of cable to be considered at a time however future work would allow the program to switch between different types of cable within the same simulation as required.

3.3.2 Initialization

Before this section explains the implementation of Esau-Williams heuristic some tree terminology that will be used needs to be defined. A sub tree refers to a tree of nodes that contains a path back to the root, or source node. A parent node is considered as the next upstream (towards the source) node that a given node is connected to. Conversely a child node is defined as any downstream (away from the source) node that a given node is connected to. A node is considered a descendant of a given node if it can be reached through a path of child nodes.

Upon initialization of Esau-Williams heuristic each load node starts off connected to the generation or root node as shown by the figure below:

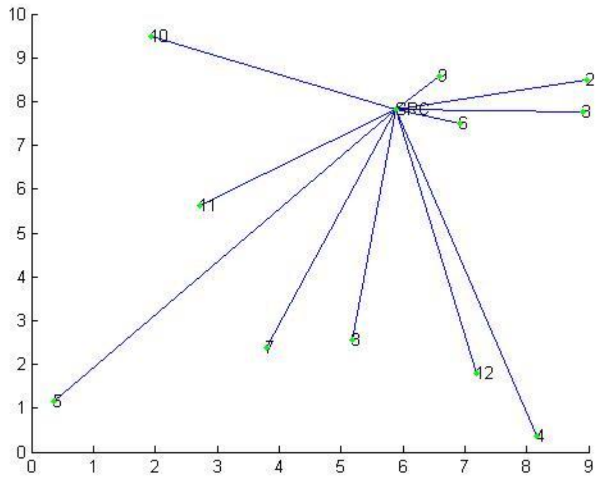


Figure 3.3.3 Initial Topology of Esau-Williams Heuristic

Within this configuration each load node can be considered as being a part of its own sub-tree. The source node can also be considered as being the next upstream, or parent, node of each child load node.

In order to navigate each sub-tree and properly implement the voltage regulation constraint, the program stores each node’s parent within the previously mentioned multi-dimensional array. In addition to this a connectivity matrix is used to remember the connections formed between nodes. A connectivity matrix is 2-dimensional array that stores active connections between two nodes as a logical 1 while using a 0 to represent no existing connection. An example of this is shown on figure 3.3.4:

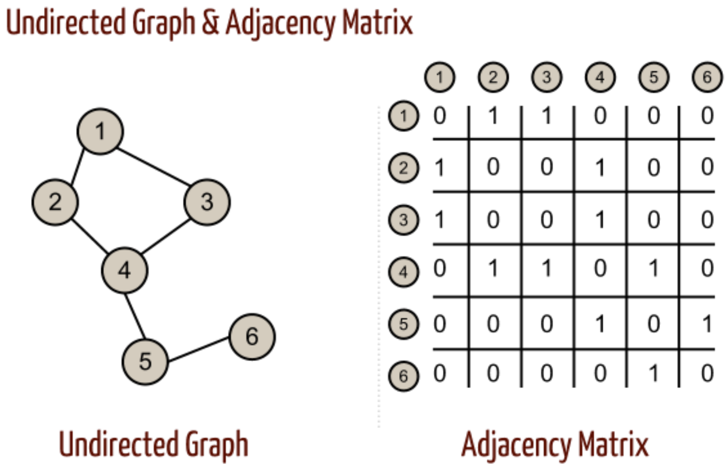


Figure 3.3.4 Connectivity matrix example [35]

Storing both the parent of each node and its connections makes it much easier to distinguish between upstream nodes and downstream nodes. In addition the distance between nodes is fundamental to calculating the trade-off values as well as line resistance. The distance that every node is from every other node is therefore calculated using the Euclidian distance formula:

$$dist = \sqrt{(y_2 - y_1)^2 + (x_2 - x_1)^2} [3.13]$$

The answer to each calculation can then be stored in a distance matrix for future use within the program. With this pre-processing done the program then implements Esau-Williams to find the near-optimal topology for the network. This is described below on figure 4.3.5:

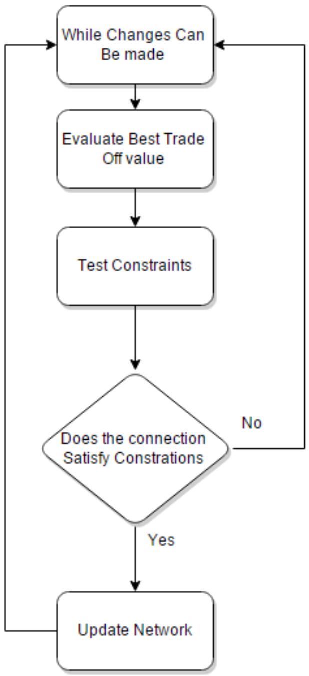


Figure 3.3.5 Flowchart of Steps Required for Esau-Williams Heuristic

3.3.3 Calculating Trade-Off Values

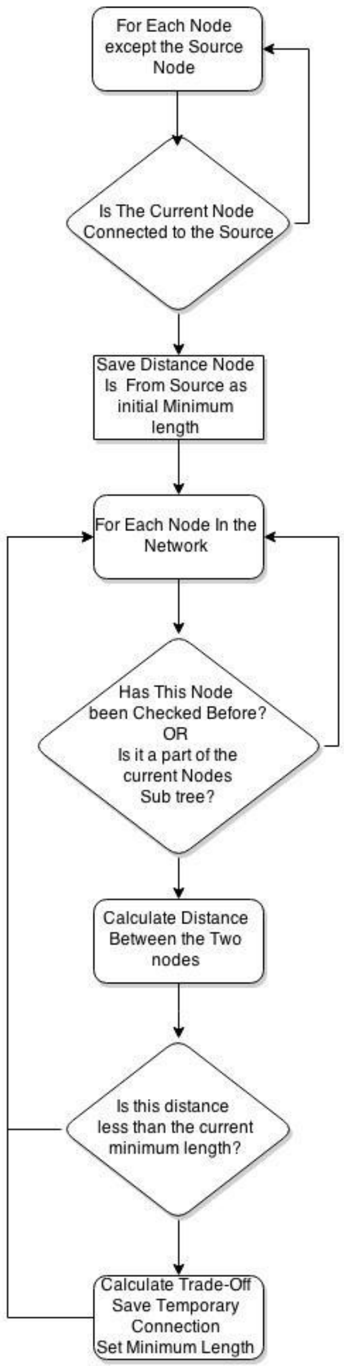


Figure 3.3.6 Trade Off function flow diagram

As mention in section 2.5, Esau-Williams works by evaluating trade-off values between each node. This returns the best connection for that evaluation that will minimise network length, In order to implement this; the program uses two for loops as shown on figure 3.3.6. The first for loop is used to select each node, making it the active node, in the network and checks to make sure that it is a part of its own sub-tree. This prevents nodes that have already been added to another sub-tree from being reconsidered. The initial minimum distance for that node is then set as the length between the active node and the source. The program then moves onto a second for loop that is embedded within the first.

Within this loop the program evaluates the closest node to the currently active node that has not already failed the constraints. In addition the program makes sure that the node being considered for a new connection is not already a part of the active nodes sub-tree. This prevents the program from becoming stuck in a loop during the constraints check. Once the program identifies the best, valid trade off value for that node, it returns to the original loop and selects a new active node to calculate the trade-off value for. This process repeats until the trade-off value is calculated for every node within the network. The program then uses the connection that produced the highest trade off value and tests if the connection can be made while maintaining voltage regulation.

3.3.4 Testing Constraints

Once the program calculates the best connection between two nodes for a given iteration, the connection is then tested to ensure that all nodes within the sub-tree that the node is connecting to are able to maintain the voltage regulation constraint. As well as this the current rating of the conductors cannot be exceeded. To implement this, the current flowing in each distribution line used to connect loads together must be calculated for every hour of the day. This in tandem with line resistance ultimately affects the voltage drop at each node in the network. The current each node draws from the source is dependent on the amount of power required at a given point in time as well as the network voltage as shown by equation 3.14

$$I(t) = \frac{P(t)}{V} \quad [\mathbf{3.14}]$$

In order to calculate the current flowing in every length of cable Kirchhoff's current law (KCL) must be used. KCL states that the sum of currents flowing into a node must equal the sum of the currents flowing out of a node. Given current is always flowing from parent nodes to child nodes within a radial system, the upstream voltage drop will be dependent on how much current a given node and its child nodes are consuming. This means that the current drawn by child nodes must be ascertained before the total current passing through the parent's line can be calculated. The program evaluates this based on the flow diagram shown on figure 3.3.7.

Initially the program starts by considering the node that is trying to connect to the sub-tree. It then enters a *'for loop'* used to iterate through every other node in the network, checking the connection matrix to see if the node has any child nodes with uncalculated currents. If the active node does have child nodes then the first one found becomes the new

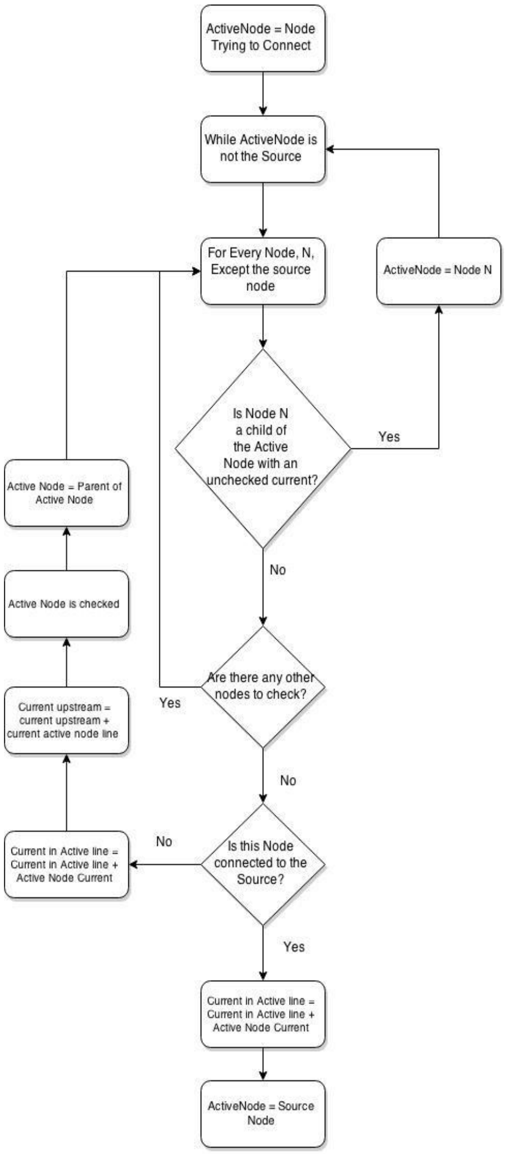


Figure 3.3.7 Line Current Calculation Flow Diagram

active node. This process repeats until the program finds the furthest downstream node with no child connections. At this stage the program will calculate the current drawn by that node and add the value to its personal line current as well as the line current of its parent node. In order to prevent the program from becoming stuck in a loop, a check variable is used to keep track of which nodes have had their current calculated. The parent of this node then becomes the active node.

