TECHNO-ECONOMIC ANALYSIS FOR EMPLOYING OF ON-SITE HYDROGEN PRODUCTION & STORAGE SYSTEMS WITH RENEWABLE ENERGY FOR TELECOMMUNICATION SITES IN SRI LANKA

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DECLARATION

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ABSTRACT

Energy can be termed as the life blood of the telecommunication industry even its technologies had evolved very rapidly. The concern is focused not only on the way of the energy is supplied, but also on the continuity of the supply and the cost of the same are critical concerns in the industry.

With the ever-increasing price of the fossil fuel and the commercial electricity supply which depends on the fossil fuel, telecommunication industry had begun the seeking of options with renewable energy. The inherent limitations of renewable energy were identified and introduced the hydrogen storage concept in to the renewable energy conversion system to overcome them and maintain an un-interruptible power supply.

Under this research, the determination of the optimum composition of the system components is done which yields the best advantage of the proposed technological concept. Since the cost is a major concern when it comes to the industry, a mathematical model had been developed to perform the techno-economic analysis of the viability of deploying hydrogen storage with renewable energy system to power a given base station site under Sri Lankan context. In addition, the sensitivity analysis was performed taking the price of inputs as variables.

Tool HOMER had been used to validate the results of the developed mathematical model.

The developed model can be used to check whether the telecommunication operator can omit the capital expenditure of Diesel generator and Battery bank when investing on the power system for a particular base station site.

Key words: Techno-economic analysis, Hydrogen Storage, Optimum Cost.

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LIST OF ABBREVIATIONS

2G	Second Generation Cellular Technology
AC	Alternating current
CAPEX	Capital Expenditure
DAP	Dialog Axiata PLC
DC	Direct Current
GUI	User Interface
HOMER	Hybrid Optimization Model for Multiple Energy Resources
kVA	Kilo Volt Ampere
kW	kilo Watt
MS	Micro Soft
OPEX	Operational Expenditure
PLC	Public Limited Company
PV	Photo Voltaic
W	Watt

1 INTRODUCTION

1.1 Background

The energy supply being the life blood of the oxygen of the telecommunication industry in an environment which the price of energy keeps increasing, the telecommunication operators now tend towards the options of renewable energy where possible. Since the telecommunication industry desperately requires the continuous supply of energy to the systems without interruption, the challenge is because of the inherent limitations of commonly renewable energy. The mostly available renewable sources are wind and solar when the intended usage is concerned and this study limits analysis to use solar as the source of renewable energy.

In general, the common practice among Sri Lankan telecommunication operators is to employ the solar power system with a battery bank and a diesel generator at base station sites to generate power when solar radiation is not available. Here the telecommunication equipment are powered by solar energy and the batteries get charged with additional electricity generated. The energy stored in the batteries is used to power the system when the solar radiation is not present. The gap of the requirement and supply of energy is filled up by the diesel generator and the excess is again stored in the batteries for latter usage. This coordination is governed by a solar controller unit.

Under this practice, the battery bank experiences the cycles of deep charging and discharging which causes the reduction of life time of batteries. In addition, the diesel generator operates for a considerable time portion in a day.

Based on above, it is worth to look for room for further improvements of the way of utilizing the way of harvesting the solar energy in to electricity for telecommunication base station sites in the sense of overall of techno-economic viability.

1.2 Problem statement / justification

Because of the deep charging-discharging cycles undergone with the battery banks, the life time of the batteries is reduced by a great extent. As such a battery bank used with a traditional solar power system is to be replaced within 2-3 years in general practice, it adds a substantial cost impact in the form of operational expenditure of the site, when the financial performance is considered. In addition, the capital expenditure to be invested on the diesel generator is considerable as well as the routine maintenance cost of the same. Because of the decreasing price of the telecommunication services in Sri Lanka, the above-mentioned cost centers are considerable concern to the Engineers and financial managers of the telecommunications industry.

It is worth to conduct a research to find out the available options to omit the above-mentioned limitations along with their technical capabilities and economic viabilities in practical scenario.

1.3 Motivation

The outcome of this project is to the check the techno-economic viability of introducing the Hydrogen storage concept for the solar power system in a telecommunication base station site and to derive the most cost optimum configuration of system components. It will help the decision makers of the telecommunication operators to minimize the overall cost of energy used for the operation, while maximizing the investment made on the deployment of solar power systems at base station sites.

1.4 Objectives of the study

The Objective of the study is to perform the techno-Economic analysis of employing on-site Hydrogen production & storage systems with renewable energy for telecom sites in Sri Lanka.

1.5 Methodology

For the timely completion of the research, the work flow was arranged in the manner given below.

i. **Literature Survey**

Under the literature survey, literatures in relation to on-site Hydrogen production by solar energy and usage of renewable energy for telecom base stations were referred. Some of the papers contained only the direct usage of solar energy and some papers contained only the technical viability. None of them were extended to developing of a mathematical model for the concept.

ii. **Gathering of data from the telecommunication network**

Data on historical practices entangled with solar energy systems used in the telecommunication networks under Sri Lankan context is vital to determine the direction of the research. In addition, the general distribution of power usage of base station sites of a telecommunication network is essential to evaluate the technical viability of the concept.

iii. **Data gathering on the technological development of the concept in the industry**

Various advancements of the technologies which are connected with the proposed system components are to be studied along with the cost of them which those can be found at the market. These data is essential to determine both the technical and economic viability of the concept.

iv. **Modeling.**

The system is modeled in the HOMER tool against the parameters of the given arbitrary base station sites and determine the configuration optimum to the case.

Mathematical model for economic viability is formulated using the equations derived on the behavior of the system components.

v. **Defining cases for simulation.**

The cases were selected and defined using the energy consumption of base station sites considering the distribution of same against the availability of land area to deploy sufficient number of solar panels. The geographical distribution of base station sites was considered when defining the cases to account for the viability against different solar radiation patterns.

vi. Validation of the results

The results obtained in this research were validated against the results of the model developed using HOMER.

1.6 Contributions

Owing to the intensified rivalry among the competitor operators in the present telecommunication industry, every operator focusses on the technological advancements in every area which yield them the cost leadership above others. Energy is the commodity which none of them can get negotiated with using their bargaining powers gained through economies of scales or market position. Hence the investments on renewable energy had been increased, but no operator started deviating from traditional renewable setup seeking unseen advantages over others.

The outcome of this study will check whether that the battery bank, which requires frequent replacement can be completely omitted from the picture of renewables when Hydrogen storage is introduced. Further, the technical viability and the economic feasibility of the proposal in connection with a given arbitrary base station site will be determined with technical and economic parameters for the easy decision making by Engineers and financial managers in the industry. Finally, the below listed benefits will be yielded by the outcomes of this study.

- Ease in decision making for the investors and Engineers
- Improved cost savings encourage the investments on renewable energy
    - Environment will be benefitted
- Reduces the usage of batteries
    - Environment will be benefitted

2 LITERATURE REVIEW

A thorough literature review was done at the outset of this research to identify the benefits and concerns of having a Hydrogen storage. In addition to above, later the literature review was focused on the technological developments of the concept and the possible measures to be taken with the Hydrogen storage when the safety factors are considered. Further, the already published research papers were reviewed to identify the limitations and the rooms for further extensions of the scopes of them come under the described concept.

There are a considerable number of researches had been carried out in the area of renewable energy to check the viability of utilizing of renewable sources optimally to generate and supplying of reliable electricity supply using various types of software tools [5]. The software tool HOMER had been used for most of the cases for the purpose analyzing the stand-alone renewable energy systems [6], [7].

Since the scarcity of the fossil fuel is most likely to threat the world energy sector within next couple of decades, the attention of numerous amount of research work had been grabbed by the topic and researchers have carried out a considerable number of studies to determine the optimum system configurations for the scenarios even with the availability of commercial grid power [8], [9], [10], [11]. In general, the economic viability is more positive with the grid-connected configurations, as the possibility of entering in to net-metering agreements with the grid operator; but still the most of the studies carried out under the above topic, was limited to a few of case studies and not been extended up to a level of developing a tool to check the viability [12], [13], [14].

<u>Deployment of Solar PV system for on-grid Dialog Axiata sites [1]</u>

One of the major publication referred for the study was Deployment of Solar PV system for on-grid Dialog Axiata sites. The above had discussed the technical feasibility and financial viability for 2 options of using solar PV as the source for telecommunication sites under Sri Lankan context.

1. Solar PV integrated to inverter DC bus

   Under this option, the system runs with the backing up of a battery bank and a diesel generator.

2. Solar PV integrated with grid-tie inverter

   This option facilitates the feeding the extra energy in to the commercial grid under "Net Metering".

3. Hydrogen storage had not been considered

Solar PV with Hydrogen storage for an Off-grid Telecom base station site [2]

This publication incorporates the on-site production and storage of Hydrogen using the solar energy for a base station site. The researchers discuss the technical feasibility of using the concept for a particular site with an extra low load of 150 W.

The location considered for the study was in a European country which accommodates only the 2G services in a site. This differs from the Sri Lankan context to a great extent where multiple types of base stations are served with different technologies with a minimum load of 500 W in average. In addition, the pattern of variation of solar radiation differs to a substantial extent from that of Sri Lanka.

According to the study, the concept is technically feasible for the considered scenario. This study was limited to consider for a single site and not extended to formulate a techno-commercial model for an entire network.

Optimization of Solar PV and Hydrogen supply system for a remote Off-grid telecom base station [3]

The study carried out under the above topic, the considerations of the researchers were limited to the site loads less than 1kW. The scope was to check the technical viability under European context and the economic returns were not considered.

Techno-economic evaluation for Renewable Hybrid power solution for Off-grid telecom base station [0]

Under this research, the authors have performed an economic analysis targeting a load of 500W only. The focus was given to the Solar-Wind-Battery combination; the production and storage of Hydrogen at the site had not been considered. In addition, the possibility of utilizing the required area for solar panels at the site was not taken in to the consideration of the feasibility study. The study had been conducted under the Indian context which the service levels of the telecommunication industry shows considerable deviations from the Sri Lankan environment.

2.1 General Information

In general, the power supply required by telecommunications systems in the Sri Lankan context is 48V DC. By the nature of the business it is mandatory to maintain an un-interruptible power supply for the system throughout.

In practice, the network locations are segregated in to several layers namely Core, Aggregation & Access sites based on the network architecture and the importance of the particular site for stability of the rest of the network. The required backup mechanism and backup capacity of the power system for a site is decided based on the above-mentioned layer which the site is categorized in to. Decision to deploy a diesel generator and the size of the required battery bank is determined under above criteria.

The major motive to move towards the harvesting of solar energy for base station sites is in two aspects;

1. Reduced cost
2. Corporate social responsibility by moving to green options.

Therefore, the solar power is generally used for the sites in access layer which are less critical when compared to the sites in other two layers.

In terms of cost, the optimization of both operational and capital expenditure will be the parameters to be considered prior to the making of the decision on any investment. Hence there is no difference with the investment decision on the solar energy system for power supply. At present, as the composition of the solar energy harvesting system is used in connection with batteries and diesel generator, the actual cost felt to the operation is fairly high as the frequent replacement of battery banks and the base cost on generator maintenance. DAP does not differ the size of the diesel generator from site to site when the solar PV powered site is considered. As a common practice, DAP used install a diesel generator with a rating of 10 kVA irrespective of the possibility of changing this with the other parameters. In addition, the maximum possible utilization of the available solar energy is not met because of the limitation in storage. Therefore, the possibility of the business case to be positive is low when the cost is compared against the available other options.

As at present the with the increasing trend of electricity tariff, operator organizations are seeking for the possibilities of maximization of the harvesting of solar energy to power the base station sites.

3 GATHERING OF DATA

3.1 From the telecommunication network

The base station sites in a telecommunication network are different from one another. The difference may be by the power load, cooling methodology, available land area (for solar for this interest of this research) etc. The network of Dialog Axiata PLC was taken as the sample space of sites for this research work, extracted the power load and the land area available within each of the sites for the purpose of data analysis. These data were extracted referring to the operator’s internal databases. A special focus was given to the details of the off-grid sites and the methodology of power supply for those.

3.2 Gathering of data – Technical development

In the industry, there are various methods for storing of energy harvested through a solar energy system.

3.2.1 Net metering

The virtual method of storing of energy is by entering in to a net-metering agreement with the operator of a large grid of electricity supply. Here, the excess of the harvested electrical energy is fed in to the grid and make the other customers of the grid can consume the same; later in the periods which no harvesting is done, the grid feeds the system. This virtually acts as a storage.

