PARAMETRIC ADAPTIVE MODEL FOR OPTIMUM ELECTRICAL SYSTEM CONFIGURATION IN TELECOMMUNICATION BASE STATIONS CONSISTING OF DIESEL GENERATORS, LI-ION BATTERY BANKS AND SOLAR PHOTOVOLTAIC

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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. I retain the right to use this content in whole or part in future works (such as articles or books).

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The above candidate has carried out research for the Master of Science by Research Thesis under my supervision. I confirm that the declaration made above by the student is true and correct.

Name of Supervisor: Prof. D.P. Chandima

Signature of the Supervisor: Date: 15/06/2025

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ABSTRACT

With the rapid development of next generation telecommunication devices and applications, demand for reliable, wider coverage and speed telecommunication networks has been a fundamental infrastructure prerequisite around the globe. For a highly reliable and wider coverage, the electrical system of the telecommunication base station should have the capacity to effectively maintain an uninterrupted power supply for smooth operations of radio and cooling equipment of the telecommunication base station. Development and operations of electrical systems for a network operator typically cost in the range of 20% to 30% of the total cost of ownership of a telecommunication network. Therefore, a significant impact on the bottom-line targets of the network operator can be achieved by evaluating the impact of optimization of power infrastructure deployed in telecommunication base stations.

In this research, a parametric approach has been discussed to quantify multi dimensional characteristics affected when determining the optimum electrical system configuration for telecommunication base stations. Results of the proposed model have highlighted that when functional constraints become strict, the optimization model changes its proposed configuration with higher Levelized Cost of Energy (LCOE) with a change ranging from 5.7% to 15.3% which indicated the adaptive behaviour of the model. Further from the results, it is evident that the increase in expected network availability leads to an exponential increase in LCOE in the proposed electrical system which indicates the importance of correct benchmarking of the expected network availability of considered base station. When it comes to the behaviour of LCOE within the optimization model, even when 100% network availability is considered and when grid availability is dropped to 89.5%, LCOE of proposed optimum electrical system configuration maintained under 0.1 $/kWh, compared to the industry average of between 0.15 $/kWh to 0.3 $/kWh for a typical hybrid electrical system consisting of diesel generator, li-ion battery bank and solar Photovoltaic.

Keywords: Telecommunication Base Station, Genetic Algorithm Optimization, Hybrid Energy System, Adaptive Optimum Sizing, Network Availability

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LIST OF ABBREVIATIONS

Abbreviation	Description
AC	Alternating Current
BMS	Battery Management System
BOS	Balance of System
BSS	Battery Storage System
Capex	Capital Expenditure
DC	Direct Current
DG	Diesel Generator
EMU	Energy Management Unit
ITU	International Telecommunication Union
LCOE	Levelized Cost of Energy
LOLP	Loss of Load Probability
LPSP	Loss of Power Supply Probability
MPPT	Maximum Power Point Tracking
Opex	Operational Expenditure
PV	Photovoltaic
ROI	Return on Investment
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index

CHAPTER 1

INTRODUCTION

The telecommunications sector has been a fundamental pillar for the development of modern society which drives the backbone of global connectivity, innovation, public security, healthcare, entertainment, economy, education and in countless other aspects. With the introduction and development of 5G technology, surge in usage of mobile devices and applications is inevitable which demand higher bandwidth, speed and most importantly reliable connectivity of network with 100% availability [1]. To ensure reliable and efficient network performances, uninterrupted power supply is essential for telecommunication base stations.

However, development and maintaining power infrastructures in telecommunication cost for network operators in the scale of 20% to 30% of overall cost which is the largest cost component incurred on a single domain. Therefore, a considerable impact on the bottom-line targets of the telecommunication network can be achieved through optimization of power infrastructure of telecommunication base stations. The saturation of revenues generated by voice and data services, while increasing cost of development and operations activities in telecommunication networks has been a key confront to encourage network operators to review its investments strategies in the network [2]. To be competitive with rivals in the industry, it is essential to utilize available resources in an optimum approach with a trade-off in both efficiency and effectiveness. In this research, a parametric approach has been discussed to quantify multi-dimensional characteristics affected when determining the optimum configuration of electrical system of telecommunication base stations.

1.1 Problem Statement

Cost elements involved in the development and operations of a telecommunication network can be categorized into two types, Capital Expenditures (capex) and Operational Expenditures (opex). However, among the sub cost elements of capex and

Opex, as elaborated in Figure 1.1, the highest and common cost contributor to both capex and opex is the cost spent on Power Infrastructure in telecommunication base stations. Percentages of capex and opex involved in power infrastructure of a typical telecommunication base station, are approximately 30% and 21% respectively, which is intensive cost element for an individual domain in development and operations of telecommunication base station.

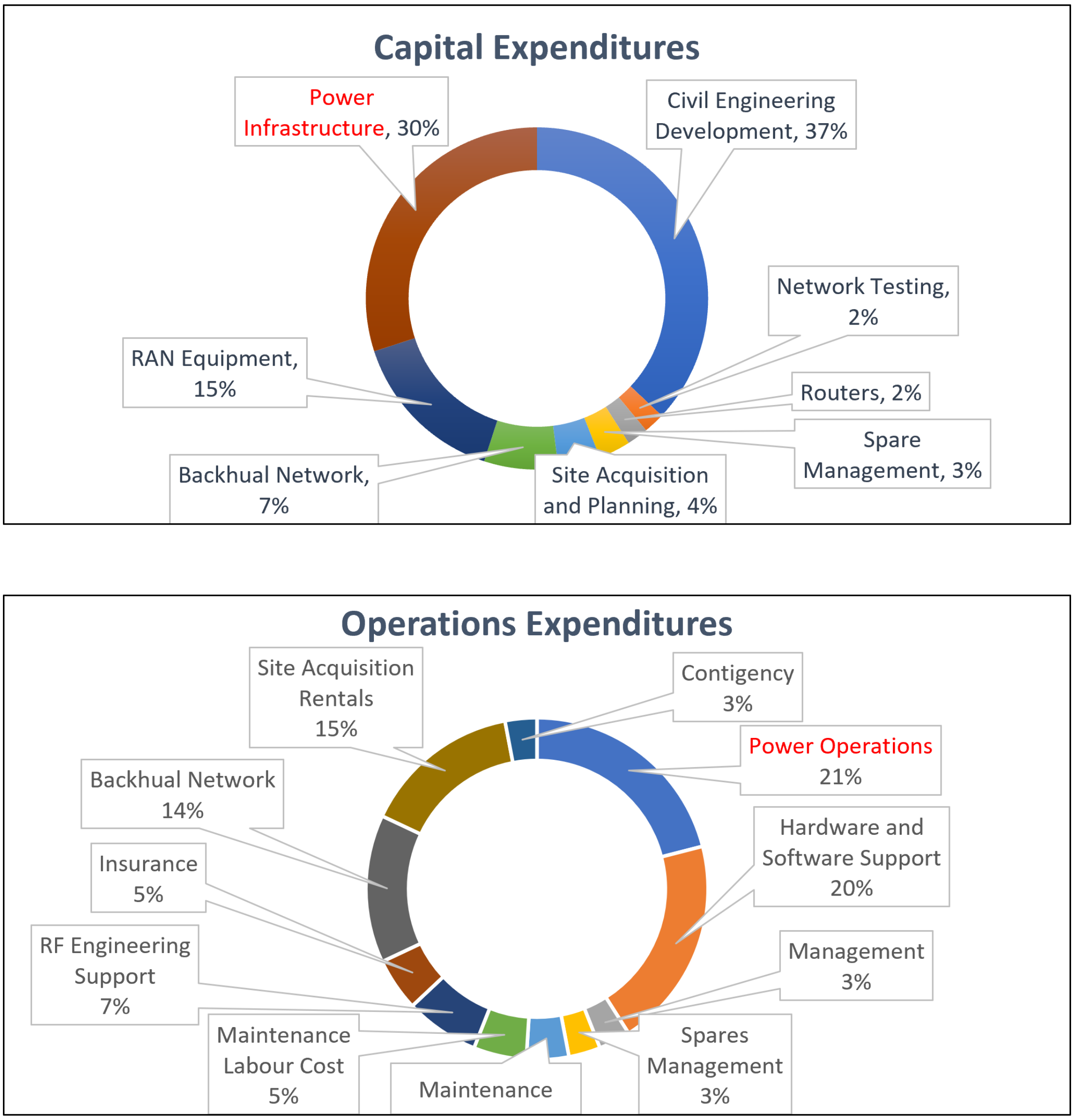


Fig. 1.1: Capital and Operational Expenditures of Telecommunication Network

Source:[3]

Reliable and uninterrupted power supply is paramount important to ensure continuous and smooth operations of electronic processing equipment and amplifiers deployed in telecommunication base stations. To provide a quality and reliable network service to subscribers with wide coverage, mobile network operators are extensively investing in capital expenditures for rolling out power infrastructures and operational expenditures for maintenance activities in the network without thorough assessment of optimum configurations with extended economic benefits for higher Return on Investment (ROI).

Recent literature reviews reflect that most of the scholars are also focused on more generalized models for optimizing power infrastructures of telecommunication base stations considering constant and unique power system characteristics [4],[5]. However, next generation telecommunication base stations are designed focusing on the balance of both efficiency and effectiveness, hence adaptive optimization strategies and models will be widely focused to propose the best and optimum electrical system configuration appropriate to each individual base station by considering important characteristics of telecommunication base station listed below.

- Network Availability [6]
- Geographical positioning and base station load profiles [7]
- Regulatory, functional and technical feasibility and constraints on power infrastructural development [5],[3]
- Grid power availability and modelling (Novelty in this research)
- Social revenue and economic revenue [8]

The motivation of this research is to study and discuss all the above-mentioned important multi-dimensional characteristics in detail and quantify these characteristics using parametric indices and consider through system constraints for the optimization model to explore the most optimum configuration for electrical system in telecommunication base station. The main component considered in the optimization of electrical system will Solar Photovoltaic (PV), Battery Storage System (BSS) and Diesel Generator (DG).

1.1.1 Network Availability

According to the International Telecommunication Union (ITU), network availability is defined as ability of functional unit to be defined state to accomplish a vital objective under the given circumstances and time over considered time interval, given that the required resources are adequately provided [9]. In simple terms, as elaborated in Eq. 1.1, network availability defines the percentage between network actual uptime divided by the total time duration which network is expected to be up and running [9]. The actual uptime of the network is calculated from the difference between the total time duration considered and the downtime of the network during the considered period.

$$Network\ Availability = 1 - \frac{Downtime\ of\ the\ network}{Total\ time\ duration\ considered} \tag{1.1}$$

1.1.2 Geographical positioning and base station load profiles

The geographical location of a telecommunication base station is a major parameter which determines the behaviour of traffic load depending on the time of the day, day of the week and month of the year in consideration in the analysis [7]. If the base station is located near to an industrial zone, most of the data and call traffic will be concentrated to daytime of a working day and during holidays, data and call traffic load will be significantly reduced. In contrast, if telecommunication base stations are located around domestic non-urban territory, data and call traffic load will be significantly reduced during the daytime of a working day and on holidays, data and call traffic load will be increased during daytime. This behaviour is mainly occurring due to movement of subscribers for their day-to-day activities around different locations, depending on the considered time day and month [10], [11], [12], [13].

On the other hand, Electrical power consumption, network data and call traffic load of telecommunication base station have direct relationship [14], hence same pattern of data and call traffic load variation will affect the electrical load profile of the base station. Therefore, geographical location of the base station is key parameter when determining an optimum configuration of electrical system configuration for telecommunication base station.

1.1.3 Regulatory, functional and technical feasibility and constraints on power infrastructural development

Most prominent challenges in development of electrical system infrastructure for a telecommunication base station can be identified as regulatory and functional restrictions such as space and logistics restrictions [15]. Telecommunication base stations deployed in urban cities are often developed on top of roofs of high raised buildings and acquiring a roof space could be even challenging in some commercial buildings and alternatives are also limited due to restrictions on limited radius of target coverage to be achieved [16].

On the other hand, regulatory approvals such as permits for land, aviation clearances and environmental authority clearances can be other challenges which could limit the degree of freedom on development of desired electrical system for the proposed base station [3]. Logistics challenges can constrain the development and operations of electrical system infrastructures. Most of the base stations deployed on mountain terrains are developed on hill tops for better coverage, which makes access and transportation extremely difficult for breakdown maintenances, fuel fillings and transportation of heavy power equipment such as generators which could introduce unforeseen cost to the overall capex and opex indicators of the electrical system [17].

Therefore, regulatory and functional constraints need to be considered as input parameters for the parametric model when determining optimum electrical system which is practical feasible to achieve expected ROI under given constraints. Further technical constraints on designing electrical systems can be identified as correct cable sizes, maximum power ratings, operating temperature ranges, manufacturer recommendations and system stability. Most of the time technical constraints can be overcome with appropriate engineering solutions.

1.1.4 Grid power availability and modelling

Utility grid power can be unavailable due to numerous reasons and all such reasons can be categorized into scheduled and unscheduled power interruptions. Scheduled power interruptions are usually triggered by utility service providers targeting grid network development and routine maintenance activities in the network. Scheduled power interruptions are acknowledged by utility service providers in advance to their consumers for early preparedness and duration of the outage is limited to predefined time frame and with defined number of occurrences.

In contrast unscheduled power cuts may occur at any given time without prior acknowledgment regardless of the situation. Unscheduled power cuts may occur due to natural and man-made events. Natural events lead to grid power failures can be identified as lightning, wind, rain, ice storms, electromagnetic solar waves and collapsing physical structures on to the distribution lines [18]. The occurrences of natural events are mainly determined by the weather conditions and other natural characteristics of the considered geographical location where the grid power is accessing, and these characteristics can be changed across different geographical locations.

On the other hand, man-made events for grid power unavailability can be identified as poor routine maintenances in the grid by utility service provider, road accidents, underground power cable damages due to road excavations and non-standard electrical installations.

When considering these causes for power interruptions, it is evident that the occurrence of most of these interruptions cannot be predict with 100% accuracy. However, based on the past behaviour of the grid, utility service providers are defining probabilistic parameters which can be used to get idea on nature of grid power availability in considered geographical areas. Most of these indices are developed by probabilistic techniques [19]. In this research, it is expected to use these probabilistic indices to mathematically model the grid power behaviour to incorporate that into the optimization algorithm to explore optimum electrical system configuration for telecommunication base stations.

1.1.5 Social and Economic Revenue

Telecommunication services generate mainly two types of revenue which can be identified as social and economic revenues. Social revenue is a qualitative measure which indicates how network service providers contribute to societal needs and how society values its contribution in return. Efforts taken in maximizing social revenue by network operators can be sometimes a voluntary project implemented as a cooperate social responsibility targets and sometimes it is implemented as an obligation assigned as government mandated.

The importance of telecommunication services emerged during the COVID 19 pandemic when people restrained within homes causing higher demand on telecommunication services decentralize from urban to domestic and rural areas. Telecommunication networks development in rural areas are not always cost effective due to its associated cost in development of infrastructure, which is negatively impacting for the ROI with lesser utilization of network due to minor economic activities and low density of population [3]. However, network operators were voluntarily invested in development of the network to fulfil network coverage for rural areas, which in return generates social revenue for the network operator. Therefore, it is important to identify sources and groups having higher potential of social revenue generation such as education, health and security, so that network operators can utilize their resources in a way that maximizes the social revenue.

In contrast, economic revenue is measured purely based on financial indicators where the achievement of bottom-line targets of the network operators is focused. To achieve economic revenue targets, available resources are utilized in areas where higher potential of ROI is expected.

1.2 Research Objectives

The main objective of this research is to identify the optimum electrical system configuration for telecommunication base stations to achieve Expected Network Availability against different combinations of power sources and load profiles.

1.3 Specific Objectives

Specific objectives considered in this research which highlight the roadmap in achieving the main objective of the research are elaborated in Figure 1.2.

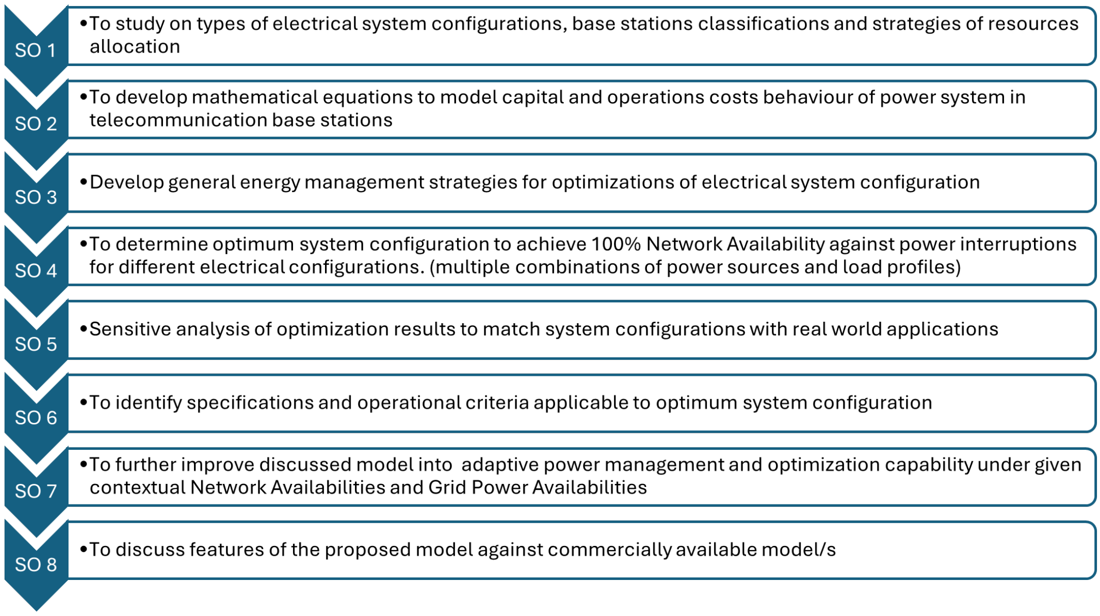


Fig. 1.2: Specific Objectives

1.4 Electrical System Configuration in a Typical Telecommunication Base Station

Electrical system is a crucial sub system in a telecommunication base station to ensure uninterrupted, reliable and smooth power supply to the sensitive radio equipment and cooling devices [20]. Block diagram of a typical electrical system configuration in telecommunication base station is illustrated in Figure 1.3. The electrical system of a typical telecommunication base station is an integration of several electrical sub systems such as main power sources, redundancy power sources, rectifier system with power management unit, BSS, cooling system, and power distribution systems. Main power sources for a grid connected telecommunication can be considered as grid power and renewable sources such as solar PV power.

