UNIVERSITY OF NAIROBI

Faculty of Engineering

DEPARTMENT OF ELECTRICAL AND INFORMATION ENGINEERING

Modelling and Optimized Placement of a Grid Scale Energy Storage System based on Li-Ion batteries for the Kenyan Grid

Thesis submitted for the Degree of Master of Science in Electrical and Electronics Engineering, in the Department of Electrical and Information Engineering of the University of Nairobi.

BY

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F56/37513/2020

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November 2023

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FACULTY/ SCHOOL/ INSTITUTE: Engineering

DEPARTMENT: Electrical and Information Engineering

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Acknowledgement

I acknowledge my supervisors Dr. Abraham M. Nyete and Dr. Peter Moses Musau for their encouragement and guidance throughout this work, the University; for the part it has played to enable my studies by offering me the UoN scholarship and my family for their support, love and encouragement. I am also very grateful to my primary school science teacher Mr. Maundu for instilling the love of science in me at a young age and not also forgetting my mentor for his support and mentorship in this field of Electrical and Electronics Engineering.

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Abbreviations

BESS - Battery Energy Storage System
BOP - Balance Of Plant
CAES - Compressed Air Energy Storage
CG - Centralized Generation
DG - Distributed Generation
DNLF - Decoupled Newton Load Flow
DOD – Depth of Discharge
ECD - Energy Conversion Device
ECM - Energy Conversion Module
EES - Electrical Energy Storage
ESM - Energy Storage Medium
EV - Electric Vehicle
FCES - Fuel Cell Energy Storage
FDLF - Fast Decoupled Load Flow
FES - Fly-wheel Energy Storage
GS – Gauss Seidel
GSES - Grid Scale Energy Storage
HES - Hydrogen Energy Storage
IEEE - Institute of Electrical and Electronics Engineers
KETRACO - Kenya Transmission Company
LCOE - Levelized Cost Of Electricity
LCOS - Levelized Cost Of Storage
LTWP - Lake Turkana Wind Project
NR – Newton Raphson
O&M – Operation and Maintenance
PAY-Go - Pay-As-You-Go
PCS - Power Conditioning System
PHS - Pumped Hydro Storage
R&D – Research and Development
RES - Renewable Energy Sources
ROI – Return On Investment
SCES - Supercapacitor Energy Storage
SMES - Superconducting Magnetic Energy Storage
TES - Thermal Energy Storage
UETCL - Uganda Electricity Transmission Company Limited
UPHS – Underground Pumped Hydro Storage
VR – Vanadium Redox

Abstract

Grid Scale Energy Storage (GSES) is attracting significant attention in the electrical power investment sector. While we have an understanding of the technical and economic limits of Renewable Energy Sources (RES) integration, such an understanding is limited with GSES, more so on the Kenyan grid. This study aimed at deepening knowledge on the potential benefits of GSES particularly arbitrage and peaking capacity. The study modelled the Kenyan grid based on the IEEE 14-Bus system and applied load flow analysis, simulation tools (on DigSilent Power Factory) together with analysis for different test cases to equip policy makers, regulators and investors on the technical and economic limits of GSES and also the interaction between GSES and grids integrated with RES. From analysis and simulation, specific knowledge was gained on where to optimally place grid-scale Battery Energy Storage Systems (BESS) in Kenya that was based on the Lithium-Ion chemistry. For best results, the Li-Ion BESS was optimally placed on the 33kV distribution buses of the 4 regions in Kenya: Nairobi, West, Mt. Kenya and Coast Regions. Further, the potential for Arbitrage and Peaking Service Provision was demonstrated and both were found viable, having an ROI of 109.35% and 104.51% respectively on the Kenyan grid. Other consequential benefits of having the BESS on the Kenyan grid were: the possibility of having the BESS act as spinning reserve and the de-loading of lines that are highly loaded at peak times.

Chapter 1: Introduction

1.1: Background

The electric power grid – one of the most complex and sophisticated infrastructure creations by mankind, with its origins in the late 19th century [1, 2] – principally serves as an interconnected power structure for delivery of electric power from electricity generation points to utility areas. Due to various technical factors, the power grid is organized around three main subsystems: generation, transmission and distribution. The subsystems differ significantly in terms of the voltages at which they handle power. Typically, commercial utilities' generation voltages are rated between 11 kV and 25 kV, though industrial plant generators are normally rated 2.4 kV to 13.8 kV, coinciding with standard distribution voltages [3, 4].

The generated power is transformed in a substation, located at the generating station, for transmission. Standard nominal transmission system voltages [5, 6] are 69 kV, 115 kV, 138 kV, 161 kV and 230 kV; however, some transmission voltages may be at 23 kV to 69 kV, levels normally categorized as primary distribution system voltages. Further, there are a few transmission networks operating in the extra-high-voltage class (345 kV to 765 kV). The transmission system voltage is stepped-down to lower levels by distribution substation transformers. Primary distribution system voltages range from 2.4 kV to 69 kV, while common secondary distribution voltages are 120, 208, 240, 277 and 480 volts [4, 7].

Generally, electricity generation can either be centralized or distributed. In centralized generation (CG), electricity production is done by power plants that provide bulk power to the transmission system. Further, this type of generation is characterized by unidirectional flow of power, from source to consumer, and in the event of loss of a generating plant or a large load, the power system is prone to wide instability and unreliability and is easily attackable [8]. On the other hand, in distributed generation (DG), the generators – utility or customer owned – serve power at distribution level voltages. If utility owned, the generators inject power to the grid for distribution network support, support that includes but is not limited to power quality and reliability [8, 9]. The robustness that this kind of system offers is the key driver to its favorability.

The electric power industry has for the longest time been dominated by a large single utility player doing generation, transmission and distribution to majority of consumers in a locality or multiple localities – the vertically integrated utility model. Changes in this type of operation have been necessitated by an ever-increasing demand for electric power with reliability and quality of power becoming a concern in modern times, coupled with a shift in electric energy mix towards variable renewable energy sources (RES) and smaller generators on the supply side. Other drivers for change include an aging grid as well as availability of advanced technology to better manage the grid resources and a dynamic electric load [10]. In trying to integrate RES and also keep up with the changing times, several technologies and concepts are in the forefront spearheading the evolution of the grid, such as DG, grid scale energy storage (GSES) and smart grids; there is also the development of micro and mini-grids, smaller generations with a push towards localized generation and consumption (independent grids) [11].

It is instructive to note that the Kenyan grid has also seen its own share of evolution with a move towards a greener grid with integration of RES, typical cases being the recently completed 310 MW Lake Turkana Wind Project (LTWP) [12], the largest on the continent, and the Garissa Solar Power Plant with its 50 MW [13]. There are also small mini-grids such as the SOS 60 KW and numerous micro-grids throughout the country [14]. Furthermore, pay-as-you-go (PAYG) solar systems served by lithium battery packs and stand-alone small solar systems with behind the meter energy storage or off-grid micro-grids are very popular in Kenyan rural areas [14, 15].

The world over, RES uptake for electricity generation has seen substantial growth. In 2011, for example, the share of RES in the world's electric power energy mix was estimated at 11%, a figure that was projected to grow to 35% by 2035 [16].RES – including solar, wind, hydro, geothermal, tidal and biomass energies – occur naturally and replenish over time and cannot be exhausted like fossil fuels, unless by some change in the natural order [17]. On top of this, RES exploitation generates limited greenhouse gas emissions. Further, RES are characterized by intermittency (output variability and uncertainty), non-synchronicity, location dependence and generation that is generally/inherently distributed [18, 19, 20].

While there has been a lot of exploitation of legacy RES such as hydro and geothermal, variable RES (solar and wind) are getting traction due to advancements in their technologies that have pushed the levelized cost of electricity (LCOE)to 0.26-0.71 USD/KWh for solar [21] and 0.06-

0.17 USD/KWh for wind [22]. Also, there is a significant reduction in equipment costs, costs that were very high only a few years ago, an example being that solar panels' prices have fallen to as low as 0.57 USD/Watt [21]. Despite this, network constraints and system curtailments have been an issue in grand RES integration, necessitating innovation and changes in approach by having RES generation take on a more distributed arrangement forming micro and mini-grids such as rooftop solar, small-scale hydro and small wind generators with behind the meter energy storage [9, 19].

The capture of energy produced at one time – often when energy is produced in excess – for later use (that is, energy storage**)** is crucial if we are to integrate high levels of variable RES and keep the gains in efficiency and cost reductions made in solar and wind so far [23]. In leveraging their capacity value and dispatch flexibility by stacking outage mitigation, capital deferral, grid support and a better end user experience, storage can have a lower lifetime cost than legacy peaking sources like diesel fired plants despite it having larger capital costs [24, 25]. These stacked services can be grouped and detailed as follows [26]: operating reserves and ancillary services, RES curtailment mitigation, arbitrage, load leveling, transmission services (such as relieving transmission congestion, deferring transmission upgrades) and distribution services (such as reduced distribution losses, distribution voltage support and deferrals in distribution network upgrades).

GSES is attracting significant attention in the electrical power investment sector. Currently, more than 95% of grid scale energy storage is pumped hydro [27]. Battery energy storage systems (BESS) as an option has been limited by a number of factors: high costs on both kW and KWh basis, less than desirable charge and discharge rates, life cycle limitations and unstable (unsafe) cell chemistries. However, companies such as Tesla Motors and Panasonic have advanced lithium-ion battery technology so that as at 2016, 97% of grid scale battery storage was Li-ion [25]. Further, due to the interdependence between battery storage and variable RES, decline in costs in battery storage and development has mimicked that of solar in the past decade. In addition, electric vehicles [EVs] with their large battery packs are also expected to play a major role in GSES and grid dynamics in the coming decade.

In [28, 29], an investigation was done on the potential size of the electrical energy storage market in the US, the impact of RES on various grids across the US, and how cheap storage had to be to compete with traditional peaking capacity resources such as gas turbines. Further investigation was done [30] with the aim of understanding the potential operational benefits that could come from achieving energy storage targets in California. In an Indian national study [31], a team of researchers developed a tool to simulate various dispatch characteristics and operational procedures (mostly scheduling) with the aim of meeting India's RES integration goals. Numerous studies in RES and GSES indicate that these are the future systems of the grid and warrant further research.

1.2: Problem Statement

Due to their little or no marginal costs, falling capital costs and support from both the private and public sectors, RES continues to dominate the energy conversation in Kenya and on the world stage, with an estimated 19.5% of the global energy share as at 2016 and Kenya being on 11% stochastic renewables as at 2020 [32]. This proliferation can be expected to continue decades ahead [16]. Indeed, it can be even more expected in societies with energy access deficits such as Kenya [14]. Coupled with this growth in RES, has been growth in electrical vehicle (EV) market as well as growth and cost reductions in GSES, particularly BESS [25]. Kenya is also experiencing uptake of e-mobility with hybrid vehicles taking over the market and also the BasiGo project that was recently launched, opening the floor for future ventures in the public EV-transport sector [33].

RES is characterized by intermittency (output variability and uncertainty), non-synchronicity, location dependence and generation that is generally/inherently distributed [19] and this possess challenges in high-level integration the same in a grid. Some of the challenges include but are not limited to: power system instability due to non-synchronicity, short to long term system power imbalances (supply not matching demand) due to variability, problems in dispatch planning since RES is variable, RES is also unavailable to ramp up utilization since it is often small in capacity and also stochastic. Further, due to their location constraints, long transmission lines lead to inefficiencies in power transfer to load centers. Most of these challenges are overcome when RES is interfaced with storage.

Electricity infrastructure in Kenya is aging, and experiences frequent cases of transmission line congestion. There is also the common case of deploying expensive traditional peaking capacity resources such as gas turbines and diesel generators during times of peak load [34, 35]. The potential for capacity credit service provision from BESS, entailing drawing cheap off-peak power from RES and discharging the same during peak hours, has not been adequately explored.

Significant resources have thus been used to upgrade transmission facilities and fuel thermal power plants, costs that are ultimately transferred to consumers.

There have been limited studies on GSES' impact on the grid, particularly grids integrated with RES such as the Kenyan grid and how GSES changes the load profile of such grids [28]. There is limited knowledge base regarding interactions between storage and renewable energy integrated power grids. The benefits that GSES provide – transmission congestion relief, arbitrage, peaking capacity, etc. – need further investigation. The limited knowledge base is exemplified in cases where policy makers have had to curtail investment in RES and GSES, resulting in delayed policy development. On top of that, investors shy away from unregulated markets, leading to a lag in critical investments [36, 37]; currently, Kenya does not have regulations in place for GSES. Furthermore, system planners and investors in Kenya do not have the necessary knowledge to work with regarding where to best place such storage facilities and RES for optimal system performance and good Return on Investment (ROI). General knowledge exists on placement such as is provided in [38]; however, the uniqueness of the Kenyan grid and its dynamics make further studies crucial to integration of RES and GSES.

1.3: Objectives

1.3.1: Main Objective

To evaluate arbitrage and peaking capacity services provision by a Li-Ion BESS grid scale energy storage system in a power grid integrated with renewable energy (RE).

1.3.2: Specific Objectives

i) To analyze the dispatch characteristics of a power grid integrated with RE generation.
ii) To assess candidate grid locations for installing a grid-scale Li-Ion BESS and develop an algorithm for placement in the Kenyan Grid.
iii) To evaluate grid-scale storage services by a Li-Ion BESS focusing on arbitrage and peaking capacity service provision at the chosen grid locations.
iv) Validation by way of comparative analysis of the grid as is (without storage) and a grid model with GSES in the form of a Li-Ion BESS.

1.4: Research Questions

i) What are the dispatch characteristics of a grid that is highly integrated with RES such as the Kenyan grid?

ii) What are the candidate placement locations for GSES on the Kenyan Grid and can we develop an adaptable algorithm for placement based on the strength of benefits such locations offer?

iii) Is arbitrage and peaking capacity service provision practical (cost-benefit analysis) using Li-Ion BESS technology on a grid that is integrated with RES? What other benefits can the BESS offer to such a grid on the candidate locations?

1.5: Justification

The grid is evolving as we know it today and the world is tending towards RES. Studies show GSES is key to grand RES integration, there is also general knowledge on the benefits of GSES and its placement. While we have an understanding of the technical and economic limits of RES integration, such an understanding is limited with GSES. This study aims to deepen knowledge on the potential benefits of GSES. The study will also equip policy makers, regulators and investors on the technical and economic limits of GSES and also the interaction between GSES and grids integrated with RES. More importantly the study will provide specific knowledge on where to optimally place grid-scale BESS for least disruption to the grid while reaping all the socio-economic benefits it provides.

1.6: Scope of Study

During the course of the study, analysis was done on the dispatch characteristics in the Kenyan Grid and modelling done on it including all the major RES generations. In addition, modelling was also done on Lithium-ion battery energy storage systems including aspects such as state of charge, cycle life and depth of discharge. By using these models to modify an IEEE 14-Bus test bus system, aspects such as voltage, frequency and energy were analyzed using the simulation tool known as DigSilent Power Factory and from said analysis a cost benefit analysis was done on injecting or placing Lithium BESS on the Kenyan grid at various points focusing on arbitrage and peaking capacity.

1.7: Thesis Organization

The thesis is organized in the following broad sections; Chapter 1, is Introduction: where an overview of what the study intended to achieve is provided and the reader gains an understanding of why the said study is necessary. Chapter 2 is Literature Review, which forms the body of the report and reviewed works that had been done on the field with an aim of identifying gaps in said works; and also laying grounds for the study and work. Chapter 3 is Methodology where materials and the systematic way in which the study achieved its objectives is provided. After methodology, the results of the work are shown and validation of the same done in the Results and Discussion section. Finally, the Conclusion and Recommendations of the study are given in the last chapter of the work.

Chapter 2: Literature Review

2.1: Introduction

The merits of RES outweigh its demerits on a balance of scales [39]; cheap, renewable, low carbon footprint (essentially clean) are the whys behind its proliferation. Chief among limitations presented by RES harvesting and the reason why market domination has been elusive, is its intermittent and unpredictable nature. Observations have however led to the **duck curve** that characterizes RES, Figure 2.1; where energy production is more during off peak consumption and rolls off during peak demand [40]. Storage has been proposed and is being implemented as a solution to this problem; a good example is the Tesla battery storage facility in Australia [41].

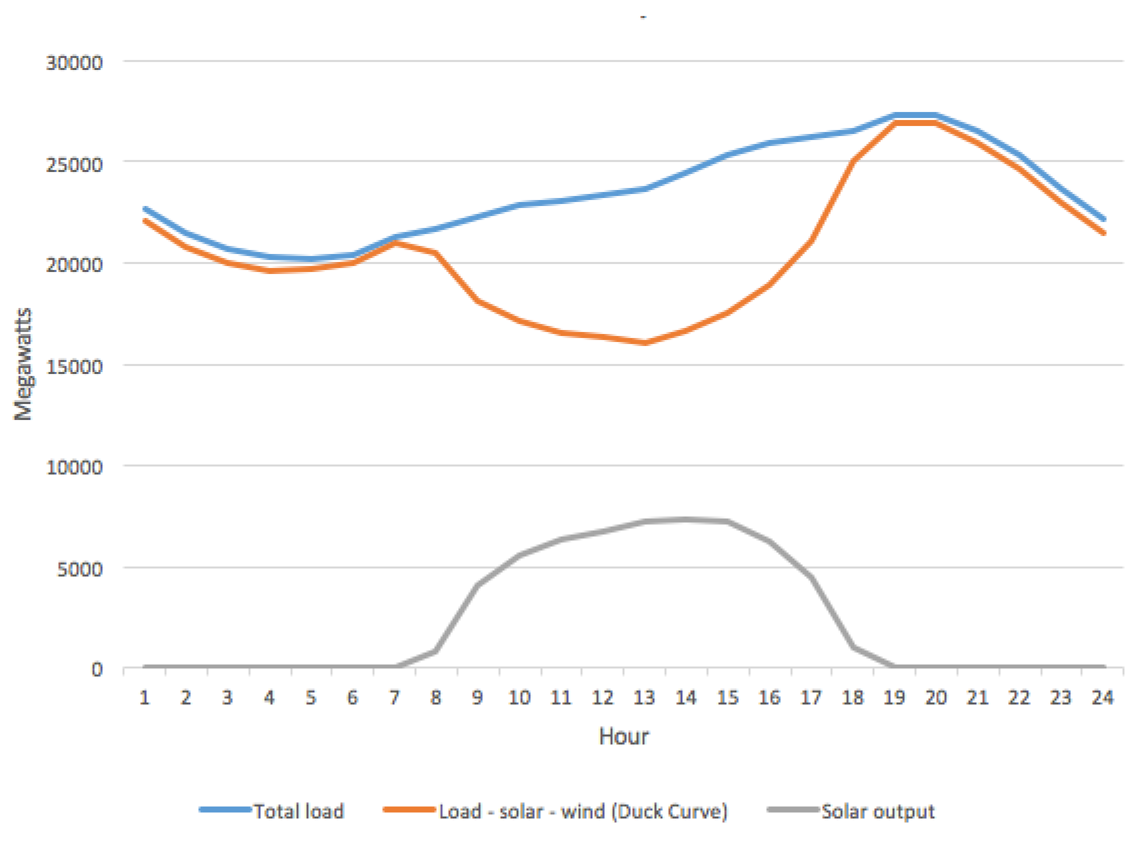

Figure 2. 1: The Duck Curve (Sample Hourly Electricity Load vs. Solar Production) [40]

As cheap as it is, easy to transmit and use, like any other commodity, electric energy can be wasted if proper care is not taken to preserve it when consumption is not possible, one conservation method is the use of storage. Low-cost storage has benefitted the consumer electronic industry and EV industry to mention a few and the new frontier is the electric power industry [42] where it is projected to add resiliency and flexibility as it can be used at all levels of the power system [43] as shown in Figure 2.2 where we see the new grid configuration with ESS as a component linked to all dimensions in the grid and providing services to all of them (see section 2.2.3 for said services). Numerous storage options each with its own perks and peculiarities exist and what follows is a discussion on them.

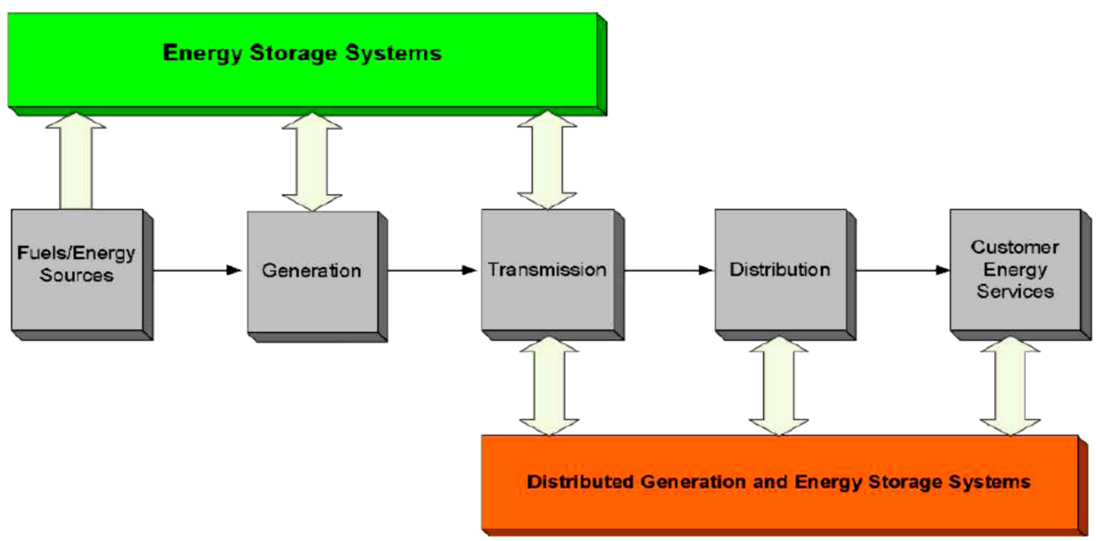

Figure 2. 2: Energy Storage Systems as a Component in the "Neo-Grid" [42]

2.2: Fundamentals of Energy Storage

2.2.1: The Basic Electrical Energy Storage Cycle

Energy storage is basically the harvesting of available energy for use at a later time. It involves energy conversion from one medium to another and back to the original or otherwise for utilization. From [44], P. Medina et al zoom in on electrical energy storage (EES) and define it as a process that converts electrical energy via an energy conversion device (ECD) such as a pump (motor) to another form such as mechanical energy or thermal energy; the electrical power could be sourced from a single source or a power network such as the grid. Figure 2.3 shows their representation of the EES cycle.

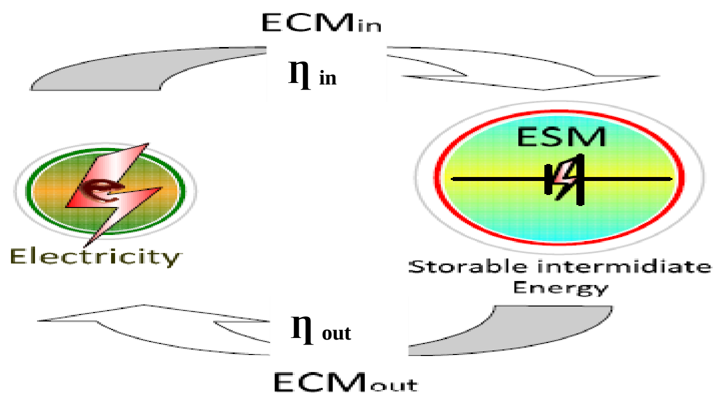

Figure 2. 3: *The Basic Electrical Energy Storage (EES) Cycle [43]*

From the definition of EES, for it to work and for the cycle to be completed; an EES system has to have [45, 51]:

An energy conversion device/module (ECD)/ (ECM); a device which transforms the available energy to a form that can be stored or from the stored form to a form that can be utilized and usually involves conditioning on top of conversion so that no harm comes to the storage equipment or to the consumer equipment. A good example of a conversion device is the **inverter** that converts DC current from a battery to AC current for utility in AC powered devices. This component of the EES system accounts for between one third and 50% of the overall cost of the system [45] and thus present good opportunities for marginal cost cutting in said systems.

An energy storage medium (ESM); this component encompasses the storage devices such as batteries and the forms of energy that the stored energy exists in, an example being chemical or mechanical forms or the energy capturing substance such as compressed air or pumped heat.

A balance of plant (BOP) component or components; which includes all the supplementary systems that are auxiliary to the other two components of an EES system and play a support role to the system. That said; without BOP components the system cannot operate and includes things such as racking equipment, connecting wires, protection equipment, site facilities etc. Since every facility is unique in its operation, size and specification, the requirement for BOP is very diverse and thus costs for the same can vary widely from system to system and facility to facility [46]. Costs such as administrative costs, licensing costs, maintenance and stuff are also part of BOP and further add to its diversity [47].

Focus has been on cost reductions in ESM to make EES cheap but considering how much the other two components contribute to the final costs of said systems and how little in the ways of research and funding that goes in cost cutting initiatives in the other two [48]; more can be done.

2.2.2: Energy Storage Technologies Overview

Historically and even currently the technology that has dominated GSES with upwards of 90% market share has been Pumped Hydro Storage (PHS) [27]. PHS together with Lead-Acid battery technology enjoy wide market adoption by virtue of them being what would be described as mature technologies [49] i.e., they have been in existence for more than a century and their development has largely stagnated while others such as Metal-air batteries are still in their infancy. Figure 2.4 shows Hussein Ibrahim and Adrian Ilinca's developmental chart of storage technologies [45]

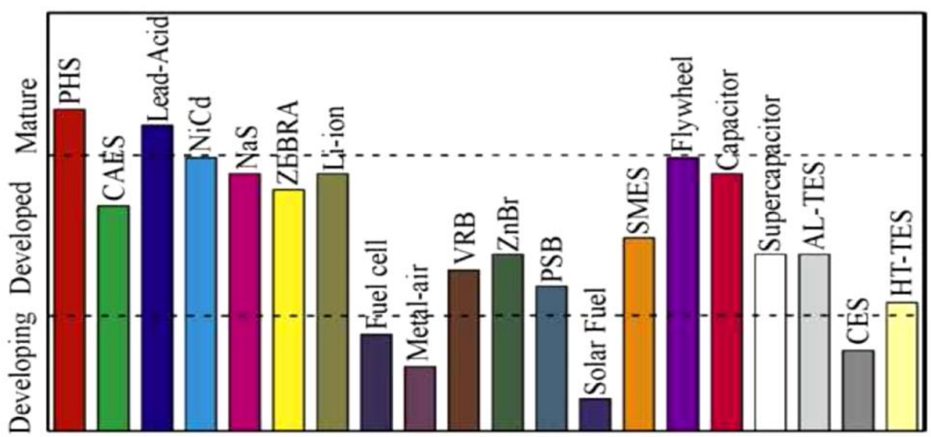

Figure 2. 4: *Development Status Chart for EES Systems [44]*

By convention, energy storage systems or technologies are classified by the form of energy they store as shown in Figure 2.5. This classification will not however be the basis on which we discuss the various technologies and discussions will be almost entirely individualistic.

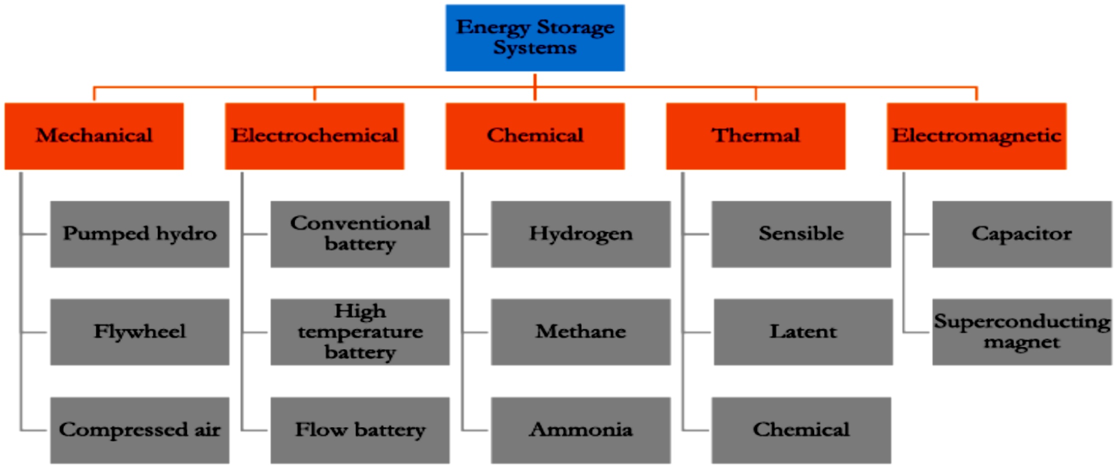

Figure 2. 5: EES Storage Systems Classification with Select Examples [50]

While classification as portrayed in Figure 2.5 is the one that is widely adopted, others exist but are often absorbed in what is called **storage evaluation factors**; for example, Canan Acar's classification based on power ratings in [50]. Some like in [49] classify them according to their function as seen in Figure 2.6, where **power quality and reliability** entails the maintenance of clean waveforms in the system where we have to maintain voltage and frequency within certain ranges and also eliminate harmonics and power outages while **energy management** (matching demand and supply) involves the proper utilization of energy resources so that energy is available when needed and at an economically viable pricing by storing it in times of excess production and releasing the same when demand has increased.

