SOLAR ENERGY-BATTERY STORAGE OPTIMIZATION FOR SATELLITE-TO-GROUND COMMUNICATION

By

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Dr K. Moloi Date

27/06/2023

I. Preface

This thesis Titled Solar Energy-Battery Storage Optimization for Satellite-To-Ground Communication is hereby approved in partial fulfilment of the requirements for the degree of Master in Electrical Power Engineering.

The work described in this thesis was carried out at the Durban University of Technology from January 2020 to June 2022, under the supervision of Prof IE Davidson and Dr. Moloi. These studies represent original work by the author and have not otherwise been submitted in any form for a degree or Diploma to any institution.

I. DECLARATION

(Simphiwe A Ntlela) Declare that.

This thesis serves as a presentation of my work, which I wrote and produced. All information from written works, whether they were published or not, has been recognized. IE Davidson, a professor at the Durban University of Technology, served as the thesis advisor.

The thesis has not been submitted to another university for a degree or examination.

Other people's data, photographs, graphs, or other information are not included in the thesis unless they are expressly cited as coming from them. In cases when quotations from other written sources have been made:

- Although their words have been changed, the general knowledge that they are credited with has been cited.
- Their writing has been sourced and put in quotation marks wherever it has been used.

Signed by ………………………………. Date……26/06/2023…………………….

II. DEDICATION

This Thesis report is wholeheartedly dedicated to my beloved Baby for the constant spiritual and emotional support.

To my friends who have shared their words of encouragement to finish this report.

III. ACKNOWLEDGMENT

I cannot express enough gratitude to the lord my creator for giving me the strength to tackle every obstacle and for protection when undertaking every procedure for this Thesis and My Supervisors, Prof Innocent E Davidson, and Dr K. Moloi, for wisdom, encouragement, and patience. Your unwavering support, motivation, and kind supervision during the entire period of my research. You so understood and were patient with me, your guidance is deeply appreciated. You have given me so many excellent chances that have helped me develop both personally and professionally.

A brief acknowledgement in this thesis is insufficient to express my gratitude for your unwavering support and inspiration in all of my attempts. Finding the right words to express my gratitude for all you have done for me would be like starting a new dissertation from scratch. I only know it's feasible and conceivable because of you. As usual, you went above and above.

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- I must also express my gratitude to CA Sibiya for his help and support during the course of my research. I appreciate your assistance and your patience in responding to my requests.
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IV. ABSTRACT

The creation of ubiquitous broadband systems has piqued the interest of both academics and industry to fulfil the exponential growth in demand for multimedia services on mobile devices and to support access anywhere on the earth. The implementation of such systems is anticipated to heavily rely on satellite networks in general and Low Earth Orbit (LEO) satellite constellations. Therefore, increasing their service life has become a significant engineering and scientific challenge. The main finding of this thesis is that by sharing the power of a satellite's batteries with another spacecraft that is still in the sun, one may considerably extend the service life of a satellite. Over 30% of the time that LEO constellation satellites are in the earth's shadow, they are powered by batteries. Although the batteries are replenished by sunlight, the depth of discharge they experience during an eclipse has a major impact on their lifetime and, consequently, the service life of the satellites. A 15% increase in the DoD can almost halve the service life of the batteries. The major section of this thesis includes a variety of strategies we think may help LEO constellations' batteries last longer.

The market's demand for satellite communication networks has changed recently. Low-Earth-Orbit (LEO) satellite constellations have therefore received increased attention because they are expected to address these needs. In the current LEO satellite constellation-based communication system, the satellite close to the satellite terminal that submits the communication request answers to it regardless of the state of its battery. However, in cases of significant battery deterioration, this communication technique reduces the lifetime of the satellite. This means that in big satellite constellations when operating costs are a concern, this communication mechanism is unsuccessful. To extend the battery's lifespan, we design a communication mechanism in this work that regulates the transmission power and transmission gain of a satellite antenna based on the battery's state of deterioration. Large-scale LEO satellite constellations can be created and used thanks to the decrease in operating expenses that results from extending battery life. Future demands for satellite communication should be met by the system that has been put in place. Through simulation, the usefulness of the suggested approach is confirmed.

V. ABSTRACT CORRECTED

The use of solar energy for satellite power is an attractive option due to its sustainability and cost-effectiveness. However, satellite communication requires a constant and reliable power supply, which is challenging to achieve with solar energy alone, particularly in periods of low solar activity or during eclipses. This is where battery storage optimization comes into play.

In this study, we propose an optimization model for the use of solar energy and battery storage in satellite-to-ground communication systems. The model takes into account various factors such as solar irradiance, battery capacity, and communication power requirements. The optimization objective is to maximize the utilization of solar energy while ensuring uninterrupted communication.

We apply the proposed model of Q-theory to a case study of a Low Earth Orbit (LEO) satellite. The simulation results show that the proposed optimization model can significantly improve the performance of the satellite power system. Specifically, it can reduce the reliance on battery power during periods of low solar activity, leading to longer battery life and more reliable communication.

VI. DECLARATION 2 – PUBLICATION

[1] Ntlela, S. A., & Davidson, I. E. (2022, January). Solar Irradiation Forecasting for the City of Durban Using Time Series Analysis. In *2022 30th Southern African Universities Power Engineering Conference (SAUPEC)* (pp. 1-5). IEEE.

[2] Ntlela, S.A, & Davidson, I.E. (2023, January). Satellite to Ground Communication Energy Storage Selection. In 2023 31st *Southern African Universities Power Engineering Conference (SAUPEC)* (pp. 1-4). IEEE.

Table of Contents

VII. List of Figures

VIII. LIST OF TABLES

IX. ACRONYMS

AC	alternating current
ANN	artificial neutral network
COE	Cost of Energy
COMSAT	Communications Satellite Corporation
DC	direct current
DOD	Depth of discharge
FCC	Federal Communications Commission
GPS	Global Positioning System
HF	high-frequency
HOMER	Hybrid Optimization Model for Electric Renewable
ICBMs	intercontinental ballistic missiles
Ii-ion	Lithium-ion
INMARSAT	International Maritime Satellite Organization
INTELSAT	International Telecommunication Satellite Organization
IoT	Internet of Things
IRBMs	intermediate-range ballistic missiles
LCOE	Levelized cost of energy
LEO	Low Earth Orbit
MEO	Medium earth orbit satellite
NASCOM	NASA Communications Network
NiCd	Nickel-cadmium
Ni-Cd	Cadmium Nickel
NiMH	Nickel-metal hydride
O&M	Operation & Maintenance
PV	photovoltaic
SEI	solid electrolyte interphase
SOC	State of Charge
TVRO	TV-Receive Only
VSARs	very small aperture terminals

CHAPTER 1 - INTRODUCTION

1.1 Background

The use of satellites to gather solar energy in space and send it back to Earth has been extensively studied over the past 30 years. The sun's atmosphere is pure. Solar energy is a renewable resource that has the potential to be more ecologically friendly than fossil fuels and can contribute a sizable amount of electricity to the global power system. In recent years, there has been an increase in the demand for safe communication channels during emergencies. It is common knowledge that satellite communication works quite well for communication during emergencies. A powerful energy system known as a space solar power satellite gathers solar energy in space, transforms it into electric power, and then wirelessly transfers the electric power to Earth. [1].

Since it was first put forth by Dr. Peter Glaser in 1968 [2], it has garnered attention on a global scale, leading to the development of numerous concepts in the US, Japan, Europe, and China [3]. The LEO satellite needs the power to send data to the ground. LEO satellites use solar power to handle traffic throughout the day and use the extra energy to recharge the battery. Under cover of shade, the battery's electrical energy is used to process the traffic. LEO satellites typically can only be operated using their battery while they are in the shade. Additionally, the depth of discharge (DOD) has an impact on the battery life of LEO satellites [4]. The lifespan of the satellite battery increases with the quantity of charge required per cycle. Therefore, the cost of building and maintaining satellite constellations can be decreased by lowering the depth of discharge (DOD) per cycle and increasing the battery life of LEO satellites [5].

The demand impost on a satellite communication network has recently increased as a result of changes in the interaction between satellite communication networks and ground communication networks. The low earth orbit (LEO) satellite constellation, which uses collaboration between numerous tiny satellites in low orbit to cover the entire surface of the globe, is currently drawing attention in this category of networks [6]. When LEO satellites communicate with terrestrial terminals, power is used. These satellites, however, are forced to run only on battery power when there is no solar light, which puts a huge burden on the batteries and reduces the lifespan of the satellites [7-10]. For a satellite communication network, this comes at a high cost. By distributing the burden of overworked satellites among neighbouring satellites with low loads, the research will be cantered on prolonging the lifespan of LEO satellite batteries over the same orbital plane and solar irradiation projections [8].

The public's concern over producing grid electricity by burning fossil fuels to prevent air pollution, energy imports, and global warming has led to the emergence and rapid growth of the renewable energy sector in the 21st century. Renewable heat, renewable power, and biofuels for motor vehicles are the three main uses for renewable resources. The International Energy Agency projects that among these three applications, renewable energy in the electrical sector would increase at the quickest rate over the next five years, meeting approximately 30% of the power demand in 2023, up from 24% in 2017 [11]. Renewable energy sources are anticipated to provide 70% of the increase in worldwide electricity output during this time, with solar supplying the most, followed by wind, hydropower, and biofuels [1]. Grid-connected power plants commonly use solar and wind energy to produce electricity and cut down on carbon emissions. Sun and wind energy can be converted into electricity and fed into the power system using power electronics [12]. One innovation, the photovoltaic (PV) system, converts sunlight into direct current (DC) electricity using solar panels. Concentrated solar power is an additional option. This method employs mirrors and lenses to collect heat from the sun and then uses that heat to power generator systems. Although both approaches have benefits and drawbacks, PV systems are much more common than concentrators. Large-scale PV systems, which are intended to provide utility-level power to the electric grid, can be used to implement utility-scale solar. The majority of solar parks are built at least 1 megawatt-peak in size (MWP). The biggest PV power plants in the world ran at over 1 gigawatt until 2018 [13-16].

Table 1.1 compares lead-acid batteries, lithium-ion batteries, VRB batteries, and NaS batteries [17] [19] [21].

Composition	Nas	VRB	Li-ION	Lead Acid
Usable life/shelf life	Grid-scale battery storage for 15 years 10 years of active business	20-30 years	2-3 years	10 years
Advantages	Long discharge time; low maintenance requirements; high energy density; eco-friendly.	Using an electrochemical reaction that is reversible, you can store and release energy.	Low maintenance; high energy; low self-discharging; high resistance to both deep and rapid discharge.	Cheap and reliable long discharge time
Charge cycle	4500	>10 000	7000 before they lose something.	200-300
Efficiency	89-92%	75-80%	90%	80%
Drawback	operating at a temperature greater than 300°C; Metalic sodium is a substance that becomes dangerous when it comes into contact with water; Added expense to stop leaks	System complexity; demands for pumps, sensors, flow, and power control.	Li-ion batteries must be protected from being overcharged and discharged since they degrade with each charge and discharge.	High maintenance needed; lead acid battery damage from deep discharge is substantial.
Temperature	>300C	-5-50 C		
Cost (Dollar/kwhr)	500	300-500	Average 209	186

The NaS battery is best used for peak shaving, managing the transmission and distribution networks, and load-levelling; the VRB battery is best used in high-capacity power systems with a range of 100kW to 10MW; and both the Li-ion battery and the lead acid battery are suitable for intermittent source power storage in renewable energy systems [19]. Each type of battery has advantages and disadvantages of its own. Consequently, further comparisons between the Li-ion battery and the lead acid battery are possible. Lithium-ion batteries were just starting to be employed for large-scale solar power systems in 2016, according to O'Connor [22]. Li-ion batteries have recently displaced lead-acid battery power grid energy storage devices. Lead acid batteries are inferior to lithium-ion batteries for a variety of reasons. First, Li-ion batteries can store a lot of power in a little amount of space thanks to their increased energy density. A typical lithium-ion battery has a storage capacity of 150 watt-hours per kilogram, compared to only 25 watt-hours per kilogram for lead-acid batteries [23]. Li-ion batteries also offer better resilience, which enables them to withstand rapid and deep discharge without being harmed. Lead acid batteries lose potential cycles if they are discharged below 50% of their SOC or at a pace higher than C/8, whereas lithium-ion batteries may be discharged to roughly 80% State of Charge (SOC) and at a rate of C/2 (more on that in Chapter 4) without any long-term damage [4]. Despite having a higher initial cost, Li-ion batteries' cost per cycle ($0.19) is lower than that of most lead acid batteries ($0.71) due to their superior cycle life, low maintenance requirements, deep discharge capabilities, and high energy efficiency, as shown in Table 1.2 [21], which compares two types of lead acid batteries with one type of Li-ion battery. The flooded lead acid battery has a marginally lower cost per cycle than the Li-ion battery, but it needs regular maintenance, offers much less load power and specific energy, and charges four times slower. Thus, in conclusion, for the highest cost-saving and superior performance purposes, the Li-ion battery is most suitable for intermittent source power storage due to its long lifecycle, high energy density, low cost per cycle, and deep and fast discharge ability [25-28].

1.2 Problem Statement

Satellite communication is essential They serve a variety of functions, including the Global Positioning System, amateur radio, television transmission, and weather forecasting. In order to conduct study and acquire data, they also employ telescopes to view outward at the solar system. This constellation contains LEO satellites whose batteries have deteriorated due to test operation before the completion of the constellation. In the transmission power control method in the existing satellite communication system, the LEO satellite that exists in the sky where the traffic request is generated must process the traffic regardless of the deterioration state of the satellite battery. If satellites with severe deterioration continue to process the traffic generated to the extent possible in the same manner the battery life of the degraded satellites will be further reduced, as the maximum capacity of the battery will cause the depth of discharged (DOD) to become larger than that, in the case of the battery will little deterioration.

1.3 Aims and Objectives

To achieve in line with solving the identified problem the following objectives must be achieved.

The objectives include:

- To calculate signals to noise ratio.
- Proposed efficient power control using Queue theory.

- To assess satellite-based solar resource.
- To process radiation data for location understudy.
- To calculate life cycle.

1.4 Research Methodology

The research consolidates dynamic models of the different components of a satellite including the solar panels, shape, transmission, size, and weight as well as battery storage Queuing theory technique will be used to optimize the satellite battery life cycle. Comparative analysis of different versions of the models for each component is derived and artificial neutral network (ANN) will be used for solar irradiation prediction. HOMER will be used for simulations.

1.6 Dissertation Structure

The following chorological methodology to achieve the detailed objectives is outlined as:

Chapter 1 – Introduction

Chapter 2 – Literature Review

Chapter 3 – Efficient Power control of a battery

Chapter 4- Calculation of Battery life cycle

Chapter 5 – Design and result

Chapter 6- Conclusion and future work which summarises the main findings of the study and describes further areas of research.

1.7 Publications Emanating from the Thesis

Include here your SAUPEC 2022 conference paper.

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In this chapter a brief discussion of the background, problem statement, objectives, research and methodology are covered. The intention of the chapter is to introduce the context of the subject matter for chorological development. In chapter two, a literature review will be covered. The review is aimed at discussing the state of the art of the satellite communication.

CHAPTER 1 – INTRODUCTION CORRECTED

Satellite communication plays a vital role in modern society, enabling global connectivity for a wide range of applications, including navigation, weather forecasting, and disaster management. However, ensuring reliable power supply for satellite communication systems is a significant challenge. Solar energy is a promising source of power for satellites due to its sustainability and cost-effectiveness. However, solar energy alone may not be sufficient to meet the power requirements of satellite communication systems, particularly during periods of low solar activity or eclipses.

Battery storage provides a solution to this challenge by enabling the storage of excess solar energy generated during periods of high solar activity, which can be used to power satellite communication systems during periods of low solar activity. However, the optimization of the use of solar energy and battery storage in satellite communication systems is a complex problem due to various factors, including solar irradiance, battery capacity, and communication power requirements.

In this project, we propose an optimization model for the use of solar energy and battery storage in satellite-to-ground communication systems. The model takes into account various factors such as solar irradiance, battery capacity, and communication power requirements. The optimization objective is to maximize the utilization of solar energy while ensuring uninterrupted communication. The proposed model is applied to a case study of a Low Earth Orbit (LEO) satellite, and simulation results demonstrate its effectiveness in improving the performance of the satellite power system.

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The rest of the paper is organized as follows. Section II provides a literature review of relevant work in the field of solar energy and battery storage optimization for satellite communication systems. Section III presents the proposed optimization model, while Section IV describes the case study and simulation results. Finally, Section V concludes the paper and discusses future work

CHAPTER 2 - LITERATURE REVIEW

The serious consideration of the provision of satellite communications from space dates from 1945 when the first technical descriptions were written about launching a spacecraft into geosynchronous orbit and the design of space stations as extra-terrestrial radio relays were specifically outlined.

2.1 Brief History of Satellites

In the historical section that follows [29], however, it becomes clear that the idea or concept had been around many years, indeed centuries before [30]. The 1945 article, however, described the possible delivery of telecommunications services from space and presented detailed calculations as to how this might efficiently be done from a special orbit known as the geosynchronous (or sometimes the geostationary) orbit (Clarke 1945) [31]. The use of radio waves for long-distance communications up until the 1960s was limited to microwave relay between towers or the use of shortwave or high-frequency (HF) transmissions that were, in effect, bounced off of the ionosphere [32]. This latter technique was quite limited in transmission throughput and unreliable because the ionosphere was subject to distortions largely due to solar radiation and the so-called solar wind and solar storms. Launch technology that could place satellites in orbit came into being in the late 1950s [9].

The first satellites provided a low capacity at a relatively high cost for example intel sat 1 weighed 68Kg at launch for a capacity of 480 telephone channels and an annual cost of $32 500 per channel at the time. This cost resulted from a combination of the cost of the launcher, that of the satellite, the short lifetime of the satellite (1.5 years), and its low capacity [33]. Production of the satellite is evolving as a business and its application is broader than before. This makes companies focus on reducing the time taken to develop prototypes, costing of producing spacecraft, minimize failures on satellites [34].

The launch of the first artificial satellite, Sputnik 1, into earth's orbit marks the first instance of satellite remote sensing. Sputnik 1, which the Soviet Union placed into an elliptical low earth orbit on October 4, 1957 [35], transmitted back radio signals that researchers used to investigate the ionosphere. [13]. On January 31, 1958, NASA launched Explorer 1, the nation's first satellite. The Earth's Van Allen radiation belts were discovered thanks to data from the satellite's radiation sensors [36] The satellite orbited the planet in 96.2 minutes while traveling at 29,000 kilometres per hour [37]. The first television film of weather patterns captured from space was sent back by the TIROS-1 spacecraft, which was launched on April 1, 1960, as a part of NASA's TIROS (Television Infrared Observation Satellite) Program [38].

NASA Launched the first United States space station called Skylab that orbited for about 24 weeks between May 1973 and February 1974 with a mass of 77000kg and a speed of 7.5km/s [39]. The Russians (Soviet Union) introduced a MIR space station that operated in low earth orbit from 1986 to 2001 [40], It has a greater mass of 129 700Kg than any previous spacecraft and a speed of 7.7 km/s [41]. Ariane 5 from the Guyana Space Centre in Kourou launched inactive earth observing satellite on 1 March 200 which was the world's largest civilian Earth observation satellite, it orbits the Earth in about 101 minutes, with a repeat cycle of 35 days its mass was 8,211 kg, power of 6,500 watts and speed.

In a brief piece published in Wireless World in the fall of 1945, RAF electronics officer and BIS member Arthur C. Clarke described the deployment of human satellites in 24-hour orbits high above the planet's supercontinent to transmit television content. Despite the fact that Clarke retold the tale in The Exploration of Space in 1951–1952, his essay seems to have had little long-term impact. John R. Pierce of AT&T's Bell Telephone Laboratories may have been the first to carefully consider the various technical options in satellite communications and evaluate the financial prospects. In a 1954 speech and a 1955 article, he elaborated on the utility of a communication’s "mirror" in space, a medium-orbit "repeater," and a 24-hour "repeater." In contrasting the capability of communication of Pierce questioned whether a satellite would be worth a billion dollars by contrasting its communications capacity, which he approximated to be 1,000 simultaneous telephone calls, with that of the first transatlantic telephone cable (TAT-1), which could carry 36 simultaneous telephone calls at a cost of 30–50 million dollars [42,43,44,45,46]. [42-46].