For a grid connected telecommunication base station, deployment of DG is considered as redundancy source of power due to its high-cost intensity in terms of operations and maintenance compared to per unit cost of energy supplied by grid [21]. For a telecommunication base station with the off-grid configuration where grid power is unavailable or not feasible to access, solar PV and DG can be considered as primary sources of power in electrical system [22].

The rectifier system can be identified as the integration unit of all electrical sub systems in a telecommunication base station. The primary function of a rectifier system is the conversion of Alternating Current (AC) into Direct Current (DC) with 48V [5]. Modern rectifier systems deployed in telecommunication base stations are incorporated with integrated features such as smart remote monitoring and controlling, Maximum Power Point Tracking (MPPT) of solar PV output, Battery Management System (BMS) and environmental alarms of the electrical system.

BSS in an electrical system of telecommunication base station is coupled with DC bus bar of the rectifier and delivers two main objectives. The principal objective of deploying a battery storage system in the electrical system of a telecommunication base station is to ensure uninterrupted power supply to radio and cooling equipment when primary and redundancy power sources are unavailable [20]. The second objective is to facilitate smooth transition among primary and redundancy power sources in the electrical system and absorb any fluctuations in primary and redundancy power sources for smooth output with -48V voltage regulation in the DC bus bar [23].

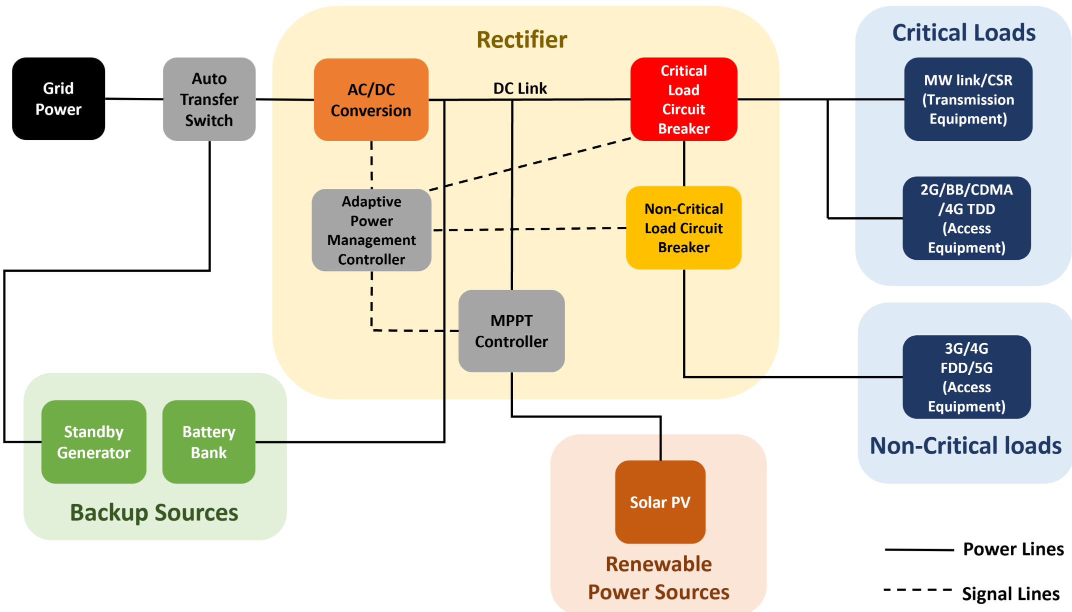


Fig. 1.3: Typical Electrical System Configuration of Telecommunication Base Station

1.5 Thesis Outline

The outline of the thesis can be summarized as follows. Chapter 2 summarizes a detailed literature review on other strategies and approaches on optimization of electrical systems in telecommunication base stations. Chapter 3 summarizes the approach on developing objective function and mathematical equations to model the proposed electrical system into optimization algorithm. Chapter 4 summarizes the system constraints and energy management strategy evaluated within the optimization algorithm. Chapter 5 summarizes the details of parameters considered for operational constraints, electrical loads, grid power behaviour, network availability benchmarks and technical parameters of all electrical system components considered for optimization. Chapter 6 elaborates a detailed discussion on optimization approach and configurations of the MATLAB optimization toolbox to execute the developed code which contains the fitness function and constraints of optimization problem. Chapter 7 summarizes the results of the optimization and discussion of each scenario of electrical system considered within the optimization. Finally, Chapter 8 summarizes the conclusions of this research study and how its results support on the achievement of research objective.

CHAPTER 2

LITERATURE REVIEW

The study [24] has proposed and discussed a model which can reduce the cost of operations in telecommunication base stations by using strategies to minimize the power consumption of electrical systems. The discussed model in study [24], authors have highlighted three types of configurations in the electrical system in determining optimized solutions. The first configuration is grid as primary source of power with BSS and no DG backup in the system (configuration 1). The second configuration is grid power as primary source of power with BSS and integrating generator as redundancy power source (configuration 2). The third configuration is configuration with grid power and solar PV as primary source with BSS and no DG in the electrical system. Under the pre-defined constraints, these three configurations were analysed using the proposed model for the parameters of actual user case.

Based on the results of proposed model in the study [24], authors have determined that configuration 2 can deliver uninterrupted power supply for the telecommunication base station for a continuous grid power unavailability of 8 hours, which is the best-case scenario compared to other two configurations. In terms of operations cost, deploying configuration 2 will incur an operations cost of $12.86 per day which is comparatively higher than that of configuration 1 and configuration 3 where the operations costs are $12.44 and $10.56 respectively. Although configuration 3 has the lowest operations cost, reliability of electrical system is very less specially when solar power is unavailable and grid power interruption is extended to long period. Based on the conclusions of this study, research is mostly focused on minimizing operational cost while increasing reliability of the electrical system for an 8-hour long grid power unavailability and has justified the feasibility of specific configuration generalized to all similar base stations. However, this research has not given appropriate stress on the impact of geographical positioning, variation of base station load profiles, practical constraints of power infrastructure development and social revenue when deciding the optimum configuration. There can be infrastructural constraints in deploying DG in telecommunication base stations such as space restrictions and access restrictions due to difficult terrains with hill tops and mountains, which will cause effective operation costs to be raised beyond the initial estimations and proposed configuration become less feasible.

The study [25] has proposed and discussed strategies on energy saving in telecommunication base stations to minimize the operations cost by reducing electricity usage through the utility grid. In study [25], authors mainly focus on the possibility of saving energy by switching off power to the radio equipment when network traffic of base station reaches zero. Authors in their research results have observed 19% saving in overall energy consumption when implementing power switching off strategy during idling mode of the base station. Further authors have observed that integrating renewable energy sources into electrical system of base station could produce 51% energy saving with solar PV generation capacity of 20% relative to overall energy demand of the base station. In the study [25], authors have considered a new algorithm to estimate state of charge (SOC) of the storage unit, renewable energy integration intensity and cost of electricity. Although authors considered overall site load in determining capacity of solar PV, variation of site load and how constraints for power infrastructures affect with higher solar capacities in base stations are not discussed in detail. Further, the impact on network availability and customer experience due to planned power interruptions in base station for power saving, is not discussed in detail, which is a major gap in this research.

The study [26] has proposed and discussed the cost efficient and reliable base station with the integration of solar PV power into the electrical system. Authors have considered four configurations in their analysis with solar PV power integration into grid connected electrical system with no battery backup, grid connected electrical system with battery backup, off grid electrical system with battery backup and hybrid electrical system with battery backup and multiple power sources such as grid power and DG. Considered configurations are then simulated using PVSYST6.0.7 software and based on the simulation results authors proposed that grid connected electrical system with Solar PV is more feasible than deploying an off-grid electricals system for a higher efficiency and cost effectiveness of operations. In the study [26], authors have not focused on the impact of network availability, geographical positioning, constraints on power system infrastructure development and availability of grid. According to authors they rely on grid connected electrical system without sufficient estimation on quality and reliability of the grid and whether grid power availability is sufficient to maintain expected availability and uptime in the network.

The study [8] has proposed and discussed an innovative strategy on allocating limited resources to telecommunication base station with revenue management approach. The study [8] is conducted based on a case study of China Mobile Sichuan (CMS), telecommunication network operator giant in China and subsidiary of China Mobile which is the largest telecommunication network operator in the world. Authors in the study [8] have broadly discussed the strategies of base station classification based on both economic and social revenue perspectives. Visual illustration of relationship between social and economic is elaborated in Figure 2.1. Economic revenue is determined by directly linking to financial benefits generated from considered base station. According to the authors, more investments and resources shall be utilized for the base stations with higher economic benefits which reflects the ROI objectives of the organization.

However, authors in the study [8] suggest that thriving merely into economic revenue is not a sustainable approach in the telecommunication sector as it serves fundamental infrastructural need of people in the global as essential service. Social revenue can be identified as the indirect financial benefits generated by fulfilling the public interest even at a higher cost which does not reflect ROI straightforward. This extra effort taken by network operators can be sometimes a voluntary project implemented as a cooperate social responsibility targets and sometimes it is implemented as an obligation assigned as government mandated. For example, network coverage provided for healthcare services, military services and educational services can be important at national level, and unavailability of network coverage for such areas will be considered as loss of social revenue to telecommunication network operators. Social revenue therefore is linked directly to the contribution of network operators to social well-being and welfare, which is often born at a cost to the network operators.

However, the study [8] focused on the overall cost of the telecommunication network and does not stress specifically the importance of electrical system optimization in telecommunication base stations. Furthermore, the study [8] is not given a focus on network availability in its analysis on base station classification which is also important when determining the strategy on resources allocation in the telecommunication network. A comparison between key features of the study [8] and proposed model are summarized in Table 2.1.

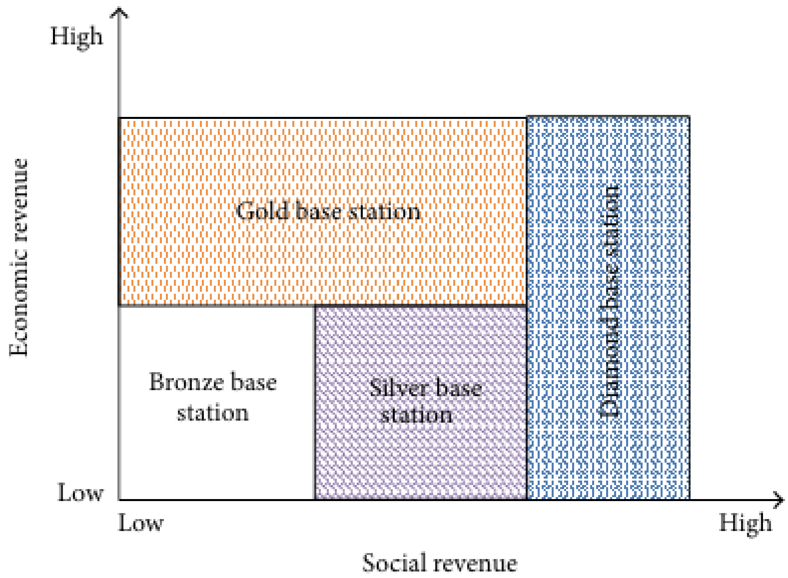


Fig. 2.1: Social and Economic Revenue Comparison

Source:[17]

TABLE 2.1: RESOURCE ALLOCATION BASED ON REVENUE MANAGEMENT VS. PROPOSED MODEL

Features and Functionalities	**Proposed Model in This Research**	**Resource Allocation based on Revenue Approach [8]**
Optimization Approach	Parametric Approach on Optimum Sizing of Electrical System	Base station classification and resource management
Optimization technique	Genetic Algorithm	Economic Revenue-based Ranking of base stations
Concept	Correct Sizing of System	Optimizing resource allocation for base stations based on revenue
Considered Types of ESS/s	Battery Bank (Li-ion)	Not Specified
Considered System Configuration	Grid / DG / Solar PV	Overall System (Transmission Equipment + Power System)
Network Availability Improvement / Target	Specified focusing Customer Segments/SLAs	Increase availability for VIP/top revenue customers
Service Level Agreement (SLA)	Considered	Not considered
Customer Severities/Segments	Considered	Considered

CHAPTER 3

MATHEMATICAL MODELLING AND RESEARCH DESIGN

To achieve the main objective of this research through mathematical modelling and optimization, anticipated main objective is converted into mathematical expression, which is identified as the objective function that quantifies the expected outcome of the optimization. The important steps to be followed in the general approach before evaluating the objective function for the electrical system of a telecommunications base station can be summarized as defining the objective function, identifying the decision variables, and formulating mathematical expressions for each component of the electrical system. These main steps will be discussed in detail under this section.

3.1 Total Cost Function of Electrical System

The total cost (f_{total}) of electrical system of telecommunication base station considered in this analysis comprises of total capital expenditures (f_{capex_total}) and operational expenditures (f_{opex_total}) incurred during the development and maintenance of the electrical system. Therefore, the total cost function can be expressed as in Eq. 3.1.

$$f_{total} = f_{capex\_total} + f_{opex\_total} \tag{3.1}$$

Total capital expenditures (f_{capex_total}) and total operational expenditures (f_{opex_total}) are formulated based on the capital and operational expenditures generated by the individual components of the considered electrical system. The main components of electrical system considered in this research are Solar PV, BSS and DG. Therefore, f_{capex_total} and f_{opex_total} can be expressed based on capital and operational expenditure as in Eq. 3.2 and Eq. 3.3 respectively.

$$f_{capex\_total} = f_{SolarPV\_capex} + f_{BSS\_capex} + f_{DG\_capex} \tag{3.2}$$

$$f_{opex\_total} = f_{SolarPV\_opex} + f_{BSS\_opex} + f_{DG\_opex} \quad (3.3)$$

3.2 Objective Function

In this research, the objective function is formulated to minimize the total cost (f_{total}) of the proposed electrical system under given system constraints in telecommunication base station. Therefore, objective function can be expressed as in Eq. 3.4.

$$min\{Total\ Cost\ of\ Electrical\ System\ (f_{total})\} \quad (3.4)$$

3.3 Decision Variables

Decision variables in an objective function can be identified as the variables which can be controlled or adjusted in the optimization process. The objective function typically depends on one or more decision variables. In this research, 3 decision variables can be identified in exploring the optimum configuration of electrical system for telecommunication base station. Those are deployed number of solar PV panels ($N_{SolarPV}$), rated capacity of BSS (E_{BSS_rated}) and rated capacity of DG (P_{DG_rated}). These decision variables are controllable in the optimization process subjected to its upper and lower bounds defined under functional constraints. Therefore, the optimum solution for the decision variables can be identified as $N_{SolarPV}*$, $E_{BSS\_rated}*$ and $P_{DG\_rated}*$ such that the f_{total} is minimum which can be expressed as in Eq. 3.5 ("*" indicates the optimum value for considered decision variable).

$$min\{f_{total}(N_{SolarPV}, E_{BSS\_rated}, P_{DG\_rated})\} \quad (3.5)$$

3.4 Mathematical Modelling of Cost - Solar PV System

Proposed mathematical model to determine the capital expenditure of development of solar PV system ($f_{SolarPV\_capex}$) is formulated by incorporating the number of solar PV panels ($N_{SolarPV}$), rated power of an individual panel ($P_{SolarPV\_rated}$) and capital cost per unit of rated power ($\alpha_{SolarPV\_capex}$) in development of solar PV system including Balance of System (BOS). Using these parameters, capital expenditure of solar PV system ($f_{SolarPV\_capex}$) can be expressed as in Eq. 3.6.

$$f_{SolarPV\_capex} = \alpha_{SolarPV\_capex} * N_{SolarPV} * P_{SolarPV\_rated} \tag{3.6}$$

Proposed mathematical model to determine the present value of operational expenditure of solar PV system ($f_{SolarPV\_opex}$) incurred throughout the operation and maintenance activities is formulated by incorporating the number of solar PV panels ($N_{SolarPV}$), rated power of an individual panel ($P_{SolarPV\_rated}$) and operations and maintenance cost of solar PV system per annum per unit of rated power ($\alpha_{SolarPV\_opex}$). Considering these parameters, the present value of the operational expenditure incurred in operations and maintenances of the solar PV system which is determined by considering discount rate (r) and expected life span of the system (T_{System}), is expressed as in Eq. 3.7.