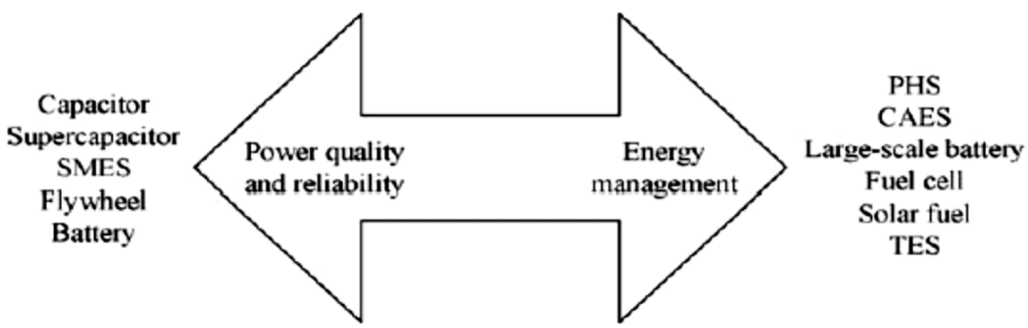

Figure 2. 6: Energy Storage Classification by Function [49]

2.2.2.1: Pumped-Hydro Storage (PHS)

This storage technique centers on the utilization of potential energy to generate electricity and the recycling of excess generated energy to store up potential energy for later electrical energy generation. It involves the movement of large quantities of water to achieve this fete through electro-mechanical devices such as pumps and turbines in the configuration shown in Figure 2.7.

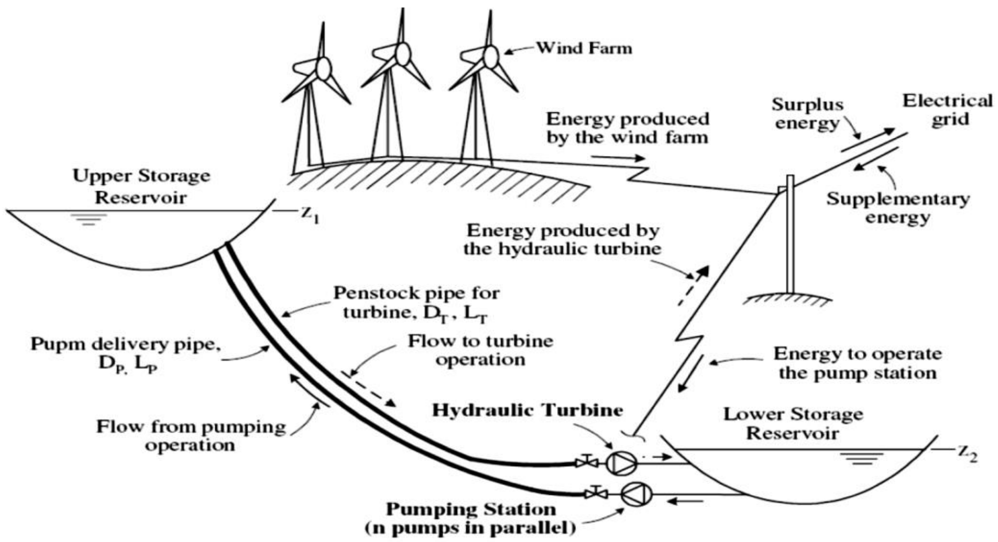

Figure 2. 7: PHS Typical Configuration [44]

The kW value of such a plant is dependent on the rate of flow of water and the head while its kWh value is a function of the volumetric capacity of the reservoir and the head [51]. That is to say if one wanted to improve the energy potential of the plant one would have to either increase the volume of the reservoir or increase the hydraulic head. The latter is usually preferred due to cost considerations.

The power capacity of a PHS system is given by [52]:

$$P_c = \eta \rho H Q g \qquad (2.1)$$

Where: P_c is the Wattage in Watts, η is efficiency of the system, P is the density of water, H is the actual hydraulic head, Q is the rate of flow and g is gravitational acceleration.
It is important to note that typical plants have H as 300m [53] and efficiencies of about 77% [54], limited by electromechanical efficiency of the pump unit(s) and the turbine when generating [55].

Being one of the most matured technologies, there are about 250 PHS sites across the globe with an estimated generation capacity of about 100 GW [55] with capacities ranging from as low as <3MW in the Greek Island of Ikaria to much larger facilities such as the Bath Country facility in the USA with >3000 MW [56]. While the majority of PHS facilities use fresh water due to the corrosive nature of salty sea water, some do use see water to achieve GSES [57]. Alternate arrangements of the PHS have been proposed such as Underground-PHS to overcome the site abundance limitation posed to the establishment of PHS. With all other factors held constant an UPHS facility has its lower reservoir dug below ground level for the development of head.

2.2.2.2: Battery Energy Storage Systems (BESS)

Unlike the previous system which uses electromechanical means to achieve storage; batteries are electro-chemical in nature, using chemical processes (reactions) they are able to store energy within themselves or give off electrical energy to an external circuit [58].

Various battery technologies exist but all work on the principle described above; some more advanced (mature) than others such as Lead-Acid (Pb-Acid) technology that has been around for more 100 years [49] and Lithium Ion (Li-ion) battery technology that is receiving most of the attention and has a lot invested in R&D [25]; Others such as Zinc-Bromide [Zn-Br] battery technology are relative new comers to the space [50].

While non-rechargeable (primary) batteries are useful in other applications, only rechargeable batteries are used in GSES for obvious reasons. Favored by their flexibility and high power (in some cases) and high energy densities (in most cases) they are a prime candidate for GSES and these were the primary reasons why this thesis was based on BESS. More detailed discussions on BESS can be found under Section 2.3 of this thesis.

2.2.2.3: Compressed Air Energy Storage (CAES)

By utilizing excess generation to power drive trains that are coupled to a compressor, air is pressurized into caves (usually underground); good examples being abandoned mines and salt caverns and later when power is needed the compressed air is used to drive turbines that generate electricity. Figure 2.8 shows the schematic of a CAES facility [59].

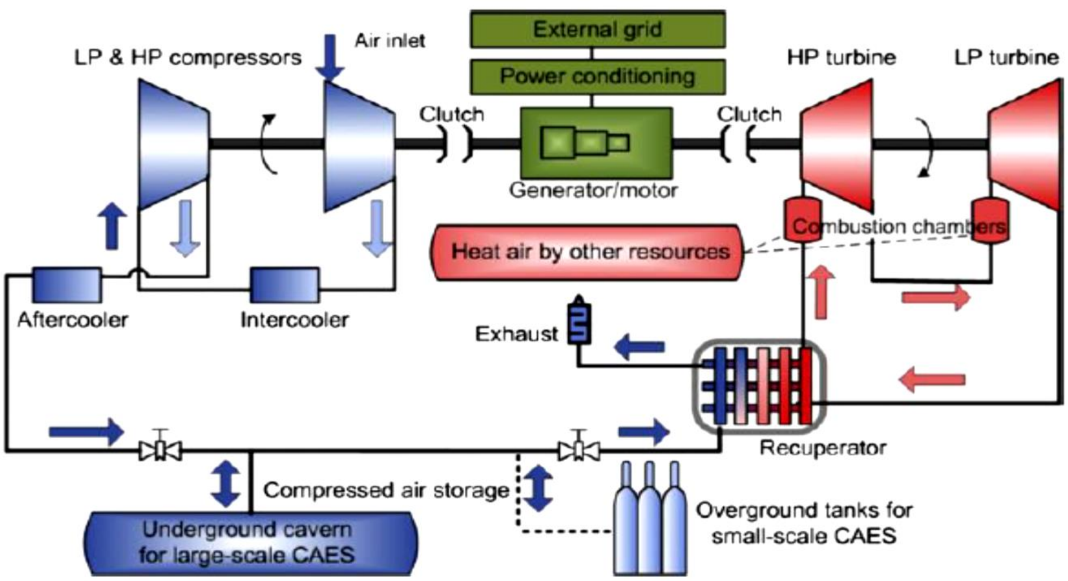

Figure 2. 8: *CAES Facility Schematic [59]*

Despite being a relatively mature technology with minimal capital investment requirements and able to store large amounts of energy, there are less than 5 operational CAES facilities around the globe [60]; the major limiting factor being it requires existing geological features for installation. An example of a running CAES facility is the Huntorf plant in North German with 290 MW.

2.2.2.4: Supercapacitor Energy Storage (SCES)

Like all capacitors, ultra-capacitors or supercapacitors are constructed using a dielectric separating two plates that are parallel to each other. How they differ from other capacitors is in the separation distance of their plates usually in the sub-nanometer order [61] and the having a special dielectric usually of the liquid-electrolyte type [62]. This special construction enables ultra-capacitors to be tightly packed and hence have high capacitances and by extension a higher energy storage capacity than conventional capacitors. Typical values for power and energy densities are 10,000 W/Kg and 5 Wh/Kg respectively [61]. By separating electric charges at the plates in a supercapacitor (UCAP in Figure 2.9 which is the plant representation), an electric field is induced that is able to store electric energy leading to them being referred as direct storage devices.

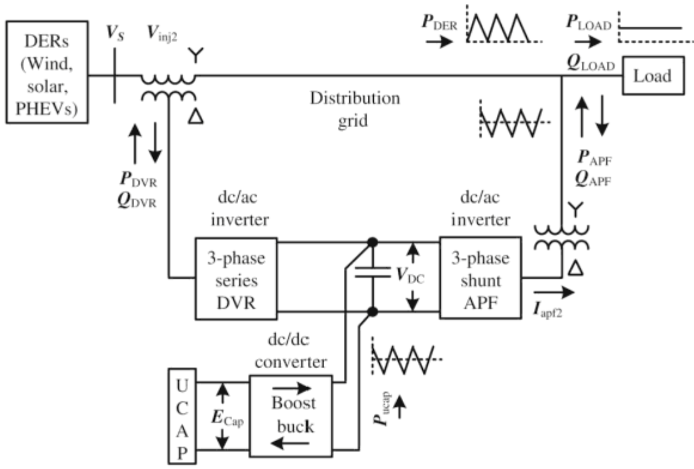

Figure 2. 9: *Simplified Supercapacitor Plant Representation [56]*

The capacitance of a capacitor and the energy stored within are given by the following equations:

$$C = \varepsilon_o \varepsilon_r \frac{A}{d} \tag{2.2}$$

$$E = \frac{1}{2} CV^2 \tag{2.3}$$

Where C is the capacitance, A is the area of the plates, d is the separation distance of the plates, ε_o is the permittivity of free space, ε_r is the relative permittivity of the dielectric material, V is the voltage across the plates and E is the energy stored.

Limited by field strength of the dielectric, super capacitors have efficiencies of up to 98% although they are also haunted by self-discharge, some losing even 15% of their rated capacities per month [63].

Favored by quick charge and discharge rates –hence able to produce short quick power bursts- in deep discharge cycles (0-100 even) at relatively low degradation levels [63]; ultra-capacitors have found applications in the UPS and EV industries. They are particularly useful when it comes to re-gen (regenerative braking) technologies in EVs.

2.2.2.5: Superconducting Magnetic Energy Storage (SMES)

The basic premise of this technology is that current in a superconductor will continue to flow even after the e.m.f. source is disconnected. By driving the temperature of a coil made of a superconducting material below the material's critical temperature {usually 0K to 7K for low temperature ones and 100±10K for high temperature ones [51]}, and driving a current through the coil that has now achieved negligible resistance; an energy storing magnetic field is generated [64]. The stored energy can then be released by discharge through a power conditioning system (PCS) on demand.

Figure 2.10 is a representation of an SMES system with the following main components; a PCS, the superconducting coil and a cooling system that significantly increases the cost of the system.

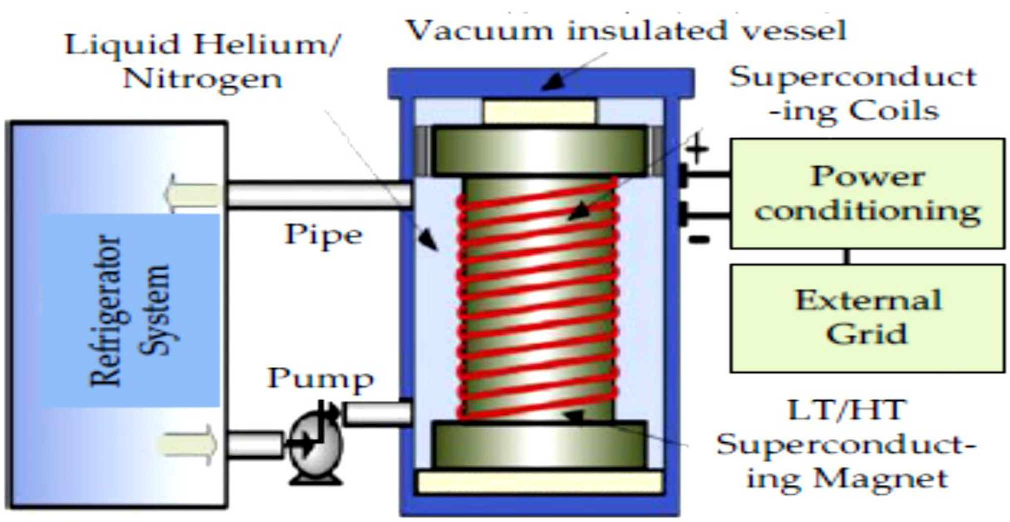

Figure 2. 10: *SMES System Schematic [59]*

With efficiencies close to 100% [65] since storage is direct and with only parasitic losses due to the refrigerator system, the energy stored in a SMES system is given by:

$$E = \frac{1}{2} LI^2 \quad (2.4)$$

Where E is stored energy in joules, L is the coil inductance and I is the current through the coil.

Like the SCES system, the SMES systems also a direct storage technology, are favored by long life spans (>20 years) [51], even with deep discharges since degradation is very minimal as it cycles, by extremely fast charge and discharge rates and by high efficiencies. The technology is however expensive and very sensitive to temperature variations.

2.2.2.6: Fly-wheel Energy Storage (FES)

When engineered to have as little frictional losses as possible – housed in a vacuum environment and being suspended by magnetic bearings – a simple rotating object can be utilized for the purpose of storing mechanical kinetic energy [66]; this is what a flywheel is. By accelerating a disc shaped mass using a motor, energy is stored up in the disc and when roles are reversed and energy is required from the system the motor becomes a generator and the disc decelerates. Figure 2.11 shows the schematic of a FES system.

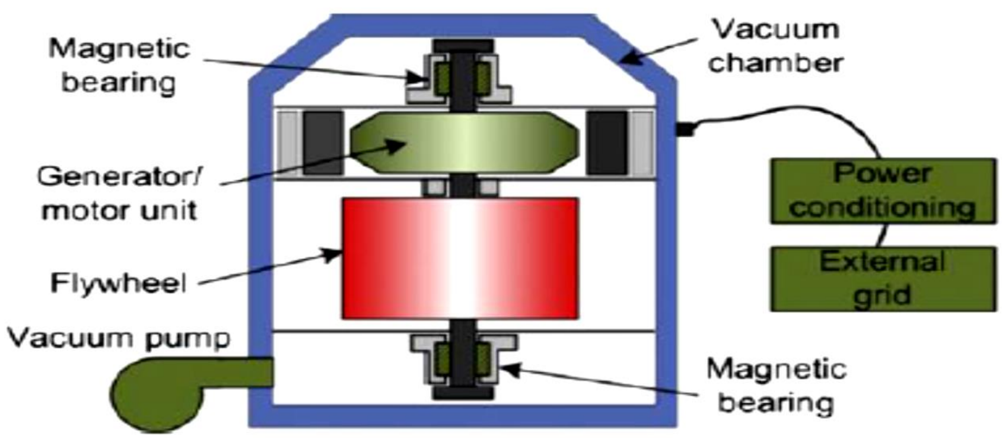

Figure 2. 11: FES System Schematic [55]

With medium to short term efficiencies of about 80% [67] and initial charge to discharge ratios of 1:1 hence efficiency values as high as 95% due to its mechanical nature [68], the energy stored within an FES system is given by:

$$E = \frac{1}{2} I\omega^2 \quad (2.5)$$

where $I = \frac{1}{2} mr^2$ (2.6)

hence $E = \frac{1}{4} m(r\omega)^2$ (2.7)

Where I is the moment of inertia, ω is the angular velocity, m is the mass and r is the radius of the disc. This implies that increasing the angular velocity of the disc is a better prospect to increasing its energy storage capability than increasing its mass. It is common to have rotational speeds of 6,000 RPM to even 50,000 RPM [69].

Since they have fast response times, high short-term efficiencies and very high full-cycle counts; they are have found applications in the UPS industry with an estimated 20% market share [51]. The technology is however not feasible for long-term energy storage since efficiencies deteriorate to unacceptable figures even after a day of storage, below 50% efficiency is not uncommon [45]. It is also important to note that due to speed variations as the disc decelerates the output of a FES system which is usually AC, has to be first converted to DC then back to AC to meet system requirements.

2.2.2.7: Fuel Cell Energy Storage (FCES)

Sometimes called **Hydrogen Energy Storage (HES)** since most if not all of the fuel cells have hydrogen as the main chemical energy source. Fuel cell technology uses chemical reactions to produce oxygen, much like batteries, although unlike in batteries the chemicals in a fuel cell are used up in the reaction and more have to be generated for it to work [70, 71].

A FCES system consists of:

- Hydrogen generator as a source of the hydrogen fuel and can either be by methanation (reacting steam and methane), electrolysis (preferred since it uses off-peak electricity) or by extraction from fossil fuels.
- A fuel cell that is made up of an anode and a cathode separated by an electrolyte.

- Hydrogen storage facilities; hydrogen can either be stored as liquefied hydrogen, as a metal hydride or in compressed form usually at about 5000 psi [45].

Figure 2.12 shows an illustration of a FCES system.

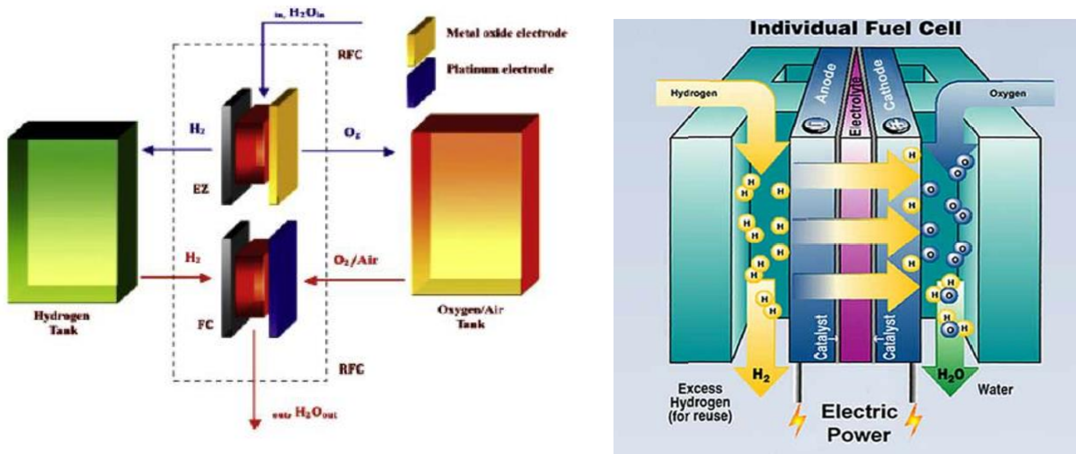

Figure 2. 12: *FCES System with a Snapshot of the Fuel Cell [56, 51]*

Their small size, reliability, lack of moving parts, flexibility and zero carbon footprint means the technology has a future. The technology is still in its infancy and quite costly, it is also plagued by low combined efficiency, typically 30-40% [51, 72].

2.2.2.8: Thermal Energy Storage (TES)

In this storage technique, off-peak or RES electricity is converted to thermal energy (heat or cold) stored as latent heat, sensible heat or chemicals which react in thermo-chemical processes to release heat (exothermic processes) or take heat (endothermic processes) [72]. This stored heat or cold is later utilized in heat engines to generate electricity.

When storing sensible heat, water is usually heated and stored in underground thermally insulated tanks. Chosen for its specific heat property, abundance and ease of handling, water is not the only storage medium that is used for the purposes of sensible heat storage; other media include soil and rocks. Sensible heat storage has obvious limitations such as variable thermal outputs and relatively low energy storage densities [73]. Higher densities can be obtained from latent heat releasing processes such as the phase changes usually of the solid to solid or solid to liquid type. But for significant energy storage densities, chemical heat storage is the go-to-choice.

Generally, TES systems are classified into low-temperature TES (<25^{0}C) or high-temperature TES (>25^{0}C) [45]. Figure 2.13 shows a representation of a TES system.

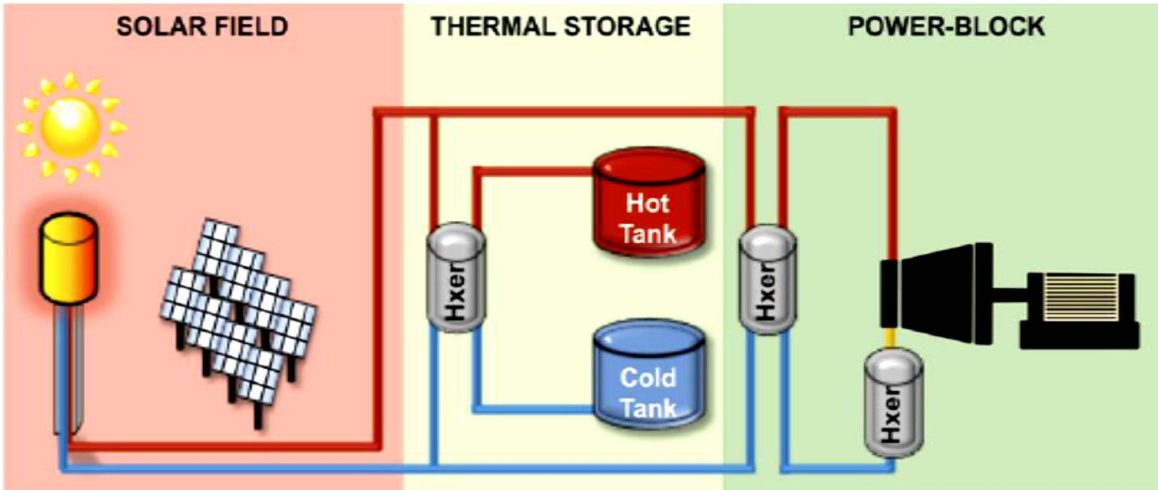

Figure 2. 13: TES System Example [74]

2.2.2.9: Others

These include **metal air** storage and the relative new comer (to energy storage) **Electric Vehicles** (EVs) that offer adoptive and smart charging and discharging for backup and grid support.

2.2.2.10: Hybrid EES

Hybrid ESS comprises of non-homogeneous EES, that is, EES systems that are not of the same kind but are combined to serve the same function. For example, Li-Ion batteries are combined with Super-capacitors in the EV industry where Super-capacitors are useful in re-gen and quick acceleration while the Li-Ion batteries are utilized for range extension due to their high energy density [119].

It is important to note that any number of EES systems can be combined to for a hybrid EES system provided the combination is stable and are feasible from both a utility point of view i.e., their useful combination makes sense and economic aspect. Most, if not all Hybrid ESS make use of a controller to coordinate between the heterogeneous systems; controlling their replenishing and exploitation to ensure safety, sustainability and stability. Lastly, Hybrid ESS favors fully disposable systems for ease of maintenance and overall simplicity of the system [119].

Table 2. 1: Snapshot of World GSES Projects Excluding PHES [75]

	NUMBER OF PROJECTS BY REGION					Installed Capacity	
EES Technologies	North America	West Europe	Asia Pacific	RoW	Global	Global MW	% Total
CAES	1	1	0	0	2	400	33.9%
NaS BESS	8	3	171	0	182	316	26.8%
Molten Salt TESS	0	3	0	0	3	150	12.7%
Flow BESS	11	2	19	1	33	89	7.5%
Lead Acid BESS	19	1	0	0	20	75	6.4%
Lithium Ion BESS	6	1	5	2	14	49	4.2%
Fly Wheels FESS	1	0	1	0	2	40	3.4%
New PHES	0	0	1	0	1	30	2.5%
NiCd BESS	1	0	0	1	2	26	2.2%
Thermal TESS	68	4	9	1	82	3	0.3%
Hydrogen HESS	2	2	0	0	4	1	0.1%
Lead/Carbon BESS	0	0	1	0	1	0	0.0%
Superconductor	0	0	0	0	0	0	0.0%
Total (excluding PHES)	117	17	207	5	346	1179	100.00%
PHES (as at 2013)					about 350	152,000	excluded

As seen in Table 2.1, the combined installed capacity of BESS is second only to PHES and while in the discussion above we had lumped all of BESS together, the differences in application and technicalities in the various BESS technologies warrant a deeper understanding, see Section 2.3 for more.

2.2.3: Applications and Benefits of Electrical Energy Storage

The fundamental idea of the grid is that power is provided where it is needed, as needed and when needed at an economically viable cost. The question would then be; how can storage (GSES) help to better facilitate this?

We had earlier seen that a grid integrated with RES has a characteristic load-demand curve that shows a mismatch between generation and load demand [40]; it is this **duck curve** that storage purposes to address. Figure 2.14 shows the effects storage has on the characteristic duck curve.

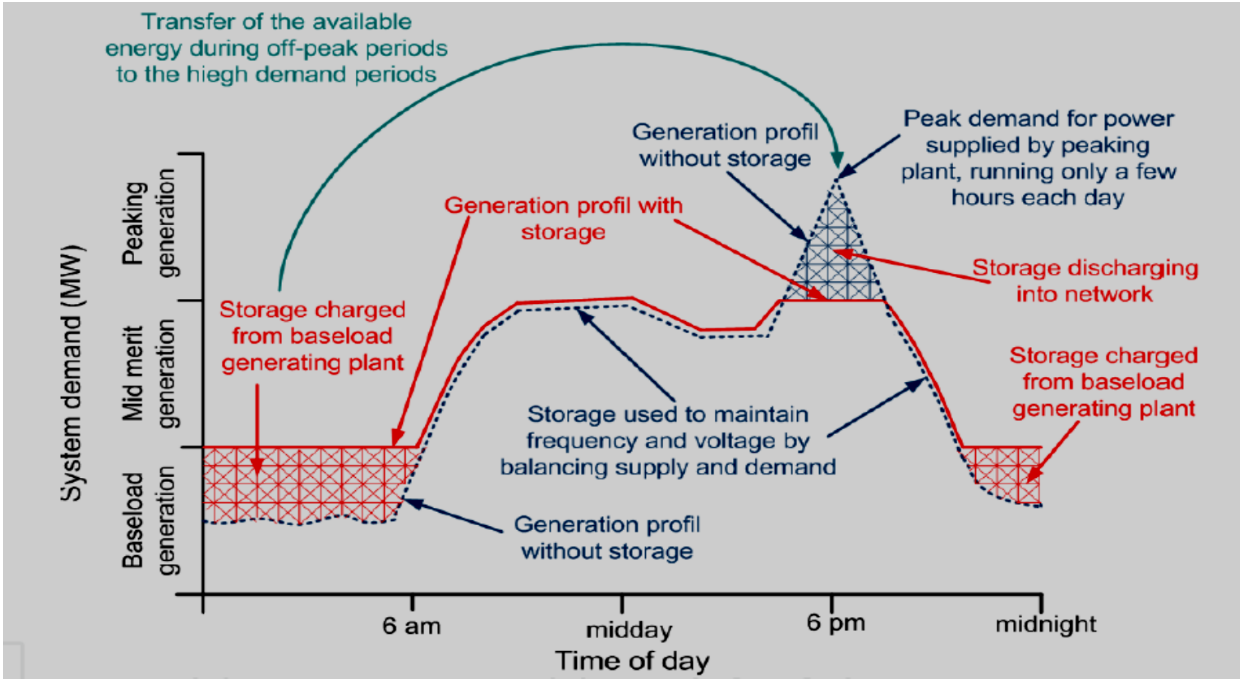

Figure 2. 14: Curve Showing the Effect of GSES on Generation Profile [76]

From the Figure 2.14 it is clear that storage acts to flatten the load demand curves in a power system. In so doing storage touches every facet of the grid and by its action; the numerous techno-economic benefits are realized. Value is created when one aims to solve a problem; Figure 2.15 tries to illustrate the problems that are most prominent at every dimension in a grid and how storage tries to solve said problem and hence the creation of value.