Several people thought about the advantages, earnings, and prestige involved with satellite communications after the 1957 launch of Sputnik I. The Department of Defence was in charge of "repeater" or "active" satellites, which amplify the frequency spectrum at the satellite and provide communications of much higher quality, while NASA was limited to experiments with "mirrors" or "passive" communications satellites (ECHO) due to concerns from Congress about "redundancy." In order to quickly construct an operational system, AT&T applied to the Federal Communications Commission (FCC) in 1960 for authorization to launch an experimental communications satellite. The American government was taken aback because there was no established policy to guide the execution of the numerous choices associated with the AT&T proposal. [47,48] A 24-hour (20,000-mile-high) satellite was being built by Hughes Aircraft Company, and AT &T was building its own medium-orbit satellite (TELSTAR), which NASA would release on a cost-reimbursable basis. By the centre of 1961, RCA had won a challenging NASA contract to build a medium-orbit (4,000 miles high) active communication satellite (RELAY), AT&T had won a contract to build its own medium-orbit satellite (SYNCOM). Due to cost overruns, launcher delays, and spacecraft complexity, the military program ADVENT was cancelled a year later [49,50].

Two TELSTARs, two RELAYs, and two SYNCOMs had completed successful space missions by the year 1964. The Communications Satellite Corporation (COMSAT), established because of the Communications Satellite Act of 1962, was amid awarding contracts for their first satellite, so the timing was fortunate. It was believed that COMSAT's initial funding of $200 million would be adequate to construct a system of numerous satellites in medium orbit. COMSAT finally decided to reject the joint AT&T/RCA offer of a medium-orbit satellite combining the best of TELSTAR and RELAY due to several factors, primarily pricing. For the initial two systems, they used the geosynchronous (24-hour orbit) satellite provided by Hughes Aircraft Company, and for their third system, they selected a TRW geosynchronous satellite. Early Bird, the first satellite for COMSAT, was launched from Cape Canaveral on April 6, 1965. International satellite communications had started [51].

Experiments with TELSTAR, RELAY, and SYNCOM had already given some glimpses of the Global Village. Television coverage of the 1964 Tokyo Olympics was one of them. Other nations had been engaged from the start, even though COMSAT and the initial launch vehicles and satellites were American. In order to construct earth stations for the TELSTAR experiment, AT&T first entered into negotiations with its European telephone cable "partners." These discussions had been widened by NASA to cover the RELAY and SYNCOM experiments. There was existing communication ground stations in the United Kingdom, France, Germany, Italy, Brazil, and Japan at the time EARLY BIRD was launched. A new international organization was created because of additional negotiations in 1963 and 1964. This body would eventually take ownership of the satellites and oversee managing the worldwide system. Agreements were reached on August 20th, 1964, establishing the International Telecommunication Satellite Organization (INTELSAT) [52-54].

By the end of 1965, EARLY BIRD had offered 80 hours of television service and 150 telephone "half-circuits." The INTELSAT II series was an improved and more durable iteration of the EARLY BIRD series. Early on, the COMSAT/INTELSAT system was primarily used to supply circuits for the NASA Communications Network (NASCOM) [55]. The Indian Ocean was initially covered by the INTELSAT III series, completing the global network. Just a few days later, on July 20, 1969, a billion people witnessed APOLLO 11 touch down on the moon [56].

In 1965, INTELSAT had a small number of telephone circuits and a few members. Today, it has more members than the United Nations and can provide hundreds of thousands of telephone connections. Carriers now pay only a few thousand dollars per circuit as opposed to approximately $100,000 previously. Consumers now pay less than $1 per minute instead of more than $10 per minute. If the impacts of inflation are considered, this drop is enormous! Not just the industrialized nations, but the entire world, is served by INTELSAT [57,58].

A domestic satellite system for distributing television signals was proposed by ABC in 1965. Although the plan was briefly forgotten, TELESAT CANADA launched the first domestic communications satellite, ANIK, in 1972 to service the enormous Canadian continental territory. Before they could launch their own satellite, RCA quickly leased circuits on the Canadian satellite. The WESTAR I satellite, launched by Western Union on April 13, 1974, was the country's first domestic communications satellite. The subsequent December, RCA debuted their RCA SATCOM F- 1. The initial COMSTAR of the series was introduced by AT&T and COMSAT in early 1976. Although telephony and data were the first uses for these satellites, television swiftly overtook them as a key user. There were 120 transponders accessible over the United States by the end of 1976, each able to deliver 1500 telephone channels or one television channel. The majority of Americans were able to access "movie channels" and "super stations" rather rapidly. Without a low-cost method of video distribution, cable TV's explosive growth would not have been conceivable.

Some modifications have occurred over the subsequent 20 years: Western Union is no longer in business, Hughes is now both a manufacturer and an operator of satellites, AT&T is still an operator of satellites but is no longer affiliated with COMSAT, and GTE, which collaborated with Hughes in the early 1960s to develop and run a global system, is now a significant domestic satellite operator. While domestic satellite communications are still dominated by television, data has increased significantly with the introduction of very small aperture terminals (VSATs). All around the nation, small antennas, whether TV-Receive Only (TVRO) or VSAT, are a regular sight [59].

2.2 A Chronology of Selected Communications Satellites

- 1945 Extra-Terrestrial Relays by Arthur C. Clarke, 1955 Article by John R. Pierce on "Orbital Radio Relays"
- 1956 TAT-1, the first transatlantic telephone cable; 1957 Sputnik, the first earth satellite launched by Russia.
- First successful DELTA launch vehicle in 1960
- 1960 AT&T submits a license request to the FCC for experimental satellite communications.
- 1961: The TELSTAR, RELAY, and SYNCOM programs formally launch
- 1962 introduction of TELSTAR and RELAY
- Communications Satellite Act of 1962 (U.S.)
- Launch of SYNCOM in 1963
- INTELSAT was founded in 1964.
- The first commercial communications satellite was launched in 1965 by COMSAT.
- The INTELSAT-III series from 1969 offers worldwide coverage.
- First domestic communications satellite, ANIK in 1972 (Canada)
- 1974 FIRST U.S. DOMESTIC COMMUNICATIONS SAFARI 1975 Dual-polarization was first used with INTELSAT-IVA.
- 1975 RCA First body-stabilized communication satellite launched in 1976. MARISAT: the first satellite for mobile communications
- Indonesia launched its domestic communications satellite, PALAPA, in 1976. INMARSAT was founded in 1979.
- • 1988 TAT-8: the first fibre -optic telephone cable across the Atlantic.

2.3 satellite technology categories

2.3.1 GEO Satellite

The ADVENT communications satellite, developed by the Defence Department, was the first significant geosynchronous satellite project. It wasn't whirling; it was three-axis stable. It possessed an antenna that pointed the earthward direction of its radio radiation. It was quite substantial and sophisticated. It could only be launched by the ATLAS-CENTAUR launch vehicle because it weighs 500–1000 pounds. Because of issues with the satellite as well as the fact that the CENTAUR stage wasn't completely reliable until 1968, ADVENT was never put into flight. Three-axis stabilization, the ATLAS-CENTAUR, geosynchronous satellites, and sophisticated communications satellites in general were all thought to be doomed when the program was terminated in 1962. In 1963, geosynchronous satellites became a possibility; by 1965, they were the only option. In the years that followed, the other traits of ADVENT also spread like wildfire.

Early 1960s launch vehicles included repurposed intercontinental ballistic missiles (ICBMs) and intermediate range ballistic missiles (IRBMs). All of them shared the same flaw: they were created to transport objects to the planet's surface, not to orbit them. To circularize the orbit, upper stages required to be built with a Delta-Vee (velocity change) at apogee. All of the early communications satellites were launched into orbit by THOR IRBMs called DELTA launch vehicles, which employed the VANGUARD upper stage to produce this Delta-Vee. Since the DELTA was considered to be quite tiny, a project to create CENTAUR, a high-energy upper stage for the ATLAS ICBM, was started. In 1968, ATLAS-CENTAUR gained reliability, and the fourth generation of INTELSAT satellites launched with it. The fifth generation launched satellites with ATLAS-CENTAUR and the European ARIANE, a new launch vehicle. Since then, other competitors have entered the market, such as the Chinese LONG MARCH and the Russian PROTON launch vehicle. All have the ability to launch satellites that are almost thirty times as heavy as EARLY BIRD.

Several satellites were constructed in the middle of the 1970s employing three-axis stabilization. They were more intricate than spinners, but they offered more flat surface area for mounting antennas and allowed the deployment of very large solar arrays. The benefit of three-axis stability seems to increase with increasing mass and power. The fact that Hughes, a company closely associated with spinning satellites, switched to this type of stabilization in the early 1990s may be the clearest sign of its effectiveness. in figure 1, the most is recent products from the makers of syncom.

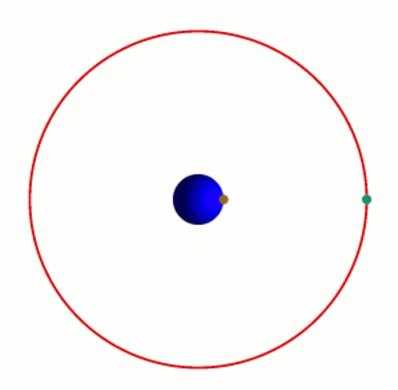

Figure 2.1: Syncom

The most recent products from the makers of SYNCOM resemble the discredited ADVENT design from the late 1950s quite a bit. A spectator on earth perceives a satellite in a geostationary orbit as being in a fixed position. Over the equator, a geostationary satellite makes one circuit of the planet at a steady speed.

Since ground-based antennas must face the satellite in order to function properly, the geostationary orbit is ideal for communications applications since it eliminates the need for expensive equipment to track the satellite's movements. Lifting a satellite into the relatively high geostationary orbit might be expensive and complicated on board, but the cost savings in ground equipment can more than make up for it, especially for applications that require a lot of base antennas (like direct TV distribution).

2.3.2 LEO Satellite

MARISAT, a novel type of satellite that COMSAT deployed in February 1976, offered mobile services to the US Navy and other maritime clients. The MARECS series was introduced by the Europeans to offer the similar services around the beginning of the 1980s. In a way similar to INTELSAT, the UN International Maritime Organization sponsored the founding of the International Maritime Satellite Organization (INMARSAT) in 1979. After originally renting the MARISAT and MARECS satellite transponders, INMARSAT launched INMARSAT II F-1 in October 1990, the first of its own satellites. INMARSAT III, the third generation, has already been launched.

In the middle of the 1970s, an aeronautical satellite was suggested. General Electric was given a contract to build the satellite, but it was later cancelled; INMARSAT now offers this service. Although INMARSAT was first intended to be used as a way to provide phone line and traffic monitoring services on ships at sea, it has now delivered much more. The briefcase phone for journalists has been commonplace for some time, but the Gulf War made this technology more widely known.

A North American Mobile Satellite was a topic of discussion between the US and Canada for long time. The first MSAT satellite, developed by AMSC (the United States) and TMI (Canada), will be launched the following year, bringing mobile phone coverage through satellite to all of North America.

When the satellite EARLY BIRD was launched in 1965, it offered about 10 times the capacity of submarine telephone cables for approximately a tenth of the cost. Up until the laying of TAT-8 in the late 1980s, this price gap was kept in place. The first fiber-optic cable to cross the Atlantic was TAT-8. For point-to-point communications, satellites and cable remain competitive, but fiber-optic cable might have an edge in the future. Satellites continue to have two advantages over cable: they are more dependable and allow for point-to-multipoint communication (broadcasting).

All other forms of telephony are now being challenged by cellular telephone services. At a very affordable price, a cellular system can be installed in a poor nation. Long-distance calls require additional technology, which could be fiber-optic cable or satellites.

The personal communications system is a new technology "system" that has been made possible by cellular telephony (PCS). The person would take his phone with him into the fully formed PCS. Anywhere in the world could utilize this telephone, which could be used for voice or data. A number of businesses have committed to offering a version of this system that uses satellites in low Earth orbit (LEO). Compared to the TELSTAR/RELAY orbits of the early 1960s, these orbits are substantially lower.

The initial "low orbit" satellites had elliptical orbits that passed into the lower van Allen radiation belt. The brand-new systems will be in lower-earth orbits at 500 miles or so.

Motorola-sponsored Iridium is the most ambitious of these LEO networks. In order to reach polar orbit at a height of around 400 miles, Iridium intends to launch 66 satellites. Eleven satellites will be spread across six orbital planes that are 30 degrees apart from one another. The name Iridium comes from the company's first plan to launch 77 satellites. Dysprosium, an unappealing name for element 66, is used. In 1998, Iridium plans to start offering hand-held telephonic communications services. Over three billion dollars were spent on the Iridium system in its whole. There are other "small LEOs" in addition to the "Big LEOS," such as Iridium and Globalstar. These businesses intend to provide fewer services, typically confined to data and radio determination. One such example is ORBCOM, which has already launched a trial satellite and anticipates beginning to provide limited service soon.

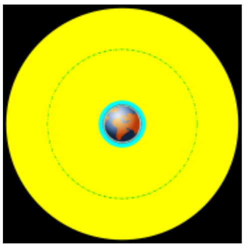

Figure 2.2: Low Earth Orbit

(LEO) is normally a circular orbit with a period (the amount of time it takes for the earth to rotate around it) of around 90 minutes that is 400 kilometres above the surface of the planet. These satellites are only observable from a distance of about 1000 kilometres from the sub satellite point because to their low height. Additionally, satellites in low earth orbit rapidly alter their position with respect to the ground. Therefore, if the mission demands constant connectivity, even for local applications, many satellites are required.

Low earth orbiting satellites are inexpensive to launch into orbit than geostationary satellites due to their proximity to the earth (Recall that signal strength falls off as the square of the distance from the source, so the effect is dramatic). As a result, the quantity and cost of satellites are traded off. The tools required to support the two distinct processes on board and on the ground vary greatly as well.

A satellite constellation is a collection of spacecraft's that cooperate with one another. The Iridium and Global star systems are two such constellations that are designed to offer satellite phone services, mainly to remote locations. There are 66 satellites in the Iridium system. With funding from Microsoft entrepreneur Paul Allen, another LEO satellite constellation called Teledesic was set to feature more than 840 satellites. Later, this was reduced to 288 and finally only one test satellite was launched. Using a low Earth orbit satellite that can store data collected while traveling over one area of the Earth and broadcast it later while passing over another area of the planet is another option for providing patchy coverage. This will be true of the CASCADE system of the CASSIOPE communications satellite from Canada. Orbcomm is another system utilizing this store and forward technique.

2.3.4 MEO satellite

MEO: A medium earth orbit satellite (MEO) orbits the planet at a height of about 22,300 miles (35,888.71 km), halfway between geostationary satellites and low earth orbit (LEO) satellites, which orbit at distances of about 200-930 miles (321.87-1496.69 km) and 200-930 miles (321.87-1496.69 km, respectively). Different satellite types could provide varying coverage possibilities for wireless and communication equipment. Like LEO satellites, MEOSats do not maintain a consistent altitude above the earth. In contrast, satellites in a geostationary orbit are always located around 22,300 miles from Earth.

An MEO is any satellite that circles the planet at an altitude of between 1609.34 and 35,405.57 kilometres (1000–22,000 miles). A medium earth orbit satellite typically travels 10,000 miles (16,093.44 km) above the surface of the planet. These satellites orbit the globe in a variety of patterns, taking ranging from 2 to 12 hours to complete the journey, giving them better coverage than LEOs over a wider area.

Telstar, the first communications satellite, was launched in 1962. Scientists immediately discovered some of the drawbacks of a single MEO in space, despite the fact that it was a medium earth orbit satellite (MEO) intended to assist in the facilitation of high-speed telephone signals. It only offered transatlantic phone signals for the first 20 minutes of each orbit, which lasted about 2.5 hours. It became clear that using numerous MEOs was necessary to offer continuous coverage.

Since then, a large number of businesses have started LEOs and MEOs. For continuous coverage, you need fewer MEOs and around 20 LEOs. But LEOs normally follow a circular orbital path around the equator. If there are enough of them in place and the orbit is quick, a medium earth orbit satellite may have a variety of orbits, including elliptical ones, and may offer better overall coverage of satellite communications. The area that an object covers on Earth is referred to as its footprint, and MEOs are often able to do so because to their distinct orbital patterns and higher altitude than LEOs.

Today, the medium earth orbit satellite is the one that is most frequently employed in global navigation systems. The Global Positioning System (GPS) and the Russian Glonass are two examples. 2013 is the anticipated launch date for the European Union's Galileo MEO navigation system. In figure 3 represent the Satellite Constellation.

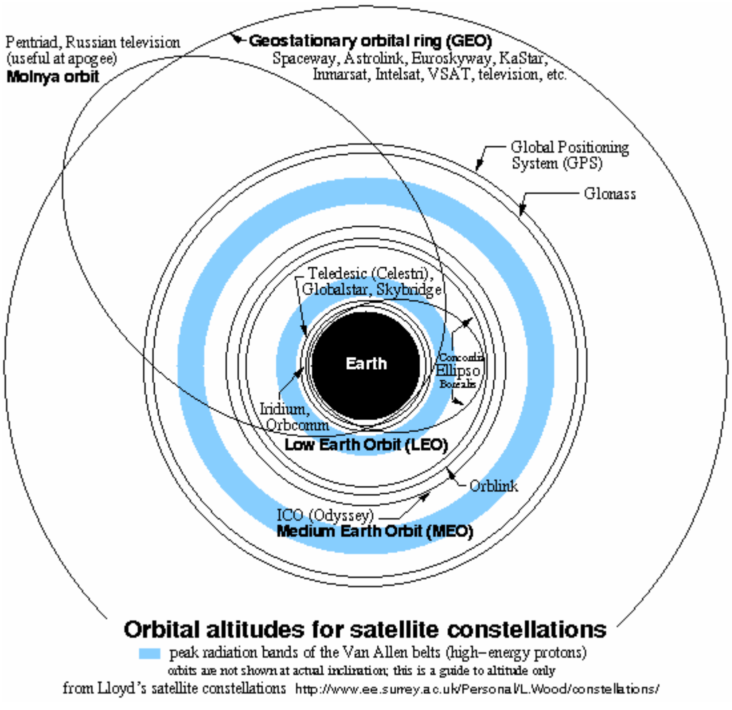

Figure 2.3: Satellite constellation

2.3.5 LEO Satellite

A low Earth orbit is one that is between 160 and 2000 kilometres (100 to 1240 miles) above the planet's surface. Almost all of human spaceflight, with a few notable exceptions, has occurred in low Earth orbit. Along with the International Space Station, many satellites are also in a low Earth orbit.

What many people assume to be space based on images is still firmly ensconced within a low Earth orbit. The innermost Van Allen radiation belt, which is maintained in place by the geomagnetic field of the Earth, roughly encloses the low Earth orbit. The Van Allen belt and low Earth orbit are somewhat overlapping, with some satellites staying there. Since satellites must be protected from the high energy levels present, the inner Van Allen radiation belt itself creates challenges for satellite operation. There is a plan to significantly reduce the energy in this belt, which would lessen the amount of shielding required and the risk to people from the power state.

Depending on their height, objects in a low Earth orbit experience a large amount of drag. Objects are in the thermosphere below about 310 miles (500 km), and in the exosphere above this altitude. Both contain different gases that cause spacecraft to drag and require some energy to stay in orbit. It is uncommon for items to be positioned lower than around 185 miles (300 km) high since this drag rises as height decreases.

In this chapter the literature review is discussed. The review covers different satellite communication technologies, their development and application. Chapter three will discuss the control philosophy of the battery power when supplying the satellite communication.

2.4 Introduction to Battery Technology

The rechargeable battery is the energy storage technology that is most frequently employed in business and daily life. In preparation for how these technologies might be applied to grid storage, which will be covered in the following chapter, this part will briefly review some of the many types of technology and how they generally function. This Section discussion of how these technologies can be used to satellites will be prefaced by a discussion of some of the various sorts of technology and their basic operation.