$$f_{SolarPV\_opex} = \sum_{n=0}^{T_{System}-1} \frac{\alpha_{SolarPV\_opex} * N_{SolarPV} * P_{SolarPV\_rated}}{(1+r)^{(T_{System}-n)}} \tag{3.7}$$

3.5 Mathematical Modelling of Cost – BSS

Proposed mathematical model to determine the present value of capital expenditure incurred in development of BSS system (f_{BSS_capex}) is formulated by incorporating rated capacity of BSS (E_{BSS_rated}), minimum and maximum bounds of SOC (SOC_{min} and SOC_{max}), expected life span of the battery (T_{BSS}), number of replacements of BSS within the life span of base station (N_{r_BSS}) and capital cost per unit of energy (μ_{BSS_capex}) in development of BSS including BOS. Considering these parameters, the present value of the capital expenditure incurred in development of BSS (f_{BSS_capex}) which is determined considering the discount rate (r) can be expressed as in Eq. 3.8.

$$f_{BSS\_capex} = \sum_{n=0}^{N_{r\_BSS}} \frac{\mu_{BSS\_capex} * E_{BSS\_rated}}{(SOC_{BSS\_max} - SOC_{BSS\_min})} \cdot \frac{1}{(1+r)^{(N_{r\_BSS}-n)\cdot T_{BSS}}} \tag{3.8}$$

Proposed mathematical model to determine the present value of operational expenditure of BSS (f_{BSS_opex}) incurred throughout the operation and maintenance activities is formulated by incorporating the variable operations cost per unit of energy handled by BSS (β_{BSS_opex}), fixed operations cost per unit of energy handled by BSS (γ_{BSS_opex}), energy throughput of the BSS per annum (E_{BSS_annum}) and plant capacity of the electrical system (P_{plant}). Considering these parameters, the present value of the operational expenditure incurred in operations and maintenances of the solar PV system which is determined by considering discount rate (r) and expected life span of the system (T_{System}), is expressed as in Eq. 3.9.

$$f_{BSS\_opex} = \sum_{n=0}^{T_{System}-1} \frac{\beta_{BSS\_opex} \cdot E_{BSS\_annum} + \gamma_{BSS\_opex} \cdot P_{plant}}{(1+r)^{(T_{System}-n)}} \tag{3.9}$$

3.6 Mathematical Modelling of Cost - DG System

Proposed mathematical model to determine the present value of capital expenditure incurred in deployment of DG system (f_{DG_capex}) is formulated by incorporating the rated capacity of the generator (P_{DG_rated}), expected life span of the DG (T_{DG}), number of replacements of DG during within the life span of the base station (N_{r_DG}), capital cost per unit of power (σ_{DG_capex}) in deployment of DG including BOS. Considering these parameters, the present value of the capital expenditure incurred in deployment of DG (f_{DG_capex}) which is determined considering the discount rate (r) can be expressed as in Eq. 3.10.

$$f_{DG\_capex} = \sum_{n=0}^{N_{r\_DG}} \frac{\sigma_{DG\_capex} * P_{DG\_rated}}{(1+r)^{(N_{r\_DG}-n) \cdot T_{DG}}} \tag{3.10}$$

Proposed mathematical model to determine the present value of operational expenditure of DG (f_{DG_opex}) incurred throughout the operation and maintenance activities is formulated by incorporating the rated capacity of the generator (P_{DG_rated}), energy generated by DG per annum (E_{DG_annum}), average fuel consumption of the DG (δ_{fc}), fuel price (l_d) and non-fuel operations and maintenance cost per unit of rated capacity (δ_{non_fc}). Considering these parameters, the present value of the operational expenditure incurred in operations and maintenances of the DG system which is determined by considering discount rate (r) and expected life span of the system (T_{System}), is expressed as in Eq. 3.11.

$$f_{DG\_opex} = \sum_{n=0}^{T_{System}-1} \frac{(\delta_{fc} \cdot l_d \cdot E_{DG\_annum}) + (\delta_{non\_fc} \cdot P_{DG\_rated})}{(1+r)^{(T_{System}-n)}} \tag{3.11}$$

CHAPTER 4

ENERGY MANAGEMENT STRATEGY AND CONSTRAINTS

4.1 System Constraints

Consideration of system constraints is essential to ensure the solutions provided by an optimization model are realistic and feasible. In this research, energy management strategy is developed subjected to main constraints affected on the proposed electrical system. Equation 4.1 elaborates the constraint which governs the power balance of the system to maintain system stability.

$$P_{Load} \leq P_{Grid} + P_{DG} + P_{BSS} + P_{SolarPV} \tag{4.1}$$

Where;

- P_{Load} is the Radio and cooling equipment load power
- P_{Grid} is the Grid power
- P_{DG} is the DG Power
- P_{BSS} is the BSS power
- $P_{SolarPV}$ is the Solar PV power

Equation 4.2 defines the constraint which reflects the permitted Loss of Load Probability (LOLP) within the optimization algorithm of considered electrical system. This permitted LOLP is governed by the expected Network Availability of considered telecommunication base station, as represented by Eq. 4.2.

$$LOLP \leq 1 - Network\ Availability \tag{4.2}$$

Constraints affected SOC and power limits of BSS are also considered in the optimization algorithm. SOC and power ratings are typically defined by the manufacturer of the BSS. SOC of the BSS (SOC_{BSS}) is bound by its permitted minimum (SOC_{BSS_min}) and maximum (SOC_{BSS_max}) levels as mentioned in Eq. 4.3 and power exchange capacity BSS (P_{BSS}) is bound by the maximum power rating of BSS

(P_{BSS_max}) as expressed in Eq. 4.4.

$$SOC_{BSS\_min} \leq SOC_{BSS} \leq SOC_{BSS\_max} \tag{4.3}$$

$$P_{BSS\_min} \leq P_{BSS} \leq P_{BSS\_max} \tag{4.4}$$

Constraints affected on maximum power capacities of DG and solar PV considered in the optimization algorithm, are also bounded by its respective rated power capacities defined by the manufacturer and these constraints are expressed in Eq. 4.5 and Eq. 4.6 respectively. In Eq. 4.6, $P_{SolarPV}$ represents the power generation of the solar PV system, and $P_{SolarPV\_rated}$ represents the rated power generation of the solar PV system.

$$P_{DG} \leq P_{DG\_rated} \tag{4.5}$$

$$P_{SolarPV} \leq P_{SolarPV\_rated} \tag{4.6}$$

4.2 Energy Management Strategy

The energy management strategy is accountable for determining the type and capacity of the available energy resources to be utilized and dispatched at a given time and under given constraints in the electrical system in most cost effective, efficient and sustainable approach. Energy management strategy in an electrical system is implemented by the Energy Management Unit (EMU) which is an integrated digital controller into rectifier system in telecommunication base station. Energy management strategy considered in this research which imitates the expected behaviour of electrical system within the optimization algorithm, is graphically elaborated in Figure 4.1. In this research, energy management strategy is unchanged for all the scenarios evaluated in optimization.

Main sources of power considered in this research are the solar PV, utility grid power and DG. However, within the context of electrical system in telecommunication

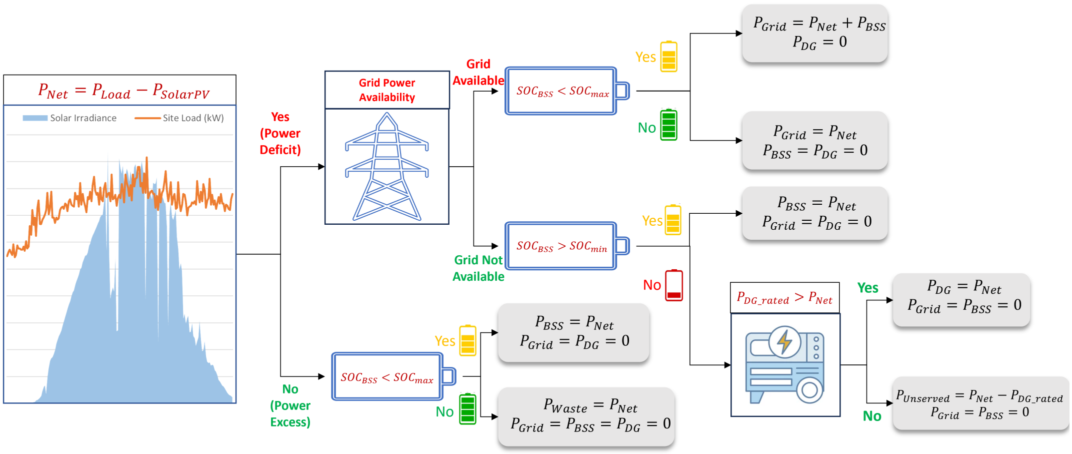


Fig. 4.1: Energy Management Strategy

base station, solar PV cannot be considered as dis-patchable source of power due to its intermittency issues with Solar irradiance fluctuations in nature [27]. Therefore, in the proposed electrical system, net power demand of the telecommunication base station (P_{Net}), is determined based on the difference between power generated by solar PV ($P_{SolarPV}$) and power demand of the radio and cooling equipment of the base station (P_{Load}) as elaborated in Eq. 4.7.

$$P_{Net} = P_{Load} - P_{SolarPV} \tag{4.7}$$

P_{Net} is supposed to be handled by other alternative power sources to maintain power balance of the electrical system. If P_{Net} is positive at a given instant, it reflects that there is deficit of power in the electrical system. When there is a deficit power state in the system, as the next step of energy management strategy, EMU will check the availability of utility grid power since grid power is the feasible alternative source of power compared to the DG in terms of [28]. If grid power is available, and if SOC of BSS is less than its upper bound of SOC level (SOC_{BSS_max}), grid power will be utilized to supply P_{Net} while charging BSS in parallel and corresponding behaviour is represented by Eq. 4.8 and Eq. 4.9 in the energy management strategy.

$$P_{Grid} = P_{Net} + P_{BSS} \tag{4.8}$$

$$P_{DG} = 0 \tag{4.9}$$

However, if SOC of BSS is equal or above its upper bound level (SOC_{BSS_max}), only P_{Net} will be supplied by the grid power, keeping other DG and BSS in standby mode and corresponding behaviour is represented by Eq. 4.10 and Eq. 4.11.

$$P_{Grid} = P_{Net} \tag{4.10}$$

$$P_{BSS} = P_{DG} = 0 \tag{4.11}$$

On the other hand, if grid power is not available, since utilizing BSS compared to DG is still feasible in terms of Levelized Cost of Energy (LCOE) [29], SOC level of BSS will be evaluated by EMU and if SOC is within its minimum (SOC_{BSS_min}) and maximum (SOC_{BSS_max}) bounds, stored energy in BSS will be utilized to supply P_{Net} while keeping DG in standby mode and this behaviour is represented by Eq. 4.12 and Eq. 4.13.

$$P_{BSS} = P_{Net} \tag{4.12}$$

$$P_{Grid} = P_{DG} = 0 \tag{4.13}$$

However, if the SOC level of BSS is less than SOC_{BSS_min}, DG is dispatched to supply P_{Net} in the system while keeping BSS is unutilized. If rated power of the DG (P_{DG_rated}) is greater than P_{Net}, DG is used to supply both P_{Net} and P_{BSS} to charge BSS. This behaviour is represented by Eq. 4.14 and Eq. 4.15.

$$P_{DG} = P_{Net} + P_{BSS} \tag{4.14}$$

$$P_{Grid} = 0 \tag{4.15}$$

If P_{DG_rated} is less than P_{Net}, part of the P_{Net} will be supplied DG with its P_{DG_rated}, while remaining part is considered as unserved power to the electrical system. This behaviour is expressed by Eq. 4.16 and Eq. 4.17.

$$P_{DG} = P_{DG\_rated} \tag{4.16}$$

$$P_{Unserved} = P_{Net} - P_{DG\_rated} \tag{4.17}$$

If P_{Net} is negative, it reflects that there is excess power state in the electrical system. In this research, exporting power from the electrical system to utility grid is not considered, the only available alternative to handle excess energy is storing in BSS of the electrical system. Therefore, if P_{Net} is negative, EMU will check the SOC status of BSS, and if SOC is less than its upper bound (SOC_{BSS_max}), excess energy will be delivered to BSS and it is expressed by Eq. 4.18. And if SOC is equal or greater than its upper bound, excess energy will be considered as waste to the system which expressed by Eq. 4.19.

$$P_{BSS} = P_{Net} \tag{4.18}$$

$$P_{Waste} = P_{Net} \tag{4.19}$$

CHAPTER 5

PARAMETERS CONSIDERED IN OPTIMIZATION

To study and analyse the effect of different characteristics of telecommunication base stations discussed in this research, five different scenarios of base stations proposed to developed in five locations are considered. In the analysis, base stations are proposed to develop and operate with optimum electrical system configurations. Characteristics which are unique to selected locations such as operational constraints, DC load born by expected network traffic and most importantly grid power availability are considered as inputs to the optimization model. Since optimization model is ran for 8 days, all the parameters are considered and collected for 8 days.

5.1 Operational Constraints Considered for Optimization

The objective of considering operational constraints into the optimization model is to reflect the impact of regulatory, functional and technical constraints affected during development and maintenance of electrical systems in telecommunication base stations. In this section, it will be mainly focused on functional constraints affected on development and maintenance of electrical systems. Functional constraints for electrical systems can arise mainly due to space restrictions, shading effects, weight restrictions and logistics restrictions.

Functional constraints are mainly affected on the development and operations of electrical subsystems such as Solar PV, BSS and DG. To study the impact and variation of the functional constraints on electrical system optimization in telecommunication base stations, five different locations were formulated assuming different functional constraints based on considered characteristics specific to the selected location. For each location, two levels of constraints formulated as moderate and strict conditions, based on the nature of the constraints, which provides a clear overview to network operator on what would be the behaviour of LCOE if nature of the constraints changes moderate to strict conditions, in development and operating electrical system for telecommunication base station. Five locations formulated in this research with their expected functional constraints and resulting maximum and minimum rated capacity bounds of electrical subsystems are summarized in Table 5.1. In practical implementation, these constraints are defined and identified during the initial site surveys done by skilled engineering team in planning and development stage of the telecommunication base stations. In this research, for the analysis purpose, upper and lower bounds for the functional constraints are decided and determined by authors.

TABLE 5.1: FUNCTIONAL CONSTRAINTS AND SYSTEM CAPACITY LIMITS

Inputs		Solar Panel Count		Li-ion Battery Capacity (kWh)		Generator Capacity (kW)	
Territory	**Operation Constraints**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Location 1	Moderate	0	25	5	50	0	15
Location 1	Strict	0	0	5	20	0	0
Location 2	Moderate	0	25	5	50	0	15
Location 2	Strict	0	20	5	20	0	15
Location 3	Moderate	0	25	5	50	0	15
Location 3	Strict	0	10	5	30	0	15
Location 4	Moderate	0	25	5	50	0	15
Location 4	Strict	0	25	5	30	0	10
Location 5	Moderate	0	25	5	50	0	15
Location 5	Strict	0	0	5	20	0	15

5.2 DC Load Profile Derived using Expected Network Traffic

Variation of the DC load demand occurred in the electrical system due to network traffic in the subjected geographical location can be predicted and estimated using DC load demand data of exiting telecommunication base station having similar characteristics in terms of number of subscribers, nature of socio and economic activities conducting near to the tower and considered time of the day or month. Based on these fundamental characteristics, and DC load behaviour discussed in [10], [11], [12] and [13] of telecommunication base station, five DC load profiles for five geographical locations were developed by authors, and developed load profiles are elaborated in Figure 5.1. These load profiles will be considered as inputs to the optimization model using Genetic Algorithm implemented in MATLAB Simulink software. The variation of average and maximum load is elaborated in Table 5.2. When referring to Table 5.2, it can be observed that the base station with the highest peak load shall not be the base station with highest average load. Therefore, in the optimization, consideration should be given to variation of the load through the time rather than considering only its average or peak load.