From the Figure 2.15 we can now see why Alaa Mohd et al in [78] describe Energy storage as the 6^{th} dimension in the electric grid value chain. A fact that is further emphasized when Linden S. in [79], depicts in Figure 2.16 the applications of storage in the grid and also shows in effect, where storage can be placed.

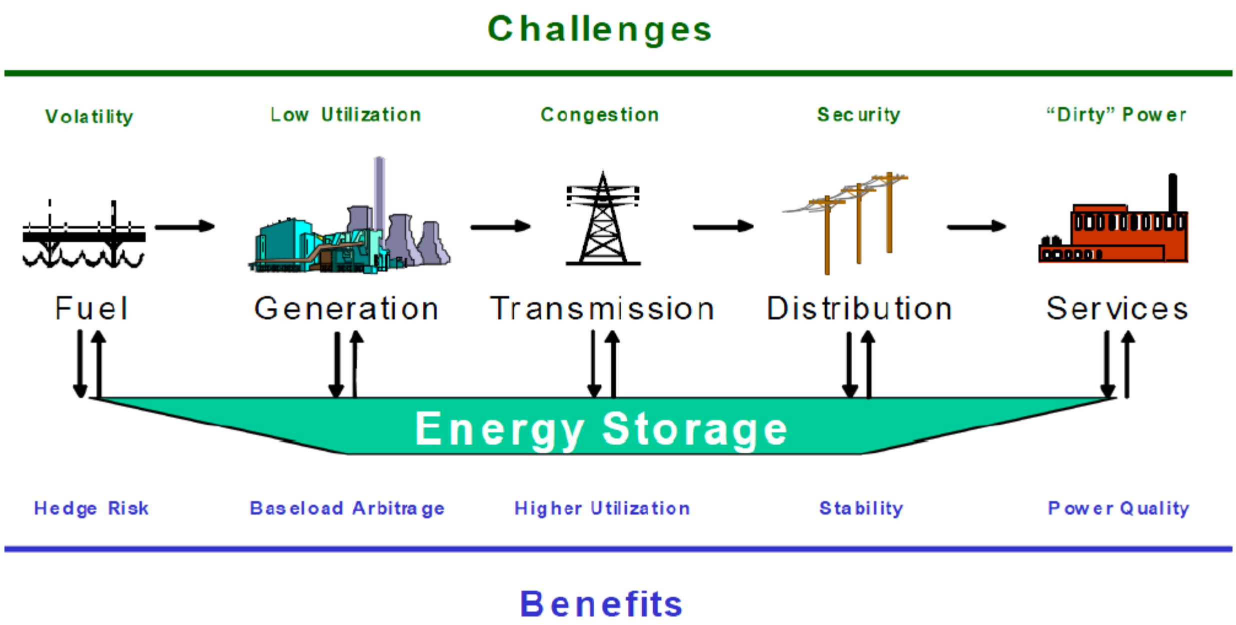

Figure 2. 15: *EES Contribution to the 5 Grid Dimensions [77]*

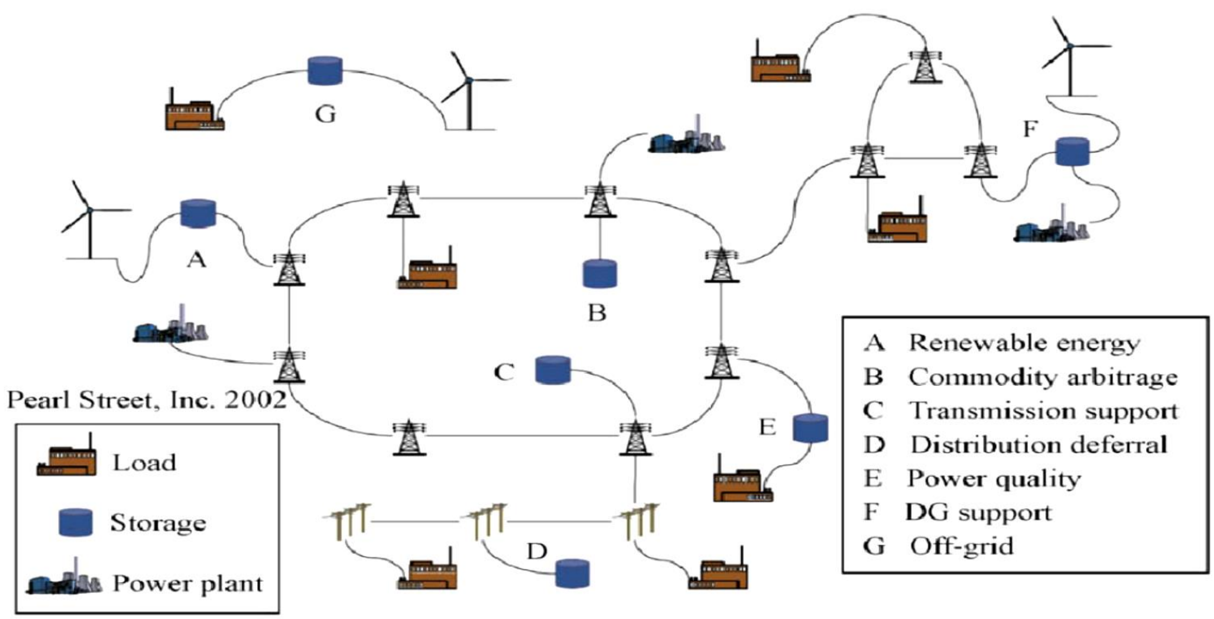

Figure 2. 16: *Linden’s Depiction of EES Applications in the Grid and GSES Placement [79]*

While depictions and graphs serve well in understanding the benefits and applications of EES; it is prudent to classify the services and benefits EES provides to the grid and also properly explain what these entail.

Xu X. et al in [15] classify the applications of GSES into 5 categories: Transmission services, Distribution services, Energy management services, Bulk energy services and Ancillary services. Figure 2.17 shows the classification.

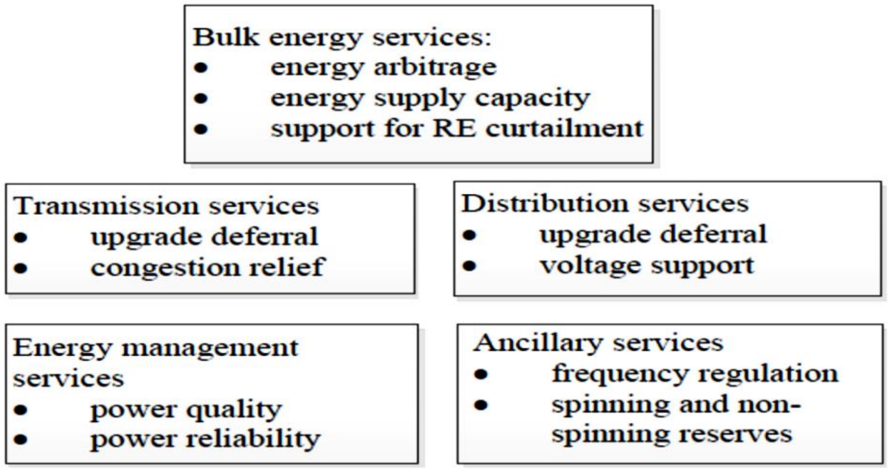

Figure 2. 17: *GSES Service Classification [15]*

While some services such as support for RE curtailment are self-explanatory; others require some explanation and that is what is provided in Table 2.2;

Table 2. 2: *GSES Applications [26]*

Application	Description	Duration of Service Provision
Arbitrage	Purchasing low-cost off-peak energy and selling it during periods of high prices.	Hours
Firm Capacity	Provide reliable capacity to meet peak system demand.	4+ hours
Operating Reserves		
• Primary Frequency Response	Very fast response to unpredictable variations in demand and generation.	Seconds
• Regulation	Fast response to random, unpredictable variations in demand and generation.	15 minutes to 1 hour
• Contingency Spinning	Fast response to a contingency such as a generator failure.	30 minutes to 2 hours
• Replacement/ Supplemental	Units brought online to replace spinning units.	Hours
• Ramping/Load Following	Follow longer-term (hourly) changes in electricity demand.	30 minutes to hours
Transmission and Distribution Replacement and Deferral	Reduce loading on T&D system during peak times.	Hours
Black-Start	Units brought online to start system after a system-wide failure (blackout).	Hours

A more detailed and perhaps a better description of the services provided by GSES can be found in P. Medina's et al [75] as shown in Table 2.3.

Table 2. 3: GSES and its Applications [75]

SIZE OF APPLICATION	EES TECHNOLOGIES → VS APPLICATIONS ↓			APPLICATIONS REQUIREMENTS: POWER RATING (MW)	APPLICATIONS REQUIREMENTS: DISCHARGE DURATION (Hrs)	APPLICATIONS REQUIREMENTS: RESPONSE TIME	1 PUMPED HYDRO-POWER ENERGY STORAGE (PHES)	2 COMPRESSED AIR ENERGY STORAGE (CAES)	3 SMALL-SCALE COMPRESED AIR ENERGY STORAGE (SSCAES)	5 HIDROGEN ENERGY STORAGE SYSTEM (HESS)	6 CHEMICAL STORAGE / BATTERIES ENERGY STORAGE (BESS)	7 FLOW BATTERIES ENERGY STORAGE (FBES)	8 FLYWHEELS ENERGY STORAGE SYSTEM (FESS)	9 SUPER-CAPACITORS ENERGY STORAGE (SCES)	10 SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES)
100s MW	ELECTRIC SUPPLY	UTILITY SYSTEM	Provide System Capacity-Resource Adequacy / Electric Supply Capacity / Baseload investment deferral	1 - 1000	4 - 6	Mins	●	●							
		ISO (Independent System Operator) MARKETS	Energy Price Arbitrage / Electric Energy Time-Shift / Renewable Energy Time-Shift / Load Leveling and Peak Shaving	10 - 1000	2 - 10	Mins	●	●		●	●	●			
	ANCILLARY SERVICES		Load following / Provide Spin & Non-Spin Reserves / Electric Supply Reserve Capacity / Conventional Spinning Reserve / Terciary Regulation (deployment time 15 - 30 minutes)	10 - 1000	2 - 4	Mins.	●	●	●	●	●	●			
			Provide Spin & Non-Spin Reserves / Electric Supply Reserve Capacity / Fast Response Spinning Reserve / Secondary Regulation (deployment time 2 - 10 minutes)	10- 1000	1 - 2	< 30 Secs	●	●	●	●	●	●			
			Provide Voltage & Frequency Regulation / Area Regulation / Primary Regulation (deployment time 15 - 30 seconds)	1 - 1000	15 - 30 Mins	Inmediate				●	●	●	●		●
			Provide Black-Start and Ramp / Power system Start - Up	100 - 1000	1 - 6	Secs	●	●		●	●	●			
10s MW	RENEWABLES INTEGRATION	UTILITY SYSTEM	Renewable Energy Integration (seasonal output shifting) / Renewable Capacity Firming / Renewables Back - Up	0.001 - 400	2 - 4	Mins	●	●	●	●	●	●			
			Renewable Energy Integration (daily output shifting) / Renewables Generation Grid Integration (long duration) / Load Leveling	0.2 - 400	1 - 6	Mins	●	●	●	●	●	●			
			Centralized Renewable Energy Integration (smoothing) / Renewables Generation Grid Integration (short duration) / Fluctuation Supression	0.2 - 400	10 Secs - 15 Mins	Secs - Mins		●	●	●	●	●	●	●	●
	GRID SYSTEM	TRANSMISSION	Transmission Congestion Relief / Defer Transmission Investment / Transmission Upgrade Deferral	0.25 - 100	2 - 6	Mins	●	●	●	●	●	●			
100s kW		DISTRIBUTION	Reduce Outage Frequency-Duration / Electric Service Reliability / Uninterrumpible Power Supply (UPS)	0.002 - 10	4 - 10	Secs - Mins			●	●	●	●	●		
			Defer Distribution Investment / Distribution Upgrade Deferral	0.25 - 10	2 - 6	Mins			●	●	●	●			
			Provide Voltage Support Grid Stabilization / Transmission Support / Voltage Control Support	10 - 100	> 15 Mins	< 1/4 cycle	●		●	●	●	●	●	●	●
10s kW	END-USER / UTILITY CUSTOMER	END-USER	Improve Power Reliability / Electric Service Reliability / UPS	0.002 - 10	5 Mins - 2	< 1/4 cycle				●	●	●	●	●	
			Improve Power Quality / Electric Service Power Quality / Transit and end-use ride-through / LVRT / Oscilation Damping	0.002 - 10	10 Secs - 15 Mins	< 1/4 cycle				●	●	●	●	●	●

In addition to describing the various applications, Table 2.3 also shows what storage technologies can suit particular applications. While we would like to adopt any available technology or perhaps the cheapest available technology there is to apply to the services we want to provide, it is not a randomized undertaking. Technologies have to be matched with the services they can provide. The question would then be how do we know what technology best suits a particular application?

The answer lies in asking what the requirements for the particular service we want to provide are as seen in column 4 of Table 2.3 and how we evaluate storage technologies to ascertain if they meet said requirements.

2.2.4: Energy Storage Evaluation Factors

Since the storage evaluation factors form the matrix on which we compare the various forms of storage and judge their capability to perform different purposes on a power system; in addition to defining the said evaluation factors; comparisons of the various storage technologies shall be done within each section and later a table of the most relevant factors or easily quantifiable factors shall be drawn up.

2.2.4.1: Storage Capacity

This is a measure of how much energy an EES system can hold, usually measured in MWh or in the case of batteries Ah. Some storage technologies can only store little amounts of energy such as supercapacitors while others such as PHS can store much larger amounts hence why it dominates GSES.

2.2.4.2: EES System Power

Defined as the maximum power output a system can provide starting as a full state of charge under normal operating condition. It is also known as the nameplate power or nominal power output. To compare these two parameters Figures 2.18 and 2.19 are used.

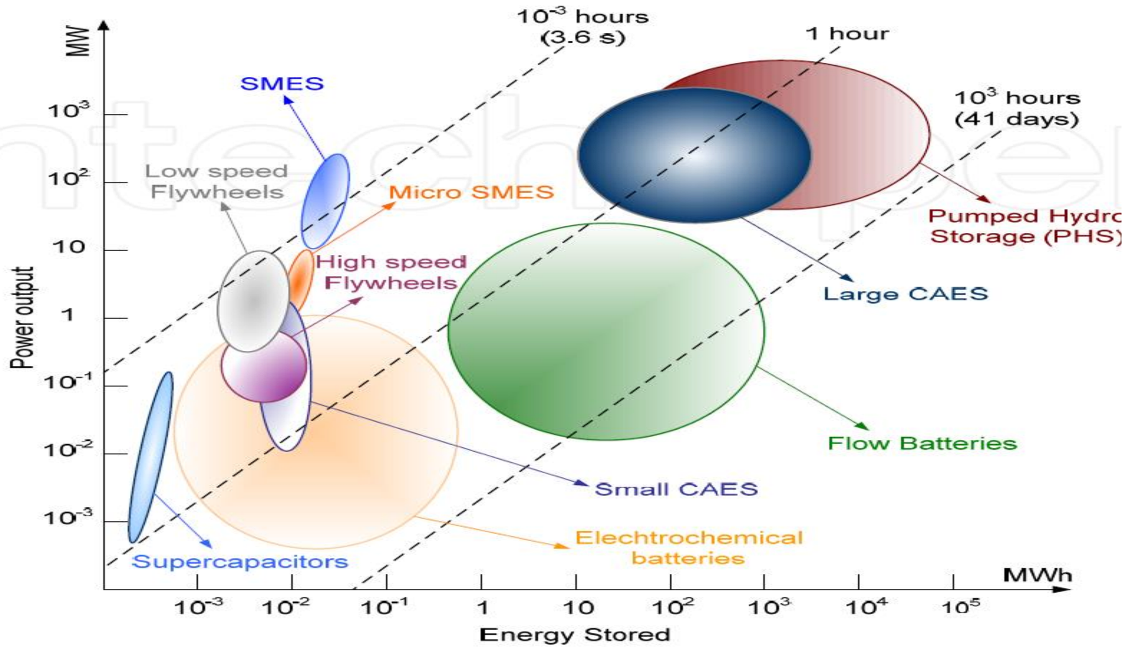

Figure 2. 18: *Graph of Power Output Against Energy Capacity for Different EES Systems [80]*

In [81] and [82], all the applications in section 2.2.3 can be grouped and organized around Energy Management, Power Quality and UPS and Bridging power; the ability of EES systems to perform these functions is tied to storage capacity and power rating. Figure 2.19 shows the comparison of the two parameters with the added dimension of role within a power system.

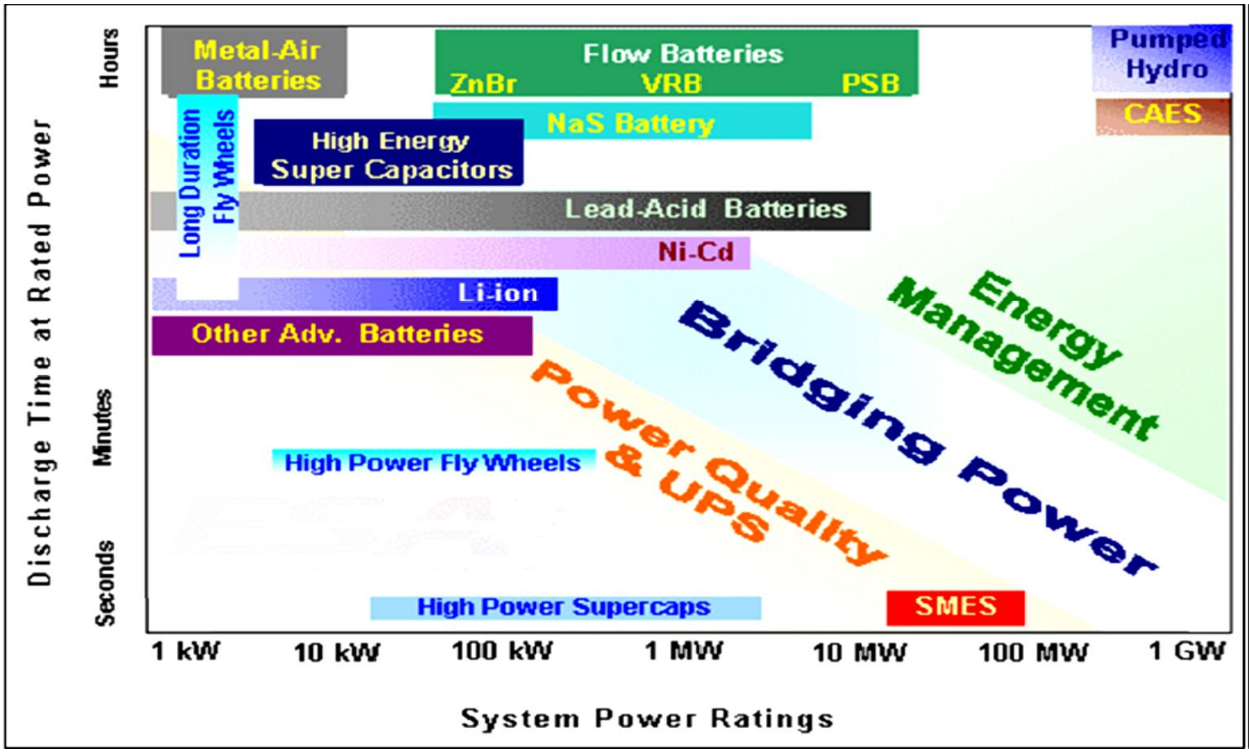

Figure 2. 19: *Role of Various EES Systems Based on Energy Capacity and Power Rating [101]*

2.2.4.3: Storage Duration

This is the amount of time that an EES system can give off power at nominal power before its energy is depleted. It is important to note that although an important parameter, it can easily be calculated by dividing Storage capacity and rated power bearing in mind conversion efficiencies.

It is also prudent to note that under storage duration that a phenomenal called **self-discharge** significantly affects storage duration. So, what exactly is self-discharge in the context of EES systems? Well, often expressed as a percentage with a time duration attachment, it is the measure of the percentage of stored capacity an EES system losses through internal processes without any quantifiable energy output.

2.2.4.4: Round Trip Efficiency

It is a ratio of the amount of energy an EES system receives when charging and the amount it is able to give off when discharging.

2.2.4.5: Cycle Life or Lifetime

This is a measure of time or how many times a battery can go through charge and discharge at manufactures recommended specifications until it loses about 20% of its capacity. This parameter is often affected by DOD (earlier defined). The Figure 2.20 compares the two parameters.

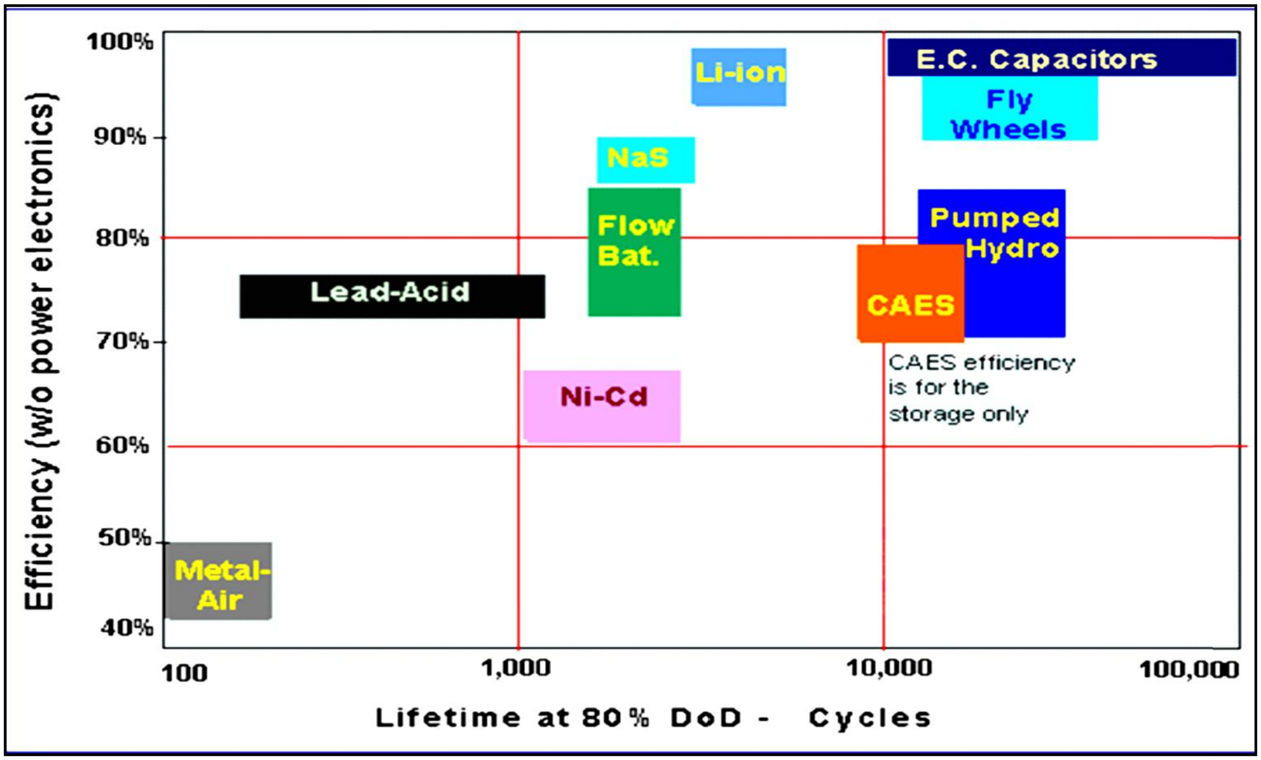

Figure 2. 20: Comparing Efficiency and Cycle Life of Different EES Systems [83]

2.2.4.6: Response Time and Ramp Rate

Response time is a measure of how fast an EES system can get to rated power while ramp rate is the how fast the EES system can change its output power to meet demand (increased or otherwise). It is important to note that a slow response time often implies a slow ramp rate hence the two can be bundled [84].

2.2.4.7: Cost

This is the monetary investments necessary to procure (setup), run and maintain an ESS system.

It involves capital costs and O&M costs and the mode of presentation is usually cost per unit power ($/kW) or cost per unit energy ($/kWh) as seen in Figure 2.21. Sometimes cost per kWh of production is also used.

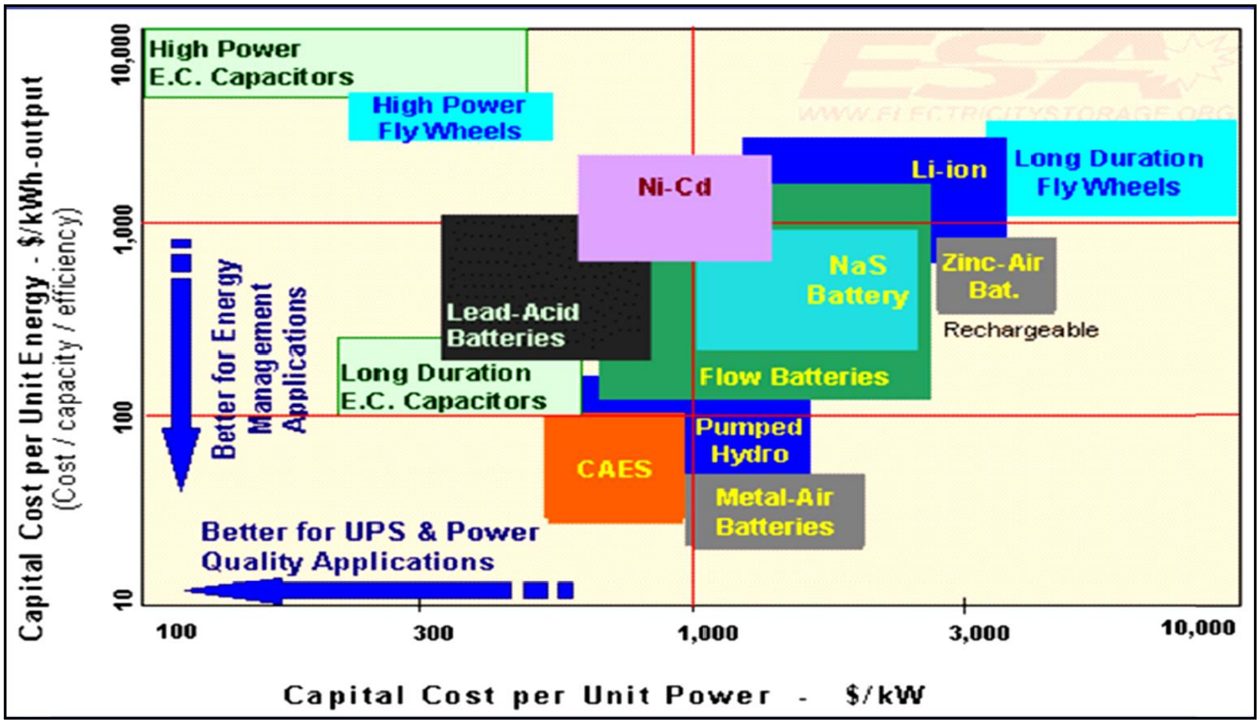

Figure 2. 21: *Graphical Representation of Cost in EES Systems [83]*

2.2.4.8: Power Density

This is the ratio of rated power to a unit volume or weight of the device, i.e. W/L or W/Kg. This is the evaluation factor that favours BESS since it takes into account all of the EES system. Batteries are compact powerful devices hence are favoured for portable applications.

2.2.4.9: Energy Density

This is the ratio of stored energy to a unit volume of the EES system. Although simingly equivalent to power density; it is so different that a device can have a low energy density but a very high power density as is the case for FES,SCES and SMES technologies which all have high power densities but poor energy densities.

2.2.5: EES Systems Comparison

Now that we have established the matix of comparison in Section 2.2.4; it is only fair that we compare the different EES systems. Tables 2.4, 2.5, 2.6 and 2.7 provide a comprehensive comparison for the different EES systems.