The graphic below displays a condensed diagram of a battery energy storage system. The system is made up of several electrochemical cells that are linked together either in series or parallel to create an electrochemical reaction that generates energy. One anode and one cathode make up a cell, and the electrolyte can exist in solid, liquid, or viscous phases [63].

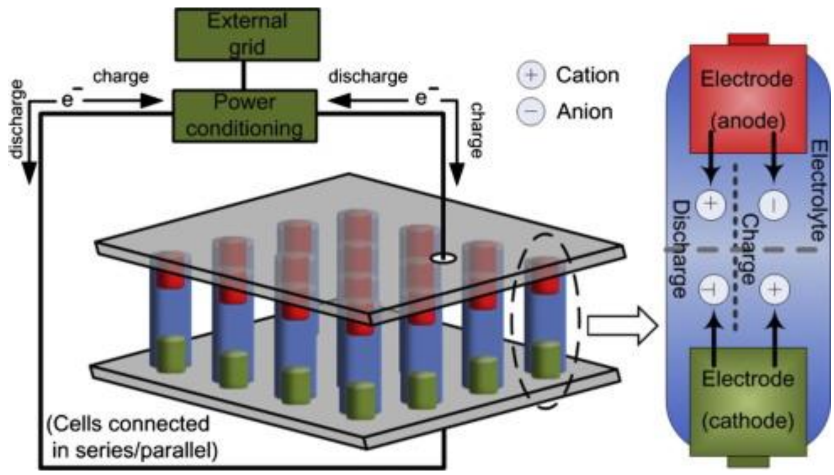

Figure 2.4: Schematic diagram of a typical battery energy storage system operation [63]

A cell can convert electrical and chemical energy in both directions. The electrochemical processes take place simultaneously at the anodes and cathodes during discharge. Electrons are supplied from the anodes and collected at the cathodes for the external circuit. When the battery is being recharged, the opposite processes take place, and the two electrodes are subjected to an external voltage [64-66].

Although there are many other storage technologies, several of which are mentioned previously in this thesis, this part will focus on those that, due to their technical maturity and supply chain, are most likely to be adopted by power grids during the next 10 to 15 years. Since their application will depend on design criteria to meet user requirements, the following section will cover a few battery technologies without particularly endorsing any one of them [67,68,70].

Figure 2.5: Lithium-ion Battery [68]

From megawatt batteries storage units in containers to energy type batteries of a few kilowatts in household systems with rooftop photovoltaic, lithium-ion batteries have been utilized in a variety of energy-storage applications. The first commercial lithium-ion battery was introduced in 1991 by Sony and Asahi Kasei. The idea for lithium-ion batteries was first developed in the 1970s and began to be used more often in the 1990s [32].

In order to create the flow of electrons inside a circuit, a battery is made up of one or more cells that undergo chemical processes. Battery technology is undergoing a lot of research and development, and as a result, ground-breaking technologies are currently being utilized and felt all over the world. The requirement to store electrical energy created led to the development of batteries. Even though a sizable amount of energy was being produced, it was still crucial to store the energy so it could be used when production was low or when it was necessary to power freestanding devices that couldn't be kept permanently connected to the mains supply. It should be emphasized that only direct current (DC) may be stored in batteries; alternating current (AC) cannot [71-73].

2.4.1 Typically, battery cells consist of three basic parts

- Its anode (Negative Electrode)
- a cathode (Positive Electrode)

- The ionic compounds

A negative electrode called the anode generates electrons for the battery's external circuit. A potential difference between the two electrodes results from an electron build-up that occurs at the anode when batteries are connected. When an electrical circuit is connected, it creates a clear path for the electrons to go from the anode to the cathode, powering the circuit to which it is connected [9]. The electrons then naturally try to redistribute themselves, but the electrolyte prevents this. We can create a wide range of battery chemistries that allow us to create different sorts of battery cells by altering the configuration and material used to construct the anode, cathode, and electrolyte. Let's discover about the many battery kinds and their functions in this thesis.

2.4.2 Various Battery Types

Batteries can generally be separated into a variety of categories and types based on their chemical composition, size, form factor, and use cases, but there are two main battery types that fall under all of these categories:

- Initial Batteries (Primary)
- Additional Batteries (Secondary)

Let's look more closely to comprehend the key distinctions between a primary cell and a secondary cell.

2.4.3 Initial Batteries

When they run out, primary batteries cannot be recharged. Electrochemical reactions in electrochemical cells used in primary batteries are irreversible.

Coin cells and AA batteries are only two examples of the different primary battery configurations that are available. They are widely used in stand-alone situations when charging is challenging or impossible. Battery-operated equipment and military-grade gadgets are two examples of this. Rechargeable batteries will not be viable since soldiers will not be thinking about charging batteries. Primary batteries always have a high specific energy, and the systems in which they are utilized are always built to consume little power in order to maximize battery life [33],[40].

Figure 2.6: Primary Battery [40]

2.4.4 Additional Batteries

Secondary batteries are electrochemical batteries that can have their chemical processes changed by delivering a certain voltage to them in the other direction. Because they may be recharged after the battery's energy has been used up, secondary cells, sometimes referred to as rechargeable batteries, are different from primary cells [74].

In applications with significant drain and other circumstances where single charge batteries would be either too expensive or impractical. Small capacity secondary batteries are used to power portable electronic devices like mobile phones, other gadgets, and appliances, whereas heavy-duty batteries are used to. They can also be utilized to provide electricity independently of inverters. Rechargeable batteries always have a far greater initial cost than primary batteries, but over the long run, they are the most economical option [75].

Based on their chemistry, secondary batteries can be further divided into a number of distinct categories. This is crucial since the battery's chemistry affects a number of characteristics, including its price, specific energy, cycle life, and shelf life, to name a few [76].

2.4.5 The various types of rechargeable batteries that are often used are listed below.

- Lithium-ion (Li-ion)
- Cadmium Nickel (Ni-Cd)
- Lead-Acid
- Flow Battery
- Sodium sulphur (NAS) batteries

2.5 Different types of battery technologies

2.5.1 Lead acid batteries

Of all rechargeable batteries, lead-acid batteries are by far the most popular and traditional [76]. This type was evaluated for utility peak shaving in the 1980s and found to be effective, but due to the high price, it was not extensively used. Costs for these technological advancements have recently begun to decline.

The voltage exists between the cathode and the anode when the battery is fully charged. Internal chemical reactions at the electrolyte and electrodes balance the charge as electrons move through the load externally during the discharge process.

An affordable and dependable power workhorse utilized in heavy-duty applications are lead-acid batteries. In non-portable applications like solar-panel energy storage, car ignition and lights, backup power, and load levelling in power generation and distribution, they are typically very large and heavy [77[. The earliest type of rechargeable battery is the lead-acid, which is still widely used and significant in today's society. Lead-acid batteries have very low energy to volume and weight ratios, but they have a very high power to weight ratio, which allows them to produce big surge currents when necessary. These qualities, together with their affordability, make these batteries appealing for use in a variety of high current applications, such as starting motors for automobiles and storing backup supplies of power [78-81].

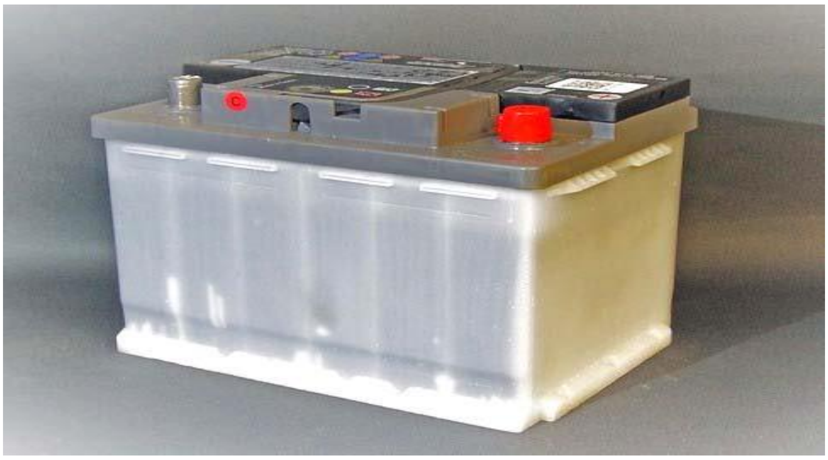

Figure 2.7: lead Battery The oldest and most prevalent type of rechargeable battery is the lead acid battery [25].

This type was evaluated for utility peak shaving in the 1980s and found to be effective, but due to the high price, it was not extensively used. Costs for these technological advancements have recently begun to decline.

The chemical states of a fully charged and discharged lead acid battery are depicted in the following figure.

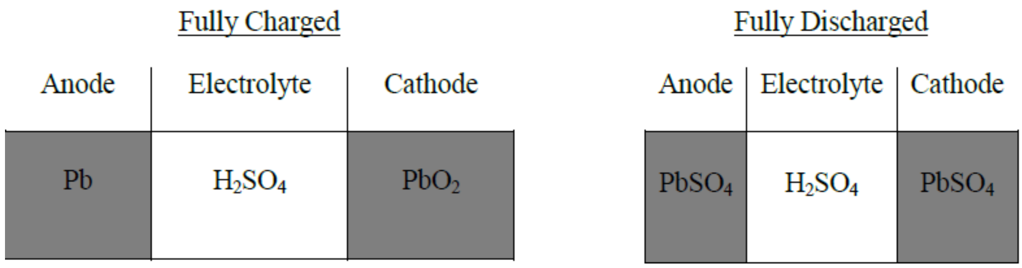

Figure 2.8: Lead acid battery charge and discharge state

when fully charged a voltage exists between the cathode and the anode. When in the process of discharging, electrons move through the load externally while internally chemical reactions at the electrolyte and electrodes balance the charge.

Sulfuric acid serves as the electrolyte, and lead (Pb) and lead dioxide (PbO2) serve as the anode and cathode, respectively. Fast response times, great cycle efficiency, low capital costs, and low daily self-discharge rates are all characteristics of this kind of battery. Lead acid batteries installed globally are included in the table below [82-86].

Table 2.1: Lead Acid battery energy storage systems

Location	**Power/Output**	**Application**
Berlin	8.5MW	Spinning reserve and frequency control
California	10MW	Spinning reserve and load control
Puerto Rico	20MW	Spinning reserve and frequency control
Alaska	1MW	Stabilising an island grid
Hawaii	15MW	Wind integration, power management, load control
USA, Texas	36MW	Wind farm integration

Lead acid batteries can be classified into two primary categories: seal lead acid (SLA) and valve-regulated lead acid (VRLA). As can be seen in the accompanying diagram, both of these categories have relatively similar internal chemistry. The fundamental distinction between the two is that the SLA type has less design requirements than the VRLA, such as a ventilated atmosphere to diffuse gases produced during charge and discharge (cycling), an upright orientation to prevent electrolyte leakage, and regular electrolyte maintenance [89].

Both deep cycle and shallow cycle lead acid batteries are found in SLA and VRLA. Shallow cycle VRLA batteries are typically utilized for automobile start, light, and ignition batteries that supply high power for brief periods of time [90].

2.5.2 Lithium-ion (Li-ion) batteries

From megawatt batteries storage units in containers to energy type batteries of a few kilowatts in household systems with rooftop photovoltaic, lithium-ion batteries have been utilized in a variety of energy-storage applications. The first commercial lithium-ion battery was introduced by Sony and Asahi Kasei in 1991[32], while the idea behind them was first developed in the 1970s and began to be utilized more commonly in the 1990s.

The anode and cathode of this type of battery are made of graphitic carbon and lithium metal oxide, respectively. The electrolyte is often a non-aqueous organic liquid with dissolved lithium salts. The basic idea is that during charge and discharge, the charged lithium-ions move back and forth (reversibly) between the anode and the cathode. Chemical variations in the anode, cathode, electrolyte, and cell packaging all have an impact on how well the cells work.

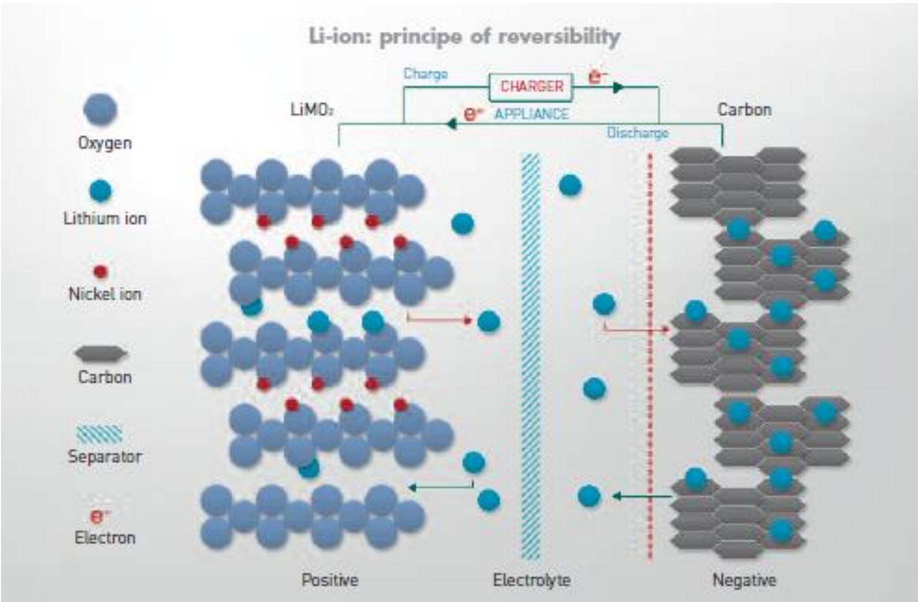

Figure 2.9: Li-ion principle of reversibility [36]

Since lithium-ion batteries have a deep cycle, they can be fully charged and drained. If each discharge cycle is restricted to an 80 percent level, the battery life will greatly increase in terms of rated capacity.

Due to the fact that lithium-ion is the only rechargeable battery suitable for grid-scale and commercial-scale deployment, it is anticipated that lithium-ion will play a significant role during the next two years. As manufacturers invest more in R&D, the prior drawbacks with this type of energy storage batteries, such as their high cost, short lifespan, and safety concerns, are fading away. Lithium-ion batteries dominated the developing grid storage industry in 2014–15, with this kind of battery technology being chosen for over 90% of proposed grid storage projects. [33].

When it comes to lithium-ion battery systems for grid storage, Saft [91] is at the forefront. Large renewable energy sources may more easily be integrated onto transmission and distribution networks thanks to battery systems from Saft. They offer a few various modular systems that may be customized to fit any solutions (see diagram below).

Figure 2.10: Li-Ion Storage solutions available from SAFT [92]

The most demanding applications for Saft Li-ion technology include satellite stations and spacecraft. The same design and manufacturing concepts have also been employed in other industries, including rail, aviation, communications, automobiles, data centres, and energy storage.

2.5.4 Sodium sulphur (NAS) batteries

A sodium-sulphur battery is a particular kind of molten salt battery that is made of liquid sodium and sulphur. Excellent energy density, high charging and discharging efficiency, and a lengthy life cycle are all characteristics of sodium sulphide [34]. This type of battery is suitable for stationary energy storage applications due to its high corrosive nature and operating temperature range of 300 to 350 degrees Celsius. Despite the pricey materials used to construct this battery, larger cells are more cost-effective [93].

The cell has a cylindrical shape and is protected by a steel shell that surrounds it. The sodium liquid serves as the negative electrode, and the container on the exterior serves as the positive electrode. The top of the container is sealed with an alumina cover to make sure it is airtight [94].

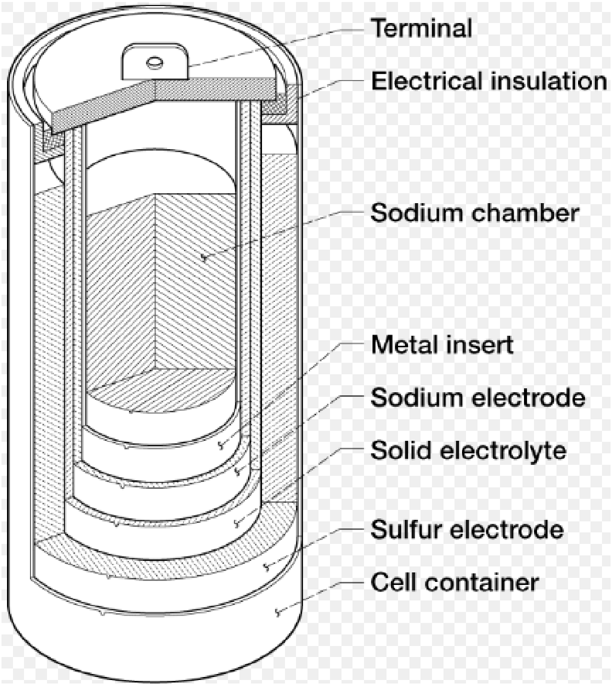

Figure 2.11: Cut-away schematic of a Sodium Sulphur Battery [NASA John Glenn Research Centre]

The battery system is comprised mostly of a PCS (AC/DC power conversion system), battery modules, and battery enclosures as illustrated in the illustration of a typical sodium battery system below.

Figure 2.12: Sodium Sulphur Battery System [Courtesy of NGK]

The unit needs to be secured from water and air because sodium offers a risk when it comes into contact with either. When this happens, sodium spontaneously burns. A system of 40 sodium sulphide batteries with 384 cells per module were produced by NGK in 2011 [95],[96]. At a Tokyo Electric power company-owned plant in Japan, the devices were being used for energy storage when the batteries caught fire. When the fire's investigation was finished in 2012, it was discovered that one battery cell had a defect, a breach, and was leaking hot, molten material into the module, which led to a short circuit between cells in the adjacent module. According to the inquiry, there was no fuse fitted between the shorted battery cells, thus the short circuit current kept flowing and produced heat, which killed many additional cells and started a fire that quickly spread. Refer to the graphic below, which illustrates the fire's origin [97]

Corrected

electrode. The top of the container is sealed with an alumina cover to make sure it is airtight [94].

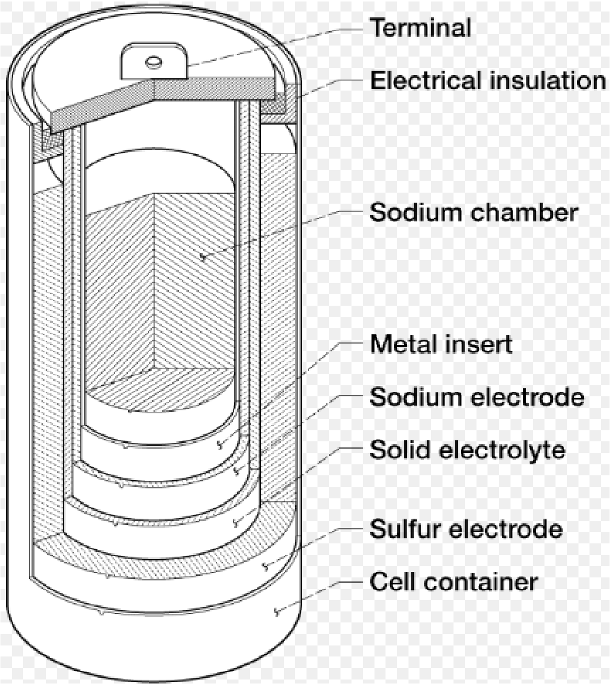

Figure 2.11: Cut-away schematic of a Sodium Sulphur Battery [18]

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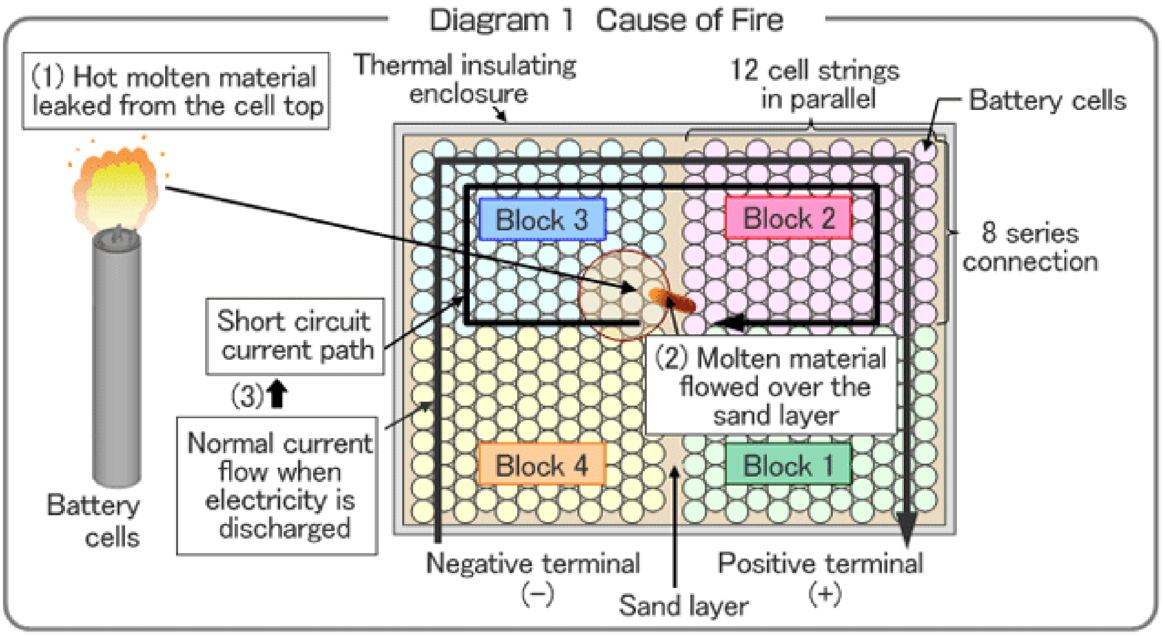

Figure 2.13: Cause of the Fire at Tsukuba Plant [97]

Following the incident, NGK temporarily halted the production of sodium sulphate batteries but voluntarily adopted safety improvement measures to provide fire containment, see figure below.

