DESIGN OF AN OPTIMUM POWER SOLUTION FOR TELECOM BASE STATION SITES

Gayathri Maheshika Amarakoon

(128851P)

Degree of Master of Science In Electrical Engineering.

Department of Electrical Engineering

University of Moratuwa
Sri Lanka

May 2016

DESIGN OF AN OPTIMUM POWER SOLUTION FOR TELECOM BASE STATION SITES

Gayathri Maheshika Amarakoon

(128851P)

Thesis/Dissertation submitted in partial fulfillment of the requirements for the degree Master of Science in Electrical Engineering.

Department of Electrical Engineering

University of Moratuwa
Sri Lanka

May 2016

DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief, it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my thesis, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature: Date:

………………………..
Gayathri M. Amarakoon

The above candidate has carried out research for the Masters thesis under my supervision.

Signature of the supervisor: Date:

………………………..
Dr. Asanka S. Rodrigo

ABSTRACT

The amount of power required to operate the telecom network is getting much higher depending on the size of the system deployed at the base stations. This may exceed a couple of kilowatts, occurring a high electrical and diesel cost. Considering the high operational and environmental cost of diesel generators and back-up batteries, major issues of power supplies such as cost effectiveness, energy efficiency etc. need to be addressed in optimum manner. This report is a comprehensive effort to identify the optimum way of providing grid power and the backup power for the telecom base stations. A user simulation model is proposed which result in the optimum power integration model with the best combination of battery backup, solar PV and diesel generator, that determines the optimal capital and operational cost for an on-grid site to give load, type and environmental factors. The techno economical feasibility is done for 6 nos of configurations and yields detailed graphical dashboard which enables the user to correlate the state of load, the power source combination and their conditions.

ACKNOWLEDGEMENT

First and foremost, I would like to express my sincere gratitude to my advisor Dr. W. D. Asanka S. Rodrigo, Senior Lecturer from Electrical Engineering Department at University of Moratuwa for the continuous support of my M.Sc. Study and research, for his patience, motivation, enthusiasm, and immense knowledge. Besides my advisor, I would like to thank the rest of the lecturers from Electrical Engineering Department at University of Moratuwa for their encouragement, insightful comments, and hard questions in progress reviews.

This research was supported by Dialog Axiata PLC. I thank the Head and my peers from Energy Management Division of Dialog who provided insight and expertise that greatly assisted in this research even with a massive workload and a special gratitude to Kasun Wijesinghe former MSc in Electrical Installations from University of Moratuwa as well as my office colleague for proving me the resource and a valuable knowledge in technical calculations and also with industrial references.

Last but not the least; I would like to convey my sincere gratitude to my spouse, parents and family members helping me in numerous ways to help achieving my targets all the time.

TABLE OF CONTENT

LIST OF FIGURES

Page

LIST OF TABLES

Page

LIST OF ABBREVIATIONS

Abbreviation	Description
RBS	Radio Base Station
GP1	General Purpose 1
DAP	Dialog Axiata PLC
PV	Photovoltaic
Li Ion	Lithium Ion
UPS	Uninterrupted Power Supply
CO2	Carbon Dioxide
Ni-Cd	Nickel Cadmium
VRLA	Valve Regulated Lead Acid
BTS	Base Transceiver Station
ATS	Automatic Transfer Switch
DG	Diesel Generator
AC	Alternative Current
DC	Direct Current
AGM	Absorbent Glass Mat
EC	Ethylene Carbonate
DMC	Dimethyl Carbonate
FCB	Free Cooling Box
DoD	Depth of Discharge
ID	Indoor
OD	Outdoor

CPH	Consumption Per Hour
CEB	Ceylon Electricity Board
O & M	Operation & Maintenance
TCO	Total Cost of Ownership
NPV	Net Present Value
RMS	Remote Monitoring System

CHAPTER 1

Introduction

1.1 Background

The mobile telecom sector is one of the fastest growing industries in Sri Lanka today. Telecom Radio Base Station (RBS) sites are mostly constructed as green field self-support towers, roof top sites with towers & mono pole structures, indoor base stations, etc. Irrespective of site infrastructure, these networks need to assure power supply either from grid power or backup power. Depending on the deployed systems, the power requirement varies at each RBS site.

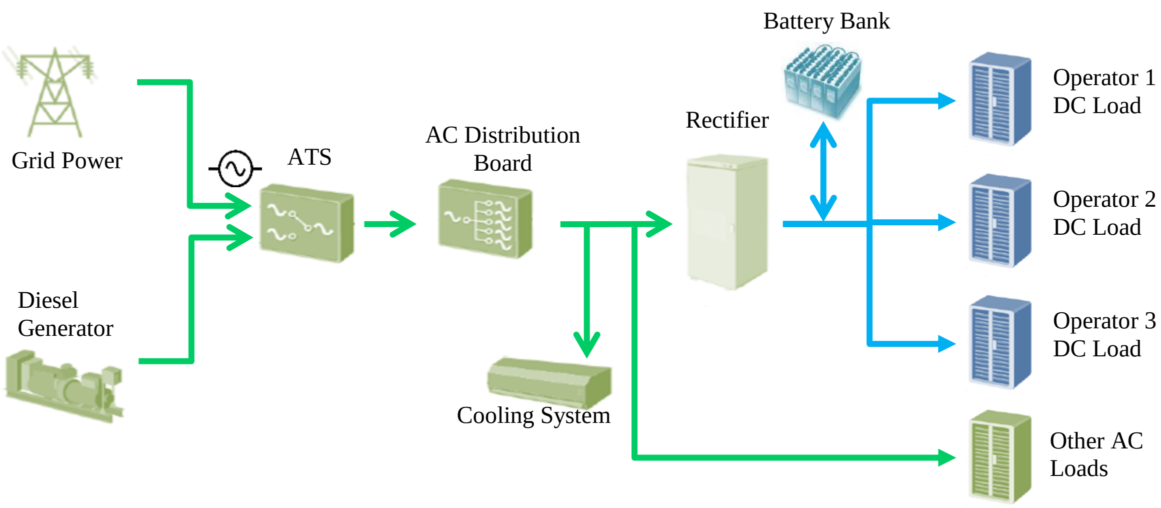


Figure 1.1: Basic power components in RBS site

Primary power sources of radio base station sites are grid power, a battery backup and a diesel generator. Nearly 98.64% of 2282 on-air RBS sites (as end of August 2014) that are operated by Dialog Axiata PLC (DAP) are grid powered with the grid availability over 23.54 hours per day [1]. In Sri Lankan, most of these telecom base stations are coming under the General Purpose (GP1) tariff structure, also have a few sites under domestic (D1) tariff structure and owner imposed tariff rates especially for sites establish for indoor building coverage.

In order to provide an uninterrupted service, all the on-grid sites have equipped with a battery backup. At the same time, diesel generators are used together with the battery backup for more than 1200 sites. Thus, most of Dialog RBS sites are powered by a combination of supply from the grid, batteries and diesel generators.

Also, renewable sources like solar and wind power have already harnessed on the off-grid sites. Furthermore, feasibility studies have carried out on the possibility of solar integration into the on-grid RBS sites.

1.2 Problem Statement

Operating a telecom network is getting more expensive due to increasing of energy cost; both electricity price and fuel price. Also the capacity of the backup power requires to be increased where the grid availability is poor, especially in rural areas. The company consumes more than 1.5 million liters of diesel per year and has spent Rs. 106.6 million as average monthly electricity cost in 2014 [1]. Approximately total electricity and fuel cost is 23-27% of total network Opex. Furthermore, pilferage of diesel has become a problem; hence the exact consumption cannot be measured and this adds significant cost to total diesel amount.

Considering the high operational and environmental cost of diesel generators and back-up batteries, major issues of power supplies such as cost effectiveness, energy efficiency and reliability need to be addressed in optimum manner.

1.3 Objective

The main objective of this research is to obtain the optimum power integration model with the best combination of battery backup, solar PV and diesel generator, that determines the optimal capital and operational cost for an on-grid site with given load, type and environmental factors. Thus the operator can track and analyze the optimality of their power arrangement if the pre-define inputs change.

1.4 Methodology

This study focus on the grid connected Radio Base Stations that belongs to Dialog Axiata PLC, almost around 2250 numbers. These sites can be categorized according to site location, applicable tariff category, tenancy count and load profile. Various configurations of backup power integration will be considered and analyzed for each category and the cost of backup power can be evaluated.

A mathematical model that can receive inputs of pre-defined parameters will be developed to obtain the optimum power integration and will further improve to a user simulation interface. The model will follow technical sizing of the solution, financial projection and optimization before presenting the output.

The developed model will be further improved into a user simulation interface where the user can run the model himself.

CHAPTER 2

Literature Review

Being one of the fastest growing industries around the world with an exponential growth rate, telecommunication network has changed the way people live and work. Thus the challenge to provide reliable and cost effective power solutions to these expanding networks is vital for telecom operators. This chapter presents a review of the literature concerning the various approaches for powering the telecom base station sites.

It was predicted 75,000 new off-grid telecom base stations to be built in developing countries in 2012 and the wireless market to grow about 7–10% every year for the next five years [2]. This growth can be expected to be accelerated in forthcoming years, facing a challenge to provide an uninterrupted coverage throughout the country.

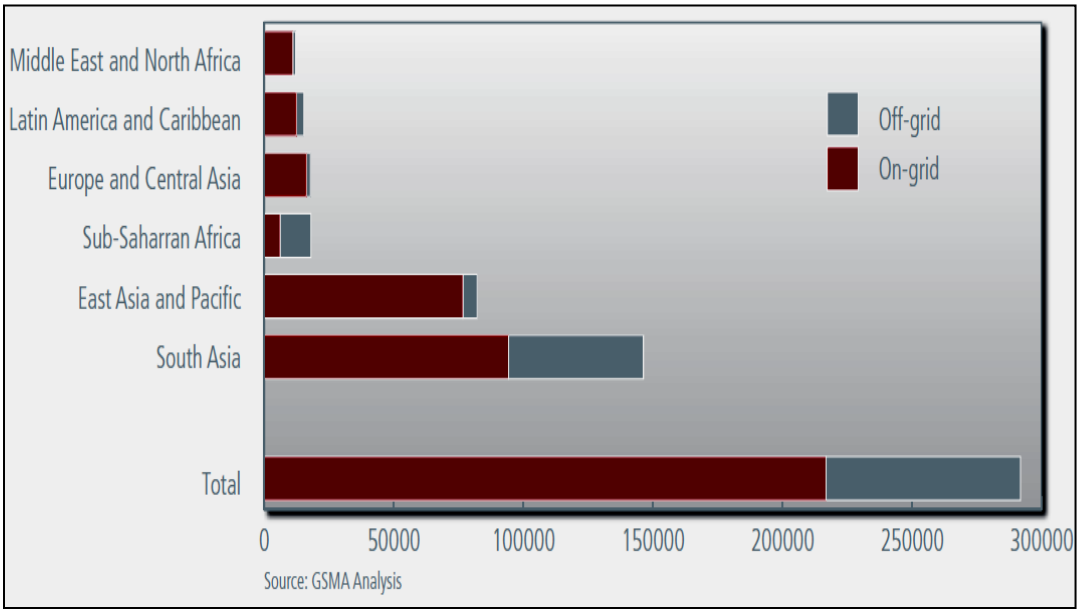


Figure 2.1: Annual growth in base transceiver station sites in developing regions over the period 2007–2012 (Source: GSMA Analysis)

Telecom networks consume a huge amount of energy for data delivery. According to the recent researches, telecommunication sector utilizes approximately 4% of the global electricity consumption [3]. Thus, it is important to have a way of identifying the optimum power integration approach for a telecom base station site resulting optimal capital and operational cost. A proper, effective literature study is worthy to recognize the methodologies and approaches that have used currently to power up sites.

Several researchers have identified various approaches of powering up off-grid telecom base stations where the gird power is impossible to connect. There is a high feasibility of using renewable energy sources such as wind, solar, biomass to provide electricity to telecommunication base stations, where the grid extension is not feasible or economical. According to GSMA data, the target is to power up 18.5% of off-grid BTS sites across the world by renewable energy sources [4].

The study by Arthur D. Sams (2011) highlights the importance of implementing the DC hybrid solution for off-grid BTS sites, integration with the optimal operation of DC generator, Solar Photovoltaic, DC air conditioning, Li Ion batteries and Lead acid batteries [4]. The expectation is to reduce the fuel consumption by 30 to 70% and reduce the overall carbon footprint by half. Also the author has briefly discussed the possibility of using Hydrogen fuel cells as a future technology to back up the utility grid at sites where disruption of power is very rare.

Qiguo Han (2007) focused on having telecom power solutions based on reliability analysis. Different reliability models are created for system equipment as well as different function styles that used in sites including commercial AC mains model, stand-by diesel generator model, AC busbar and switchgear, DC power and battery backup system, UPS system and other AC loads [5]. By studying the alternative system solutions based on these reliable models, the result shows that a single busbar system could be a weak point and a special designed busbar system is required in order to achieve the reliability of a data-telecom site. But the author has not taken economic comparison in the study, has compared only estimated costs between alternatives.

Considering a contrary situation to a traditional telecom site conditions, Alexis and Krein (2006) present a systematic micro grid based telecom power system configuration analysis with 156 V main DC bus voltage [6]. The study compares several configurations using a value function that includes several site characteristics, such as cost, availability, flexibility, etc. Different types of sites such as small tx sites, TX node/hub are considered and compared micro grid value function outcome with a traditional site. The authors suggested focusing on safety standards and protection design of micro grid based telecom system which they have not presented in this study.

The foremost focus of the recent researches is on the off-grid telecom sites targeting to reduce the Opex cost of the site. According to the research done by Brunarie, Myerscough, Nystrom and Ronsen (2009), deployment of hybrid power system with a diesel generator with a cyclic battery operation for off-grid sites can reduce operating cost for fuel and maintenance by up to 66%, while decreasing the CO_2 emission in the same range [7]. The test result provided for the addition of Ni-Cd battery as the primary source is overall a better solution than the use of tubular gel or VRLA technology, expecting an Opex cost reduction by 50% to 85% and carbon footprint reduction by an average of >60%.

Feasibility of integrating renewables, especially wind and solar, required to be more focused in the literature review in order to determine the optimum methodology of integration.

The importance of maintaining accurate battery thresholds that leads to the lower kWh cost in PV-hybrid system configuration for an off-grid sites is highlighted in the study done by Muselli, Notton, Poggi and Louche (2000). Simulation calculations have used to determine the optimum configuration of the starting threshold (SDM=30%) and the stopping threshold (SAR=70%) of generator as part of nominal storage capacity [8].

Kellogg, Nehrir, Venkataramanan and Gerez (1998) developed an algorithm to determine the optimal capacity and storage for standalone wind, PV and hybrid wind/PV system considering the load profile of a typical resident [9]. The methodology used for sizing, wind/PV generation will be applicable for telecom site load profile and can be integrate when there is a grid. Total cost per year has calculated for all three configuration considering the capital cost, installation cost and maintenance cost.

The very recent study has carried out to determine the technical and economic feasibility of integrating solar PV into the grid connected telecommunication base station sites at Dialog Axiata PLC [10]. The study concludes that solar PV energy integration directly on to the DC bus (96% or more efficient) is much more financially beneficial than integrating it into the A/C bus through Grid tie inverter for Net Metering for telecom applications. Furthermore, it is identified that higher capacity solar PV systems will pay back much faster than lower capacity Solar PV installations. Also, there is a possibility of replacing the conventional standby diesel generator set by Solar PV backup with adequate battery backup.

CHAPTER 3

Research Design

3.1 Site Categorization

Grid connected Radio Base Station sites belongs to Dialog Axiata PLC which are scattered island wide among 9 operational regions, have categorized under several sorts in order to identify their current arrangements and configurations.

3.1.1 Site categorization according to the applicable tariffs

Monthly electricity usage costs of most telecom base stations are calculated under the category General Purpose category 1 (GP1) where a unit cost would be around Rs.22.85/kWh with a fixed charge of Rs.240/month at present.

Grid connected 2251 nos of sites are categorized to their applicable tariff categories are shown in Table 3.1.

Table 3.1 : Site categorization according to the applicable tariff categories

				Applicable Tariff Categories		
	Region	Site Count	Grid Connected Sites	D1	GP 1	GP 2
1	Western Central	715	714	50	655	9
2	Western North	261	260	15	243	2
3	Western South	96	95	5	89	1
4	North Western	232	232	14	216	2
5	Southern	193	190	11	175	4
6	Central	251	241	13	220	8
7	North Central	103	103	8	92	3
8	Eastern	135	135	8	125	2
9	Northern	146	133	2	131	0
10	Uva	150	148	1	141	6
	Sub Total	**2282**	**2251**	**127**	**2087**	**37**

Also, some sites fall under the domestic tariff rate (applicable to households) and it would become an average unit cost of Rs.45/kWh with a fixed charge of Rs.540/month for consumptions around 1500 units per month, since average 2 kW constant loads are available in most telecom sites. Furthermore, there are 37 nos of RBS sites having General purpose category 2 (GP2) where the DC load is higher than typical site.

3.1.2 Site categorization according to the power loading

DAP owned 2282 nos of sites that are distributed among 10 regions are categorized according to their power loading levels are shown in Table 3.2.

Table 3.2 : Site categorization according to the power loading

			Power Loadings		
	Region	Site Count	0< Low <2kW	2 kW< Medium <4 kW	4kW <High<
1	Western Central	715	409	253	53
2	Western North	261	181	66	14
3	Western South	96	30	43	23
4	North Western	232	129	76	27
5	Southern	193	74	79	40
6	Central	251	115	97	39
7	North Central	103	67	26	10
8	Eastern	135	54	69	12
9	Northern	146	87	48	11
10	Uva	150	85	48	17
	Sub Total	**2282**			

3.2 Loads at Radio Base Station Site

In order to provide an uninterrupted telecom service, ensuring reliable connectivity, it is required to be powered up RBS sites 24×7 three-sixty-five days a year without any disruption.

RBS site can be either an indoor site or an outdoor site depending on the location where the BTS (Base Transceiver Station) equipment is fixed.

For an indoor site, electronics are in a shelter or in a cabin near the tower and these are designed to operate at the maximum of 35 to 45 ^{o}C [11], thus the cooling mechanism is required to lower the temperature. Further, the power equipment such as batteries, rectifiers, ATS panel is placed inside the shelter except the backup generator. Typically the cabin temperature will affect the battery lifetime as well.

At present, new sites build as outdoor sites where the electronics and the power equipment are outdoors at the base of the tower. As the batteries need to operate typically at 27 – 30 ^{o}C, they are fixed in a battery cooler / chiller and the shelters are avoided.

Telecom equipment is designed to operate at 48V DC as its power input. Rectifiers are used to convert AC voltage (either from grid or diesel generator) to 48V DC.

Energy loads at the RBS site can be listed as below.

<u>BTS Equipment Load:</u>

BTS and transmission load which consider as active loads may vary depend on the deployed technology type (2G only, 2G+3G etc.) at the site. Generally BTS load profile is assumed to be a constant, considering very slight changes over the day.

Average site loading of the site corresponding to the installed technology type is shown in Figure 3.1.