This process of moving up and down the sub-tree continues until the current in every line of the sub tree has been found. At this stage the current in the line connected to the source will be calculated and the program will move onto determining the voltage at each node. If however at some stage during this part of the program a line current exceeds the conductors current rating then the constraint will be broken. Under this condition the network will reset to its pre-connection state, marking the attempted joining of the two nodes as unachievable. This prevents that connection from being reconsidered upon the next iteration.

Once the current in each line is calculated the voltage drop at each node is evaluated. The program does this in a similar manner as the voltage calculation but in reverse, starting at the node connected to the source and working its way through the sub-tree from there. This is done because the voltage at nodes downstream will be dependant not only on the voltage drop in the line, but the voltage of the parent node as well. This can be described by equation 3.15 shown below:

$$V_{i+1}(t) = V_i(t) - I_{i+1}(t)R_{i+1} \ [\mathbf{3.15}]$$

Where: $V_{i+1}(t)$ is the voltage at the child node at time t.

$I_{i+1}(t)$ is the current drawn by the child at time t

$V_i(t)$ is the voltage of the parent node at time t.

R_{i+1} is the resistance of the line connecting the child node to the parent node.

The resistance of the line is measured based on the line resistance input by the user and the distance between the two connected nodes. The implementation of this part of the program can be described by the flow diagram shown on figure 3.3.8.

Upon each loop of this section, the program checks the currently active node to see if its voltage has been calculated. If the voltage hasn't been calculated this will be done according to equation 3.17.

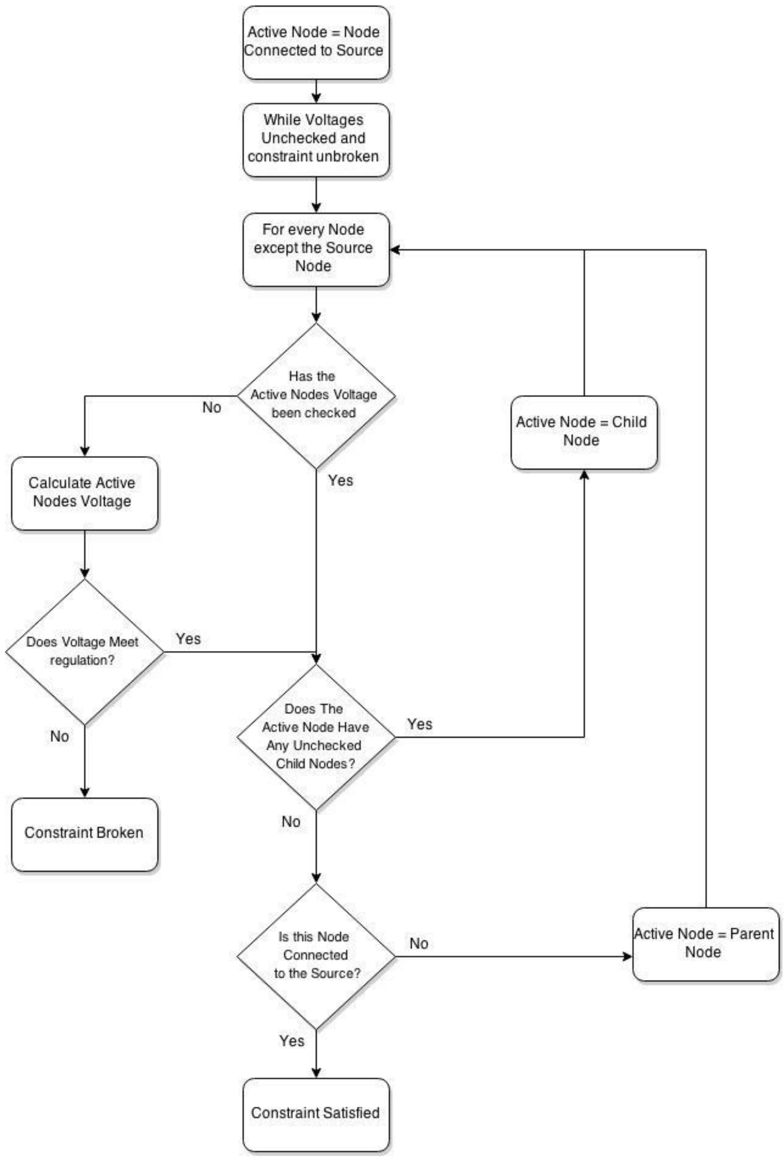


Figure 3.3.8 Node Voltage Calculation Flow Diagram

If the result of this calculation is below the minimum limit for voltage then the constraint is broken and the network resets to its pre-connection attempt state with the connection marked as infeasible. If however the node's voltage is within statutory limits then the program will mark the node as checked then iterate through the connectivity matrix to see if that node has any child nodes with unchecked voltages. If a child node is found then the program will select the first located to be the new active node and the process repeats. If however the active node has no more child nodes that require voltage calculation then the parent node is selected. This process continues until the active node is that which is connected to the source and no child nodes that require voltage evaluation can be found. At this stage the constraint is considered satisfied and the program updates the topology of the network as shown on figure 3.3.9:

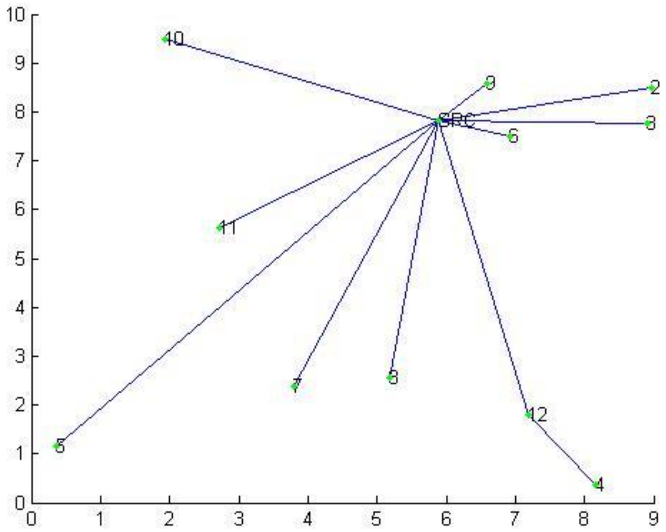


Figure 3.3.9 Topology following a single Loop of the program

If the figure above is compared to figure 3.3.3 it can be seen that the connection node 4 had to the source has been removed, replaced with a connection to node 12. The program will continue to follow the process outlined in figure 3.3.5 until there are no more possible changes and the final topology is found as shown below:

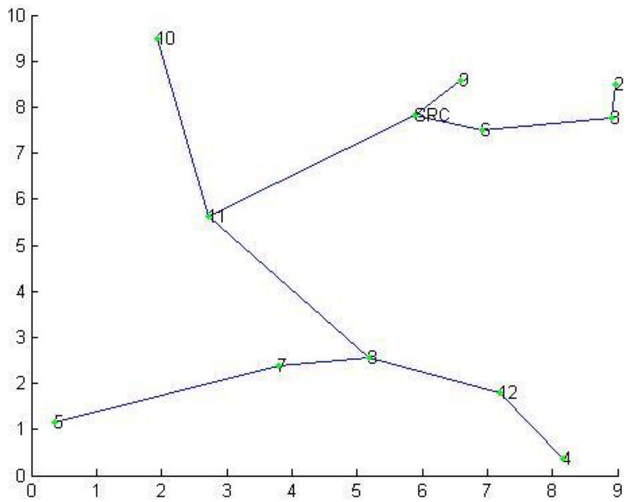


Figure 3.3.10 Output from Esau-Williams heuristic

The program will then return the line length to the user so that the cost of the distribution network can be calculated.

3.4 Particle Swarm Optimization for Optimal Generation Mix

3.4.1 Initialization

The implementation of PSO using MATLAB for this project is based on an original implementation of the algorithm to solve a simple two-dimensional quadratic and can be located at [36]. Optimizing the generation mix for the lowest cost of a PV-diesel hybrid system however is a three dimensional problem that requires time changing constraints that vary according to the consumer demand profile and available solar resources. To implement this each power source is assigned a dimension of its own: x corresponds to the number of solar panels while y and z store the size of the battery bank and generator respectively. Each particle stores its coordinates for each component in a multi-dimensional array. In addition the amount of fuel consumed is calculated and stored for each particle during the constraints loop as described in section 3.4.3. As well as storing the coordinates of its current position, each particle remembers the location of both its personal best evaluation of the objective function, P_{best}, and the global best located by the swarm, G_{best} for each dimension of the problem.

In order to implement PSO the user is required to input a range of site specific parameters including:

- Solar Panel Cost (£)
- Battery Cell Cost (£)
- Battery Lifetime (Years)
- Battery Depth of Discharge (%)
- Battery Ah Capacity and String Voltage
- Diesel Generator Rating (W)
- Fuel Requirement for an hour of Rated generation (lt)
- Fuel Cost (£/lt)
- Discount Ratio (%)
- Availability Requirement (%)
- Days of Autonomy Requirement (Days)

These can be input on the GUI as shown on figure 3.4.1:

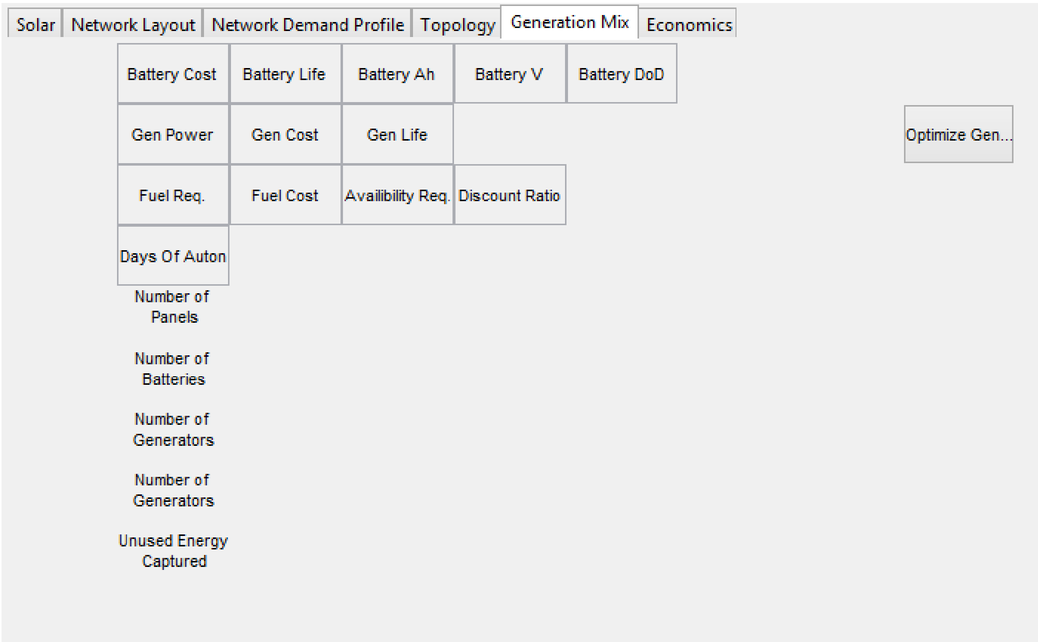


Figure 3.4.1 Generation Mix Tab

3.4.2 Objective function

Before implementing the PSO algorithm the objective function that needs to be optimized, maximized or minimized for the given constraints must be established. For this problem the objective function that needs to be minimized is the cost of generation and this is evaluated based on the user inputs. However the aim is to reduce not just the capital cost of the system but the lifetime cost of the system. To do this future costs must be calculated in terms of today's money i.e. the Net present cost, NPC. This is why the user is asked for the lifetime of components as well as the discount ratio.