3.2.2 Battery banks

Having batteries installed in the system is one of the common practices use in the industry, especially in telecommunications industry under the discussed purpose. Here several types of batteries are used based on their specialties, and the requirements of the purpose of use as well as the cost component contaminated with the choice.

3.2.3 Hydrogen storage

Storing the energy in the form of Hydrogen is one of the non-traditional concepts, which yield substantial benefits over other methods. Still there are negative impacts which are to be managed based on the requirements, to make the techniques feasible for the purpose.

3.2.3.1 Storing as a gas

Here the harvested energy is used to electrolyze the water and get the Hydrogen is separated and stored in the form of gas. Once the recovery of stored energy is required, the Hydrogen gas will be set to flow through a fuel cell to react with Oxygen in the environment and form water vapor again. While at the process, the flow of electrons between anode and cathode of the fuel cell, obviously from an electric current and the same can be taken out from the terminals of the fuel cell as recovery of the stored electrical energy.

The major concern to be addressed when using a storage system for Hydrogen to be stored in the form of gas, is the safety as hydrogen is very explosive. Making the concern much more severe, the storage is to be done at a higher pressure in order to withdraw the stored gas for the usage in later time.

As a safety concern, the allowable limit for Hydrogen composition in air is 4%. Any leakage causing the composition above this point is considered as flammable. Hence the considerations should be given to store the compressed Hydrogen gas in and well ventilated outdoor environment with proper safety valves are employed in the gas systems to minimize the risk of explosion.

For further proactive measures, a surveillance system with Hydrogen leakage detection system is recommended to be installed at the locations where Hydrogen was stored in the form of a gas.

In addition to above concerns, another negative factor acts on Hydrogen gas storage is the energy to be consumed for the process of compression. Here an extra energy is to be consumed to compress the generated Hydrogen gas while at the point of storage.

3.2.3.2 Storing as a metal hydride

Storing the Hydrogen as a metal hydride is one of the safest methods which can be used. This method provides a very high storage density even greater than the liquid Hydrogen.

The major limitations can be found in the method are that the low rate in release of Hydrogen back in the recovery cycle and the inability of controlling the flow of releasing of gas at the recovery.

However, even whatever the storage method, here the overall system experiences an issue with the efficiency of complete cycle owing to the efficiencies of several processes.

4 ANALYSIS OF GATHERED DATA

For the purpose of checking the viability of the proposed concept under the practical scenarios, the sample size of the gathered data is an essential factor. As there are five organizations engaged in the business of mobile telecommunications operators having their network spread almost all over the island. I selected the network of Dialog Axiata PLC (DAP), the leading mobile operator in Sri Lanka with the most number of base station sites in the country to check the practical viability of the proposed concept.

The network of DAP consists of 3039 base station site locations with a spread over all of the administrative districts in Sri Lanka. There are 54 off grid sites which the power supply for the operations is managed locally. 41 sites out of the above 54 off-grid sites, powered through the fulltime operation of diesel generators with battery banks at site for the purpose of maintaining the uninterruptible power supply at a failure or shut down of the generator for maintenance purposes.

The rest 13 of the off-grid sites are running primarily based on solar PV with the backing up of diesel generators and battery banks which are to be used when solar harvesting is not possible.

4.1 Categorization of site – On power demand

When the power demand of a site is considered, with the network, the variation ranges from 200W to 8000W. For the purpose of checking the feasibility of the proposed solution, the whole sample space was segregated in to 9 categories based on the demanded load in interval of 1000W.

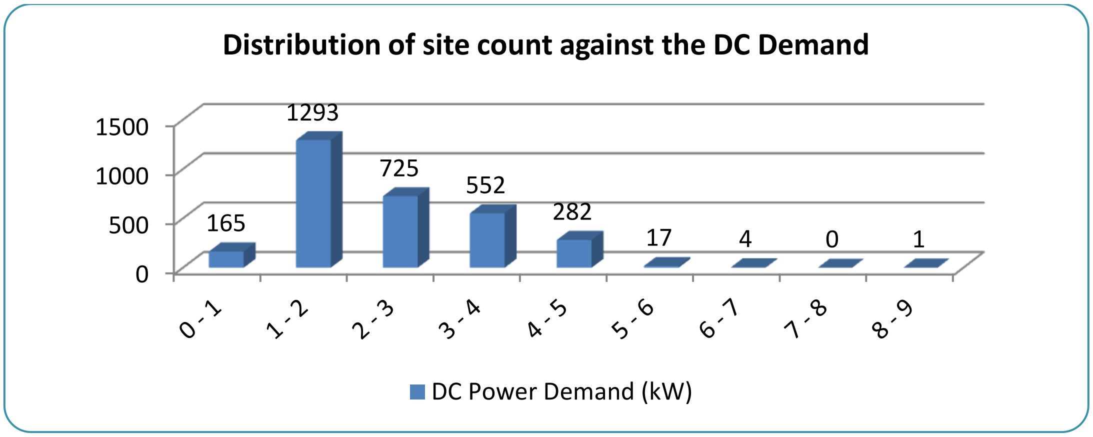


Figure 4-1 Segregation of sites based on power demand

Not only the power demand, but also the area available within the site premises is to be considered here for the purpose of deciding the maximum possible power which can be harvested using solar energy system at site.

4.2 Categorization of site – On available land area

In general, the available land area at a site, varies in a range from 300 square meters to 1000 square meters. The above segregation shown in Figure 4-1 was re-segregated in to 3 ranges for the ease in analyzing work as well as to increase the meaningfulness when the practical scenario is considered.

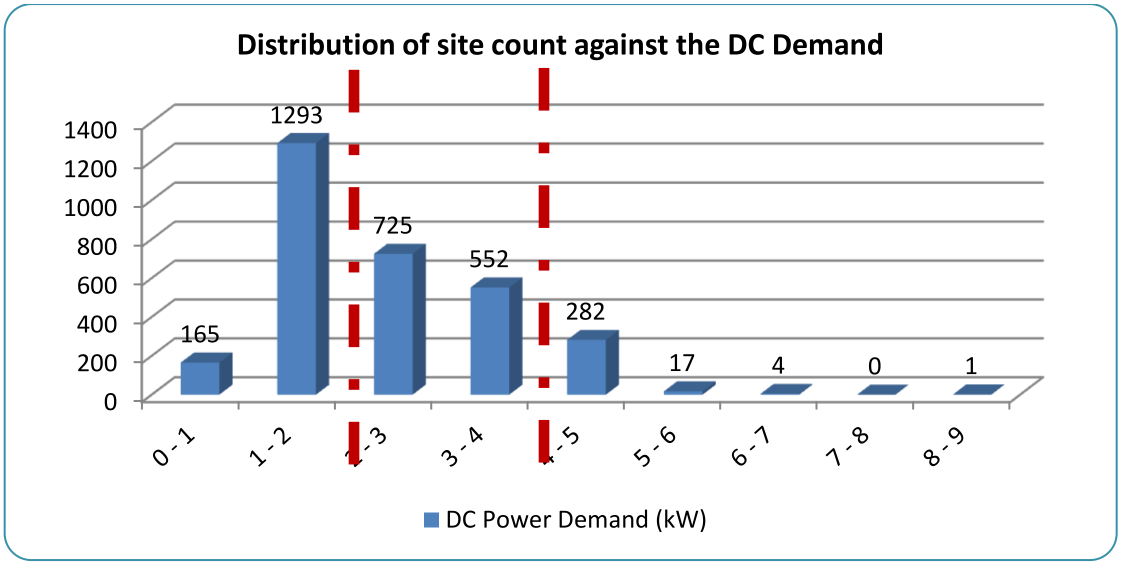


Figure 4-2 Re-segregation of power demand to accommodate information on area availability

The area available within the sites was tabulated separately for each 3 categories of sites based on above segregation shown in Figure 4-2.

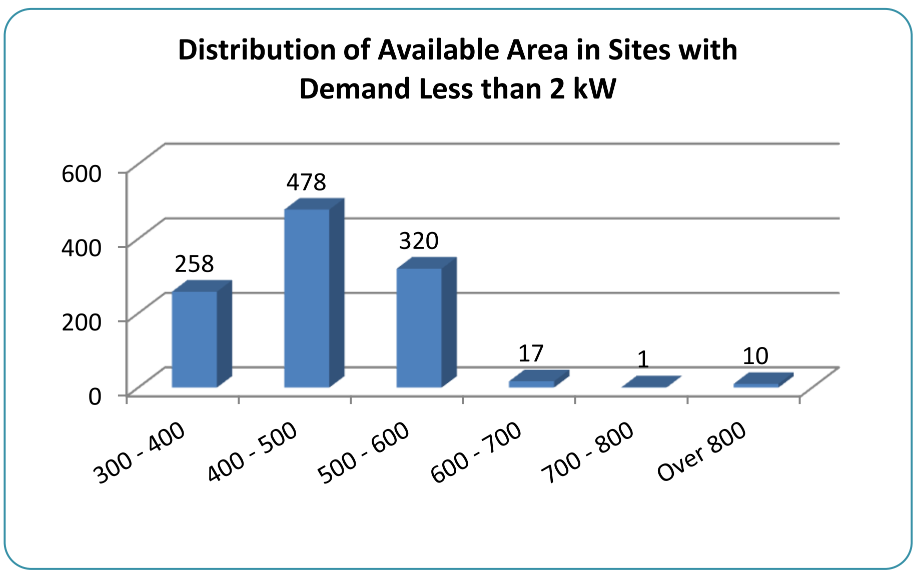


Figure 4-3 Distribution of Available Area in Sites with Demand Less than 2 kW

The above Figure 4-3 shows the number of sites fall in to each category identified based on the available land area within the sites which the total power demand is less than 2 kW.

Similarly, below Figure 4-4 and Figure 4-5 show the area distribution for rest of the two categories of power demand between 2 kW – 4 kW and above 4 kW respectively.

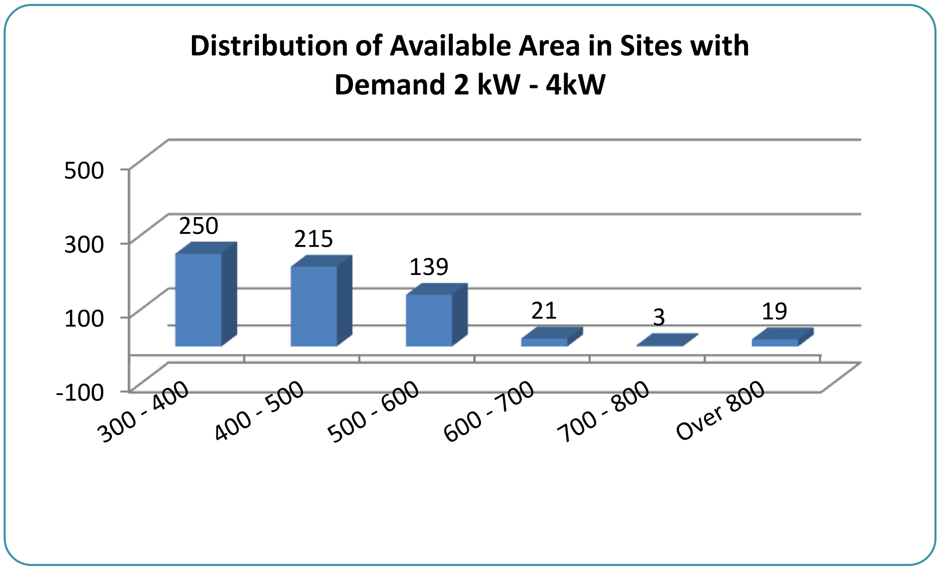


Figure 4-4 Distribution of Available Area in Sites with Demand between 2 kW - 4kW

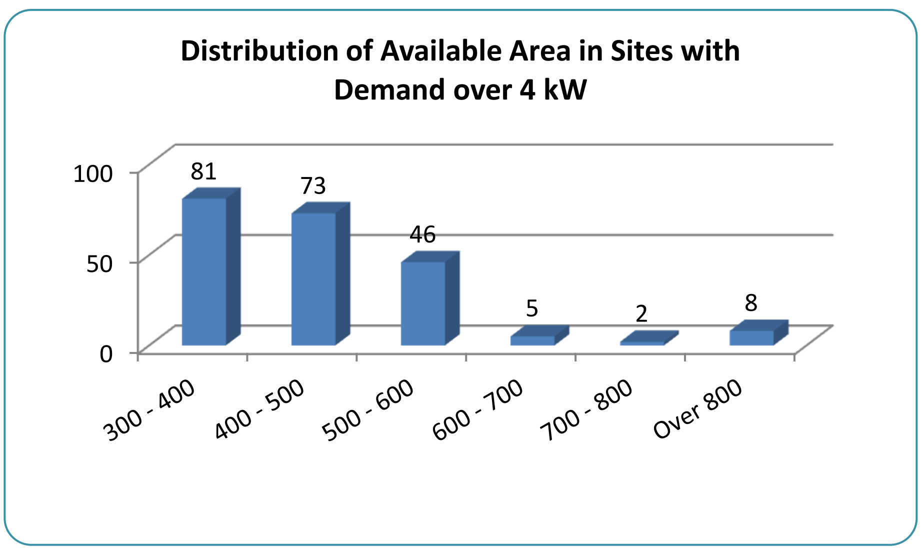


Figure 4-5 Distribution of Available Area in Sites with Demand over 4 kW

With the above segregation, the basic set of information to be extracted from the network had almost reached the completion. This is for the purpose of the basic validation of the viability of the solution against the power requirement at sites and the practical probability of producing the same using the solar PV energy harvesting system.