Table 2. 4: EES Comparison 1 [45]

Systems	Energy and power density				Life time and cycle life		Influence on environment	
	Wh/kg	W/kg	Wh/L	W/L	Life time (years)	Cycle life (cycles)	Influence	Description
PHS	0.5–1.5		0.5–1.5		40–60		Negative	Destruction of trees and green land for building the reservoirs
CAES	30–60		3–6	0.5–2.0	20–40		Negative	Emissions from combustion of natural gas
Lead-acid	30–50	75–300	50–80	10–400	5–15	500–1000	Negative	Toxic remains
NiCd	50–75	150–300	60–150		10–20	2000–2500		
NaS	150–240	150–230	150–250		10–15	2500		
ZEBRA	100–120	150–200	150–180	220–300	10–14	2500+		
Li-ion	75–200	150–315	200–500		5–15	1000–10,000+		
Fuel cell	800–10,000	500+	500–3000	500+	5–15	1000+	Negative	Remains and/or combustion of fossil fuel
Metal-Air	150–3000		500–10,000			100–300	Small	Little amount of remains
VRB	10–30		16–33		5–10	12,000+	Negative	Toxic remains
ZnBr	30–50		30–60		5–10	2000+		
PSB	—	—	—	—	10–15			
Solar fuel	800–100,000		500–10,000		—	—	Benign	Usage and storage of solar energy
SMES	0.5–5	500–2000	0.2–2.5	1000–4000	20+	100,000+	Negative	Strong magnetic fields
Flywheel	10–30	400–1500	20–80	1000–2000	~15	20,000+	Almost none	
Capacitor	0.05–5	~100,000	2–10	100,000+	~5	50,000+	Small	Little amount of remains
Super-			capacitor	2.5–15	500–5000			100,000+
						10–30		
20+		100,000+	Small	Little amount of remains				
AL-TES	80–120		80–120		10–20		Small	
CES	150–250	10–30	120–200		20–40		Positive	Removing contaminates during air liquefaction (Charge)
HT-TES	80–200		120–500		5–15		Small	

Table 2. 5: *EES Comparison 2 [45]*

Systems	Power rating and discharge time		Storage duration		Capital cost		
	Power rating	Discharge time	Self discharge per day	Suitable storage duration	$/kW	$/kWh	¢/kWh-Per cycle
PHS	100–5000 MW	1–24 h+	Very small	Hours–months	600–2000	5–100	0.1–1.4
CAES	5–300 MW	1–24 h+	Small	Hours–months	400–800	2–50	2–4
Lead-acid	0–20 MW	Seconds–hours	0.1–0.3%	Minutes–days	300–600	200–400	20–100
NiCd	0–40 MW	Seconds–hours	0.2–0.6%	Minutes–days	500–1500	800–1500	20–100
NaS	50 kW–8 MW	Seconds–hours	~20%	Seconds–hours	1000–3000	300–500	8–20
ZEBRA	0–300 kW	Seconds–hours	~15%	Seconds–hours	150–300	100–200	5–10
Li-ion	0–100 kW	Minutes–hours	0.1–0.3%	Minutes–days	1200–4000	600–2500	15–100
Fuel cells	0–50 MW	Seconds–24 h+	Almost zero	Hours–months	10,000+		6000–20,000
Metal-Air	0–10 kW	Seconds–24 h+	Very small	Hours–months	100–250	10–60	
VRB	30 kW–3 MW	Seconds–10 h	Small	Hours–months	600–1500	150–1000	5–80
ZnBr	50 kW–2 MW	Seconds–10 h	Small	Hours–months	700–2500	150–1000	5–80
PSB	1–15 MW	Seconds–10 h	Small	Hours–months	700–2500	150–1000	5–80
Solar fuel	0–10 MW	1–24 h+	Almost zero	Hours–months	–	–	–
SMES	100 kW–10 MW	Milliseconds–8 s	10–15%	Minutes–hours	200–300	1000–10,000	
Flywheel	0–250 kW	Milliseconds–15 min	100%	Seconds–minutes	250–350	1000–5000	3–25
Capacitor	0–50 kW	Milliseconds – 60 min	40%	Seconds–hours	200–400	500–1000	
Super-capacitor	0–300 kW	Milliseconds – 60 min	20–40%	Seconds–hours	100–300	300–2000	2–20
AL-TES	0–5 MW	1–8 h	0.5%	Minutes–days		20–50	
CES	100 kW–300 MW	1–8 h	0.5–1.0%	Minutes–days	200–300	3–30	2–4
HT-TES	0–60 MW	1–24 h+	0.05–1.0%	Minutes–months		30–60	

Now that comparison is complete using all the figures in Section 2.2.4 and an adequate summary given in Tables 2.4 and 2.5; we can now evaluate the suitability of various EES systems in performing various functions and report what is observed.

Table 2. 6: EES Evaluation [51]

Storage Technologies	Pimped hydro	Underground pumped hydro	Compressed air	Lead-acid batteries	Advanced batteries	Flow batteries	Flywheels	Supercapacitors	Superconducting magnetic	Hydrogen cell	Hydrogen engine
Storage Application											
Transit and end-use ride through				X		X	X	X	X	X	
Uninterruptable power supply				X	X	X	X			X	X
Emergency back-up	X	X	X	X	X	X				X	X
T&D stabilization and regulation	X	X	X	X		X			X	X	
Load levelling	X	X	X	X	X	X				X	X
Load following	X	X	X	X	X	X				X	X
Peak generation	X	X	X	X	X	X	X			X	X
Fast response spinning reserve	X	X	X	X	X	X	X			X	X
Conventional spinning reserve	X	X	X	X	X	X	X			X	X
Renewable integration	X	X	X	X	X	X	X			X	
Renewables back-up	X	X	X	X	X	X				X	

Table 2. 7: BESS Evaluation [85]

	Advantages	**Disadvantages**	**Applications**					
			Power Quality	**Demand Management**	**Load Leveling**	**Grid Extension**	**Grid Support**	**Voltage Regulation**
Lead-acid	Low investment cost	Low energy density	√	√	√	√	√	√
UltraBattery	Lower investment costs and better performance than lead-acid batteries	Low energy density	√	√	√		√	√
Sodium-sulfur (NaS)	High energy density and efficiency	High production cost, recycling need for sodium	√	√	√	√	√	√
Lithium-ion (Li-ion)	High efficiency with high energy and power density	High cost of lithium and the need for recycling	√	√	√	√	√	√
Nickel-sadmium (NiCd)	High power and energy density and efficiency	Highly toxic components	√	√	√	√	√	√
Metal-air	Low cost, high energy density and environmentally friendly technology	Low recharging ability	√	√	√	√	√	√

From all the discussions we have had so far it is pretty evident that an ideal EES system does not exist and will probably never exist. Some technologies better suit some applications better than others and while technologies may be found that suit one application; there are often tradeoffs that make one technology to emerge on top.

It is also clear from evaluation that BESS technology presents a strong case for utility scale applications and more so Li-ion technology. Be it energy density, power density, efficiency, response time and other parameters, Li-ion battery technology is the best or hangs in with the best with the only limitation at this point being cost. This is however being addressed and soon it will have a better priced technology that will revolutionize the grid as we know it and make fossil fuel technology obsolete as we move towards a grid better integrated with RES. This is already in the works with the Tesla BESS facility in Australia [41] and more recently the 300MW Moss Landing battery facility in California with more to come in the next years such as a 182.5MW Tesla plant to be deployed in California [86]. The future of the grid is in GSES and the future is BESS with Li-ion technology leading the charge.

Section 2.3 discuses battery energy storage technologies with greater detail, establishing why Li-Ion batteries have such potential for grid scale applications.

2.3: Battery Energy Storage Systems (BESS)

We had established the basic definition of batteries as electrochemical devices which use chemical processes (reactions) to store energy within them or give off electrical energy to an external circuit [58]. Further, we had seen that only rechargeable or secondary batteries are applicable for storage. Secondary batteries are further categorized into the following that will form the basis of our discussion:

- Conventional batteries
- Molten Salt or High Temperature batteries
- Flow or redox batteries

It is prudent however, to discuss how batteries operate when we first have an idea of how we can measure performances of a battery and how we rate batteries.

2.3.1: Battery Key Performance Indicators

These are the parameters that are used to compare the strengths and weaknesses of the various battery technologies [87].

a) Battery (or Energy) capacity; this is a measure of the amount of energy stored in a battery or the energy a battery can provide for a certain amount of time maintaining a threshold voltage. Usually measured in Watt-Hours (Wh), it is the most commonly used metric when evaluating batteries.

b) Power Rating; also, one of the more important metrics, it is the measure of the maximum power a battery can provide at a go; usually measured in Watts (W) or Kilowatts (kW).

c) Round-Trip Efficiency; this is a ratio of the amount of energy a battery receives when charging and the amount it is able to give off when discharging.

d) Depth of Discharge (DoD); usually recommended by the cell manufacturer, it gives the percentage of the battery capacity that can be safely discharged for maximizing the life time of the battery. A fully charged battery has a DoD of 0% while a fully discharged battery has a DoD of 100%.

e) Cycle life; this refers to how many times a battery can go through charge and discharge at manufacturer recommended specifications until it loses about 20% of its capacity.

f) Battery lifetime; closely related to cycle life, it is a measure of how long a battery is expected to keep its rated capacity when used within recommended guidelines; usually measured in hours or years.

2.3.2: Conventional Batteries

In these types of batteries, the cell is usually made up of two electrodes (an anode and a cathode) immersed in an ionic solution (electrolyte) [88]. There are several examples of conventional batteries with the separating factor being the type of electrolyte used; they include lead acid, lithium-ion and Nickel Cadmium batteries.

2.3.2.1: Lead-Acid (Pb-Acid) Batteries

Considered a mature technology, it is one of the most popular BESS and EES technologies with development through an estimated 150 years [51]. This battery type uses sulfuric acid as the electrolyte, lead as the anode and lead dioxide as the cathode; its construction is shown in Figure 2.22 [88].

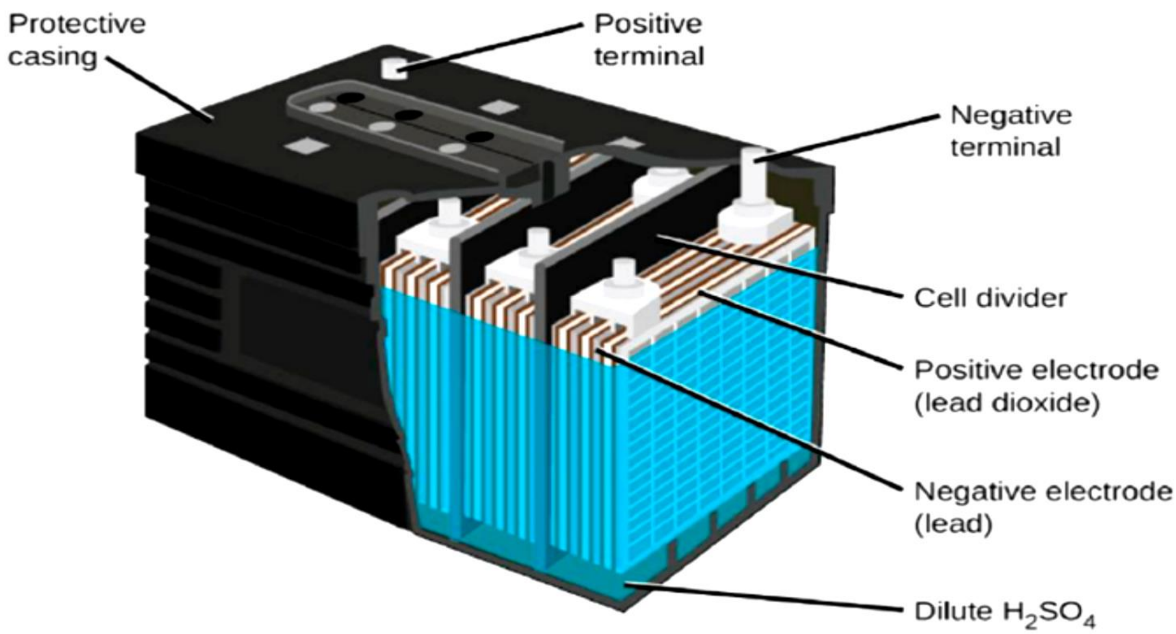

Figure 2. 22: *The Basic Structure of a Pb-Acid Battery [88]*

Favored by its maturity, cost effectiveness, quick discharge rates high energy densities (70 to 100Wh/L) or about 65Wh/Kg when packaged [89]; the technology has found applications in the motoring industry, powering starter motors. The technology is however plagued by low life cycles dependent on the usage cases; some even as low as 50 cycles [90], environmental concerns and relatively low efficiencies (about 80%) [91].

2.3.2.2: Lithium-Ion Batteries

Most lithium-ion batteries are made up of a graphite anode, lithium oxide cathode and a lithium-based electrolyte. In recent years lithium-ion batteries have received a lot of attention; this because they have very high efficiencies (90 to 100%), suffer no memory effects, have very low self-discharge rates (about 5% per month) [61], have long life cycles some even exceeding 10000cycles and good energy density as good as 300Wh/Kg [91]. This technology is however prone to temperature effects and requires temperature of about 25^0C for optimal operation [91].

2.3.2.3: Nickel Cadmium Batteries

The other type of conventional battery is the **Nickel cadmium battery** that is favored for its long lifetime (typically around 10 to 15 years) but is plagued by low efficiencies (about 65%) [61], the toxicity of Nickel and Cadmium to the environment [92] and high capital costs due to the manufacturing processes involved in the production of **Ni-Cd batteries**.

2.3.3: Molten Salt or High Temperature Batteries

These batteries have a similar operating principal to conventional batteries with two key differences; one their electrolyte is solid and they operate at high temperatures (270^0C to 350^0C) [50]. The two prominent types of batteries in this category are sodium nickel chloride and the much more popular Sodium Sulphur (Na-S) battery.

These batteries have good life cycles typically at 2500, 4500 and 20000 cycles at 100%, 90% and 20% DOD respectively [93]. They also have good average roundtrip efficiency numbers about 85 % [95], a decent enough energy density and great specific energies typically 150 - 200Wh/Kg which is actually 3-4X that of Pb-Acid batteries. These batteries are also able to produce powerful short bursts 5 times their rated power making them a prime candidate for power quality maintenance within a power system [96].

Figure 2.23 shows the structure of a sodium sulphur battery.

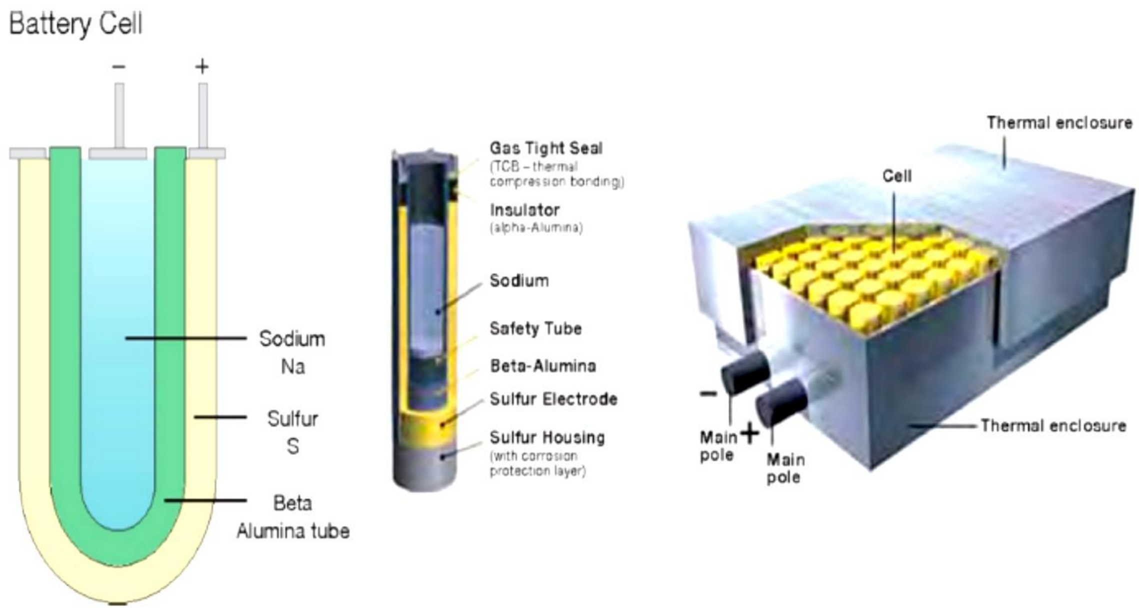

Figure 2. 23: *Na-S Battery Construction Representation [93]*

The only limitation that Na-S batteries and Molten Salt batteries face in general, is the volatile state of sodium that poses a danger to the environment, system maintainers and operators; moreover, the corrosion effects of chemical reactions within the batteries means some of the components corrode and wear out faster, an issue that is further exacerbated by the high temperatures needed to keep the electrolytes in a molten state [97].

The attractiveness of the properties and nature of Na-S batteries has led to them being used by The Tokyo Electric Power Company for power quality maintenance [98].

2.3.4: Flow Batteries o Redox Batteries

Also known as **reverse fuel cells**, since the electrolyte (quasi-fuel) has electro-active components dissolved in it that enable reversibility [99]; the electrolytes normally stored in tanks outside the reaction cell, either give off energy or receive energy by reduction-oxidation (redox) reactions [100]. The three most popular flow batteries are the Vanadium redox (VR), Polysulphide-bromide (PSB), and Zinc-bromine (ZnBr) batteries. Of the three types the most widely adopted is the VR variety because they are more flexible in the kind of services they provide [101].

Figure 2.24 shows the basic structure of a flow battery.

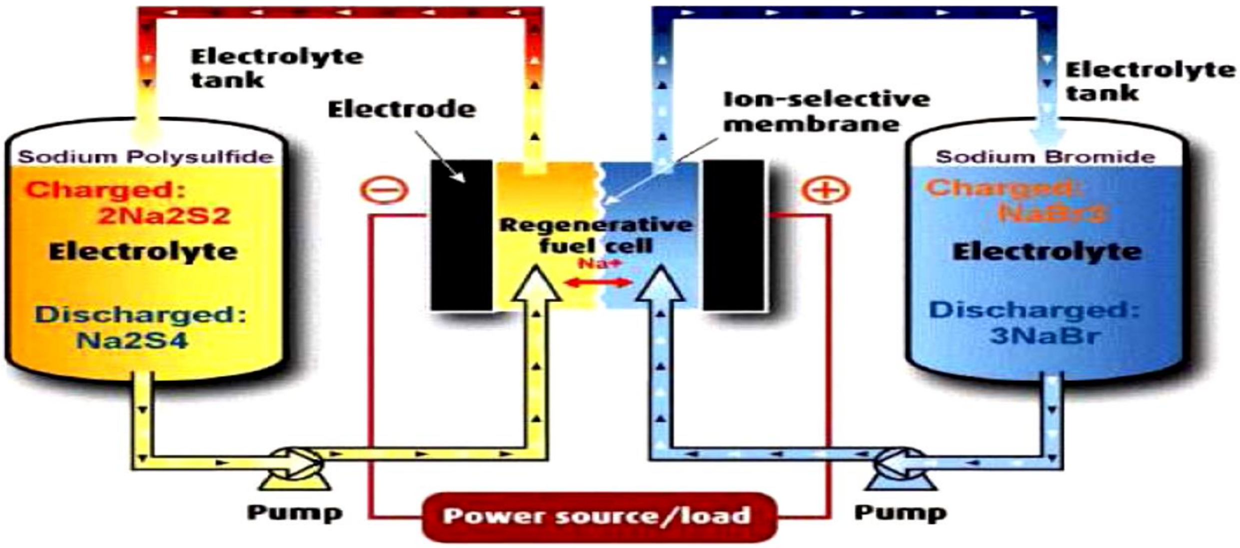

Figure 2. 24: *Flow Battery Basic Structure [45]*

With relatively low efficiencies (about 75% round trip) [102], flow batteries are useful for low-power applications and space is not an issue since miniaturization of the technology is difficult due to the low energy densities meaning larger tanks for compensation [103].

By having its power and energy densities not coupled to the cell mass or volume, flow batteries have the advantage of having flexible power to energy ratios; meaning also power and energy densities can be high. They also have long life since the electrolytes can just be replaced and fast recharge rates by the same action.

2.3.5: Battery Technology Comparison

In trying to compare battery technologies; charts, tabulated figures and facts was deemed most appropriate due to the compactness of the information they provide and the side-by-side presentation that has the advantage of ease of understanding. Figure 2.25 is a chart comparing the three types of battery technologies to an ideal case.

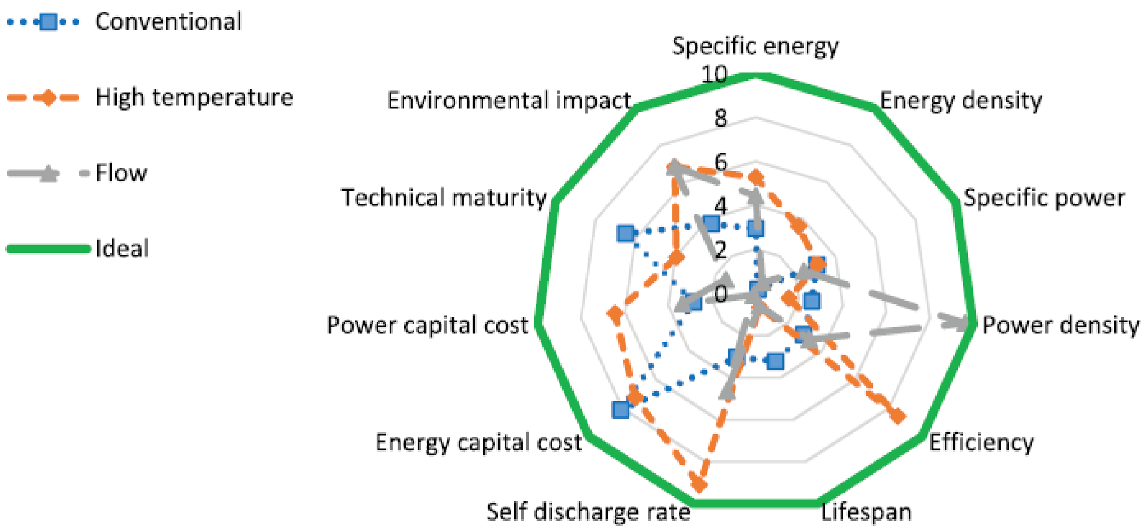

Figure 2. 25: *Ideal Battery Vs Existing Battery Technologies [50]*

While no battery technology closely approximates the ideal case, each battery technology has its strengths and weaknesses. For example, while flow batteries have exceptional power densities, it scores poorly in almost all other parameters; poor energy densities necessitating larger tanks, hence a more significant capital cost.

It is however difficult to compare batteries when bundled in the categorizations specified before; this is because while they are similar in the mechanisms they use to accomplish "battery-action", the chemistries are different leading differences in technical parameters.

For us to see why some chemistries are more widely adopted than others, it is necessary to compare the different chemistries side by side and that is where Tables 2.8 and 2.9 come in handy. In Table 2.8 we shall compare the techno-economic peculiarities of the various cell chemistries while Table 2.9 will add the response time and the impact to the environment as extra parameters.

Table 2. 8: *Techno-Economic Parameter Comparison of Various Cell Chemistries [104]*

		Conventional Battery			Molten Salt Bat.		Flow Battery		
		LA	NiCd	Li-ion	NaS	ZEBRA	ZnBr	PSB	VRB
Techno. Params.	Roundtrip Efficiency [%]	70-82	60-70	85-98	70-90	85-90	60-75	57-75	60-85
	Self-discharge [%Energy/day]	0.033-0.3	0.067-0.6	0.1-0.3	0.05-20	15	0.24	≈0	0.2
	Cycle Lifetime [cycles]	100-2k	800-3.5k	1k-10k	2.5k-2.5k	2.5k	2k	2k	12k-14k
	Expected Lifetime [Years]	3-20	5-20	5-15	5-15	10-14	5-10	10-15	5-15
	Specific Energy [Wh/kg]	30-50	50-75	75-200	150-240	100-120	30-50	10-50	10-30
	Specific Power [W/kg]	75-300	150-300	150-315	150-230	150-200	0	0	0
	Energy Density [Wh/L]	50-80	60-150	200-500	150-250	150-180	30-60	16-60	16-33
	Power Density [W/L]	10-400	0	0	0	220-300	0	0	0
Costs	Power Cost [$/kW]	175-600	150-1500	175-4000	150-3000	150-300	175-2500	330-2500	175-1500
	Energy Cost [$/kWh]	150-400	600-1500	500-2500	250-500	100-200	150-1000	120-1000	150-1000
	BOP Cost [$/kWh]	120-600	120-600	120-600	120-600	120-600	120-600	120-600	120-610
	PCS Cost [$/kW]	58-180	50-180	0	0-120	0-120	0-120	60-120	36-120
	O&M Fixed Cost [$/kW-y]	1.8-52	6-32	12-30	23-61	23-61	15-47	18-96	24-65

Table 2. 9: *Broad Spectrum Battery Technology Comparison [85]*

Battery Technologies	Applicable Capacity (MW)	Efficiency (%)	Respond Time (ms)	Life (cycle)	Investment Cost ($/kWh)	Charge Discharge (Time)	Environmental Impact
Lead-acid	0–40	70–90	5–10	3–15(1500)	200–400	min-day sec-hour	medium
UltraBattery	0–36	–	5	3–15(3000)	200	min-day sec-hour	medium
Sodium-sulfur	0.05–34	80–90	1	10–15(2500–4500)	300–500	sec-hour sec-hour	medium
Lithium-ion	0–100	85–90	20–1000	5–15(1000–15000)	600–3800	min-day min-hour	medium
Nickel-cadmium	0–40	60–65	1–1000	10–20(2000–3500)	400–2400	min-day sec-hour	medium
Metal-air	0–0.01	50	1–1000	– (100–300)	10–60	hour-month sec-24+hour	low

For the longest time Lead-Acid batteries had dominated the battery industry and it is easy to see why from Tables 2.8 and 2.9; with some of the lowest self-discharge numbers in the game, second only to Polysulphide-bromide batteries, good life expectancy, good response time, high power density and specific power and the biggest motivator of all; reasonable costs, both in terms of initial investment and operational and Maintenance (O&M) expenses; it is a natural choice for many industries.

The only other cell chemistry that appears to rival Pb-Acid technology and is already disrupting the battery industry despite its higher capital cost as seen in the Tables 2.8 and 2.9, is Li-Ion batteries. With efficiencies north of 90%, quick charge and discharge rates and some of the highest life cycles in the industry; Li-Ion technology is poised to become the technology of choice not only among batteries but also EES. All of those aside; the attributes of Li-Ion batteries that make it such a good choice for its various applications and the reason why interest is ever growing in it, is its exceptionally high energy density, specific power and specific energy; these give the technology versatility in terms of sizing, portability and application.

2.4: Load Flow Analysis

Load flow is a common term used to refer to a power system analysis method formally known as **power flow analysis.** In load flow analysis we seek to solve for the steady state operational conditions of a power system. Given line data, bus data, power input and load draw; we can be able to solve a system procedurally to determine steady-state conditions of a network in the form of voltage magnitude and angle, real and reactive power, current flows and system power losses as illustrated in Figure 2.26.

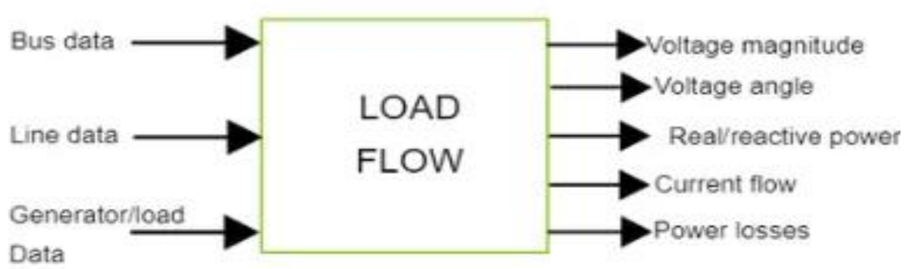

Figure 2.26: Elements of Load Flow

The load Flow Procedure

There are 3 main steps in performing load flow analysis. They include:

i) System modelling, where the power system layout and components are represented using discrete components and mathematical representations.
ii) Formulation of load flow equations.
iii) Numerical solution of load-flow equations.

It is instructive to note that due to the non-linearity of load flow equations coupled with a sizable system size in most cases, it is important that the procedural way of solving these equations be efficient and accurate in addition to being fairly fast.