Taking into account the lifetime of components and maintenance, the program calculates the lifetime cost of the project through the following equation:

$$Cost_{life} = \sum_{t=1}^{20} \frac{C_{sol}(t)}{(1+D)^t} + \sum_{t=1}^{20} \frac{C_{bat}(t)}{(1+D)^t} + \sum_{t=1}^{20} \frac{C_{gen}(t)}{(1+D)^t} + \sum_{t=1}^{20} \frac{M_{sol}(t)}{(1+D)^t} + \sum_{t=1}^{20} \frac{M_{bat}(t)}{(1+D)^t} + \sum_{t=1}^{20} \frac{M_{gen}(t)}{(1+D)^t} + \sum_{t=1}^{20} \frac{F(t)}{(1+D)^t} \quad [3.16]$$

Where: $Cost_{life}$ is the life time net present cost of the system.

$C_i(t)$ is the capital cost of component i in year t.

$M_i(t)$ is the Maintenance cost of component i in year t.

F(t) is the cost of fuel in year t.

D is the discount ratio.

Equation 3.16 is objective function that requires minimisation in order to optimise the generation mix for the lowest cost. This function is evaluated for each particle upon every iteration of the PSO loop. The capital cost for components is determined by the current position of the particle in the x, y, z search space and the cost for a single component. The maintenance costs use assumptions of 2% capital for solar and batteries per year while 10% capital is adopted for generators to take into account the moving parts. In addition the project life is assumed to be the life of the solar panels, taken as 20 years. The fuel cost is dependent on how much fuel the particle requires in order to maintain the constraint with its current generator size, z.

3.4.3 Constraints

The constraint loop works by checking the each particle to make sure that based on the number of solar panels, batteries and generators it is able to satisfy the demand at every hour of the year. These constraints are based on previous work conducted by the authors of [21]. To implement the constraints the first thing that must be ascertained is the demand at every hour of the day and the solar resource at every hour of the year. Evaluation of these parameters can be completed as shown in earlier sections of this report. Once calculated these variables are loaded into the PSO program. The constraints loop works by iterating through every hour of the year and attempting to meet the community demand at a given time firstly through the user of solar panels as shown by the figure 3.4.2:

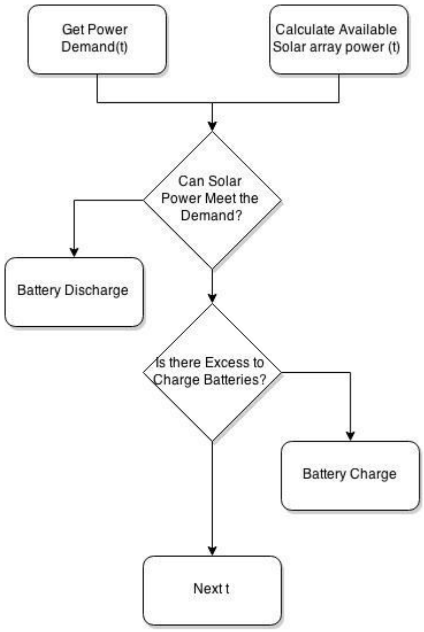


Figure 3.4.2. Solar Array Operation

The Available solar power is calculated using the number of solar panels that the particle, is considering: it's x-coordinate. This is multiplied by the output of a single panel at that point in time for the location:

$$P_{solar}(t) = N_{solar}(particle)P_{solavailable}(t) \text{ [3.17]}$$

If the solar power is able to meet the demand requirement at that hour then the program will check to see if there is any excess energy available that can be used to charge the batteries. If there is no excess energy available the program will move onto the next hour of the year, satisfied that the demand constraint has been met for that point in time. If however there is excess energy available then the program will move onto the battery charge routine described below on figure 3.4.3:

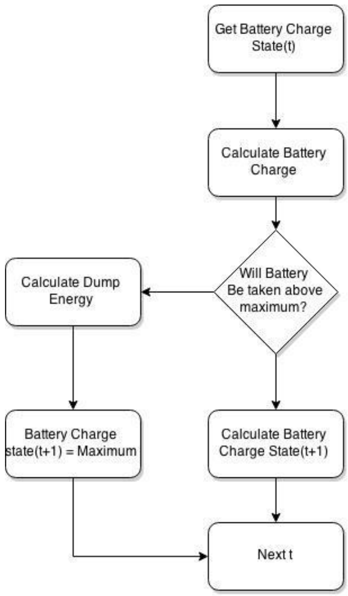


Figure 3.4.3 Battery Charge Operation

Based the demand and the solar power available at a given time, t, the amount of excess power that can be used for charging the batteries is calculated using equation 3.18:

$$P_{charge}(t) = P_{solar}(t) - P_{demand}(t) \text{ [3.18]}$$

The program will then check to make sure that the energy that this charging power does not take the battery above its maximum state of charge. The maximum, and minimum, state of charge depends on the number of batteries the particle is considering: it’s y-coordinate. If the state of charge isn’t taken above maximum then it is updated according to its current state and the amount of excess energy. Battery state of charge is stored as watt-hours within the program to make calculations simpler:

$$E_{BatteryState}(t+1) = E_{BatteryState}(t) + P_{charge}(t) \text{ [3.19]}$$

If the battery is taken above its maximum state of charge then some of the energy must be dumped, or wasted. Calculating this parameter allows evaluation of the performance ratio for the system. The amount of energy that is dumped during this period is described by the equation shown below:

$$E_{dump}(t) = E_{charge}(t) + E_{batterstate}(t) - E_{maximum}(t) \text{ [3.19]}$$

However if the power available from the solar panels is unable to meet the demand requirements of the mini grid then the first course of action that the program will attempt in order to meet the constraints is to discharge energy from the batteries. The battery discharge operation is shown below:

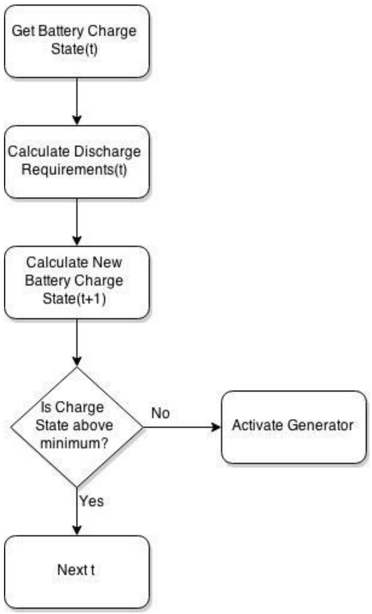


Figure 3.4.4 Battery Discharge Operation

During battery discharge operation the program will calculate the required charge that the batteries need to supply based on the difference between the demand and the solar power available from the panels:

$$P_{discharge}(t) = P_{demand}(t) - P_{solar}(t) \text{ [3.20]}$$

Next the new state of charge for the battery bank is calculated based on the current state of charge and the amount of energy that is required to meet the current demand:

$$E_{BatteryState}(t+1) = E_{BatteryState}(t) - P_{discharge}(t) \text{ [3.21]}$$

In order to make sure that the batteries do not go beyond their maximum depth of discharge the program will then check to make sure that the new state of charge is above the minimum state of charge allowed. If the battery is able to obey this constraint then the program will move onto the next time interval. Otherwise the program will activate the generator in attempt to supply the demand and recharge the batteries. The operation of the generator can be described as shown on figure 3.4.5:

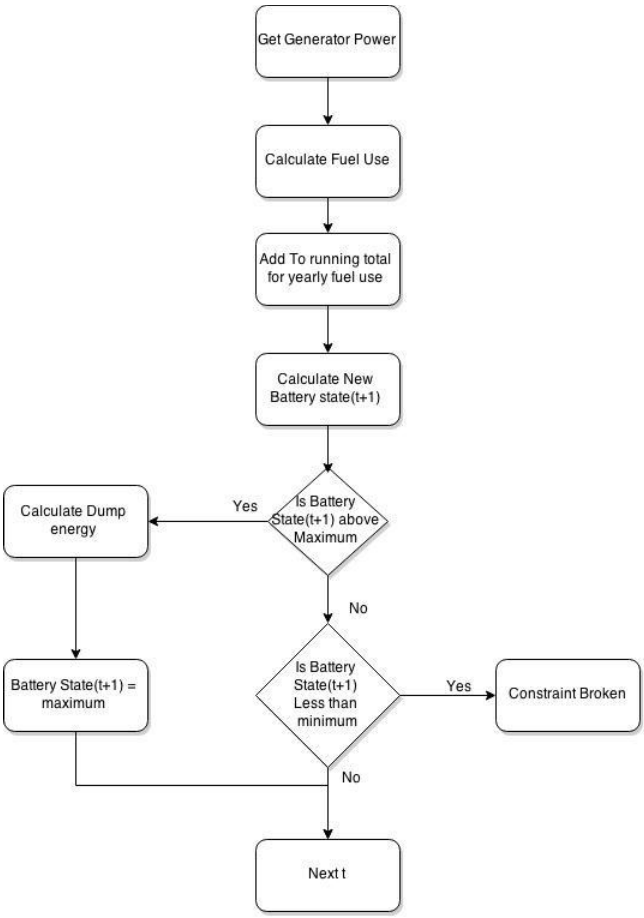


Figure 3.4.5. Generator Operation

The generator is implemented such that it will only operate when neither the solar panels nor the batteries are able to satisfy the demand. This is done in order to reduce the fuel requirements and hence running costs of the system over the lifetime of the project. In addition, it is assumed that the generator will always operate at rated power. The power available from the generator depends on the size of the generator and the initial power specified by the user:

$$P_{gen}(t) = N_{gensize}(particle)P_{genspecified}(t) \text{ [3.22]}$$

In this respect the program considers the size and cost of the generator to be multiples of the user's specifications. Activating the generator requires fuel, the cost of which needs to be taking into account during the evaluation of the objective function for each particle. To incorporate this, whenever a particle has to use its generator to meet the demand the fuel use is calculated according to the size of the generator and the fuel requirements for user's specification. The new battery state of charge is then recalculated to include the generators influence:

$$E_{BatteryState}(t+1) = E_{BatteryState}(t) + P_{gen}(t) + P_{sol}(t) - P_{dem}(t) \quad [3.23]$$

If the generator is able to keep the batteries state of charge above minimum levels then the program will check to make sure the particle doesn't go above its maximum state of charge. If it does then the amount of energy that must be dumped is calculated. However, if the demand cannot be met while keeping the battery's state of charge above minimum, even with the inclusion of the generator, then the particle is unable to satisfy the constraint for that hour.