5 MODELING OF THE SYSTEM

The proposed concept includes the production and storing of the gas Hydrogen using the energy harvested from solar for the electricity generation at later time. The above generation of electricity is done using a fuel cell.

To execute the above process, the system should be comprising of below basic components.

- Solar PV panels
- Electrolyzer
- Hydrogen storage tank
- Fuel cell

In addition, the total power system to be deployed at the site, may have other components for the purpose of maintaining an uninterruptible power supply.

- Diesel generator
- Battery bank
- rectifier

At the stage of modeling the system components, the appropriate sizes of each of above components are to be decided. The pattern of the solar radiation at the site location and the power load of the site are the location specific factors.

The above-mentioned system modeling is done using the HOMER tool and later the developed mathematical model is used to validate the techno-commercial viability of the solution under different scenarios.

5.1 Overview of HOMER

HOMER is a software tool to determine the optimum design for the micro-grids powered by multiple energy sources. The name, HOMER stands for Hybrid Optimization Model for Multiple Energy Resources.

The HOMER tool provides the flexibility to the designer to determine the components of the system which he wishes to have. Figure 5-1 shows the system components being modeled in using HOMER tool. The tool compute against the other facts and gives the optimum sizes of the components which the designer wanted to have. The output result of HOMER does not limit to the sizes of the components, but it provides the energy used/produced by each component and the amount of time which every component was in operation as well.

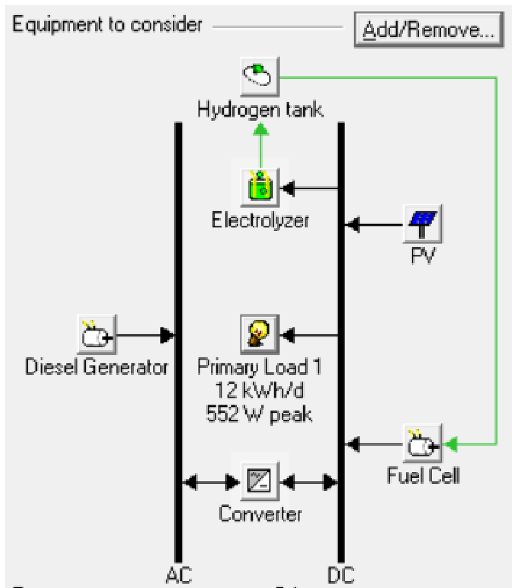


Figure 5-1 System components Modeled in HOMER tool

The tool retrieves the solar radiation pattern from the internet for a particular location when the GPS coordinates of the location is entered. It calculates the scaled annual average of solar intensity for the location given. Below Figure 5-2 shows the annual solar radiation being input to HOMER tool as an example.

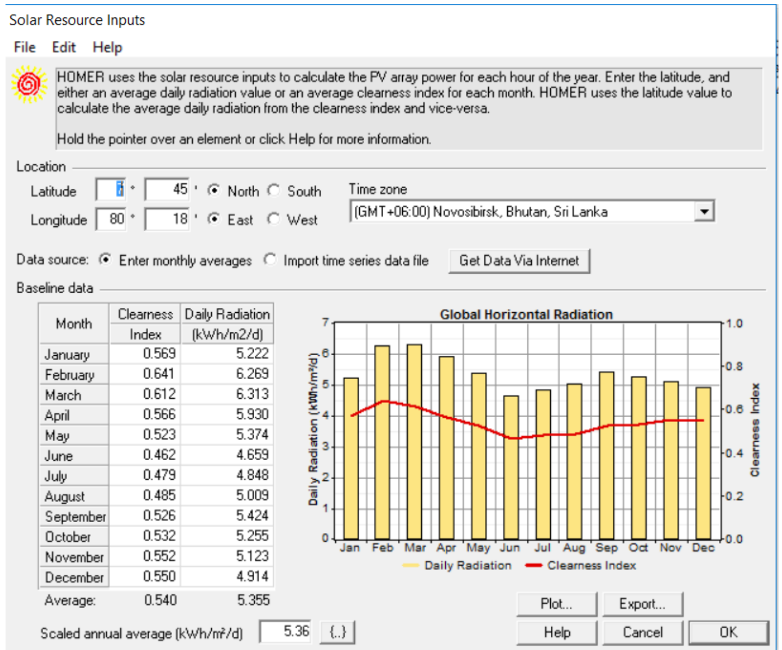


Figure 5-2 Pattern of solar radiation over the year – As an input to HOMER tool

The tool HOMER is capable of modeling the system against a time varying load; but here the load of a site is considered as constant over the time. Below Figure 5-3 shows the same as an example.

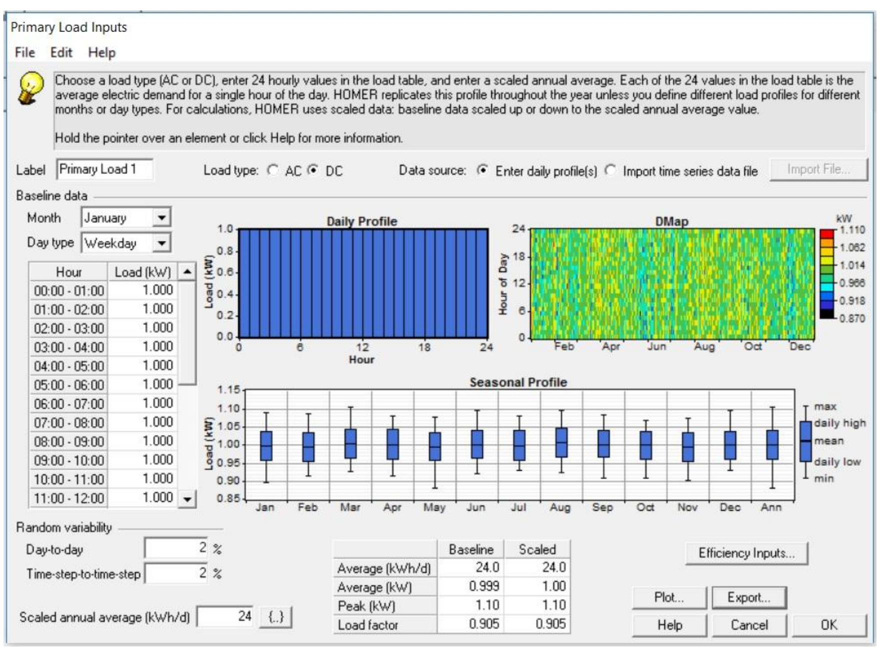


Figure 5-3 Input of load data

5.2 Development of mathematical model

In the process of developing a mathematical model for the behavior of the system, separate equations were derived for the technical function of each system component and the cost behavior of same.

The behavior of each system component was considered in the process of deriving the mathematical equations to represent the technical functionality. In the meantime, as the output of the study is to be with the techno-economic feasibility of the proposed concept, the cost components entangled with the system were modeled by taking the accounting concepts of CAPEX, maintenance cost, fueling cost and depreciation etc.

5.2.1 Solar PV panels

Solar PV panels hold the responsibility of converting the energy incident on the panel in the form of radiation in to the electrical energy. The efficiency of the panels, solar incident angle based on the geographic location of installation, employment of solar tracking mechanisms were the factors which required a special consideration when building up the mathematical equations.

Cost of maintenance, repairing, fueling are the factors to be considered under general operational expenditure. Under the case of solar PV panels, by nature of the operation, all of above factors are very negligible when the value of depreciation is considered. Hence only the conceptual cost of depreciation was considered as the total annual OPEX of the component.

Below Figure 5-4 shows the building up of the two-equations derived for the functions of solar PV panels.

- Electrical energy produced
- OPEX per annum

Solar PV

Installed Capacity – S_C
Factor for Solar incident angle – 0.6
Plant factor – S_{PF}
Capacity factor - S_{CA}
Correction for solar tracking - S_{TR}
Initial CAPEX – S_{CX}
Life time – S_{LT}
Solar Intensity – S_I
Installed Area – S_A
Annual Maintenance Cost – S_{MA}

Electric Energy Produced, E_{SO}

$$E_{SO} = \int 0.6 \times S_C \times S_I \times S_{PF} \times S_{CA} \times S_{TR} \times S_A \, dt$$

OPEX per year, OP_{SO}

$$OP_{SO} = \frac{S_{CX}}{S_{LT}} + S_{MA}$$

Figure 5-4 Mathematical Equations - Solar PV

5.2.2 Fuel cell

Fuel cell is the component introduced in to the system for the purpose of extracting the chemical energy stored in the form of Hydrogen gas. When the gas Hydrogen flows through the fuel cell, the flow is arranged in a manner so that it gets contaminated with Oxygen to react and form water vapor. When the chemical reaction between Hydrogen and Oxygen, the flow of electrons forms an electric current with an energy equal to the enthalpy difference between the 2 forms of the matters, ie. $O_2 + 2 H_2 \rightarrow 2 H_2O$

Similar to the case of solar PV panels, the equations on the operational functions of the fuel cell were derived as depicted in below Figure 5-5. Here, for the case of fuel cell, the annual OPEX includes a considerable portion of maintenance cost and hence the same was taken in to the account when the equation for the representation of cost factors was deriving.

Fuel Cell

Installed Capacity – F_C
Efficiency – F_{CE}
Initial CAPEX – F_{CX}
Life time – F_{CLT}
Annual Maintenance Cost – F_{CMA}

Electric Energy Produced, E_{FC}

$$E_{FC} = \int F_C \times F_{CE} \times dt$$

OPEX per year, OP_{FC}

$$OP_{FC} = \frac{F_{CX}}{F_{CLT}} + F_{CMA}$$

Figure 5-5 Mathematical Equations – Fuel Cell

5.2.3 Hydrogen storage tank

Since there is no power generation linked with the Hydrogen storage tank, only one equation is to be derived linking to the same and that is for the operational expenditure (OPEX) of the tank. Here in this case the annual depreciation value of the tank as per the accounting books was considered as the total OPEX of the storage tank assuming the cost to be incurred on the maintenance work is minimal when compared with the depreciation of the capital investment. Figure 5-6 shows the derivation of the equations of Hydrogen storage.

Hydrogen Storage

Tank Capacity – H_{2C}
Initial CAPEX – H_{2CX}
Life time – H_{2LT}

OPEX per year, OP_{H2}

$$OP_{H2} = \frac{H_{2CX}}{H_{2LT}}$$

Figure 5-6 Mathematical Equations – Hydrogen storage

5.2.4 Converter

The functionality expected by the converter in the system is to manage the synchronization of the system between AC and DC power usage of components. Hence there will not be a generation or production of power from the converter, but it uses a considerable energy to carry out its functionality and operation. Therefore, differing from other components discussed so far, the equation related to energy is to be derived to represent the energy consumption of the converter. The same scenario is applicable for the electrolizer as well. This is explained under 5.2.5

Still the concept of mathematical equation on the cost components of the converter remains equal to the other scenarios discussed with other system components. Refer to Figure 5-7.