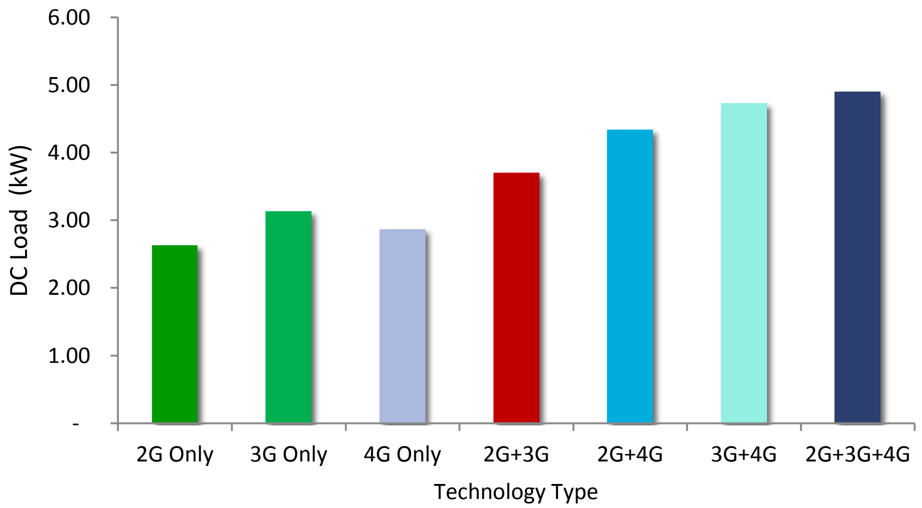


Figure 3.1: Average site load / site

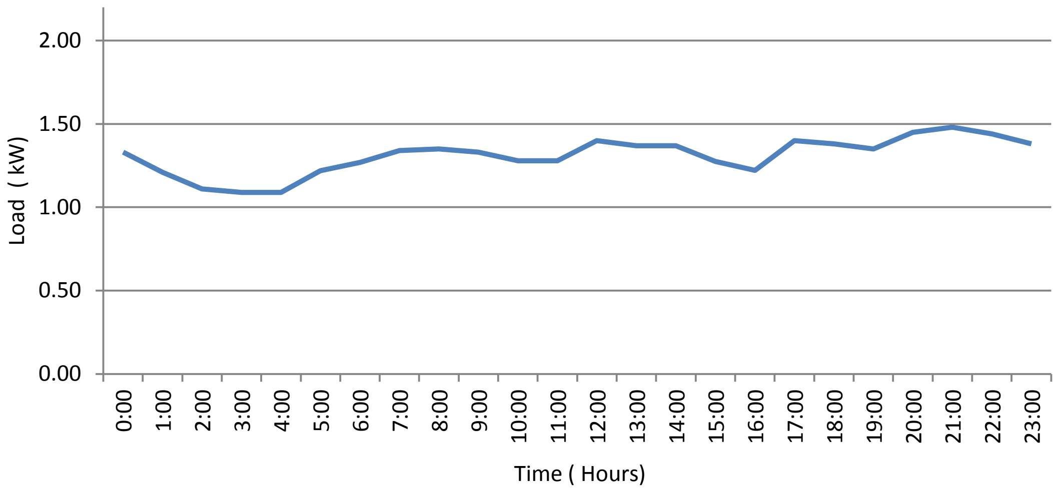


Figure 3.2: Measured load profile of Narahenpita East site on 16 Aug 2013

Cooling Load:

This considers the energy consuming by the cooling equipment which use to remove the heat from the shelter in order to maintain the required temperature condition for BTS electronics. Deployed cooling solution (i.e. Non inverter / inverter air conditioners, free cooling systems, heat exchanges, DC fans, etc.) can vary according to the environmental climate conditions of the site location area and BTS type (indoor or outdoor), thus the power consumption varies.

Other Miscellaneous Loads:

This includes additional loads as lights in a shelter which typically consume less power (60 – 100W). Also it is required to consider the battery charging current at the time of batteries are being charged.

3.3 Energy Sources at Radio Base Station Site

The primary energy sources of radio base station sites are grid power, a battery backup and a diesel generator. Also, renewable sources like solar and wind power have already harnessed on the off-grid sites of the company. Furthermore, feasibility studies have carried out on the possibility of solar integration into the on-grid RBS sites.

3.3.1 Grid Power

Grid power availability is particular to the site depending on the specific location within the country. Nearly 98.64% of 2282 on-air RBS sites (as end of August 2014) that are operated by Dialog Axiata PLC (DAP) are grid powered with the grid availability over 23.54 hours per day [1].

In Sri Lanka, most of these telecom base stations are comes under the General Purpose (GP1) tariff structure, also have few sites under domestic (D1) tariff structure and owner imposed tariff rates specially for sites establish for indoor building coverage.

3.3.2 Diesel Generator (DG)

In order to provide an uninterrupted service, all the on-grid sites have equipped with a battery backup. Once the battery discharges to a defined level to cater the site load, diesel generator is turned ON and supplies the power to cater the site load and to charge the batteries as well. At the same time, generators are used as back up, in the event of unavailability of all other power sources at the base station site.

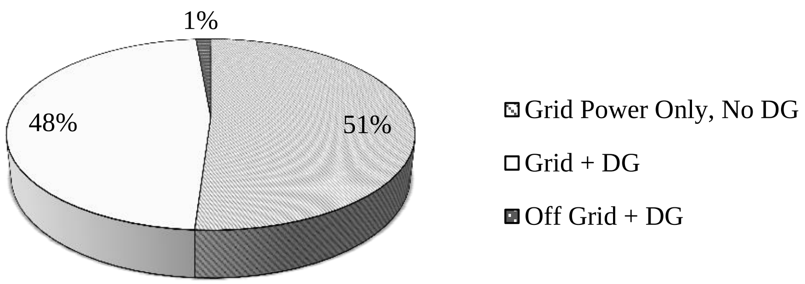


Figure 3.3: Usage of Diesel Generators in Dialog RBS Sites

Diesel generators have installed together with the battery backup for more than 1200 Dialog RBS sites. For the sites where no generator has installed, portable generators are used when the power demand cannot drive from other sources.

During the selection and sizing of generators, it is required to consider the following factors.

- Load profile of the site and maximum load which is to be catered with the generator.

It is required to consider all the possible loads such as BTS & TX equipment loads, cooling system loads and all possible inrush loads such as air conditioner starting and battery charging loads.

- Expected operational duty of the generator

Generator ratings are defined based on its operational duty and accordingly two rating categories; standby and prime power.

There are two kinds of diesel generators; Alternative Current (AC) generator and Direct Current (DC) generators. All of the generators used in Dialog network are conventional AC generators where AC power is converted to DC power using rectifiers before supplying to the batteries or telecom equipment. Depending on the loading percentage of the generator, the fuel consumption varies.

3.3.3 Battery

Batteries are used in radio base station sites as backup to ensure an uninterrupted function of the site during grid power failure. In the early days, Valve Regulated Lead Acid (VRLA) battery technologies such as Tubular Gel (OPzV) batteries and Absorbent Glass Mat (AGM) batteries have predominantly used in RBS sites due to lower price and availability and currently transferring to Lithium Ion batteries due to their high performance.

The battery capacity to be used in a base station depends on several factors such as grid quality, criticality, accessibility, agreed up time for the sharing operators and generator availability at the considered base station etc.

When determining the backup time for the off-grid sites, it is required to consider the configuration in which the particular site has been planned to operate, i.e. full time generator, generator/ battery cyclic, renewable energy.

Table 3.3 : Specifications of Battery Technologies

Item Description	**Tubular Gel VRLA (OPzV)**	**AGM VRLA**	**Li-Ion**
Electrolyte	Sulfuric acid, immobilized as Gel	Sulfuric acid, absorbed in glass matted fiber	LiPF6 in ethylene carbonate (EC)/dimethyl carbonate (DMC)
Voltage (Bank)	48V (nominal)	48V (nominal)	48V (nominal)
Cell voltage	2V (Nominal)	2V, 6V, 12V	3.2V
Designed lifetime	>15 years at 20ºC	>10 years at 20ºC	>20 years at 20° C
Cyclic life (@80% DoD & 20° C)	900	1000	5000
Recommended charge rate	0.25 C	0.25 C	0.5C
Working temp. range	-20°C to 30°C	-20°C to 30°C	-20°C to 60°C
Battery efficiency (%)	85	80	96

3.3.4 Solar

As a tropical country, Sri Lanka has a higher capability of deploying solar PV in RBS sites in most areas as the number of daylight hours are high compared to the countries away from the equator.

Renewable sources like solar and wind power have already harnessed together with diesel generators to power up the off-grid sites. These projects are economically viable & payback soon rather than an extension of grid for most of the time. Furthermore, feasibility studies have carried out on the possibility of solar integration into the on-grid RBS sites.

One of the main limitations to deploy solar is the unavailability of sufficient space in RBS sites in Sri Lanka. Thus, for the most of the sites, the space is not adequate to cater the total site load by solar.

Currently, DAP has 15 nos of off-grid sites where solar PV has installed, but none is capable to run the total site load by only solar.

Table 3.4: Currently Installed Solar Capacity Vs Site Full Load

Site ID	Sites	Region	Required Solar Capacity to cater full site load (kW)	Installed Solar PV capacity (kWp)
NU0011	Pattipola Dialog	Central	12.4	4.1
JA0093	Chawakachcheri South	North	7.3	4.1
MU0038	Chalai Dialog	Northern	9.3	4.1
MU0030	Mundimuruppu Dialog	Northern	11.7	4.5
MA0009	Palampiddy Dialog	North Central	18.1	4.5
VA0022	Maruthodai Dialog	Northern	8.9	4.5
KA0106	Malwattagama Dialog	Central	7.8	4.5
VA0060	Putuvilankulam Dialog	North	5.6	2.6
VA0045	Vedivaittakallu Dialog	Northern	14.9	4.5
VA0048	Semamadu Dialog	Northern	12.4	5.6
CM0501	Kadugoda Dialog	WC	6.5	4.5
NU0084	Dimbula Mobitel	Central	17.3	3.0
NU0032	Randenigala Dialog	Central	24.4	6.3
GA0020	Kahaduwa Dialog	Southern	22.2	4.2
KE0053	Paththampitiya Dialog	Central	9.9	4.2

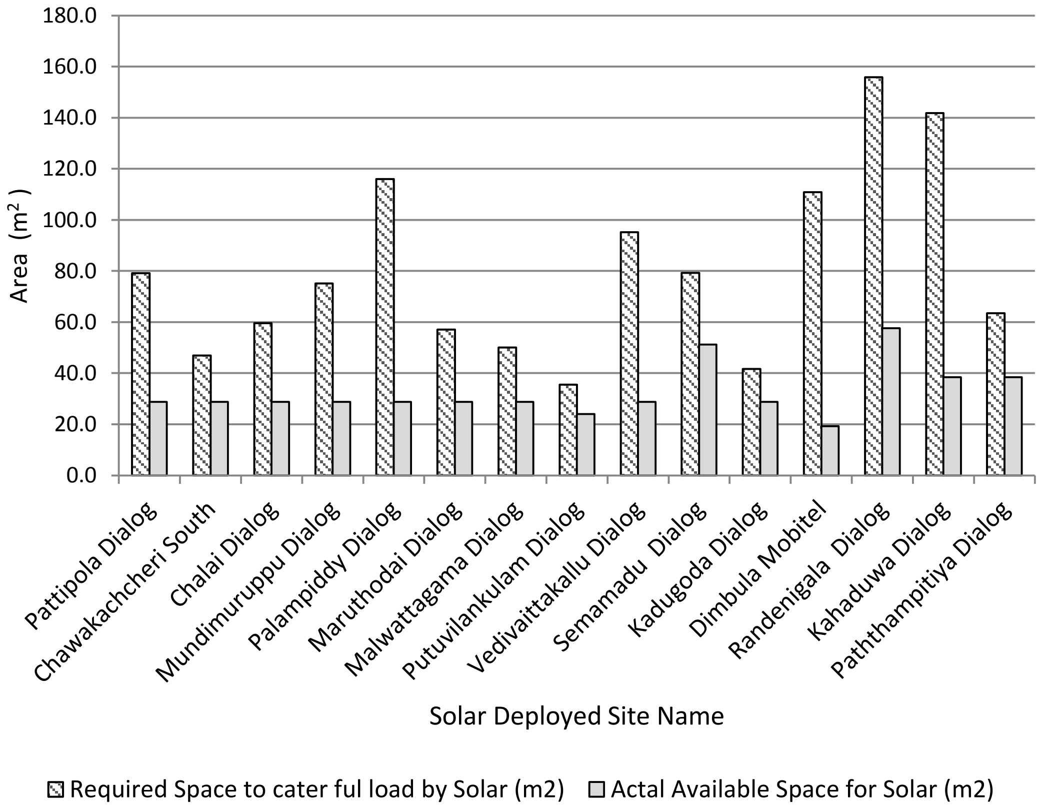


Figure 3.4: Actual Space Availability vs Required Space for Solar

Proposed Simulation Model for Energy Options for BTS Sites

4.1 Purpose of the Model

The simulation model obtains the optimum power solution with the best combination of battery backup, diesel generator and solar PV, that determines the optimal capital & operational cost for an on-grid site with given load, type and environmental factors.

This model has been developed as it can be used either for on-operational site or for a newly constructing site to determine the best way of powering the BTS site. As the power equipment has already installed in an on-operational site, the model can use to find the optimum operational process with existing equipment. For a newly constructing site, the simulation model can develop and identify the best combination of power equipment according to the known inputs that can be chosen to install on the site.

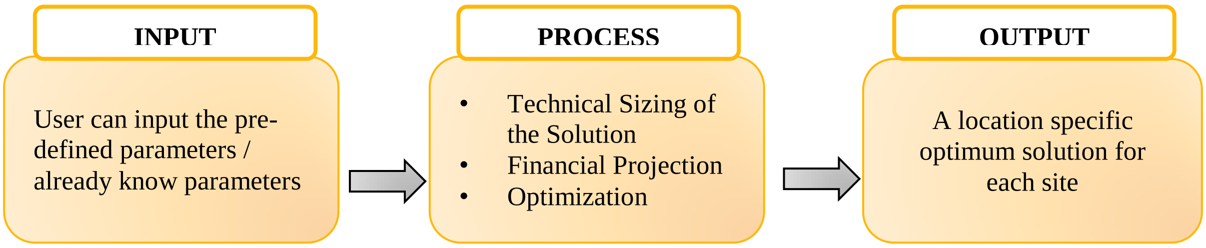


Figure 4.1: The Methodology Carried Out by the Simulation Model

4.2 Input to the Model

The simulation model ensures that all the calculations and the dependencies for calculation processors are considered depending on the inputs that has provided by the user.

Depending on the specific location is an already on-operation site or newly constructing site, the inputs varies.

4.2.1 Input for a New Site Model

User Inputs					
BTS Type	Indoor				
District	Colombo				
Peak DC Load	1.5	kW	Average DC Load Factor	80	%
Peak Cooling Load	1.1	kW	Average AC Load Factor	60	%
Grid Availability	23.0	Hours			
Rectifier Efficiency	92	%			
Inverter Efficiency	95	%			
Open Space Available	10	m^2			
Duration of Direct Sunlight		Hours / Day			

Figure 4.2: Interface for User Input for a New Site

BTS Type : This allows the user to choose between indoor and outdoor type BTS, which impacts both the air conditioner load on the site as well as the lifetime of the batteries installed on the site.

District : Depending on the selected district where the site is located, Maximum radiation incident on an equator-pointed tilted (8^0) surface (kWh/m^2/day) for solar integration is calculated from the pre-defined data.

Peak DC Load : This allows the user to enter custom values of the peak DC load on the site.

Peak Cooling Load : This allows the user to enter custom values of the peak load required for cooling configuration (inverter air con, free cooling box, DC fan etc.) on the site

Average DC/ AC Load Factor : This allows the user to enter custom values of the peak to average load factor on the site.

Grid Availability: User can define the grid availability of the site, thus calculate the hours of backup required

Rectifier Efficiency: This allows the user to enter the manufacturing values for the efficiency of the rectifiers that are installed at the site.

Inverter Efficiency: This allows the user to enter the manufacturing values for the efficiency of the inverters that are installed at the site.

Open Space Available : This parameter acts as limitations on the implementation of solar systems on the site. This allows to user to enter the space availability of the chosen site in order to calculate the possibility of integrating solar in to the site.

Duration of Direct Sunlight : User can enter the direct sunlight hours to the specific location. If left blank, it will consider as 50% of the averaged daylight hours for particular district taken from NASA Surface Meteorology and Solar Energy website

4.2.2 Input for an On-Operational Site Model

Other than the inputs filled for a new site, there are a few more items to be filled the user for an on-operational site as the power equipment has already installed and is functioning.

User Inputs

Site Type	Access				
BTS Type	Outdoor				
District	Ratnapura				
Peak DC Load	2.0	kW	Average DC Load Factor	80	%
Peak Cooling Load	0.1	kW	Average AC Load Factor	60	%
Grid Availability	-	Hours			
Rectifier Efficiency	92	%			
Inverter Efficiency	95	%			
Diesel Generator Capacity	8.0	kVA			
Battery Type	VRLA AGM				
Battery Bank Capacity	300	Ah			
Cooling Mechanism					
Open Space Available		m^2			
Solar Capacity if already installed		kW			
Duration of Direct Sunlight		Hours / Day			

Figure 4.3 : Interface for User Input for Already On-Operational Site

Site Type : This allows to user to select the type of the selected site out of Access, Tx Node, Core & Other from a drop-down. Depending on the site type, normalized load profile of the site varies.

Diesel Generator Capacity : User can enter the generator kVA rating installed at the site. If left blank, it will consider as no generator installed at the site.

Battery Type & Capacity : This allows the user to enter the installed battery type & it's AH capacity at the site which effects to calculate the possible running hours from the battery.

Cooling Mechanism : User can select the cooling method installed at the site among air conditioner / FCB or air conditioner +FCB. If left blank, it is considered as none of cooling mechanism has installed at the site.

Solar Capacity Installed : If the solar system has already deployed at the site, user can enter the solar capacity here.

4.3 Working of the Model

The model follows three key steps before presenting the output:

1. Technical Sizing of the Solution
2. Financial Projection
3. Optimization

4.3.1 Technical Sizing of the Solution

The designed model collects the various inputs given above by the user and sizes the solution for the site based on the following technologies:

- VRLA (AGM) Batteries (+ DG)
- Li Ion Batteries (+ DG)
- OPzV (T Gel VRLA) Batteries (+ DG)
- Solar + VRLA (AGM) Batteries (+ DG)
- Solar + Li Ion Batteries (+ DG)
- Solar + OPzV (T Gel VRLA) Batteries (+ DG)

The sizing is based on the load, grid availability, space availability, as well as the technical characteristics of each individual technology.

4.3.2 Financial Projection

Once each solution has been sized, the costs are projected over a twenty year period. The costs can be divided into the following components:

- Initial Capex – This is dependent on the sizing of the solution.
- Replacement Capex – This is determined by various usage based intervals, quantified during system sizing.
- Maintenance Costs – This is determined by both fixed as well as usage based intervals quantified during sizing.
- Grid / Fuel Costs – This is determined by both actual consumption as well as system sizing.

The projection is used to finally arrive for the optimum power combination model at the Total Cost of Ownership for each system.

User has the option to select the final outcome solution based on the site specific crucial factors such as initial capex for total solution, energy cost / month, opex / month, replacement capex / month etc.

4.3.3 Optimization

Each solution is then optimized for the lowest Total Cost of Ownership based on variations in the following parameters:

- DG Size / Grid Line Capacity (affects maximum current)
- Battery Depth of Discharge (affects lifetime and capacity)
- Site Availability / Up time

4.3.4 Algorithms

Below are the algorithms that follow the model for the outcome of the site specific final solution.