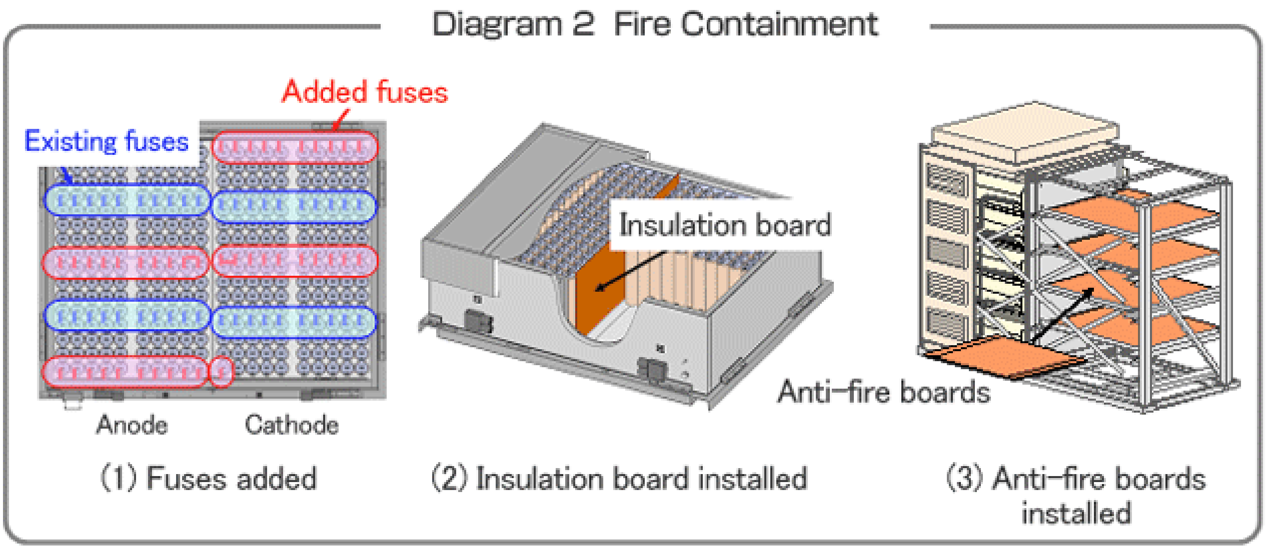

Figure 2.14: Fire containment implemented by NGK [97]

NGK restarted production activities in late 2012 after the cause of the incident was determined and safety improvement strategies were developed. NGK anticipated that the use of sodium sulphate batteries in the storage of renewable energy would rise, and it has been working hard to improve battery performance in order to fulfil market expectations.

2.5.5 Nickel-metal hydride (NiMH)

As both nickel-cadmium and nickel-metal hydride batteries fall under the umbrella term of alkaline batteries, they appear to share a number of similar traits (Nazarko, 2017; Nousdilis et al., 2018). Compared to nickel-cadmium, which has an energy density of 60–120 Wh/kg, nickel-metal hydride has an energy density that is 30–40% higher. But life cycles are drastically cut to 300–500 while charging time is only marginally extended to 2-4 h [98]. On the other hand, they have less of an impact on the memory phenomenon, which is one of many batteries types of major downsides. Lastly, this type is composed of non-toxic, largely recyclable materials (Battery Information Table of Contents, Basic to Advanced, - [99]. To replace conventional non-rechargeable batteries, they are available as rechargeable disposable batteries in a variety of sizes for use in computers, medical equipment, and other applications (Battery Information Table of Contents, Basic to Advanced, n.d.; Nazarko, 2017; Nousdilis et al., 2018). They are also appropriate for inclusion in applications utilizing renewable energy sources (Akimoto et al., 2020) [100],[101].

5.5.6 Nickel-cadmium (NiCd)

The present design of a battery uses a positive electrode made of nickel hydroxide and a negative electrode made of cadmium hydroxide, while an aqueous solution of potassium hydroxide and lithium hydroxide is used as the electrolyte (Nazarko, 2017; Nousdilis et al., 2018). Although their energy density is higher than lead acid, it is still modest (45–80 Wh/kg. The drawbacks include a higher discharge rate (around 20 percent), along with low voltage in each cell. Finally, one of the inherent negatives of this battery type is the use of harmful components (Nousdilis et al., 2018). This battery type mostly finds use in power tools, medical equipment, and communications. By storing enormous amounts of energy, they can also be utilized in power generation systems for renewable energy sources, but this type is typically not chosen due to their high price (4 times more expensive than lead acid and 2 times more expensive than lithium-ion) (Nazarko, 2017; Nousdilis et al., 2018) [102].

Figure 2.15: Ni-CD battery [102]

2.5.7 Flow Batteries

A brand-new class of batteries called flow batteries is particularly appealing for larger-scale utility applications. A typical battery, such as a lead-acid or nickel-metal hydride battery, operates on a different concept than a flow battery. Because the power conversion and electrolyte storage functions of traditional batteries are merged within the battery, both the power rating and the energy rating are fixed, depending on the battery's size and type. The way that flow batteries function is different from how ordinary batteries do. [38].

Because the power and energy ratings are independent, the system is particularly adaptable. Liquid electrolytes flow through an electrochemical cell in a flow battery, which converts chemical energy into electricity. The power rating is determined by the cell stack's architecture. The power of the entire system is determined by the stack, which has a reversible chemical reaction between the two electrolytes. Outside of the battery stack, the two electrolytes are kept in storage tanks separately. The size of the tanks and the quantity of electrolytes are therefore determined by the complete energy storage system. A flow cell's schematic layout is depicted in the figure below.

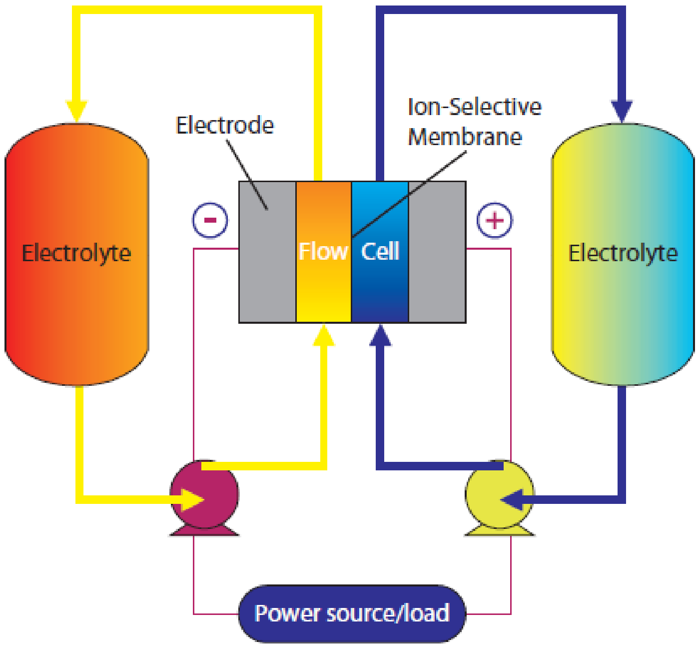

Figure 2.16: Schematic overview of a flow cell energy storage system [38]

The expenses of the electrolytes in tanks and the electrochemical reactor are separated from the costs of flow battery cells. The price of electrolytes will rise as the system's storage capacity does, but the price of the electrochemical reactor will be unaffected.

Flow batteries do not have any obvious scale limits because the storage capacity only depends on the size of the electrolyte tanks therefore this makes this battery system a promising technology for large-scale electricity storage.
Because of the redox reaction that occurs in the system between the two electrolytes, flow batteries are frequently referred to as redox flow batteries. Reduction-oxidation reactions are referred to as "redox" reactions. The three most prevalent forms of flow batteries are zinc bromine, polysulfide bromide batteries, and vanadium cells (V/V) (ZnBr). The three existing systems each have unique features, yet they can all be utilized for all sizes. However, each

manufacturer and developer has focused on a certain range of power and energy. The comparison of the three types is shown in Table 3 below.

Table 2.2: Comparison of flow batteries [38]

	Vanadium	**Zinc Bromine**	**PSB**
Typical power range (MW_e) [2]	> 3	> 1	> 15
Typical size range (MWh) [3]	0,5 -5	0,01 - 5	0 -120
Energy density (Wh/liter) [1]	16-33	60-90	20-30
Cycle efficiency [Wh^{out}/Wh^{in}](%) [1,2]	70-85	65-75	60-75
Cycle life (Cycles) [1]	>12,000	>2,000	n/a
Life time (years) [1]	5-10	5-10	15
Stage of Development [2]	Demonstration/ Commercial units	Demonstration/ Commercial Units	Demonstration
Companies involved [3]	VRB, SEI, Pinnacle, Cellenium	ZBB, Premium power	TVA, VRB (using Regenesys technology)

3.3.8 Flow battery properties can be summed up as follows [38], [71]:

- High power: the design and size of the power stack cell determine the power rating;
- Long duration: the energy rating is based on the quantity of electrolyte used and the size of the storage tanks required.
- The design of the power rating and the energy rating is decoupled.
- The system is refillable; electrolytes can be replaced easily.
- The majority of redox reactions have very quick reaction times because of their fast reaction kinetics. Flow batteries respond quickly and can switch between charge and discharge modes in just 1/1000 of a second.
- The battery's full-cycle efficiency is only about 75 to 80 percent because of the energy required to circulate the electrolyte and losses from chemical processes, such as the formation of hydrogen.
- Since the electrolytes cannot react while they are held separately, the system does not self-discharge. This is a significant benefit when electricity is stored for longer periods of time.
- Flow batteries have the advantage of being versatile in system design for either power (e.g., short-term frequency control) or energy application (e.g., long-term load shifting), which is an important asset for the integration of renewable energy.

2.6 Comparison of Battery Types

2.6.1 lithium-ion and lead acid batteries

The technology of lithium-ion and lead acid batteries is briefly compared in the table below. [31].

Table 2.3: Comparison of lithium-ion and lead acid batteries [31]

	Flooded lead acid	**VRLA lead acid**	**Lithium-ion (LiNCM)**
Energy Density (Wh/L)	80	100	250
Specific Energy (Wh/kg)	30	40	150
Regular Maintenance	YES	NO	NO
Initial Cost ($/kwh)	65	120	600
Cycle life	1200 @ 50%	1000 @ 50% DoD	1900 @ 80% DoD
Typical state of charge window	50%	50%	80%
Temperature sensitivity	Degrades significantly above 25ºC	Degrades significantly above 25ºC	Degrades significantly above 45ºC
Efficiency	100%@20-hr rate	100%@20-hr rate	100%@20-hr rate
	80%@4-hr rate	60%@4-hr rate	99%@4-hr rate
	60%@1-hr rate	60%@1-hr rate	92%@1-hr rate
Voltage increments	2V	2V	3.7V

In deep discharge applications, lithium-ion batteries have a longer life cycle than lead acid batteries, and this life cycle lengthens as the ambient temperature rises. The life cycle of a lead acid battery can fall to half of what is recommended. Lead acid and lithium-ion both lose capacity in colder conditions, although lithium-ion loses capacity considerably more slowly after the temperature drops to -20 C.

Lead acid batteries do not hold a candle to lithium-ion batteries in terms of environmental impact. Lead acid has a significantly greater environmental impact because it needs far rawer materials to obtain the same energy storage. Due to the energy-intensive nature of the lead industry, processing plants are more polluted.

Lithium carbonate, copper, aluminium, and iron ore must be mined to make the main lithium-ion cell components. The mining process itself uses a lot of resources, but as lithium makes up a relatively small fraction of the bulk of the battery cell, the environmental effects of copper and aluminium are far more important. The term "thermal runaway" refers to the rapid heating, flames, and toxic gases that can occur with both lead acid and lithium-ion batteries.

In terms of energy storage, both of these technologies have benefits and drawbacks, and the best option truly depends on the application. When choosing a battery technology, factors including initial cost, lifespan, size, volume, temperature sensitivity, and accessibility for maintenance are crucial.

2.6.2 Technical Comparison of Common Battery Types

The technical comparison statistics below may not completely reflect all current uses or future markets as battery storage technologies are continually evolving. Figures may not be entirely exact or full because they are based on a variety of literature reviews.

Table 2.4: Technical Comparison of common types of batteries

	Value regulated Lead-Acid	**Advanced Lead-acid**	**Lithium-Ion**	**Sodium-Sulphur**	**Flow Batteries**
Power Range (MW)	1-50	1-50	<100	5 - 100	1 - 100
Storage Duration	2 – 4h	1 min – 8h	1mon – 8h	1 min – 8h	1 – 5h
Cycles	1 000 – 5000	4500-10 000	1 000 – 10 0000+	2 500 – 4 500	>10 000
operating life (years)	3 – 15	5 – 15	5 - 15	5 - 15	15 - 20
Efficiency (%)	70- 90	90 – 94	85 - 98	70 - 90	65 - 85
Response Time	<Secs	<Secs	<Secs	<Secs	<Secs

2.6.3 Cost comparison of battery technology

The capital costs for the typical battery types are provided in the tables below. Apart from NaS, battery systems with these costs in mind are suitable for small-scale battery storage. For the majority of battery types, especially Li-ion and flow batteries, significant cost reductions are predicted. Cost comparison often takes into account each type's limits as well as the underlying presumptions of each cost. When taking into account storage duration, longevity, and operating principles, levelized cost of energy (LCOE) is also crucial.

Table 2.5: Battery Technology Capital Cost Comparison [39-44]

Technology	**Source / Year**	**USD /W**	**Assumptions**
Lead Acid battery	IRENA/2012	$1.50 - $2.00	3-20MW in size, 10 seconds to 14 hours of storage
	EPRI /2012	$2.50 - $5.00	50Kw to 10MW in size, total installed cost
Flow batteries (VRB)	IRENA /2012	$3.00 - $4.00	50Kw to 10MW in size, up to 8 hours of storage
Li-ion battery	IRENA / 2012	$2.50 - $3.00	Up to 50MW in size,15 minutes to 4 hours of storage
	EPRI / 2012	$2.00 - $6.00	50kW -1MW in size, total installed cost

	AECOM / 2015	$1.00 - $1..80	Current market price based on recent tenders MW scale systems (includes balance of plant costs) 15 mins to 1 hour storage
NaS	EPRI / 2012	$2.50 - $3.00	1MW – 50MW in size, total installed cost

Table 2.6: Battery Technology LCOE costs [39-41]

Technology	**Source/Year**	**USD/kWh**	**Assumptions**
Lead acid batteries	IRENA /2012	$0.25 - $0.35	Small to medium applications, less than 10MW in size
Flow batteries (VRB)	IRENA / 2012	$0.25 - $0.30	50Kw to 10MW in size, up to 8 hours of storage
	EPRI / 2012	$0.60 - $1.00	1MW to 50MW in size, total installed cost
Li-ion battery	IRENA / 2012	$0.25 - $0.50	Projected costs up to 5MW in size (for large Li-ion cells), 15 minutes to 4 hours of storage.
NaS battery	EPRI / 2012	$0.40 - $0.60	1MW to 200MW in size, total installed cost

Table 2.7: literature review optimization

Battery type	**Main characteristics**	**Advantages**	**Disadvantages**
Lead acid	•Mature and reliable technology • Oldest type of rechargeable batteries	•Low rate of discharge • Ability to operate at wide range of temperatures	•Low energy density • Short life cycle • Slow charging • High maintenance
Nickel-cadmium (NiCd)	•Used in communication applications, medical materials, power tools •Can be met in RES applications	• Able to store a large amount of energy	• Increased cost • Low energy density • Low voltage • Increased discharge • Toxic materials
Nickel-metal hydride (NiMH)	• Alkaline batteries • Rechargeable disposable batteries in various sizes	• Non-toxic materials •Possibility of material recycling •Memory phenomenon is not a problem	• Low charging time • Low life cycles
Lithium-ion (Li-ion)	• Upcoming technology	•Highest energy density • Increased life cycle •Increased energy efficiency •Self-discharge is very low •They do not need maintenance as they are affected by the memory phenomenon	• High initial cost • Low resistance to stress • Reduction of life cycle at high Temperature
Flow batteries	• Upcoming technology	• Long-life cycle	• Low energy density

	• Various types • Battery can be used as a fuel cell or as a rechargeable battery	• Increased safety • Flexible layout • Low emissions	• Low charge and discharge • Increased cost

2.7 Li-ion batteries and how they work

An electrolyte, a lithium compound-based cathode, and a typically graphite-based anode make up a Li-ion battery, a form of rechargeable battery. Lithium-ions flow from the cathode to the anode during charging and in the opposite direction during discharge.

The internal reactions and current change during battery charge and discharge are shown in Figure 13[31]. Lithium compounds split into lithium-ions, electrons, and other lithium compounds as they charge. External conductors carry electrons from the cathode to the anode, the electrolyte transports lithium-ions from the cathode to the anode, and current flows from the anode to the cathode.

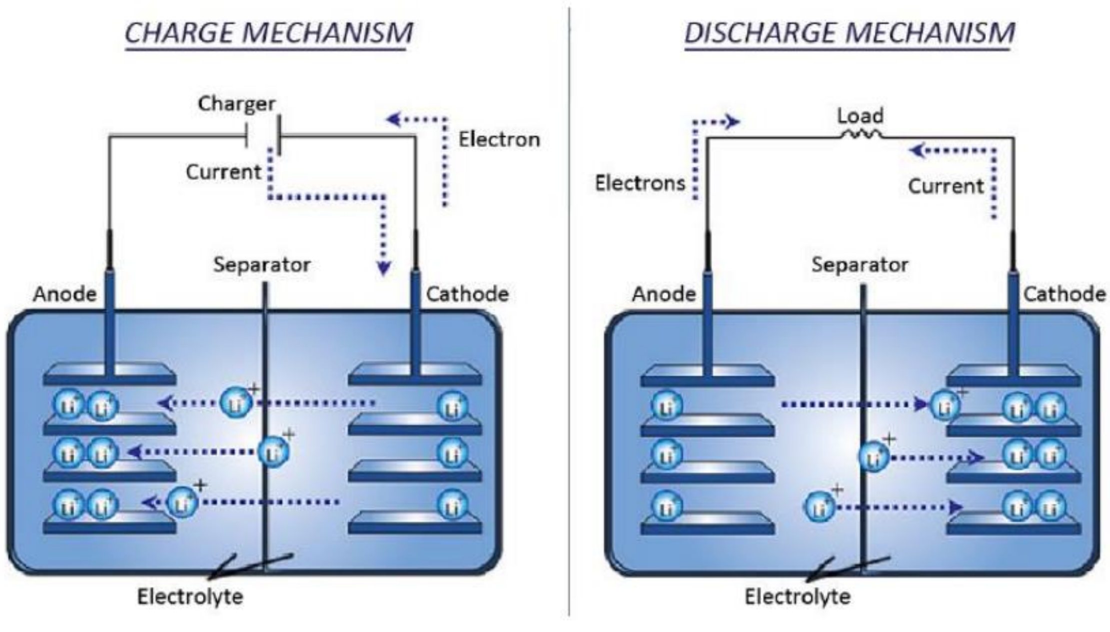

Figure 2.17: internal reaction and current change during charge and discharge state [31]

Because it possesses an intercalated structure that can store lithium-ions and boost battery capacity, graphite is typically employed as the anode in Li-ion batteries. Carbon on the anode reacts with the lithium-ions and electrons to produce a carbon lithium complex. Equation below shows the chemical reactions inside Li-ion batteries when being charged. When discharged, the procedure is reversed.

$$Cathode: LiXXO_2 \rightarrow Li1 - x\ XXO_2 + Li + xe \tag{2.1}$$

$$Anode : C + xLi + xe \rightarrow LixC \tag{2.2}$$

$$Overall : LiXXO_2 + C \rightarrow LixC + Li1 - xXXO_2 \tag{2.3}$$

XX means various combining elements of the battery cathode material.