Converter

Installed Capacity – C_C
Efficiency – C_{CE}
Initial CAPEX – C_{CX}
Life time – C_{LT}

Electric Energy Loss, E_{CL}

$$E_{CL} = \int F_C \times (1 - C_{CE}) \times dt$$

OPEX per year, OP_C

$$OP_C = \frac{C_{CX}}{C_{LT}}$$

Figure 5-7 Mathematical Equations – Converter

5.2.5 Electrolizer

Electrolizer also a component which uses the energy from the system to carry out its operational functionality. Hence similar to the concept explained for the converter under 5.2.4, the energy consumed by the electrolizer was taken in to the consideration when the equation is derived. Refer to Figure 5-8

Electrolyzer

Installed Capacity – E_C
Initial CAPEX – E_{CX}
Life time – E_{LT}
Power Rating– E_{PR}
Annual Maintenance Cost – S_{MA}

Electric Energy Consumed, E_{EC}

$$E_{EC} = \int E_{PR}\, dt$$

OPEX per year, OP_{SO}

$$OP_{SO} = \frac{E_{CX}}{E_{LT}} + S_{MA}$$

Figure 5-8 Mathematical Equations – Electrolizer

5.2.6 Diesel generator

The diesel generator is included in the system as a component for the purpose of maintaining the continuity of the power supply as the solar PV is not considered as a type of dispatchable. Hence the diesel generator is supposed to function as a backup power source.

When the factors on diesel generator is considered for derivation of equations, being different to other system components, diesel generator uses fuel from outside of the system. In addition, by the operational nature of the device, diesel generator is tagged with a substantial cost on maintenance irrespective of the level of operation. Hence, the cost of fuel and cost of maintenance occupy a considerable portion of the operational expenditure of diesel generator per a m. Refer to Figure 5-9

Diesel Generator

Installed Capacity – DG_C
Efficiency – DG_{EF}
Initial CAPEX – DG_{CX}
Life time – DG_{LT}
Fuel Consumption Rate – DG_{FUEL}
Cost of Fuel – DG_{FC}
Annual Maintenance Cost – DG_{MA}

Electric Energy Produced, E_{DG}

$$E_{DG} = \int F_C \times F_{CE} \times dt$$

OPEX per year, OP_{DG}

$$OP_{DG} = \frac{DG_{CX}}{DG_{LT}} + DG_{MA} + \int DG_{FUEL} \times DG_{FC} \times dt$$

Figure 5-9 Mathematical Equations – Diesel Generator

Once the derivation of the equations was done, the economic model was to be formulated once the technical feasibility of the concept is tested against the practical on field conditions and the expectations of the industrial requirements.

6 GENERATION OF TEST CASES

A typical system with the employment of a Hydrogen storage is shown in the below Figure 6-1

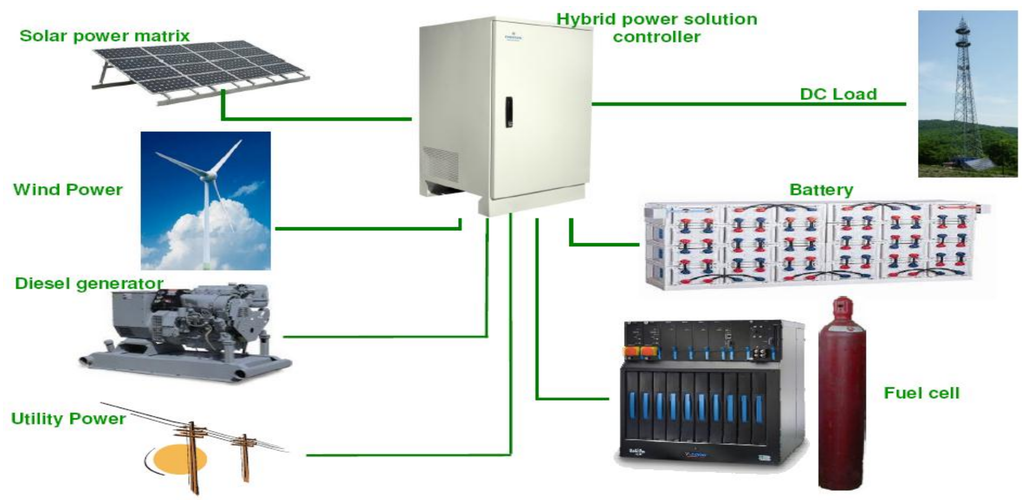


Figure 6-1 Sample system with a Hydrogen storage

Under the study, searching for the possibility of omitting the requirement of employing a battery bank at the bases station site for the purpose of backup power is a major objective targeting to make the proposal attractive to the industry in terms of financial performance. Hence the modeling of the system was started omitting the function of a battery bank and tested the performance of continuity of power supply with solar PV system, Hydrogen storage, fuel cell, converter and the diesel generator.

The testing cases were defined based on 2 parameters,

- The geographical location of the bases station site
- Power load of the site

6.1 Geographical Location

Selected 3 sites in the network from 3 different regions of the island. The solar pattern of 3 locations were expected to be different from one another up to a considerable extent.

Therefore the 3 sites were selected at least with a separation of 1 degree of latitudes. Refer Figure 6-2.

This was because of the necessity to test the concept against the climates of whole island to the maximum possible extent.

Site Name	Administrative District	Coordinates
Amunakole	Kurunegala	7^0 45' N; 80^0 18' E
Nelumkulama	Vavunia	8^0 43' N; 80^0 22' E
Gavaragiriya East	Rathnapura	6^0 39' N; 80^0 15' E

Figure 6-2 Selected base station site locations

Below figures shows the geographical locations (Figure 6-3, Figure 6-5, Figure 6-7) and the distribution of solar radiation (Figure 6-4, Figure 6-6, Figure 6-8) relevant to each of the selected base station sites respectively.

6.1.1 Amunakole - Base station site

One of the fairly sunny area in the dry zone of the island with a considerable sun shine. In general, the location receives a level of solar radiation which encourages the investment on solar PV systems to harvest the freely available renewable energy.

Figure 6-3 Geographical location of Amunakole site

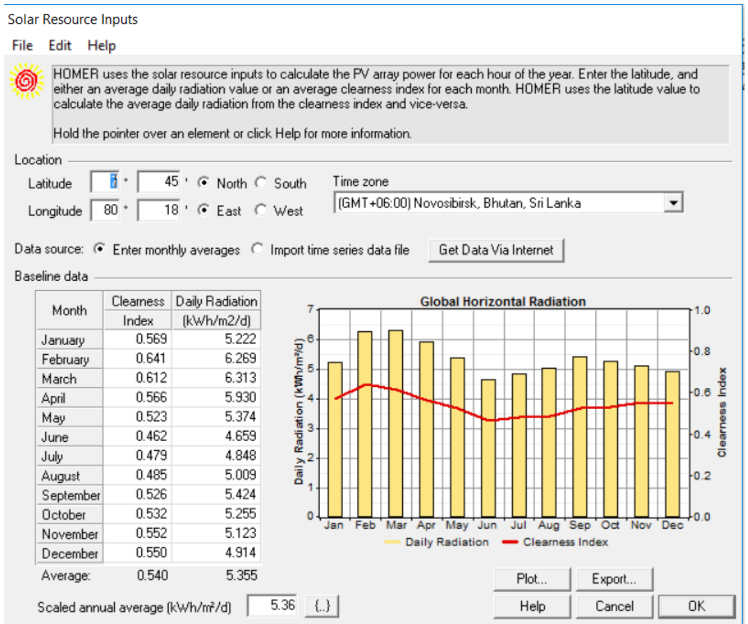


Figure 6-4 Annual distribution of solar radiation - Amunakole

6.1.2 Nelumkulama - Base station site

Nelumkulama is also an area belongs to the dry climate zone of the country. Since the area has a lesser rainfall when compared to Amunakole, the period which the solar radiation impacts is fairly higher than Amunakole. This situation leads for the possibility of harvesting an additional level of energy per annum when compared with previous option.

Hence Nelumkulama site was selected along with Amunakole site for a test case, giving an additional weight to the dry zone areas.

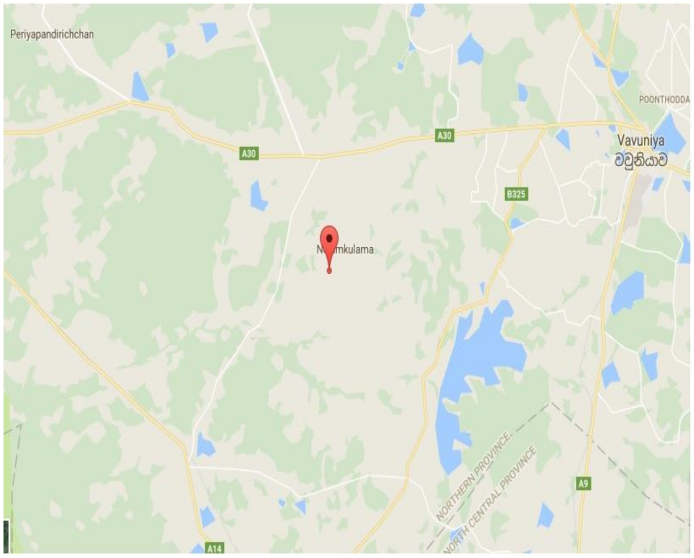


Figure 6-5 Geographical location of Nelumkulama site

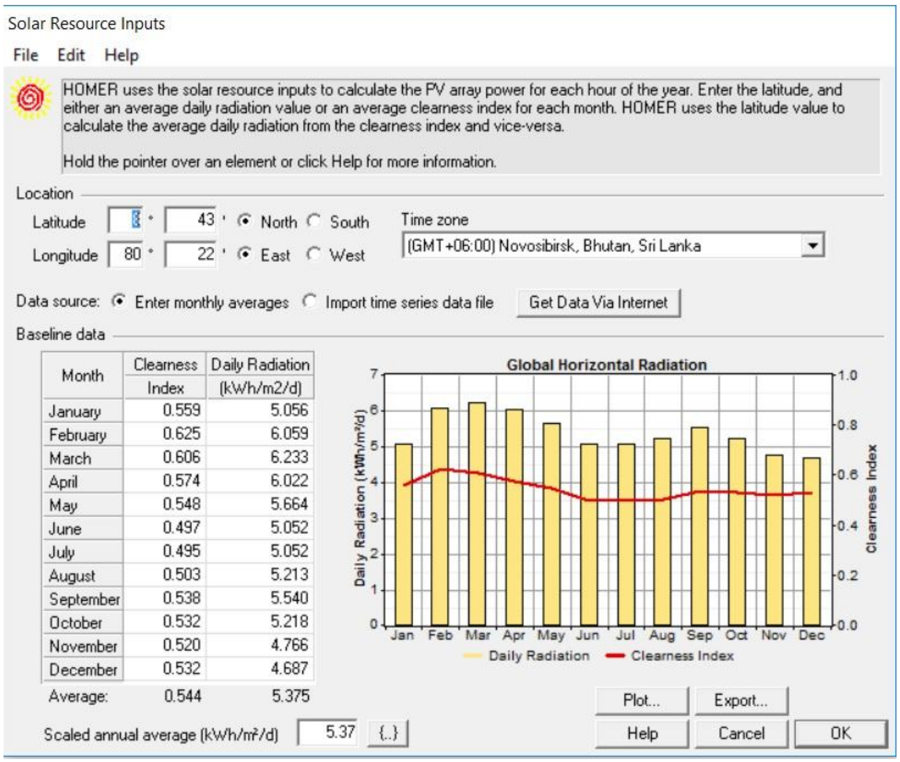


Figure 6-6 Annual distribution of solar radiation – Nelumkulama

6.1.3 Gawaragiriya East - Base station site

Gawaragiriya East is a site location situated in Rathnapura district which belongs to the wet climate zone of Sri Lanka, with considerably a high annual rainfall records. Here the demarcation of the solar capability between these 3 candidate sites locations is determined by the effective period of the solar radiation throughout the year. Since Gawaragiriya area is more inclined to rainy weather, the possible annual energy for harvesting is comparatively less than that of other 2 candidate site locations. Hence, Gawaragiriya East site location also selected to generate practical test cases for the purpose of testing the technical viability of proposed concept.