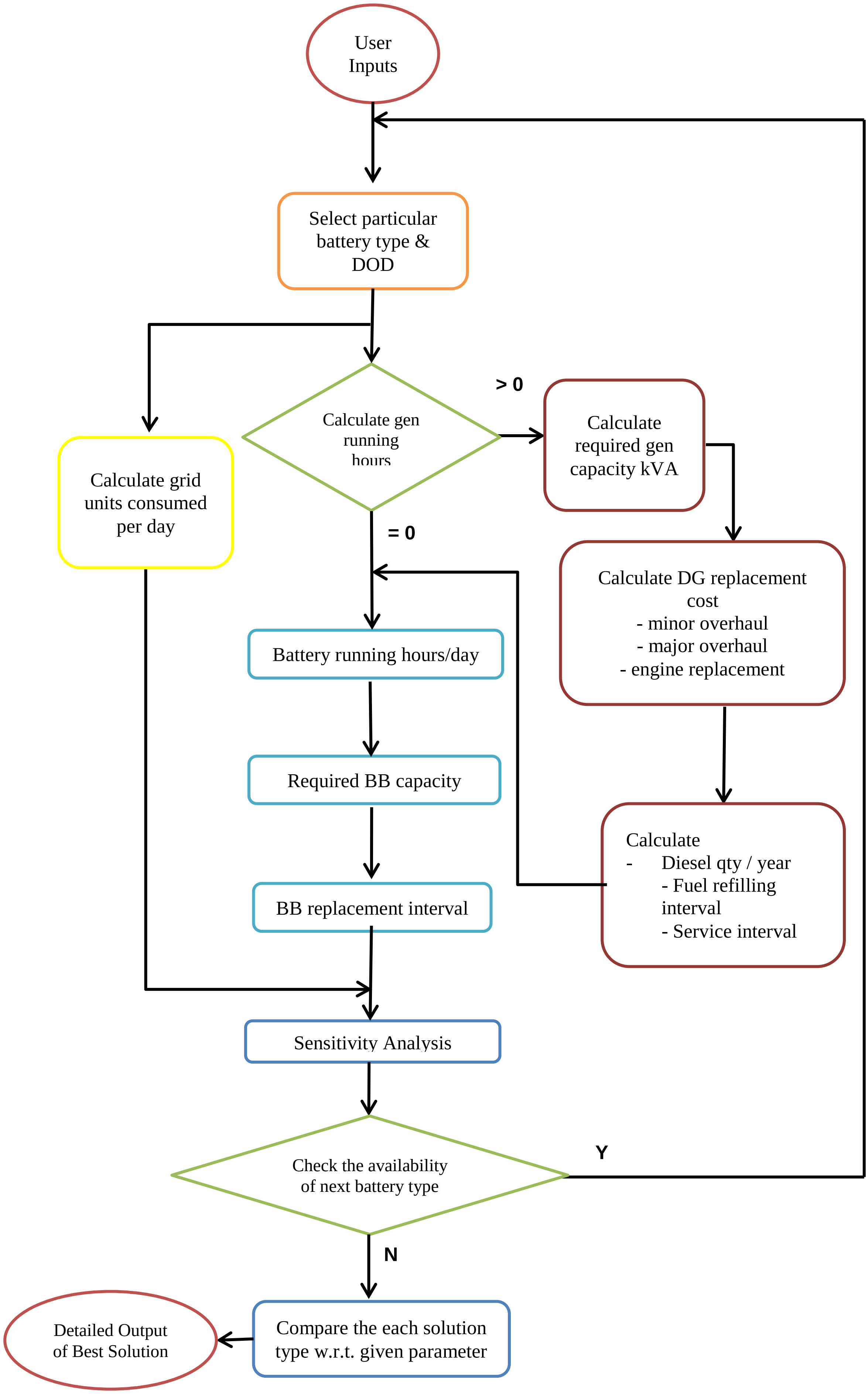


Figure 4.4 : Algorithm for Grid + Battery Technology + (DG)

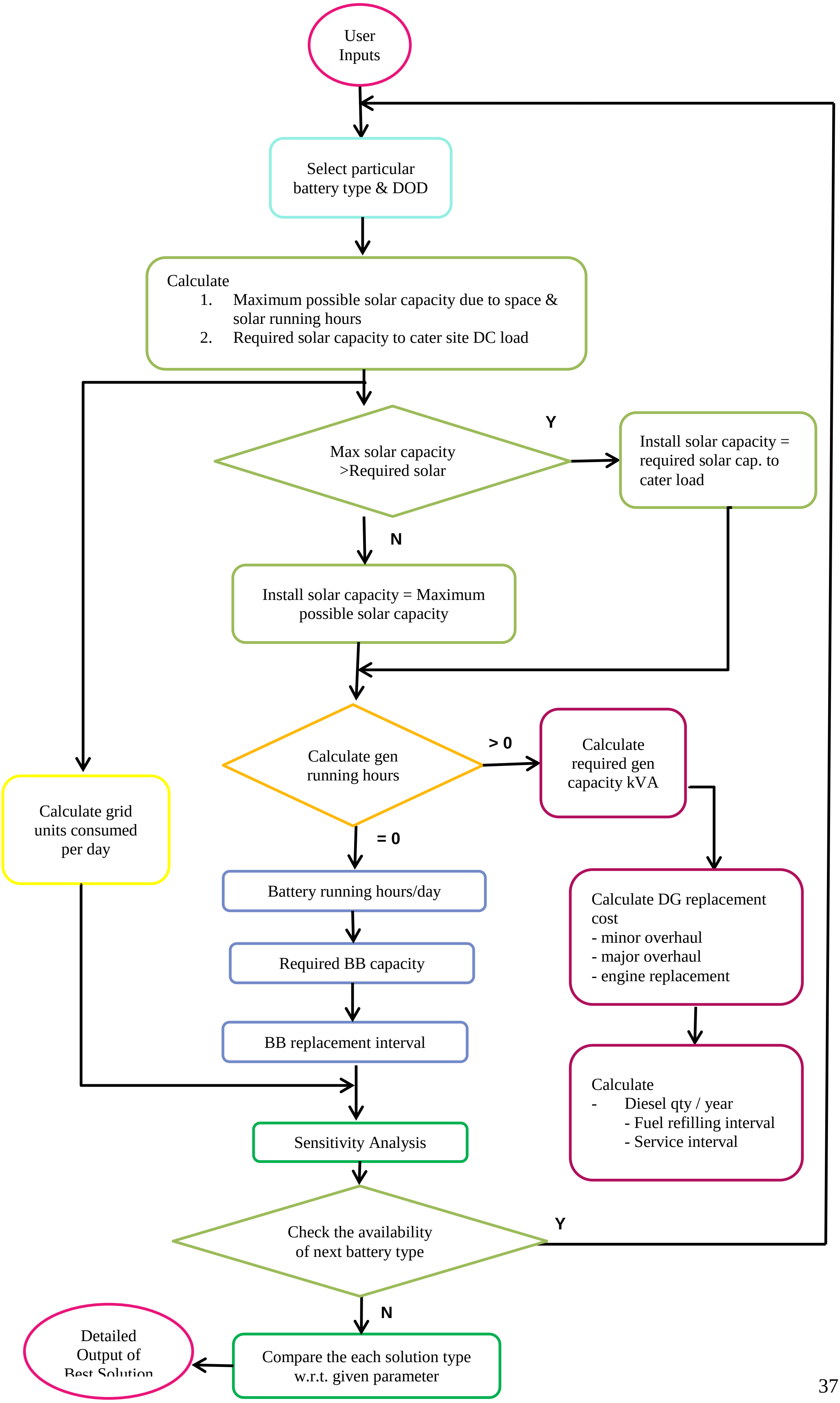


Figure 4.5 : Algorithm for Grid + Battery Technology + Solar + (DG)

4.4 Output of the Model

4.4.1 Output of New Site Model

The model yields a detailed graphical dashboard which enables the user to correlate the state of load, the power source combination and their conditions.

The user has the opportunity to select the required parameter in order to have the optimum power configuration details accordingly. The model output provides the technical details of the best solution according to the selected parameter. Thus the model can become a tool for optimizing opex or capex, if one wants.

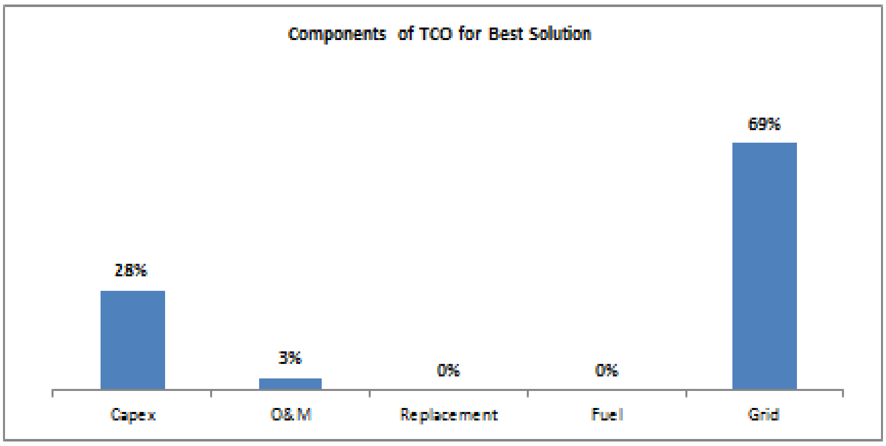
Output

Parameter	Total Cost of Ownership (TCO)
Best Option based on Selected Parameter	Solar + Li Ion + Grid

Back to Input

Reset

Complete Output for Best Solution (USD)	Total Cost of Ownership (TCO)	Initial Capex	Energy Cost / Month	Opex / Month	Replacement Capex / Month
Solar + Li Ion + Grid	42,626	11,785	123	6	-



Solution Summary	Solar + Li Ion + Grid	
Storage Type	Li Ion	Batteries
Battery Bank Capacity (AH	100	AH
Battery Run Hours / Day	1	Hours/Day
Generation Type	-	
Generator Size (kVA)	-	kVA
Generator Run Hours / Da	0	Hours/Day
Solar Panel Capacity	2	kW
Battery DoD %	80	%

Figure 4.6 : Dashboard of the Detailed Technical Output of the Best Solution in New Site Model

It also provides annual cost components of the best solution over a period of 20 years. Furthermore, the user can obtain a comparison of the selected parameter across the other combinations of power sources that are used for simulation.

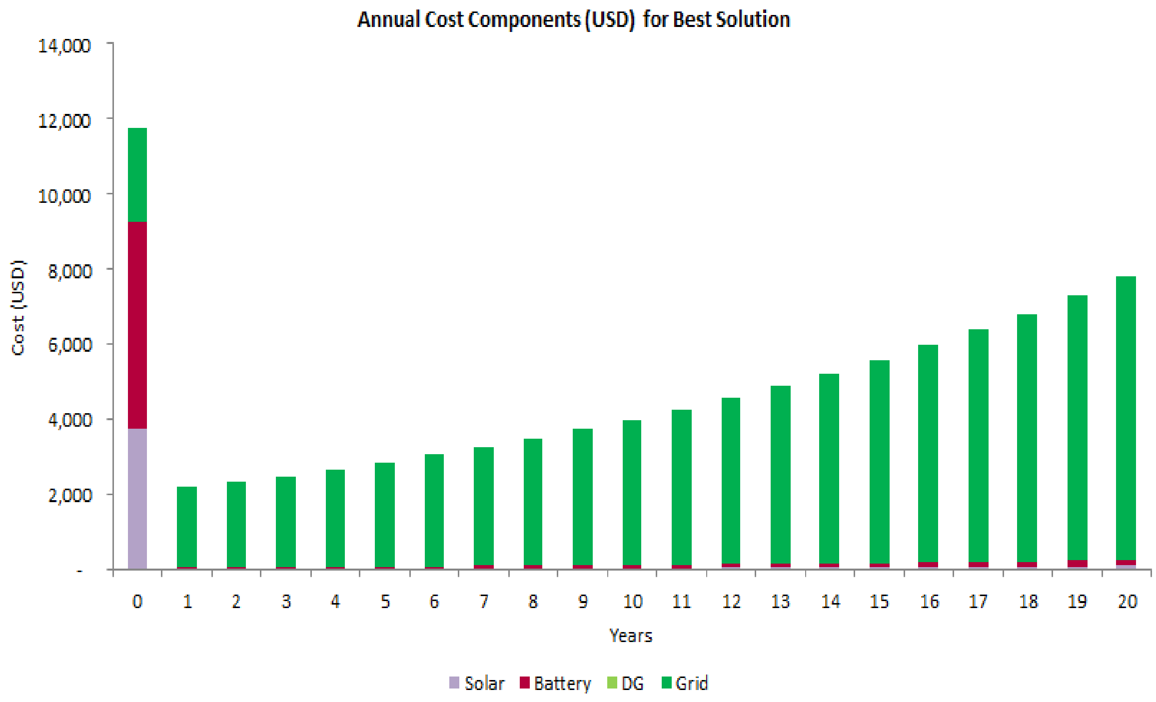


Figure 4.7 : Annual Cost Components for the Best Solution

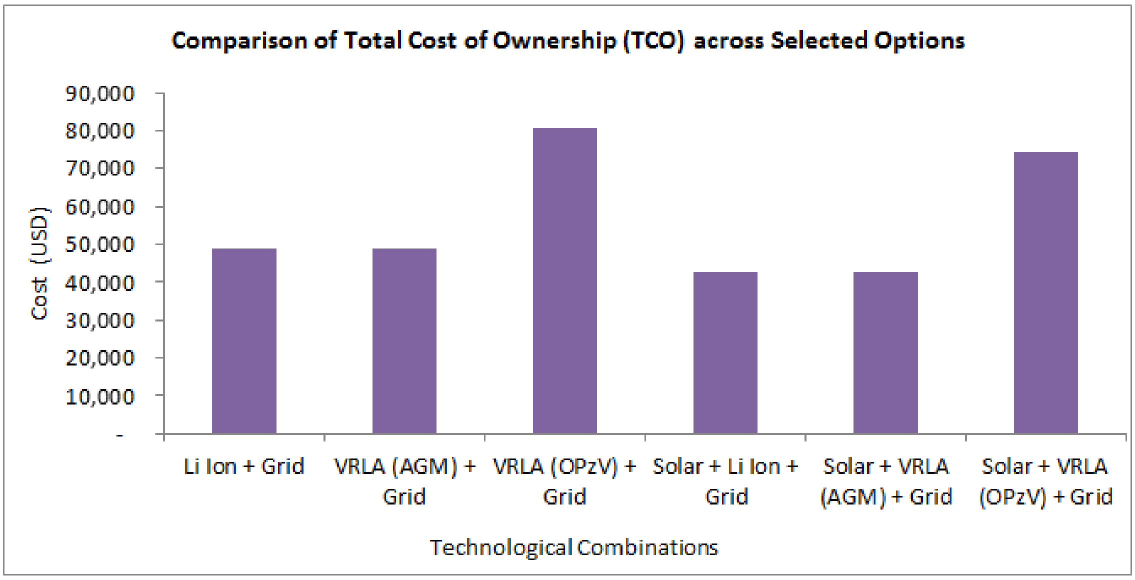


Figure 4.8 : Comparison of the Selected Parameter across Other Options

4.4.2 Output of On-Operational Site Model

Similar to the new site model, this model too provides a detailed graphical output of optimal operation process with the existing power equipment.

Thus the user can be verified whether the current power operational process of the site is the best way or not, so that change the operational procedure to its optimum approach with the existing power equipment at the site. Accordingly the model can become a tool for optimizing opex of the site, if one wants.

Output

Back to Input

	Total Cost of Ownership (TCO)	Initial Capex	Energy Cost / Month	Opex / Month	Replacement Capex / Month
Li Ion + DG [Off Grid]	278,457	-	691	110	358.74

Components of TCO	Li Ion + DG [Off Grid]	
Capex	-	0%
O&M	26,464	10%
Replacement	86,097	31%
Fuel	165,896	60%
Grid	-	0%

Solution Summary	Li Ion + DG [Off Grid]	
Storage Type	Li Ion	Batteries
Battery Bank Capacity (Ah)	300	Ah
Battery Run Hours / Day	4.9	Hours / Day
Generation Type	DG	
Generator Size (kVA)	8	kVA
Generator Run Hours / Day	19.1	Hours / Day
Battery DoD %	80	%
Solar Panel Capacity	-	kW

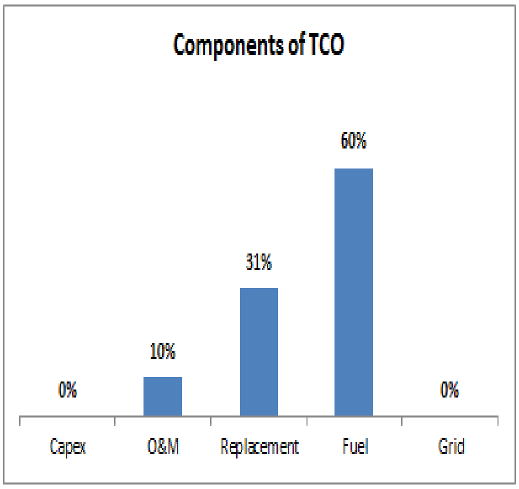


Figure 4.9 : Dashboard of the Detailed Technical Output of the Best Operational Process in On-Operational Site Model

Furthermore, it provides annual cost components of the best operational process over a period of 20 years.

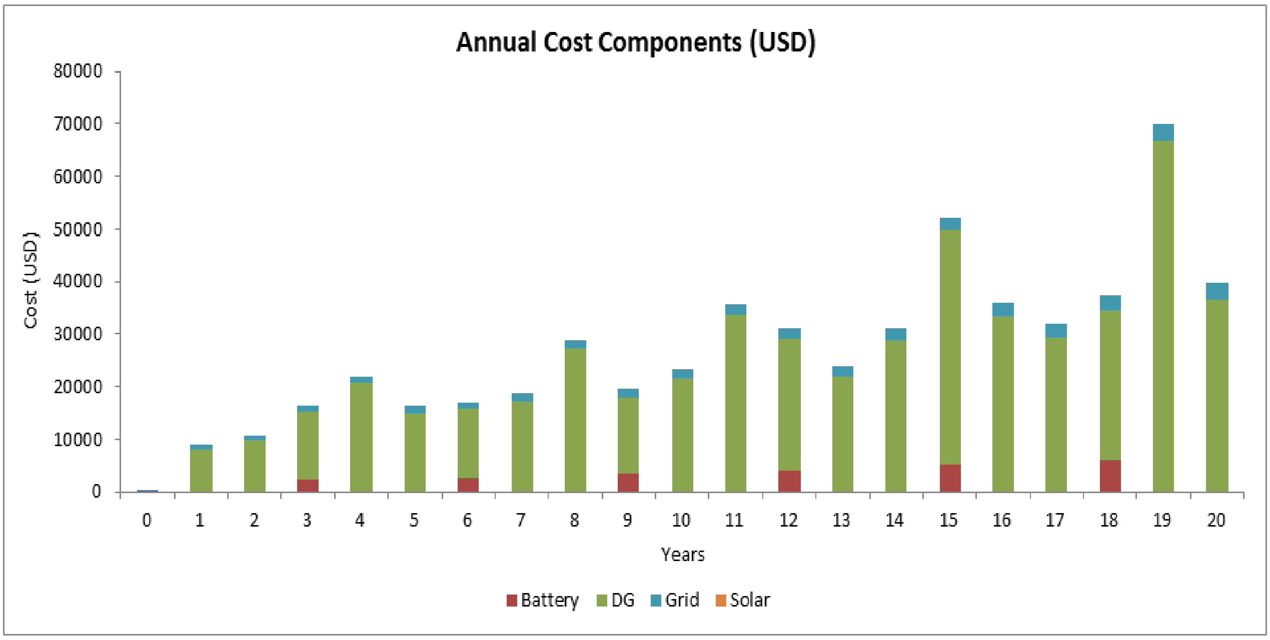


Figure 4.10 : Annual Cost Components for the Best Operational Process

Parameters Used In the Model

5.1 Parameters for Battery

Three types of battery technologies have been used in the model; Li-Ion battery, VRLA (Valve Regulated Lead Acid) AGM (Absorbent Glass Mat) battery & OPzV (Tubular Gel) battery. The company currently uses AGM and OPzV battery technologies only. Table 5.1 presents the parameters of the three battery types used in the model.

Table 5.1 : Parameters of each Battery Technologies Used in the Model

	Li-Ion Batteries	VRLA AGM Batteries	Tubular Gel (OPzV) Batteries
Battery Cost (USD)	1,500	490	950
Working Voltage of Single Battery (V)	48	12	2
Nominal Battery Capacity (Ah)	50	300	300
Operating Voltage (V)	48	48	48
Series Combination Required	1	4	24
Battery Charging	0.5C	0.25C	0.25C
Battery Efficiency	96%	80%	84%
Installation Cost (USD)	1,000	1,000	1,000
Cabinet / Shelter Cost (USD)	1,500	1,500	1,500

Recommended Depth of Discharge (DoD) percentage of the battery varies depending on the battery technology as well as the site configuration. Cycle lifetime is defined as number of discharging and charging cycles until the actual remaining battery capacity drops below 80% of the nominal capacity (C10) [11]. Thus the cycle lifetime of a battery is directly depending on the regular DoD during these cycles. Depending on different types of batteries and the design of the plates and electrodes, the cycle lifetime may vary significantly.

Table 5.2 : DoD % vs Cycle Lifetime of each Battery type

Li-Ion Batteries				VRLA AGM Batteries				Tubular Gel (OPzV) Batteries			
DoD (%)	Life Cycles (ID)	Life Cycles (OD)	Minimum Charging Time (Hrs)	DoD (%)	Life Cycles (ID)	Life Cycles (OD)	Minimum Charging Time (Hrs)	DoD (%)	Life Cycles (ID)	Life Cycles (OD)	Minimum Charging Time (Hrs)
30	10,000	5,000	1.8	30	2,400	1,200	2.5	30	3,000	2,100	4
40	9,000	4,500	2	40	2,200	1,100	4	40	2,400	1,680	5
50	8,000	4,000	2.5	50	1,800	900	5	50	1,800	1,260	6
60	7,600	3,800	3	60	1,400	700	6	60	1,400	980	7
70	6,600	3,300	4	70	1,200	600	13	70	1,100	770	8
80	5,000	2,500	5	80	1,000	500	16	80	900	630	12

Typically it is considered 3 times of battery maintenance per year.

5.2 Parameters Diesel Generator

Diesel Generators used as a backup power supply at the BTS sites in order to provide an uninterrupted service. Currently Dialog uses the generator capacities varies from 8kVA to 50kVA. Table 5.3 shows generator capacity in kWh and generator capex for each capacity used in the model.

Table 5.3 : General Data of Diesel Generators for Different Capacities

Generator Capacity (kVA)	Generator Capacity (kWh)	DG Tank Capacity (Liters)	P.F	Generator Cost (USD)
8	5.44	400	0.85	9,000
11	7.48	600	0.85	11,000
15	10.20	800	0.85	13,000
25	17.00	1000	0.85	15,000
50	34.00	1500	0.85	17,000

The generator load depends on the BTS equipment using at the site and the state of battery when the generator is turned on. The amount of fuel consumption per hour (CPH) of the generator varies according to the loading percentage.