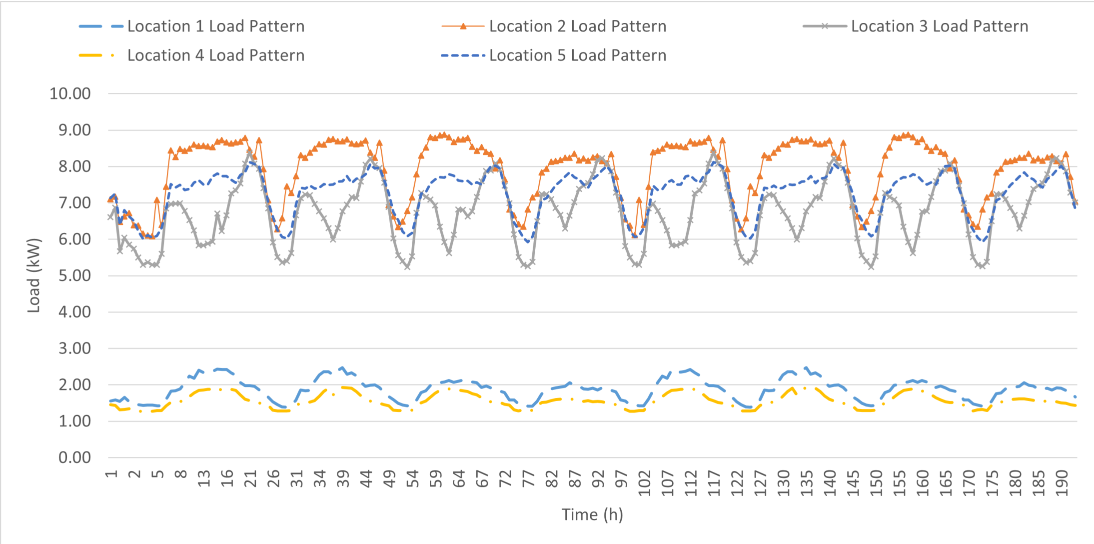


Fig. 5.1: Expected Load Behavior in Considered Base Station Locations

TABLE 5.2: EXPECTED AVERAGE AND PEAK LOADS OF CONSIDERED LOCATIONS

Base Station Locations	Average Site Load (kW)	Peak Site Load (kW)
Location 1	1.89	2.43
Location 2	7.97	8.9
Location 3	6.77	8.39
Location 4	1.57	1.95
Location 5	7.29	8.19

5.3 Grid Power Availability and Modelling with Grid Parametric Indices

Since the characteristics and behaviour of the grid power availability varies from terrain to terrain, it is important to incorporate the effect of grid power variation into optimization model when determining optimum electrical system configuration. However, as there is no direct method to predict and model grid power availability behaviour, in this research, a novel model is developed to mimic and model grid power curves based on the parametric indices of performances of grid calculated by utility service provider.

Main grid parameter indices used in this research are System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) [19]. In this research, SAIDI is considered as the probability of power interruptions in considered location and this parametric indices is used to calculate Loss of Power Supply Probability (LPSP) [30] as in Eq. 5.1. And also, SAIFI is considered as number of power interruptions experienced in considered location and this parametric indices is used to calculate the average of Loss of Power Supply Frequency (LPSF) [31] for a given period of time as in Eq. 5.2. Using the LPSP, Power Availability % can be calculated as in Eq. 5.2.

$$LPSP = \frac{SAIDI}{Considered\ Period\ of\ Time\ (h)} \tag{5.1}$$

$$LPSF = \frac{SAIFI}{Considered\ Period\ of\ Time\ (h)} \tag{5.2}$$

$$Power\ Availability\ (\%) = 1 - LPSP \tag{5.3}$$

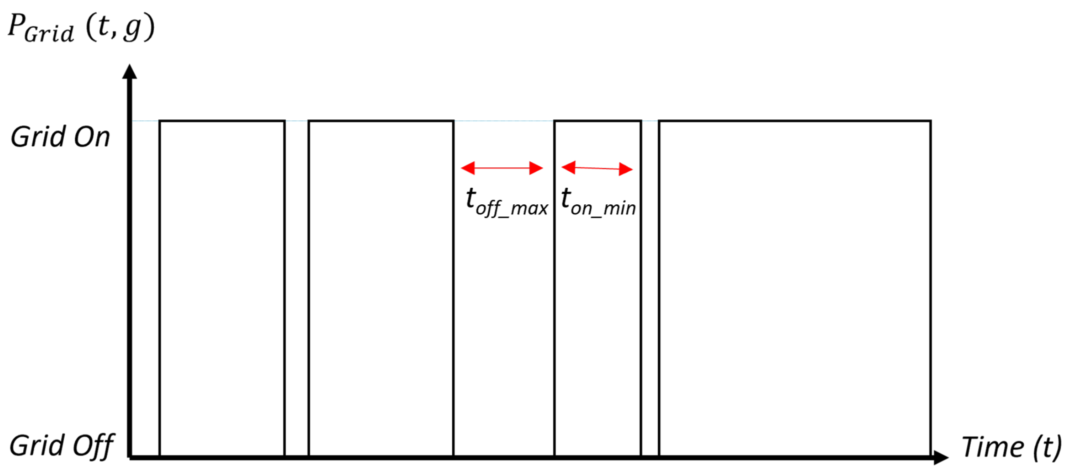


Fig. 5.2: Square Wave Form of Grid Power Behavior Modelling

To incorporate interruption duration and time interval between consecutive interruptions as inputs to the model, grid power availability is modelled using a special mathematical model as square wave form with two levels as elaborated in Figure 5.2.

Proposed model to capture the worst-case scenario, maximum interruption duration (t_{off_max}) and minimum on time (t_{on_min}) were introduced as inputs to the model and t_{on_min} is to be occurred immediately after t_{off_max} occurrences, so that within the optimization, algorithm will detect the worst-case scenario when determining the optimum electrical system configuration. LPSP and LPSF parameters are then used within the mathematical model in optimization code to mimic the grid power curves with respective outage frequency with t_{on_min} and t_{off_max}. Parametric indices considered in grid power availability in Sri Lanka [32] are elaborated in Table 5.3 and remodelled grid power curves generated by new algorithm for 8 days are elaborated in Figure 5.3.

In Figure 5.3, it can be seen that, in all the territories, grid power availability pattern is developed with an incident having t_{on_min} time following the incident of having t_{off_max} time. Remaining interruptions are modelled randomly by algorithm according to overall power availability and number of interruptions for the considered simulation period. Final grid power curves developed using this new model are plotted in Figure 5.3, and these curves will be considered as grid power input curves for the five locations considered in the optimization

TABLE 5.3: GRID PERFORMANCE PARAMETRIC INDICES

Location	**SAIDI**	**LPSP (%)**	**SAIFI**	**LPSF (%)**	**t_{on_min} for any incident (min)**	**t_{off_max} for any incident (min)**
Location 1	131.4	1.5	87	0.99	600	120
Location 2	289.1	3.3	119	1.36	180	180
Location 3	919.8	10.5	178	2.03	120	420
Location 4	547.5	6.25	93	1.06	300	480
Location 5	867.2	9.9	210	2.40	360	300

5.4 Technical Parameters of Electrical Subsystems

Technical parameters of electrical subsystems Solar PV, BSS, DG and Grid considered in the development of electrical system for telecommunication base station are sum-

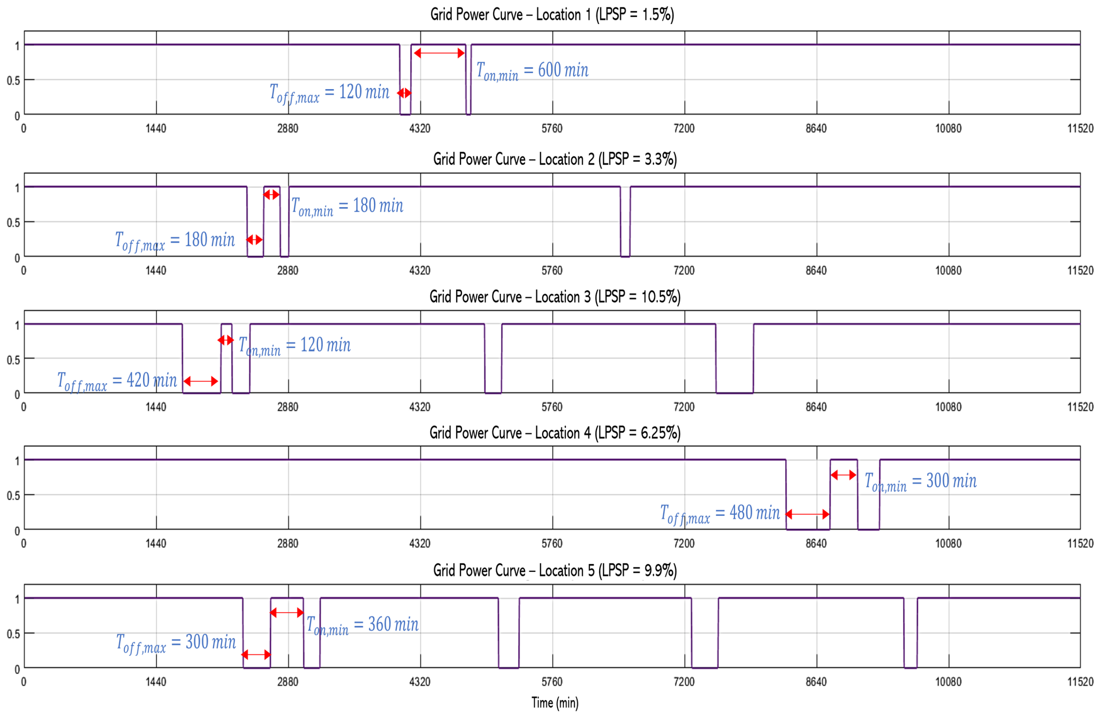


Fig. 5.3: Developed Grid Power Curves for Five Locations of Base Station

marized in Table 5.4, Table 5.5 and Table 5.6. Unit price of grid energy is considered as 0.17 $/kWh [33].

TABLE 5.4: SOLAR PV SYSTEM PARAMETERS

Parameter	**Value** [34], [35]	**Unit**
Area per Panel	1.76	m^2
Panel Efficiency (η)	16.5	%
Temp Coefficient	-0.004	°C^{-1}
Standard Temp	25	°C
Investment cost of Solar PV	1248	USD/kW
Solar PV rated capacity per panel	0.32	kW
Operations cost of Solar PV	15.33	USD/kW-yr
System life span	20	yr
Peak sun hours	5	h
Discounting rate	10	%

5.5 Network Availability Benchmarks

In this research Network Availability is considered as constraint to the objective function, which needs to be satisfied when achieving optimum electrical system configura-

TABLE 5.5: BSS PARAMETERS

Parameter	**Value** [36], [37], [38]	**Unit**
Battery life Cycles	10,000	cycles
Investment cost of Batteries	372	USD/kWh
Converter cost	388	USD/kW
Operations cost of Batteries	10	USD/kW-yr
SOC_{min}	10	%
SOC_{max}	90	%

TABLE 5.6: DG SYSTEM PARAMETERS

Parameter	**Value** [39], [40], [41]	**Unit**
Generator Life Cycles	25,000	hr
Investment cost of Generator	800	USD/kW
Operations cost of Generator	35	USD/kW-yr
Fuel cost of Generator	1.36	USD/L
Discounting rate	6	%

tion. Network availability value is decided based on the network performance benchmark defined by the network operator. In this research, four main types of consumers are considered, and each group is expected to serve with respective committed Network Availabilities as mentioned in Table 5.7.

TABLE 5.7: NETWORK AVAILABILITY AND RESPECTIVE BASE STATION CLASSIFICATION

Classification/Base Station Severity	**Network Availability [6],[9]**
Diamond	100.00%
Gold	99.00%
Silver	98.00%
Bronze	95.00%

5.6 Solar Irradiance and Power Generation

Solar irradiance is given as input for 8 days into the model to estimate the solar PV generation of the system. A single pattern of solar irradiance is considered for all the locations to maintain the equal conditions for all the scenarios evaluated under the optimization. The considered solar irradiance curve is elaborated in Figure 5.4 along with the expected load variation pattern in each base station considered.

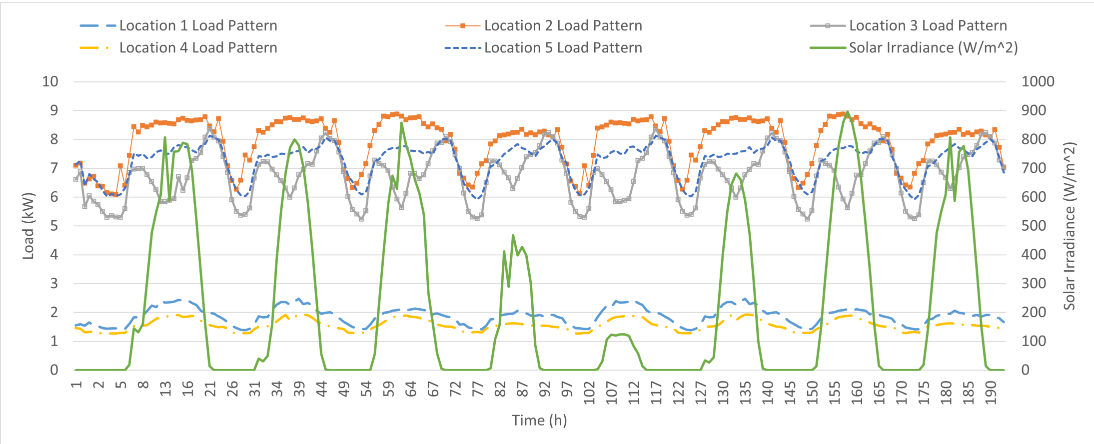


Fig. 5.4: Developed Grid Power Curves for Five Locations of Base Station

CHAPTER 6

SIMULATION AND OPTIMIZATION

6.1 Optimization Approach

In this research, MATLAB will be used as the simulation tool to implement optimization of single objective function under given constraints and to determine optimum capacities for decision variables. There are several optimizations functions available in MATLAB environment. However, fmincon and genetic algorithm are the most widely used optimizations functions in MATLAB. Genetic algorithm function is more likely to find the global minimum, especially when problem is non-smooth and global search is required, whereas genetic algorithm takes longer time in computations.

In contrast, fmincon function is generally faster than the genetic algorithm in exploring solution. However, for a well-defined optimization problem with smooth gradient, fmincon is the most suitable optimization function. Since in this research, optimization involves complex and non-smooth variations with multi-variable non-linear constraint function, genetic algorithm is considered in this research to evaluate objective function under given constraints.

6.2 Problem Setup in Optimization Toolbox

This optimization is done using the inbuilt optimization toolbox integrated into MATLAB. To solve the optimization through MATLAB inbuilt toolbox, it is required to configure problem setup using developed fitness and constraints functions. The optimization algorithm which is followed by the genetic algorithm in MATLAB is elaborated in Figure 6.1. The general interface of the optimization toolbox with problem setup and options are elaborated Figure 6.2. The programmed code of the proposed energy management, objective function, constraints functions and mathematical equations are incorporated into MATLAB script file and this file is call by optimization toolbox to execute the code.

6.2.1 Solver Type

In this research since genetic algorithm optimization approach is selected, to consider that in the optimization, solver type in the toolbox of problem setup is selected as ga – Genetic Algorithm as mentioned in Figure 6.3.

6.2.2 Problem and Constraints

Under the problem field, fitness function needs to be called from the script file (.m) which includes the developed objective function. Since all the developed constraints are non-linear constraint functions, linear equalities and linear inequalities fields are kept empty in optimization toolbox. Furthermore, the non-linear constraint functions need to be called from the script file to incorporate considered constraints to the optimization. Fitness function and constraint function are not changing throughout all the scenarios considered in the optimization.

Since there are three decision variables, the number of variables for the problem in toolbox should be configured as 3. Under the bounds filed, it is required to provide lower and upper bounds applicable to the decision variables under considered multi-dimensional system characteristics. The upper and lower bounds considered in the optimization are summarized in Table 5.1 and these bounds need to be changed based on the base station considered and its location. In this research, results of all three decision variables are considered as integers and Integer Variable Indices configured accordingly. Example case of Problem Setup configuration is highlighted in Figure 6.3. using the constraints applicable to the base station in location 1.

6.2.3 Options

Under the options in the toolbox, the population type is selected as Double Vector and Population size is configured as 100 extended precisions. Other fields in Options are kept as default values. Relevant configurations are elaborated in Figure 6.4.

6.2.4 Run Solver

After configuring the relevant fields in the problem setup, the optimization process can be started using the start command button. Number of interruptions considered during the optimization are shown in Current iteration field as elaborated in Figure 6.5.