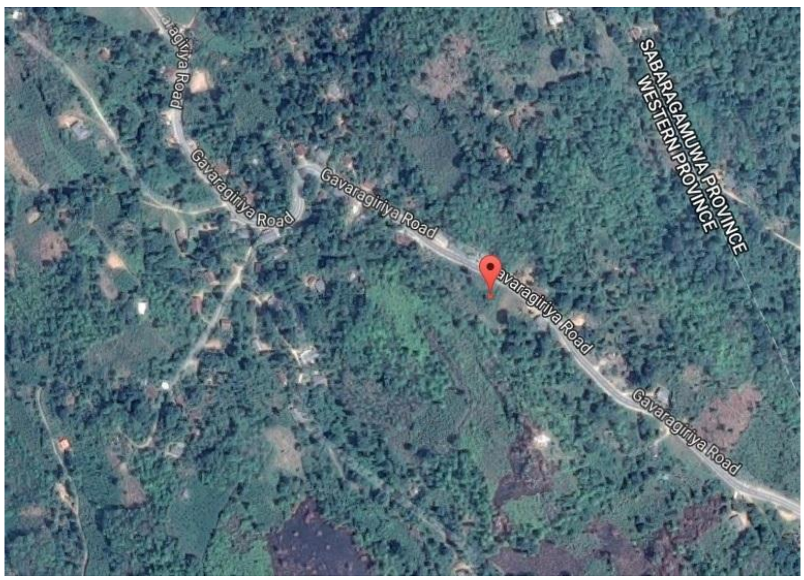


Figure 6-7 Geographical location of Gawaragiriya East site

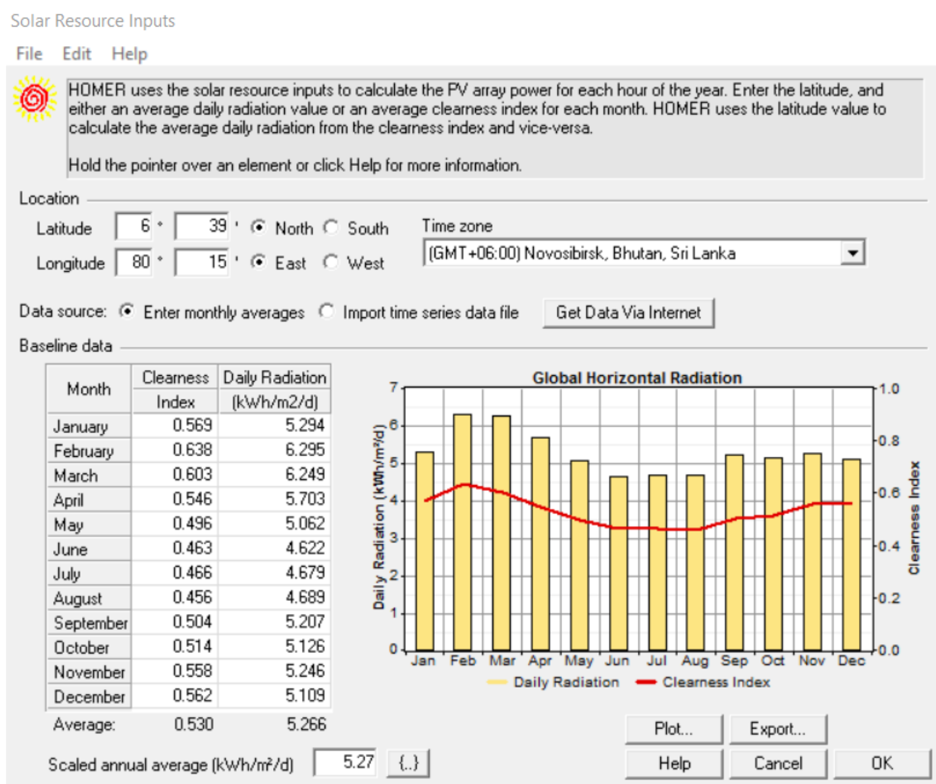


Figure 6-8Annual distribution of solar radiation – Gawaragiriya East

6.2 Power load of the site

When the distribution of the power demand among the sites in the network is considered, it was found that the majority of the sites consume a power load less than 2 kW. It is 1455 in number and accounts to a share of nearly 50% of total 3039 sites in the network. Figure 4-2

Hence defined 3 levels of power demands to represent the 0-2 kW demand interval considering the fairly distribution of test cases among the entire sample space.

- 0.5 kW
- 1.5 kW
- 1.8 kW

In addition to the above 3 power demand levels, 1 demand level was defined so that it falls in the demand interval of 2-4 kW.

- 2.5 kW

Did not consider accommodating a test case to represent the 3rd demand interval of above 4 kW, as the interval contains on 304 sites which is just 10% of the total sample space. Figure 4-2.

In addition to above, the network specific information and requirements were considered for this exclusion. In general, a site with a higher power demand means that the site serves for an extensive number of equipment working within its premises. Basically these additional equipment are microwave transmission links which are used to connect the other site locations to the transmission network. Higher this number means that the subjected site location acts as a hub location in the network and obviously a critical location for the network belonging to the aggregation layer or the core layer of the network. In other words, the operation of this site location affects the performance of the other segments of the network. Hence, when the business perspective of the incurring cost is considered, this type of site would not be mandatory to run on renewable energy, as the Engineers are much concerned on the overall big picture on the network performance rather limiting to the electricity cost of a particular bases station site.

7 TESTING OF TECHNICAL VIABILITY AGAINST THE TEST CASES

Based on the criteria defined for test cases as described above, there are 12 unique test cases available for the testing of the technical viability of the proposed concept.

Defining of Test Cases	0.5 kW load	1.5 kW load	1.8 kW load	2.5 kW load
Amunakole	Test Case 1	Test Case 2	Test Case 3	Test Case 4
Nelumkulama	Test Case 5	Test Case 6	Test Case 7	Test Case 8
Gawaragiriya East	Test Case 9	Test Case 10	Test Case 11	Test Case 12

Figure 7-1 Table of test cases

12 test cases were built in the HOMER tool in line with the above and tested the viability as depicted in Figure 7-1.

7.1 Test case 1

- Site location : Amunakole
- Demand load : 0.5 kW

The result given by HOMER under the *Test case 1* is given in Figure 7-2, Figure 7-3, Figure 7-4 and Figure 7-5 below.

System architecture

PV Array	30 kW
Diesel Generator	1 kW
Fuel Cell	1 kW
Inverter	1 kW
Rectifier	1 kW
Electrolyzer	20 kW
Hydrogen Tank	80 kg

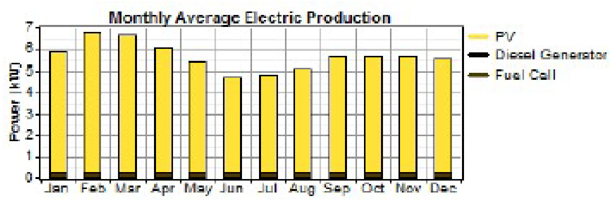
Cost summary

Total net present cost	$ 72,741
Levelized cost of energy	$ 1.299/kWh
Operating cost	$ 2,399/yr

Figure 7-2 Optimum System Architecture - Test case 1

Electrical

Component	Production (kWh/yr)	Fraction
PV array	47,390	96%
Diesel Generator	0	0%
Fuel Cell	2,226	4%
Total	49,616	100%



Load	Consumption (kWh/yr)	Fraction
DC primary load	4,380	9%
Electrolyzer load	43,492	91%
Total	47,872	100%

Quantity	Value	Units
Excess electricity	1,744	kWh/yr
Unmet load	0.000000209	kWh/yr
Capacity shortage	0.00	kWh/yr
Renewable fraction	1.000	

Figure 7-3 Summary of electricity generation - Test case 1

Diesel Generator

Quantity	Value	Units
Hours of operation	0	hr/yr
Number of starts	0	starts/yr
Operational life	1,000	yr
Capacity factor	0.00	%
Fixed generation cost	0.610	$/hr
Marginal generation cost	0.250	$/kWhyr

Figure 7-4 Operational summary of Diesel Generator - Test case 1

Fuel Cell

Quantity	Value	Units
Hours of operation	4,547	hr/yr
Number of starts	375	starts/yr
Operational life	3.30	yr
Capacity factor	25.4	%
Fixed generation cost	0.433	$/hr
Marginal generation cost	0.00	$/kWhyr

Figure 7-5 Operational summary of Fuel Cell - Test case 1

7.1.1 Discussion on result – Test case 1

When the above result is being analyzed, it was easily found that the power supply was fully based on the harvesting of solar energy, making the renewable factor equals to unity. Further, when the Figure 7-4 Operational summary of Diesel Generator - Test case 1 is studied, the diesel generator had neither been started nor run for the entire year, meaning that the diesel generator is not a mandatory component in the system to maintain an uninterruptable power supply to meet the demanded load of 0.5 kW.

The fuel cell had been operated for 4575 hours throughout the year (52% of time period) meaning that the base station site was powered by the energy stored as gas Hydrogen for more than 50% of time while the rest was managed directly by the output of the solar PV panels.

The system was modeled purposely omitting the presence of a battery bank and the HOMER simulation suggests that the diesel generator is not necessary to be included in the system. Hence it can be concluded that, under the test case 1, the Hydrogen storage is effectively viable to be use with the solar PV panels to maintain an uninterruptable power supply. The cost benefits are yield through the savings gained by exclusion of capital and operational expenditure on batteries and diesel generator.

The next best solution given by HOMER simulation under Test case 1 is as below. Figure 7-6

According to the results, there is no Hydrogen storage mechanism and hence the diesel generator has to be operated throughout the year under prime operation.

System architecture

PV Array	2 kW
Diesel Generator	1 kW
Inverter	1 kW
Rectifier	1 kW

Cost summary

Total net present cost	$ 84,590
Levelized cost of energy	$ 1.511/kWh
Operating cost	$ 6,375/yr

Diesel Generator

Quantity	Value	Units
Hours of operation	8,760	hr/yr
Number of starts	1	starts/yr
Operational life	1.71	yr
Capacity factor	46.1	%
Fixed generation cost	0.610	$/hr
Marginal generation cost	0.250	$/kWhyr

Figure 7-6 Next best solution – Test case 1

7.2 Test case 2

- Site location : Amunakole
- Demand load : 1.5 kW

The result given by HOMER under the ***Test case 2*** is as below. Refer Figure 7-7, Figure 7-8 and Figure 7-9.

System architecture

PV Array	25 kW
Diesel Generator	2 kW
Fuel Cell	1 kW
Inverter	2 kW
Rectifier	2 kW
Electrolyzer	20 kW
Hydrogen Tank	30 kg

Cost summary

Total net present cost	$ 167,232
Levelized cost of energy	$ 0.996/kWh
Operating cost	$ 9,962/yr

Electrical

Component	Production (kWh/yr)	Fraction
PV array	39,492	82%
Diesel Generator	7,369	15%
Fuel Cell	1,083	2%
Total	47,944	100%

Load	Consumption (kWh/yr)	Fraction
DC primary load	13,140	30%
Electrolyzer load	30,996	70%
Total	44,136	100%

Quantity	Value	Units
Excess electricity	2,703	kWh/yr
Unmet load	0.000127	kWh/yr
Capacity shortage	0.00	kWh/yr
Renewable fraction	0.846	

Figure 7-7 Optimum System Architecture - Test case 2

Diesel Generator

Quantity	Value	Units
Hours of operation	4,692	hr/yr
Number of starts	380	starts/yr
Operational life	3.20	yr
Capacity factor	42.1	%
Fixed generation cost	1.22	$/hr
Marginal generation cost	0.250	$/kWhyr

Figure 7-8 Operational summary of Diesel Generator - Test case 2

Fuel Cell

Quantity	Value	Units
Hours of operation	4,685	hr/yr
Number of starts	727	starts/yr
Operational life	3.20	yr
Capacity factor	12.4	%
Fixed generation cost	0.433	$/hr
Marginal generation cost	0.00	$/kWhyr

Figure 7-9 Operational summary of Fuel Cell - Test case 2

7.2.1 Discussion on result – Test case 2

According to the results of the HOMER simulation, the Hydrogen storage concept is technically viable to deploy under the scenario of Test case 2.

When the demand load reaches the value of 1.5 kW, the diesel generator should be employed in the installation as the energy harvested from solar radiation is not sufficient to meet the demand. Still the operational time of the diesel generator is 4692 hours per year (53% of the period) with a share of 15% in electricity generation. The share accounted by the solar PV panels for electricity generation is 82%, leaving just a share of 2% for fuel cell.

In addition to above, when the focus is given to the number of starts taken place for diesel generator (380 starts) and fuel cell (727) separately along with the hours of operation for both components (approximately 4700 hours), it is understood that the Hydrogen storage was utilized to feed the balance requirement of demand when the system runs on diesel generator. Further, the Hydrogen storage had managed to fill the function of a battery bank to maintain the uninterruptable power supply to the load, while at the switching of power sources between solar PV and diesel generator. The saving was derived by employing a diesel generator with a capacity less than the demanded load, utilizing the grace of having a Hydrogen storage.

Similar to the result obtained under Test case 1, the next best solution for the scenarios of test case 2, there is no Hydrogen storage mechanism and hence the diesel generator has to be operated throughout the year under prime operation as shown in Figure 7-10.