Table 5.4 : Generator CPH with Loading Percentage

Generator Capacity (kVA)	Generator Efficiency	Generator CPH (liters / hour)			
		100% Load	75% Load	50% Load	25% Load
8	80 %	2.20	1.79	1.24	0.83
11	80 %	3.26	2.64	1.83	1.22
15	80 %	4.31	3.50	2.42	1.62
25	80 %	6.05	4.91	3.40	2.27
50	80 %	15.12	12.10	8.69	6.05

Service durations of the generator and the operational costs concurred with the generator services were considered as below in the model.

- Generator Servicing / Oil Filling / Fuel Filter Change : 500 hours
- Servicing Cost : 90 USD

- Generator Minor Overhaul / Servicing : 5000 hours
- Minor Overhaul Cost : 10% of Generator Capex

- Generator Major Overhaul : 10000 hours
- Major Overhaul Cost : 25% of Generator Capex

- Engine Replacement : 16000 hours
- Engine Replacement Cost : 85% of Generator Capex

- Maintenance Cost : 300 USD
- Cost of Civil Installation Work : 1500 USD
- Cost of Electrical Installation Work : 500 USD

5.3 Parameters for Solar Installation

For Sri Lanka, the number of daylight hours is high compared to the countries away from the equator and the seasonal variations are almost negligible. Table 5.5 shows the average daylights hours and maximum daily solar radiation incident on an equator-pointed tilted (8^0) surface depending on the site located district [12].

Table 5.5 : Sri Lankan Average Daylight Hours & Maximum Solar Radiation

District	Maximum Radiation Incident On An Equator-pointed Tilted (8^0) Surface ($kWh/m^2/day$)	Averaged Daylight Hours (hours)
Ampara	5.8	12.08
Anuradhapura	5.92	12.08
Badulla	5.85	12.08
Batticaloa	5.8	12.08
Colombo	4.80	12.08
Galle	3.93	12.08
Gampaha	4.08	12.08
Hambantota	4.22	12.08
Jaffna	4.35	12.08
Kalutara	4.52	12.08
Kandy	4.08	12.08
Kegalle	4.08	12.08
Kilinochchi	4.35	12.08
Kurunegala	4.08	12.08
Mannar	4.93	12.09
Matale	4.08	12.08
Matara	4.51	12.08
Moneragala	4.22	12.08
Mullaitivu	4.35	12.09
Nuwara Eliya	3.93	12.08
Polonnaruwa	4.08	12.07
Puttalam	4.93	12.07
Ratnapura	3.93	12.08
Trincomalee	4.4	12.08
Vavuniya	4.29	12.08

Resource:
https://eosweb.larc.nasa.gov "A renewable energy resource web site developed by NASA" about Surface meteorology and Solar energy resource. (release 6.0)

Several other costing data were considered in the model when considering the solar integration at a site. Solar PV can be integrated in scalable on to the telecom radio base station sites on to the cabin rooftops, as a shelter to the outdoor RBS sites, or to the tower structures.

Equipment cost & installation cost has been assumed as follows.

- Poly Crystal Module Cost : 1,000 USD / kW
- Size of Panel : 1.6 m^2 / 250 W
- Cost of Hybrid Controller : 6,500 USD
- Cost of Civil Installation Work :1,500 USD
- Cost of Electrical Installation Work : 5,00 USD
- Solar Panel Efficiency : 17%
- Solar Maintenance : 2 times / year

5.4 General Parameters

Apart from the equipment parameters mentioned in the above sections 5.1 to 5.3, some general parameters that specific to the country have considered to the calculations.

According to the World Bank database, inflation rate is considered as 6.9% (decade average) for Sri Lanka. Minimum wage is 88.20 USD / month (current price LKR 11,730) for the country. Assuming five times of minimum wage markup, skilled labor cost per day is considered as 14.5 USD.

Most of Dialog RBS sites count under CEB tariff plan General Purpose 1 (GP1) category. This rate shall apply to supplies at each individual point of supply delivered and metered at 400/230 volt nominal and where the contract demand is less than or equal to 42 kVA.

Tariff applicable to GP1 category is shown in Table 5.6 [13].

Table 5.6 : Tariff Applicable for GP1 Category

Consumption per month(kWh)	Energy Charge (LKR/kWh)	Fixed Charge(LKR/month)	Maximum Demand Charge per month(LKR/kVA)
< 301	18.30	240	–
>300	22.85		

Considering 300m distance away from the point of connection, cost for the grid connection is assumed as 2,535 USD (30A / 3P grid connection cost = 6000 LKR & 1100 LKR/m).

Diesel price is considered as 0.71 USD per liter. According to fifteen years average of World Bank database, fuel price growth rate is taken as 7.8%.

Conversion rate of 1 USD considered as 133 LKR as at 2015 march.

CHAPTER 6

Calculation Procedure

6.1 Battery Bank Sizing

Battery capacity to be used in a base station depends on several factors such as grid quality, criticality, accessibility, agreed up time for the sharing operators and generator availability at the considered base station etc. When determining the backup time for the off-grid sites, it is required to consider the configuration in which the particular site has been planned to operate, i.e. full time generator, generator/ battery cyclic, renewable energy.

Proper design of a battery system is essential to ensure reliable protection of critical telecom loads. Operating voltage is 48V DC. All deep cycle batteries are classified and rated in amp-hours. Amp-hours (Ah) is the term used to describe a standardized rate of discharge measuring current relative to time. Ah capacity of the battery bank is computed by multiplying the number of hours of battery reserve by the total load current.

For typical RBS sites where the solar integration is possible,

Backup hours required = 24 hours – grid availability

For solar integration possible sites,

Backup hours required = 24 hours - grid running hours - solar running hours

The approach to decide whether the backup required hours will run via batteries or diesel generator is as follows.

If the minimum battery charging time related to battery DoD% is less than the grid availability hours, then the battery can be fully charged during the grid available hours. Thus the generator does not need to run as the backup required hours can be driven by batteries. Otherwise the generator will run until the battery becomes fully recharged.

Battery running hours = Backup required hours – Generator running hours

$$\text{Required Battery Capacity (Ah)} = \frac{\text{Battery running hours} \times \text{Total average dc load}}{\text{Battery DoD \%} \times \text{Operating voltage}}$$

$$\text{Required Number of Batteries} = \frac{\text{Required battery bank capacity (Ah)}}{\text{Nominal battery capacity (Ah)}}$$

Next to calculate the battery replacement interval which is dependable on number of consumed battery cycles per day.

$$\text{Battery replacement interval (years)} = \frac{\text{No of cycles w.r.t battery DoD\%}}{365 \times \text{No of cycles per day}}$$

6.2 Diesel Generator Requirement

Once the battery discharges to a defined level to cater the site load, diesel generator is turned ON and supplies the power to cater the site load and to charge the batteries as well. Also, generators are used as back up, in the event of unavailability of all other power sources at the site.

Proper generator capacity is selected according to peak AC load at the site. Peak AC load is calculated considering all the possible loads including BTS load, battery charging current and other miscellaneous loads such as air conditioners, lights etc.

In order to calculate the opex cost related to the diesel generator, consumable diesel liter quantity and generator service cost is taken into the consideration.

Diesel consumed per year = Diesel consumption per hour (CPH) × running hours per day × 365

$$\text{Fuel Refilling Interval (days)} = \frac{\text{Fuel tank capacity (liters)}}{\text{Gen running hours per day} \times \text{Diesel CPH}}$$

$$\text{Generator service interval (days)} = \frac{\text{Recommended oil filling \& filter changing hours}}{\text{Gen running hours per day}}$$

Minor overhaul cost, major overhaul cost and engine replacement cost have considered as the generator replacement expenditure.

$$\text{Minor overhaul interval (days)} = \frac{\text{Recommended minor overhaul service hours}}{\text{Gen running hours per day}}$$

$$\text{Major overhaul interval (days)} = \frac{\text{Recommended major overhaul service hours}}{\text{Gen running hours per day}}$$

$$\text{Engine replacement interval (days)} = \frac{\text{Recommended engine replacement hours}}{\text{Gen running hours per day}}$$

6.3 Solar Installation

In industry, 1kW Solar PV installation comprise of 4 nos of 250W Solar PV panels each dimensions around 1.6m x 1m with total surface area of 6.4 m2 with the Solar PV panel energy output efficiencies around 17%. The solar irradiated energy ($kWh/m^2/day$) for the location of the site is considered according to Table 5.5 depending on its located district.

For 1kW solar installation,

Panel Area = 1.6 m^2 x 4 panels = 6.4 m^2

Module efficiency = 17% (according to the common Solar PV data sheets)

$$\text{Daily energy generation (kWh /day)} = \text{Panel area} \times \text{Module efficiency} \times \text{Solar irradiance of the site location}$$

Required solar capacity to cater the site load can be calculated using following equation.

$$\text{Required solar capacity} = \frac{\text{Average site DC load (kW)} \times 24 \text{ hours}}{\text{Battery DoD\%} \times \text{Battery Efficiency} \times \text{Daily kWh generation from 1kW solar}}$$

Unavailability of sufficient space in RBS sites is one of the main limitations to deploy solar in Sri Lanka. Thus, for the most of the sites, the space is not adequate to cater the total site load by solar. So it is required to calculate possible solar installation capacity at the site with the available open space.

$$\text{Possible maximum solar capacity due to space} = \frac{\text{Available open space at the site } (m^2) \times 250W}{\text{Area on 250 W panel } (m^2)}$$

It is essential to compare the required solar capacity to cater the site load and the possible solar installation with the available space in order to decide the capacity of solar PV to install at the site.

$$\text{Solar panel cost} = \text{Solar capacity kW} \times \text{Solar module cost (USD/kW)}$$

6.4 Sample Calculation for New Site Model

6.4.1 Technical Sizing for New Site Model

Figure 6.1 shows the dashboard of the model which specifies the inputs that considered for the sample calculation using new site model. Calculations have worked out to size the solution for the given inputs on the following technologies:

- VRLA (AGM) Batteries (+ DG)
- Li Ion Batteries (+ DG)
- OPzV (T Gel VRLA) Batteries (+ DG)
- Solar + VRLA (AGM) Batteries (+ DG)

- Solar + Li Ion Batteries (+ DG)
- Solar + OPzV (T Gel VRLA) Batteries (+ DG)

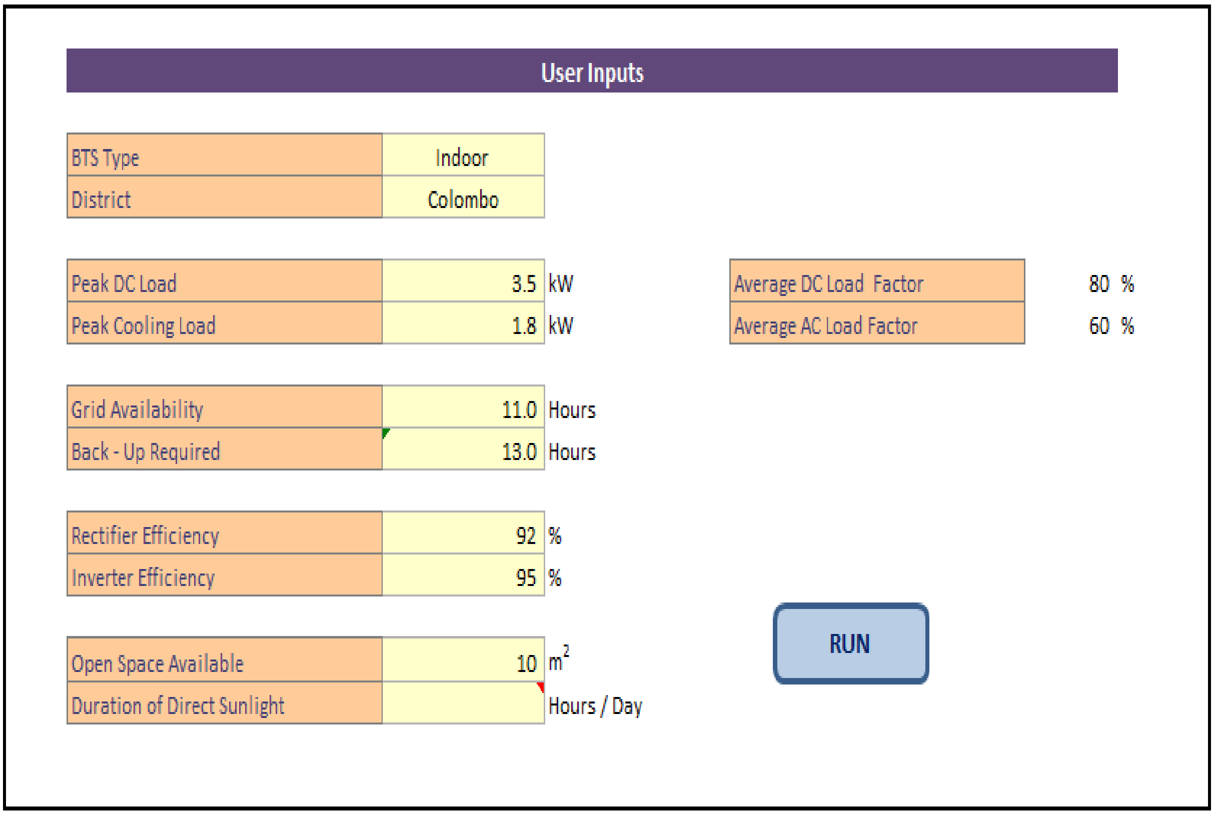


Figure 6.1 : Considered Inputs for the Sample Calculation in New Site Model

$$\text{Total average DC load on Site} = (\text{Peak DC load} \times \text{Average DC load factor }\%) + \frac{\text{Peak cooling load} \times \text{Average AC load factor}\%}{\text{Inverter Efficiency}}$$

$$= 3.5\times 80\% + 1.8\times 60\% / 95\%$$

$$= 3.9 \text{ kW}$$

$$\text{Total average AC load on Site} = (\text{Peak cooling load} \times \text{Average AC load factor }\%) + \frac{\text{Peak DC load} \times \text{Average DC load factor}\%}{\text{Rectifier Efficiency}}$$

$$= 1.8\times 60\% + 3.5\times 80\% / 92\%$$

$$= 4.1 \text{ kW}$$

Total Peak Load on AC side = (Peak DC load / Rectifier Efficiency) + Peak cooling load

= 3.5/ 92% + 1.8

= 5.6 kW

Total Peak Load on DC side = (Peak cooling load / Inverter Efficiency) + Peak DC load

= 1.8/ 95% + 3.5

= 5.4 kW

6.4.1.1 Technical Sizing for VRLA (AGM) Batteries (+ DG)

Backup hours required = 13 hours/day

Battery DoD% = 70%

According to Table 5.2,

Minimum battery charging hours related to battery DoD% = 13 hours

As the grid availability is only 11 hours/day for this particular site, it is required to run the diesel generator for 2 hours in order to charge the batteries.

Diesel generator running hours = 2 hours / day

Generator capacity is decided as to cater total peak load on AC side which is 5.6kW for these example inputs. According to Table 5.3, the nearest maximum value of the standard generator is 7.48kW, thus the required diesel generator capacity will be 11kVA.

Required diesel generator capacity = 11kVA

Diesel generator capex = 11,000 USD (from Table 4.3)

Minor overhaul interval = 5000 hours / (2 hours/day × 365) = 6.85 years

Minor overhaul cost = 11,000 USD × 10% = 1,100 USD

Major overhaul interval = 10,000 hours / (2 hours/day × 365) = 13.70 years

Major overhaul cost = 11,000 USD × 25% = 2,750 USD

Engine replacement interval = 16,000 hours / (2 hours/day × 365) = 21.92 years

Engine replacement cost = 11,000 USD × 85% = 9,350 USD

Diesel CPH = 3.26 liters / hour (from Table 4.4)

Diesel consumption per year = 3.26 l/hour × 2 hours/day × 365 = 2.376 liters

Fuel tank capacity = 600 liters (from Table 4.3)

Fuel refilling interval = 600 liters / (2 hours/day × 3.26 l/hour) = 92.17 days

Generator service interval = 500 hours / (2 hours/day × 365) = 0.68 years

Battery running hours = 24 – 11 – 2 = 11 hours / day

Required battery bank capacity = (11 hours/day ×1.1× 3.9kW) / (70% × 48V)

= 1,417.73 Ah

Required no of battery banks = Roundup (1417.73A / 300Ah) = 5 battery banks

Required no of batteries = 5 bb × 4 = 20 batteries

Battery capex = 490 USD × 20 = 9,800 USD

Battery cyclic life w.r.t. to the selected DoD% = 1,200 cycles

No of consumed cycles per day = (3.9kW×11hours/day) / (48V×5×300Ah×70%)

= 0.86 cycles / day

Battery replacement interval = 1,200 cycles / (0.9 cycles/day × 365) = 3.83 years

Grid units consumed per day = 11 hours/day × 4.1 kW = 45 kWh / day

6.4.1.2 Technical Sizing for Li Ion Batteries (+ DG)

Backup hours required = 13 hours/day

Battery DoD% = 80%

According to Table 5.2,

Minimum battery charging hours related to battery DoD% = 5 hours

As the grid is already available for 11 hours/day for this particular site, battery can be charged during the grid available hours, thus there is no requirement to run the diesel generator at the site.

Diesel generator running hours = Nil

So there is no requirement of deploying a diesel generator at the site, thus generator capex and opex cost will be zero if the site is implemented with Li Ion batteries.

Battery running hours = 24 – 11 = 13 hours / day

Required battery bank capacity = (13 hours/day ×1.1× 3.9kW) / (80% × 48V)

= 1,466.06 Ah

Required no of battery banks = Roundup (1466.06A / 50Ah) = 30 battery banks

Required no of batteries = 30 bb × 1= 30 batteries

Battery capex = 1,500 USD × 30 = 45,000 USD

Battery cyclic life w.r.t. to the selected DoD% = 5,000 cycles

No of consumed cycles per day = (3.9kW×13hours/day) / (48V×30×50Ah×80%)

= 0.89 cycles / day

Battery replacement interval = 5,000 cycles / (0.89 cycles/day × 365) = 15.42 years

Grid units consumed per day = 11 hours/day × 4.1 kW = 45 kWh / day

6.4.1.3 Technical Sizing for OPzV (T Gel VRLA) Batteries (+ DG)

Backup hours required = 13 hours/day

Battery DoD% = 40%

According to Table 5.2,

Minimum battery charging hours related to battery DoD% = 5 hours

As the grid is already available for 11 hours/day for this particular site, battery can be charged during the grid available hours, thus there is no requirement to run the diesel generator at the site.

Diesel generator running hours = Nil

So there is no requirement of deploying a diesel generator at the site, thus generator capex and opex cost will be zero if the site is implemented with OPzV batteries.

Battery running hours = 24 – 11 = 13 hours / day

Required battery bank capacity = (13 hours/day ×1.1× 3.9kW) / (40% × 48V)

= 2,932.13 Ah

Required no of battery banks = Roundup (2932.13A / 300Ah) = 10 battery banks

Required no of batteries = 10 bb × 24= 240 batteries

Battery capex = 950 USD × 240 = 228,000 USD

Battery cyclic life w.r.t. to the selected DoD% = 2,400 cycles

No of consumed cycles per day = (3.9kW×13hours/day) / (48V×10×300Ah×40%)

= 0.89 cycles / day

Battery replacement interval = 2,400 cycles / (0.89 cycles/day × 365) = 7.40 years

Grid units consumed per day = 11 hours/day × 4.1 kW = 45 kWh / day

6.4.1.4 Technical Sizing for Solar + VRLA (AGM) Batteries (+ DG)

Open space available = 10 m^2 (according to Figure 6.1)

Battery DoD% = 70%

As per Table 5.5,

Solar running hours per day = 12.08 × 50% = 6.04 hours/day

Possible max solar capacity due to space = 10 m^2 × 0.25kW / 1.6 m^2

= 1.56 kW

According to Table 5.4,

Solar irradiance of the site location = 6.54 kWh/day/m^2

Possible kWh generation from 1kW solar installation = 1.6 m^2×4×17%×6.54

= 7.1 kWh / day

Required solar capacity to cater site load = $\frac{(3.9\text{kW} \times 24 \text{ hrs})}{(70\% \text{ DoD} \times 80\% \text{ bat. effi.} \times 7.1 \text{ kWh/day})}$

= 23.71 kW

Due to the space restriction, it is not possible to install the required solar capacity that needs to cater the site load. Thus installable solar capacity at the site would be 1.56 kW only.

Solar panel cost = 1,750 USD

Effective grid running hours = 11 – 6.04 = 4.96 hours

Effective backup hours required = 24 – 6.04 – 4.96 = 13 hours

According to Table 5.2,

Minimum battery charging hours related to battery DoD% = 13 hours

As the grid+solar availability will be only 11 hours/day for this particular site, it is required to run the diesel generator for 2 hours in order to charge the batteries.