The impact of particles breaking the constraint depends on the stage of the program and the user's definition of the availability requirement. The availability factor lets the user consider systems that aren't able to meet the power demand 100% of the time in order to see the impact this has on network cost. Essentially it defines the time in hours that the particle is allowed to break the constraint.

3.4.4 Particle Swarm Optimization loop

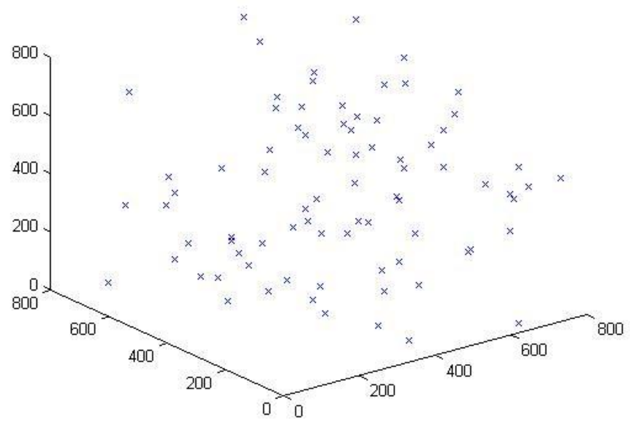


Figure 3.4.6 Swarm initialisation

Initially every particle in the swarm is spawned with random values for solar, battery bank and generator size as shown on figure 3.4.6. Doing this randomly leads to some particles being initialized outside of the feasible search space in which the solutions exist. These Particles are removed before the main iteration of the PSO loop by evaluating each particle against the constraints and eliminating those that are unable to satisfy. Once the infeasible particles have been removed the main PSO loop begins. This is implemented through the use of a *'for loop'* that continues until the maximum specified iterations has been reached. This is chosen to be 500 as a default however in many cases the particles converge on a solution before this point. It is also possible for the particles to converge on local minimums rather than the global so to confirm results it is recommended that the random number generator seed is altered and tests re-evaluated. Figure 3.4.7 describes the main operation of the PSO loop:

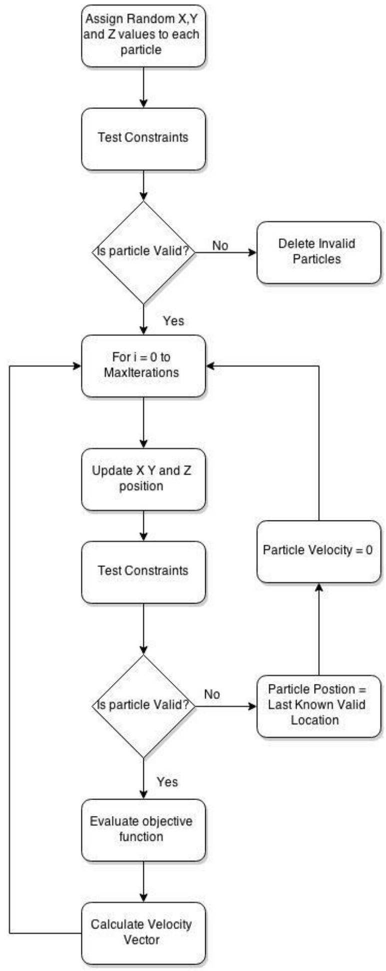


Figure 3.4.7 Particle Swarm Optimisation loop

Upon each iteration of the PSO loop the X, Y and Z, positions of each particle are updated according to their previous position and the result of their personal velocity vectors for each dimension as discussed in section 2.3. The particle's new position will then be tested against the constraints. If it is unable to satisfy the constraint then this means that the particle has passed through the boundaries of the feasible search space. When this happens within the main loop, the particle is moved back to its last known position and waits for its velocity vector to be updated on the next iteration. This is done because many optimal solutions can be found along the wall of the search space as well as to keep particles contained within it. If the particle is valid however then its objective function will be evaluated. The velocity vector is then calculated as described in section 2.3 for each dimension of every particle and the positions are updated accordingly. This process continues until the maximum number of iterations is reached by which point the particles should have converged as shown below on figure 3.4.8:

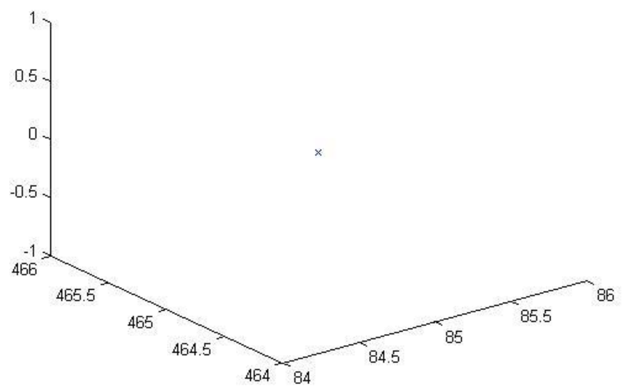


Figure 3.4.8 Particle Swarm Convergence

3.5 Evaluating the Mini-Grid's Economic Feasibility

3.5.1 Levelized cost of electricity calculation

To implement the levelized cost of electricity (LCoE) calculations, the cost of every component needs to be entered into the program through the user interface. Sizing of components and network topology must be completed before this stage can take place or else errors will occur. The user is also requested to input the percentage of cost that balance of systems components such as power condition units, charge controllers and inverters will account for. Reference [10] estimates that these components can make represent up to 30% of the initial capital before the inclusion of the distribution network. In addition, to take into account the availability of subsidies for renewable mini grids and home systems the user is also able to input these as percentages on the economy tab of the user interface.

The yearly maintenance cost is calculated using the same assumptions outlined in section 3.4 for the components. In addition to this, maintenance for the distribution network is assumed to be 4% of the total line routing cost. In attempt to incorporate the cost of a technician performing routine maintenance on a mini-grid, the yearly cost is multiplied by a further 20%. Fuel cost is calculated using the requirement returned by the PSO method. Once all these variables are calculated the LCoE is ascertained at the users request according to equation 2.5.

3.5.2 Net present value calculation

As shown earlier in section 2.6 another useful method for evaluating the economic potential of both mini-grids and the alternatives is by calculating the net present value of the project. This can be calculated using equation 2.6. The cash flowing out of the project is calculated in the exact same manner as the LCoE calculation for each year. Given that selling energy at the LCoE presents a net present value of 0, the user is able to define the price as a multiple of this in order to determine the profitability of a mini grid at different tariffs. In order to see how the cash flows of the project impact NPV over the course of the projects lifetime, the program graphs the yearly NPV as shown on figure 3.5.1 below:

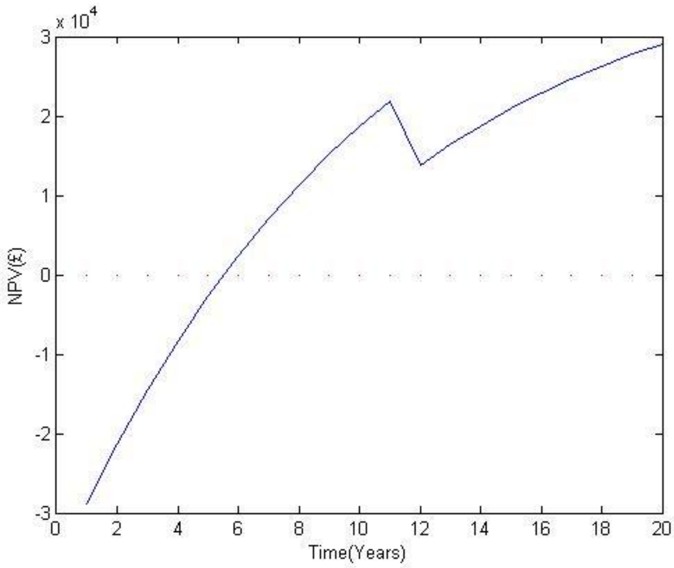


Figure 3.5.1 NPV and Pay-back of mini-grid Example

This also allows the pay-back period, the point at which the project begins to make money, to be evaluated as represented by the red line on the figure above.

3.5.3 Comparison with Alternatives

To compare the different options for rural electrification the user needs to be able to evaluate the cost of each alternative. This is achieved for grid extension through evaluation of NPV based on the cost of grid extension, village network topology and the set electricity price chosen by the user. The NPV of both solutions can then be plotted on the same graph. This allows the user to see the distance at which a mini grid will become a more viable alternative to grid extension. An example of this is shown below on figure 3.5.2:

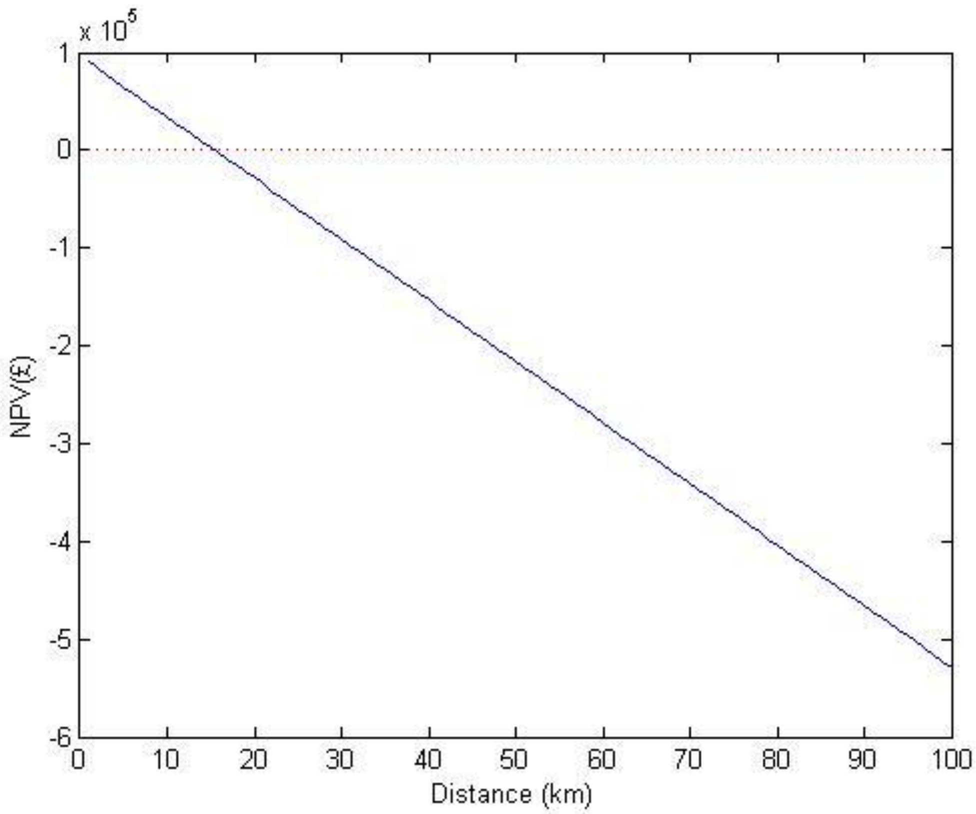


Figure 3.5.2 Example Comparison between mini-grid (red dot) and grid Extension (blue line)

In order to compare the cost of solar home systems to a mini grid implementation, the LCoE can be calculated for a standalone system serving each individual consumer. This is done by applying the PSO method to each individual consumer demand profile, allowing optimisation of the solar home systems component sizing. The LCoE function is then applied. Through this approach insight into the benefits of being in a mini-grid can be evaluated on a household by household basis, allowing network designers to identify consumers that could benefit from being served by alternative methods.