System architecture

PV Array	4 kW
Diesel Generator	2 kW
Inverter	2 kW
Rectifier	2 kW

Cost summary

Total net present cost	$ 180,100
Levelized cost of energy	$ 1.072/kWh
Operating cost	$ 13,604/yr

Diesel Generator

Quantity	Value	Units
Hours of operation	8,760	hr/yr
Number of starts	1	starts/yr
Operational life	1.71	yr
Capacity factor	65.6	%
Fixed generation cost	1.22	$/hr
Marginal generation cost	0.250	$/kWhyr

Figure 7-10 Next best solution – Test case 2

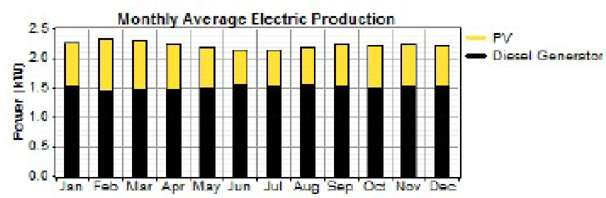
7.3 Test case 3

- Site location : Amunakole
- Demand load : 1.8 kW

The result given by HOMER under the *Test case 3* is as below. Refer Figure 7-11 and Figure 7-12.

Electrical

Component	Production (kWh/yr)	Fraction
PV array	6,319	32%
Diesel Generator	13,196	68%
Total	19,515	100%



Load	Consumption (kWh/yr)	Fraction
DC primary load	15,316	100%
Total	15,316	100%

Quantity	Value	Units
Excess electricity	2,391	kWh/yr
Unmet load	453	kWh/yr
Capacity shortage	1,341	kWh/yr
Renewable fraction	0.324	

System architecture

PV Array	4 kW
Diesel Generator	2 kW
Inverter	2 kW
Rectifier	2 kW

Cost summary

Total net present cost	$ 185,555
Levelized cost of energy	$ 0.948/kWh
Operating cost	$ 14,030/yr

Figure 7-11 Optimum System Architecture - Test case 3

Diesel Generator

Quantity	Value	Units
Hours of operation	8,760	hr/yr
Number of starts	1	starts/yr
Operational life	1.71	yr
Capacity factor	75.3	%
Fixed generation cost	1.22	$/hr
Marginal generation cost	0.250	$/kWhyr

Figure 7-12 Operational summary of Diesel Generator - Test case 3

7.3.1 Discussion on result – Test case 3

At the point of reaching to 1.8 kW in demand, the Hydrogen storage concept had turned to be not the optimum under the scenarios defined under Test case 3.

Under the optimum solution, the diesel generator is supposed to run on prime basis, while the solar PV panels supply its harvest to the load under non-dispatchable basis. Therefore, the diesel generator had to be sized at a 2kW rating, in order to be sufficient to meet the demand when solar PV panels does not supply the electricity.

The result obtained for Test case 3 depicts that the Hydrogen storage option does not yield the best solution at every case and hence it's viability is to be tested under the applicable scenario, prior to make the decision on investment.

7.4 Test case 4

- Site location : Amunakole
- Demand load : 2.5 kW

The result given by HOMER under the *Test case 4* is as below. Refer Figure 7-13, Figure 7-14 and Figure 7-15.

System architecture

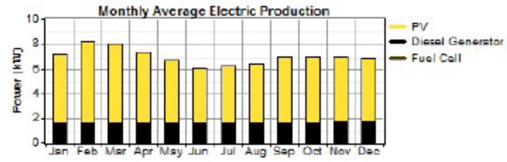
PV Array	30 kW
Diesel Generator	4 kW
Fuel Cell	1 kW
Inverter	4 kW
Rectifier	4 kW
Electrolyzer	6 kW
Hydrogen Tank	10 kg

Cost summary

Total net present cost	$ 260,534
Levelized cost of energy	$ 0.932/kWh
Operating cost	$ 17,568/yr

Electrical

Component	Production (kWh/yr)	Fraction
PV array	47,390	77%
Diesel Generator	14,004	23%
Fuel Cell	373	1%
Total	61,768	100%



Load	Consumption (kWh/yr)	Fraction
DC primary load	21,863	55%
Electrolyzer load	18,173	45%
Total	40,036	100%

Quantity	Value	Units
Excess electricity	19,630	kWh/yr
Unmet load	0.000323	kWh/yr
Capacity shortage	0.00	kWh/yr
Renewable fraction	0.773	

Figure 7-13 Optimum System Architecture - Test case 4

Diesel Generator

Quantity	Value	Units
Hours of operation	5,035	hr/yr
Number of starts	410	starts/yr
Operational life	2.98	yr
Capacity factor	40.0	%
Fixed generation cost	2.44	$/hr
Marginal generation cost	0.250	$/kWhyr

Figure 7-14Operational summary of Diesel Generator - Test case 4

Fuel Cell

Quantity	Value	Units
Hours of operation	3,725	hr/yr
Number of starts	409	starts/yr
Operational life	4.03	yr
Capacity factor	4.26	%
Fixed generation cost	0.433	$/hr
Marginal generation cost	0.00	$/kWhyr

Figure 7-15 Operational summary of Fuel Cell - Test case 4

7.4.1 Discussion on result – Test case 4

Under the conditions defined under Test case 4, the concept of having a Hydrogen storage had being selected as technically viable according to the simulation results of the HOMER tool. Under the test case, system requires a diesel generator to be employed in the system along with the solar PV panels, Hydrogen storage, fuel cell and the electrolizer.

The next best solution does not contain the Hydrogen storage option and designed the system so that the diesel generator runs on fulltime basis while the solar PV panels provide a non-dispatchable supply while the fuel cell contributes with a 1% share to the whole electricity requirement. Refer Figure 7-16.

System architecture

PV Array	4 kW
Diesel Generator	4 kW
Inverter	4 kW
Rectifier	4 kW

Cost summary

Total net present cost	$ 347,556
Levelized cost of energy	$ 1.244/kWh
Operating cost	$ 26,531/yr

Diesel Generator

Quantity	Value	Units
Hours of operation	8,760	hr/yr
Number of starts	1	starts/yr
Operational life	1.71	yr
Capacity factor	58.3	%
Fixed generation cost	2.44	$/hr
Marginal generation cost	0.250	$/kWhyr

Figure 7-16 Next best solution – Test case 4

8 Testing the viability using Developed mathematical model

According to the mathematical equations derived according to the description given under the Development of mathematical model, a model was developed using Microsoft Excel spreadsheet application. The below Figure 8-1 shows the Graphical User Interface (GUI) of the developed mathematical model.

	Capex per Unit Power ($)	Capex ($)	Operated Time (Hours)	O&M Per Unit Power per Year ($)	Life Time (Yr)	Opex ($)	Installed Capacity (kW)	Efficiency	Electricity Generated (kWh/Yr)	Annual Fuel Consumption (kg/Yr)
Solar PV	1,000	30,000	4368	1	20	30	30	16%	48,841	
Fuel Cell	5,500	5,500	4547	454.7	5	455	1	100%	2,300	920
Hydrogen Storage	6	480		1	25	80	80	100%		
Converter	600	600		1	15	40	1	90%	-	
Electrolyzer	1,000	20,000		2	15	40	20	85%	(41,400)	
Diesel Generator	500	500	0	0	5	100	1	35%	-	

Energy Calculations

Site Power Load (kW)	0.5
Telecom Energy Consumption (kWh/Yr)	(4,380)
Comparison	**Output of Model**
Total Generation (kWh/Yr)	51,141
Total Consumption (kWh/Yr)	(45,780)
Excess Electricity Generated (kWh/Yr)	5,361

Financial Calculations

Comparison	Output of Model
Total Capex - Net Present ($)	42,080
Total Capex - Annualized ($)	3,259
Total O&M	745
Fuel Cost	-
Total OPEX	745

Figure 8-1 GUI of the mathematical model to test the viability

The test cases which the system modeling was finalized by simulation using HOMER tool, were re-tested using the above mentioned mathematical model developed as a part of this study.

Test case 1

Option 1 - Configuration						
	Capex ($)	Operated Time (Hours)	Opex ($)	Installed Capacity (kW)	Electricity Generated	Annual Fuel Consumption (kg/Yr)
Solar PV	20,000	4368	30	30	48,841	
Fuel Cell	5,500	4547	455	1	2,300	920
Hydrogen Storage	480		80	80		
Converter	600		40	1	-	
Electrolyzer	15,000		40	20	(41,400)	
Diesel Generator	500	0	100	1	-	

Site Power Load (kW)	0.5
Telecom Energy Consumption (kWh/Yr)	(4,380)

Comparrison	Output of Model	Output of HOMER
Total Generation (kWh/Yr)	51,141	49,616
Total Consumption (kWh/Yr)	(45,780)	47,872
Excess Electricity Generated (kWh/Yr)	5,361	1,744
Total Capex - Net Present ($)	42,080	42,080
Total Capex - Annulaized ($)	3,259	3,292
Total O&M	745	566
Fuel Cost	-	-
Total OPEX	745	566
Total Annual Cost ($) (Option 1)	4,004	3,858

Option 2 - Configuration						
	Capex ($)	Operated Time (Hours)	Opex ($)	Installed Capacity (kW)	Electricity Generated	Annual Fuel Consumption (kg/Yr)
Solar PV	2,000	4368	102	2	3,256	
Fuel Cell	-	0	-	0	-	0
Hydrogen Storage	-		-	0		
Converter	600		40	1	-	
Electrolyzer	-		-	0	-	
Diesel Generator	500	8760	4,480	1	4,030	

Site Power Load (kW)	0.5
Telecom Energy Consumption (kWh/Yr)	(4,380)

Comparrison	Output of Model	Output of HOMER
Total Generation (kWh/Yr)	7,286	7,196
Total Consumption (kWh/Yr)	(4,380)	4,380
Excess Electricity Generated (kWh/Yr)	2,906	2,343
Total Capex - Net Present	3,100	3,100
Total Capex - Annulaized	240	243
Total O&M	4,622	4,383
Fuel Cost	2,002	1,710
Total OPEX	6,624	6,093
Total Annual Cost ($) (Option 2)	6,864	6,336

Figure 8-2 Comparison of the results with HOMER – Test case 1

When the above Figure 8-2 is studied, it clearly shows that the selection done through the developed mathematical model fits with the simulation result of the HOMER tool on Test case 1.

Similarly, the developed mathematical model was tested against the simulation results of the HOMER tool for several other test cases.

In addition, below Figure 8-3, Figure 8-4, Figure 8-5, Figure 8-6, Figure 8-7 shows the fitness of the mathematical model against the HOMER result under the test cases 2, 3, 4, 5 and 9 respectively.