Definitions of Li-ion battery terms The terms used to describe battery conditions, such as C-rate, state of charge (SOC), depth of discharge (DOD), terminal voltage, and open-circuit voltage, are defined below. Additionally, the battery's specifications, such as cut-off voltage, capacity, cycle life, specific energy, energy density, internal resistance, charge voltage, and charge current, are defined.

2.7.1 Battery conditions

- C-rate

A battery's discharge current is normalized against its maximum capacity using a unit called a C-rate. According to one C rate, the battery will be completely discharged in an hour by the discharge current. The discharge current is equal to the battery's maximum capacity multiplied by the C-rate. For a battery with a capacity of 100 Ah, for instance, 1C rate indicates a discharge current of 100 Amps. The identical battery would be discharged completely in 0.2 hours at a 5C rate of 500A. The discharge time decreases with increasing C-rate. A C/2 rate would correspond to a discharge current of 50A and a discharge duration of 2 hours [103],[104].

- State of charge (SOC)

SOC (%) measures how much of the battery's current capacity is over its maximum.

- Depth of discharge (DOD)

The percentage of a battery's capacity that has been discharged beyond its maximum is known as DOD (%). Deep discharge is defined as 80% DOD or higher.

- Terminal voltage (V)

when linked to a load, the voltage between the battery terminals. Battery SOC and charge/discharge current affect terminal voltage.

- Open-circuit voltage (V)

the voltage when there is no load placed between the battery terminals. Battery SOC affects the open circuit voltage [9].

- Charge retention

The amount of battery capacity that is still usable after a certain length of time has passed since the battery was last used or stored.

2.7.2 Battery Specification

- Cut-off voltage (V)

The battery is deemed "empty" at the cut-off voltage, which is the lowest permissible voltage. When the cut-off voltage (3V/cell) is reached, some electronic devices powered by Li-ion batteries, such as laptops and cell phones, will turn off automatically [97].

- Capacity ($A\boldsymbol{h}$)

The total Amp hours (Ah) available when the battery is discharged at a specific C-rate from 100 percent SOC (full) to the cut-off voltage is the battery capacity, also referred to as the coulometric capacity (empty). To determine the battery's condition, multiply the discharge current by the discharge time. This will give you the battery's capacity. A criterion for retiring batteries is based on capacity. Batteries should be replaced when they are charged to 80% of their full capacity, according to the manufacturers.

- Cycle life

The battery's cycle life is the total number of discharges and charges it can withstand before failing to fulfil certain performance standards. A battery's actual operational life is influenced by a number of variables, such as C-rate, DOD, temperature, load size.

- Specific energy (Wh/kg)

The nominal battery energy per unit mass is known as specific energy, also referred to as the gravimetric energy density. It determines the weight of the battery necessary to produce a specific total energy together with energy consumption in various applications.

- Energy density (Wh/L)

The nominal battery energy per unit volume is referred to as energy density or volumetric energy density. It determines the size of the battery needed to produce a specific amount of total energy along with the energy consumption of various applications.

- Internal resistance (IR) (Ω)

The battery's internal resistance. When charging and discharging, it typically differs, and it is influenced by the battery SOC. The efficiency of the battery decreases as internal resistance increases.

- Charge current (A)

Prior to switching to constant voltage charging, the battery's voltage is raised by constant current to roughly 70% SOC. [9]

- Charge voltage (V)

The voltage at which a battery is charged to its maximum capacity. The charge voltage typically becomes steady until the charging process is complete after the battery has been charged by the charge current to about 70% SOC.

- Lithium-ion Battery Degradation

One of the key elements to take into account when evaluating the financial viability of Li-ion battery applications is battery life.

2.8 Definition of battery life

Cycle life and calendar life are two ways to describe battery life. Capacity fade, which happens as the battery's ability to store energy declines over time, is one of the key characteristics of battery life loss or degradation. Usage amplifies a battery's capacity deterioration. In this thesis, capacity loss—which is quantified as a percentage of the battery's initial capacity—is utilized to demonstrate battery degradation. For instance, if a battery's capacity has decreased by 20%, it can only be charged and discharged to 80% of its original capacity [80].

Cycle life is the number of full charges and discharges a battery can withstand before losing 80% of its initial capacity. The full discharge of a charged battery and subsequent recharge are known as a discharge/charge cycle. Numerous partial discharges and charges can also work together to create a cycle. A battery's calendar life is the amount of time it may be kept dormant before losing 80% of its initial capacity. Loss of calendar life begins soon after Li-ion. The production of batteries grows over time. [1], [92] Cycle-life loss increases as batteries are used. Depending on the environment and cycle conditions, the typical estimated life of a lithium-ion battery is between two and three years or 300 and 500 charge cycles, whichever occurs first. Calendar life and cycle life are intertwined. The number of calendar cycles that remain drops as battery cycles rise, and a battery that has been sitting around for a while offers less cycles. Temperature, DOD, and cycling parameters like charge/discharge current can all have an impact on how quickly things degrade.

2.8.1 Methods for the capacity reduction of Li-ion batteries

Li-ion battery deterioration is primarily brought on by several chemical exothermic reactions that take place inside the battery. These reactions include internal short circuit caused by charge effects, chemical oxidation of the electrolyte on the cathode, thermal decomposition of the electrolyte, the cathode, and the anode, and chemical reduction of the electrolyte and the growth of solid electrolyte inter phase (SEI) on the anode [11],[101]. More details on the first two methods are provided below.

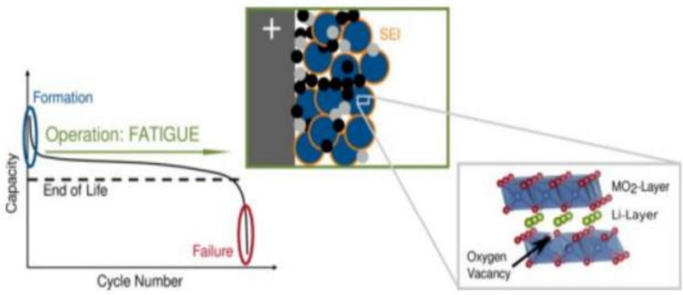

Figure 2.18: SEI formation [101]

2.8.1.1 Growth of the Solid Electrolyte Interphase (SEI)

Lithium-ions travel to the anode during Li-ion battery charging, and the battery voltage rises. Solid electrolyte interphase (SEI), a layer made of lithium oxide and lithium carbonate, develops on the anode's surface as a result of the electrochemical breakdown of the electrolyte on the anode. Figure 3.3 [33] depicts this creation occurring during the first cycles, which uses recyclable lithium-ions to fuel the process. 31 Figure 3.3 Production of SEI [33] During discharge, the battery capacity decreases as a result of the formation of the SEI layer, which prevents all lithium-ions from returning to the cathode. The SEI layer thickens over time after the initial cycles, eventually preventing the contact between the graphite and electrolyte and causing battery failure. The initial capacity loss, self-discharge traits, rate capabilities, and safety of Li-ion batteries are all influenced by the SEI. It is necessary for Li-ion batteries to operate well over the long term. By using proper solid-state electrolytes and Li-containing anodes, additional lithium-ion consumption and capacity loss can be prevented [17]. As a result, the electrode's cycle performance and service life can be improved. The creation and expansion of the SEI layer is influenced by a variety of internal battery variables, including as the type of graphite used, the composition of the electrolyte, and the electrochemical conditions. High SOC and temperature are two external factors that reduce battery life. The development of the SEI is accelerated by these conditions as well.

2.8.1.2 Electrolyte oxidation

Electrolyte oxidation, which is analogous to the development of the SEI layer, is the process of creating a layer in the cathode during cycling as a result of high battery voltage (over 4.1V/cell) and rising temperature. The battery 32 deteriorate more quickly the longer it can maintain a high voltage. More capacity loss in batteries may result from this response than from cycling effects. Battery self-discharge is also partially a result of cathode electrolyte oxidation. Battery operating factors, such as temperature, charge and discharge rate, DOD, and charge voltage over cycles, have a significant impact on how quickly capacity degrades. Stress on the battery is accelerated by high temperatures, deep discharge, high SOCs, and high cycle rates. Lithium-ion batteries were found by NASA to degrade owing to electrolyte oxidation on the cathode when the voltage is over 4.1 V/cell and due to SEI layer formation on the anode when the voltage is below that [12].

2.8.1.3 Lithium plating

Lithium plating, also known as intercalation, is the process by which lithium-ions from the cathode are introduced into compounds having layered structures in the anode during charging, resulting in the creation of metallic lithium surrounding the anode of a Li-ion battery. Lithium-ions build up and become metallic lithium when their rate of movement is greater than that of intercalation. Li-ion batteries experience this phenomenon most frequently while being overcharged (above 4.2V/cell), charging at low temperatures (below 15°C), and charging at high currents [18].

2.9 Factors that affect Li-ion battery lifespan

To minimize battery capacity loss and achieve maximum battery efficiency, it is crucial to understand the elements that influence battery capacity loss. A Li-ion battery's lifespan is affected differently by factors such as battery age, temperature, SOC, and DOD as a result of battery calendar-life loss and cycle-life loss. This section discusses how environmental considerations during battery storage and consumption, as well as cycle circumstances, impact battery life.

2.9.1 During storage

- Temperature

The primary factor in battery capacity reduction while storage is temperature. The electrodes and electrolyte thermally decompose at high temperatures. The thickness of the SEI coating on the anode rises due to electrolyte decomposition, consuming lithium-ions, increasing cell IR, and decreasing battery capacity. Additionally, as gases develop throughout the breakdown, the internal pressure in the cell rises and safety concerns arise Table 3.1 displays the percentage of capacity lost by Li-ion batteries when kept at various temperatures over the course of a year [16]. The SOC (40%) for the Li-ion batteries during storage was the same. The degradation of batteries increases with temperature.

Additionally, Table 3.1 demonstrates that high temperatures sharply speed up capacity loss. Compared to the 20-degree increase from 40°C to 60°C, the 25-degree increase from 0°C to 25°C only resulted in a 2% increase in capacity loss.

Table 2.8: Li-ion batteries' estimated recoverable capacity when kept at various temperatures and SOC levels.

Temperature	40 % Charge	100% charge
0°C	98% (after 1 year)	94% (after 1 year)
25°C	96% (after 1 year)	80% (after 1 year)
40°C	85% (after 1 year)	65% (after 1 year)
60°C	75% (after 1 year)	60% (after 3 months)

- Depth of discharge (DOD)

Li-ion battery cycle life is mostly influenced by DOD. Deep discharges increase cell damage risk and hasten capacity loss in Li-ion batteries by putting pressure on the cells and damaging the negative electrode sites.

Deep discharges are defined as DODs greater than 50%. A Li-ion battery loses around 95% of its energy when it is depleted from 4.2 V to 3.0 V, and repeated cycling will result in the shortest battery life. Li-ion battery users should prevent full discharge.

cycling to lessen the loss of capacity. Li-ion batteries should be partially discharged and recharged to increase battery life.

CHAPTER 3 EFFICIENT POWER CONTROL OF BATTERY

3.1 INTRODUCTION

The market's requirements for satellite communication networks have altered recently. In the past, remote locations like suburbs, mountains, and airspace had a need for satellite communication networks. The Internet of Things (IoT)-based factory management operations, for example, are increasing the demand for satellite communication networks in urban areas [60], [2], In the event of a natural disaster, early and extensive situational awareness is necessary, as is infrastructure management of traffic information for vehicles like cars and trains [3], [4]. Due to changes in demand, communication requests for satellite communication networks are moving from hour units to minute and second units. [5]. Because non-geostationary artificial satellites are placed in lower earth orbits than medium-earth orbit satellites and geostationary satellites, a high-speed Internet environment known as a low earth orbit (LEO) satellite constellation at a low altitude from the earth and with a small propagation delay is thus feasible. This technology is gaining appeal because of its capacity to satisfy these altering communication needs.

Communication between satellites and satellite terminals is necessary for an LEO satellite constellation. Power resources must be secured to connect with the satellite, yet these resources are scarce for the satellite due to solar power generation and battery storage. Consequently, it's important to utilize the satellite's power sources wisely. The satellite must frequently run only on the power stored in its battery because it cannot generate electricity while it is in the shade. The lifespan of the battery deployed on the satellite may be reduced if the power resources of the battery are not considered during this time and are used inefficiently. However, the idea of mass-producing satellites, which has recently been taken into consideration in large-scale LEO satellite constellations, runs counter to renewing the satellite battery and launching the rocket according to the battery life. Consequently, it is crucial to consider the battery's lifespan on the satellite. Numerous research that are now being conducted concentrated on controlling satellite communication resources by just considering the traffic's spatial and temporal variations and the propagation path conditions [61] through [62]. These types of communication can reduce the battery life of the satellite. There hasn't been any research on this subject, even though satellite communication-resource control has a considerable impact on battery lifetime. In order to increase the battery's lifespan, we propose in this Thesis a communication technique that appropriately manages the communication capabilities of LEO satellites. Then, by extending the lifespan of the battery installed on the satellite, we suggest building a system that can lower the operating costs of LEO satellite constellations. This system will be able to meet the communication requirements for present satellite communications as well as enable the construction and use of large-scale LEO satellite constellations.

3.8 CONSIDERED ARCHITECTURE AND PROBLEM FORMULATION

This section provides an introduction to LEO satellite trends and network architecture. The battery's lifetime and the stress it is under, which are the study's main objectives, are then defined. Finally, we go over current difficulties and potential issues with the network.

3.8.1 Trends in LEO Satellite

The LEO satellite constellation consists of hundreds to thousands of small, inexpensive spacecraft’s. In order to establish this broad satellite network, it is essential to launch a large number of satellites, place them all in the same orbit, and launch these satellites repeatedly. Once the LEO satellite constellation has been formed, new satellites are launched as needed to sustain this enormous network of satellites. Large firms like Google, Apple, Facebook, and Amazon are also interested in the development and utilization of such vast LEO satellite constellations. About 3,000 LEO satellites will be launched by Amazon. Additionally, SpaceX and Boeing plan to launch thousands of LEO satellites. [10Azure Orbital is the name of Microsoft's satellite operation platform. Additionally, satellite operators are planning services that leverage plentiful terrestrial satellite facilities rather than only processing detailed data in the cloud. However, there are significant ongoing expenses associated with running and maintaining this extensive satellite network. Therefore, companies are currently attempting to mass produce satellites at a low cost with the intention of setting up a constellation using those small satellites. Companies attempting to build expansive LEO satellite constellations, nevertheless, have not been able to reduce the high-cost cost requirements. One Web, for instance, launched dozens of satellites before going bankrupt. Reducing the astronomical running cost is made possible by extending the lifespan of satellites.

3.8.2 Assumed Network Environment

We concentrate on the LEO satellite constellation from the background described in Subsection 2.1. Fig. 1 displays a schematic of the LEO satellite constellation presumption in this work. There is no communication among the satellites in this constellation, only between the satellites and the ground. Furthermore, the satellite's test procedures may have worn it out by the time this network is finished. Additionally, as technology develops, the effectiveness of the satellite itself could get better. [11], [12]. As a result, it is assumed that the installed equipment performs differently. In addition, a ground station known as the gateway (GW) for satellite communication exists in terms of ground apparatus. A facility for controlling and running communication networks and resources for satellites in LEO satellite constellations is the network operation centre (NOC). It is assumed that the GW and one or more satellites are always linked in this scenario. On the other hand, it is expected that the satellite in this constellation, which is a space station, has a digital beam-forming capability. With the use of space-division multiplexing, high-speed digital signal processing, and propagation route data like amplitude and phase, digital beam-forming technology aims to restrict the beam by intensely emitting radio waves in a certain direction [13]. As a result, it is possible to increase the frequency utilization efficiency and effectively employ transmission power [14].

3.8.3 Lifetime of a Satellite-mounted Battery

In this subsection, we focus on the satellite's battery life after discussing the topic of exorbitant running expenses in Subsection 2.1. In this work, we focus on the battery depth of discharge throughout the communication period and the power consumption required when communicating with satellite terminals. Several variables, including the depth of discharge (DOD), discharge rate, charge rate, and temperature are linked to the battery's lifespan. Because the LEO satellite is an orbiting satellite with repeated and alternate periods of darkness and sunlight, the time of charging or discharging is controlled by the orbit. Therefore, it is assumed that DOD during the shadowed time is the primary factor impacting battery life. Every time a satellite orbits the earth, the number of times it can charge, or discharge vary based on the DOD, using the battery inefficiently. In relation to the discharge capacity, the DOD is the amount of discharge. Typically, the DOD at time t is represented by D(t). The formula for the number of satellites that can orbit with lifetimes L is.

$$log_{10} L + A.D = K \tag{3.1}$$

where, D is the average DOD when the spacecraft orbits the earth before it reaches the end of its lifespan since the satellite is frequently charged and discharged and because A and K are battery-dependent constants. The number of satellites that can orbit based on the period of DOD = 1 is established here in order to demonstrate the maximum number of satellites that can be in orbit. As a result, when the current DOD is D, the consumption rate, f (D), of the battery's lifetime is written as follows. The effect of the discharge on the number of satellites that may orbit. [18]

$$F_{(D)} = 10A\ (D - A)(1 + Aln_{10}.D \tag{3.2}$$

The number of satellites that can orbit and be consumed by the discharge from time t to t + δ, Lt,t+δ, can be stated as follows using the equation above.[18]:

$$L\ cons\ t, t + \delta = \{0\ D_{(t)} \leq\ D(t + \delta) \int D(t + \delta)\ D_{(t)}.f_{(D)}dD \qquad \text{, otherwise.} \tag{3.3}$$

Fig. shows the battery's lifetime consumption rate. When A is 0.8, the answer is 2. Even with the same amount of discharge, a greater DOD results in a higher battery load, as seen in Fig. 2. In this study, the number of these orbiting satellites that are completely depleted is determined by the battery load.

3.9 PROPOSED COMMUNICATION RESOURCE CONTROL POLICY

Here, we provide a summary of the suggested approach. The parameters that should be considered when managing communication resources are then discussed in connection to one another. The challenges surrounding the creation of this suggested method are then examined.

3.9.1 Overview of the Proposed Method

In Fig. 3. Outline the proposed structure of the advised communication plan. By using the proposed communication method, it will be possible to extend the life of the batteries used on satellites that are in the same orbital plane. The proposed approach aims to maintain all satellites in the same orbital plane by controlling their transmission power and antenna gain using the battery's status. The transmission antenna gain can be altered to manage the satellite's beam coverage as well as the data rate of the satellite terminal. On the other hand, within the satellite's beam coverage area, the transmission power can be changed to control the satellite terminal's communication data rate. Section 5 provides a specification of the data rate at which the satellite and satellite terminal can communicate while still being covered by the satellite beam. This control decreases the number of terminals that meet the communication needs between terminals and satellites with severe battery degradation, while also meeting the requirements for low-battery degradation. The ideal transmission power and transmission antenna gain for each satellite is then identified [111,112].