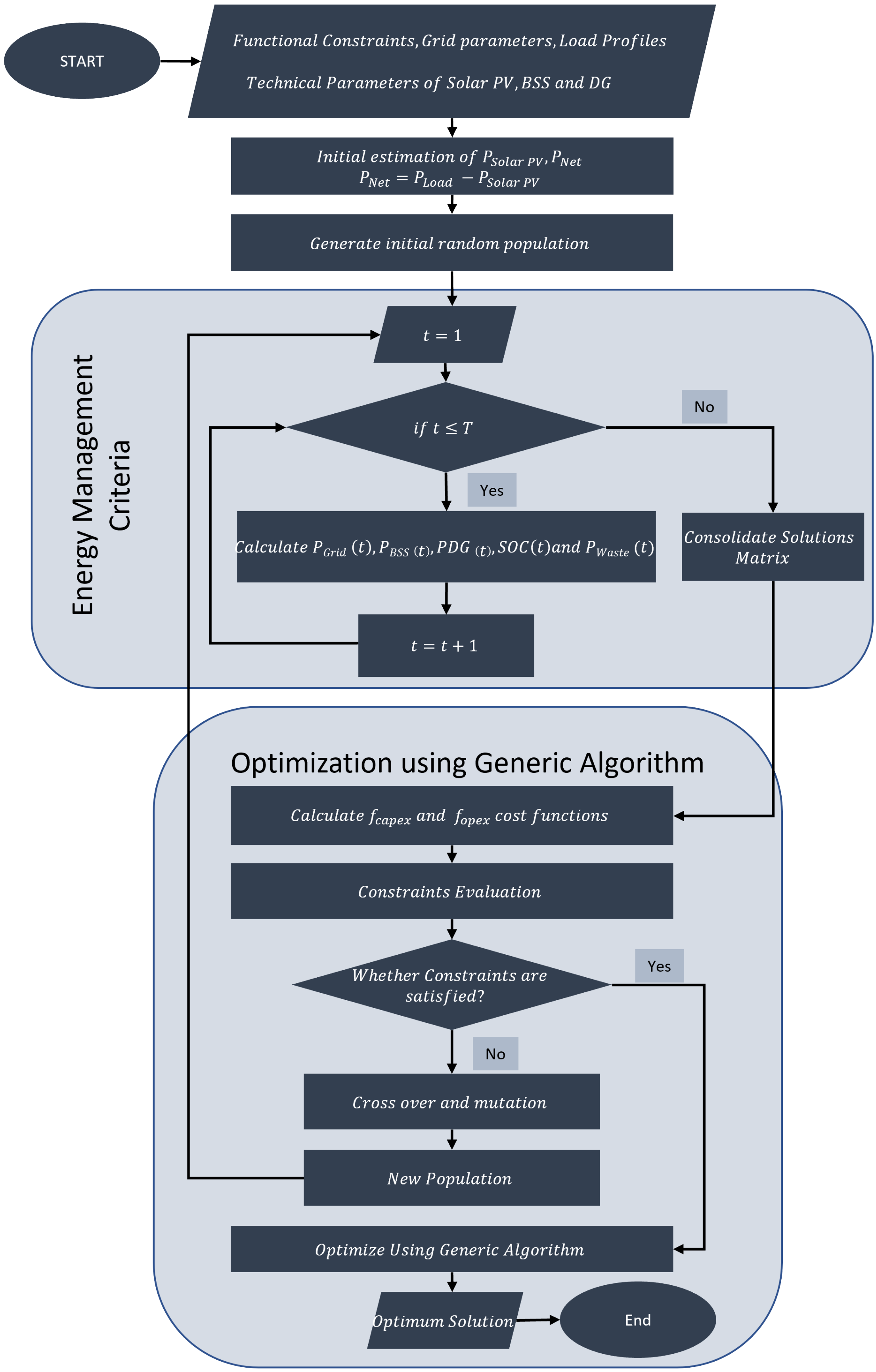


Fig. 6.1: Optmization Algorithm

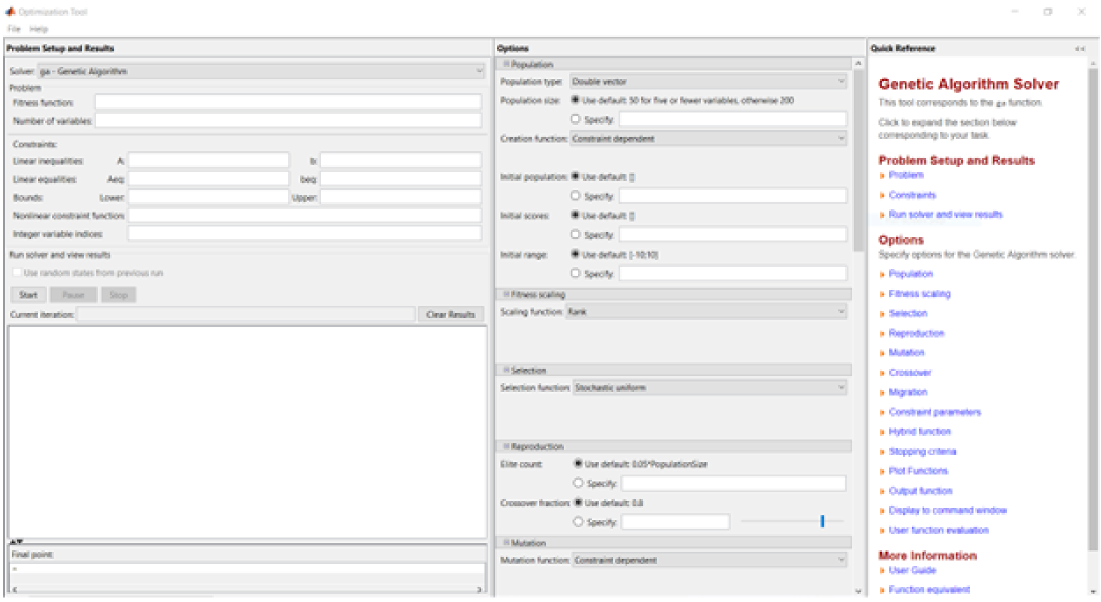


Fig. 6.2: General Interface of Optimization Toolbox

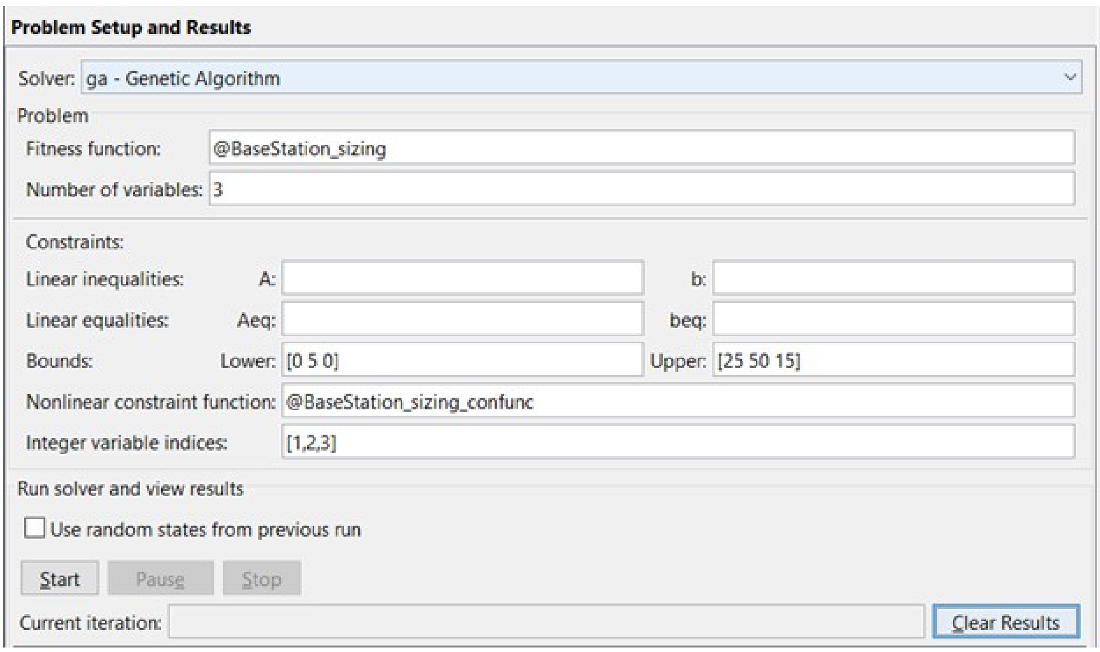


Fig. 6.3: Problem Setup and Constraints Configurations

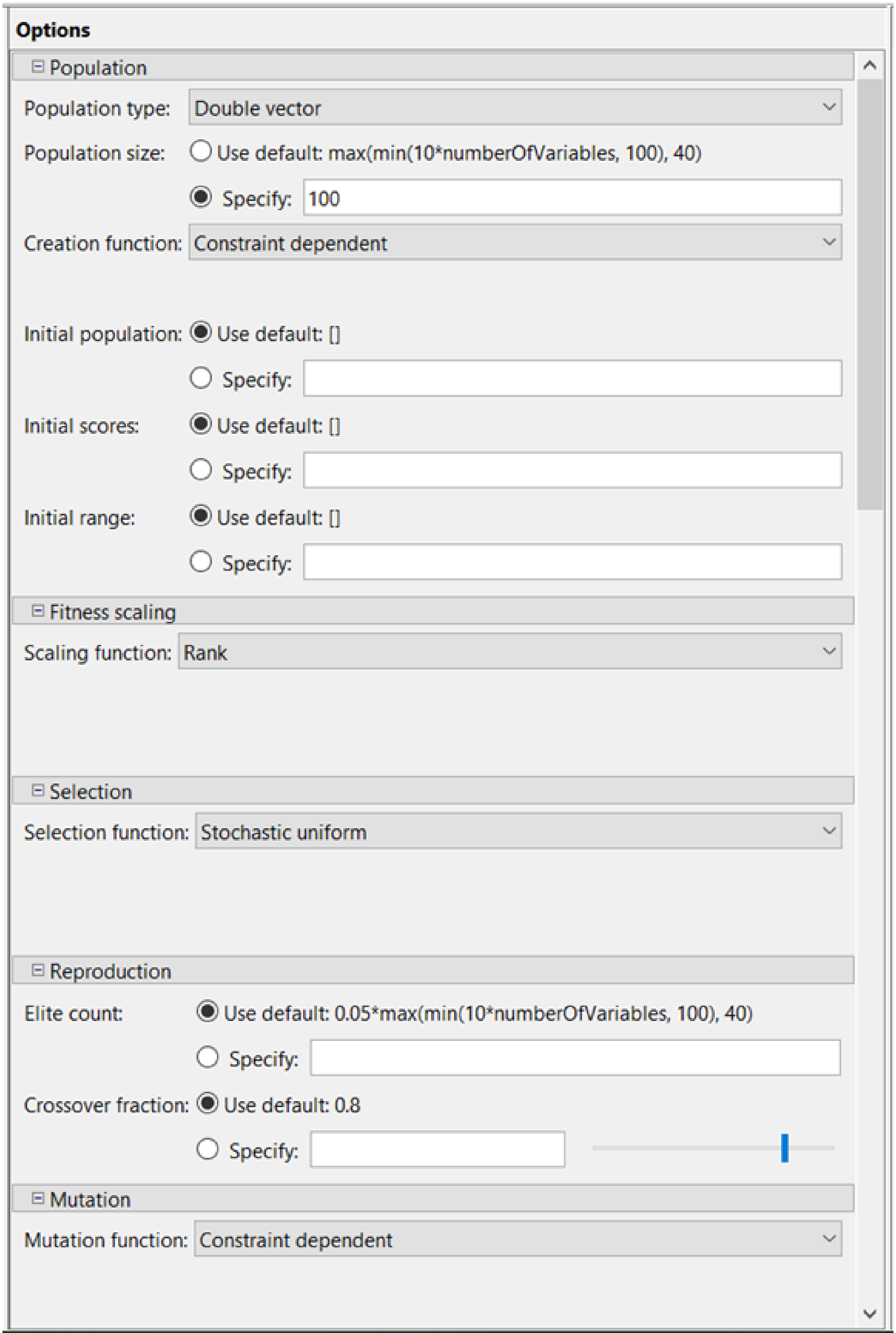


Fig. 6.4: Options in the Toolbox

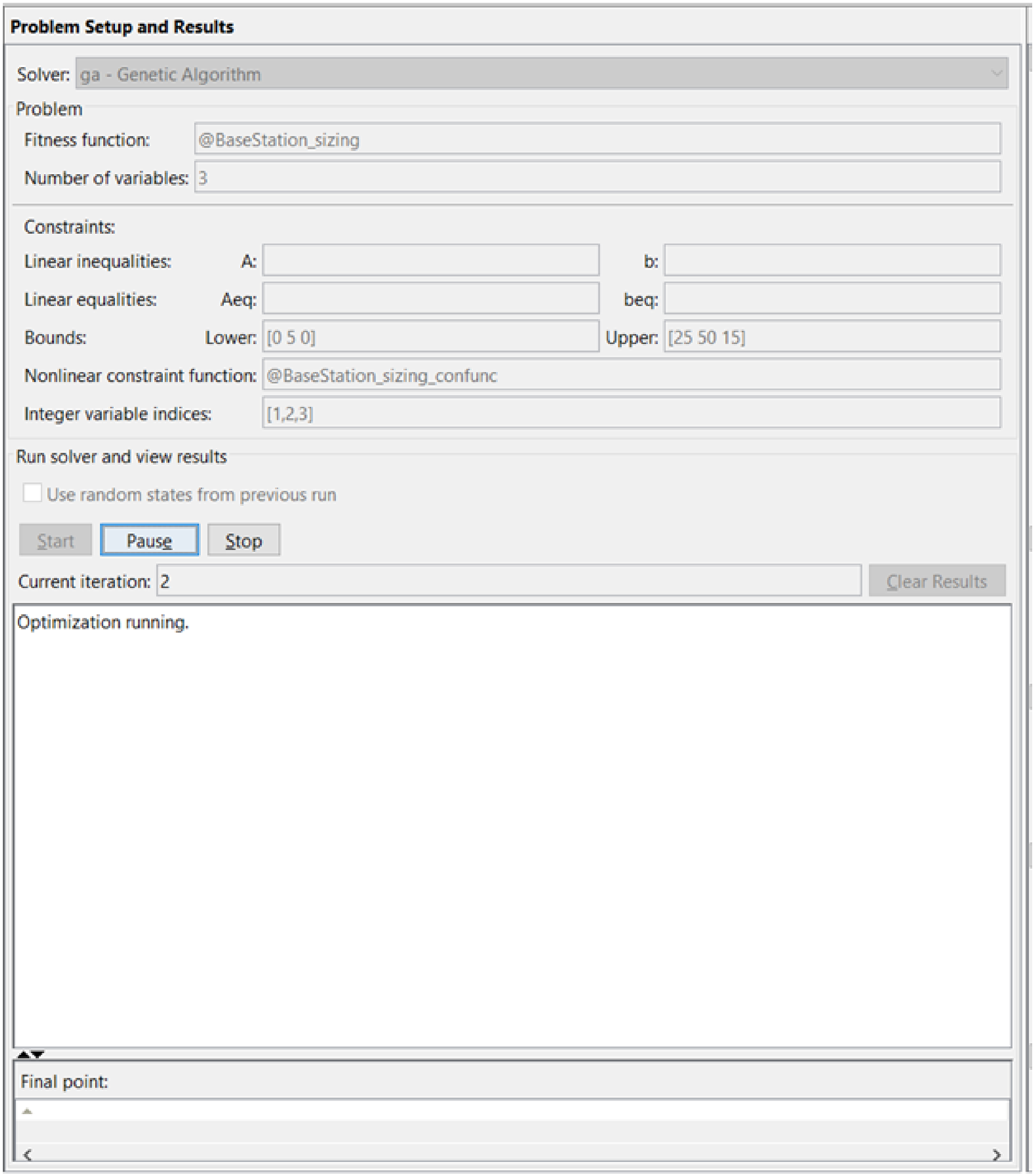


Fig. 6.5: Optimization Iterations

CHAPTER 7

SIMULATION AND OPTIMIZATION

In this section, the results of proposed optimization models will be discussed under two perspectives. Those are,

- Analysis 1 – Behaviour of Operational Constraints, Power Availability and LCOE (100% Network Availability unchanged for all scenarios)
- Analysis 2 – Behaviour of LCOE and Network Availability (Power availability, interruption durations, operational constraints and location of the base station kept unchanged)

Considered functional constraints for each base station and how it impacts on sub-components of the electrical systems are summarized in Table 5.1. As elaborate in Table 5.1, the minimum bound of BSS capacity under both moderate and strict functional constraints in all cases has been on purpose configured as 5 kWh to maintain the electrical system stability throughout the transitions between different power sources and to ensure smooth power supply for radio equipment with less interferences [42]. The value of 5 kWh for minimum bound of BSS is determined by the rated capacity of the individual Li-ion cell deployed in the electrical system [38]. Subjected to the defined functional constraints in Table 5.1, optimum results were obtained for decision variables in base stations located in five locations to achieve optimum electrical system configurations, considering the load profiles as mentioned in Figure 5.1, grid power input profiles as elaborated in Figure 5.3 (which were modelled using grid performance indicators elaborated in Table 5.3) and technical parameters summarized in Table 5.4 to 5.6.

Power dispatch scheduling patterns of the optimized electrical systems in analysis 1 are elaborated in Figure 7.1 to 7.10 and power dispatch scheduling patterns of optimized electrical systems in analysis 2 are elaborated in Figure 7.13 to 7.15.