Test case 2

Option 1 - Configuration

	Capex ($)	Operated Time (Hours)	Opex ($)	Installed Capacity (kW)	Electricity Generated	Annual Fuel Consumption (kg/Yr)
Solar PV	17,000	4368	25	25	40,701	
Fuel Cell	5,500	4685	469	1	1,615	646
Hydrogen Storage	180		30	30		
Converter	1,200		80	2	-	
Electrolyzer	15,000		40	20	(29,070)	
Diesel Generator	1,000	4692	4,892	2	3,284	

Site Power Load (kW)	1.5
Telecom Energy Consumption (kWh/Yr)	(13,140)

Comparrison	Output of Model	Output of HOMER
Total Generation (kWh/Yr)	46,632	47,944
Total Consumption (kWh/Yr)	(42,210)	44,136
Excess Electricity Generated (kWh/Yr)	4,422	2,703
Total Capex - Net Present ($)	39,880	39,880
Total Capex - Annulaized ($)	3,237	3,120
Total O&M	5,536	5,243
Fuel Cost	2,145	2,593
Total OPEX	7,681	7,836
Total Annual Cost ($) (Option 1)	10,918	10,956

Option 2 - Configuration

	Capex ($)	Operated Time (Hours)	Opex ($)	Installed Capacity (kW)	Electricity Generated	Annual Fuel Consumption (kg/Yr)
Solar PV	4,000	4368	204	4	6,512	
Fuel Cell	-	0	-	0	-	0
Hydrogen Storage	-	NA	-	0		
Converter	1,200		80	2	-	
Electrolyzer	-		-	0	-	
Diesel Generator	1,000	8760	8,960	2	6,132	

Site Power Load (kW)	1.5
Telecom Energy Consumption (kWh/Yr)	(13,140)

	Output of Model	Output of HOMER
Total Generation (kWh/Yr)	14,571	17,808
Total Consumption (kWh/Yr)	(13,140)	13,140
Excess Electricity Generated (kWh/Yr)	1,431	3,149
Total Capex - Net Present	6,200	6,200
Total Capex - Annulaized	480	485
Total O&M	9,244	8,766
Fuel Cost	4,005	4,274
Total OPEX	13,249	13,040
Total Annual Cost ($) (Option 2)	13,729	13,525

Figure 8-3 Comparison of the results with HOMER – Test case 2

Test case 3

Option 1 - Configuration	Capex ($)	Operated Time (Hours)	Opex ($)	Installed Capacity (kW)	Electricity Generated	Annual Fuel Consumption (kg/Yr)
Solar PV	4,000	4368	4	4	6,512	
Fuel Cell	5,500	0	0	1	-	0
Hydrogen Storage	-		-	0		
Converter	1,200		80	2	-	
Electrolyzer	6,000		12	6	(2,221)	
Diesel Generator	1,000	8760	8,960	2	11,388	

Site Power Load (kW)	1.8
Telecom Energy Consumption (kWh/Yr)	(15,768)

Comparrison	Output of Model	Output of HOMER
Total Generation (kWh/Yr)	17,900	19,515
Total Consumption (kWh/Yr)	(15,768)	17,536
Excess Electricity Generated (kWh/Yr)	2,132	1,979
Total Capex - Net Present ($)	17,700	17,700
Total Capex - Annulaized ($)	1,980	1,385
Total O&M	9,056	8,778
Fuel Cost	4,005	4,701
Total OPEX	13,061	13,479
Total Annual Cost ($) (Option 1)	15,041	14,864

Option 2 - Configuration	Capex ($)	Operated Time (Hours)	Opex ($)	Installed Capacity (kW)	Electricity Generated	Annual Fuel Consumption (kg/Yr)
Solar PV	4,000	4368	204	4	6,512	
Fuel Cell	-	0	-	0	-	0
Hydrogen Storage	-	NA	-	0		
Converter	1,200		80	2	-	
Electrolyzer	-		-	0	-	
Diesel Generator	1,000	8760	8,960	2	11,388	

Site Power Load (kW)	1.8
Telecom Energy Consumption (kWh/Yr)	(15,768)

	Output of Model	Output of HOMER
Total Generation (kWh/Yr)	17,900	19,515
Total Consumption (kWh/Yr)	(15,768)	15,316
Excess Electricity Generated (kWh/Yr)	2,132	2,391
Total Capex - Net Present	6,200	6,200
Total Capex - Annulaized	480	485
Total O&M	9,244	8,766
Fuel Cost	4,005	4,701
Total OPEX	13,249	13,467
Total Annual Cost ($) (Option 2)	13,729	13,952

Figure 8-4 Comparison of the results with HOMER – Test case 3

Test case 4

Option 1 - Configuration						
	Capex ($)	Operated Time (Hours)	Opex ($)	Installed Capacity (kW)	Electricity Generated	Annual Fuel Consumption (kg/Yr)
Solar PV	20,000	4368	30	30	48,841	
Fuel Cell	5,500	3725	455	1	2,300	391
Hydrogen Storage	70		80	10		
Converter	2,400		40	4	-	
Electrolyzer	6,000		40	6	(41,400)	
Diesel Generator	2,000	5035	100	4	-	

Site Power Load (kW)	2.5
Telecom Energy Consumption (kWh/Yr)	(21,900)

Comparrison	Output of Model	Output of HOMER
Total Generation (kWh/Yr)	51,141	61,768
Total Consumption (kWh/Yr)	(63,300)	40,036
Excess Electricity Generated (kWh/Yr)	(12,159)	19,630
Total Capex - Net Present ($)	35,970	35,960
Total Capex - Annulaized ($)	3,063	2,813
Total O&M	745	10,494
Fuel Cost	-	5,112
Total OPEX	745	15,606
Total Annual Cost ($) (Option 1)	3,808	18,419

Option 2 - Configuration						
	Capex ($)	Operated Time (Hours)	Opex ($)	Installed Capacity (kW)	Electricity Generated	Annual Fuel Consumption (kg/Yr)
Solar PV	4,000	4368	102	4	3,256	
Fuel Cell	-	0	-	0	-	0
Hydrogen Storage	-	NA	-	0		
Converter	2,400		40	4	-	
Electrolyzer	-		-	0	-	
Diesel Generator	2,000	8760	4,480	4	4,030	

Site Power Load (kW)	2.5
Telecom Energy Consumption (kWh/Yr)	(21,900)

	Output of Model	Output of HOMER
Total Generation (kWh/Yr)	7,286	38,340
Total Consumption (kWh/Yr)	(21,900)	26,243
Excess Electricity Generated (kWh/Yr)	(14,614)	9,182
Total Capex - Net Present	8,400	12,900
Total Capex - Annulaized	760	1,009
Total O&M	4,622	17,534
Fuel Cost	2,002	8,439
Total OPEX	6,624	25,973
Total Annual Cost ($) (Option 2)	7,384	26,982

Figure 8-5 Comparison of the results with HOMER – Test case 4

Test case 5

Option 1 - Configuration						
	Capex ($)	Operated Time (Hours)	Opex ($)	Installed Capacity (kW)	Electricity Generated	Annual Fuel Consumption (kg/Yr)
Solar PV	20,000	4357	30	30	48,809	
Fuel Cell	5,500	4559	456	1	2,308	923
Hydrogen Storage	480		80	80		
Converter	600		40	1	-	
Electrolyzer	15,000		40	20	(41,535)	
Diesel Generator	500	0	100	1	-	

Site Power Load (kW)	0.5
Telecom Energy Consumption (kWh/Yr)	(4,380)

Comparrison	Output of Model	Output of HOMER
Total Generation (kWh/Yr)	51,116	49,677
Total Consumption (kWh/Yr)	(45,915)	47,988
Excess Electricity Generated (kWh/Yr)	5,201	1,689
Total Capex - Net Present ($)	42,080	42,080
Total Capex - Annualized ($)	3,259	3,292
Total O&M	746	567
Fuel Cost	-	-
Total OPEX	746	567
Total Annual Cost ($) (Option 1)	4,005	3,859

Option 2 - Configuration						
	Capex ($)	Operated Time (Hours)	Opex ($)	Installed Capacity (kW)	Electricity Generated	Annual Fuel Consumption (kg/Yr)
Solar PV	2,000	4357	102	2	3,254	
Fuel Cell	-	0	-	0	-	0
Hydrogen Storage	-		-	0		
Converter	600		40	1	-	
Electrolyzer	-		-	0	-	
Diesel Generator	500	8760	4,480	1	4,030	

Site Power Load (kW)	0.5
Telecom Energy Consumption (kWh/Yr)	(4,380)

	Output of Model	Output of HOMER
Total Generation (kWh/Yr)	7,284	7,200
Total Consumption (kWh/Yr)	(4,380)	4,380
Excess Electricity Generated (kWh/Yr)	2,904	2,347
Total Capex - Net Present	3,100	3,100
Total Capex - Annualized	240	243
Total O&M	4,622	4,383
Fuel Cost	2,002	1,710
Total OPEX	6,624	6,093
Total Annual Cost ($) (Option 2)	6,864	6,336

Figure 8-6 Comparison of the results with HOMER – Test case 5

Test case 9

Option 1 - Configuration						
	Capex ($)	Operated Time (Hours)	Opex ($)	Installed Capacity (kW)	Electricity Generated	Annual Fuel Consumption (kg/Yr)
Solar PV	20,000	4371	30	30	48,966	
Fuel Cell	5,500	4447	445	1	2,248	899
Hydrogen Storage	180		30	30		
Converter	600		40	1	-	
Electrolyzer	15,000		40	20	(40,455)	
Diesel Generator	2,000	106	612	4	195	

Site Power Load (kW)	0.5
Telecom Energy Consumption (kWh/Yr)	(4,380)

Comparrison	Output of Model	Output of HOMER
Total Generation (kWh/Yr)	51,408	48,840
Total Consumption (kWh/Yr)	(44,835)	46,122
Excess Electricity Generated (kWh/Yr)	6,573	2,699
Total Capex - Net Present ($)	43,280	43,280
Total Capex - Annulized ($)	3,547	3,386
Total O&M	1,197	743
Fuel Cost	97	66
Total OPEX	1,294	809
Total Annual Cost ($) (Option 1)	4,841	4,195

Option 2 - Configuration						
	Capex ($)	Operated Time (Hours)	Opex ($)	Installed Capacity (kW)	Electricity Generated	Annual Fuel Consumption (kg/Yr)
Solar PV	2,000	4371	102	2	3,264	
Fuel Cell	-	0	-	0	-	0
Hydrogen Storage	-		-	0		
Converter	600		40	1	-	
Electrolyzer	-		-	0	-	
Diesel Generator	500	8760	4,480	1	4,030	

Site Power Load (kW)	0.5
Telecom Energy Consumption (kWh/Yr)	(4,380)

	Output of Model	Output of HOMER
Total Generation (kWh/Yr)	7,294	7,143
Total Consumption (kWh/Yr)	(4,380)	4,380
Excess Electricity Generated (kWh/Yr)	2,914	2,288
Total Capex - Net Present	3,100	3,100
Total Capex - Annulaized	240	243
Total O&M	4,622	4,383
Fuel Cost	2,002	1,711
Total OPEX	6,624	6,094
Total Annual Cost ($) (Option 2)	6,864	6,337

Figure 8-7 Comparison of the results with HOMER – Test case 9

When the figures of results obtained from mathematical model is compared closely with that of HOMER tool, a slight deviation is observed. There is a rational behind these deviations with sound backing up for the validity of the developed model.

Just refer to the Figure 8-3, which gives the comparison pertaining to the Test case 2. Below given Figure 8-8 summarizes the deviations in above mentioned comparison for the ease in discussion.

When the mathematical model is being developed, the annual solar radiation was calculated using the scaled average considering the total energy incident on the panels, rather than accounting for continuous variations. Actual radiation pattern is in the form which depicts in Figure 6-4.

Option 1 – Configuration – 1.5 kW						
	Capex ($)	Operated Time (Hours)	OPEX ($)	Installed Capacity (kW)	Electricity Generated	
					Output of Model	Output of HOMER
Solar PV	17,000	4368	25	25	40,701	39,491
Fuel Cell	5,500	4685	469	1	1,615	1,083
Hydrogen Storage	180		30	30		
Converter	1,200		80	2	-	
Electrolyzer	15,000		40	20	(29,070)	30,996
Diesel Generator	1,000	4692	4,892	2	3,284	7,369

Comparison	Output of Model	Output of HOMER
Total Generation (kWh/Yr)	46,632	47,944
Total Consumption (kWh/Yr)	(42,210)	44,136
Excess Electricity Generated (kWh/Yr)	4,422	2,703

Figure 8-8 Comparison of results - Test case 2

When the calculations for the function of the diesel generator is modeled, the efficiency was considered as a flat function even it is obvious that it varies with the load. Further, the efficiency of diesel generator and the fuel cell was considered unchanged even at the startup time period.

Above reasons led to the results obtained from developed mathematical model to be deviated slightly from that of HOMER.

Still the deviations are not significant and does not sufficient the make an impact on the designed ratings of the components. On the other hand, even the deviations in commercial figures do not sufficient to exert an impact on the investment decision.

9 INCORPORATE THE MATHEMATICAL MODEL FOR DECISION MAKING

This is the stage which the outcome of the research work meets the practical expectation of industry. As explained under section 2.1, at present DAP adhered to the traditional way of decision making on the composition of system components for the solar PV system once the financial viability is confirmed. Irrespective of the site load and the solar radiation pattern at the site location, the rating of the diesel generator is fixed to the value of 10 kVA and the capacity of the battery bank is fixed as 600 VA.

This situation leads to fixed figures for capital investment as well as operational expenditure irrespective of the base station specific data.

This section explains the methodology to be used with the developed mathematical model to determine the economic viability of the proposed concept based on the context at base station site.

Below given Figure 9-1 explains the methodology to be followed when the proposed model is used in the process of decision making to check the techno-economic viability regarding the investment on renewable energy to power the base station sites.