3.9.2 Battery Effects of Communication Resource Control

The following section explains the traits of the control parameters that should be taken into consideration when creating the algorithm suggested in this study. The act of controlling communication resources between satellites is something we focus on in particular. We begin by outlining the results of adjusting each satellite's transmission power. By adjusting the satellite's transmission power, it is possible to regulate the data rate of communication while taking into account changes in the satellite's-controlled satellite's beam coverage. Based on the communication requested by the satellite terminal (which is within the controlled satellite's coverage) and the satellite's communication data rate, the satellite terminal that satisfies the request and the satellite terminal that satisfies the request occur concurrently. The old terminal is the one that is still standing. The neighbouring satellite must process the remaining terminal when it is present in order to fulfil its communication request. Additionally, there are satellite terminal communication demands that had to first be handled by nearby satellites. Since there are more terminals for the nearby satellites to handle, the existence of leftover terminals is therefore attributed to an increase in the battery load on those satellites. Similar explanations apply to how control affects satellite transmission antenna gains. The beam coverage of the managed satellite and the communication data rate within it change as the transmission antenna gain of the satellite is changed. The satellite terminal's position information, the satellite's communication data rate, the communication requested by the satellite terminal (which is within the range of coverage of the controlled satellite) occurs concurrently with the other terminals and the satellite terminal that fulfils the request. Any surviving terminals will process and fulfil their communication request through the neighbouring satellite, if there are any. Because there are communication requests from satellite terminals that the surrounding satellites originally had to manage, the existence of the remaining terminals also increased the number of satellite terminals that the surrounding satellites had to process. This is explained by the nearby satellite's increased battery load. It is therefore evident that these two control settings interact and have an impact on the battery. However, employing an optimization technique to resolve this issue is challenging. This is due to the vast array of possible transmission power and transmission antenna gain combinations across all satellites. Calculating the ideal answer is therefore challenging. Additionally, the satellites in the envisioned environment are LEO satellites, and both the placements of satellite terminals as seen from the satellite and the communication needs inside each satellite's coverage area are continuously changing. As a result, it's important to manage each satellite's mobility as well as the communication requests sent by the satellite terminal on the ground. Consequently, the suggested communication technique entails employing Q-learning to construct a communication resource control algorithm.

3.10 ALGORITHM THE OF PROPOSED COMMUNICATION RESOURCE CONTROL METHOD

We go over the proposed method's algorithm in this part. The Q-learning system that is employed in this work is first described. The proposed method's implementation in the presumptive environment is then discussed. The proposed algorithm is then formulated, and the algorithm pseudo-code that is employed in the suggested technique is supplied.

3.10.1 Q-learning Overview and its Applications

Fig. 4 depicts the Q-learning framework. Reward-based learning includes Q-learning. In Q-learning, the agent in charge of the t action selection period chooses, depending on the state, either a) a random action with probability or b) the action with the highest reward with probability $1 - \epsilon$. A(t) is the formula for the action at time t, and s is the formula for the state at the time (t). As a result, at $(t + 1)$, the controlled side's environment changes, and this causes the reward r(t) to be achieved. The agent also develops a table of action-value functions Q for the state at that point.

Q is expressed as follows:

$$Q(s(t), a(t)) = Q(s(t), a(t)) + \alpha \{r(t + 1) + \gamma \, max \, a \, Q(s(t + 1), a(t)) - Q(s(t), a(t))\}. \quad (3.4)$$

where α is the learning rate weights of the recent and prior learning processes can be changed. Lower values show that the agent emphasizes prior learning more, where is the discount factor. It has the ability to change the Q's weight after the subsequent state. Higher values show that the agent is more concerned with the value of Q at the following state. By repeating this trial, the algorithm enables the agent to choose the best course of action. After that, the algorithm chooses the course of action that will give the agent the greatest overall benefit. [19]– [21It is feasible to learn how to use Q-learning to adjust each satellite's transmission power and transmission antenna gain according to its unique status. As a result, it is possible to implement communication resource control that anticipates the amount of communication each satellite will require from the satellite terminal that is already in place on the ground as well as changes to the satellite terminal's location information. We then discuss how to use the proposed communication technique. In the proposed communication technique, the NOC oversees controlling the satellites' communication resources. The communication request is first sent by each satellite at time $(n + 1)T$ into the NOC at time nT. Let T represent the satellite communication resource's control cycle. Following that, the NOC generates $Q((n + 1)T)$ between nT and (n+1) T based on the condition of each satellite. The NOC then controls the communication resource and notifies the $Q((n + 1)T)$ of each satellite-derived between nT and $(n + 1)T$ at time $(n + 1)T$.

3.10.2 Q-learning scheme

We go over the general format of the suggested communication algorithm in this subsection. The suggested approach is then subjected to Q-learning. First, the state is defined.

• State

The state is composed of the position of the controlled satellite m at the control interval T and the quantity of terminals that it still needs to process. The following description of the condition:

$$s(m) = [ssat(m), sre(m)]. \quad (3.)5$$

where I (m 1) is the definition of sre(m), which is the number of satellite terminals that the satellite m-1 is unable to process.

• Action

The action is defined as follows:

$$a(m) = [\, aP(m), aGpeak\,(m)]. \quad (3.6)$$

Furthermore, the satellite's transmission power is represented as

$$aP(m) = \{p|0 \leq p \leq P\,max\}. \tag{3.7}$$

Additionally, the gain of the satellite's transmitting antenna is represented as,

$$aGpeak\ (m) = \{g|G\,min \leq p \leq G\,max\}. \tag{3.8}$$

Here, we place limitations on the potential action F(s(m)). The behavioural restriction on the transmitting antenna gain is the first. In the same orbital plane, we assumed there was no unexplored range between satellites. As a result, each satellite's transmission gain, which is correlated to the size of the coverage area, is constrained. The second restriction was also the number of remaining terminals. The time it took the satellite (at time t) to move to the location where the adjacent satellite was at the time (t) was the maximum permitted delay from the terminal in this investigation. If a satellite terminal experiences a delay, the communication request for that terminal must now be handled by the satellite next to the one that did not initially process it. Control interval (T) and controlled satellite m are represented by the same period in the action selection period.

- **Reward**

Set the reward as follows:

$$r(m) = I\ (m - 1)\ L\ cons\ (n - 1)\ T, nT\ (m). \tag{3.9}$$

The satellite's energy efficiency during the action selection phase is the reward. The battery load (consumed by the satellite as a result of processing the communication request from the satellite terminal) to the number of processing terminals is used to represent energy efficiency. In order to take into account, the impacts connected with the regulation of communication resources among satellites, energy efficiency was established as a reward that can be regulated to ensure that each satellite utilizes the fewest possible communication resources if only the battery load is provided. When compared across satellites in the same orbital plane, this regulation reduces the average battery lifetime, making it suboptimal. The NOC can earn greater incentives by specifying these states because each satellite has higher energy efficiency. As a result, it is possible to choose the satellites' control parameters so that rewards are in the same orbital plane. Finally, at (m + 1), the environment on the controlled side changes, and this environment change results in the reward. After that, the agent develops a table of (Q) action value functions for the particular state. In this sentence, (Q) is stated as follows:

$$Q\left(s(m), a(m)\right) = Q\left(s(m), a(m)\right) + \alpha \left\{r\ (m + 1) + \gamma\ max\ a\ Q\left(s(m + 1), a(m)\right) - Q\left(s(m), a(m)\right)\right\}. \tag{3.10}$$

In conclusion, efficient power control of batteries is critical for maximizing battery performance, extending battery life, and reducing overall energy consumption. Power control strategies such as peak power shaving, load shifting, and demand response can help to minimize the energy drawn from batteries during peak periods, which can help to prolong battery life and reduce the overall cost of energy storage. Additionally, battery management systems (BMS) can play a critical role in controlling power usage, monitoring battery health, and ensuring safe operation of the battery system.

It is important to note that while power control strategies and BMS can help to optimize battery performance, they are not a substitute for selecting the right battery chemistry and design for the intended application. Proper battery selection is critical to ensure optimal performance and longevity, and should be based on factors such as energy density, power density, cycle life, and cost.

Overall, efficient power control of batteries is an essential component of effective energy management, and can help to reduce energy costs, improve system reliability, and mitigate environmental impact. Ongoing research and development in battery technology and power management strategies will continue to drive innovation in this field, leading to even greater efficiency and performance gains in battery systems.

CHAPTER 4 - CALCULATION OF BATTERY LIFE CYCLE

Most satellites now use lithium-ion batteries because of their high energy density, low self-discharge rate, and long cycle life. Satellites need batteries to provide energy when operating in shadow areas. A satellite battery's capacity will gradually drop as the number of cycles grows while it is operating in space, and some capacity recovery will take place. From cell phones to computers, medical equipment, satellites, and renewable energy power plants, secondary batteries are used in every facet of our lives. Long battery life and the capacity to store huge amounts of energy in small locations are two areas where lithium-ion batteries excel. But battery capacity deterioration, which leads to battery failure, poses a significant threat to people's finances and productivity in both individuals and businesses. Temperature, charge and discharge voltage, current, and the amount of charging or discharging the battery all have an impact on the degradation rate. Understanding these aspects can significantly slow down the rate of battery failure and improve the function of batteries. First, this thesis topic reviewed the literature on how factors like temperature, charge state, depth of discharge, charge voltage, and C-rate affect the rate of degradation in Li-ion batteries and the parameters required for optimum battery life.

4.1 Solar panels and battery cell aging calculation

For solar panels, the energy conversion efficiency η reduce since the beginning of service, due to contamination of radiation damage, plume flow, micrometeoroid and etc. let ηs max be the conversion energy efficiency at the beginning of the service, δ the aging rate of ηs per year, Y be the number of years been used where:

$$\eta s \ = \ \eta smax\ (1-\delta)\ Y \tag{4.1}$$

Several variables, including temperature, discharge rate, and DOD, have an impact on battery life. We concentrate on DOD in this letter when processing traffic. D(t) often represents DOD at time t, and lifetime L is given as

$$log_{10}L + A\,.\,D = B \tag{4.2}$$

where A and B are constants that depend on battery specifications. Therefore, to model the lifetime Eq. (4.2), to this end therefore we define a cycle life namely with L DOD = 1, the lifetime is

$$\frac{\int_0^D f(D)dD}{D} = \frac{L}{L} \tag{4.3}$$

Consider that the battery cells discharge from the time t, the cycle lifetime consumption rate when the current DOD is D, this discharge is defined as

$$f(D) = \ 10^{A(D-1)}(1 + Aln10.D) \tag{4.4}$$

The amount of lifetime consumed from t to $t\ +\ \delta$ is calculated as:

$$Lt, t+\delta = \begin{cases} \int^0 \\ \int_{D(t)}^{D\,(t+\delta)} f(D)dD \quad D(t)\ \le\ D\ (t+\delta) \end{cases} \tag{4.5}$$

This value can be estimated as the load over the lifecycle of the battery.

4.2 Calculation of Signal-to-Noise Ratio

On this subsection, we explain transmit antenna gain for a beam at a certain point, we define the way in which this formulates the power resource allotment per unit position from a given transmit power. [5] the transmit peak gain at a certain point i, is expressed as

$$Gipeak = \eta = (\frac{70\pi}{\theta 3dB})^2 \tag{4.3}$$

Here we set up the x-y coordinate system such that the origin is suited at the center of the beam for each satellite. The angle between position (x, y) and the satellite center position of the beam i is presented as follows: [8]

$$[\Theta\ (x, y), i\ ] = [arc\ tan\ [\sqrt{(x^{\wedge}2)}\ + y^2)\ /\ hLEO] \tag{4.7}$$

Where hLEO is the distance between the terrestrial receiving antenna and LEO satellite, hence the transmission antenna gains of the satellite beam i to position (x, y), $G_{(x, y)}$ is formulated as

$$G_{[x,y]} = \left[G_I^{peak}\right] - 12\ \frac{G_i^{peak}}{\eta}\ (\frac{\theta_{(x,y),i}}{70\pi}) \tag{4.8}$$

Where [u] is the Db value of u in other words $G_{(x, y), i.}$ is considered by G_i^{peak} i is the maximum value of the transmit antenna gain for beam, and η is the antenna aperture efficiency. Therefore, the SINR of the entire link $SINR_{(X, Y)}^{Total}$ can be calculated as follows [5]

$$SNR_{(x,y)}^{Total-1} = SINR^{UP-1} + SINR_{(x,y)}^{Down-1} \tag{4.9}$$

Where $SINR^{UP}$ uplink feeder and the value of which is assumed constant in our paper, furthermore $SINR^{DOWN}$ which is downlink user link as a position (x, y) can be formulated based on the Shannon-Hartley theorem as follows:

$$G_{(x,y),i} = \text{BWi}\ (\log 2\ (1 + SNR_{(x,y)})) \tag{4.11}$$

Where BWi indicate the frequency of a bandwidth allocated to beam i.

Therefore, the downlink SNR of the user link is expressed as follows, where G_R is the receive antenna gain, P_i is the satellite transmit power, L_{free} is the free space propagation loss, T_n is the noise temperature. L_{rain} is the rain attenuation, B_n is the noise bandwidth and F_i is the bandwidth. Therefore, the downlink SNR of the user link at position (x, y) is expressed as follows

$$SNR_{(x,y)}^{Down} = [P_i] + [\ G_{(x,y),i}] + [G_R + [\ L_{free}] + [L_{rain}] - [\text{Tn}] - [\text{k}] - [\text{Bn}]. \tag{4.12}$$

where P_i is the satellite transmit power.

4.3 Techniques for extending the life of Li-ion batteries

4.3.1 Environment for cycles and storage

Calendar time, cycle number, temperature, SOC, DOD, C-rate, SOC, and charge and discharge voltage are just a few of the variables that can determine how long Li-ion batteries last, whether they are being used or stored, as described in Section 3.3. Table 3.3 provides a list of the ideal cycle or storage conditions for maximizing Li-ion battery longevity. Power cell Specified High:

3.92V Low: 3V Around 50% Performance (maximum runtime) 25°C Energy cell =0.8C Table 3.3 Temperature SOC C-rate Voltage DOD in storage 5-20 Celsius Around 50% Cycling Longevity 20°C 25%-85%.

Table 4.1: Conditions that maximize battery life

<table>
<tr><th></th><th colspan="2">Temperature</th><th>SOC</th><th colspan="2">C-rate</th><th>Voltage</th><th>DOD</th></tr>
<tr><td>In storage</td><td colspan="2">5-20 Celsius</td><td>Around 50%</td><td colspan="2"></td><td></td><td></td></tr>
<tr><td rowspan="2">Cycling</td><td>Longevity</td><td>20°C</td><td rowspan="2">25%-85%</td><td>Power Cell</td><td>Specified</td><td rowspan="2">High 3.92V

Low: 3V</td><td rowspan="2">Around 50%</td></tr>
<tr><td>Performance (maximum runtime)</td><td>25°C</td><td>Energy Cell</td><td><=0.8C</td></tr>
</table>

A fully charged lithium-ion battery will lose roughly 20% of its capacity after a year of regular storage, claims battery testing company Cadex Electronics. The deterioration accelerates at high temperatures. Running the charge down to 50%, removing the battery from the device, and keeping it cool are the best ways to maintain long-term battery storage. However, even under perfect storage conditions, the battery could expire after three or four years without being used.

In conclusion, the calculation of battery life cycle is a critical aspect of battery management and can help to ensure optimal performance and longevity of battery systems. The life cycle of a battery is determined by various factors such as the battery chemistry, operating conditions, charging and discharging rates, temperature, and depth of discharge.

To calculate the battery life cycle, it is important to consider these factors and estimate the total number of charge-discharge cycles that the battery can endure before its capacity significantly deteriorates. This can be done through empirical testing or through simulations using mathematical models that take into account the various battery parameters.

In addition to calculating the battery life cycle, it is important to also consider other factors such as safety, cost, and environmental impact when selecting a battery for a particular application. Battery management systems (BMS) can also play a critical role in prolonging battery life by monitoring and controlling the battery's operating conditions and ensuring safe and efficient operation.

Overall, the calculation of battery life cycle is an essential component of battery management and can help to optimize battery performance, reduce costs, and mitigate environmental impact. Ongoing research and development in battery technology and management strategies will continue to drive innovation in this field, leading to even greater efficiency and performance gains in battery systems. Chapter Five will give more details about the design of the chosen region and the simulation.

CHAPTER 5 – SOLAR ENERGY-BATTERY STORAGE OPTIMIZATION FOR SATELLITE-TO-GROUND COMMUNICATION

A solar irradiation site with sufficient solar availability has been chosen for this study. However, a comparative economic study is necessary to determine the size of a standalone renewable source. Therefore, utilizing the Hybrid Optimization Model for Electric Renewable software, the primary goal of this work is to increase the lifespan of the battery system that powers the satellite when it is in the shade (HOMER). According to the results of the simulation, it is possible to extend the battery life so that the Satellite can be powered continuously.

This is crucial for satellite applications since battery systems require a steady stream of power and cannot tolerate power outages of any kind. The remaining portion of the Chapter is structured as follows. The collated data is presented, followed by descriptions of economic methodologies and comparative cost analysis, system sizing and cost estimates, Homer's findings and analysis, and, finally, a conclusion.

5.1 Data Collection

5.1.1 solar energy Assessment

Solarius PV BIM 2 was used to collect satellite-based solar resource profile data for the chosen region in Pietermaritzburg (-29.6118712 ,30.3626589), and the Southern African Universities Radiometric Network (SAURAN) database was used for validation. The solar radiation employed in this investigation is depicted in Figure 20., and Table 5.1 below lists the site's monthly average solar radiation levels. The months of November, December, January, and February experience the highest radiation levels.

Table 5.1: The selected site's annual resource data

Month	**Clearness index**	**Daily Radiation (KWh/m^2 /day)**
January	0.475	5.670
February	0.500	5.510
March	0.530	5.030
April	0.579	4.400
.May	0.634	3.810
June	0.647	3.400
July	0.655	3.650
August	0.617	4.250
September	0.556	4.840
October	0.472	4.930
November	0.455	5.300
December	0.468	5.690

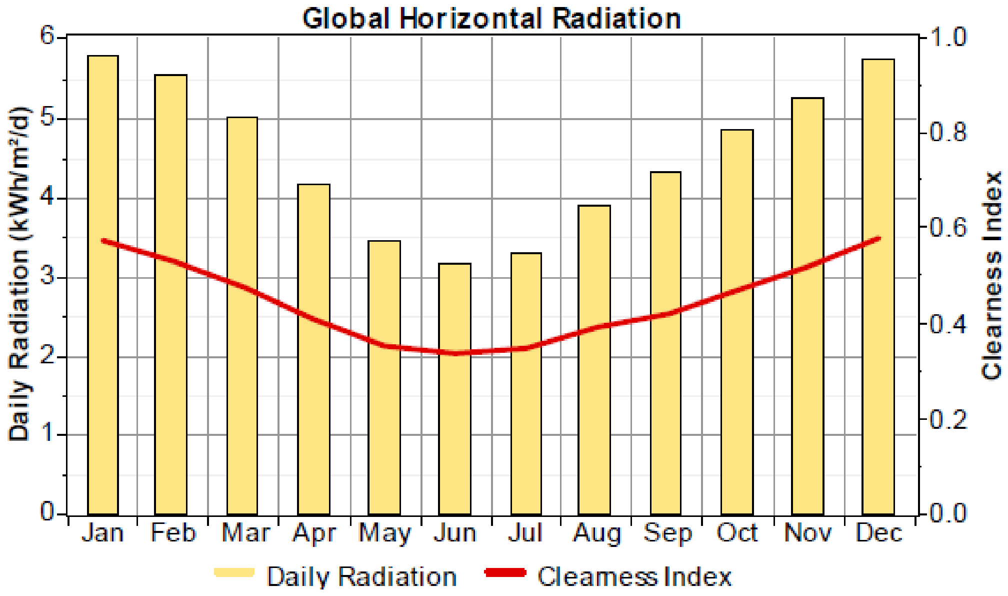

Figure 19: The solar data for 2022

Figure 5.19 above shows the PV array solar GHI resource as output, annual average GHI (kWh/m2/day) is 5.690

5.1.2 Battery data assessment

In this system the Lithium-Ion battery is used, the specification of the battery is displayed in the table 5.2 below

Table 5.2 Battery data assessment

DESCRIBTION	**LITHIUM-ION BATTERY**
Battery Abbreviation	LFP-26650-330
Manufacture	EEMB
Nominal Capacity	260 Ah
Nominal Voltage	3.7 V
Round Trip	80%
Min. State of Charge	49%
Float Life	30 years
Lifetime Throughput	1 000 kwh
Max. Charge Current	3.3 A/Ah
Max. Discharge Current	3.3A

The Table 5.3 indicate the price cost of the cells of the battery for capital, replacement and battery operation and Maintenance. For this system 24 battery system is used which cost $3000.00 per year.