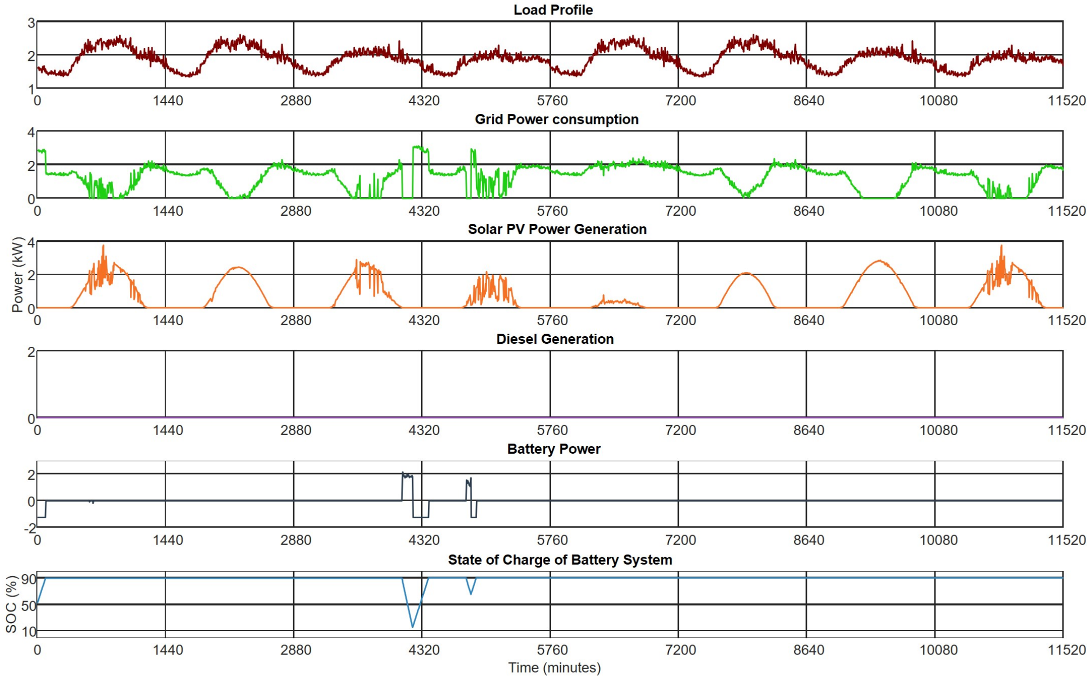


Fig. 7.1: Patterns of Power Dispatching Schedule - Location 1 (Moderate Constraints)

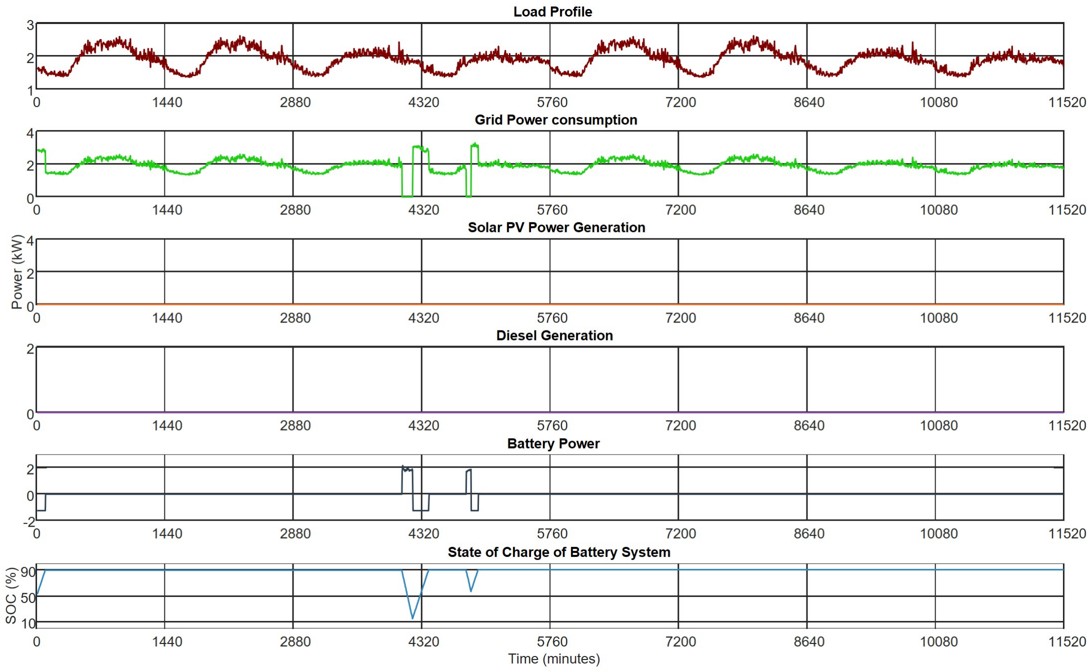


Fig. 7.2: Patterns of Power Dispatching Schedule - Location 1 (Strict Constraints)

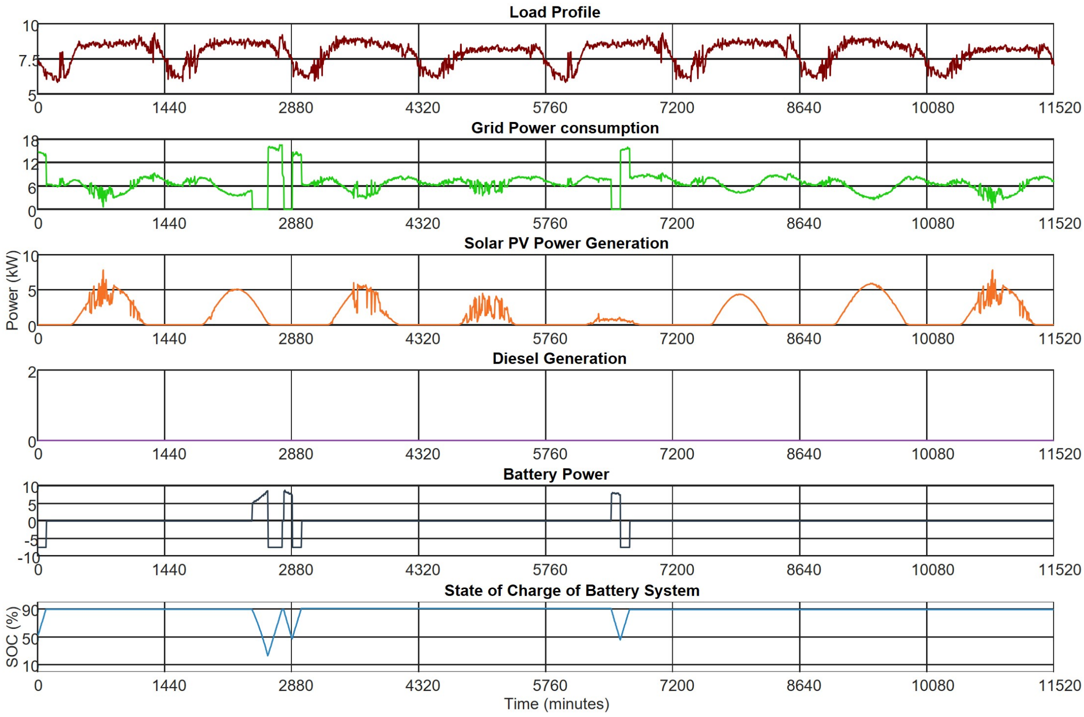


Fig. 7.3: Patterns of Power Dispatching Schedule - Location 2 (Moderate Constraints)

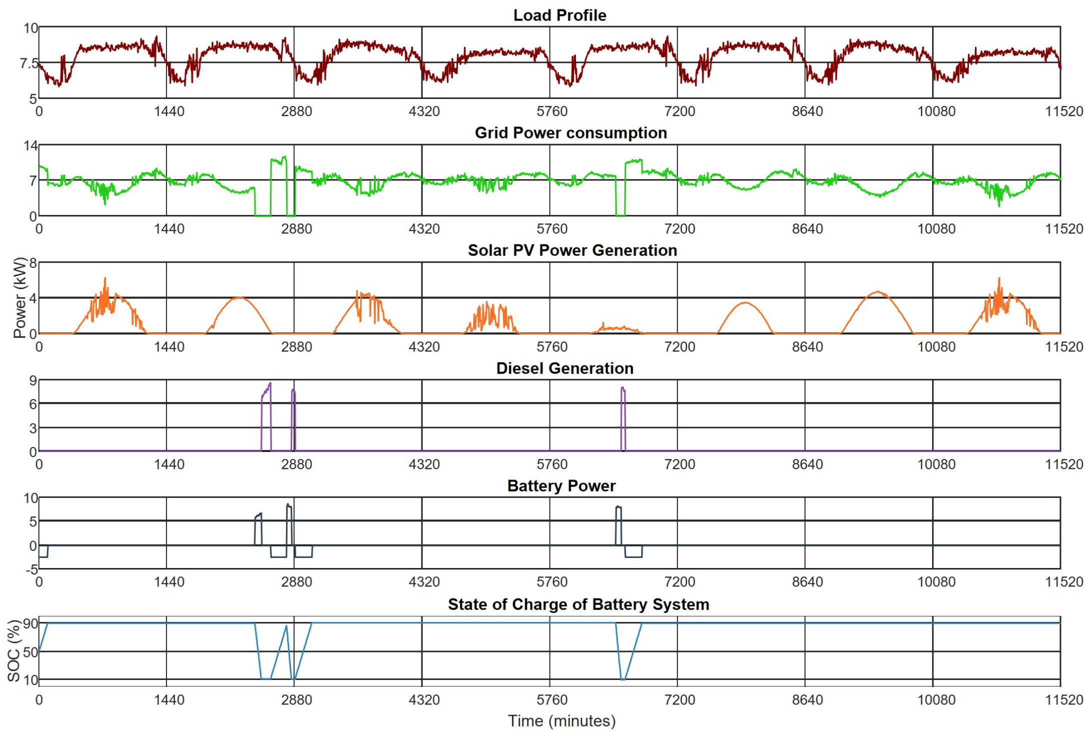


Fig. 7.4: Patterns of Power Dispatching Schedule - Location 2 (Strict Constraints)

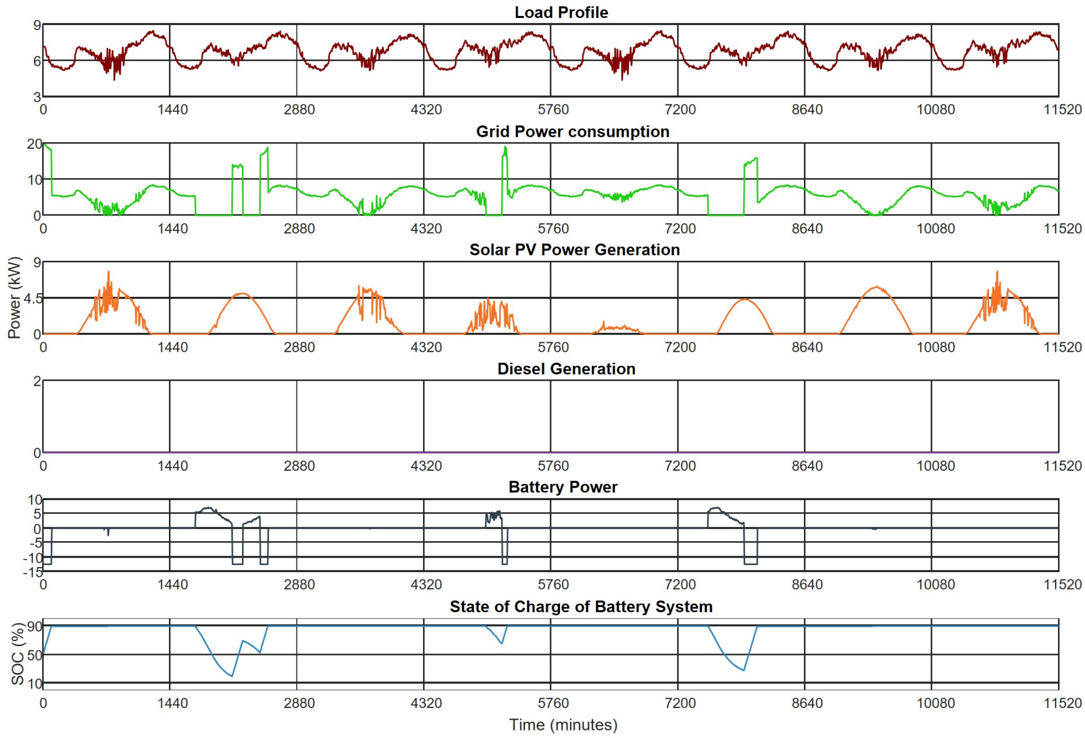


Fig. 7.5: Patterns of Power Dispatching Schedule - Location 3 (Moderate Constraints)

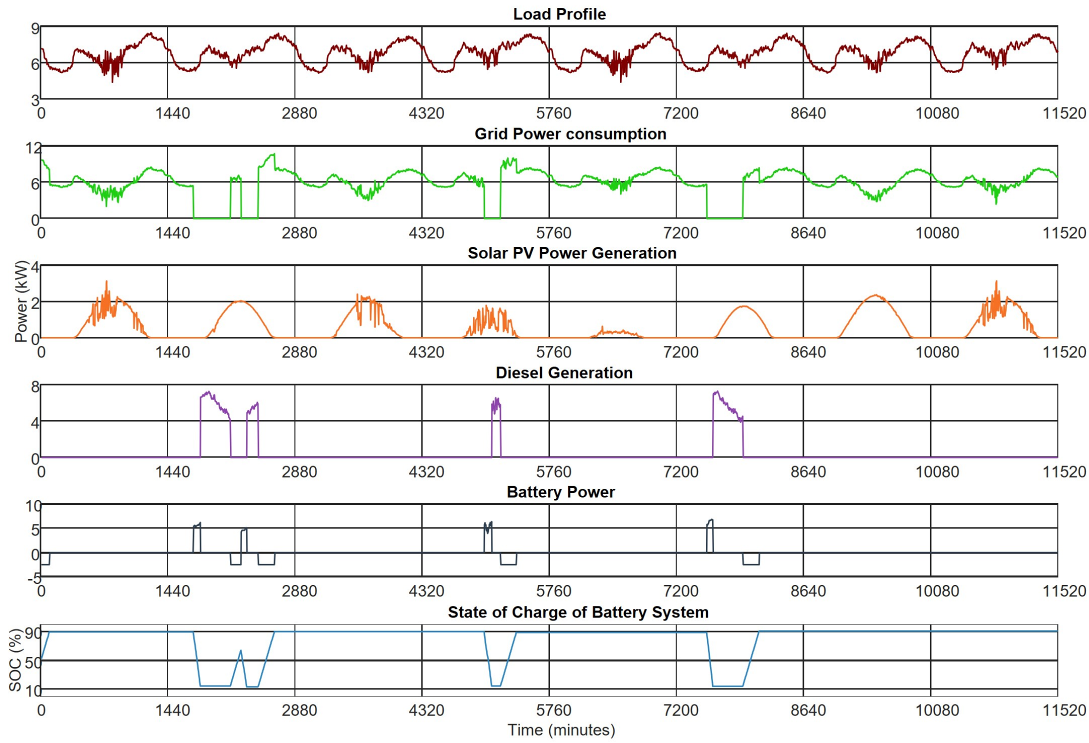


Fig. 7.6: Patterns of Power Dispatching Schedule - Location 3 (Strict Constraints)

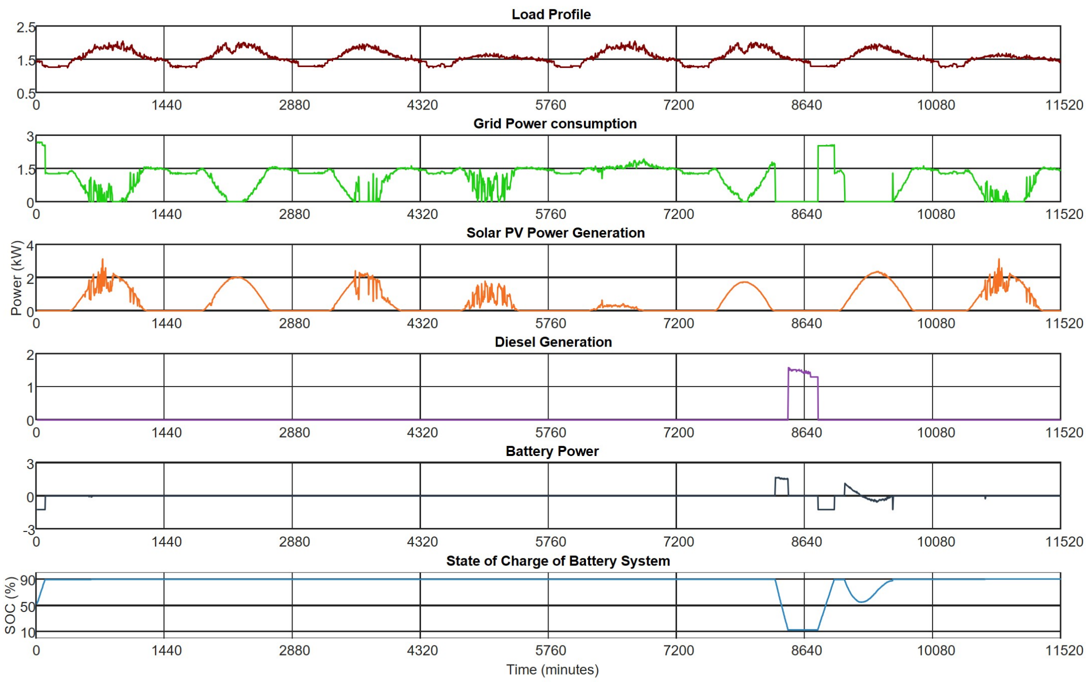


Fig. 7.7: Patterns of Power Dispatching Schedule - Location 4 (Moderate Constraints)