To that effect, several methods or algorithms have been developed for the purposes of solving the equations and what follows is a discussion on the same. The widely adopted methods of load flow analysis include:

i) Gauss-Seidel Method
ii) Decoupled Load Flow Methods
    a) The Fast Decoupled Load Flow (FDLF)
    b) The Decoupled Newton Load Flow (DNLF)
iii) Newton Rapson Method (method applied)

2.4.1: Gauss-Seidel Method

This is an iterative algorithm for solving a set of non-linear algebraic equations. A solution is first assumed then one of the equations is then used to obtain the revised value of a particular variable by substituting in it the current values of the non-assumed variables. The solution is then updated in respect of this variable. The process is then repeated for all the variables thereby completing one iteration. The iterative process is then repeated till the solution vector converges within prescribed accuracy. Figure 2.27 shows the flowchart of solving load flow using the Gauss-Seidel method.

Advantages

- Has minimal memory requirements because variables are stored in rectangular coordinates.
- It requires less computational time in each iteration.
- It has the advantage of ease of programming.
- It is a simple technique and has minimal number of arithmetic operations.

Disadvantages

- Many iterations mean that the convergence is slow.
- Convergence rate is affected by the choice of slack bus
- Number of iterations increases with number of buses since each bus is treated independently and affects all the other buses when computations are done.

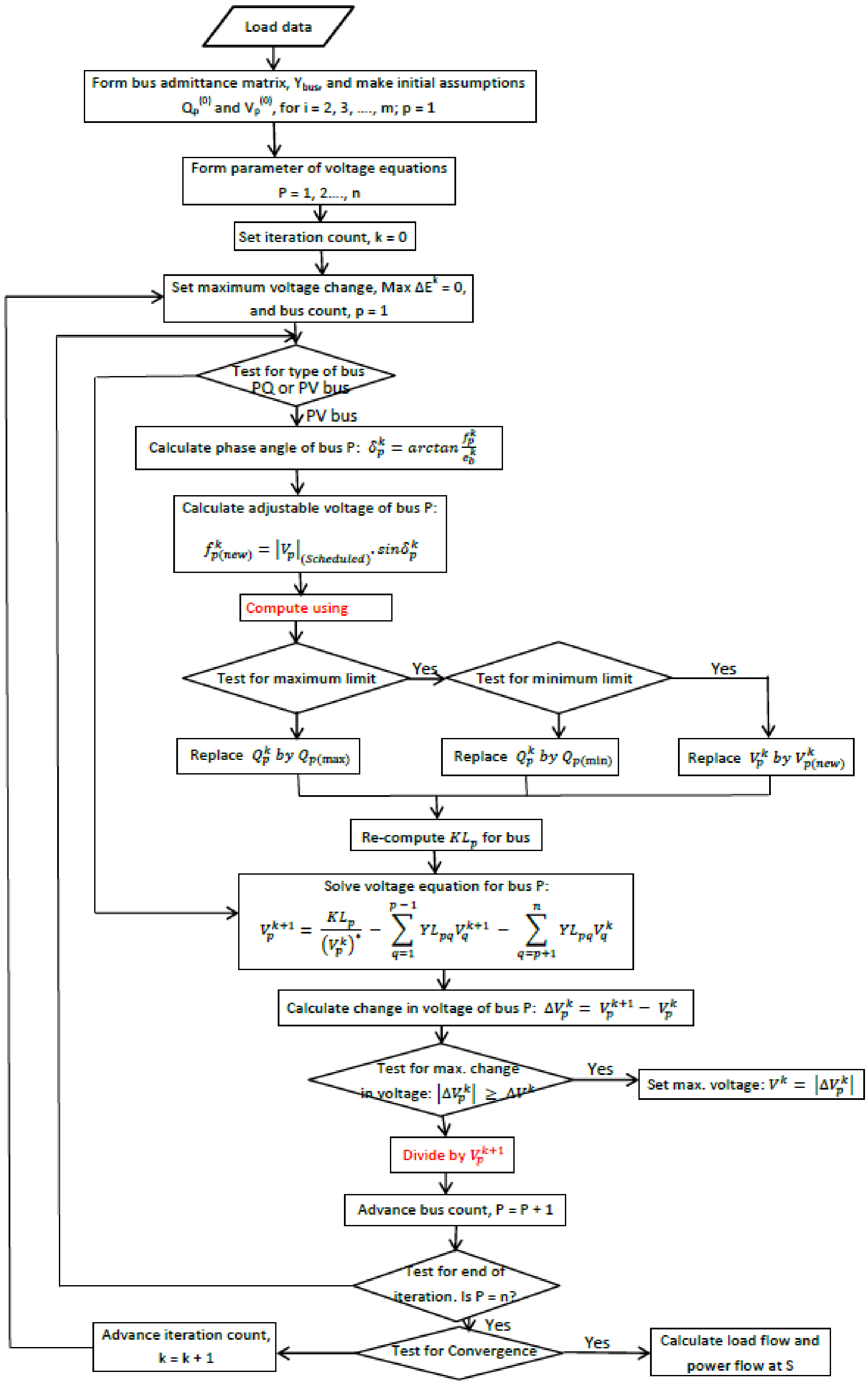

Figure 2.27: Flow Chart for Gauss-Seidel Load Flow

2.4.2: Fast Decoupled Load Flow (FDLF)

This method is considered an improvement of the Newton Raphson method. This method maintains the Jacobian matrix as a constant and also decouples the real power flows from the reactive power flows thus essentially solving the system in two parts i.e., the P-δ system and the Q-V system. This method is however not recommended for a system with high resistance to reactance (R : X) ratios or low voltage systems (heavily loaded systems) since it results in non-convergence. Figure 2.28 shows the flowchart of solving load flow using the FDLF method.

Advantages

- Has lesser memory requirements compared to the Newton Raphson method since the Jacobian matrix is kept constant in all iterations.
- Geometric convergence means that it is fast and reliable; usually taking two to five iterations to reach convergence.
- It is a simple method and very efficient since the matrix equations are linearized.
- It is very adaptable to systems with high reactance to resistance (X : R) ratios

Disadvantages

- It diverges for heavily loaded systems
- It diverges for systems with a high R:X ratio

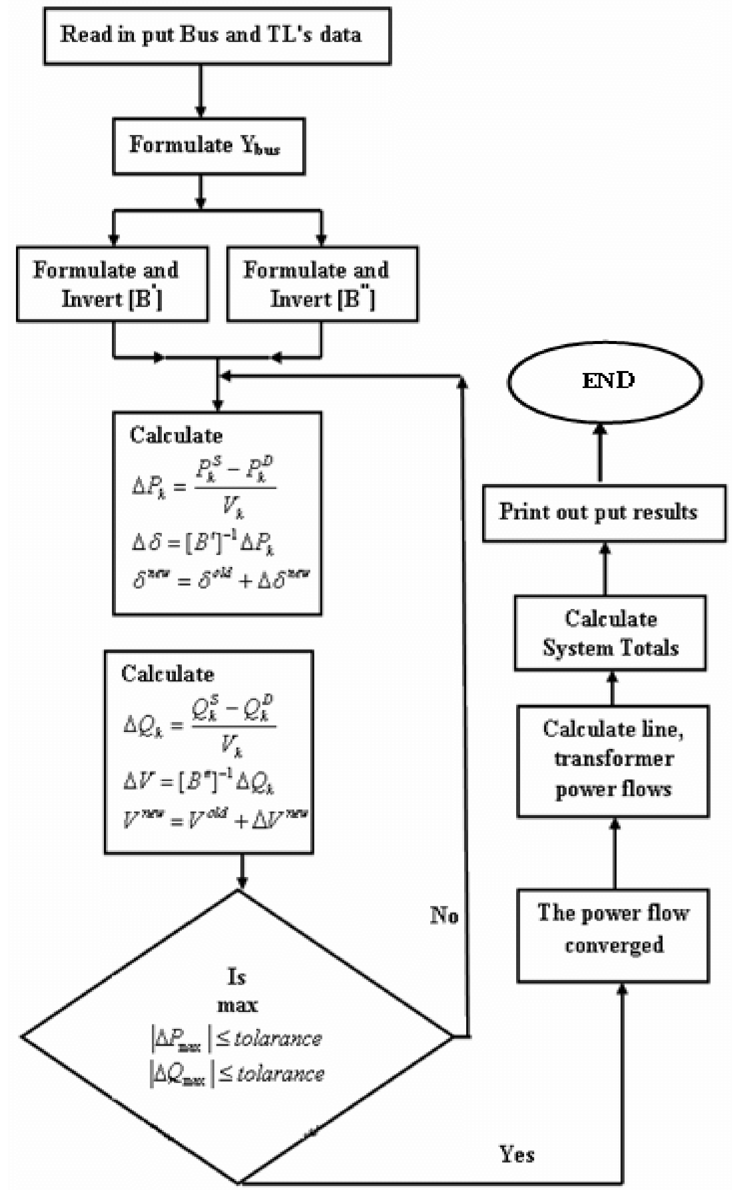

Figure 2.28: FDLF Procedure

2.4.3: Newton Raphson Method (Method Applied)

This method approximates the non-linear load flow equations to first order linear equations using the Taylor's series expansion technique. It is an improvement of Gauss-Seidel method since element values are updated as soon as they are obtained within an iteration. Figure 2.29 shows the flowchart of solving load flow using the Newton Raphson Method.

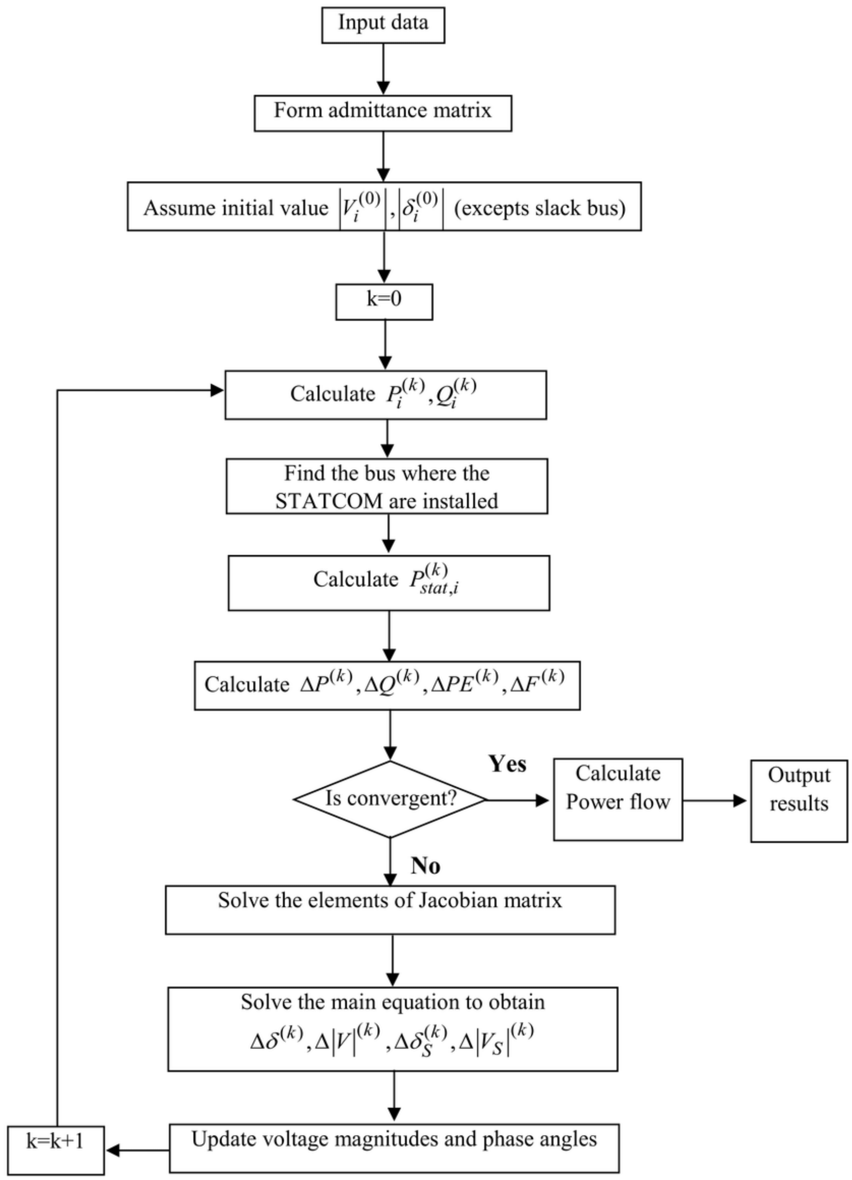

Figure 2.29: Newton Raphson Procedure

Advantages

- It is more reliable and accurate; it is almost never divergent hence it can be used for larger systems
- Its quadratic convergence makes it have fewer number of iterations hence making the method faster.
- It is also insensitive to the choice of slack bus.

The advantages outlined made this method an easy choice for application for this work; it is important to note that this method and the said advantages were further discussed in detail in the chapter on Methodology in this thesis.

Disadvantages

- Can result in longer computation times since elements of the Jacobian matrix are recomputed in every iteration.
- It is a more complex method and it follows that its programing logic is also more complex.
- More elements have to be computed and stored in memory hence it has a higher demand in terms of system memory.

Table 2.10 compares the three load flow methods where the NR load flow procedure comes out dominant with its quadratic convergence and minimal iterations among other advantages.

Table 2. 10: Comparison Between Three Different Methods of Load Flow Analysis [105]

S.No	G.S	N.R	FDLF
1	Require large number of iterations to reach convergence	Require less number of iterations to reach convergence.	Require more number of iterations than N.R method
2	Computation time per iteration is less	Computation time per iteration is more	Computation time per iteration is less
3	It has linear convergence characteristics	It has quadratic convergence characteristics	....
4	The number of iterations required for convergence increases with size of the system	The number of iterations are independent of the size of the system	The number of iterations are does not dependent of the size of the system
5	Less memory requirements	More memory requirements.	Less memory requirements than N.R.method.

2.5: Review of Previous Works on GSES

Metz, D. et al (2018) in [108] investigated the use of battery energy storage for the purposes of benefiting from rate shifts within a short window during the day in the German power system.

In [109], Y. Zhang et al (2017) optimized placement of battery energy storage for conservation voltage reduction in a grid with variable loading.

S.B. Karanki et al (2013) in [110] worked out the optimal placement of battery energy storage with the aim of integrating RES.

In [111], Hameed, Z. et al (2021) did a study on the placement of BESS on Bornholm Island by doing a scoring matrix focusing on the requirements of the BOSS (Bornholm smart-grid secured by grid-connected battery systems) project.

Zeenat, H. et al (2020) in [112] investigated the economic viability of placing battery storage at various sites in a power system by drawing up various use cases.

In [113], there is a proposed 10,000kW energy storage system daubed the Meru County Energy Park. It is however important to note that: the project is not yet operational and no study associated with the project was done.

To provide specific detailing appropriate to this study Table 2.10 was drawn up to provide a detailed summary of the works that have been conducted thus far.

For clarification, on the column of placement YES means optimal placement was evaluated while NO means it was not. For Sizing, YES means a design was calculated custom to the said function and location while NO means it was not or was just done on a randomized manner.

Table 2. 11: Summary of Previous Projects

Reference	Type of Storage	Placement	LF Analysis	Method of Placement
[108]	Li-Ion Battery	NO	NO	N/A but the author used cost benefit analysis and price simulations to come up with a price volatility index in which arbitrage becomes profitable.
[109]	Zn/Br Battery	YES	NO	Conservation Voltage Reduction by BESS effect analysis in a 15 -bus system with stochastic load.
[110]	BESS	YES	NO	Placement was done using a loss sensitivity index algorithm while Particle Swarm Optimization is used to size the BESS
[111]	BESS	YES	NO	Point based scoring where the location with the highest weight is chosen. Scoring was done as shown in figure 2.30.
[112]	BESS	YES	NO	Test case scenarios and the choice for placement was done on whichever site had the supplier, distributor and consumer all benefiting. The weights were assigned as shown in figure 2.31 and 2.32.
[113]	BESS	NO	NO	N/A
This Thesis	Li-Ion BESS	YES	YES	Combined dispatch characterization and load-flow analysis.

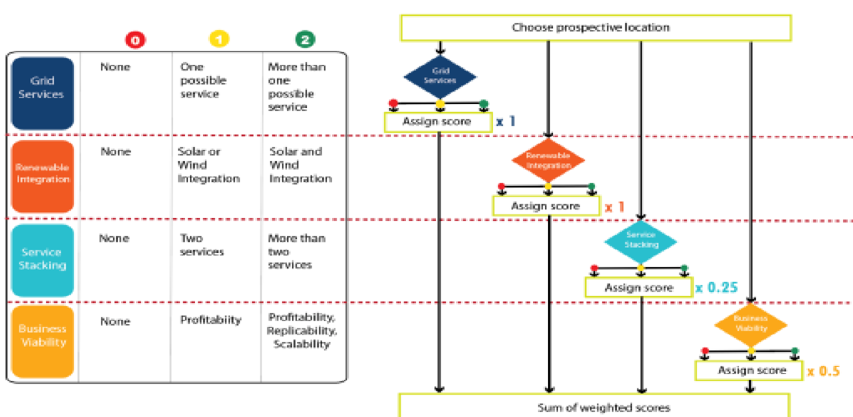

Figure 2.30: Scoring for Reference [111]

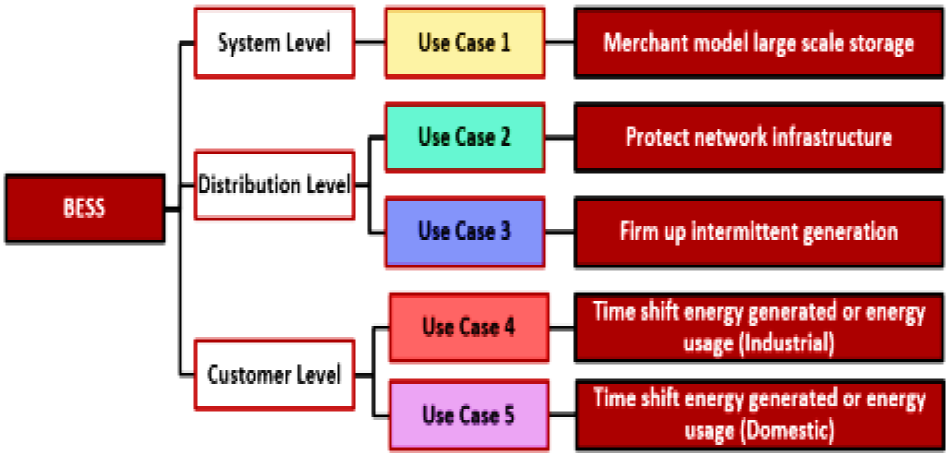

Figure 2.31: Test Scenarios for Reference [112]

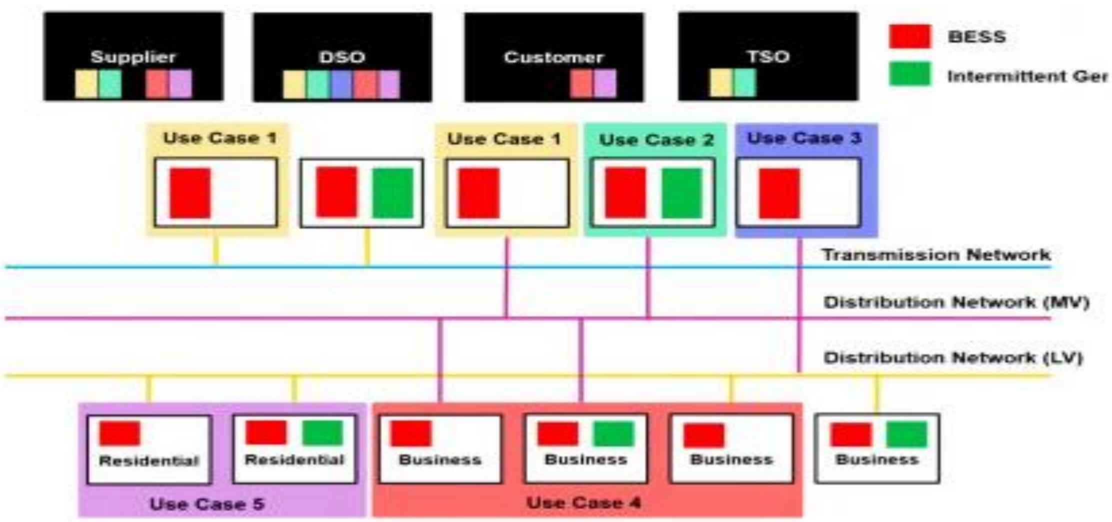

Figure 2.32: Weights for Reference [112]

2.6: Research Gaps

Every grid is different in its own right; different number of buses, different voltages and different dynamics in terms of loading. This means there is potentially myriads of studies that could be conducted on grids considering this factor alone. That said, no study had been conducted on GSES in the Kenyan Grid. Most of the studies that had been conducted had mainly focused on RES integration rather than potential benefits to a grid already integrated with RES; this study aims to bridge this gap.

Studies that have been conducted thus far had come up with possible case scenarios to determine placement and benefits of said placement of BESS without applying prevailing conditions. This study aimed to scrutinize dispatch characteristics in the Kenyan grid to determine opportunities for placement of BESS for a more targeted approach. It was also observed in literature that no study had been done on stacking arbitrage and peak capacity service provision combination and this study aimed to do that.

2.7: Chapter Conclusion

From Literature Review, Li-Ion batteries came out as a form of storage that was currently the most viable energy solution for GSES: it is important to note that this was done through comparative analysis within section 2.3. It was also noted that GSES in Kenya was at its infancy and little is known about its potential impact on the Kenyan grid and this intern limited investment in the sector. By reviewing previous works in the space, we were able to identify the gaps that need bridging and those formed the basis of goals so far as this study is concerned.

Chapter 3: Methodology

3.1: Previous Methods

The methods of placement and optimization that had been applied before had not gone so far as to do load-flow analysis to ascertain optimized placement of BESS. They only looked at a point-based scoring on specific requirements to determine optimized placement.

It also important to note that a summary of the previous methods was done in Table 2.10 under section 2.4 of this thesis.

3.2: General Approach

Dispatch data was obtained from Kenya Power and was used for modelling the Kenyan Power System. Transmission line data was also obtained in excel sheets to this effect. Apart from that line distances and bus voltages were obtained from secondary sources such as [114].

The IEEE 14-Bus standard test bus was modified for relevance to the Kenyan case [107] to the effect that bus and line voltages, loading on load buses and active and reactive power draws throughout the system were looked at where applicable and were modified to fit the Kenyan grid. It is also instructive to note that the mentioned parameters also formed the basis or matrix of comparison between the model and the actual grid.

Li-ion BESS was modelled see section with all key characteristics including power, energy, Cycle life etc. following Rancilio, G. et al. modelling technique [115] after which load flow analysis using Newton-Raphson Method was done on a Li BESS-free system and also with Li BESS injected at different buses and also near or with RES (co-location) at different conditions (loading) [106,115]. Data obtained from simulation on DigSilent PowerFactory was then plotted using Excel or internally using DigSilent plot tools for comparison.

3.3: Kenyan Grid Dispatch Characteristics

Data on how the different generation resources throughout Kenya are deployed on a daily basis to meet demand was utilized for modeling and analysis. The data was obtained from Kenya Power and Kenya Transmission Company (KETRACO) where we expected to find significant RES curtailment due to its unreliability and also its non-utilization during peak load periods again because of its unreliability and unstable capacity value [19,114].

3.4: Problem Formulation

The problem of optimal storage placement is essentially an operational and planning problem in the grid. We essentially need to know the operating conditions of the grid and what happens to voltages and power flow once a load or generator is introduced and the system settles to a steady state.

The problem described above is what is called a load flow problem and is solved by solving a system of simultaneous equations until convergence. The BESS in a power system acts as both a load when charging and a source when discharging.

That said the power injected into a bus i of a power system is given by:

$$S_i = P_i + jQ_i = V_i J_i^*; \quad i=1,2,\ldots,n. \tag{3.1}$$

Where Vi is the voltage of bus i with reference to ground and Ji is the current flowing into the bus.

Taking the complex conjugate of eqn (2.8) we have

$$P_i - jQ_i = V_i^* J_i; \quad i=1,2,\ldots,n. \tag{3.2}$$

Subing for $J_i = \sum^{n}_{k=1} Y_{ik} V_k$ in eqn (2.9)

$$P_i - jQ_i = V_i^* \sum^{n}_{k=1} Y_{ik} V_k; \quad i=1,2,\ldots,n. \tag{3.3}$$

Separating real and imaginary parts we have:

$$P_i \text{ (real power)} = \mathrm{Re}\{V_i^* \sum^{n}_{k=1} Y_{ik} V_k\} \tag{3.4}$$

$$Q_i \text{ (imaginary power)} = -\mathrm{Im}\{V_i^* \sum^{n}_{k=1} Y_{ik} V_k\} \tag{3.5}$$

Which can be expressed in polar form as:

$V_i = \mathrm{Abs}\{V_i\} e^{j\delta i}$

$Y_{ik} = \mathrm{Abs}\{Y_{ik}\} e^{j\theta ik}$

Real power then becomes:

$$P_i = \mathrm{Abs}\{(V_i\} \sum^{n}_{k=1} \mathrm{Abs}\{V_k\} \mathrm{Abs}\{Y_{ik}\} \cos(\theta_{ik} + \delta_i - \delta_k) \tag{3.6}$$

While imaginary power becomes:

$$Q_i = - Abs\{(V_i\}\sum^{n}_{k=1} Abs\{V_k\}Abs\{Y_{ik}\} \sin(\theta_{ik} + \delta_i - \delta_k) \quad (3.7)$$

The total number of equations formed in a system of x buses is 2x and a bus is characterized by the following variables: Pi,Qi,Vi and δi. Given any of the 2x variables the system can be solved simultaneously to obtain the other 2n variables.

3.5: Newton Raphson Method (Load Flow Method of Choice)

By first modeling all the grid components in the Kenyan grid including the proposed Li-BESS, developing appropriate power flow equations and ultimately solving said equation using numerical procedures such as the Gaus-Sidel (GS), Newton-Raphson (NR) or the Fast-Decoupled Load Flow (FDLF); we would be able to obtain the voltage magnitude, voltage angle, real and reactive power, power losses and current flow in all the buses and lines [105].

From Table 2.10 we can see the comparison between NR, GS and FDLF where the Newton-Raphson method of load flow analysis was ultimately chosen for its quadratic convergence characteristics and its minimal number of iterations which are independent of the number of buses [116]. This chosen method (NR) is more accurate than the other methods and does not diverge even if the system is large. Another advantage of the NR method is that it is insensitive to what bus is selected as the slack bus or the effect of regulating transformers in the system.

The equations that govern Newton Raphson Load Flow analysis stemming from the NR load flow procedure as depicted in Figure 2.29 are [106]:

$$S_i = P_i + jQ_i = V_i \sum^{n}_{k=1} Y_{ik}V_k \quad (3.8)$$

$$S_i = \sum^{n}_{k=1} (V_i\, V_k\, Y_{ik}) / (\delta_i - \delta_k - \theta_{ik}) \quad (3.9)$$

$$P_i = \sum^{n}_{k=1} (V_i\, V_k\, Y_{ik}) \cos(\delta_i - \delta_k - \theta_{ik}) \quad (3.10)$$

$$Q_i = \sum^{n}_{k=1} (V_i\, V_k\, Y_{ik}) \sin(\delta_i - \delta_k - \theta_{ik}) \quad (3.11)$$

Where S,P,Q,V and Y are Complex power, real power, apparent power, voltage and admittance matrices elements respectively while δ and θ carry their usual meaning

3.6: Battery Modelling

This section covers the modeling of the Li-Ion Battery where particular focus was drawn on the energy and power requirements and other aspects such as efficiency and lifecycle which are well documented in literature were assumed to be 96% and 8000 cycles respectively.

BESS Model for the DigSilent Power Factory

The battery as shown in Figure 3.1 was modelled as a DC voltage source with a PWM converter and was attached to the grid using a transformer whose transformer ratio was altered to conform to the bus voltage it was attached to.

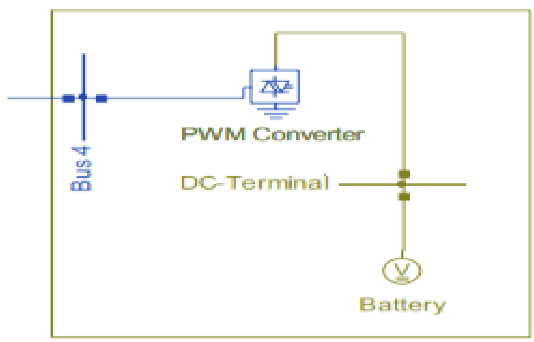

Figure 3. 1: Battery Model

It is important to note that in addition to the transformer also had to be matched to the PWM converter in terms of voltage and power; the transformer MVA was always equal to the PWM converter MVA documented in Table 4.14 and the transformer ratio was always 3:0.4 or 15:2 since the converter coupled the transformer at 0.4kV.