Diesel generator running hours = 2 hours / day

Generator capacity is decided as to cater total peak load on AC side which is 5.6kW for these example inputs. According to Table 5.3, the nearest maximum value of the standard generator is 7.48kW, thus the required diesel generator capacity will be 11kVA.

Required diesel generator capacity = 11kVA

Diesel generator capex = 11,000 USD (from Table 5.3)

Minor overhaul interval = 5000 hours / (2 hours/day × 365) = 6.85 years

Minor overhaul cost = 11,000 USD × 10% = 1,100 USD

Major overhaul interval = 10,000 hours / (2 hours/day × 365) = 13.70 years

Major overhaul cost = 11,000 USD × 25% = 2,750 USD

Engine replacement interval = 16,000 hours / (2 hours/day × 365) = 21.92 years

Engine replacement cost = 11,000 USD × 85% = 9,350 USD

Diesel CPH = 3.26 liters / hour (from Table 5.4)

Diesel consumption per year = 3.26 l/hour × 2 hours/day × 365 = 2.376 liters

Fuel tank capacity = 600 liters (from Table 5.3)

Fuel refilling interval = 600 liters / (2 hours/day × 3.26 l/hour) = 92.17 days

Generator service interval = 500 hours / (2 hours/day × 365) = 0.68 years

Battery running hours = 24 – 6.04 – 4.96 – 2 = 11 hours / day

Required battery bank capacity = (11 hours/day ×1.1× 3.9kW) / (70% × 48V)

= 1,417.73 Ah

Required no of battery banks = Roundup (1417.73A / 300Ah) = 5 battery banks

Required no of batteries = 5 bb × 4 = 20 batteries

Battery capex = 490 USD × 20 = 9,800 USD

Battery cyclic life w.r.t. to the selected DoD% = 1,200 cycles

No of consumed cycles per day = (3.9kW×11hours/day) / (48V×5×300Ah×70%)

= 0.86 cycles / day

Battery replacement interval = 1,200 cycles / (0.9 cycles/day × 365) = 3.83 years

Grid units consumed per day = 4.96 hours/day × 4.1 kW = 20 kWh / day

6.4.1.5 Technical Sizing for Solar + Li Ion Batteries (+ DG)

Battery DoD% = 80%

As the open space availability is same as the calculations done under sub topic 6.4.1.4, the solar parameters will be same as previous.

Open space available = 10 m^2

Solar running hours per day = 6.04 hours/day

Possible max solar capacity due to space = 1.56 kW

Required solar capacity to cater site load = 23.71 kW
Due to the space restriction, it is not possible to install the required solar capacity that needs to cater the site load. Thus installable solar capacity at the site would be 1.56 kW only.

Solar panel cost = 1,750 USD

Effective grid running hours = 11 – 6.04 = 4.96 hours

Effective backup hours required = 24 – 6.04 – 4.96 = 13 hours

According to Table 5.2,

Minimum battery charging hours related to battery DoD% = 5 hours

As the grid + solar will be already available for 11 hours/day for this particular site, battery can be charged during the grid + solar available hours, thus there is no requirement to run the diesel generator at the site.

Diesel generator running hours = Nil

So there is no requirement of deploying a diesel generator at the site, thus generator capex and opex cost will be zero if the site is implemented with Li Ion batteries.

Battery running hours = 24 – 6.04 – 4.96 = 13 hours / day

Required battery bank capacity = (13 hours/day ×1.1× 3.9kW) / (80% × 48V)

= 1,466.06 Ah

Required no of battery banks = Roundup (1466.06A / 50Ah)

= 30 battery banks

Required no of batteries = 30 bb × 1= 30 batteries

Battery capex = 1,500 USD × 30 = 45,000 USD

Battery cyclic life w.r.t. to the selected DoD% = 5,000 cycles

No of consumed cycles per day = (3.9kW×13hours/day) / (48V×30×50Ah×80%)

= 0.89 cycles / day

Battery replacement interval = 5,000 cycles / (0.89 cycles/day × 365)

= 15.42 years

Grid units consumed per day = 4.96 hours/day × 4.1 kW = 20 kWh / day

6.4.1.6 Technical Sizing for Solar + OPzV (T Gel VRLA) Batteries (+ DG)

Battery DoD% = 40%

As the open space availability is same as the calculations done under sub topic 6.4.1.4, the solar parameters will be same as previous.

Open space available = 10 m^2

Solar running hours per day = 6.04 hours/day

Possible max solar capacity due to space = 1.56 kW

Required solar capacity to cater site load = 23.71 kW

Due to the space restriction, it is not possible to install the required solar capacity that needs to cater the site load. Thus installable solar capacity at the site would be 1.56 kW only.

Solar panel cost = 1,750 USD

Effective grid running hours = 11 – 6.04 = 4.96 hours

Effective backup hours required = 24 – 6.04 – 4.96 = 13 hours

According to Table 5.2,

Minimum battery charging hours related to battery DoD% = 5 hours

As the grid + solar is already available for 11 hours/day for this particular site, battery can be charged during the grid + solar available hours, thus there is no requirement to run the diesel generator at the site.

Diesel generator running hours = Nil

So there is no requirement of deploying a diesel generator at the site, thus generator capex and opex cost will be zero if the site is implemented with OPzV batteries.

Battery running hours = 24 – 6.04 – 4.96 = 13 hours / day

Required battery bank capacity = (13 hours/day ×1.1× 3.9kW) / (40% × 48V)

= 2,932.13 Ah

Required no of battery banks = Roundup (2932.13A / 300Ah) = 10 battery banks

Required no of batteries = 10 bb × 24= 240 batteries

Battery capex = 950 USD × 240 = 228,000 USD

Battery cyclic life w.r.t. to the selected DoD% = 2,400 cycles

No of consumed cycles per day = (3.9kW×13hours/day) / (48V×10×300Ah×40%)

= 0.89 cycles / day

Battery replacement interval = 2,400 cycles / (0.89 cycles/day × 365) = 7.40 years

Grid units consumed per day = 4.96 hours/day × 4.1 kW = 20 kWh / day

6.4.2 Financial Projection for New Site Model

Basically initial capex, operational & maintenance cost, replacement capex and opex cost have considered for each technical combination and the costs are projected over a twenty years of period.

Initial Capex : Battery cost
Generator Cost
Grid connection cost
Solar system cost

O & M Cost : Generator service cost (material + labor)
Battery maintenance cost
Solar maintenance cost

Replacement Capex : Generator minor overhaul cost
Generator major overhaul cost
Generator engine replacement cost
Battery replacement cost

Opex cost : Fuel usage
Electricity usage

Considering the inflation rate of 6.9%, the projected costs are used to finally arrive at the Total Cost of Ownership (TCO) or Net Present Value (NPV) for each system.

Based on above parameters, the financial projection is calculated for different technical options and shown in Table 6.1 to 6.12.

6.4.2.1 Financial Projection for VRLA (AGM) Batteries (+ DG)

Table 6.1: Cash flow for VRLA (AGM) Batteries (+DG)

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Battery Capex	12,300	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DG Capex	13,000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DG Servicing Cost	-	90	96	206	110	235	126	269	144	307	164	351	187	200	429	229	490	262	560	299	640
DG Minor Overhaul Cost	-	-	-	-	-	-	-	1,642	-	-	-	-	-	-	2,619	-	-	-	-	-	-
DG Major Overhaul Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6,547	-	-	-	-	-	-
Engine Replacement Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Battery Replacement Cost	-	-	-	-	11,972	-	-	-	15,634	-	-	-	20,416	-	-	-	26,662	-	-	-	34,818
Fuel Cost	-	1,697	1,830	1,973	2,126	2,292	2,471	2,664	2,872	3,096	3,338	3,598	3,879	4,182	4,508	4,860	5,240	5,649	6,089	6,565	7,077
Battery O&M	-	44	47	50	53	57	61	65	69	74	79	85	91	97	104	111	118	127	135	145	155
DG O&M	-	57	61	66	70	75	80	86	92	98	105	112	120	128	137	146	156	167	179	191	204
Grid Connection Cost	2,535	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Grid Cost	-	2,851	3,047	3,258	3,482	3,723	3,979	4,254	4,548	4,861	5,197	5,555	5,939	6,348	6,786	7,255	7,755	8,290	8,862	9,474	10,128
Grid O&M	-	29	31	33	35	38	41	43	46	49	53	57	60	65	69	74	79	84	90	96	103

Table 6.2: Cost component for VRLA (AGM) Batteries (+DG)

	USD
TCO (NPV) (r=10%)	133,382
Initial Capex	27,835
Energy Cost / Month	274
Opex / Month	15
Replacement Capex / Month	151

6.4.2.2 Financial Projection for Li Ion Batteries (+ DG)

Table 6.3: Cash flow for Li Ion Batteries (+DG)

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Battery Cost	47,500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DG Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Servicing Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Minor Overhaul Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Genset Overhaul Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Engine Replacement Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Battery Replacement Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	122,427	-	-	-	-
Fuel Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Battery O&M	-	44	47	50	53	57	61	65	69	74	79	85	91	97	104	111	118	127	135	145	155
DG O&M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Grid Connection Cost	2,535	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Grid Cost	-	2,851	3,047	3,258	3,482	3,723	3,979	4,254	4,548	4,861	5,197	5,555	5,939	6,348	6,786	7,255	7,755	8,290	8,862	9,474	10,128
Grid O&M	-	29	31	33	35	38	41	43	46	49	53	57	60	65	69	74	79	84	90	96	103

Table 6.4: Cost component for Li Ion Batteries (+DG)

	USD
TCO (NPV) (r=10%)	117,739
Initial Capex	50,035
Energy Cost / Month	167
Opex / Month	4
Replacement Capex / Month	111

6.4.2.3 Financial Projection for OPzV (T Gel VRLA) Batteries (+ DG)

Table 6.5: Cash flow for OPzV (T Gel VRLA) Batteries (+DG)

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Battery Cost	230,500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DG Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Servicing Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Minor Overhaul Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Genset Overhaul Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Engine Replacement Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Battery Replacement Cost	-	-	-	-	-	-	-	-	363,730	-	-	-	-	-	-	580,260	-	-	-	-	-
Fuel Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Battery O&M	-	44	47	50	53	57	61	65	69	74	79	85	91	97	104	111	118	127	135	145	155
DG O&M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Grid Connection Cost	2,535	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Grid Cost	-	2,851	3,047	3,258	3,482	3,723	3,979	4,254	4,548	4,861	5,197	5,555	5,939	6,348	6,786	7,255	7,755	8,290	8,862	9,474	10,128
Grid O&M	-	29	31	33	35	38	41	43	46	49	53	57	60	65	69	74	79	84	90	96	103

Table 6.6: Cost component for OPzV (T Gel VRLA) Batteries (+DG)

	USD
TCO (NPV) (r=10%)	582,688
Initial Capex	233,035
Energy Cost / Month	167
Opex / Month	4
Replacement Capex / Month	1,286

6.4.2.4 Financial Projection for Solar + VRLA (AGM) Batteries (+ DG)

Table 6.7: Cash flow for Solar + VRLA (AGM) Batteries (+ DG)

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Solar Cost	3,750	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Battery Cost	12,300	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DG Cost	13,000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Servicing Cost	-	90	96	206	110	235	126	269	144	307	164	351	187	200	429	229	490	262	560	299	640
Minor Overhaul Cost	-	-	-	-	-	-	-	1,642	-	-	-	-	-	-	2,619	-	-	-	-	-	-
Genset Overhaul Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6,547	-	-	-	-	-	-
Engine Replacement Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Battery Replacement Cost	-	-	-	-	11,972	-	-	-	15,634	-	-	-	20,416	-	-	-	26,662	-	-	-	34,818
Fuel Cost	-	1,697	1,830	1,973	2,126	2,292	2,471	2,664	2,872	3,096	3,338	3,598	3,879	4,182	4,508	4,860	5,240	5,649	6,089	6,565	7,077
Battery O&M	-	44	47	50	53	57	61	65	69	74	79	85	91	97	104	111	118	127	135	145	155
Solar O&M	-	29	31	33	35	38	41	43	46	49	53	57	60	65	69	74	79	84	90	96	103
DG O&M	-	57	61	66	70	75	80	86	92	98	105	112	120	128	137	146	156	167	179	191	204
Grid Connection Cost	2,535	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Grid Cost	-	1,286	1,375	1,470	1,571	1,679	1,795	1,919	2,052	2,193	2,344	2,506	2,679	2,864	3,062	3,273	3,499	3,740	3,998	4,274	4,569
Grid O&M	-	29	31	33	35	38	41	43	46	49	53	57	60	65	69	74	79	84	90	96	103

Table 6.8: Cost component for Solar + VRLA (AGM) Batteries (+ DG)

	USD
TCO (NPV) (r=10%)	115,562
Initial Capex	31,585
Energy Cost / Month	182
Opex / Month	17
Replacement Capex / Month	151

6.4.2.5 Financial Projection for Solar + Li Ion Batteries (+ DG)

Table 6.9: Cash flow for Solar + Li Ion Batteries (+ DG)

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Solar Cost	3,750	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Battery Cost	47,500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DG Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Servicing Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Minor Overhaul Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Genset Overhaul Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Engine Replacement Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Battery Replacement Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	122,427	-	-	-	-
Fuel Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Battery O&M	-	44	47	50	53	57	61	65	69	74	79	85	91	97	104	111	118	127	135	145	155
Solar O&M	-	29	31	33	35	38	41	43	46	49	53	57	60	65	69	74	79	84	90	96	103
DG O&M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Grid Connection Cost	2,535	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Grid Cost	-	1,286	1,375	1,470	1,571	1,679	1,795	1,919	2,052	2,193	2,344	2,506	2,679	2,864	3,062	3,273	3,499	3,740	3,998	4,274	4,569
Grid O&M	-	29	31	33	35	38	41	43	46	49	53	57	60	65	69	74	79	84	90	96	103

Table 6.10: Cost component for Solar + Li Ion Batteries (+ DG)

	USD
TCO (NPV) (r=10%)	99,919
Initial Capex	53,785
Energy Cost / Month	75
Opex / Month	6
Replacement Capex / Month	111

6.4.2.6 Financial Projection for Solar + OPzV (T Gel VRLA) Batteries (+ DG)

Table 6.11: Cash flow for Solar + OPzV (T Gel VRLA) Batteries (+ DG)

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Solar Cost	3,750	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Battery Cost	230,500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DG Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Servicing Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Minor Overhaul Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Genset Overhaul Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Engine Replacement Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Battery Replacement Cost	-	-	-	-	-	-	-	-	363,730	-	-	-	-	-	-	580,260	-	-	-	-	-
Fuel Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Battery O&M	-	44	47	50	53	57	61	65	69	74	79	85	91	97	104	111	118	127	135	145	155
Solar O&M	-	29	31	33	35	38	41	43	46	49	53	57	60	65	69	74	79	84	90	96	103
DG O&M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Grid Connection Cost	2,535	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Grid Cost	-	1,286	1,375	1,470	1,571	1,679	1,795	1,919	2,052	2,193	2,344	2,506	2,679	2,864	3,062	3,273	3,499	3,740	3,998	4,274	4,569
Grid O&M	-	29	31	33	35	38	41	43	46	49	53	57	60	65	69	74	79	84	90	96	103

Table 6.12: Cost component for Solar + OPzV (T Gel VRLA) Batteries (+ DG)

	USD
TCO (NPV) (r=10%)	564,868
Initial Capex	236,785
Energy Cost / Month	75
Opex / Month	6
Replacement Capex / Month	1,286

6.4.3 Output of New Site Model

The model compares the cost components of each combination before presenting the optimum power configuration as the output. It formulates the actual equipment combination depending on the grid availability and generator running hours in order to compare the cost components.

Table 6.13: Comparison of cost component of each combination

	Total Cost of Ownership (TCO)	Initial Capex	Energy Cost / Month	Opex / Month	Replacement Capex / Month
Li Ion + Grid	117,739	50,035	167	4	111
VRLA (AGM) + DG + Grid	133,382	27,835	274	15	151
VRLA (OPzV) + Grid	582,688	233,035	167	4	1,286
Solar + Li Ion + Grid	99,919	53,785	75	6	111
Solar + VRLA (AGM) + DG + Grid	115,562	31,585	182	17	151
Solar + VRLA (OPzV) + Grid	564,868	236,785	75	6	1,286

All the cost figures are in USD.

The components of Total Cost of Ownership (TCO) of each solution are also compared.

Table 6.14: Comparison of component TCO of each combination

Components of TCO	Li Ion + Grid	VRLA (AGM) + DG + Grid	VRLA (OPzV) + Grid	Solar + Li Ion + Grid	Solar + VRLA (AGM) + DG + Grid	Solar + VRLA (OPzV) + Grid
Capex	50,035	27,835	233,035	53,785	31,585	236,785
O&M	1,019	3,643	1,019	1,426	4,051	1,426
Replacement	26,644	36,209	308,592	26,644	36,209	308,592
Fuel	-	25,653	-	-	25,653	-
Grid	40,042	40,042	40,042	18,064	18,064	18,064

Table 6.15 summarizes the types and the capacities of power equipment that need to deploy under each configuration.

Table 6.15: Power equipment details of each configuration

Solution Summary	Li Ion + Grid	VRLA (AGM) + DG + Grid	VRLA (OPzV) + Grid	Solar + Li Ion + Grid	Solar + VRLA (AGM) + DG + Grid	Solar + VRLA (OPzV) + Grid
Storage Type	Li Ion	VRLA (AGM)	OPzV	Li Ion	VRLA (AGM)	OPzV
Battery Bank Capacity (Ah)	1,500	1,500	3,000	1,500	1,500	3,000
Battery Run Hours / Day	13	11	13	13	11	13
Generation Type	-	DG	-	-	DG	-
Generator Size (kVA)	-	11	-	-	11	-
Generator Run Hours / Day	-	2	-	-	2	-
Solar Panel Capacity				1.6	1.6	1.6
Battery DoD %	80	70	40	80	70	40

This new site model provides the technical details of the best solution and a detailed graphical dashboard according to the selected parameter by user. The user has the opportunity to select the required parameter in order to have the optimum power configuration details accordingly. As an example, if the selected parameter by the user is “Total Cost of Ownership (TCO)”, then the best configuration will be “Solar + Li Ion + Grid”. If one need to optimize the “Opex / month” for the particular site, then it is required to run the site “Li Ion + Grid” only.

Furthermore, annual cost components of the best solution over a period of 20 years and a comparison of the selected parameter across the other considered configuration options can be derived from the model output.