Table 5.3: shows the Costing of the Battery.

Quantity	**Capital ($)**	**Replacement ($)**	**O&M ($/yr)**
1	1250	1250	50.00
8	2500	2500	1000.00
16	5000	5000	2000.00

24	7500	7500	3000.00

5.1.3 System Sizing and Costing

A DC load, solar panels, and battery storage make up the design system. Based on the necessary load, the system design is selected. In order to prevent power conversion losses, this gives the impression that the system is entirely DC. Second, this is done to guarantee supply continuity so that solar energy will provide power whenever it's sunny. Furthermore, battery storage is added to store energy when the satellite is on Eclipse because the system won't be providing power consistently.

The decision to use each component was made with the goal of supplying 947W of power at all times. Costs associated with system components include capital, replacement, and operation and maintenance expenses. US dollars are used as money in the Homer program. One (1) US dollar was equal to 18.11 ZAR (South African Rand) at the time of this study. Due to the aforementioned factors, the battery storage was taken into consideration during the simulation. It is expected that the system would last for 30 years. The models do not include in other costs like personnel, installation, or building. The suggested satellite system with battery storage system is depicted schematically in Fig. 3 using HOMER software. The data displayed in Table 3 was provided.

The data in Table 20 was entered into HOMER for system sizing. A 370W polycrystalline PV panel costs US$15,345 in South Africa (R277 897,95). With a 30-year lifespan, the O&M cost is estimated to be 6% of the overall cost. In order to meet the load demand with no electricity shortfall, HOMER calculated the ideal quantity of solar panels.

More information about this is provided under results and debates. A 260AH deep cycle battery is also part of the system for energy storage. Table 5.1 above displays this battery's technical specifications. This battery may be purchased on the South African market for US$61,875 or ZAR 1120,56, and it has a 30-year lifespan (5010+ cycles), assuming a 50% depth of discharge. The annual O&M expense is projected to equal 20% of the capital expense.

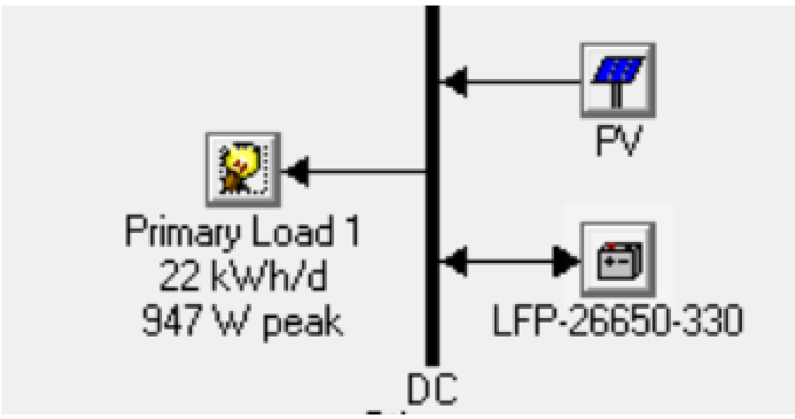

Figure 20: Design Schematic

Si-Poly PV module has been used in this system for electrical power generation because of its high energy yield efficiency. parameters of PV modules are given below on table 5.4

Table 5.4: Information on the system components' cost and technical conditions

Description	Solar panel polycrystalline	Battery Lithium-ion
Size	370 W	260AH
Voltage	48V	3.7V
Efficiency	20%	80%
Cost (US$)	49,212	316,357
Life Span	20 years	30 years
O&M/ Purchase cost	6%	20%

Table 5.1.4 and Figure 5.21 displays Hourly load profile. The load profile shows that the peak demand is Constant from the hours of 6 p.m. and 6 a.m. as it is the hours when it is dark out.

5.1.4 Load of Satellite

Hour	Load (kW)
00:00 - 01:00	0.9
01:00 - 02:00	0.9
02:00 - 03:00	0.9
03:00 - 04:00	0.9
04:00 - 05:00	0.9
05:00 - 06:00	0.9
06:00 - 07:00	0.9
07:00 - 08:00	0.9
08:00 - 09:00	0.9
09:00 - 10:00	0.9
10:00 - 11:00	0.9
11:00 - 12:00	0.9
12:00 - 13:00	0.9
13:00 - 14:00	0.9
14:00 - 15:00	0.9
15:00 - 16:00	0.9
16:00 - 17:00	0.9
17:00 - 18:00	0.9
18:00 - 19:00	0.9
19:00 - 20:00	0.9
20:00 - 21:00	0.9
21:00 - 22:00	0.9
22:00 - 23:00	0.9
23:00 - 00:00	0.9

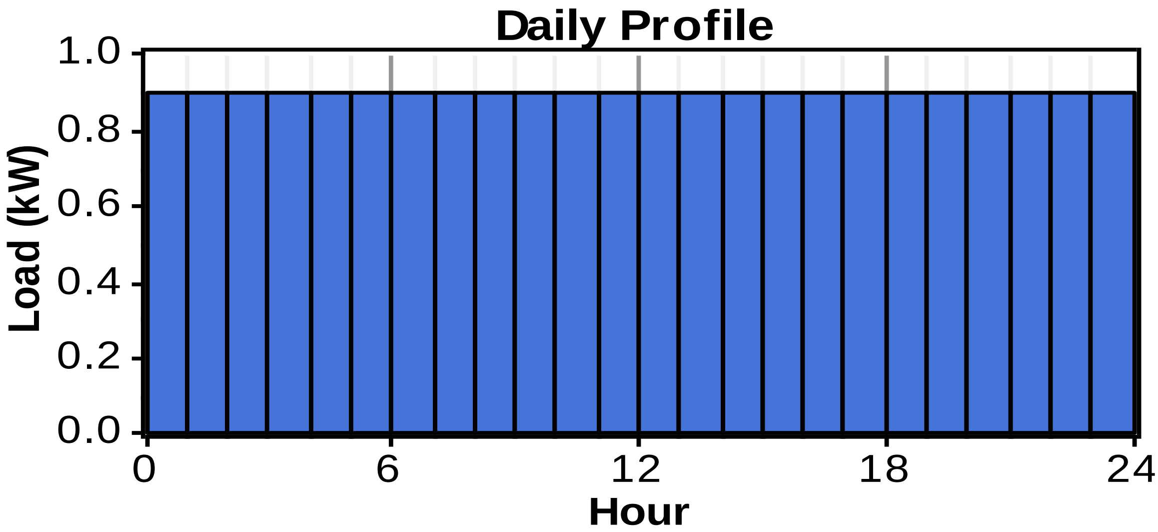

Figure 5.21 Daily Load Profile

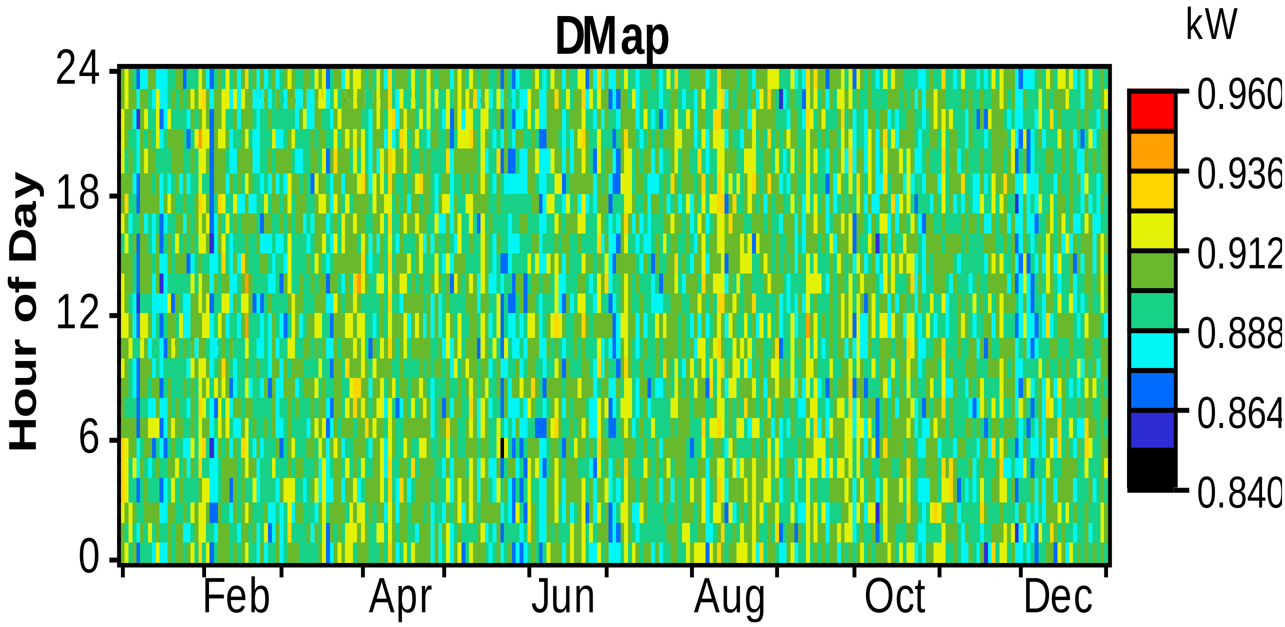

Figure 22: D-Map during hours of the day

Pietermaritzburg is a hot place as compared to wind potential energy, all year long, there is a plentiful supply of solar energy. The D-map formatted HOMER model for solar radiation and radiation incident on PV array is displayed in figure 5.22 and figure 5.23 which is seasonal profile.

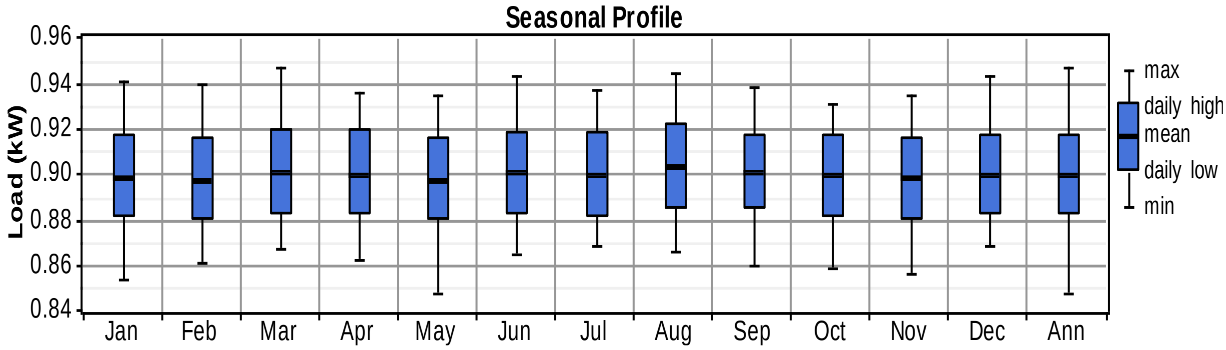

Figure 23: Seasonal Load Profile

5.1.5 PV Simulation Result

Table 5.6 Solar Simulation Result

Quantity	Value	Units
Rated capacity	9	kW
Mean output	2	kW
Mean output	48	kWh/d
Capacity factor	22.2	%
Total production	17,534	kWh/yr

Quantity		Value	Units
Minimum output	0		kW
Maximum output	8.98		kW
PV penetration	222		%
Hours of operation	4,385		hr/yr
Levelized cost	0.528		$/kWh

The majority of the power used during the year comes from solar panels. The PV panel array is 0.6KW in size, and during the day it may produce anywhere between 60 and 600W. Winter brings about a noticeable change as the solar resource declines even further, as illustrated in Fig 24. The output of solar panels decreases to 50% during this time. The generated PV energy is used by HOMER software to meet load requirements and maintain 0% capacity shortage.

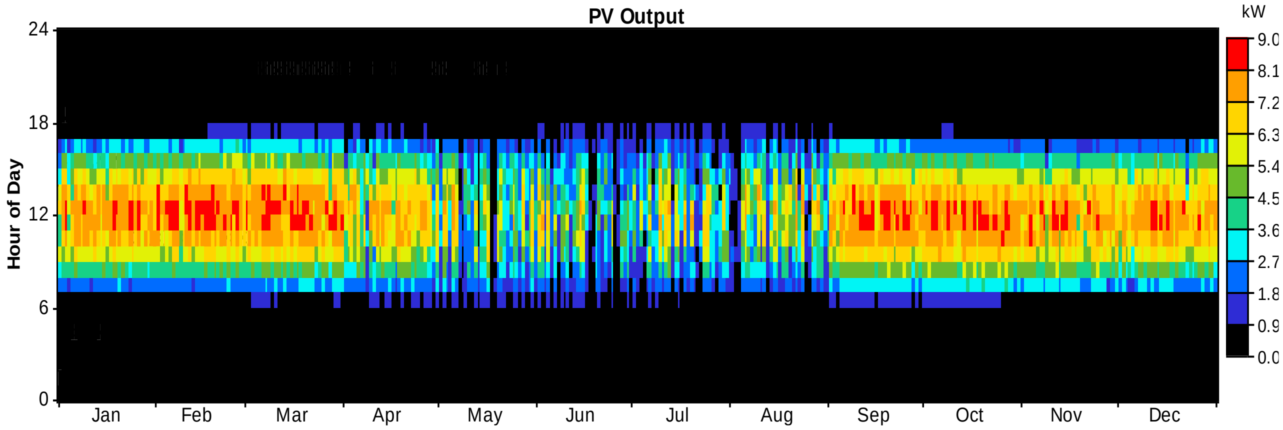

Figure 24: Solar Power Output during hours of the day

5.1.6 Battery Simulation Result

Table 5.7 Battery Result

Quantity	Value
String size	9
Strings in parallel	22
Batteries	198
Bus voltage (V)	33.3

Quantity	Value	Units
Nominal capacity	190	kWh
Usable nominal capacity	114	kWh
Autonomy	127	hr
Lifetime throughput	198,000	kWh
Battery wear cost	0.349	$/kWh
Average energy cost	0	$/kWh

Quantity	Value	Units
Energy in	5,296	kWh/yr
Energy out	4,243	kWh/yr
Storage depletion	7	kWh/yr
Losses	1,046	kWh/yr
Annual throughput	4,744	kWh/yr

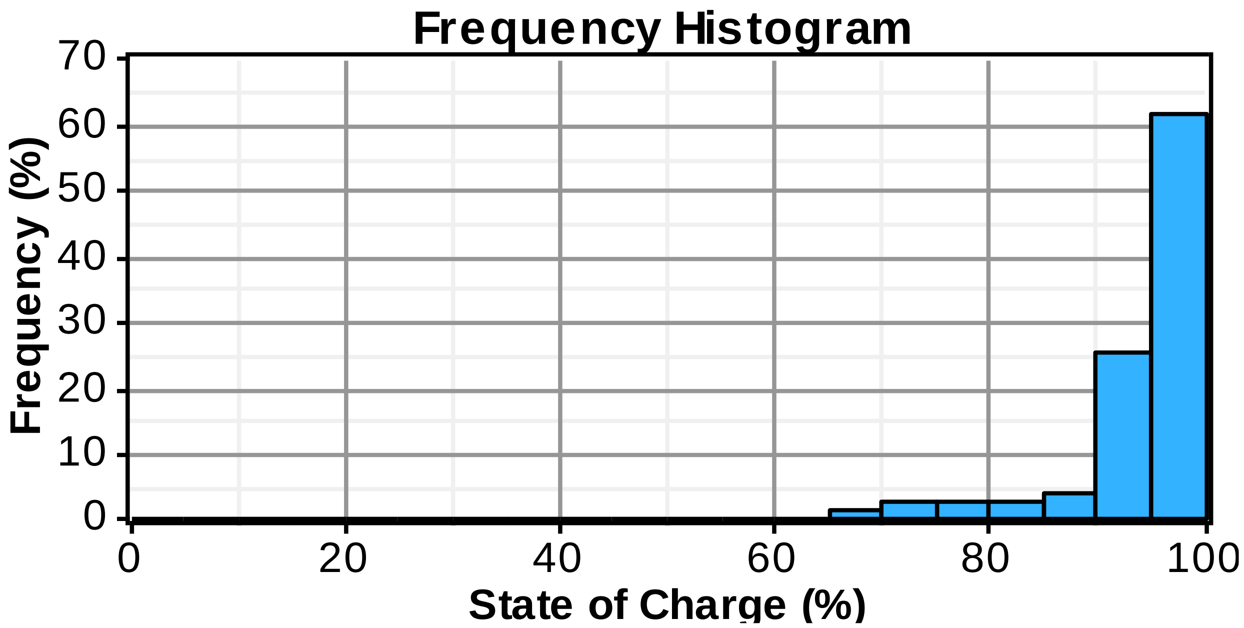

Figure 20: Frequency histogram

Figure 5.20 descibe list the amount of power generated by the solar and VRB systems for each month of the year. The graphs clearly show that the VRB is used during periods of poor or non-existent solar power output, as seen by the low state-of-charge (SOC) during these periods. Figure 5.20's frequency histogram shows that the VRB is in a high state of charge for about 63% of the year and a low state of charge for about 3% of the year, indicating that there is still room for more VRB use. This is significant given the intermittent nature of solar power and the potential for variations in solar output from year to year.

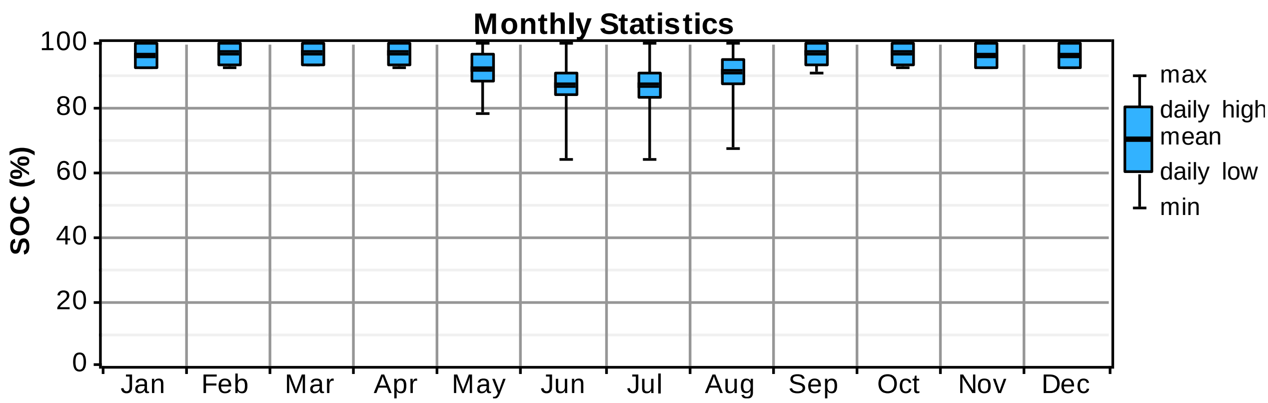

Figure 21: Monthly statistic

Figure. 21 displays annual statistics for the battery's level of charge as well as the overall amount of energy it can hold. This displays a thorough hourly battery state of charge for each month of the simulated period. This demonstrates that the battery maintains a full charge between the hours of 12 and 18 over most of the year (January to December), with a minimal state of charge occurring more frequently between 0 and 12. Only over the winter do the batteries' extended SOC levels drop. The battery bank reaches a minimum condition of 40% about 06:00 in the morning during the winter season (June to July). Most of the time the battery is used at night. Figure. 21 also demonstrates that the battery's SOC is above 90% for more than 50% of the time. This validates the fact that the battery is used in a way that extends its life.