The nominal DC voltage was set at 900v or 0.9kV. For clarity, the term source as referenced when describing the model means that the batter can act to deliver DC voltage or sink DC voltage when discharging and charging respectively. Actual sizing and other configuration details are presented in section 4.3: **Optimal Battery Size and Candidate Placement Locations**.

3.7: DigiSilent PowerFactory Software

This is the software tool that was used for load flow analysis. It gave us the ability to model a power system and also do load flow analysis on the modelled system. When properly configured, it performed load flow analysis using the Newton-Raphson technique on the Kenyan Grid (modified IEEE 14-Bus) and gave data on the voltage magnitude, voltage angle, real and reactive power, power losses and current flow in all the buses and lines [117].

The software version employed in this study was the 32bit version of DIgSILENT PowerFactory 15.1.6 and it was installed on a 64bit laptop computer (The HP Elitebook) with 8gb of RAM, 256Gb of solid-state memory and a Core !5 Intel processor. This computer was able to run the software including all the simulations without getting over clocked and showing any signs of slowing down. In order to perform load flow analysis on the software, the following steps were taken to configure it:

1. **A New Project was created:** After installation, DIgSILENT PowerFactory was launched and a new project (Kenyan Grid Model was created).

2. **Power System Model Importation:** The IEEE 14-bus standard test bus (Figure 3.2) was imported and modified by adjusting components such as buses, generators, transformers, loads, lines, and other network elements to mimic the Kenyan Grid. This was done using the graphical user interface modeling technique.

3. **Defination of Data and Parameters:** Next, data and parameters for the components in the modified power system model were defined using data obtained from KETRACO, KenGen and Kenya Power. This included voltage levels, power ratings, and other relevant data ensuring data accuracy for all the elements in the network.

4. **Network Configuration:** After parameter definitions, network configuration was done; including bus voltage and system frequency and specification of the base case conditions for load flow analysis.

5. **Load Flow Study Setup:** In the "Load Flow" section specifically in the "Steady State Analysis" tab; load flow analysis parameters and the solver options, such as the numerical method (e.g., Gauss-Seidel or Newton-Raphson), convergence criteria, and maximum

number of iterations were then specified. In this case the Newton-Raphson was specified as the solving technique.

After configuration the load flow analysis was run by clicking on the "Run" or "Solve" button within the load flow setup menu. The software then performed the load flow calculations and converged to a solution. Once the load flow analysis is complete, the results could then be viewed. These included voltage magnitudes and angles at each bus, active and reactive power flows on transmission lines. After the first successful run, different scenarios were run and investigated by adjusting the model and/or parameters and re-running the analysis.

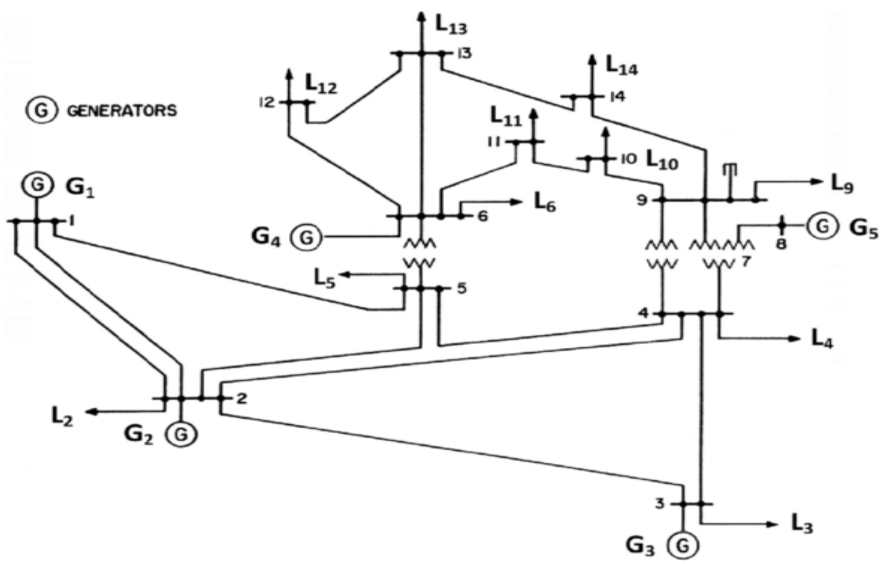

Figure 3. 2: IEEE 14-Bus Standard Test Bus System [107]

3.8: The Kenyan Grid Model

From the data sourced from Kenya Power a 14-bus grid model was done in DigSilent to accurately map the grid in terms of line lengths, line current carrying capacity, line resistance, line reactance, line susceptance, generation capacities and bus voltages. The model developed is shown Figure 3.3.

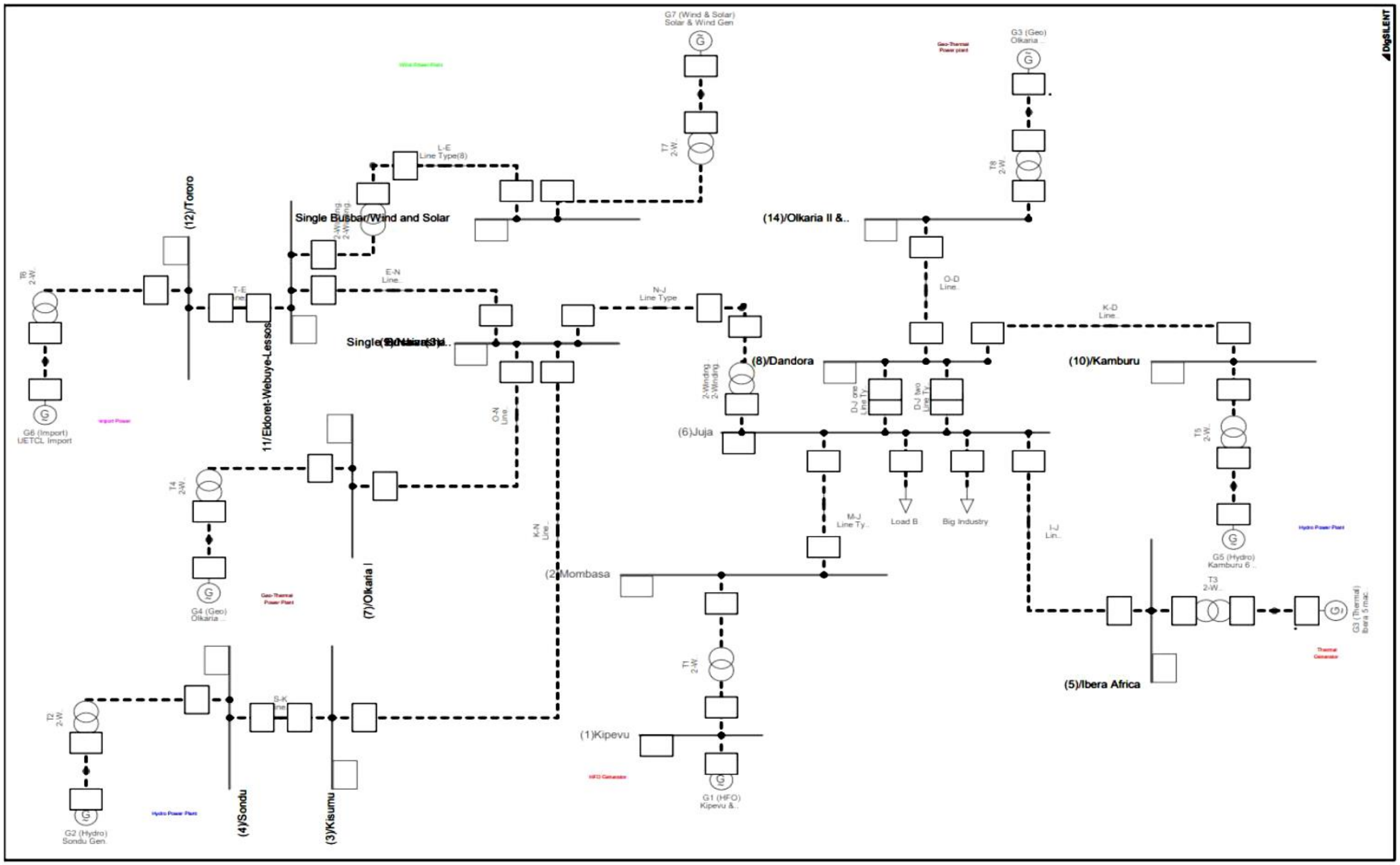

Figure 3. 3: Kenyan Grid on a 14 Bus Model

3.9: Conceptual Framework

The Li-Ion BESS will be both a load and a source depending on prevailing system conditions and the time of day. This means the system should have an intelligent controller to control; charging and discharging and scheduling of the same to ensure stability of the BESS, longevity and profitability.

It is also important to note that the intelligent controller must also be equipped with power conditioning circuitry for coupling the Grid and the BESS. Figure 3.4 shows the conceptual framework for this thesis.

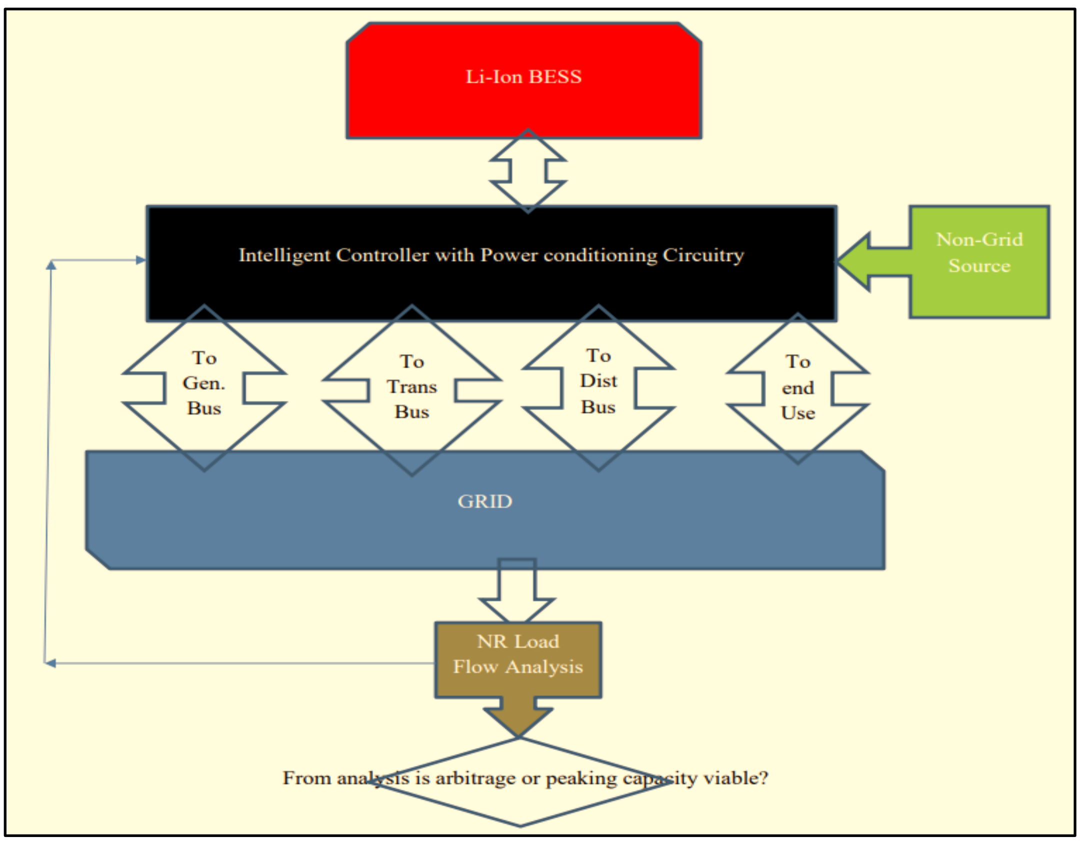

Figure 3. 4: Thesis Conceptual Framework

It is important to note that the BESS and controller as represented in Figure 3.4 have been properly sized and configured to a particular bus.

3.10: Chapter Conclusion

Chapter 3 outlined the methods employed in the formulation of this thesis: It started by first looking into methods previous used in studying GSES and later introduced the general approach that was used in meeting the study objectives. In section 3.3, the relevance of studying the dispatch characteristics of the Kenyan grid was discussed. Under section 3.4 the problem formulation was done and the choice of load flow method was also validated in section 3.5. The modeling software DigSilent Power Factory was also discussed in detail and its appropriateness for the intended purpose looked at. The conceptual framework of this thesis was also presented for clarity and ease of reference within section 3.9.

Chapter 4: Results, Analysis and Discussions

4.1: Introduction

This chapter will present the results of this study, it will cover the results of analyzing the dispatch characteristics, the modeling of the Kenyan Grid, the modeling of the Li-Ion BESS and the assessment done to place the BESS optimally.

The Chapter will also present the results of performing load flow to assess the viability of the candidate grid locations for the Arbitrage and Peaking Service Provision by the BESS. Further, the chapter will cover the sizing of the BESS(s) for said service provision.

Finally, the chapter will provide a simple financial analysis to assess BESS cost and the viability of Arbitrage service on the Kenyan grid. It will also try and substantiate the peaking service provision on the grid that the design BESS(s) will provide.

4.2: Dispatch Characteristics of the Kenyan Grid

This section offers an in-depth look at the Kenyan power system dynamics with the aim of proper modeling of both the grid and the BESS.

4.2.1: Installed Capacity and Demand

The installed capacity of the Kenyan grid was found to be 2819 MW and is distributed as shown in Figure 4.1 not counting power imports since they are not considered part of installed capacity. It was noted that the generation mix of the Kenyan Grid is mostly comprised of RES with geothermal and hydro taking the biggest share about 60% and RES as a whole having a share greater than 70%. A more detailed analysis of the installed capacities can be found in the appendix section of this report.

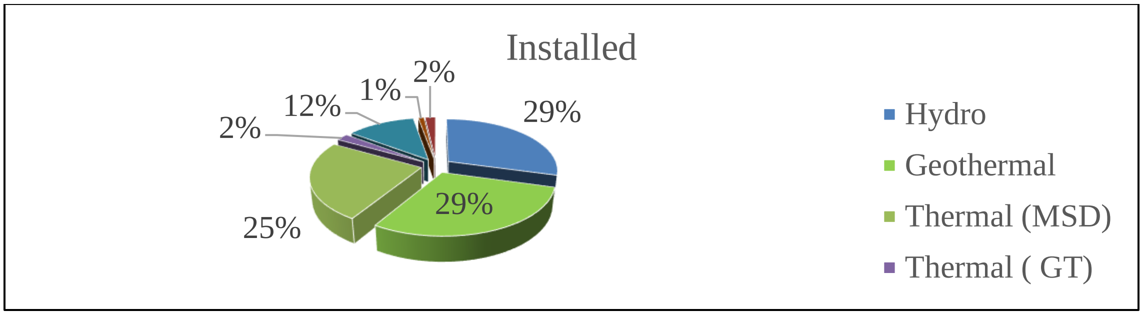

Figure 4. 1: Kenyan Grid Installed Capacity Distribution

Data was also analyzed to get the average demand in the Kenyan System and Table 4.1 gives the summary of the same. The average demand was determined to be 1851 MW and this gives a reserve margin of about 50% calculated as:

$$\text{Reserve Margin} = \frac{System\ Capacity - Average\ Demand}{Average\ Demand + \frac{largest\ single\ capacity\ plant\ (Kindaruma)}{2}} \quad \text{Eq. 4.1}$$

Table 4. 1: Average Monthly Demand

Month	**Demand**
July	1812
August	1832
September	1830
October	1830
November	1859
December	1845
January	1858
February	1882
March	1881
April	1856
May	1860
June	1867
Average	**1851**

4.2.2: Dispatch Merit

To better understand how dispatch was arrived at; a merit list of the available resources was obtained and the Table 4. 2 is the summary based on cost.

Table 4. 2: Station Dispatch Merit Analysis

STATION	VARIABLE ENERGY COST (A) (KSH/KWH)	FUEL COST (B) (KSH/KWH) 2	CAPACITY / DEEMED COST CONVERTED TO ENERGY AT CONTR. LOAD FACTOR (C) (KSH/KWH) 3	FOREX ADJUSTMENT CHARGES (D) (KSH/KWH) 4	TOTAL GEN. COST (A+B+C+D) (KSH/KWH) 5	TOTAL VARIABLE COST (A+B) (KSH/KWH) 6	MERIT ORDER BASED ON VARIABLE COST (A+B) 7
LTWP 1	0.000	0.000	0.000	0.000	0.000	0.000	**1**
Major Hydros	0.084	0.000	2.773	0.346	3.202	0.084	**2**
Olkaria II	0.110	0.000	4.573	40.781	45.464	0.110	**3**
Olkaria I	2.416	0.000	0.000	-0.004	2.412	2.416	**4**
Orpower4-Plant II	2.915	0.000	7.383		10.298	2.915	**5**
Orpower4-Plant III	2.915	0.000	7.383	0.000	10.298	2.915	**5**
Orpower4-Plant IV	2.915	0.000	7.383	0.000	10.298	2.915	**5**

Orpower4-Plant I	2.915	0.000	7.402		10.318	2.915	**6**
Olkaria IV	3.076	0.000	3.766	0.000	6.841	3.076	**7**
Olkaria I - AU	3.076	0.000	3.413	0.000	6.488	3.076	**8**
LTWP 3	4.857	0.000	0.000	0.000	4.857	4.857	**9**
Garissa Solar (REA)	5.503	0.000	0.000	0.000	5.503	5.503	**10**
Imenti Tea Factory	6.014	0.000	0.000		6.014	6.014	**11**
Sang'oro Hydro	6.769	0.000	0.000	0.000	6.769	6.769	**12**
Gura - KTDA	8.019	0.000	0.000	0.000	8.019	8.019	**13**
Wind (Ngong)	8.281	0.000	0.000	0.090	8.371	8.281	**14**
Small Hydros	8.312	0.000	0.000	0.000	8.312	8.312	**15**
WellHead (OW37 & 43)	8.520	0.000	0.000	0.000	8.520	8.520	**16**
Eburru Hill	8.520	0.000	0.000	0.000	8.520	8.520	**17**
Regen Terem	9.519	0.000	0.000	0.000	9.519	9.519	**18**
LTWP 2	9.714	0.000	0.000	0.000	9.714	9.714	**19**
Gikira Hydro Power	10.023	0.000	0.000	0.000	10.023	10.023	**20**
Biojoule (Biogas)	10.113	0.000	0.000	0.000	10.113	10.113	**21**

From Table 4. 2 it can be seen that different regimes of the same power plant are given different priorities and that the regime number is not tied to the priority/merit ranking; for example, LTWP1 has a merit order better than both LTWP2 and LTWP3 but LTWP3 has a merit order better than LTWP2. This is done to encourage cheap wind energy and the more the energy the cheaper it is to the grid. The application of the different regimes is as follows:

i) Lake Turkana Wind Power
    a. LTPW1 regime is applied for energy supplied that does not exceed 1445.4GWh in a calendar year.
    b. LTPW2 is applied for values between 1445.4GWh and 1683GWh in a calendar year.
    c. LTPW3 which has an energy charge rate of 50% is applied for energy supply above 1683GWh in a calendar year.

ii) Rabai Power
    a. Rabai1 regime is applied when power is dispatched below 33MW and/or during the first 2.5 hours after 8 hours or more of full plant shutdown.
    b. Rabai2 regime is applied for dispatch above 33MW.

iii) Thika Power
    a. Thika1 regime is applied when power is dispatched below 33MW.
    b. Thika2 regime is applied for dispatch above 33MW.

iv) Triumph Power
    a. Triumph1 regime is applied when power is dispatched below 35MW.
    b. Triumph2 regime is applied for dispatch above 35MW.

v) Orpower4 has a USD 0.004/kWh charge applied as a royalty to the Government of Kenya on its energy production.

vi) In their agreement, Uganda Electricity Transmission Company Limited (UETCL) and Kenya Power have two regimes were:
    a. Tie line flow is paid a lower variable cost amount
    b. While request above tie line flow are charged a higher amount

vii) Fossil fuel generators have higher costs associated with reactive power and this is reflected on the merit list were column (capacity / deemed cost converted to energy at contr. load factor) has entries.

4.2.3: Daily Trend Analysis (Demand and Dispatch)

To analyze the load demand and the dispatch trend of a typical day on the Kenyan Grid demand and load data was scrutinized for a week in order to establish a trend. Raw data was obtained in the form of bi-hourly logs of demand and dispatch as shown in Table 4. 3 which is representative of the kind of data that was worked on and analyzed in excel sheets.

Table 4. 3: Reduced Sample Raw Data

STATION	***00.30***	***01.00***	***01.30***	***02.00***	***02.30***	***03.00***	***03.30***	**UNITS, (KWh)**	**UNITS, KWh**	**Max Dem**	**Min Dem**	**L/F**
IMPORT FROM UETCL	0.416	0.416	4.774	4.774	14.644	14.644	2.938	322,278	322,278	60.78	0.416	22.09%
EXPORT TO UETCL	7.420	7.420	0.220	0.220	0.098	0.098	1.640	69,392	69,392	8.474	0.000	34.12%
NET IMPORT FROM UETCL	**-7.004**	**-7.004**	**4.554**	**4.554**	**14.546**	**14.546**	**1.298**	252,886	252,886	60.78	-7.250	17.34%
WANJII	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0.00	0.000	0.00%
TANA	14.72	14.72	14.72	14.72	14.72	14.72	14.72	344,860	344,860	14.72	13.720	71.85%
MASINGA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	20,000	20,000	12.00	0.000	2.08%
KAMBURU	26.00	32.00	28.00	30.00	26.00	30.00	30.00	1,266,000	1,266,000	86.00	22.000	58.61%
GITARU	68.00	66.00	66.00	66.00	68.00	66.00	66.00	2,480,000	2,480,000	216.00	60.000	47.84%
KINDARUMA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	528,860	528,860	63.40	0.000	34.43%
KIAMBERE	56.00	4.00	0.00	0.00	0.00	0.00	0.00	2,285,000	2,285,000	164.00	0.000	58.05%

MESCO	0.39	0.39	0.39	0.39	0.39	0.39	0.39	9,334	9,334	0.39	0.389	102.35 %
SOSSIANI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0.00	0.000	0.00%
SAGANA	0.83	0.83	0.83	0.83	0.83	0.83	0.83	19,920	19,920	0.83	0.830	55.33%
SANGORO	20.64	20.78	20.82	20.82	20.82	20.82	20.82	500,580	500,580	21.20	20.640	104.29 %
GOGO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0.00	0.000	0.00%
SONDU MIRIU	60.00	60.00	60.00	60.00	60.00	60.00	62.00	1,443,000	1,443,000	62.00	58.000	100.21 %
TURKWEL	90.00	100.00	60.00	50.00	46.00	48.00	44.00	2,099,000	2,099,000	104.00	44.000	83.29%
GIKIIRA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0.00	0.000	0.00%
TEREM SHP	5.00	4.87	4.94	4.92	4.89	4.76	4.85	74,086	74,086	5.00	0.000	59.36%
CHANIA-KTDA SHP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0.00	0.000	0.00%
GURA- KTDA SHP	1.05	1.05	1.05	1.05	1.05	1.05	1.05	25,301	25,301	1.05	1.054	18.18%
TOTAL HYDRO+UETC IMP	**343.049**	**305.063**	**261.523**	**253.503**	**257.343**	**261.215**	**247.601**	11,418,219	11,418,219	737.269	247.601	64.53%

It is important to note that the raw data as presented in Table 4. 3 only shows 7 data points from 0030hrs to 0330hrs and that the data is scrutinized for all 24hrs in a day for each of the 7 days. What now follows is the summary of the analyzed data on a day-to-day basis.

4.2.4: Load Demand Curves

Figure 4.2, Figure 4.3, Figure 4.4, Figure 4.5, Figure 4.6, Figure 4.7, and Figure 4.8 show the load demand curves in the grid on Monday, Tuesday, Wednesday, Thursday, Friday, Saturday and Sunday respectively of the reference week.