4.0 Case study: Pravaham, Tamil Nadu, India

4.1 Simulation Parameters

In order to apply the developed methodology and software tool to a real world situation, a case study is used in the form of a Christian charity school called Pravaham. Pravaham is located in the Tamil Nadu district of India and while the school is grid connected, they suffer from the load shedding that is commonplace in rural regions of the country. This load shedding is known to occur at least twice a week and can last anywhere from 4 to 48 hours. In addition to this, instability in the grid causes severe damage to appliances, forcing the charity to spend a significant chunk of their budget on rewiring loads. A map of the location provided by the community is shown below:

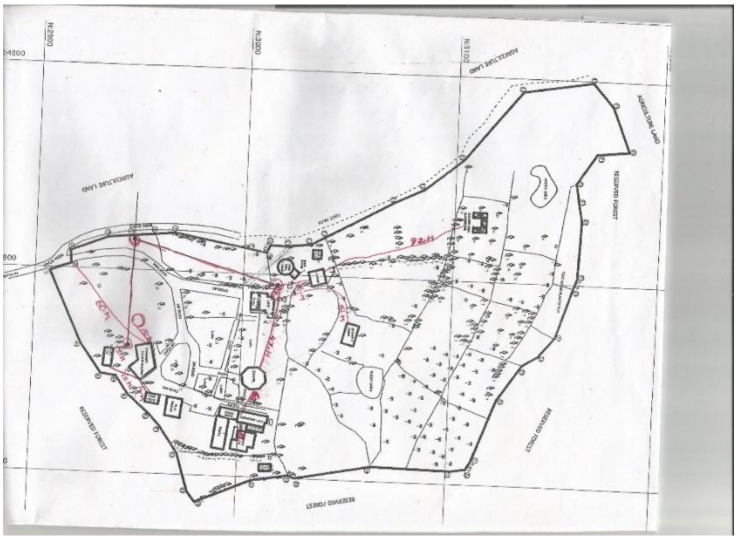


Figure 4.1.1 Pravaham Site Layout

In addition to this the community is able to provide details on their daily load profiles for six of the buildings within their compound. In order to examine the impact that consumer demand can have on employing a mini grid solution the demand profiles are split to provide three different levels of service. These include:

- Lighting only
- Lighting plus small appliances
- Electricity for all appliances

These three levels of service can be characterised by the community demand profiles shown below:

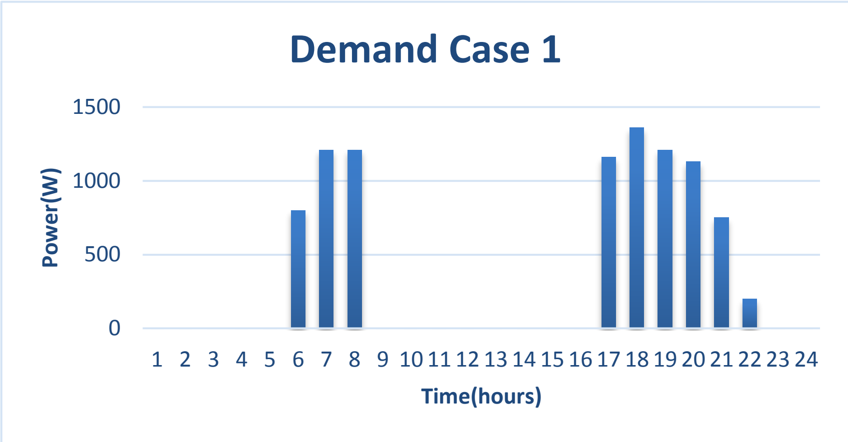


Figure 4.1.2 Lighting-only demand profile

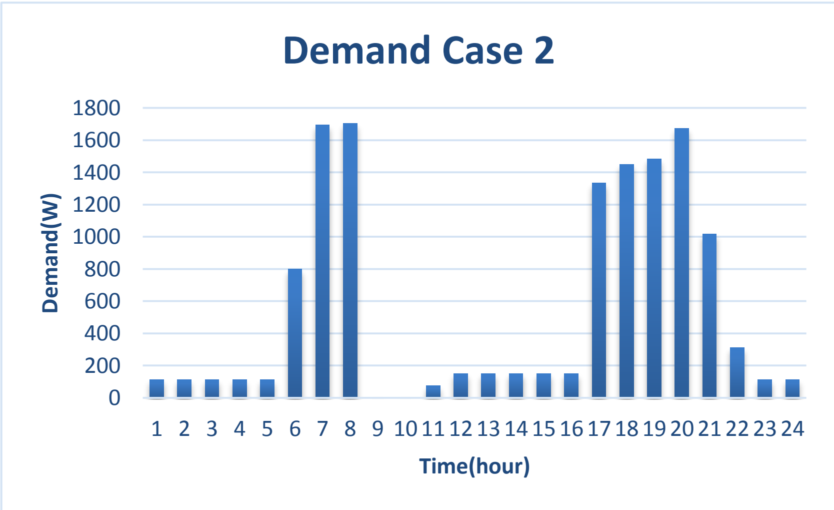


Figure 4.1.3 Lighting plus small appliance demand profile

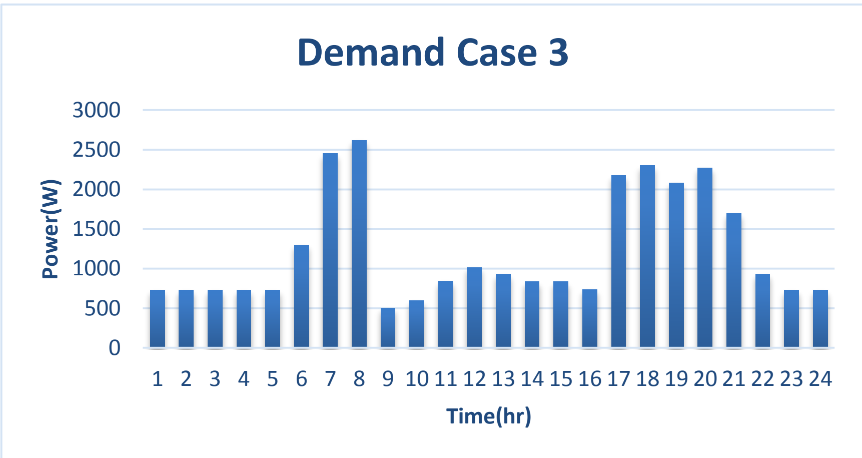


Figure 4.1.4 all appliances demand profile

In order to see how increasing the number of consumers can have an impact on the choice of rural electrification strategy, an additional case can be considered by taking into account the small town located close to Pravaham:

Figure 4.1.5

This study assumes the town is comprised of 30 households that utilise the same demand profiles as Pravaham. The following table describes the solar input parameters to the MATLAB program.

Resource:	Solar-PV
Panel Power at STC:	250 W
Cost per panel:	£150
NOCT:	47^{o}C
Cell Temperature Coefficient:	-0.4%
Local Meridian:	82.5^{o}
Longitude:	79.16^{o}
Latitude:	12.88^{o}
Ground Reflectivity:	0.03
Collector Tilt Angle:	12.88^{o}

Table 4.1 Solar Input Parameters

Information on the local solar irradiance is obtained from Indian meteorological services:[15]. This provides the global horizontal and global diffuse radiation data for the location. The global horizontal irradiance varies according to figure 4.1.6

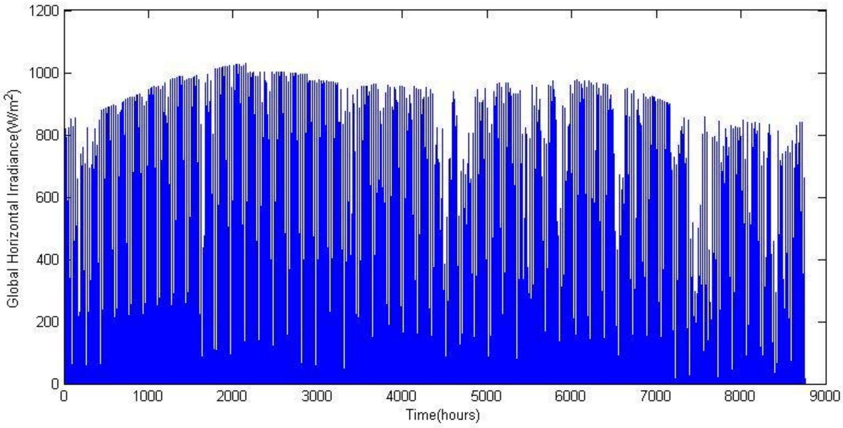


Figure 4.1.6 Global Horizontal Variation over the course a year

In addition information on the local temperature data is obtained from the same source and varies according to figure 4.1.7:

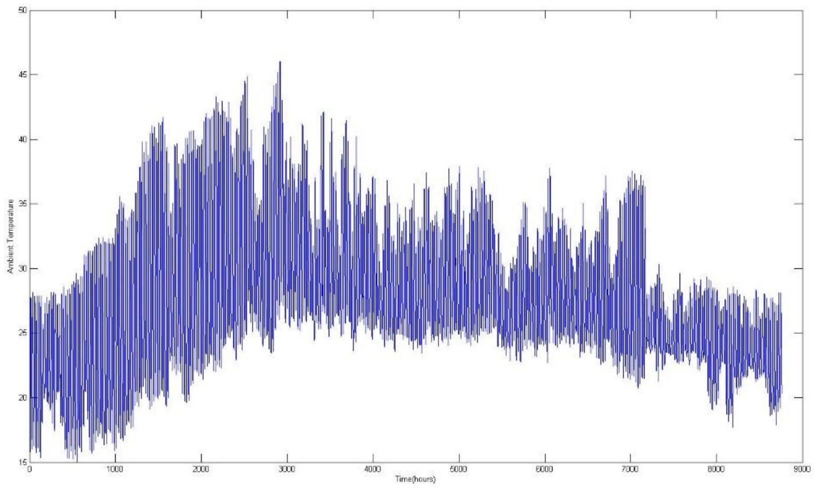


Figure 4.1.7 Temperature Data for Pravaham.