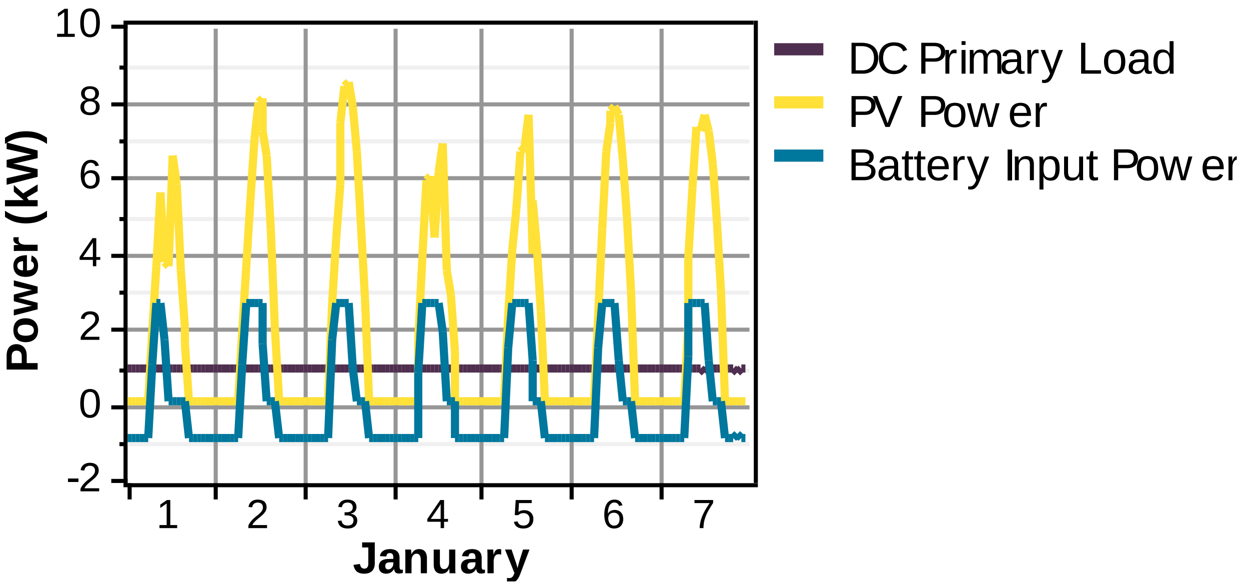

Figure 22: Power system power Flow and Consumption

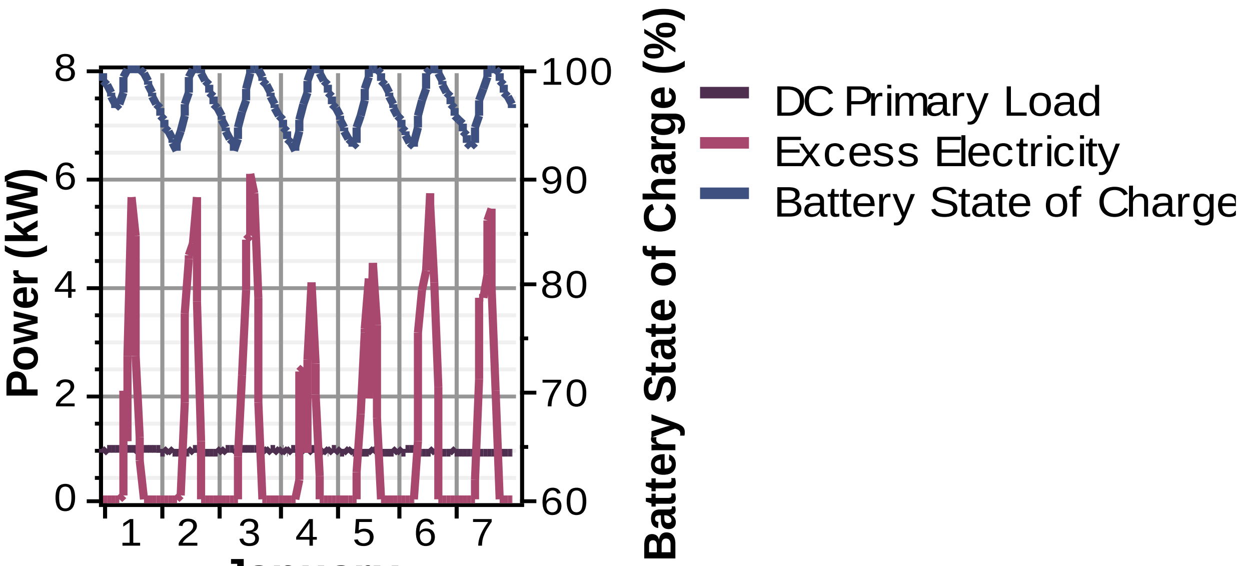

Figure 23: Battery SOC, surplus power, and system power flow.

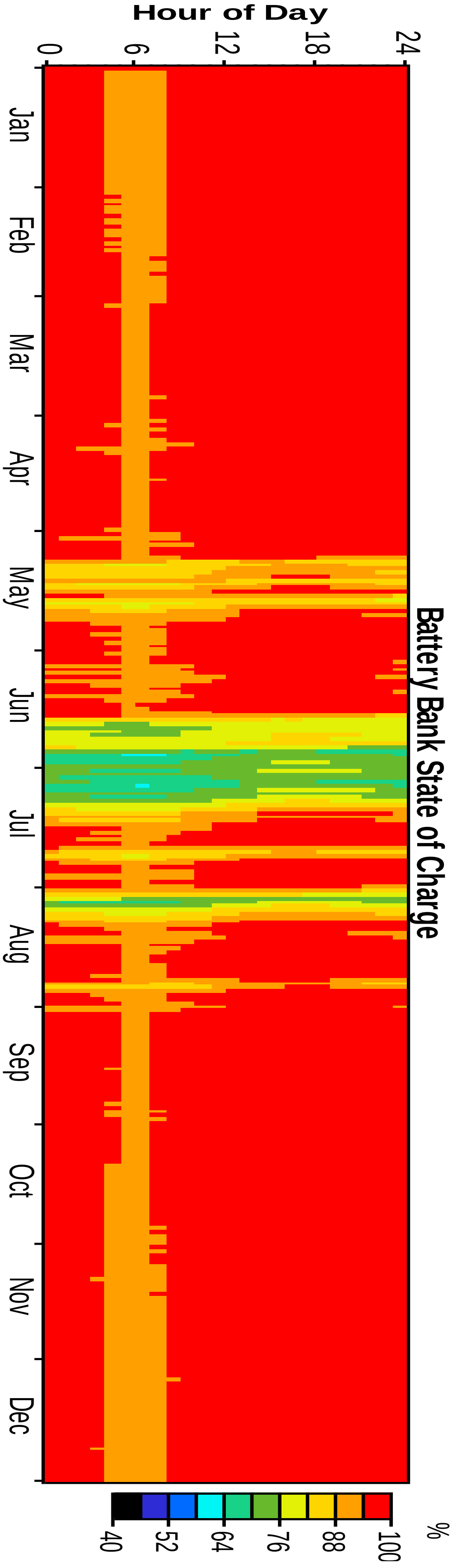

Figure 24: Battery State of charge

Figure 5.24 Displays the battery bank's state of charge, with a 30% beginning level of charge.

5.1.7 OVERALL PROJECT SIMULATION

The categorized ideal findings are displayed in Figure. These are each configuration type's most advantageous configurations economically. The system includes one or both of the two essential parts, which are mostly solar panels and battery storage systems. The system must have a battery because renewable energy sources are unreliable. The system can still work even if one or both of the Solar components are absent. As a result, a solar PV system with batteries is conceivable. The table below displays the specific outcomes for the aforementioned categories.

PV (kW)	LFP-266...	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
1.40	243	$ 84,490	31,086	$ 481,873	13.481	1.00	1.00
20.00	117	$ 144,625	26,479	$ 483,116	4.794	1.00	0.38
1.80	243	$ 86,630	31,321	$ 487,016	10.963	1.00	1.00
35.00	18	$ 193,937	22,983	$ 487,740	8.230	1.00	1.00
2.00	243	$ 87,700	31,438	$ 489,588	10.061	1.00	1.00
9.00	198	$ 111,087	29,968	$ 494,174	4.903	1.00	0.00
2.50	243	$ 90,375	31,732	$ 496,017	8.393	1.00	1.00
0.40	261	$ 82,845	32,519	$ 498,546	42.669	1.00	1.00
0.24	261	$ 83,913	32,637	$ 501,128	65.086	1.00	1.00
3.00	243	$ 93,050	32,026	$ 502,447	7.239	1.00	0.85
0.68	261	$ 86,263	32,898	$ 506,805	27.164	1.00	1.00
0.72	261	$ 86,477	32,921	$ 507,316	25.813	1.00	1.00
0.96	261	$ 87,761	33,061	$ 510,387	19.916	1.00	1.00
1.10	261	$ 88,510	33,143	$ 512,185	17.645	1.00	1.00
4.00	243	$ 98,400	32,613	$ 515,305	5.831	1.00	0.34
1.40	261	$ 90,115	33,319	$ 516,042	14.389	1.00	1.00
1.80	261	$ 92,255	33,554	$ 521,186	11.700	1.00	1.00
35.00	36	$ 199,562	25,288	$ 522,825	7.539	1.00	0.93
2.00	261	$ 93,325	33,671	$ 523,757	10.737	1.00	1.00
2.50	261	$ 96,000	33,965	$ 530,186	8.953	1.00	1.00
12.00	198	$ 127,137	31,730	$ 532,750	5.286	1.00	0.00
40.00	9	$ 217,875	24,768	$ 534,495	9.821	1.00	1.00

Figure 25: optimal configuration

Figure 25 shows the multiple simulation result, simulation number Five was chosen because of there will be no load that will be unmet and also no shortage of Capacity will be experienced.

Table 5.8: Optimum simulation summary result.

System Description	Solar with Battery
Total Rated Capacity	9 Kw
Capital Cost (US$)	111,087
(Rand)	2011,79
NPC (US$)	494,174
(Rand)	8949,49
O&M (US$)	378,746
(Rand)	6859,09
COE (US$/kWh)	4,903
Rand/kWh)	88,79
Operating cost (US$/year)	29,968
(Rand/year)	542,72

Table 5.9: show the Solar, Dc Primary and also shows that there will be no unmet electric load.

Production	kWh/yr	%
PV array	17,534	100
Total	17,534	100
Dc primary load	7,884	100
Total	7,884	100
Excess electric load	8,597	49,0
Unmet electric load	0,00	0,0
Capacity shortage	0,00	0,0

The table below shows the monthly average Electricity Production generated by the Solar throughout the year and the lowest production is on the month of June.

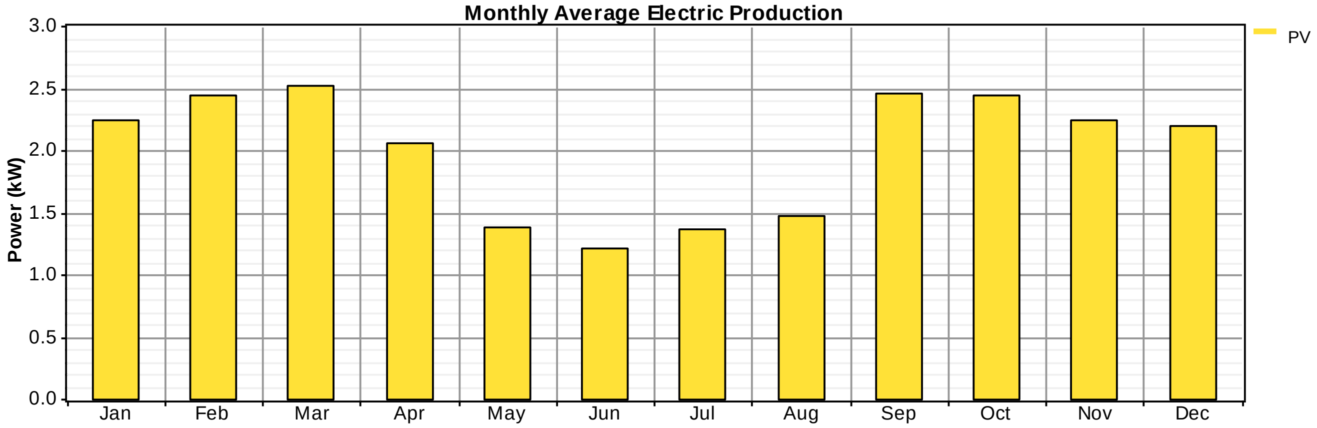

Figure 26: Monthly average Production

5.1.8 CASH FLOW

The below Graph shows the capital cost, Replacement of some system component cost and also the operating cost. The system cost is (US$) 494,174 and 8 949 491,14 in Rands, replacement cost (US$) 15,345 which is 277 897,95 in Rands after 20 years of system operation, and also operating cost of is (US$) 378,746 which is 6 859 090,06 in Rand.

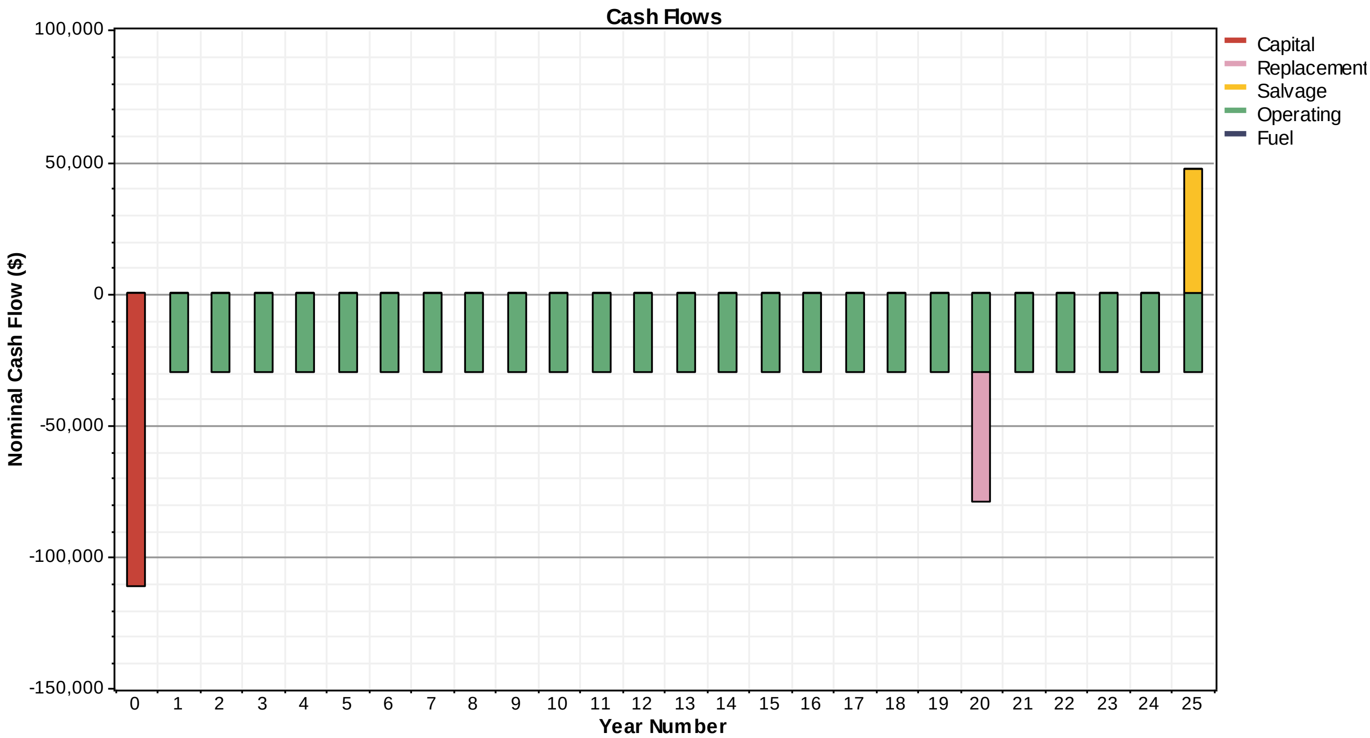

Figure 27: System Cash flow

In conclusion, optimizing the solar energy-battery storage system for satellite-to-ground communication is critical to ensure reliable and efficient communication. The solar energy-battery storage system should be designed to meet the energy demands of the communication system, while also taking into account factors such as weather patterns, satellite orbit, and battery life cycle.

To optimize the solar energy-battery storage system, it is important to select the appropriate battery chemistry and capacity, as well as the optimal solar panel configuration and size. Additionally, a battery management system (BMS) should be implemented to monitor and control the battery's charging and discharging rates, and to ensure safe and efficient operation.

The optimization of the solar energy-battery storage system can lead to several benefits, including increased reliability, improved efficiency, and reduced environmental impact. By relying on renewable solar energy, the system can reduce dependence on fossil fuels and lower greenhouse gas emissions.

Overall, the optimization of the solar energy-battery storage system is essential to ensure reliable and efficient satellite-to-ground communication. Ongoing research and development in solar energy and battery technology, as well as improvements in management and optimization strategies, will continue to drive innovation in this field and lead to even greater efficiency gains in satellite communication system.

CHAPTER 6

6.1. Conclusion and Future Work

The limits of this section's discussion of the HOMER results are as follows:

- Installation and cabling costs are included in simulations as starting expenditures because they are comparably inexpensive to the total system cost.
- Throughout the course of the project, replacement costs are seen as being equal to the capital costs of each component.
- O&M includes the repaid change in renewable energy items. However, the simulations take yearly inflections into account.

For the system's entire 20-year lifespan, there must be no yearly capacity shortfall. This will guarantee that the load is always appropriately provided during the course of a year.

Due to the presence of satellites with deteriorated batteries in LEO constellations, the primary objective of this thesis was to increase the average lifetime of batteries of satellites in the same orbital plane. The findings demonstrated that it is possible to cooperate with the ground network while lowering the cost of communication. Regardless of the load on the satellite, the battery life often decreases owing to processing traffic. The suggested approach allows the standby terminal to minimize the amount of traffic processed by the degraded satellite and extend the battery life of the satellite by controlling the transmission power.

The suggested system, along with the NPC and the levelized COE, was sized using the most unfavourable month technique. Solar irradiation, load demand, component pricing, and technical parameters were entered into HOMER software to scale the system. Levelized COE as a performance metric served as the primary criterion for choosing the best system (objective function). Net current cost and beginning cost are already included in the levelized COE.

The chosen 30-year life expectancy system for this case study has an initial capital of 111,087 US dollars (ZAR 2 011 785,57), a total net present cost of 494,174 dollars (ZAR 8 949,491,14), and an energy cost of 4,903 dollars per kWh (ZAR 88,79/kWh). 260Ah batteries and a 9.0 KW PV array make up the system architecture.

However, HOMER was unable to support the DC-DC buck booster converter required to control the energy to meet the demands of the load. This constraint highlights the need for additional modelling of the system to enable power flow analysis of each component and improve optimal decision-making. A system implementation is recommended for future study in order to validate the suggested ideal system.

Future work in the optimization of the solar energy-battery storage system for satellite-to-ground communication should focus on several areas.

Firstly, there is a need for ongoing research and development in solar energy and battery technology, with a focus on improving the efficiency and durability of these systems. This can be achieved through advancements in materials science, manufacturing processes, and system design.

Secondly, further development of battery management systems (BMS) can help to optimize the performance of the battery storage system. BMS can be improved to better monitor and control the battery's charging and discharging rates, as well as to provide real-time feedback on system performance and health.

Thirdly, there is a need to develop more accurate and sophisticated models for predicting solar energy availability and battery life cycle. This can be achieved through the use of advanced algorithms and machine learning techniques, as well as through empirical testing and data collection.

Lastly, there is a need for further testing and validation of solar energy-battery storage systems in real-world conditions. This can help to identify potential issues and improve system design, as well as to validate the effectiveness of optimization strategies.

Overall, future work in the optimization of solar energy-battery storage systems for satellite-to-ground communication should focus on improving efficiency, reliability, and performance through ongoing research and development, as well as through testing and validation in real-world conditions.

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