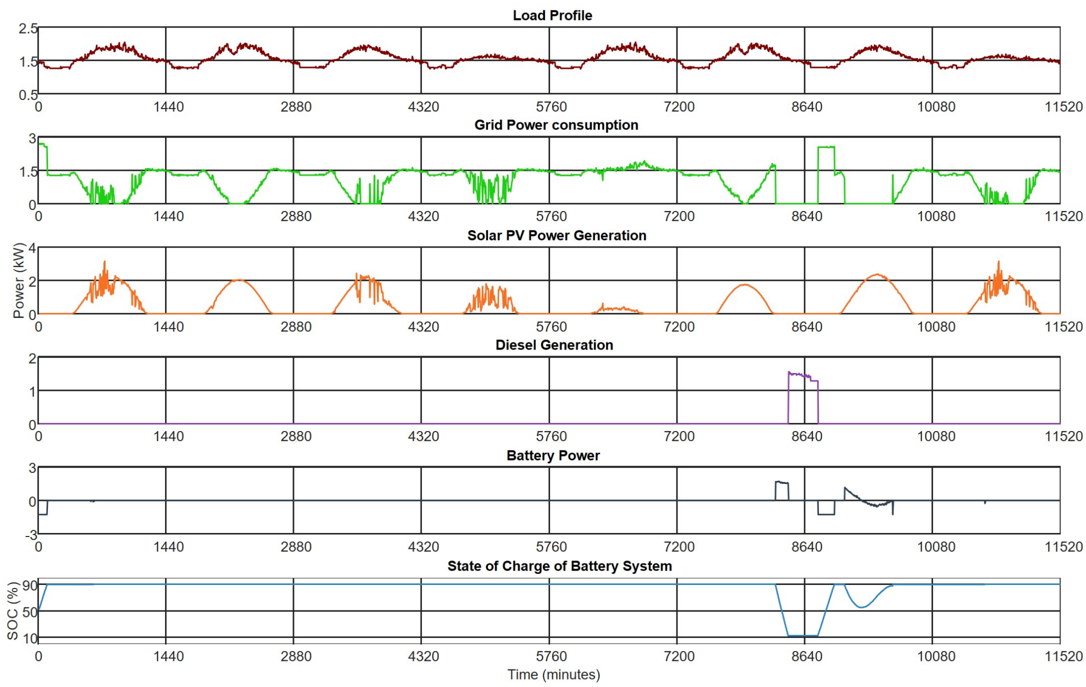


Fig. 7.8: Patterns of Power Dispatching Schedule - Location 4 (Strict Constraints)

7.1 Analysis 1 – Behaviour of Functional Constraints, Power Availability and LCOE

Under this section, relationships among functional constraints, power availability indices and LCOE of the proposed optimum electrical system are discussed under se-

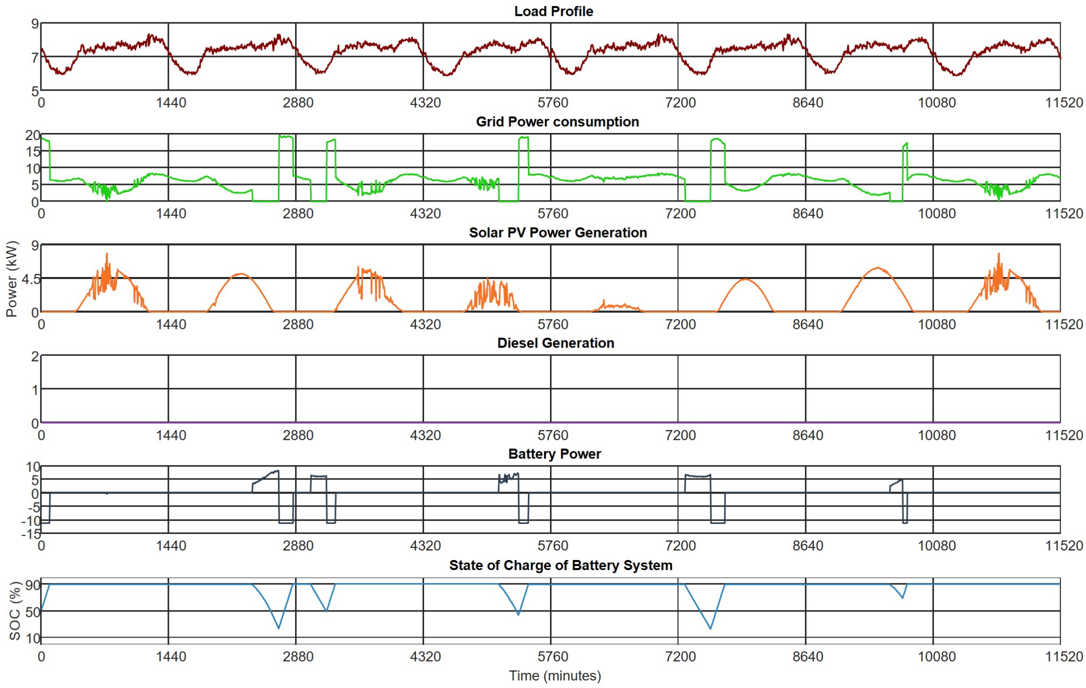


Fig. 7.9: Patterns of Power Dispatching Schedule - Location 5 (Moderate Constraints)

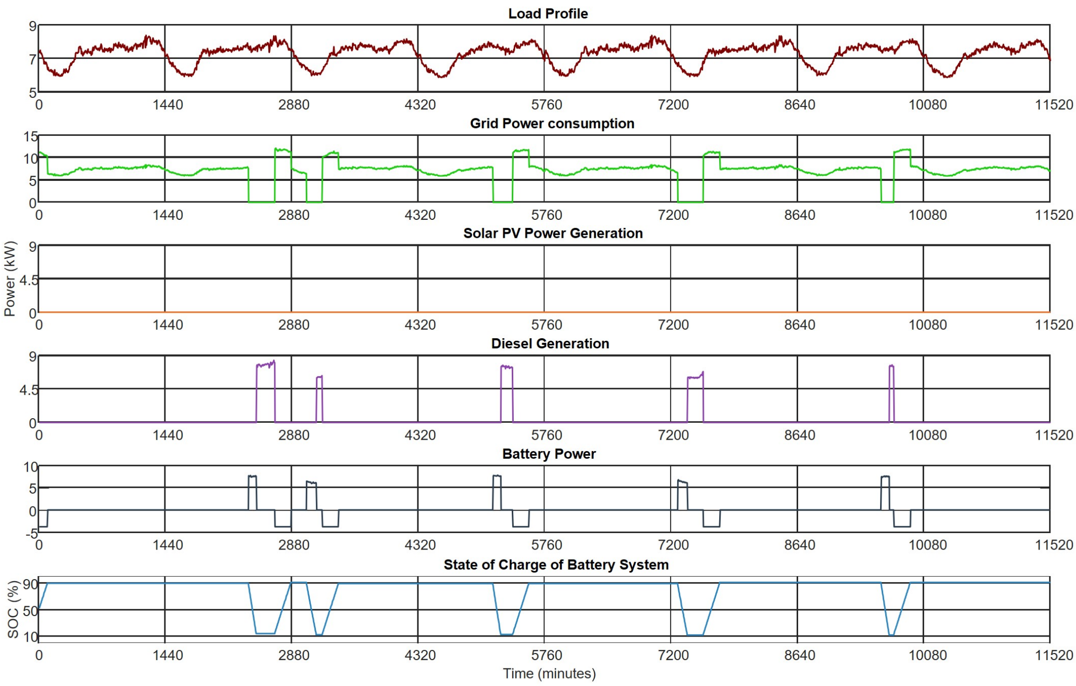


Fig. 7.10: Patterns of Power Dispatching Schedule - Location 5 (Strict Constraints)

lected telecommunication base stations in five different territories. For all the cases analysed under this section, expected network availability is kept unchanged as 100%

to maintain constant system conditions across the analysis for better comparison.

7.1.1 Behaviour of Functional Constraints and LCOE

To study and analyse how the changes of functional constraints impact on the LCOE of optimum electrical system configuration, optimization was implemented with two levels of constraints categorized as moderate and strict and considered for all five geographical locations separately. Results of the optimum electrical system configurations for base stations deployed in different locations are then analysed with the two levels of constraints based on the variations of LCOE of the proposed configuration..

Multi-dimensional characteristics considered on base stations deployed in all five locations and their associated impact on sizing of electrical subsystems are analysed with respective results of optimum electrical system configurations as highlighted in Table 7.1.

TABLE 7.1: OPTIMIZATION RESULTS - UNDER 100% NETWORK AVAILABILITY

Territory	Constraints	Power availability (%)	$N_{SolarPV}$*	E_{BSS_rated}* (kWh)	P_{DG_rated}* (kW)	LCOE ($/kWh)
Location 1	Moderate	98.5	12	5	0	0.0756
Location 1	Strict	98.5	0	5	0	0.0835
Location 2	Moderate	96.7	25	30	0	0.0814
Location 2	Strict	96.7	20	10	9	0.086
Location 3	Moderate	89.5	25	50	0	0.091
Location 3	Strict	89.5	10	10	8	0.0989
Location 4	Moderate	93.75	10	5	2	0.09
Location 4	Strict	93.75	10	5	2	0.09
Location 5	Moderate	90.1	25	45	0	0.0877
Location 5	Strict	90.1	0	15	9	0.1011

When it comes to location 1, according to the optimized results presented in Table 7.1, under moderate functional constraints, maximum possible capacities for Solar PV, BSS and DG are limited by 25 panels, 50 kWh and 15 kW respectively. However, the results of the optimization model propose an electrical system with Solar PV, BSS and DG capacities to be selected as 12 panels, 5 kWh and 0 kWh respectively with a

LCOE equal to 0.0756 \$/kWh for the optimum configuration of electrical system.

In contrast, in case of strict conditions of functional constraints to be considered due to unavoidable reason, maximum possible capacities for Solar PV, BSS and DG will be limited and bounded with 0 panels, 20 kWh and 0 kW. If strict conditions of functional constraints are considered, results of the optimization model propose an electrical system with solar PV, BSS and DG capacities to be selected as 0 panels, 5 kWh and 0 kW respectively resulting in a higher LCOE of 0.0835 \$/kWh for the optimum configuration of electrical system compared to that with moderate operation constraints. Compared to LCOE of optimum electrical system under moderate functional constraints, when constraints become strict, LCOE of optimum electrical system configuration has been increased to 0.0835 \$/kWh which is around 10% increment due to variations in functional constraints.

Similarly, analysis conducted on the deviations of operational constraints in four other locations are summarized in Table 7.2. According to the comparison elaborated in Table 7.2, it can be noticed that in location 2, location 3 and location 5, transition from moderate to strict conditions of operational constraints have led to a reduction in proposed rated capacities of solar PV and BSS, while rated capacities of DGs have been increased within its defined operational constraints resulting a higher LCOE of the proposed optimum electrical system configuration. This is evident that the operational constraints cause LCOE of proposed optimum electrical system to be increased, and therefore applying a general optimization model to determine optimum electrical system configuration without considering operational constraint can mislead on the actual LCOE in the electrical system configuration when operational constraints are applied.

However, when it comes to location 4 in Table 7.2, capacities and LCOE of the electrical system proposed by optimization model are not being affected by changes in operational conditions. This is because capacities bound by the operational constraints are still adequate to implement proposed optimum electrical system configuration by the optimization model and similar conditions are also identified by proposed optimization in this research and configuration is determined minimizing the LCOE of the system.

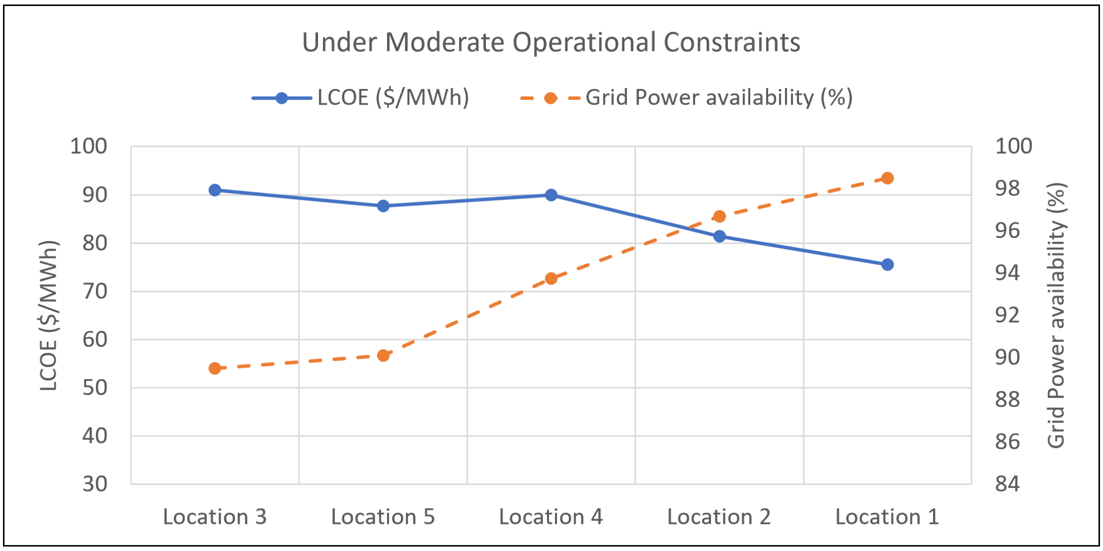
TABLE 7.2: IMPACT OF FUNCTIONAL CONSTRAINTS OF SYSTEM CAPACITIES AND LCOE OF OPTIMUM SYSTEM CONFIGURATION

Location	**Effective change in rated capacities of optimum electrical system configuration from moderate to strict functional constraints**			**% Change in LCOE**
	$\mathbf{N_{Solar\ PV}}$*	$\mathbf{E_{BSS\_rated}}$* (kWh)	$\mathbf{P_{DG\_rated}}$* (kW)	
Location 1	-12	0	0	+10.40%
Location 2	-5	-20	9	+5.70%
Location 3	-15	-40	8	+8.70%
Location 4	0	0	0	0%
Location 5	-25	-30	9	+15.30%

7.1.2 Cross Analysis of Power Availability, LCOE and Operational Constraints

Figure 7.11 contrasts the behaviour of LCOE and Grid Power Availability curves under different territories and operational constraints. When comparing the results of all territories together, from Figure 7.11, it is evident that the typical relationship is when power availability of the utility grid increases, LCOE has been decreased, which demonstrates an inverse relationship between LCOE and power availability. However, there is an anomaly of this typical relationship when it comes to LCOE of location 4 and location 5 as elaborated in Figure 7.11, which is the deviation to the expected relationship between grid power availability and LCOE. This outlier in optimum electrical system configuration for location 4 has occurred as in Figure 7.11 under moderate operational constraints is due to lower site DC load demand of the base station compared to that in other locations. When electrical load is decreased, actual BSS capacity requirement is reduced, however the minimum bound of BSS capacity is considered as 5 kWh in the optimization model, hence when the actual BSS capacity requirement is less than 5 kWh, LCOE is calculated considering BSS capacity as 5 kWh which causes to increase in LCOE than expected.

On the other hand, the outlier in optimum electrical system configuration for location 5 has occurred as in Figure 7.11 under strict operational constraints is due to larger site DC load demand and very strict operational constraints affected on the base station compared to that in other locations. Such strict operational constraints have caused



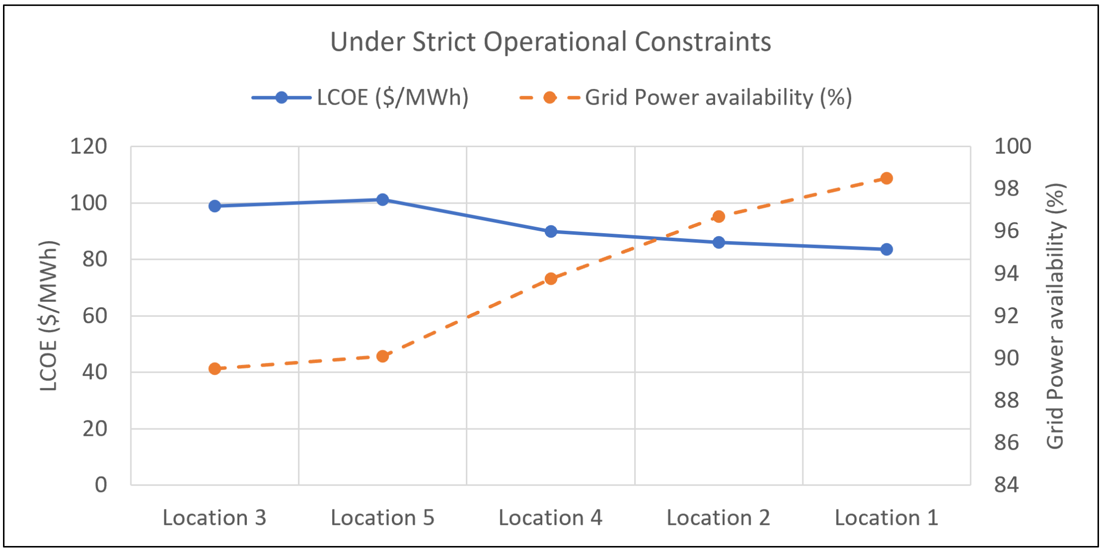


Fig. 7.11: Relationship Between Power Availability, LCOE and Functional Constraints

LCOE to increase abnormally due to zero solar PV capacity considered for optimized electrical system and reduction in BSS capacity with significant capacity which leads to higher DG running time with increase operations cost.

7.1.3 Cross Analysis of Power Availability, LCOE against Minimum Grid On and Maximum Grid Off Times

Figure 7.12 illustrates a cross analysis among grid power availability, LCOE, minimum on time between two power failure incidents in the grid and maximum off time during a power failure incident of the grid. The key observation in Figure 7.12 is that when grid power availability increases, LCOE of the system has been decreased. At the same time, it can be observed that there is a small deviation of LCOE in location 4, which has unexpected increment opposing the behaviour of LCOE in other locations. According to this analysis, this behaviour of LCOE can be influenced by rapid rise in maximum interruption duration of grid power failure incident in location 4, which lead model to respond with higher LCOE by introducing more resources to the electrical system of telecommunication base station. Therefore, the overall behaviour of these results evident that the proposed optimization model in this research has adapted to the grid power availability while considering its extreme scenarios and characteristics.