Using this resource information and the values in table 4.1 the power output of a single solar panel is obtained for each hour of the year as shown below:

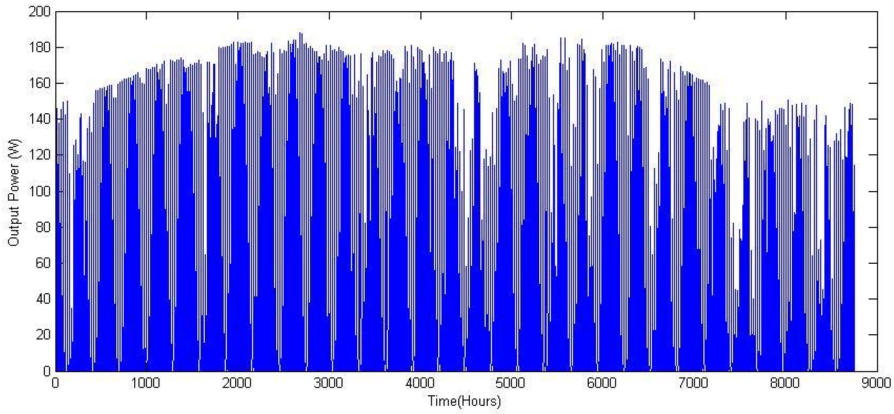


Figure 4.1.8 Hourly Output of Solar Panel at Pravaham

The locations of each consumer are entered by using the map provided and estimating the relative position of each node in the town from google maps. The locations are entered into the GUI and plotted on the scatter diagram for each case as shown below:

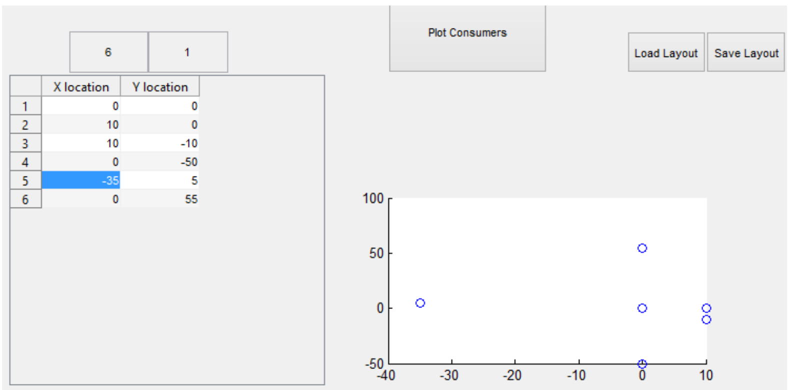


Figure 4.1.9 Layout for Pravaham

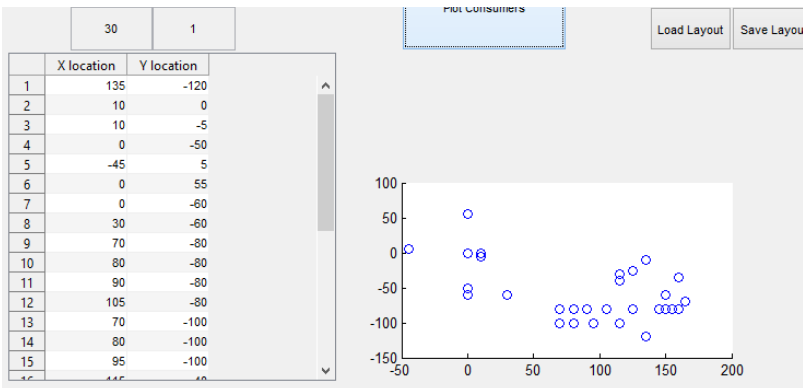


Figure 4.1.10 Layout GUI for Whole town

Depending on the type of conductor used the cost of the power distribution will change significantly. This report considers the use of 4 different copper power cables with different cross sectional areas using information obtained from RS Components. The specifications for these cables are shown below on table 4.2:

CSA(mm^2)	Ω/ km	Current Rating (A)	Cost(£) / km
4	4.61	37	1520
6	3.08	47	1920
10	1.83	64	3260
16	1.15	85	5560

Table 4.2 Conductor Parameters

The battery specifications were taken from Rolls 4000 series. It is assumed that the battery will last the warranty offered by the provider: 7 years. In addition it is also assumed that in order to reach this lifespan the batteries will be discharged to no more than 50% of their nominal capacity. The specifications for this are shown below:

Battery Code:	RB-S550
Cost:	£275
Capacity :	600 Ah
String Voltage:	6 V
Lifetime:	7 Years
Depth of Discharge:	50%

Table 4.3 Battery Specifications

In addition to this the generator is assumed to cost £350 for every 500W of rated power. Fuel cost is taken from [37] as 52.92 Rs/Ltr , corresponding to £0.56 per litre. It is also assumed that for one hour of generation at rated power, half a litre is required per 500W. In addition the life time of the generator is assumed to be 5 years.

Rated Power :	500W
Fuel cost:	£0.56
Fuel requirement :	0.5 Ltr/hr
Lifetime:	5 Years
Cost:	£350

Table 4.4 Generator Specifications

According to the World Bank, the cost of grid extension in developing countries can vary between £5400 and £11000 per km depending on the terrain [38]. This Project therefore assumes the lower end of this extreme at £5400. In addition India currently offers a 30% capital subsidy on mini-grids as well as a 40% subsidy for solar home systems. Thus the economic parameters for these simulations are described in table 4.5:

Grid Extension cost	£5400
SHS subsidy	40%
Mini-Grid Subsidy	30%
Discount Ratio	10%

Table 4.5 Economic Parameters

4.2 Proof of Concept Results

This section of the report discusses the types of results that this software model is able to obtain for a given case. This is to give an idea of the type of results that can be obtained through this methodology and software program: it does not constitute empirical evidence.

4.2.1 Increasing Demand and Number of Consumers

The initial demand profile shown in figure 4.2.2 are used as inputs for the following simulations. This part investigates the impact that using a mini-grid for both Pravaham only and for the whole town has on the LCoE required to break even for the rural electrification project. The results are compared to both individual solar home systems for each demand case and grid extension. These simulations are conducted at 220V transmission voltage. Using only the $4mm^2$ cables shown in table 4.2 the network topology for each case is ascertained as shown on figures 4.2.1 and 4.2.2:

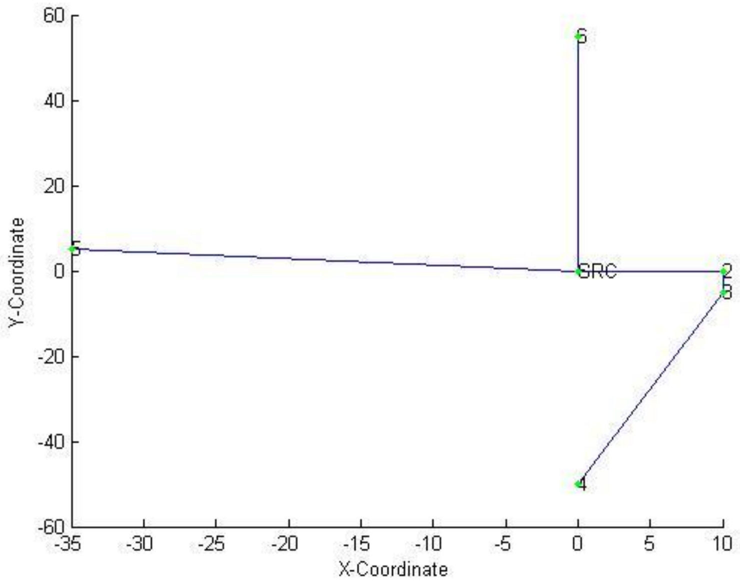


Figure 4.2.1 Network Layout for Pravaham only case

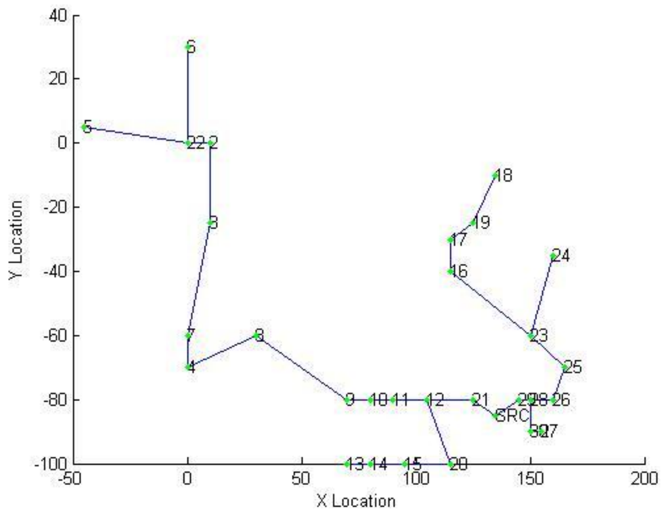


Figure 4.2.2 Network Layout for Whole-town case

The first simulation is conducted for the lighting only demand case as shown below:

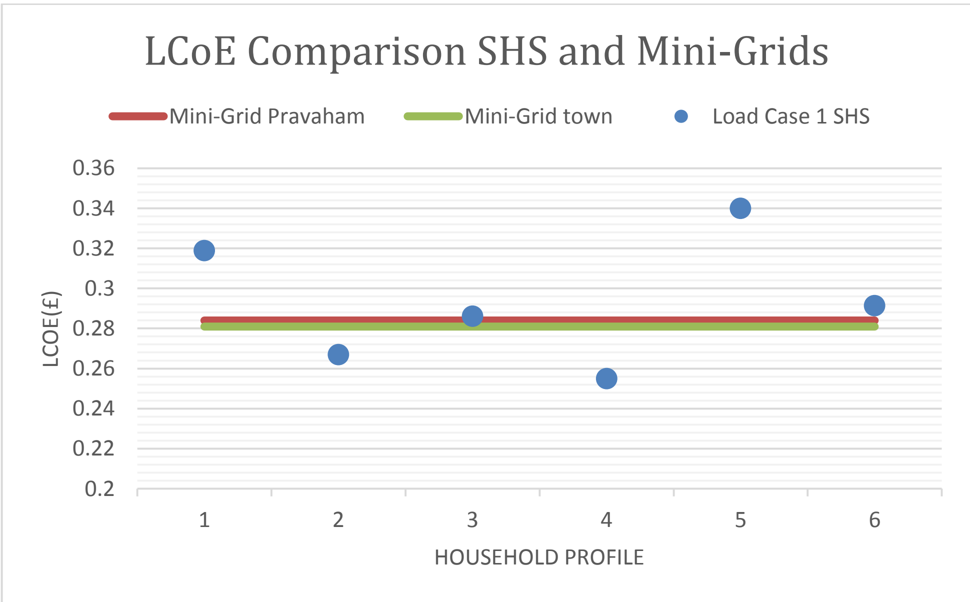


Figure 4.2.3 Demand Case 1 Simulation results

For the lighting only demand case it can be seen from this figure that two of the households, number 2 and number 4, are better off using solar home systems. These households also correspond to the higher demanding consumers of this simulation. In addition it can be seen that by increasing the no. of households, including the entire town, only a marginal gain in reduced cost is achieved. This is repeated for the second set of load profiles and similar results are found except in this scenario households 4 and 6 had similar, and high, energy consumption:

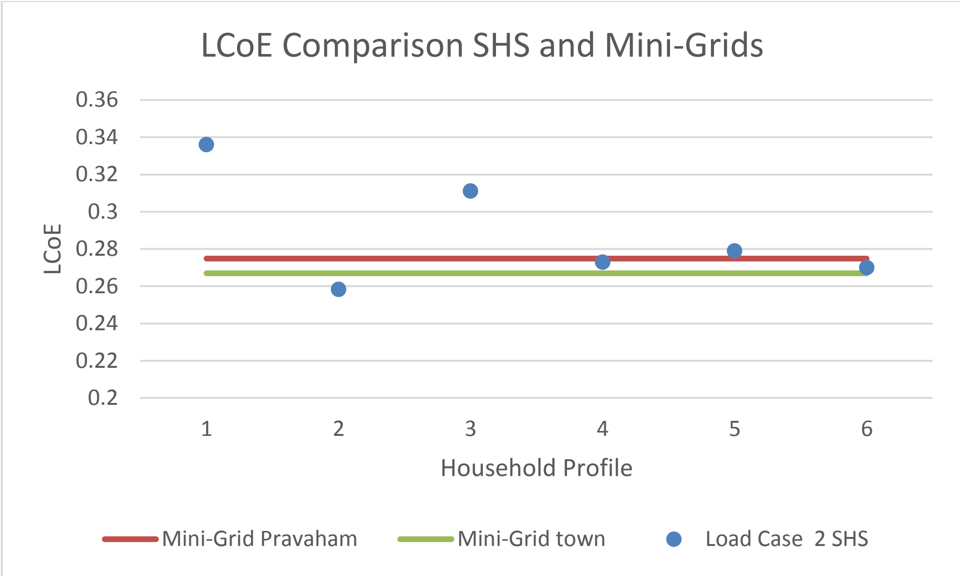


Figure 4.2.4 Demand Case 2 Simulation results

In all the cases so far the optimal generation mix is found to be a Solar based system with battery backup. However for the next set of simulations the program identifies the optimal solution for the full-town mini grid to be a Solar-diesel Hybrid. Within this system the generator runs for 90 hours each year to reduce the burden on the battery bank and solar capacity. This allows the battery's to only require supply for 19 hours of autonomous operation. This simulation also requires an increase in line length due to the voltage drop however no cable upgrade is needed. The results for these simulations are shown on figure 4.2.5

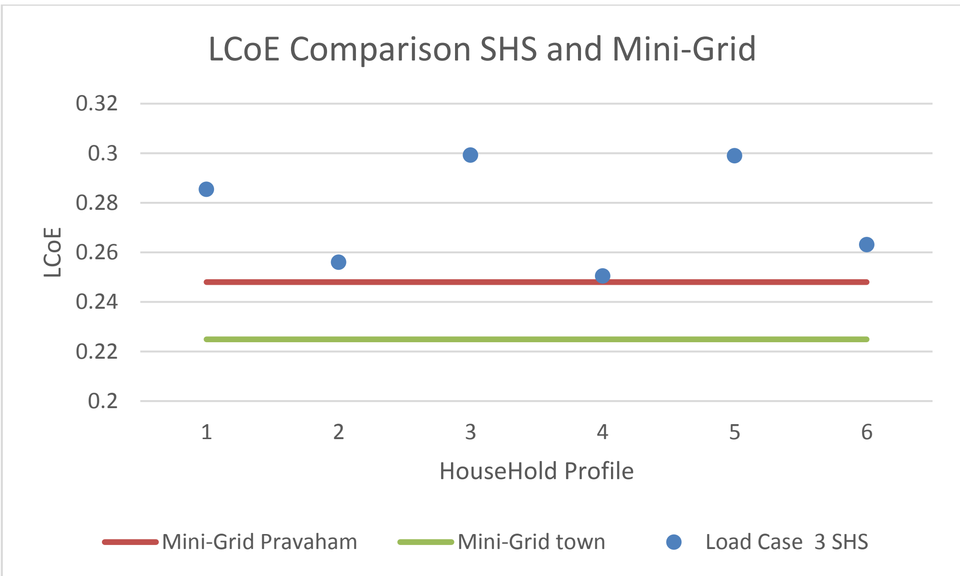
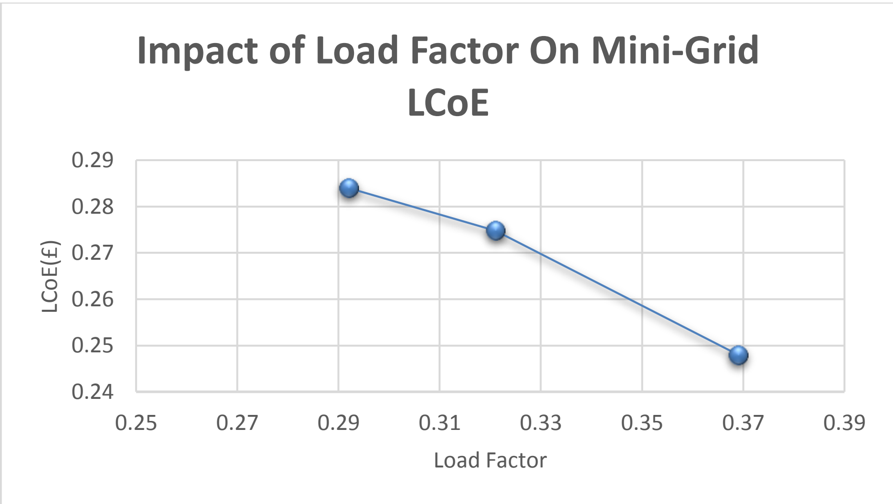


Figure 4.2.5 Demand Case 3 Simulation results

From these three results it can be seen that as the power demand increases the LCoE of mini-grids decreases and becomes a more viable alternative to each household. However given that economies of scale is not being taken into account this raises the questions about why the LCoE is decreasing. The answer to this lies in both the performance ratio and load factor of each case. This is because across each demand case the mini-grid generation source is being used more effectively for the whole town scenario than the Pravaham only scenario.

This increase in performance ratio is due to not only better sizing but because of the difference in load factor between each of the demand profiles. Increase in load factor means that the power being drawn from the generation sources is more sustained. This in turn has the impact of improving the performance ratio because less power is being wasted during periods of high resource availability. The impact that the load factor has on the levelized cost of energy is shown on figure 4.2.6:



4.2.6 Impact of Load factor on LCoE

A more sustained demand implies that the mini-grid contains productive loads during the day. This shows that not only are mini-grids capable of providing for capacity increasing loads, but that they are vital to reducing the cost to the end consumer. This can be further confirmed by running a simulation for a hypothetical case that represents a load factor of 1. The result to this found an even greater reduction in cost: 0.19 £/Kwh. This is despite the case representing smaller demand that the full-availability, whole-town case. In addition the case also required the generator to run for a greater number of hours, indicating that there could be a link between load factor and greater diversity in the generation sources required.

In order to compare the cost of mini-grid solution to grid extension the price at which they become competitive is plotted against grid extension as shown in the example on figure 3.5.3. The distance at which each system becomes competitive can then be plotted as shown on figure 4.2.7:

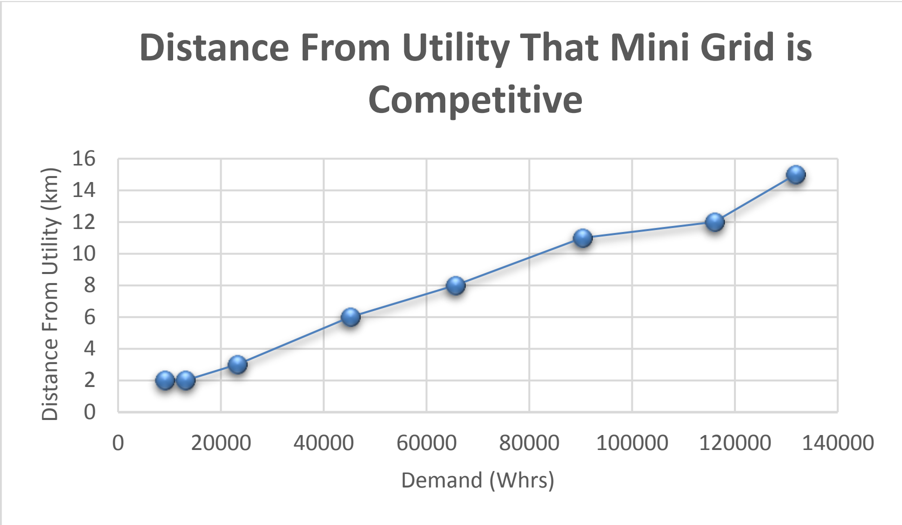


Figure 4.2.7 Distance from Utility that Mini-grid Can Compete

It can be seen from the figure above that as the power requirements of the mini-grid increase, the distance at which it has to be in order to be competitive with the utilities increases as well. This is due to the higher capital costs of large mini-grid systems. Given solar home systems represent a much smaller capital cost however; they can potentially be competitive solutions at much closer distances. This implies a design methodology where grid extension and solar home systems are used for consumers closer to the utilities and mini-grids are used for consumers very far away, increasing in size, in step with the distance.