1. Input the site-specific information in to the model developed in HOMER under this research
    a. Coordinates of the site location
    b. Demanded power load
2. Obtain the optimum system configuration for the case using the model developed in HOMER.
3. Input the result obtained under above 2 in to the Mathematical Model developed using MS Excel as an outcome of this research.
4. Follow the steps defined in the flow chart depicted in Figure 9-1

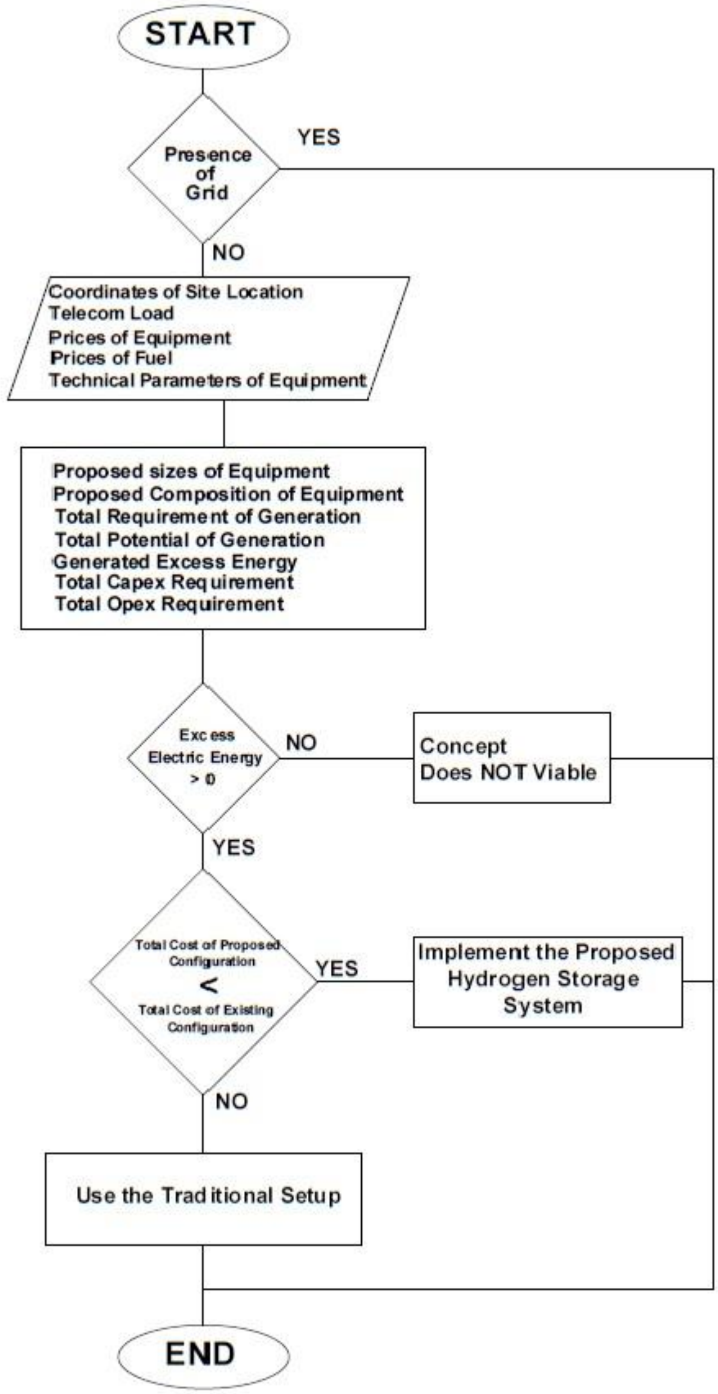


Figure 9-1 Flow chart - Decision making algorithm

Let's take the Test case 9 as an example. Figure 9-2 below shows the techno-economic output of the traditional configuration while the Figure 9-3 depicts the same for proposed concept under Test case 9.

Traditional - Configuration

	Capex ($)	Operated Time (Hours)	Opex ($)	Installed Capacity (kW)	Electricity Generated
Solar PV	2,000	4368	102	2	3,262
Battery - LiFePO4	3,000		-	0.6	-
Diesel Generator	8,000	2190	4,480	10	3,285

Site Power Load (kW)	0.5
Telecom Energy Consumption (kWh/Yr)	(4,380)

	Output of Model
Total Generation (kWh/Yr)	6,547
Total Consumption (kWh/Yr)	(4,380)
Excess Electricity Generated (kWh/Yr)	2,167

Total Capex - Net Present	13,000
Total Capex - Annulaized	2,900
Total O&M	4,582
Fuel Cost	2,002
Total OPEX	6,584

Total Annual Cost ($) (Option 2)	9,484

Figure 9-2 Techno-economic output for traditional configuration - Test case 9

Configuration with Proposed Concept						
	Capex ($)	Operated Time (Hours)	Opex ($)	Installed Capacity (kW)	Electricity Generated	Annual Fuel Consumption (kg/Yr)
Solar PV	20,000	4371	30	30	48,966	
Fuel Cell	5,500	4447	445	1	2,248	899
Hydrogen Storage	180		30	30		
Converter	600		40	1	-	
Electrolyzer	15,000		40	20	(40,455)	
Diesel Generator	2,000	106	612	4	195	

Site Power Load (kW)	0.5
Telecom Energy Consumption (kWh/Yr)	(4,380)

Comparrison	Output of Model	Output of HOMER
Total Generation (kWh/Yr)	51,408	48,840
Total Consumption (kWh/Yr)	(44,835)	46,122
Excess Electricity Generated (kWh/Yr)	6,573	2,699
Total Capex - Net Present ($)	43,280	43,280
Total Capex - Annulaized ($)	3,547	3,386
Total O&M	1,197	743
Fuel Cost	97	66
Total OPEX	1,294	809
Total Annual Cost ($) (Option 1)	4,841	4,195

Figure 9-3 Techno-economic output for proposed concept - Test case 9

Once the values for the decisive parameters are obtained using the developed models, comparison between them are performed as depicted in Figure 9-4 below.

Decision	Description	Value	Unit
Generation	Excess Electricity Generated under Proposed Concept	2,699	kWh/yr
Financial	Total Annual Cost of Proposed Concept	4,841	$
	Total Annual Cost of Existing Traditional Method	9,484	$

Figure 9-4 Comparison of decisive parameters

Hence the decision can be made as the proposed concept is technically and economically viable to be implemented under the conditions of Test case 9.

10 SENSITIVITY ANALYSIS

When the analysis is extended beyond the technical context towards commercials, the sensitivity analysis plays a great role when the validity and the utility of the model is concerned. Here for the techno-economic analysis carried out under this research work, incorporated major economic variables are price of diesel, tariff for commercial electricity and cost of Hydrogen.

Based on the proposed technological concept, the required Hydrogen volume is supplied within the site by electrolyzing making the decision insensitive to cost of Hydrogen.

Even the proposed concept is extendable to the grid-connected base station sites with the facility of net-metering, the scope of the study was limited to the off-grid scenarios. Hence the tariff of commercial electricity does not make a change on the economic viability of a particular case. In other words, the decision on investment does not sensitive to the cost of commercial electricity.

Finally, the only commercial factor which holds a control over the economic performance of the solution for a particular case, is the cost of diesel.

The below mentioned sensitivity analysis is done against the price of a liter of diesel.

Figure 10-1 and Figure 10-2 in page 55 and page 55 provides the sensitivity analysis pertaining to the conditions of Test case 9 when the price of 1 liter of diesel is 1 $ and 0 $ respectively. When the result is observed, it is self-explanatory that at any price of diesel, the proposed concept is commercially viable under Test case 9.

Proposed Concept

	Capex ($)	Operated Time (Hours)	Opex ($)	Installed Capacity (kW)	Electricity Generated	Annual Fuel Consumption (kg/Yr)
Solar PV	20,000	4371	30	30	48,054	
Fuel Cell	5,500	4447	445	1	2,248	899
Hydrogen Storage	180		30	30		
Converter	600		40	1	-	
Electrolyzer	15,000		40	20	(40,455)	
Diesel Generator	2,000	106	612	4	195	

Site Power Load (kW)	0.5
Telecom Energy Consumption (kWh/Yr)	(4,380)
Comparrison	Output of Model
Total Generation (kWh/Yr)	50,496
Total Consumption (kWh/Yr)	(44,835)
Excess Electricity Generated (kWh/Yr)	5,661
Total Capex - Net Present ($)	43,280
Total Capex - Annualized ($)	3,547
Total O&M	1,197
Fuel Cost	97
Total OPEX	1,294
Total Annual Cost ($) (Option 1)	4,841

Sensitivity Test		
Fuel Cost	1	$/L

Traditional - Configuration

	Capex ($)	Operated Time (Hours)	Opex ($)	Installed Capacity (kW)	Electricity Generated
Solar PV	2,000	4368	102	2	3,262
	-			0	-
Battery - LiFePO4	3,000		-	0.6	-
Diesel Generator	8,000	2190	4,480	10	3,285

Site Power Load (kW)	0.5
Telecom Energy Consumption (kWh/Yr)	(4,380)
	Output of Model
Total Generation (kWh/Yr)	6,547
Total Consumption (kWh/Yr)	(4,380)
Excess Electricity Generated (kWh/Yr)	2,167
Total Capex - Net Present ($)	13,000
Total Capex - Annualized ($)	2,900
Total O&M	4,582
Fuel Cost	2,002
Total OPEX	6,584
Total Annual Cost ($) (Option 2)	9,484

Decision	Description	Value	Unit
Generation	Excess Electricity Generated under Proposed Concept	5,661	kWh/yr
Financial	Total Annual Cost of Proposed Concept	4,841	$
	Total Annual Cost of Existing Traditional Method	9,484	$

Figure 10-1 Sensitivity - Test case 9 - 1$

Proposed Concept

	Capex ($)	Operated Time (Hours)	Opex ($)	Installed Capacity (kW)	Electricity Generated	Annual Fuel Consumption (kg/Yr)
Solar PV	20,000	4371	30	30	48,054	
Fuel Cell	5,500	4447	445	1	2,248	899
Hydrogen Storage	180		30	30		
Converter	600		40	1	-	
Electrolyzer	15,000		40	20	(40,455)	
Diesel Generator	2,000	106	612	4	195	

Site Power Load (kW)	0.5
Telecom Energy Consumption (kWh/Yr)	(4,380)
Comparrison	Output of Model
Total Generation (kWh/Yr)	50,496
Total Consumption (kWh/Yr)	(44,835)
Excess Electricity Generated (kWh/Yr)	5,661
Total Capex - Net Present ($)	43,280
Total Capex - Annualized ($)	3,547
Total O&M	1,197
Fuel Cost	-
Total OPEX	1,197
Total Annual Cost ($) (Option 1)	4,744

Sensitivity Test		
Fuel Cost	0	$/L

Traditional - Configuration

	Capex ($)	Operated Time (Hours)	Opex ($)	Installed Capacity (kW)	Electricity Generated
Solar PV	2,000	4368	102	2	3,262
	-			0	-
Battery - LiFePO4	3,000		-	0.6	-
Diesel Generator	8,000	2190	4,480	10	3,285

Site Power Load (kW)	0.5
Telecom Energy Consumption (kWh/Yr)	(4,380)
	Output of Model
Total Generation (kWh/Yr)	6,547
Total Consumption (kWh/Yr)	(4,380)
Excess Electricity Generated (kWh/Yr)	2,167
Total Capex - Net Present ($)	13,000
Total Capex - Annualized ($)	2,900
Total O&M	4,582
Fuel Cost	-
Total OPEX	4,582
Total Annual Cost ($) (Option 2)	7,482

Decision	Description	Value	Unit
Generation	Excess Electricity Generated under Proposed Concept	5,661	kWh/yr
Financial	Total Annual Cost of Proposed Concept	4,744	$
	Total Annual Cost of Existing Traditional Method	7,482	$

Figure 10-2 Sensitivity - Test case 9 - 0$

11 CONCLUSION

The concept was proposed to produce and store Hydrogen gas through the process of electrolyzing of water using the harvested solar energy to provide an un-interruptible power supply for telecommunication base station sites in Sri Lanka. The network operated by Dialog Axiata PLC was selected to carry out the research study as it owns the highest number of base stations among all of the Sri Lankan operators with the widest spread all over the island.

The concept can be confirmed as viable based on the results obtained against 9 test cases with entirely different scenarios.

The economic viability of the proposed concept was achieved through various improvements introduced through the concept over the traditional approach of designing the solar PV system for a base station site.

1. The traditional concept of employing a battery bank setting to run full deep discharging cycles can be completely omitted with the introduction of proposed concept. This was explained in Generation of test cases in page 25.
2. The rating of the diesel generator can be substantially optimized under scenarios of all the test cases when compared against the traditional composition of components used as at present. Refer to 7 Testing of technical viability against the test cases.
3. For some of the scenarios, the diesel generator can be completely omitted in the design and hence in the investment. Refer Figure 9-2.

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