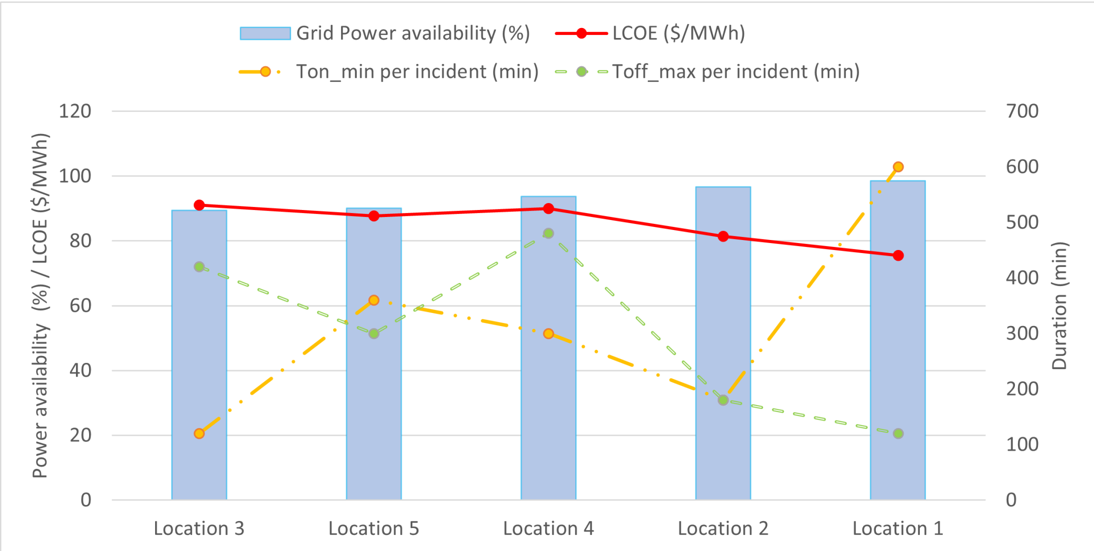


Fig. 7.12: Cross Analysis of Results in Analysis 1

7.2 Analysis 2 – Behaviour of LCOE and Network Availability

To study the impact of expected Network Availability on determining optimum electrical system configuration for telecommunication and its LCOE is discussed in this section. In this analysis, since only LCOE and network availability parameters are considered, other variables such as power availability, interruption durations, operational constraints and location of the base station kept unchanged for better comparison of results. Considering these criteria unchanged within the optimization model, results obtained on optimum system configurations under different network availability criteria for location 3 are summarized in Table 7.3.

In Figure 7.16, based on the summarized results in Table 7.3, behaviour of LCOE is plotted against the different network availabilities considered in the optimization. In Figure 7.16, it can be observed that there is exponential growth in LCOE when expected Network Availability keeps increasing, which is evident that when expected Network Availability needs to be increased in the telecommunication base station, cost of development and operations of electrical system in the base station also getting increased in exponential rate. This relationship between LCOE and Network Availability emphasizes network operators on the importance of benchmarking suitable network availability targets in a telecommunication network for best ROI.

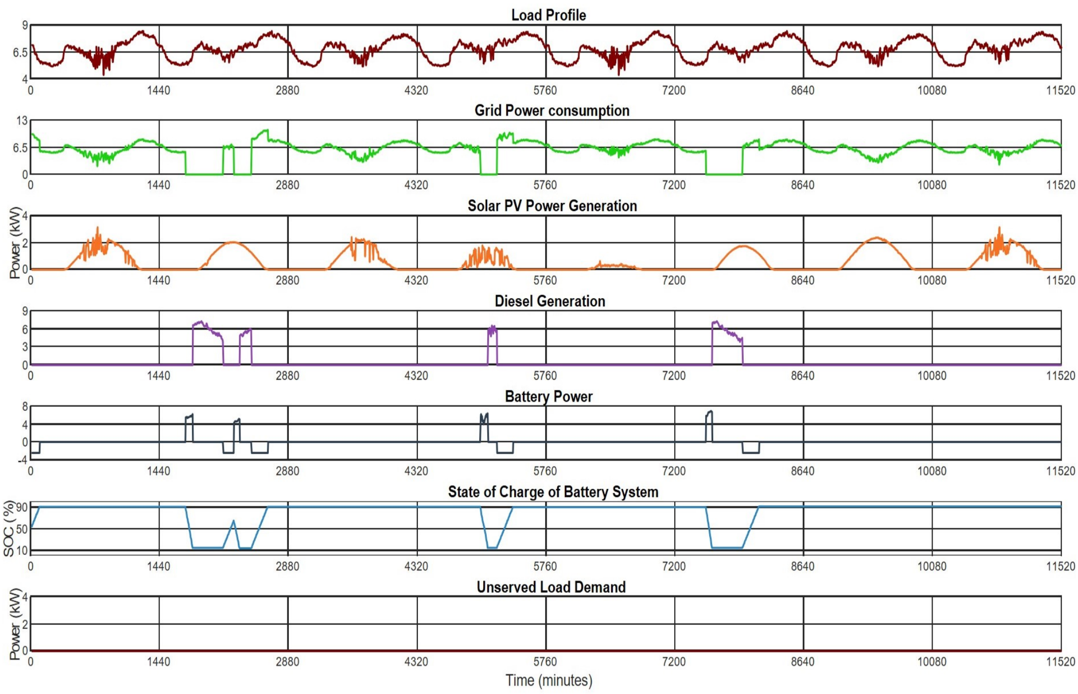


Fig. 7.13: Patterns of Power Dispatching Schedule - Location 3 (100% Network Availability)

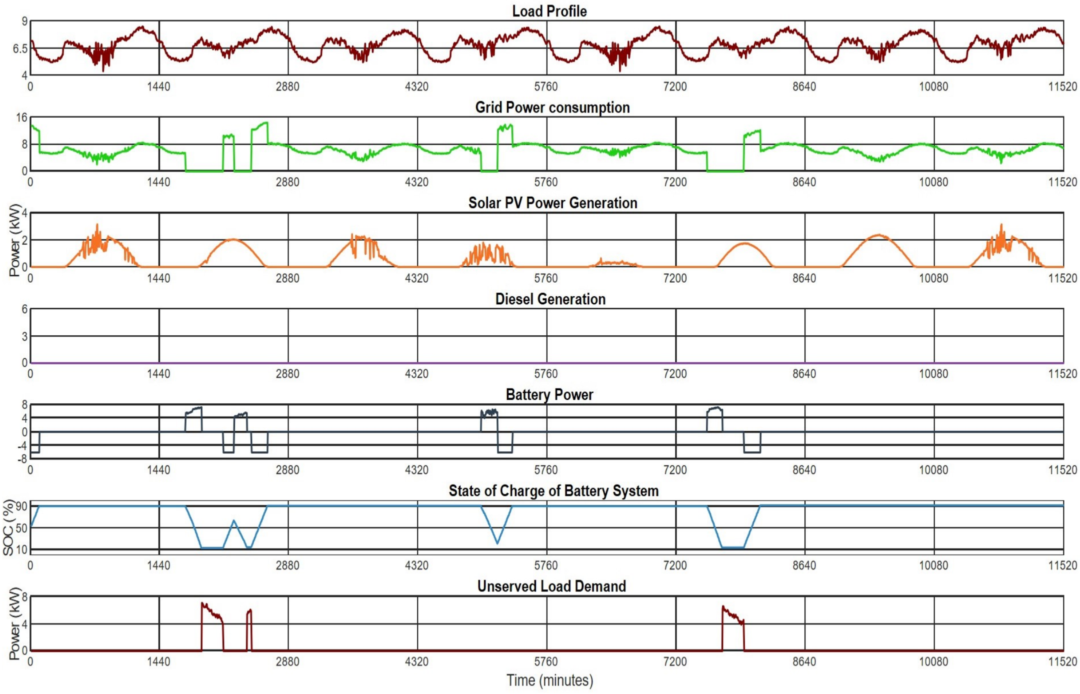


Fig. 7.14: Patterns of Power Dispatching Schedule - Location 3 (99% Network Availability

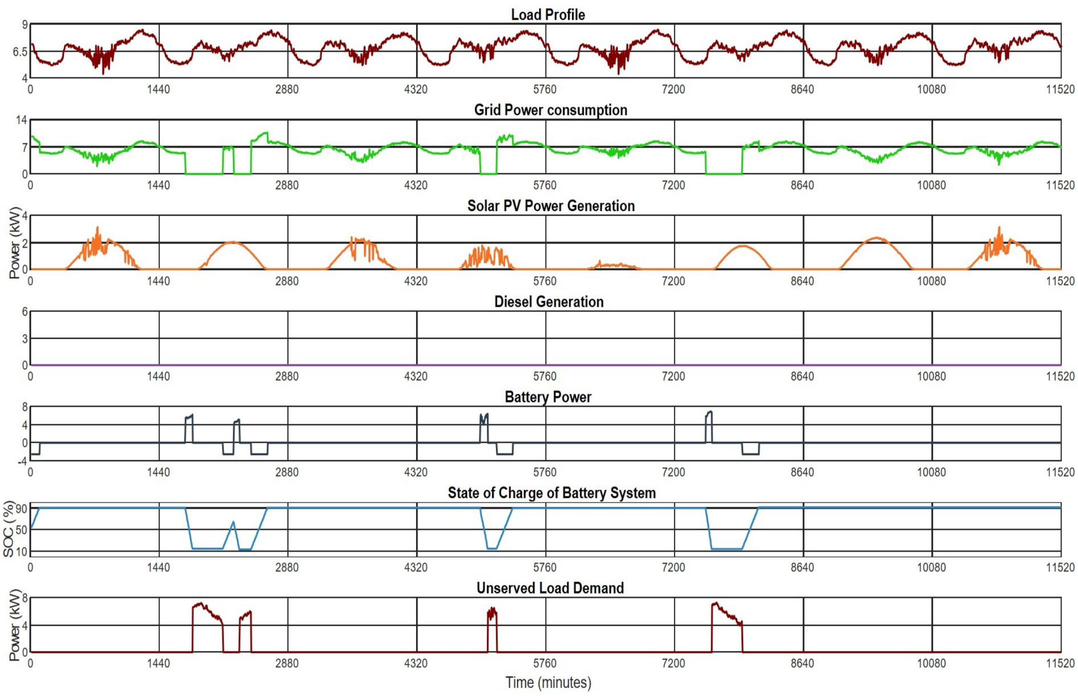


Fig. 7.15: Patterns of Power Dispatching Schedule - Location 3 (98% and 95% Network Availability

TABLE 7.3: OPTIMIZATION RESULTS - UNDER DIFFERENT NETWORK AVAILABILITIES

Territory	**Power availability (%)**	**Network Availability (%)**	$\mathbf{N_{SolarPV}}$*	$\mathbf{E_{BSS}}$* (kWh)	$\mathbf{P_{DG}}$* (kW)	**LCOE ($/kWh)**
Location 3	89.5	100	10	10	8	0.0989
Location 3	89.5	99	10	25	0	0.083
Location 3	89.5	98	10	10	0	0.0735
Location 3	89.5	95	10	10	0	0.0735

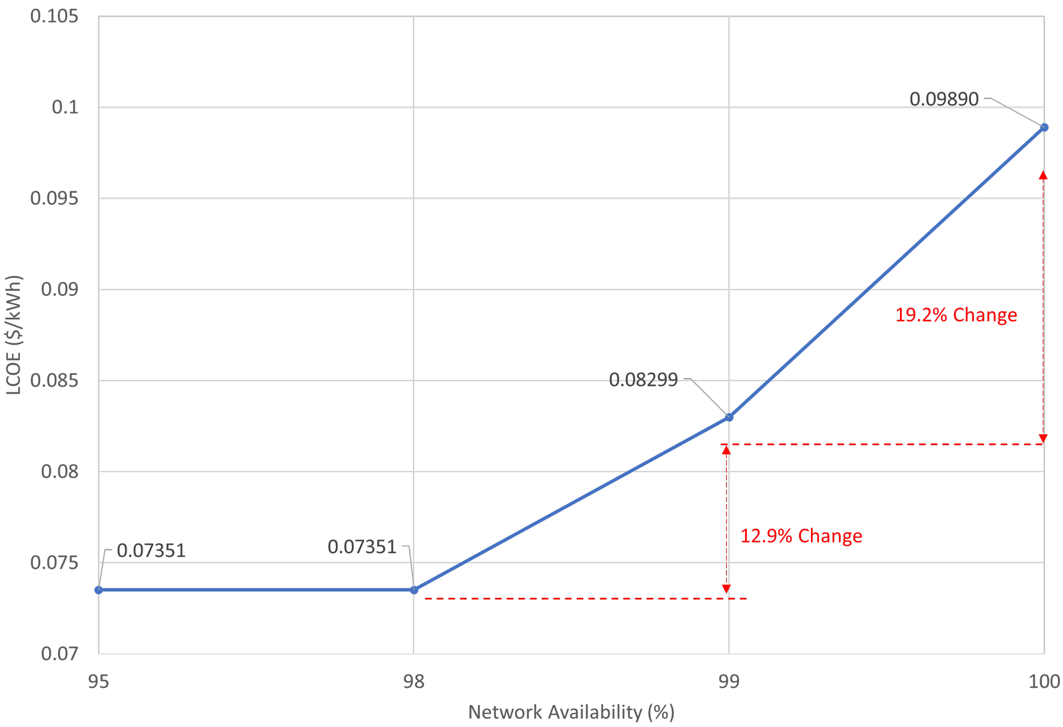


Fig. 7.16: Relationship between LCOE and Network Availability

CHAPTER 8

CONCLUSION

The development costs invested in power infrastructure of telecommunication networks generally utilize about 30% of the total capital invested in telecommunication networks. Meanwhile, the costs associated with operation and maintenance of power infrastructure usually burn around 21% of the total operational cost spent on the entire telecommunication network. Therefore, considerable impact on the bottom-line targets of the telecommunication network can be reached through optimization of power infrastructure of telecommunication base stations.

In this research, a parametric approach has been discussed to quantify multi dimensional characteristics affected when determining the optimum configuration of electrical system of telecommunication base stations. The main characteristics affected on optimization of electrical system can be identified as expected network availability, functional constraints, grid power availability, geographical positioning and electrical load profiles. Impact of these characteristics were quantified using parametric indices and applied into the model through constraints to the optimization problem. A novel method has been discussed in this research to model the grid power availability curves using the parametric indices of grid performances which are published by utility service provider. Using this model, grid power availability is analysed and discuss to capture its characteristics and extreme scenarios into the optimization model as inputs for better accuracy of the optimization.

Mathematical equations have been developed to model the cost behaviour of all the components in the electrical system, and using those equations total LCOE was determined. Objective function is evaluated using Genetic Algorithm in MATLAB under given system constraints to find the solutions for decision variable where total LCOE is minimum which reflects the optimum configuration of electrical system.

Results of the proposed optimization model have been evaluated under two analyses. The first analysis was conducted on the behaviour of the operational constraints, power availability and LCOE while maintaining 100% network availability. Under this analysis, it was highlighted that when functional constraints become strict and impact on the optimized outputs of the decision variables, the optimization model changes its solutions for the decision variables with higher LCOE with a change ranging from 5.7% to 15.3%. This behaviour emphasizes the importance of consideration of functional constraints, which otherwise could have underestimated the actual LCOE applying for the respective electrical system. Further in this analysis, the discussion on the relationship between LCOE and grid power availability suggests a negative correlation unless there is constraint which may deviate this relationship. Therefore, in general, it can be concluded that when higher the grid power availability, electrical system can be developed and maintain with a lower LCOE in telecommunication base station which is evident for adaptive resource allocation strategy can be achieved through the proposed optimization model. Under the first analysis, the discussion on how the nature of interruption of grid power is affected on LCOE is also very important. In this discussion, it is evident that, when maximum power interruption duration of grid power failure incident is increased, that behaviour leads optimization model to respond with higher LCOE by introducing more power infrastructure to the electrical system to withstand continuous power interruption for long duration. This is an evident of the adaptive behaviour of proposed optimization model capturing variation through multi dimensions in determining the optimum electrical configuration.

The second analysis is based on the variations in Network Availability and its impact on determining the optimum electrical system configuration for telecommunication. In this analysis power availability, interruption durations, operational constraints and location of the base station kept unchanged. From the results of the second analysis, it is evident that the increase in network availability leads to an exponential increase in LCOE in the proposed electrical system. That is 1% of increment in network availability from 98% to 99% causes LCOE to be increased by 12.9%, however 1% of increment in network availability from 99% to 100% causes effective LCOE to be increased by 19.2%. Therefore, from this analysis, the optimization model has clearly elaborated on the requirement of correct benchmarking of network availability, and it is very important as higher network availability can only be achieved with higher cost. Further to the main results and observations, parametric quantification of characteristics of electrical system and adopting base station classification approach in determining optimum electrical system configuration for telecommunication base station are unique aspects discussed within this research. And results of this study suggest that LCOE of optimized electrical system configuration is mostly independent from its site load but heavily depending on network availability, variation pattern of the load, system constraints and grid power availability. When it comes to the behaviour of LCOE within optimization model, even when 100% network availability is considered and when grid availability is dropped to 89.5%, LCOE of proposed optimum electrical system configuration maintained under 0.1 $/kWh, compared to industry average of between 0.15 $/kWh to 0.3 $/kWh [1], [43] for a typical hybrid electrical system consisting of DG, Lithium-ion battery bank and solar PV.

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