- If the selected parameter is “Total Cost of Ownership (TCO)” :

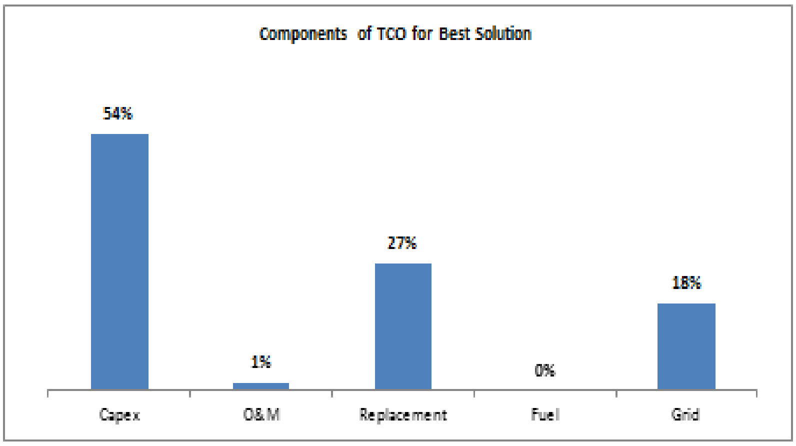
Output

Parameter	Total Cost of Ownership (TCO)
Best Option based on Selected Parameter	Solar + Li Ion + Grid

Back to Input

Reset

Complete Output for Best Solution (USD)	Total Cost of Ownership (TCO)	Initial Capex	Energy Cost / Month	Opex / Month	Replacement Capex / Month
Solar + Li Ion + Grid	99,919	53,785	75	6	111



Solution Summary	Solar + Li Ion + Grid	
Storage Type	Li Ion	Batteries
Battery Bank Capacity (AH	1500	AH
Battery Run Hours / Day	13	Hours/Day
Generation Type	-	
Generator Size (kVA)	-	kVA
Generator Run Hours / Da	0	Hours/Day
Solar Panel Capacity	2	kW
Battery DoD %	80	%

Figure 6.2 : Dashboard of the Detailed Technical Output of the Best Solution if the selected parameter is TCO

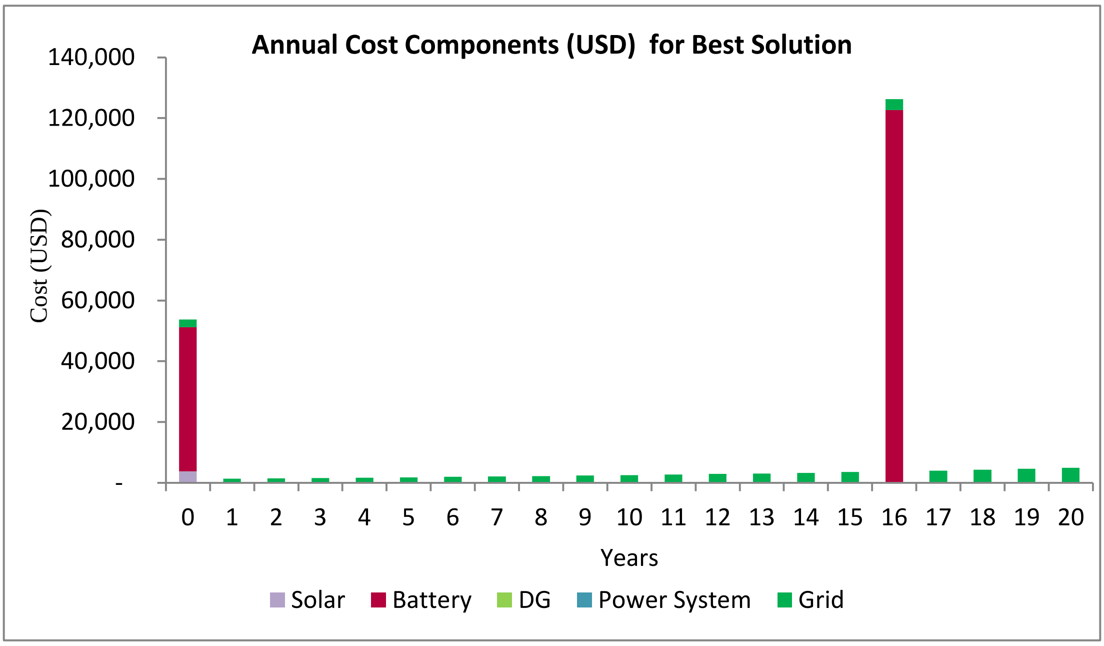


Figure 6.3: Annual Cost Components for the Best Solution if the selected parameter is TCO

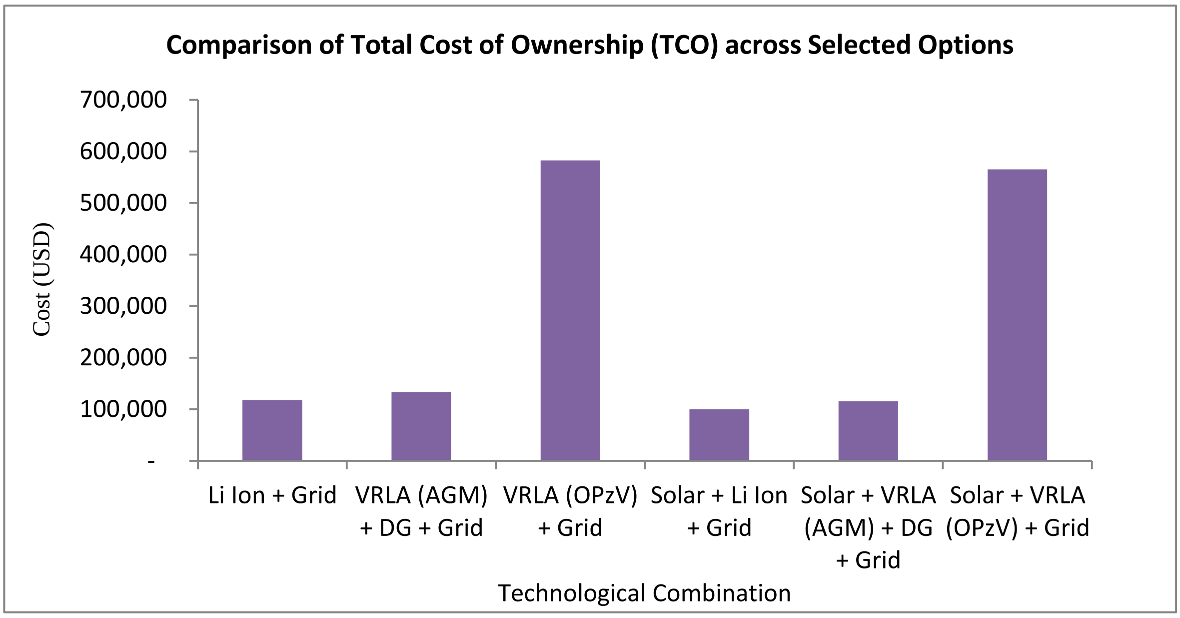


Figure 6.4 : Comparison of the Selected Parameter (TCO) across Other Configurations

- If the selected parameter is “Opex / Month” :

Output

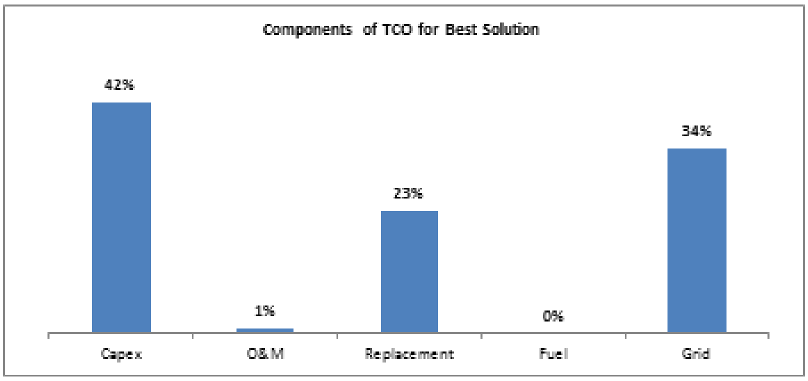
Parameter	Opex / Month

Back to Input

Best Option based on Selected Parameter	Li Ion + Grid

Reset

Complete Output for Best Solution (USD)	Total Cost of Ownership (TCO)	Initial Capex	Energy Cost / Month	Opex / Month	Replacement Capex / Month
Li Ion + Grid	117,739	50,035	167	4	111



Solution Summary	Li Ion + Grid	
Storage Type	Li Ion	Batteries
Battery Bank Capacity (AH	1500	AH
Battery Run Hours / Day	13	Hours/Day
Generation Type	-	
Generator Size (kVA)	-	kVA
Generator Run Hours / Da	0	Hours/Day
Solar Panel Capacity	0	kW
Battery DoD %	80	%

Figure 6.5 : Dashboard of the Detailed Technical Output of the Best Solution if the selected parameter is Opex / Month

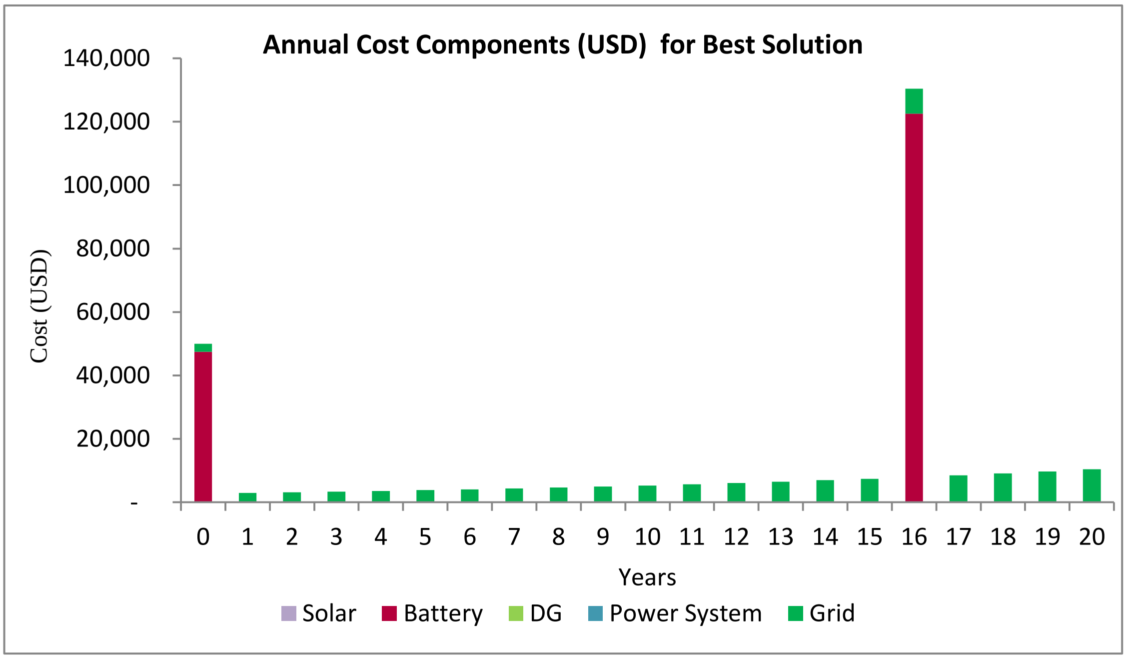


Figure 6.6: Annual Cost Components for the Best Solution if the selected parameter is Opex / Month

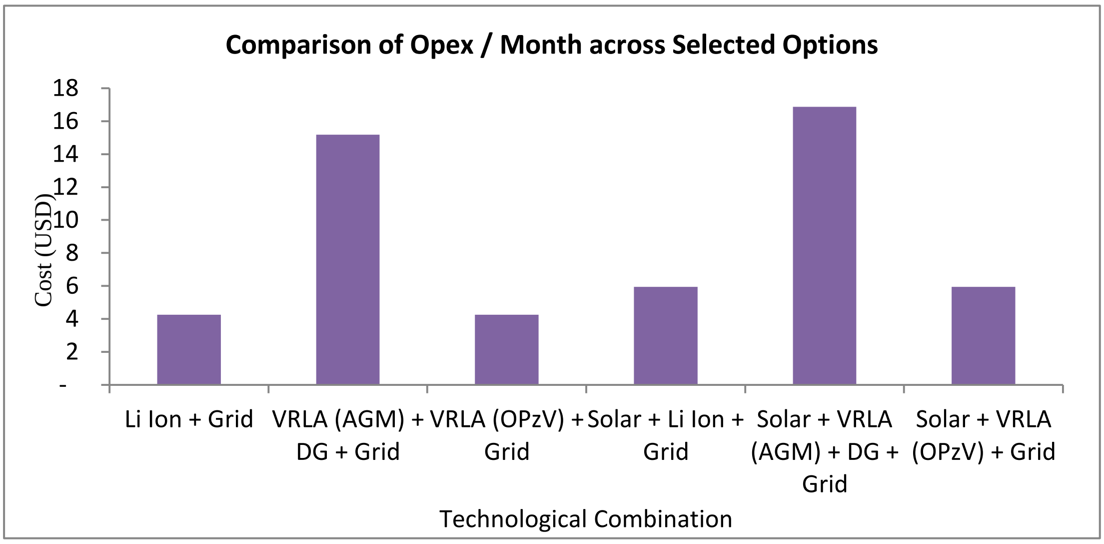


Figure 6.7 : Comparison of the Selected Parameter (Opex /Month) across Other Configurations

6.5 Sample Calculation for On-Operational Site Model

6.5.1 Technical Sizing for On-Operational Site Model

Figure 6.8 shows the dashboard of the on-operational site model which specifies the inputs that considered for the sample calculation. Calculations have worked out to come up with the best operational process with the installed power equipment.

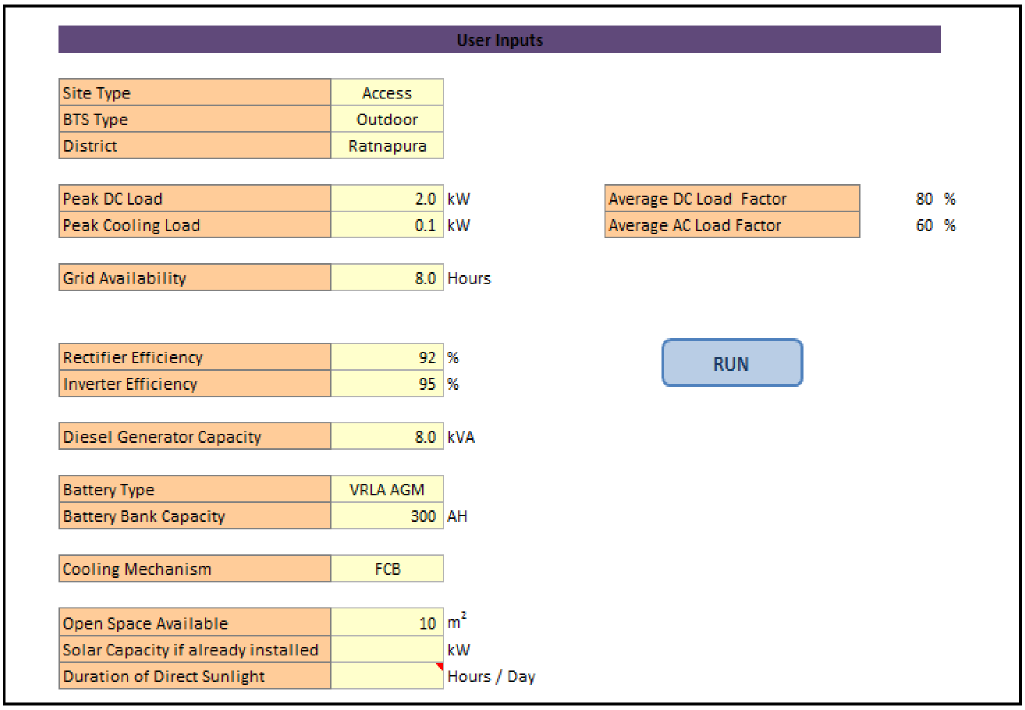


Figure 6.8 : Considered Inputs for the Sample Calculation in On-operational Site Model

Total average DC load on Site = (Peak DC load× Average DC load factor %) +

$$\frac{\text{Peak cooling load} \times \text{Average AC load factor\%}}{\text{Inverter Efficiency}}$$

= 2.0×80% + 0.1×60% / 95%

= 1.7 kW

Total average AC load on Site = (Peak cooling load× Average AC load factor %) +

$$\frac{\text{Peak DC load} \times \text{Average DC load factor\%}}{\text{Rectifier Efficiency}}$$

= 0.1×60% + 2.0×80% / 92%

= 1.8 kW

Total Peak Load on AC side = (Peak DC load / Rectifier Efficiency) + Peak cooling load

= 2.0/ 92% + 0.1

= 2.3 kW

Total Peak Load on DC side = (Peak cooling load / Inverter Efficiency) + Peak DC load

= 0.1/ 95% + 2.0

= 2.1 kW

Open space available = 10 m^2 (according to Figure 5.14)

Battery DoD% = 70%

As per Table 5.5,

Solar running hours per day = 12.08 × 50% = 6.04 hours/day

Possible max solar capacity due to space = 10 m^2 × 0.25kW / 1.6 m^2= 1.56 kW

According to Table 5.4,

Solar irradiance of the site location = 3.93 kWh/day/m^2

Possible kWh generation from 1kW solar installation = $1.6\ m^2 \times 4 \times 17\% \times 3.93$

$= 4.3$kWh / day

Required solar capacity to cater site load = $\frac{(1.7kW \times 24\ hrs)}{(70\%\ DoD \times 80\%\ bat.\ effi. \times 4.3\ kWh/day)}$

= 16.67 kW

Due to the space restriction, it is not possible to install the required solar capacity that needs to cater the site load. Thus installable solar capacity at the site would be 1.56 kW only.

Capex involvement for Solar = 1,750 USD

Effective grid running hours = 8 – 6.04 = 1.96 hours

Effective backup hours required = 24 – 6.04 – 1.96 = 16 hours

According to Table 5.2,

Minimum battery charging hours related to battery DoD% = 13 hours

As the grid+solar availability will be only 8 hours/day for this particular site, it is required to run the diesel generator minimum for 5 hours in order to charge the batteries.

Minimum diesel generator running hours = 5 hours / day

According to Table 5.3,

Installed generator capacity in kW = 5.44 kW

As the peak load on AC side at the site is 2.3 kW, existing generator can cater the peak load of the site.

Installed battery capacity at the site = 300 Ah VRLA

Maximum possible battery running hours with installed battery capacity

= (300Ah × 70% DoD × 80% bat. effi. ×48V) / (2.1 kW × 1000) = 3.82 hours/day

Thus the minimum generator running hours calculated above (5 hours) would not be sufficient with the installed battery bank type and capacity.

Actual generator running hours = 16 – 3.82 = 12.18 hours

Minor overhaul interval = 5000 hours / (12.18 hours/day × 365) = 1.13 years

Minor overhaul cost = 9,000 USD × 10% = 900 USD

Major overhaul interval = 10,000 hours / (12.18 hours/day × 365) = 2.25years

Major overhaul cost = 9,000 USD × 25% = 2,250 USD

Engine replacement interval = 16,000 hours / (12.18 hours/day × 365)

= 3.60 years

Engine replacement cost = 9,000 USD × 85% = 7.650 USD

Diesel CPH = 2.20 liters / hour (from Table 5.4)

Diesel consumption per year = 2.20 l/hour × 12.18 hours/day × 365

= 9,777 liters

Fuel tank capacity = 400 liters (from Table 5.3)

Fuel refilling interval = 400 liters / (12.18 hours/day × 2.20 l/hour) = 14.93 days

Generator service interval = 500 hours / (12.18 hours/day × 365) = 0.11 years

Battery cyclic life w.r.t. to the selected DoD% = 600 cycles (for outdoor site)

No of consumed cycles per day = $\frac{(1.7\text{kW}\times 3.82\text{hours/day})}{(48\text{V}\times 300\text{Ah}\times 70\%)}$

= 0.57 cycles / day

Battery replacement interval = 600cycles / (0.57 cycles/day × 365) = 2.87 years

Grid units consumed per day = 1.96 hours/day × 1.8 kW = 3.5 kWh / day

6.5.2 Financial Projection for On-Operational Site Model

Similar to the calculation done in new site model, initial capex, operational & maintenance cost, replacement capex and opex cost have projected over a twenty years of period and finally arrive at the Total Cost of Ownership (TCO) or Net Present Value (NPV) for each system.

Table 6.16: Cash flow for On-Operational Site Model

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Solar Cost	3,750	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Battery Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DG Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Servicing Cost	-	720	866	926	990	1,058	1,131	1,209	1,292	1,228	1,477	1,579	1,687	1,804	1,928	2,061	2,204	2,356	2,238	2,692	2,878
Minor Overhaul Cost	-	-	962	1,028	1,099	1,175	1,256	1,343	1,436	-	1,641	1,754	1,875	2,004	2,143	2,291	2,449	2,617	-	2,991	3,198
Genset Overhaul Cost	-	-	-	2,571	-	2,938	-	3,358	-	-	4,102	-	4,687	-	5,357	-	6,121	-	-	7,478	-
Engine Replacement Cost	-	-	-	-	9,345	-	-	-	12,204	-	-	14,909	-	-	-	19,469	-	-	-	25,425	-
Battery Replacement Cost	-	-	-	2,240	-	-	2,736	-	-	3,343	-	-	4,083	-	-	4,988	-	-	6,094	-	-
Fuel Cost	-	6,984	7,529	8,116	8,750	9,433	10,169	10,962	11,818	12,740	13,735	14,807	15,962	17,208	18,551	19,999	21,559	23,242	25,056	27,011	29,120
Battery O&M	-	44	47	50	53	57	61	65	69	74	79	85	91	97	104	111	118	127	135	145	155
Solar O&M	-	29	31	33	35	38	41	43	46	49	53	57	60	65	69	74	79	84	90	96	103
DG O&M	-	355	379	405	433	463	495	529	566	605	646	691	739	790	844	902	965	1,031	1,102	1,178	1,260
Grid Connection Cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Grid Cost	-	222	237	254	271	290	310	331	354	378	405	432	462	494	528	565	604	645	690	737	788
Grid O&M	-	29	31	33	35	38	41	43	46	49	53	57	60	65	69	74	79	84	90	96	103

Table 6.17: Cost component for On-Operational Site Model

	USD
TCO (NPV) (r=10%)	187,553
Initial Capex	3,750
Energy Cost / Month	453
Opex / Month	73.28
Replacement Capex / Month	240

6.5.3 Output of On-Operational Site Model

This on-operational site model provides a detailed graphical output of optimal operation process with the existing power equipment. Thus the user can derive the best way to run the site with its optimum power approach with the existing power equipment at the site.

Also annual cost components of the optimal process over a period of 20 years can be derived from the model output.