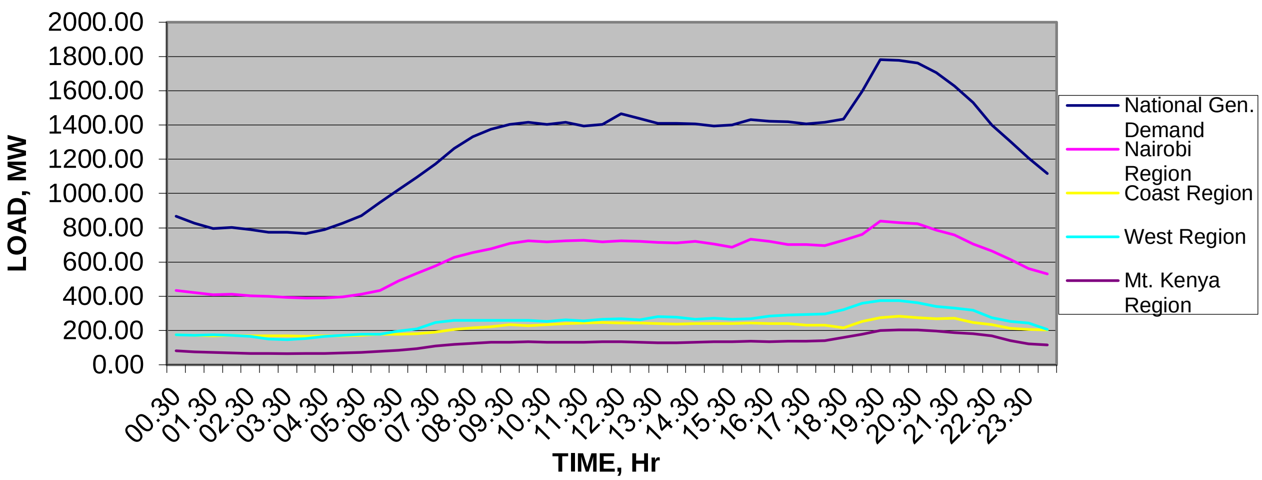

Figure 4. 2: Monday's Demand Curve

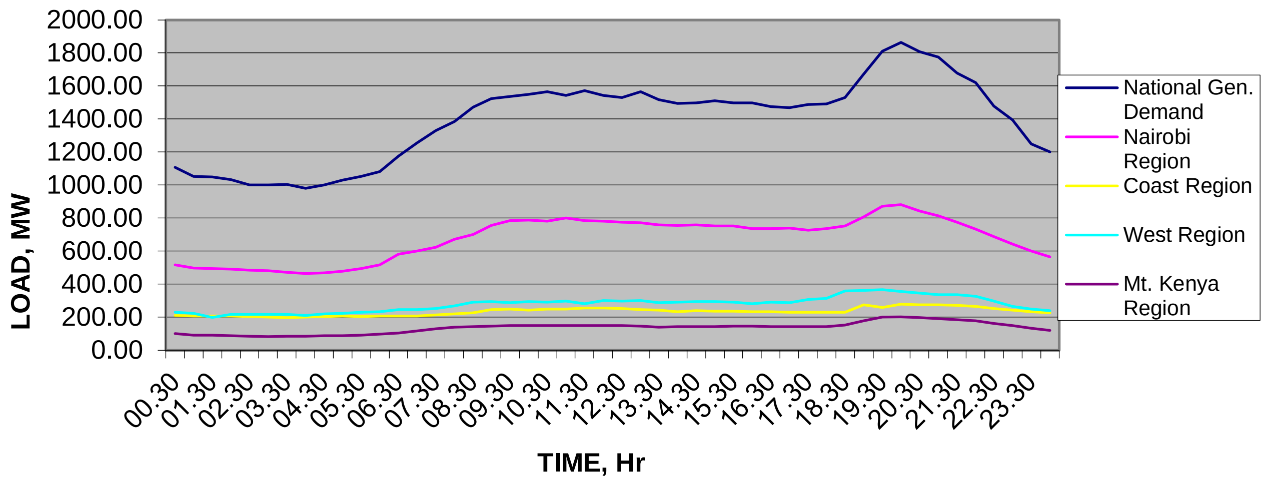

Figure 4. 3: Tuesday's Demand Curve

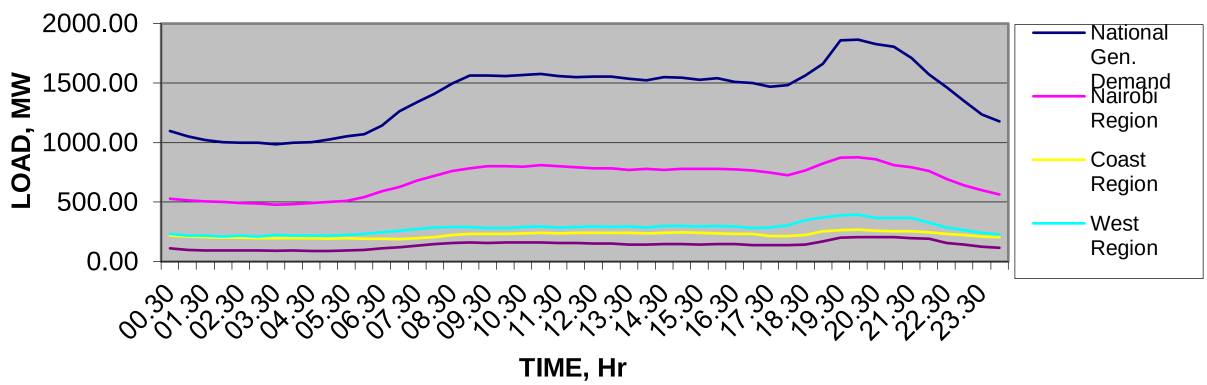

Figure 4. 4: Wednesday's Demand Curve

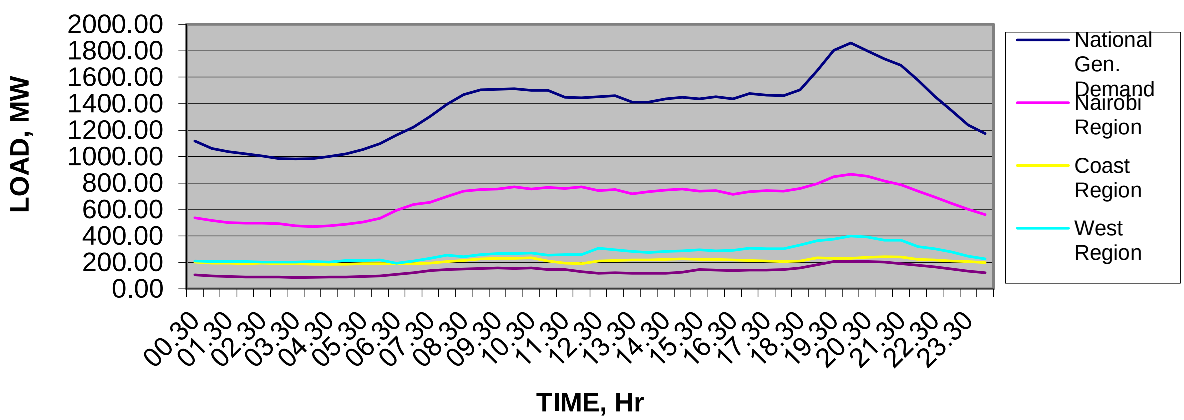

Figure 4. 5: Thursday's Demand Curve

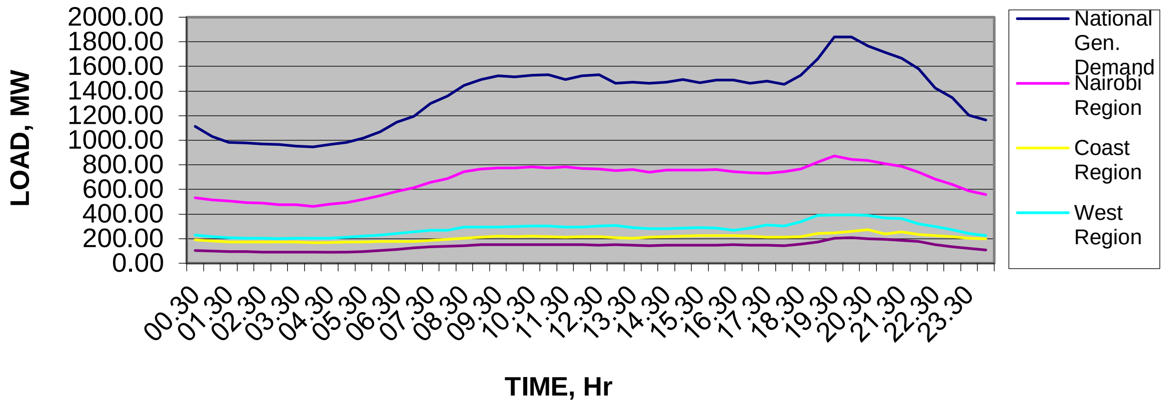

Figure 4. 6: Friday's Demand Curve

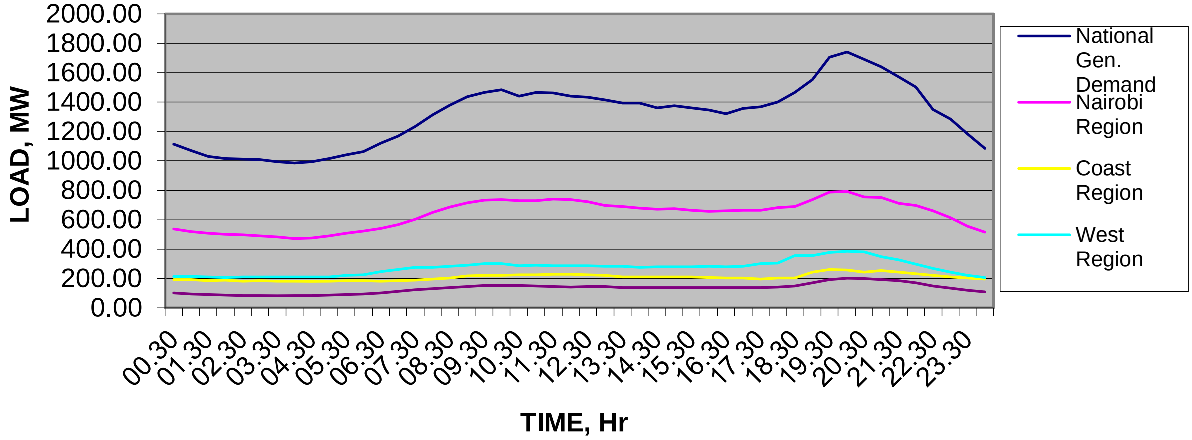

Figure 4. 7: Saturday's Demand Curve

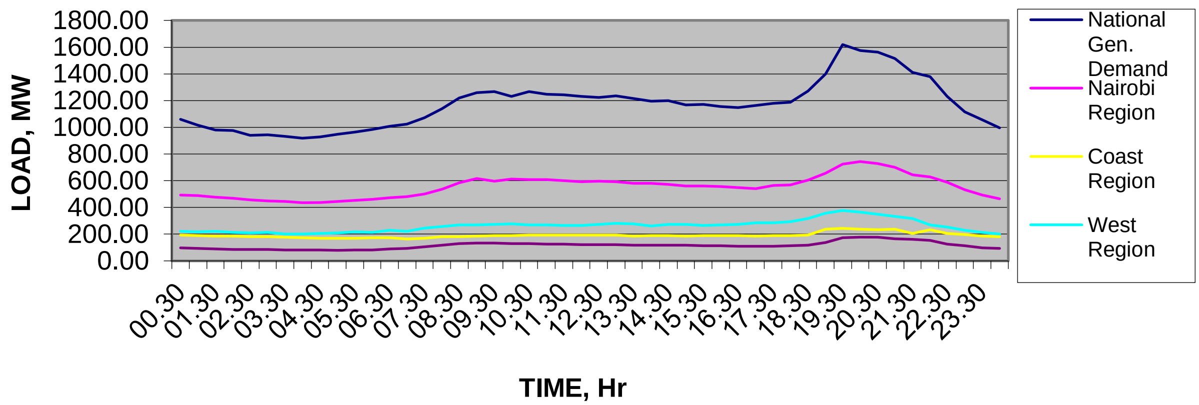

Figure 4. 8: Sunday's Demand Curve

From analyzing the Demand curves of the reference week, the following salient observations and trends were noted:

- Nairobi Region typically has the largest energy demand followed by the West, the Coast and the Mt. Kenya Regions respectively.
- Typically, demand is minimum between 0000hrs and 0500hrs attributed to the fact that the population is largely asleep and not consuming electricity (businesses are closed and most industries have ramped down production).
- Demand is typically maximum between 1900hrs and 2230hrs attributed to the fact that most of the working population have just gotten home from work and are cooking showering, using electrical devices such as electric kettles, clothes irons etc.
- Observable peak demand is about 1850 MW right at around 2000hrs.
- Generally, demand is lower on the weekends i.e., Saturday and Sunday with Sunday being lower than Saturday and again ramping up during weekdays.

From the observations made, it was noted that if we were to provide peaking capacity service, the target time for discharge would be between 1900hrs to 2230hrs and for the purposes of load equalization or peak shaving we would want to charge between the hours of 0000hrs and 0530hrs.

4.2.5: Power Balance

From the data obtained and analyzed, the following observations were made in the way power balance is worked on:

- Analysis on power balance that conforms to 3 periods in a day i.e., morning, afternoon and evening as adopted is acceptable and that it is primarily due to the 3 observable distinct regions as seen in the load curves.
- Usually, a surplus of power is realized in the power balance and it is often not predictable due to grid dynamics.
- A spinning reserve of 82MW is considered optimal for the Kenyan Grid.
- Kenya usually demands 50MW from the UETCL and about 800MW from the Independent Power Producers IPPs.

- There are generally two accepted methods of doing peak demand forecasting:
  I. Peak demand forecast equals the instantaneous sustained peak demand to date on the subject period of day
  II. Peak demand forecast equals the sustained peak demand over the last 4 weeks.

Table 4. 4 and Table 4. 5 demonstrate the influence on power balance when the two methods are applied in demand forecasting on the same day.

Table 4. 4: Method I Sample Power Balance

Period of Day		Morning	Afternoon	Evening
Expected Available Plant Capacity	KenGen	1,295	1,335	1,430
	IPPs	810	811	760
	UETCL IMPORT	50	50	50
	Total	2,155	2,195	2,240
Forecast Peak Demand*		**1,665**	**1,592**	**1,926**
Spinning Reserve		**82**	**82**	**82**
Shortfall/Surplus (-/+)		408	521	232

Table 4. 5: Method II Sample Power Balance

Period of Day		Morning	Afternoon	Evening
Expected Available Plant Capacity	KenGen	1,295	1,335	1,430
	IPPs	810	811	760
	UETCL IMPORT	50	50	50
	Total	2,155	2,195	2,240
Forecast Peak Demand*		**1,594**	**1,566**	**1,882**
Spinning Reserve		**82**	**82**	**82**
Shortfall/Surplus (-/+)		479	547	276

It is also important to note that in the end what matters is the actual capacity and demand especially for the evening period when the peak is experienced and that if peak demand exceeds available actual capacity, that some load must be shed. This information is tabulated in Table 4. 6.

Whereas Table 4. 6 shows the summary of the demand data it is of value to look at the regionalized system peak demand on the system as seen on Table 4. 7.

Table 4. 6: Summary Actual Recorded Sample Power Balance

	Evening Peak Period
Actual Available Plant Capacity, MW	1,987
Actual Peak Demand (Sustained), MW	1,864
Load Shedding*, MW/MWh	**Nil**

Table 4. 7: Sample Regionalized Peak System Demand

Region	Simultaneous Peak (MW) At 2000Hr		Non-Simultaneous Peak (at various times)	
	MW	Percentage Energy Distribution (%)	MW	Time, Hr.
Nairobi North/South /West	882.01	51.21	882.01	20.00
Coast	279.37	17.48	279.37	20.00
West Kenya/ N. Rift/C. Rift/S. Nyanza	357.03	21.06	367.24	19.30
Mt Kenya/ North Eastern	202.44	10.26	202.44	20.00
***System Gross**	1,864.43	100.00	1,864.43	20.00

4.2.6: Sample Generation Prevailing Conditions

On the other side of demand is the need to meet it and this is done by the various generation units as summarized in Table 4. 8. Here, dispatched, MWh means allocated (requested) energy from the national control center for a particular generation unit and when there is a negative % deviation; it means that Actual (MWh) generated energy fell short of the requested allocation.

Table 4. 8: Generation Summary Sample

Generation	Dispatched,MWh	Actual (MWh)	% Deviation	%of Actual Generation
Main Hydro	10,162	10,515	3%	31%
Geothermal	15,293	15,217	-1%	45%
Thermals	1,608	1,881	17%	6%
GT Muhoroni	72	85	18%	0.3%
UETCL Import	225	308	37%	1%
Small Hydros	651	657	1%	2%
Wind	4,852	4,629	-5%	13.8%
Biomas	0	0	0%	0.0%
Garissa Solar	237	203	-15%	0.6%
Total	33,101	33,493	1%	100%

For the purpose of clarity and completeness; the main hydro plants as outlined in Table 4. 8 and maintained by KenGen include: Sondu Miriu, Tana, Tarlwel and The Seven Folks; the main diesel, geothermal and Heavy Fuel Oil (HFO) power plants and their generation are outlined in Table 4. 9. These thermal plants are maintained by KenGen, various IPPs and Co-generators.

Geothermal being the main source of energy on the grid with a share of about 45% is indicative of a grid that is highly integrated with RES. Further interrogation of dispatch logs revealed that on the said sampled day, about 1154 MWh of geothermal energy was curtailed citing low night demand and the abundance of Lake Turkana Wind Power (LTWP); a situation that is not uncommon and which presents opportunities for GSES and more so for arbitrage and peaking services provision.

Further the dispatch logs showed that despite the curtailment of cheap power from geothermal, the more expensive power from diesel and HFO was dispatched in various regimes as summarized in Table 4. 10. Some of the mandatory dispatches such as the IBP II can be addressed by installing a BESS.

Table 4. 9: Sample Thermal Production

PLANT	Actual (MWh)
KenGen GTs	85
KenGen Geothermal	12,322
KenGen Diesel (KDP I)	58
KenGen Diesel (KDP III)	78
Tsavo Diesel (KDP II)	360
Iberafrica Diesel – 2	41
Wind Total	4,629
OrPower4 Geothermal	2,895
Thika Power	99
Garissa Solar	203
Rabai Power	1,174
Gulf Power	37
Triumph Power	35
Mumias	0
Bio Joule	0

Table 4. 10: Sample Circumstantial Thermal Dispatch

<table>
<tr><th colspan="5">MANDATORY DISPATCH</th></tr>
<tr><th>PLANT</th><th colspan="2">DISPATCH REGIME</th><th colspan="2">REASON</th></tr>
<tr><td>Coast Plants</td><td colspan="2">90 MW –Day & 32 MW-Night</td><td colspan="2">Voltage support & limit voltage swings.</td></tr>
<tr><td>IBP II</td><td colspan="2">0 MW –Day& 15 MW -Peak</td><td colspan="2">De-load Juja-Dandora lines and Nairobi Voltage support.</td></tr>
<tr><td>Thika Power</td><td colspan="2">0 MW- Day & 33 MW-Peak</td><td colspan="2">Merit order consideration.</td></tr>
<tr><td>Gulf Power</td><td colspan="2">0 MW –Day & 16 MW-Peak</td><td colspan="2">Merit order consideration.</td></tr>
<tr><td>Triumph</td><td colspan="2">0 MW –Day & 15 MW-Peak</td><td colspan="2">Merit order consideration.</td></tr>
<tr><td>GT Muhoroni</td><td colspan="2">15 MW –Day & 28 MW –Peak</td><td colspan="2">Western Kenya Voltage support.</td></tr>
<tr><th colspan="4">DISPATCH DEVIATION</th><th></th></tr>
<tr><th>PLANT</th><th>ACTUAL(MWH)</th><th colspan="2">DISPATCHED(MWH)</th><th>REASON</th></tr>
<tr><td>Tsavo Diesel (KDP II)</td><td>360</td><td>74</td><td></td><td>Low LTWP output at peak.</td></tr>
</table>

4.2.7: System Constraints

It is important to note that besides the main power plants already discussed, the system operator also takes ownership and control of various off-grid stations that range from as little as the 0.14MW in Elwak to as much as the 4.2MW plant in Wajir in capacity.

The system operator uses various communication apparatus at his disposal including SCADA to monitor and control various assets in the system. For various reasons which are almost always tied to a fault or a scheduled and/or required maintenance of the particular plant, some of the system resources are not always available. The capacity that was deemed unavailable on this particular sample period was right at about 127MW seen in Table 4. 11. The system operator also reported various prevailing conditions as outlined in Table 4. 11, Table 4. 12 and Table 4. 13.

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Table 4. 11: Sample Unavailable Generating Units

Plant	**Remarks**	**Effective Capacity lost, MW**
	KenGen	
Tana	Declared 14.0 MW.	6.00
Masinga	Runner overhaul.	20.00
Muhoroni GTs	Generator vibrations.	27.00
KDP I	Tripped on high oil mist detector.	12.00
	Declared 42 MW.	
Olkaria II	Broken turbine blade.	35.00
	Declared 66 MW.	
	IPPs/ EPP	
Mumias Cogen.	Disconnected.	21.50
Triumph	Planned outage.	5.40
Total Effective Capacity Unavailable, MW		**126.90**

Looking further into the fault situation in the system, Table 4. 12 reveals that there are a number of reactive power equipment that are not fully functional which means that the system operator is not able to exercise precise control on the reactive power balance component of the grid, a situation the proposed BESS is likely to alleviate.

Table 4. 12: Sample Reactors Status

Substation	Status
Embakasi	Bank 1-Step 7 faulty.
Juja Road.	Entire Bank 1 off. Bank 2 Steps 1 and 3 faulty.
Ruaraka	Entire Bank 2 Off. Bank 1 Step 2 faulty.
Nairobi North	Bank 1-Step 4 faulty.
Eldoret	All Steps ok.
Kegati	All Steps working but not switching automatically.
Kisumu	All Steps ok.
Chemosit	Bank 2-Step 2 faulty.
Suswa	Bank 1&2 faulty.

Analysis of the loading of the various equipment in the grid also revealed opportunities for arbitrage and peaking service provision. For the lines and equipment that are normally highly loaded, we can install the BESS on the load side so that when the loading is minimal, charging can be scheduled and dissipated once loading is normal and the same can be done for peak shaving on the equipment that are heavily loaded during peak times.

Table 4. 13: Sample Salient Equipment Loading

Equipment/ Substation/Lines	Rating in MVA	Remarks
Juja-Dandora lines	150 MVA	Highly loaded normally.
Suswa-N/North lines	250 MVA	Highly loaded normally.
N/North-Dandora lines	250 MVA	Highly loaded normally.
Olkaria I-Naivasha	150 MVA	Highly loaded normally.
Naivasha-Lanet lines	81 MVA	Highly loaded normally.
Muhoroni-Chemosit line	81 MVA	Highly loaded at Peak.
Lessos-Muhoroni line	81 MVA	Highly loaded at normally.
Kutus ex Masinga	81 MVA	Highly loaded at Peak.

The other notable observable dispatch feature was that the Kenyan Grid imported an average of 250MWh of energy with peak capacity draws of about 50MW at the evening peak hours on a daily basis; situation that can be remedied with the utilization of BESS to cater for both the energy and peak power needs on the Kenyan grid.

4.3: Optimal Battery Size and Candidate Placement Locations

From the analysis done it was determined that the Kenyan grid needed a battery of about 1670MWh of energy and 372MW in power if it were to be a single unit. This determination was done from the area under the peak curve of the national generation demand with Tuesday chosen for the case study.

The placement of this unit while useful after performing load flow on the grid model especially placement in the Nairobi Region in our grid model, better results were gained when we had smaller BESS units being placed at the distribution buses of the various regions according to the specifications in Table 4.14 also obtained from plot area analysis.

The candidate grid locations were set as the following distribution buses: Juja and Dandora for Nairobi Region, Webuye-Lessos combined bus for the Western Region, Mang'u-Kiambere for the Mt.Kenya Region and Mombasa for the Coast Region. Similar to the single unit model the sizes of the reginal batteries were determined from the areas under the load curves. The sizes of the transformers for coupling the Li-Ion BESS are also included in the table assuming a 0.25C rate of charge and discharge. Figure 4.9 depicts the area analyzed for both national and regionalized battery sizing.

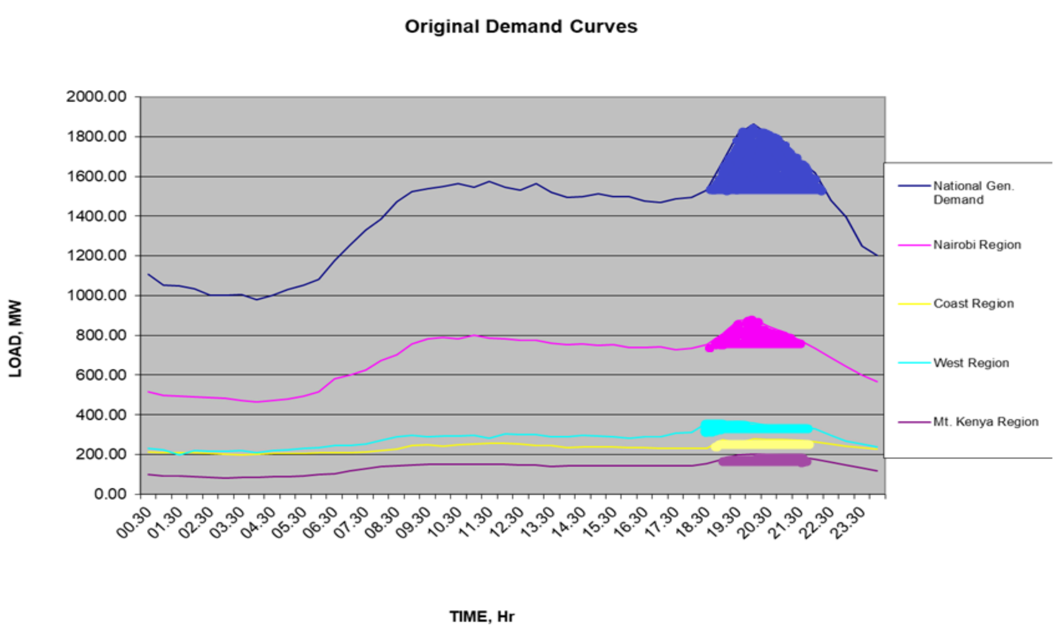

Figure 4. 9: Peak Demand Energy and Power Demand Analysis

Table 4. 14: Optimal Regionalized BESS Sizing

Region	BESS Power (MW)	BESS Capacity (MWh)	Transformer (MVA)
Nairobi	130	600	150
West	55	250	75
Coast	50	225	75
Mt. Kenya	60	250	75

4.4: Load Flow Results for the Grid-Model with Li-Ion BESS

With the grid model validated, we then went on to collect load flow data using the grid model and using the battery model which was toggled between being a source and a sink. All the BESS systems were set to bulk charge between 0100hrs and 0500hrs when demand is low and quasi-float charge between 0500hrs and 1800hrs. Further, the BESSs were to discharge during peak demand time between 1800hrs and 2230hrs and this enabled the stacking of both arbitrage and peaking service provision.

Performing load flow on the modelled grid yielded the load flow results tabulated in Appendix IV for which interest was drawn on the active power load flow results which when plotted resulted in the curves shown in Figure 4.10.

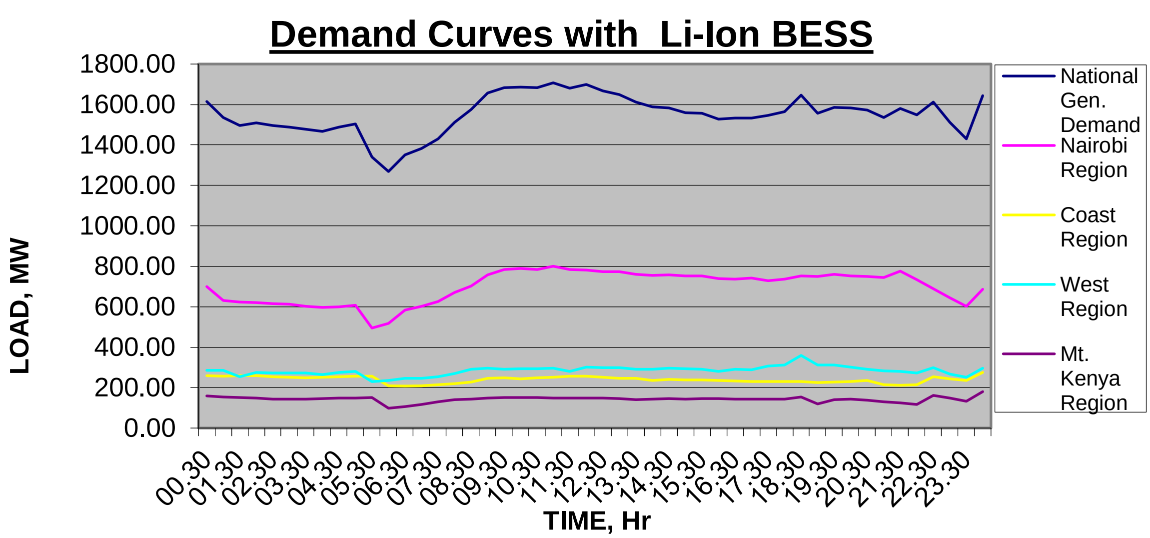

Figure 4. 10: Resulting Demand Curves

4.5: Analysis for Peaking Capacity and Arbitrage Service Provision

From Figure 4.10, it can be seen that the Li-Ion BESSs can provide both peaking capacity and Arbitrage services to the grid but the question would then be what is the cost benefit analysis of having such a system? What follows now is the financial analysis of having said BESSs on the Kenyan Grid according to the prevailing energy landscape/market in Kenya.

4.5.1: Levelized Cost of Storage (LCOS)

According to Tobiah et.al. [120] the levelized cost of a new Li-Ion BESS stands at 211($/MWh) which can also be expressed as 0.211($/KWh). This means that the design BESS cost would average as shown in Table 4. 15: LCOS of Design Li-BESS.

Table 4. 15: LCOS of Design Li-BESS

Region	BESS Power (MW)	BESS Capacity (MWh)	Cost in Dollars ('000 $)	Cost in Kenyan Shillings ('000 KES)
Nairobi	130	600	126.6	15369.24
West	55	250	52.75	6403.85
Coast	50	225	47.475	5763.465
Mt. Kenya	60	250	52.75	6403.85
TOTALS		**1325**	**279.575**	**33940.405**

4.5.2: Opportunities for Arbitrage

On average about 1200MWh of Geothermal energy is curtailed per day mostly due to high energy output of the LTWP. From Table 4. 2 the generation cost of geothermal plants averages at 6.5 KES/KWh with an average variable cost associated of about 3 KES/KWh. This means that the curtailed energy would cost 7.8M KES to generate. Assuming that the rest of the energy to make up 1325MWh is topped off by cheap wind and solar RES the energy would cost around 8M KES to generate.

During peak hours when the stored energy is being dispatched, the consolidated cost of energy (CCE) in Kenya sits at right about 12.64KES/KWh and this means that the stored energy would fetch about 16.748M KES for the day. This gives a simple ROI for the day as:

$$ROI_{day} = \frac{Net\ Return}{Cost} * 100 = \frac{16.748-8}{8} * 100 = 109.35\% \qquad \text{Eq 4.2}$$

An ROI of above 100% indicates that the project is viable on the basis of arbitrage alone.

4.5.3: Opportunities for Peaking Capacity Service Provision

While there is no formalized manner in which peak capacity service provision is compensated and that the tariffs that exist withing the country's energy markets do not accommodate such a service; from dispatch analysis we do know that the system operator keeps spinning reserves of about 82MW and demands about 50MW from UETCL. Further from analysis, we know that the system would demand 300MW of peak power above base load.

The only way assessment of the potential for Peak Capacity service provision could be done was by way of determining the avoided cost. From the dispatch logs, it was evident that the peak energy on the Kenyan grid was provided for by the more expensive thermal power plants and partially by the UETCL. An average of the available thermal power plants cost 17.401 (KES/KWh) to generate as seen in Table 4. 16.

Table 4. 16: Thermal Generation Costs

Generation Unit	Kipevu III Diesel	Kipevu Diesel I	Rabai Power2	Rabai Power1	Triumph Power2	Thika Power2	Tsavo Power	Triumph Power1	Thika Power1	Iberafrica -Additional	Gulf Power	Iberafrica -Existing	UETCL (Tie Line)	Average (KES/KWh)
Generation Cost (KES/KWh)	13.581	12.326	15.16	15.688	17.587	16.611	17.462	18.132	17.572	20.046	19.683	21.402	20.963	17.401
Variable Cost (KES/KWh)	10.73	10.813	11.492	12.021	13.219	13.317	13.374	13.763	14.277	15.702	16.285	17.788	20.963	14.13415385

For analysis in addition to the 1325MWh of energy required during peak operation we also need to add 82MW of spinning reserves for 24hrs giving an energy of 1968MWh that could be voided if we make use of the Li-Ion BESS for spin reserve.