4.2.2 The Impact of Maintaining Power Availability

Being able to access electricity whenever it is needed ultimately increases consumer satisfaction with the service. However duo to intermittency and variance of renewable resource profiles, the cost of sizing generation adequately for 100% availability can have a significant impact on the end cost that consumers have to pay. As mentioned in section 3.4, in order to assess the impact that maintaining availability can have on mini-grid implementation, this model allows the user to set the percentage of time that demand can go unmet. To measure the impact that power availability requirements can have on the end cost of the system the availability is set to 90% requirement (corresponding to 876 hours without power) and increased to 99% (88 hours without power). The impact that this has on the LCoE of a mini-grid system is shown below:

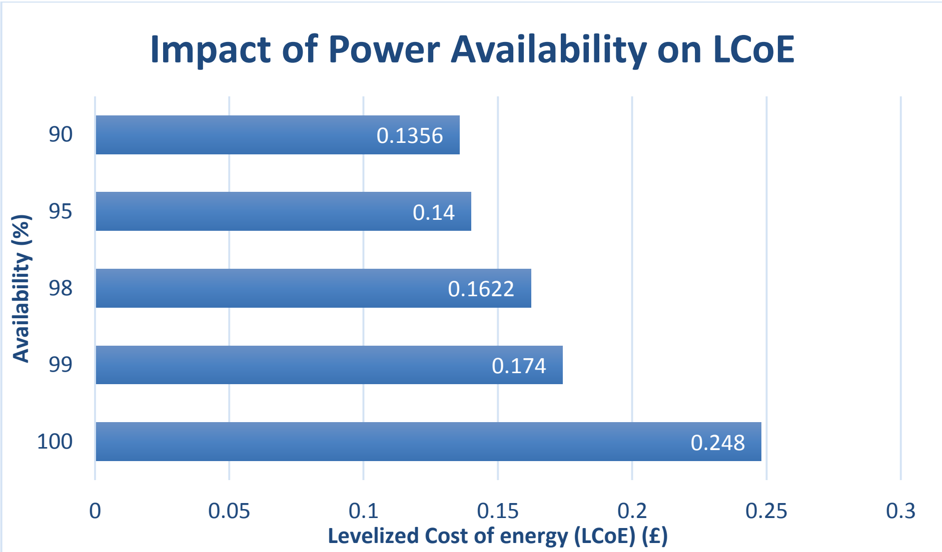


Figure 4.2.7 Impact of Availability requirement on Mini-grid LCoE

The above case considered the use of a Pravaham only mini-grid, Case A, with all appliances allowed: Demand case C. It can be seen on figure 4.2.7 that availability can have a significant impact on the LCoE of a mini-grid system. In particular the final 1% of availability increases the LCoE of the system by over 7 pence, representing a 42% increase in cost over the 99% availability case. This is because the solar array needs to be massively over-sized to meet demand during periods of low renewable resource availability. In turn this causes a lot of energy to be captured during high periods of availability that goes unused, reducing the performance ratio of the system as shown on Figure 4.2.8:

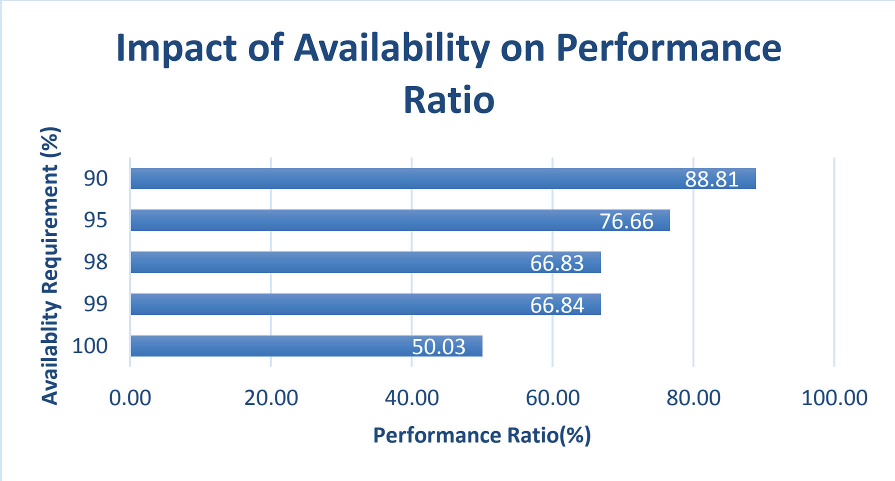


Figure 4.2.8 Impact of Availability requirement on performance ratio

It can be seen that by reducing the availability requirement, performance ratio is significantly improved. What is interesting about this result is that while a significant increase in performance ratio is achieved by reducing the availability requirement from 95% to 90%, a relatively marginal, 3%, reduction in LCoE is obtained. This could be due to the fact that less power is being sold to the consumers as well as the fact that when generation costs decrease, the cost of network infrastructure takes up a proportionally larger part of total system costs.

Compared to mini-grids however solar home systems do not benefit nearly as much from a reduction in availability requirements. The impact that this has on LCoE is marginal and infact causes it to increase in some cases. This is because these systems are much smaller and sizing for lower availability may still require the same amount of solar panels and batteries to be used. Since the LCoE takes the availability into account during calculation of annual demand, it appears to increase in some cases. This is shown below:

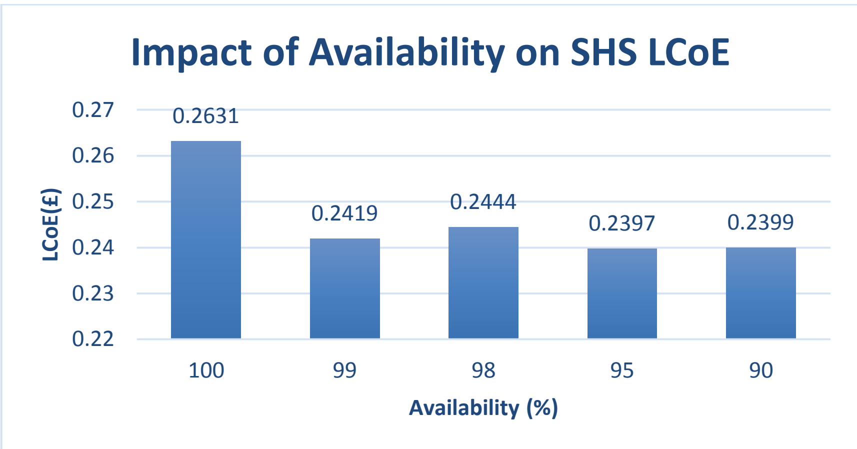


Figure 4.2.9 Impact of Availability requirement on SHS LCoE

In order to determine how sizing for availability requirements affects how far away a mini-grid needs to be from the utility to be a competitive solution, simulations are run considering the full town case with all load availability. This is chosen as it is originally the system that is required to be furthest away from the grid. The results from these simulations are shown below on figure 4.2.10:

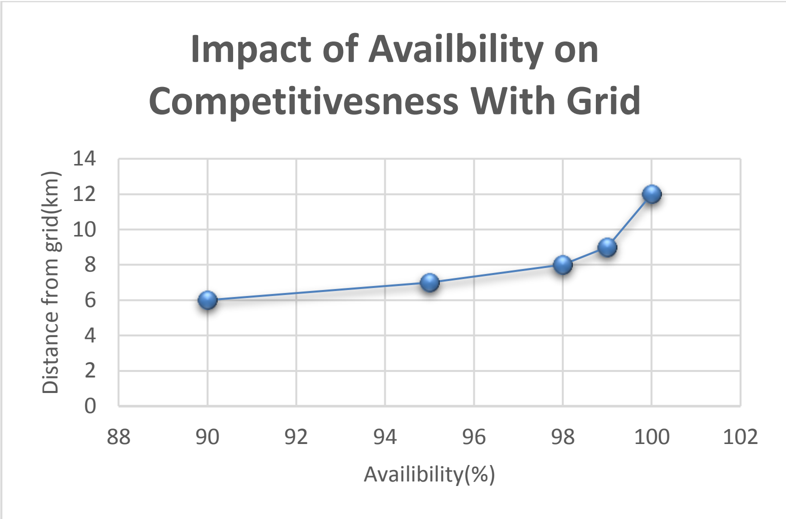


Figure 4.2.10 Availibility's impact on grid competitiveness

The above figure shows that by reducing the availability requirement that larger mini-grid systems can become more competitive solutions to rural electrification at distances much closer to the grid. This is again due to the reduced cost of implementing these systems, allowing them to be more economically feasible solutions.

Reducing the availability requirement does not mean that power needs to be completely unavailable during these time periods. This is because mini-grids can implement demand-side management strategies to reduce consumption during periods of low availability. One instance where this is applied is on the isle of Eigg in Scotland. This community uses a traffic light system to alert people to reduce consumption when power availability is forecasted to be low [39]. By doing this, a mini-grid could be made more affordable while ensuring critical needs are still met. In addition this type of approach encourages community involvement with the project which can also help to improve sustainability.

6.0 Conclusions and Further Work

In conclusion this report has demonstrated how MATLAB can be used to implement an optimisation tool that can evaluate different approaches to rural electrification. It has been shown that Particle swarm optimization can be used to ascertain the least cost generation mix for a rural hybrid mini-grid as well as optimization of solar home system components. In addition this report illustrates how Esau-Williams heuristic can be employed to find near-optimal network topologies. Ultimately these two features in combination with accurate resource measurements and economic evaluations allowed the comparison of each rural electrification solution.

Results found that one of the main factors in reducing the cost of a mini-grid is the load factor due to the impact it can have on the performance ratio of generation profiles. This indicates that productive loads are a requirement to making mini-grids a competitive solution to rural electrification. In addition the impact that maintaining service for consumers at all times is found to have an overwhelming impact on the cost of a mini-grid, so much so that the difference in a single percentage can make up approximately 40% of the final cost. It is also found that larger systems will only become competitive at distances further from utility infrastructure and this is due to high capital cost of mini-grids relative to grid extension.

While the results found in this report can be indicative of real world trends, they are only proof of concept. This is due to the lack of robustness in the models implementation and much future work is required to rectify this fact. Such work would include modelling each of the generation sources more dynamically, taking into account the impact that environment and operating conditions can have on the batteries and diesel generators operation. In addition allowing the modelling of more renewable sources such as hydro and wind, would create the opportunity to analyse a greater amount of cases and provide many sustainable solutions. Other improvements to this model include the implementation of a database that stores available resources that can be accessed at the users' request. In addition improvements could be made to the GUI to allow the user to select nodes seamlessly off of a map, possibly through an interface with google-maps.

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Appendix A: Contents of the CD

- GUI code “Indoa” file
- Esau-Williams Implementation “Topology File”
- Solar Panel output file “SolarCalc”
- PSO implementation “PSO main”
- Constraints for PSO “ConstraintsPSO”
- Various solar resource functions
- LCoE function “LCoECalC”
- NPV function “NPV”
- Excel File Containing Local Irradiance and temperature data “PravDat2”
- Excel Files Including results “Book4, NetworkMistro”
- Previous Excel File Include Origional VB implementation “ProperV”
- Excel Files Containing Different demand profiles
- Excel Files Containing Different Topology’s
- A copy of this report
- A copy of interim report
- A copy of presentation slides
- A copy of Poster Presentation Slides