Output

Back to Input

	Total Cost of Ownership (TCO)	Initial Capex	Energy Cost / Month	Opex / Month	Replacement Capex / Month
VRLA AGM + DG + Grid+Solar	187,553	3,750.00	453	73	239.77

Components of TCO	VRLA AGM + DG + Grid+Solar	
Capex	3,750	2%
O&M	17,588	9%
Replacement	57,545	31%
Fuel	105,554	56%
Grid	3,117	2%

Solution Summary	VRLA AGM + DG + Grid+Solar	
Storage Type	VRLA AGM	Batteries
Battery Bank Capacity (Ah)	300	Ah
Battery Run Hours / Day	3.8	Hours / Day
Generation Type	DG	
Generator Size (kVA)	8	kVA
Generator Run Hours / Day	12.2	Hours / Day
Battery DoD %	70	%
Solar Panel Capacity	2	kW

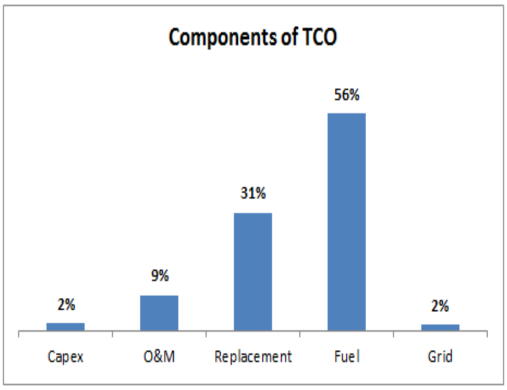


Figure 6.9: Dashboard of the Optimal Operational Process in On-Operational Site Model

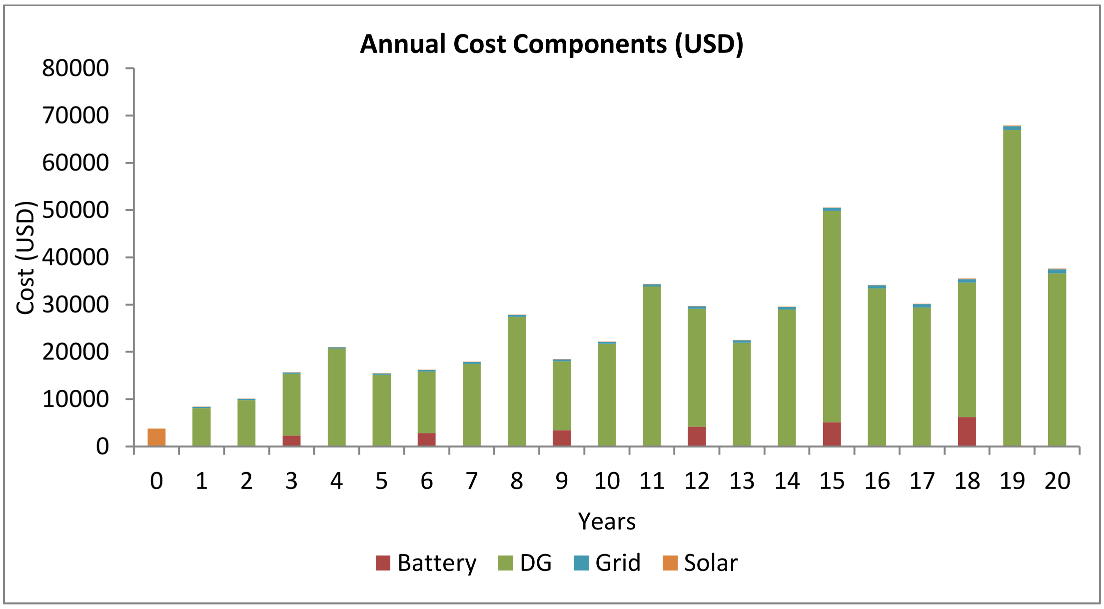


Figure 6.10: Annual Cost Components for the Optimal Operational Process in On-Operational Site Model

CHAPTER 7

Result Verification

Result verification has done with the on-operational site model at two selected on-air sites; Welimuwapotana Dialog site and Karandana Mobitel site.

7.1 Case 1 - Welimuwapotana Dialog

This site is a grid connected dialog owned site located at Anuradhapura district. The attempt was to check whether the current power operation process is the best way to run the site in order to optimize the energy opex cost per month.

Table 7.1: General Data of the Selected Site for Case Study 1

Site Name	Welimuwapotana Dialog
Region	North Central
District	Anuradhapura
Latitude \ Longitude	8.57125 \ 80.779
Site Category	Access
Indoor/Outdoor	Indoor
Site DC kW	1.7 kW
Power Connection	Grid
# phase	3
Capacity	30A
Grid Availability	22 hours per day
Tariff	GP1

Figure 7.1 : Installed 8kV Generator at Welimuwapotana Dialog Site

Table 7.2: Power Equipment Details Installed at the Site

Diesel Gen	Brand	Soar Power
	Capacity (kVA)	8
	Avg. Run Hours (Daily)	2
Cooling	Type of Cooling System	AC
	Make/Brand of Cooling Sys.	Panasonic
	Capacity	18k Btu / hr
	Energy Consumption (kW)	1.5
BB	Battery Type	AGM
	Make/Brand	Fiamm
	Capacity (Ah)	800
Rectifier	Make / Brand1	Delta
	Efficiency	92 %

Currently the site is powered by the grid power and the generator is on operation for no grid hours. Thus actually both electrical and diesel cost occur for this site. Actual electricity and diesel cost based on the utility bills and invoices for 7 months of period (from January 2015 to July 2015) as shown in Table 7.3.

Table 7.3: Actual Energy Cost of the Site From Jan to July 2015

	Jan	Feb	Mar	Apr	May	Jun	Jul	Average Cost / Month (LKR)
Electricity Cost	28,391	30,950	26,814	30,013	36,000	30,127	43,312	32,230
Diesel Cost	5,700	3,800	-	5,985	-	3,325	-	2,687

Energy cost per month = 34,917 LKR = 264.5 USD

Generator service cost (2 services/year) = 106.06 USD / year

Distance to site from fuel station = 20 km

Diesel transport cost = 18.18 USD / year

Opex cost / Month = 10.35 USD

Figure 7.2 : Installed 800Ah Fiamm VRLA Batter Bank at Welimuwapotana Dialog Site

Once the on-operation site model runs with this selected site parameter inputs, model output appears as Figure 7.3.

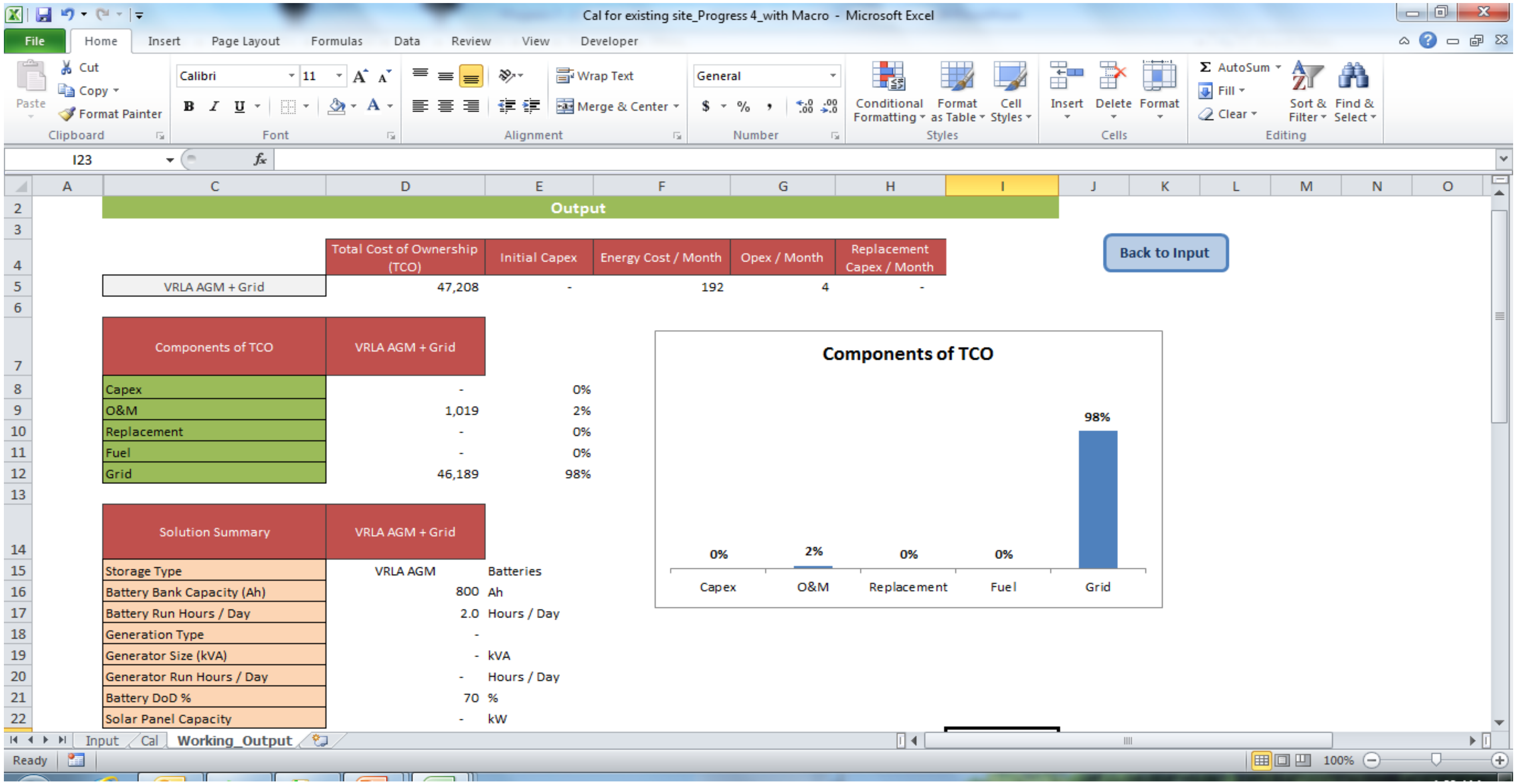


Figure 7.3 : On-Operation Model Output w.r.t. Welimuwapotana Site Inputs

According to the model output shown in Figure 7.3, even though a generator is installed already at the site, there is no requirement of run the generator. The installed battery capacity is sufficient to cater the site load when grid is unavailable at the ordinary process. Thus the generator need not run in normal operational process unless there is heavy power cut from grid.

Therefor it can be assumed that the current power operational process can be optimized following the model output, so that the considerable fuel cost can be saved per month.

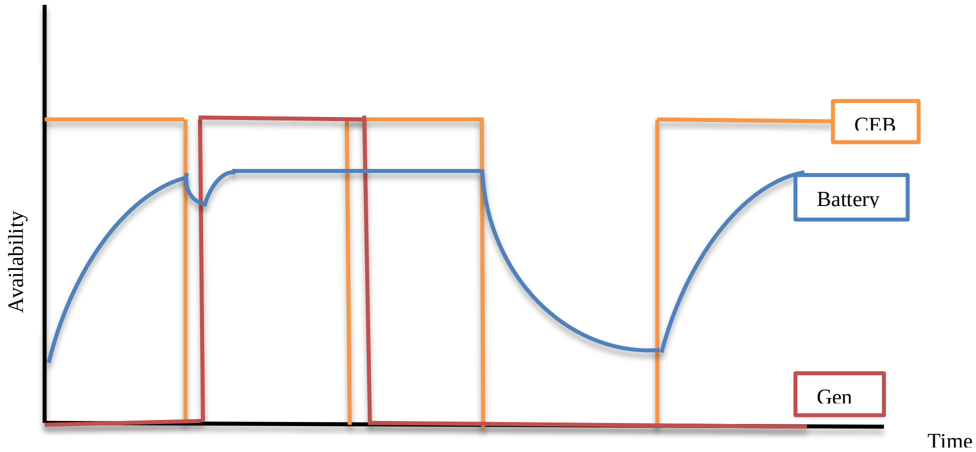


Figure 7.4 : Present Power Operational Process at Welimuwapotana Site

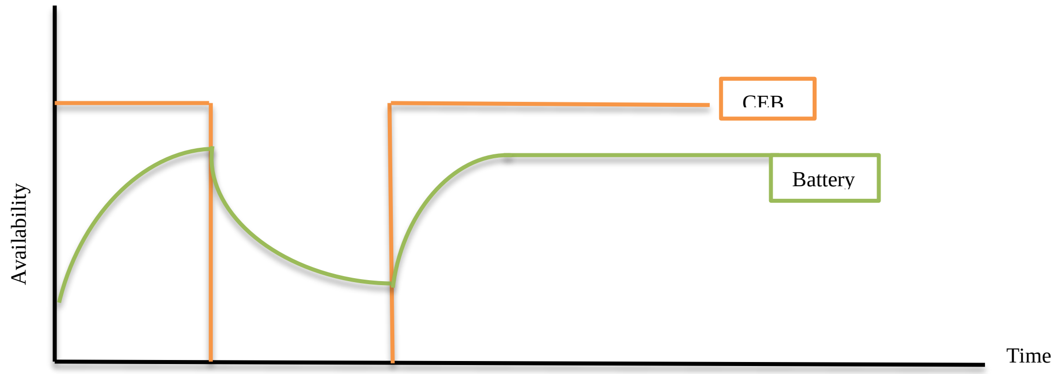


Figure 7.5 : Proposed Power Operational Process by Model for Welimuwapotana Site

With the proposed operation process shown in Figure 7.3,

Energy cost / month = 192 USD

Opex cost / month = 4 USD

7.2 Case 2 – Karandana Mobitel

This site is located in Rathnapura district where Dialog is sharing other operator's tower, but having owned power equipment. Site has no grid connection, thus powered by the generator and the batteries.

Currently site holds 300Ah VRLA AGM battery bank. The objective of this attempt was to test the performance of Li Ion batteries over existing VRLA AGM batteries and check whether the similar result can be derived as per the on-operational model output.

Table 7.4: General Data of the Selected Site for Case Study 2

Site Name	Karandana Mobitel
Region	Uva
District	Rathnapura
Site Category	Access
Indoor/Outdoor	Outdoor
Site DC kW	2 kW
Power Connection	Off-grid
Grid Availability	-

Table 7.5: Existing Power Equipment Details Installed at the Site

Diesel Gen	Brand	Tempest
	Capacity (kVA)	8
Cooling	Type of Cooling System	Free Cooling / Outdoor Fan
	Energy Consumption (kW)	0.1
BB	Battery Type	AGM
	Make/Brand	Fiamm
	Capacity (Ah)	300
Rectifier	Make / Brand	Eltek
	Efficiency	92 %

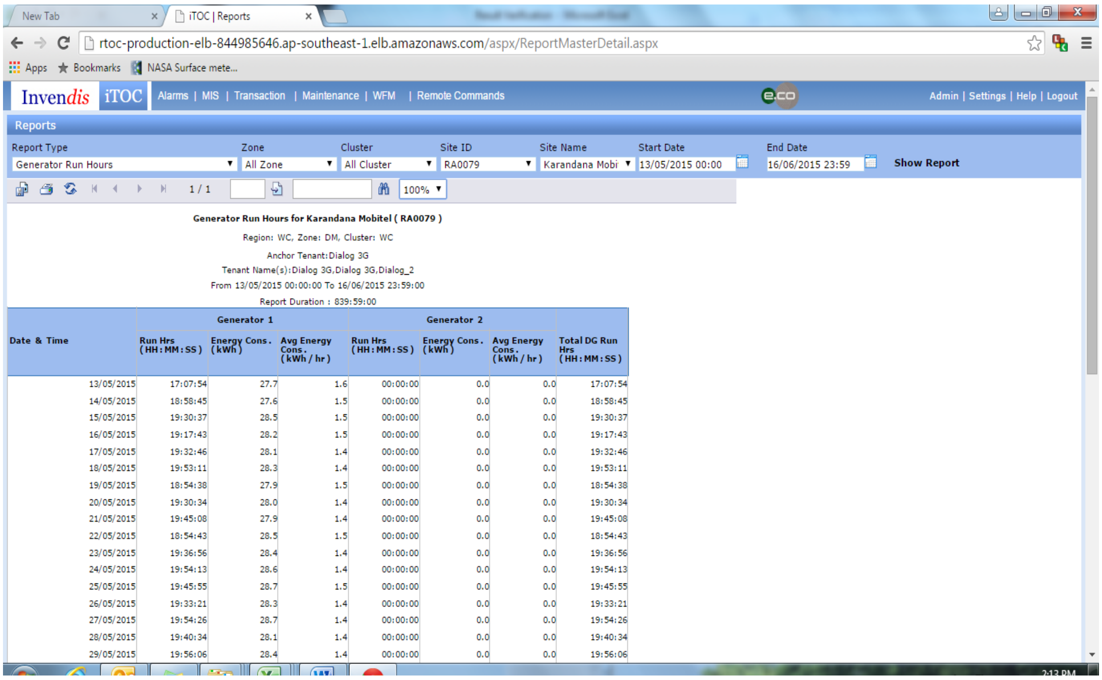
Figure 7.6 : Existing VRLA AGM 300Ah Battery Bank at Karandana Mobitel Site

Table 7.6: Test Period

	Start Date	Stop Date	Time Period (days)
VRLA Battery	13/02/15	25/02/2015	12 days
Li-Ion battery	13/05/15	16/06/15	35 days

Figure 7.7 : Tested Li Ion 300Ah Battery Bank at Karandana Mobitel Site

Generator meter readings for running hours were taken manually when VRLA AGM batteries were installed at the site. For Li Ion batteries, generator running hours were recorded by the Remote Monitoring System(RMS) installed at the Karandana Mobitel site, calling “iTOC”.



Date & Time	Generator 1			Generator 2			Total DG Run Hrs (HH:MM:SS)
	Run Hrs (HH:MM:SS)	Energy Cons. (kWh)	Avg Energy Cons. (kWh / hr)	Run Hrs (HH:MM:SS)	Energy Cons. (kWh)	Avg Energy Cons. (kWh / hr)	
13/05/2015	17:07:54	27.7	1.6	00:00:00	0.0	0.0	17:07:54
14/05/2015	18:58:45	27.6	1.5	00:00:00	0.0	0.0	18:58:45
15/05/2015	19:30:37	28.5	1.5	00:00:00	0.0	0.0	19:30:37
16/05/2015	19:17:43	28.2	1.5	00:00:00	0.0	0.0	19:17:43
17/05/2015	19:32:46	28.1	1.4	00:00:00	0.0	0.0	19:32:46
18/05/2015	19:53:11	28.3	1.4	00:00:00	0.0	0.0	19:53:11
19/05/2015	18:54:38	27.9	1.5	00:00:00	0.0	0.0	18:54:38
20/05/2015	19:30:34	28.0	1.4	00:00:00	0.0	0.0	19:30:34
21/05/2015	19:45:08	27.9	1.4	00:00:00	0.0	0.0	19:45:08
22/05/2015	18:54:43	28.5	1.5	00:00:00	0.0	0.0	18:54:43
23/05/2015	19:36:56	28.4	1.4	00:00:00	0.0	0.0	19:36:56
24/05/2015	19:54:13	28.6	1.4	00:00:00	0.0	0.0	19:54:13
25/05/2015	19:45:55	28.7	1.5	00:00:00	0.0	0.0	19:45:55
26/05/2015	19:33:21	28.3	1.4	00:00:00	0.0	0.0	19:33:21
27/05/2015	19:54:26	28.7	1.4	00:00:00	0.0	0.0	19:54:26
28/05/2015	19:40:34	28.1	1.4	00:00:00	0.0	0.0	19:40:34
29/05/2015	19:56:06	28.4	1.4	00:00:00	0.0	0.0	19:56:06

Figure 7.8 : iTOC recordings for the Test Period at Karandana Mobitel Site

Table 7.7: Observations

Description	Date	Generator Meter Reading	Time period	Total DG Run Hours	DG Run Hour/day
VRLA Battery	13/02/15	16962.56	12 days	257.86	21.5
	25/02/2015	17220.42			
Li-ion battery	13/05/15	Observed via RMS	35 days	678.26	19.4
	16/06/15				

According to Table 7.7,

Reduction of generator running hours / day = 21.5 – 19.4 = 2.1 hours / day

Reduction of Energy cost / month = 2.1 × 30 days × 95 / 133

= 45.5 USD / month

Next step was to compare the outputs using the implemented on-operational model, so that to check whether the similar saving can be obtained. The model runs twice with the same site input expect the battery type.

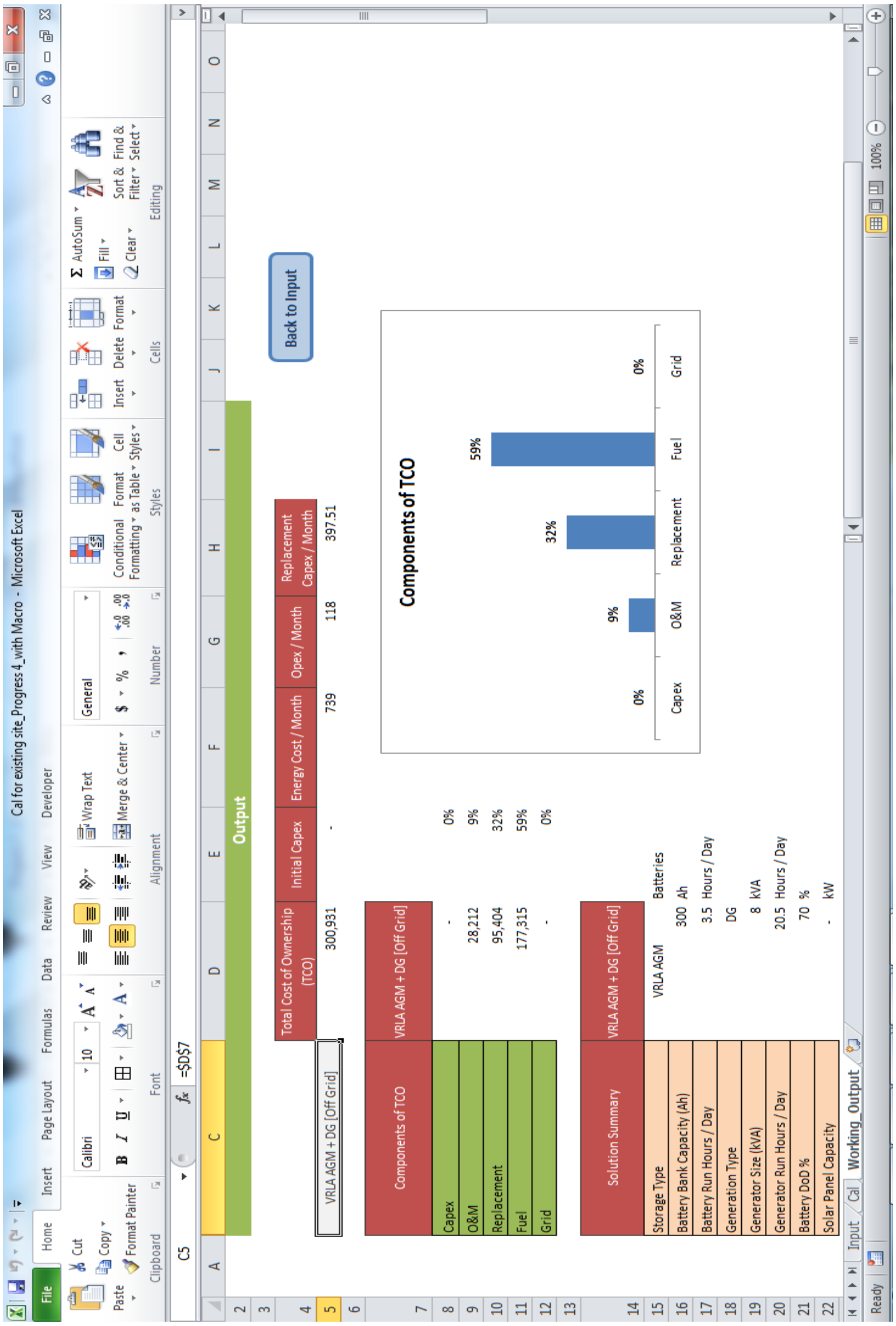


Figure 7.9 : On-Operational Model Output with VRLA AGM Batteries

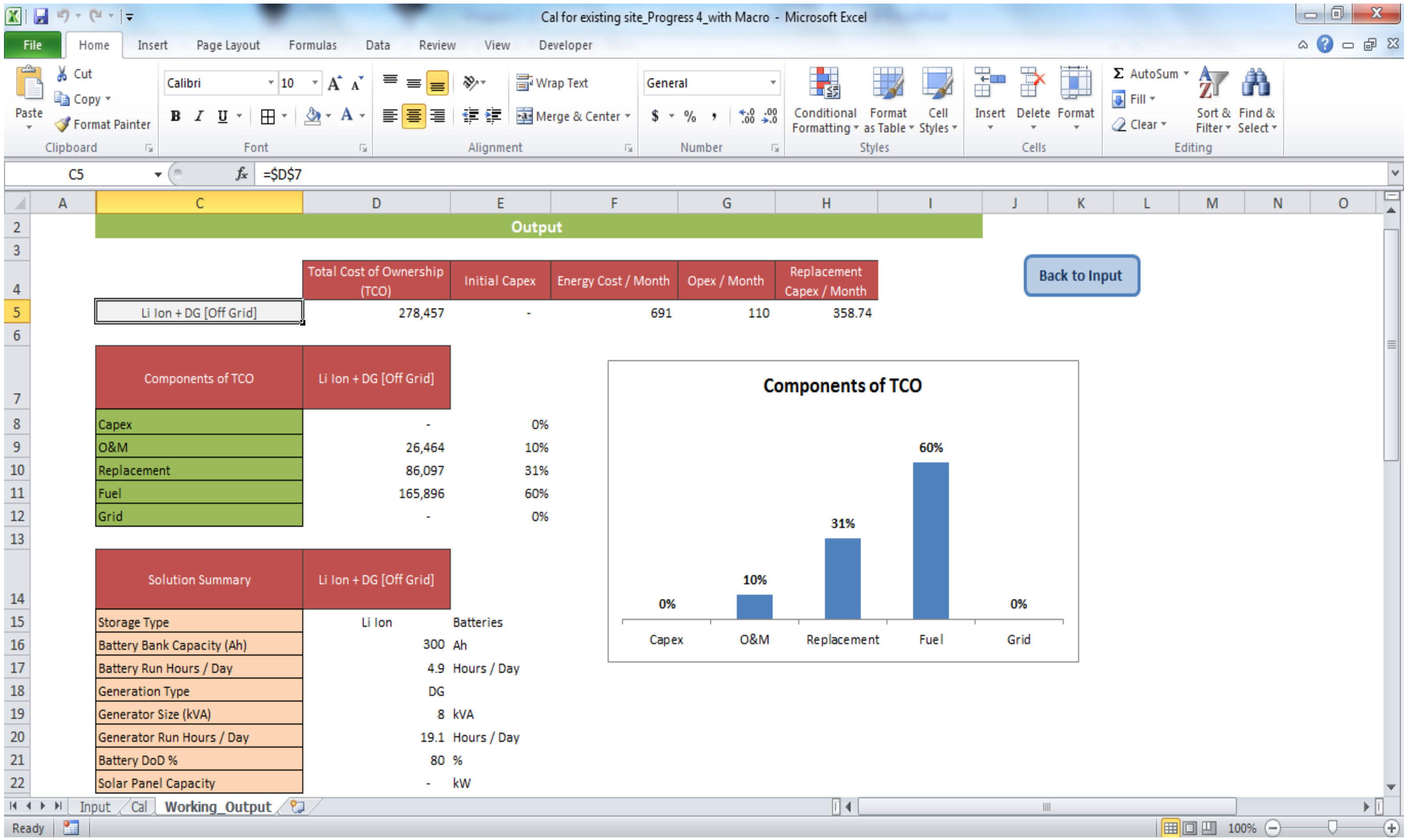


Figure 7.10 : On-Operational Model Output with Li Ion Batteries

According to Figure 7.8 & Figure 7.9,

Energy cost / month with VRLA AGM batteries = 738.8 USD / month

Energy cost / month with Li ion batteries = 691.2 USD / month

Reduction of energy cost = 738.8 – 691.2 = 47.6 USD / month

It is observed that, according to the implemented model, 47.6 USD saving in energy cost per month can be expected by replacing Li ion batteries over VRLA AGM batteries for this particular site which leads to have an optimal power model at the site.

From the actual tested results, the saving is 45.5 USD per month which is much similar to the saving observed via the model.

CHAPTER 8

Conclusion

8.1 Simulation Result Discussion

Simulation starts with conventional indoor BTS site. For easy comparison, the simulation is focused a site located in Colombo district with available space of $10m^2$, so as to bring out the importance of optimization.

Table 8.1 : Selected Site Parameters for Simulation

BTS Type	Indoor
District	Colombo
Rectifier Efficiency	92 %
Inverter Efficiency	95 %
Open Space Available	10 m^2
Average DC Load Factor	80 %
Average AC Load Factor	60 %

The focus is to compare the simulation results of the each parameter when the grid availability and the site peak DC load vary. Therefore start with the case where the site peak DC load is 2kW and the grid availability is 4 hours/day and then increase the grid availability for the particular peak DC load to see how the optimum combination results. Subsequently, the site peak DC load increases by 2kW and the result is compared with different grid availabilities.

8.1.1 Comparison for TCO

The summary of the result of the optimum configuration based on the Total Cost of Ownership (TCO) when the site peak DC load and the grid availability vary is given in Table 8.2

Table 8.2: Simulation Result of the Optimum Configuration based on TCO

Site Peak DC load kW						
8	Solar + Li Ion + DG	Solar + Li Ion	Solar + VRLA (AGM) + DG	Solar + VRLA (AGM)	Solar + VRLA (AGM)	Solar + Li Ion
6	Solar + Li Ion + DG	Solar + Li Ion	Solar + VRLA (AGM) + DG	Solar + VRLA (AGM)	Solar + VRLA (AGM)	Solar + Li Ion
4	Solar + Li Ion + DG	Solar + Li Ion	Solar + Li Ion	Solar + VRLA (AGM)	Solar + VRLA (AGM)	Solar + Li Ion
2	Solar + Li Ion + DG	Solar + Li Ion	Solar + Li Ion	Solar + VRLA (AGM)	Solar + VRLA (AGM)	Solar + Li Ion
Grid hours	4	8	12	16	20	24

It is important to compare the cost effect when the site power configuration differs from the best option which comes from the simulation output. In order to compare this, specific site DC load and grid availability have selected for the site parameters shown in Table 8.1.

By comparing the simulation result matrix shown in Table 8.2, it is observable that diesel generator is required only when the grid availability is low. If the grid availability is almost 24 hours/day, then the best combination to power up the site would be "Solar + Li Ion + Grid" for the selected site parameters. Deploying solar when there is space availability can be recommended for any site load and grid availability.

According to Table 8.2, the optimum power configuration for 2kW load & 20 grid hours/day is "Solar + VRLA (AGM) + Grid".

Table 8.3 presents the cost comparison of TCO for if any other configuration is deployed at the site with 2kW peak DC load and 20 grid hours /day.

Table 8.3: Cost Comparison of TCO with Other Configurations at 2kW DC load & 20 Grid Hours / Day

Configuration	TCO (USD)
Solar + VRLA (AGM) + Grid	49,008.54
VRLA (OPzV) + Grid	153,230.57
VRLA (AGM) + Grid	57,637.96
Solar + Li Ion + Grid	53,815.55
Li Ion + Grid	62,444.97

According to the simulation result, use of VRLA (AGM) batteries along with solar and grid the optimum solution for the particular site with selected parameters of 2kW peak DC load and 20 hours of grid availability, which occurs TCO of 49,008.54 USD.

If the site is deployed only with VRLA (AGM) along with grid without deploying solar (57,637.96 USD), TCO will increase by 15%. Also use of VRLA (OPzV) batteries (153,230.57 USD) will increase the TCO by 68%.

Thus the user can finalized the best option for powering up the site and also able to compare the effect of other configurations as well.

8.1.2 Comparison for Initial Capex

The summary of the result of the optimum configuration based on the initial capex when the site peak DC load and the grid availability vary is given in Table 8.4

Table 8.4: Simulation Result of the Optimum Configuration based on Initial Capex

Site Peak DC load kW \ Grid hours	4	8	12	16	20	24
8	VRLA (AGM) + DG	VRLA (AGM) + DG	VRLA (AGM) + DG	VRLA (AGM)	VRLA (AGM)	Li Ion
6	VRLA (AGM) + DG	VRLA (AGM) + DG	VRLA (AGM) + DG	VRLA (AGM)	VRLA (AGM)	Li Ion
4	VRLA (AGM) + DG	VRLA (AGM) + DG	VRLA (AGM) + DG	VRLA (AGM)	VRLA (AGM)	Li Ion
2	VRLA (AGM) + DG	VRLA (AGM) + DG	VRLA (AGM) + DG	VRLA (AGM)	VRLA (AGM)	Li Ion

In order to optimize the initial Capex at the site, diesel generator is required when the grid availability is less than 12 hours/day for any load condition. Even though the space is available for solar, the model is not recommended to deploy solar for any selected DC load or grid availability. If the grid availability is almost 24 hours/day, then the best combination to power up the site would be "Li Ion + Grid" only for the selected site parameters for optimal usage of initial Capex.

According to Table 8.4, the optimum power configuration for 2kW load & 20 grid hours/day is "VRLA (AGM) + Grid". At the same time, the cost effect of initial Capex by using other configuration than the optimum solution is shown in Table 8.5.

Table 8.5: Cost Comparison of Initial Capex with Other Configurations at 2kW DC load & 20 Grid Hours / Day

	Initial Capex (USD)	% of Capex increment w.r.t. optimum configuration
VRLA (AGM) + Grid	8,955.11	
Solar + VRLA (AGM) + Grid	12,705.11	30%
VRLA (OPzV) + Grid	50,635.11	82%
Solar + Li Ion + Grid	17,785.11	50%
Li Ion + Grid	14,035.11	36%

8.1.3 Comparison for Opex / Month

The summary of the result of the optimum configuration based on the opex per month when the site peak DC load and the grid availability vary is given in Table 8.6

Table 8.6: Simulation Result of the Optimum Configuration based on Opex/month

Site Peak DC load kW						
8	VRLA (OPzV) + DG	Li Ion	VRLA (OPzV)	VRLA (OPzV)	Li Ion	Li Ion
6	Li Ion+ DG	VRLA (OPzV)	LI Ion	VRLA (OPzV)	VRLA (OPzV)	Li Ion
4	Li Ion+ DG	Li Ion	VRLA (OPzV)	VRLA (AGM)	VRLA (AGM)	Li Ion
2	Li Ion+ DG	VRLA (OPzV)	Li Ion	Li Ion	VRLA (OPzV)	Li Ion
Grid hours	4	8	12	16	20	24

8.1.4 Comparison for Energy Cost/ Month

The summary of the result of the optimum configuration based on the energy cost per month when the site peak DC load and the grid availability vary is given in Table 8.7

Table 8.7: Simulation Result of the Optimum Configuration based on Energy Cost/month

Site Peak DC load kW						
8	Solar + Li Ion + DG	Solar + Li Ion	Solar + Li Ion	Solar + Li Ion	Solar + Li Ion	Solar + Li Ion
6	Solar + Li Ion + DG	Solar + Li Ion	Solar + Li Ion	Solar + Li Ion	Solar + Li Ion	Solar + Li Ion
4	Solar + Li Ion + DG	Solar + Li Ion	Solar + Li Ion	Solar + Li Ion	Solar + Li Ion	Solar + Li Ion
2	Solar + Li Ion + DG	Solar + Li Ion + DG	Solar + Li Ion	Solar + Li Ion	Solar + Li Ion	Solar + Li Ion
Grid hours	4	8	12	16	20	24

8.1.5 Comparison for Replacement Cost/ Month

The summary of the result of the optimum configuration based on the replacement cost per month when the site peak DC load and the grid availability vary is given in Table 8.8

Table 8.8: Simulation Result of the Optimum Configuration based on Replacement Cost/month

Site Peak DC load kW						
8	Li Ion+ DG	Li Ion	Li Ion	Li Ion	Li Ion	Li Ion
6	Li Ion+ DG	Li Ion	Li Ion	Li Ion	Li Ion	Li Ion
4	Li Ion+ DG	Li Ion	Li Ion	Li Ion	Li Ion	Li Ion
2	Li Ion+ DG	Li Ion	Li Ion	Li Ion	Li Ion	Li Ion
Grid hours	*4*	*8*	*12*	*16*	*20*	*24*

8.2 Conclusions from Trials

Two tests were carried out at two separate site locations in order to check the implemented model can be used to identify the optimum power model or operational process for a particular location.

By comparing the actual data observed at the trials, following conclusions can be concluded.

- As recommended by the implemented on-operational model, 27% saving from energy cost per month & 61% saving from opex cost per month can be achieved by disconnecting the diesel generator at Welimuwapotana Dialog site since the existing battery bank is sufficient to power up site for typical non grid hours.

Table 8.9: Saving Percentages Expected at Welimuwapotana Dialog Site

	Actuals with current setup at the site	With the proposed optimal process by the model	Reduction of Cost USD	Saving %
Energy Cost / Month (USD)	264.5	192	72.5	**27%**
Opex Cost / Month (USD)	10.35	4	6.35	**61%**

- According to on-operational model output, 6% saving (47.6 USD) energy cost per month can be achieved by using Li Ion over VRLA AGM at Karandana Mobitel site.
- From the tested trials, it can be observed 45.5 USD saving per month from energy cost at the site where the equal saving can demonstrate by the developed model.

Table 8.10: Saving Comparison at Karandana Mobitel Site

	From Trial	From Model
Saving from Energy Cost /Month (USD)	45.5	47.6

The saving percentage will be depend with the conditions of the particular site (load, grid availability etc.), so that the implemented model can derive the location specific optimum solutions for the sites.

It is recommended to use this develop model to identify the optimum way of using power equipment as per the site conditions for the newly constructing telecom base stations in future. Furthermore this can be used to obtain the optimal power operational process with the already existing equipment for currently on-operational sites.

8.3 Limitations

Whilst the findings of the study could be applied in most instances, there will some important exceptions where the optimal design of the energy system could be different or the recommendations would not be applicable.

In particular, if the site is operated for a long period, power equipment that already installed at the sites may have depreciated with years. In case, the equipment ratings that user inputs to the model (battery bank Ah capacity, generator kVA rating etc.) may not the actual accurate values. Thus the outcome values for the solution can be increased in actual scenario.

Furthermore, as the sites are located all over the country, there can be places where we have the access difficulties. So before deploying the optimum solution for the site, it is important to consider the potential of arrange portable generators or additional battery backups in case of emergency.

Thus it is important to acknowledge the limitations of this study openly in order to uphold an uninterrupted service as well.

8.4 Suggestion for Further Study

Continuous research is essential to come up with further solutions even in future with the innovative use of the new technology.

Sustained study on new battery technologies like Nickel Cadmium, Sodium Nickel Chloride is required to find the viability of deploying them on telecom RBS sites in order to reduce Opex cost further. Also the feasibility of technologies like DC air conditioners, DC diesel generators, fuel cells can be explored to power up sites as new solutions.

Furthermore effect of the carbon footprint due to the site specific solutions is another key area to study in time ahead as it is much important same as the energy cost reduction.

References :

[1] “Monthly Energy Cost Tracker,” Dialog Axiata PLC, Colombo, Sri Lanka, 2014, unpublished.

[2] W. Balshe, “Power system considerations for cell tower applications,” Cummins Power Generation, Power topic 9019, 2011.

[3] G. Koutitas and P. Demestichas, “A Review of Energy Efficiency in Telecommunication Networks,” *Telfor Journal,* Vol. 2, No. 1, pp 02 – 07, 2010.

[4] A. D. Sams, “Various Approaches to Powering Telecom Sites,” in *IEEE 33rd International Telecommunications Energy Conference (INTELEC)*, Amsterdam, 2011, pp. 01-08.

[5] Q. Han, “Data-telecom Power System Solution Based on Reliability Analysis,” in *IEEE 29th International Telecommunications Energy Conference 2007 (INTELEC)*, Rome,2007, pp 917 – 922.

[6] A. Kwasinski and P. T. Krein, “Optimal Configuration Analysis of a Microgrid-Based Telecom Power Systems,” in *INTELEC 06 - Twenty-Eighth International Telecommunications Energy Conference*,2006, pp 01-08.

[7] J. Brunarie et al., “Delivering Cost Savings and Environmental Benefits with Hybrid Power,” in *INTELEC 2009 - 31st International Telecommunications Energy Conference*, Incheon, 2009, pp 01-09.

[8] M Muselli et al., “PV – hybrid systems sizing incorporating battery storage : an analysis via simulation calculations,” in *Renewable Energy, Volume 20, Issue 1*, May 2000, pp 01-07.

[9] W. D. Kellogg et al., “Generation unit sizing and cost analysis for stand-alone wind, photovoltaic, and hybrid wind/PV systems,” in *IEEE Transactions on Energy Conversion*, March 1998, Vol.13, Issue 1, pp 70-75.

[10] K.C. Wijesinghe, "Feasibility Study On Solar Pv Integration in to the Celluler Mobile Telephony Base Station Sites," M.Sc Thesis, Elect. Installations, Dept. of Elect. Eng., Univ. of Moratuwa, Moratuwa, Sri Lanka 2013.

[11] A. Jhunjhunwala et al. "Powering Cellular base Stations," Telecom Center of Excellence (RiTCOE), Indian Institute of Technology, Madras, 2012.

[12] (2015, Oct). *NASA Surface meteorology and Solar Energy - Location* [Online]. Available: https://eosweb.larc.nasa.gov

[13] (2015, July). *Tariff Plan* [Online]. Available: http://www.ceb.lk/for-your-business/