This means that the avoided costs for both peaking capacity and spinning reserves are as shown in Table 4. 17.

Table 4. 17: Avoided Costs

Service	Avoided Energy (MWh)	Avoided Costs (‘000 KES)
Peaking Capacity	1325	23056.325
Spinning Reserve	1968	27816.01477

$$ROI_{day} = \frac{Net\ Return}{Cost} * 100 = \frac{(23.056325+27.81601477)-24.87552}{24.87552} * 100 = 104.51\% \qquad \text{Eq 4.3}$$

4.6: Placement Algorithm

In addition to quantifying the opportunities for arbitrage and peaking service provision, one of the other key deliverables of the study was to come up with an algorithm for placement of BESS systems in the grid. Figure 4.11 shows the developed and recommended algorithm for sizing and placement for a Li-Ion BESS with regards to the two services.

4.7: Validation

Comparing the results obtained with those Metz, D. et al got in [107], where investigations were done to determine the viability of arbitrage in a 15-minute and 60-minute interval; we also came to the same conclusion that the longer the arbitrage period or storage period the better the economics of arbitrage. For our case, a simple ROI 109% was possible when doing storage intervals of about 4 hours while shorter periods yielded ROI values lower than 102% just as Metz, D, had concluded that the profits gained in a 15-minute arbitrage period did not warrant the capital costs involved in development unlike the 60-minute period that was deemed viable from the study [108].

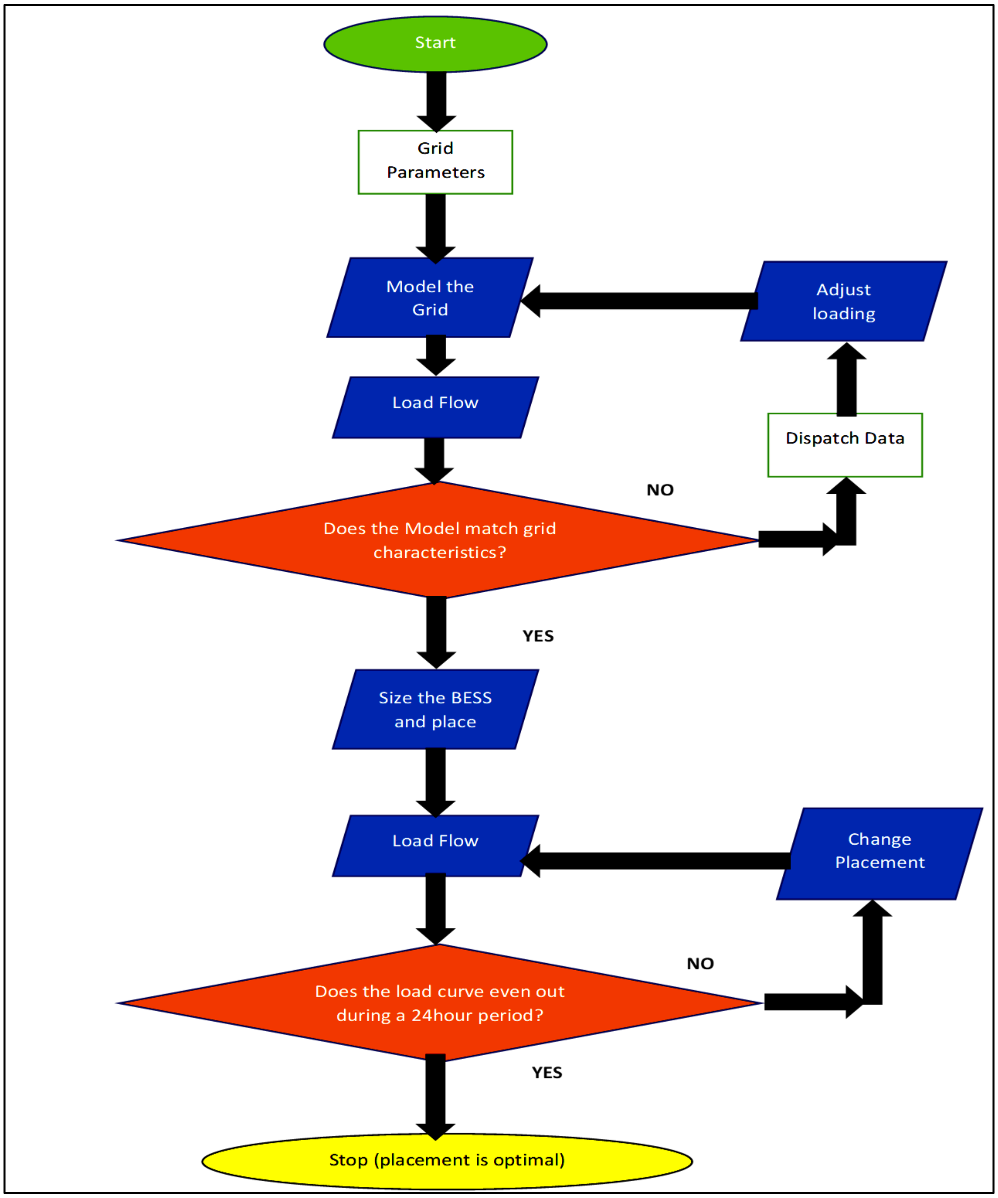

Figure 4. 11: Developed Placement Algorithm

Grid operations were worked on using dispatch data together with load parameters by the system operator so that the load curves closely mimicked those in Figure 4.4 which was our case study of choice. This means that whatever results that were gotten after the fact had a close correlation of what would happen to the grid when the Li-Ion BESS were to be injected into the grid.

Further the choice of 33kV buses on the candidate grid locations is supported by numerous studies that point to distribution buses as the best placement locations for placement of GSES. As such the choice of 33kV buses is validated since in Kenya, the distribution level voltages start at 33kV.

4.8: Chapter Conclusion

From analysis it is clear that there is potential for GSES for Arbitrage and Peaking Service provision on the Kenyan Grid where best results were obtained when a Li-Ion BESS was placed at distribution levels and distributed according to appropriately sized BESSs in the different Kenyan Buses.

In the end, Arbitrage alone had an ROI of 109.35% while Peaking Capacity had an ROI of 104.51% in avoided costs. The challenge come when it was time to combine the two benefits; a simple combination yielded an ROI of 397.55%. Since the two benefits are gotten at the same time on the same grid location, it means that the two cannot be charged separately and thus the ROI is only but a trivial conclusion. Other benefits realized as a consequence were line relief and spinning reserve services provision.

Chapter 5: Conclusions and Recommendations

5.1: Conclusions

The work set out to assess the viability of arbitrage and peak service provision for the Kenyan grid and asses candidate grid locations for placement of such a BESS. Using dispatch characteristics, we were able to size the Li-Ion BESS to be applied on the grid to 1325MWh. The BESS was later split into four regionalized and appropriately sized BESSs for optimal placement.

Using system data, a 14-bus grid model was modelled in DigSilent Power Factory software and the system operator used dispatch data to match the grid characteristics. After the model was adequately matched to the prevailing conditions, the system was then injected with the designed BESSs for assessment of placement appropriateness.

The best results were obtained when the BESSs were placed at the 33kV distribution busses of the 4 regions according to Table 4.14. In the end arbitrage and peaking service provision although lacking a clear structure in Kenya's energy market were deemed viable. Arbitrage was determined to have an ROI of 109.35% while Peaking Capacity had an ROI of 104.51% in avoided costs. Steps in development of a placement algorithm were also made and algorithm in Figure 4.11 is recommended for sizing and placement for a Li-Ion BESS with regards to the two services.

5.2: Recommendations

5.2.1: Further Work

With regards to further studies, it is recommended that system operations be automated; during the study the system designer was also the system operator and the human factor limited the study in terms of time and resolution. This would further enable the assessment to be done on more complex models (models with more buses).

5.2.2: Adoption of Results

During analysis, there was an apparent gap when it came to the Kenyan energy market with regards to the provision of services that GSES offers. It is therefore recommended that the Kenyan energy market adopts regimes to compensate Arbitrage and Peaking Service Provision among other services for the grid whether stacked or not. This thesis has demonstrated the viability of said services on the local grid and the adoption of the recommended service provision regimes would see the expansion of the Kenyan energy market.

5.3: Contributions

The successful conclusion of the works saw a significant contribution placement of BESS in grid systems: The algorithm as outlined in Figure 4.10 is a first of its kind in the world of GSES and can be used on any grid for placement for both arbitrage and peaking services provision provided all relevant data on grid characteristics is available. The same algorithm can also be utilized for placement for other service provisions with appropriate modifications to suit use-cases.

The potential for GSES was also demonstrated for the Kenyan grid and the work can be used as reference for any investor seeking to establish peaking capacity and arbitrage services for the Kenyan Grid. The work also showcased the weaknesses in the Kenyan energy markets with regards to the GSES services. Additionally, the study also saw significant gains when it came to modelling the Kenyan Grid; the Kenyan grid was modelled on a 14-bus system which is small enough that fast analysis can be done on the same as opposed to the traditional 39-bus system.

References

[1] Robert Belfield; "The Niagra System – The Evolution of Electric Power Complex at Niagra Falls – 1883 – 1896"; Proceedings of the IEEE; Volume: 64, Issue 9: Publication Year: 1976.

[2] M. Safiuddin; "History of Electric Grid"; University at Buffalo, the State University of New York, 2013. https://www.researchgate.net/publication/312189966

[3] Voltages in Power Lines https://www.electrical4u.com/voltage-in-power-lines/ Accessed October 2022.

[4] Tony Samaritano, Power Systems: Secondary Distribution Systems; Rowan University, 2012.

[5] Fundamentals of Electricity: Transmission Voltages. https://c03.apogee.net/mvc/home/hes/land/el?utilityname=med&spc=foe&id=4454 Accessed October 2022.

[6] The Need Project; SwitchCurricula-Secondary-ElectricityFActsheet.pdf. Manassas, Virginia, 2013. Pdf available at www.NEED.org

[7] Fundamentals of Electricity: Distribution Voltages. https://c03.apogee.net/mvc/home/hes/land/el?utilityname=mp&spc=foe&id=4476 Accessed October 2022.

[8] Jordan Radosavljević; "Centralized versus distributed electricity generation," Faculty of Technical Sciences, University of Priština in Kosovska Mitrovica, Serbia. Email correspondence to jordan.radosavljevic@pr.ac.rs

[9] Distributed generation: international experiences and comparative analyses by Nivalde de Castro e Guilherme Dantas. ‑ Rio de Janeiro : Publit, 2017.

[10] Quadrennial technology review; An assessment of energy technologies and research opportunities Chapter 3: Enabling Modernization of the Electric Power System, September 2015.

[11] Alexandros Korkovelos, Hisham Zerri, Mark Howells, Morgan Bazilian, H-Holger Rogner, and Francesco Fuso Nerini; "Sustainability: A Retrospective Analysis of Energy Access with a Focus on the Role of Mini-Grids," Switzerland, February 2020.

[12] Sustainable Energy: The biggest wind farm in Africa is officially up and running. https://www.cnbc.com/2019/07/22/the-biggest-wind-farm-in-africa-is-officially-up-and-running.html Accessed October 2022.

[13] The 50 MW Garissa solar power plant. https://www.rerec.co.ke/index.php?option=com_content&view=article&id=53&Itemid=234 Accessed October 2022.

[14] Energy Regulatory Commission and Rencon Associates Ltd; "Solar Photovoltaic Industy Baseline Study," Kenya, October 2020. A copy of the report is available for download at the commission's website www.epra.go.ke

[15] IRENA (2020), *Innovation landscape brief: Pay-as-you-go models*, International Renewable Energy Agency, Abu Dhabi.

[16] IEA.Worldenergyoutlook2013.InternationalEnergyAgency; 2013. Available at: ⟨http:/www.worldenergyoutlook.org/media/weowebsite/2013/WEO2013_ Ch06_Renewables.pdf ⟩.

[17] Renewable Energy: The Clean Facts https://www.nrdc.org/stories/renewable-energy-clean-facts Accessed October 2022.

[18] Mills, Andrew D., Millstein, Dev, Wiser, Ryan H., et al; "Impact of Wind, Solar, and Other Factors on Wholesale Power Prices: An Historical Analysis—2008 through 2017," Lawrence Berkeley National Laboratory, USA, November 2019.

[19] Denholm, Paul, Kara Clark, and Matt O'Connell. 2016. *On the Path to SunShot: Emerging Issues and Challenges in Integrating High Levels of Solar into the Electrical Generation and Transmission System*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-65800. http://www.nrel.gov/docs/fy16osti/65800.pdf

[20] IRENA (2017), Planning for the Renewable Future: Long-term modelling and tools to expand variable renewable power in emerging economies, International Renewable Energy Agency, Abu Dhabi.

[21] IRENA (June 2012), Renewable Energy Technologies: Cost Analysis Series. Volume 1: Power Sector Issue 4/5, Solar Photovoltaics. International Renewable Energy Agency, Abu Dhabi.

[22] IRENA (June 2012), Renewable Energy Technologies: Cost Analysis Series. Volume 1: Power Sector Issue 5/5, Wind Power. International Renewable Energy Agency, Abu Dhabi.

[23] Pramod Jain; "Energy storage in grids with high penetration of variable generation," Asian Development Bank, Philippines, February 2017.

[24] Benefit Analysis of Energy Storage: Case Study with Sacramento Municipal Utility District. EPRI, Palo Alto, CA: 2011. 1023591.

[25] Derek Stenclik, Paul Denholm, and Babu R. Chalamala. "The Role of Energy Storage for Renewable Integration," Sandia Corporation, USA, 2017.

[26] Grid Energy Storage. U.S. Department of Energy, 1000 Independence Ave., SW Washington, DC 20585. December 2013.

[27] DG ENER Working Paper: The future role and challenges of Energy Storage. European Commission Directorate-General for Energy, Brussels 24-26, rue Jean-André de Mot / Jean-André de Motstraat B-1049. October 2014.

[28] Denholm, Paul. "Batteries and Storage: Truly a Game Changer?" presented at the JISEA 2018 Annual Meeting in Golden, CO. April 4, 2018. https://www.jisea.org/assets/pdfs/denholm-jisea-2018.pdf.

[29] Denholm, Paul, and Robert Margolis. *The Potential for Energy Storage to Provide Peaking Capacity in California under Increased Penetration of Solar Photovoltaics*. NREL/TP-6A20-70905. Golden, CO: NREL. March 2018. https://www.nrel.gov/docs/fy18osti/70905.pdf.

[30] Eichman, Josh, Paul Denholm, Jennie Jorgenson and Udi Helman. 2015. Operational Benefits of Meeting California's Energy Storage Targets. NREL/TP.5400.65061. Golden, Co: National Energy Renewable Laboratory.

[31] Palchak, David, Jaquelin Cochran, Ali Ehlen, Brendan McBennett, Michael Milligan, Ilya Chernyakhovskiy, Ranjit Deshmukh, et al. *Pathways to Integrate 175 Gigawatts of Renewable Energy into India's Electric Grid, Vol. I—National Study*. Golden, CO: NREL. June 2017. https://www.nrel.gov/docs/fy17osti/68530.pdf.

[32] REN21. 2017. *Renewables 2017 Global Status Report* (Paris: REN21 Secretariat). ISBN 978-3-9818107-6-9.

[33] Ndombi, E., (2023, January 25). 'Matatu investors feel electric buzz': Matatu investors now

eye electric vehicles. The Standard: Enterprise | The Entrepreneurs' Magazine. https://transformative-mobility.org/wp-content/uploads/2023/06/230125_NAIROBI_TheStandard_News.pdf

[34] Ministry of Energy and Petroleum and Lahmeyer International GmbH (2016) Power Generation and Transmission Master Plan, Kenya Long Term Plan 2015 - 2035 – Vol. I.

[35] Business Daily: Kenya power on the spot for ignoring Cheaper Electricity https://www.businessdailyafrica.com/bd/corporate/companies/kenya-power-on-the-spot-ignoring-cheaper-electricity-2485982 Accessed November 2022.

[36] Business Daily: Green energy firms face tough times on production freeze https://www.businessdailyafrica.com/bd/economy/green-energy-firms-tough-times-on-production-freeze-2565738 Accessed November 2022.

[37] Anton Eberharda, Katharine Gratwick and Laban Kariuki, "Kenya's lessons from two decades of experience with independent power producer," Elsevier Ltd, Amsterdam, Netherlands, April 2018.

[38] Thomas Bowen, Ilya Chernyakhovskiy and Paul Denholm, "Grid-Scale Battery Storage

Frequently Asked Questions,” NREL/TP-6A20-74426. September 2019.

[39] R. Ramakumar and P. Chiradeja, “Distributed generation and renewable energy systems,” IECEC ’02. 2002 37th Intersociety Energy Conversion Engineering Conference, 2002.

[40] California ISO (2016). What the duck curve tells us about managing a green grid. 250 Outcropping Way, Folsom, CA 95630 | 916.351.4400

[41] Introducing Megapack: Utility-Scale Energy Storage htt\ps://www.tesla.com/en_AU/blog/introducing-megapack-utility-scale-energy-storage Accessed November 2022.

[42] International Finance Group (IFC) (2020). Emerging Energy Solutions Series. Battery Storage: A Primer.

[43] Alaa Mohd, Egon Ortjohann, Andreas Schmelter, Nedzad Hanmsic, Danny Morton. Challenges in integrating distributed energy systems into future smart grid. IEEE International Symposium on Industrial Electronics, June 30-July 2, 2008.

[44] Chen H., et al.; ”Progress in Electrical Energy Storage Systems: A Critical Review”, Progress in Natural Science, 2009.

[45] Hussein Ibrahim and Adrian Ilinca,” Techno-Economic Analysis of Different Energy Storage Technologies” IntechOpen Limited, 5 Princes Gate Court, London, SW7 2QJ, UK, 2013.

[46] Baxter, R., “Energy Storage-A Nontechnical Guide”, PennWell Corporation, Oklahoma, 2006.

[47] Gonzalez, A., Ó'Gallachóir, B., McKeogh, E. & Lynch, K. “Study of Electricity Storage Technologies and Their Potential to Address Wind Energy Intermittency in Ireland”. Sustainable Energy Ireland, 2004.

[48] MITEI (2015). The Future of Solar Energy. (MIT) ISBN (978-0-928008-9-8).

[49] Haisheng Chen, Thang Ngoc Cong, Wei Yang, Chunqing Tan, Yongliang Li, Yulong

Ding. Progress in electrical energy storage system: A critical review. Progress in Natural

Science. July 2008.

[50] Canan Acar, “A comprehensive evaluation of energy storage options for better sustainability”. John Wiley & Sons, Ltd. Int J Energy Res. 2018; 42:3732–3746.

[51] Connolly, D. (2010). A Review of Energy Storage Technologies: For the integration of fluctuating renewable energy.

[52] Wong, I. H., An Underground Pumped Storage Scheme in the Bukit Timah Granit of Singapore.*Tunnelling and Underground Space Technology,* 11(4), pp. 485-489, 1996.

[53] Ramos, J.S. and Ramos, H.M. Sustainable application of renewable sources in water pumping systems: Optimized energy system configuration. Energy Policy 2009, 37, 633-643.

[54] Anagnostopoulos, J. S. & Papantonis, D. E., Pumping station design for a pumped-storage wind-hydropower plant. *Energy Conversion and Management,* 48(11), pp. 3009-3017, 2007.

[55] Gonzalez, A., Ó'Gallachóir, B., McKeogh, E. & Lynch, K. Study of Electricity Storage Technologies and Their Potential to Address Wind Energy Intermittency in Ireland. *Sustainable Energy Authority of Ireland*, 2004.

[56] Farihan Mohamad, Jiashen Teh 1, Ching-Ming Lai and Liang-Rui Chen (2018). Development of Energy Storage Systems for Power Network Reliability: A Review.

[57] Fulihara, T., Imano, H. & Oshima, K., Development of Pump Turbine for Seawater Pumped-Storage Power Plant. *Hitachi Review,* 47(5), pp. 199-202, 1998.

[58] Huggins, R.A. Energy Storage; Springer: Berlin, Germany, 2010; Volume 391.

[59] Amrouche, S.O.; Rekioua, D.; Rekioua, T.; Bacha, S. Overview of energy storage in renewable energy systems. Int. J. Hydrog. Energy 2016, 41, 20914–20927.

[60] Kousksou, T.; Bruel, P.; Jamil, A.; El Rhafiki, T.; Zeraouli, Y. Energy storage: Applications and challenges. Sol. Energy Mater. Sol. Cells 2014, 120, 59–80.

[61] Ioannis Hadjipaschalis, Andreas Poullikkas and Venizelos Efthimiou (2008).Overview of current and future energy storage technologies for electric power applications.

[62] Chen, H.; Cong, T.N.; Yang,W.; Tan, C.; Li, Y.; Ding, Y. Progress in electrical energy storage system: A critical review. Prog. Nat. Sci. 2009, 19, 291–312.

[63] Investigation on storage technologies for intermittent renewable energies: evaluation and recommended R&D strategy, INVESTIRE-NETWORK (ENK5-CT-2000-20336), Storage Technology Reports (http://www.itpower.co.uk).

[64] Buckles, W. & Hassenzahl, W., 2000. Superconducting Magnetic Energy Storage. IEEE Power Engineering review 2000; 16: 16–20.

[65] Gardner, P., McGoldrick, S. H. & Ó'Gallachóir, B., The effect of increasing wind penetration on the electrcity systems of the Republic of Ireland and Northern Ireland., *Proc. of the European Wind energy Conference*, pp. 16-19, Madrid.

[66] Mustafa E. Amiryar and Keith R. Pullen. A Review of Flywheel Energy Storage System Technologies and Their Applications. Applied Sciences 2017.

[67] Baxter, R., Energy Storage - A Nontechnical Guide, PennWell Corporation, Tulsa, Oklahoma, USA, 2006.

[68] Cheung, K. Y., Cheung, S. T., Navin De Silva, R. G., Juvonen, M. P., Singh, R. & Woo, J. J. Large-Scale Energy Storage Systems. *Imperial College London*, 2003.

[69] Investigation on storage technologies for intermittent renewable energies: evaluation and recommended R&D strategy, INVESTIRE-NETWORK (ENK5-CT-2000-20336), Storage Technology Reports, 2000.

[70] Koohi-Kamali, S.; Tyagi, V.; Rahim, N.; Panwar, N.; Mokhlis, H. Emergence of energy storage technologies as the solution for reliable operation of smart power systems: A review. Renew. Sustain. Energy Rev. 2013, 25, 135–165.

[71] Suberu, M.Y.; Mustafa, M.W.; Bashir, N. Energy storage systems for renewable energy power sector integration and mitigation of intermittency. Renew. Sustain. Energy Rev. 2014, 35, 499–514.

[72] O. ACHKARI, A. EL FADAR (2018).Renewable Energy Storage Technologies - A Review.

[73] IEA-ETSAP and IRENA. Thermal Energy Storage Technology Brief E17, January 2013.

[74] Satyawan Singh, Pradeep Kumar Sharma, Neeru Goyal, Prashant KumarTayal. Thermal Energy Storage: A Process to Increase Efficiency and to Save our Environment. ICLISEM 2016; 81-87.

[75] P. Medina, A. W. Bizuayehu, J. P. S. Catalão et al. (2014).Electrical Energy Storage Systems: Technologies' State-of-the-Art, Techno-Economic Benefits and Applications Analysis. 47th Hawaii International Conference on System Science.

[76] Energy Storage Association, www.electricitystorage.org. Accessed November, 2022.

[77] Makansi J, Abboud J. Energy storage: the missing link in the electricity value chain-An ESC White Paper. Energy storage Council 2002; p. 1-23.

[78] Alaa Mohd, Egon Ortjohann, Andreas Schmelter, Nedzad Hamsic, Danny Morton. Challenges in integrating distributed Energy storage systems into future smart grid. IEEE International Symposium on Industrial Electronics, June 30 - July 2, 2008.

[79] Linden S. Bulk energy storage potential in the USA, current developments and future prospects. Energy 2006; 31:3446–57.

[80] Emerging Energy Storage Technologies in Europe. Rapport Frost & Sullivan; 2003.

[81] Haisheng Chen, Thang Ngoc Cong, Wei Yang, Chunqing Tan, Yongliang Li, Yulong

Ding. Progress in electrical energy storage system: A critical review. Progress in Natural

Science. July 2008.

[82] H. Ibrahim, A. Ilinca, J. Perron, Energy storage systems—Characteristics and comparisons, Renewable and Sustainable Energy Reviews, Volume 12, Issue 5, June 2008, Pages 1221–1250.

[83] Technology and Comparisons, Electricity Storage Association, 5th November 2007, http://electricitystorage.org/tech/technologies_comparisons.htm

[84] Jim Eyer, Garth Corey. Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide. SANDIA REPORT SAND2010-0815, February 2010.

[85] Mustafa Cagatay Kocer et al. (2019). Assessment of Battery Storage Technologies for a

Turkish Power Network. Sustainability 2019, 11, 3669; doi:10.3390/su11133669.

[86] The batteries that could make fossil fuels obsolete https://www.bbc.com/future/article/20201217-renewable-power-the-worlds-largest-battery Accessed December 2022.

[87] Asian Development bank (2018). Handbook on battery energy storage system.

[88] Chemistry LibreTexts 17.5: Batteries and Fuel Cells. Available online: https://chem.libretexts.org/Bookshelves/General_Chemistry/Book%3A_Chemistry_(OpenSTAX)/17%3A_Electrochemistry/17.5%3A_Batteries_and_Fuel_Cells Accessed November 2020.

[89] May, G.J.; Davidson, A.; Monahov, B. Lead batteries for utility energy storage: A review. J. Energy Storage 2018, 15, 145–157.

[90] Skyllas-Kazacos, M. Electro-chemical energy storage technologies for wind energy systems. Stand Alone Hybrid Wind Energy Syst. 2010, 323–365.

[91] Battery University. How to Prolong Lithium-Based Batteries. Available online: https://batteryuniversity.com/learn/article/how_to_prolong_lithium_based_batteries Accessed November 2022.

[92] European Parliament. MEPs Ban Cadmium from Power Tool Batteries and Mercury from Button Cells | News | European Parliament. Available online: http://www.europarl.europa.eu/news/en/pressroom/20131004IPR21519/meps-ban-cadmium-from-power-tool-batteries-and-mercury-from-button-cells Accessed November 2022.

[93] IEC. Electrical Energy Storage Executive Summary; IEC: Geneva, Switzerland, 2011.

[94] Baxter, R., Energy Storage - A Nontechnical Guide, PennWell Corporation, Tulsa, Oklahoma, USA, 2006.

[95] Breeze, P. Power System Energy Storage Technologies. In Power. Generation Technologies, 2nd ed.; Elsevier Ltd.: Oxford, UK; Boston, MA, USA, 2014; pp. 195–221.

[96] A. Gonzalez, B. Gallachir, E. McKeogh, and K. Lynch, “Study of electricity storage technologies and their potential to address wind energy intermittency in Ireland,” tech. rep., Sustainable Energy Research Group, University College Cork, 2004.

[97] Rajagopalan, R.; Balakrishnan, A. Innovations in Engineered Porous Materials for Energy Generation and Storage Applications; CRC Press: Boca Raton, FL, USA, 2018; ISBN 1138739022.

[98] E. Kodama and Y. Kurashima, “Development of a compact sodium sulphur battery,” *Power Engineering Journal*, vol. 13, no. 3, p. 136141, 1999.

[99] Suberu, M.Y.; Mustafa, M.W.; Bashir, N. Energy storage systems for renewable energy power sector.

integration and mitigation of intermittency. Renew. Sustain. Energy Rev. 2014, 35, 499–514.

[100] Kousksou, T.; Bruel, P.; Jamil, A.; El Rhafiki, T.; Zeraouli, Y. Energy storage: Applications and challenges. Sol. Energy Mater. Sol. Cells 2014, 120, 59–80.

[101] Chen, H.; Cong, T.N.; Yang,W.; Tan, C.; Li, Y.; Ding, Y. Progress in electrical energy storage system: A critical review. Prog. Nat. Sci. 2009, 19, 291–312.

[102] www.cea.fr Accessed November 2022.

[103] Alotto, P.; Guarnieri, M.; Moro, F.; Stella, A. Redox Flow Batteries for large scale energy storage. In Proceedings of the 2012 IEEE International Energy Conference and Exhibition (Energycon), Florence, Italy, 9–12 September 2012; pp. 293–298.

[104] Kyle Bradbury (2010). Energy Storage Technology Review. https://www.researchgate.net/publication/265064873

[105] Power System Analysis | Compare the Gauss Seidel and Newton Raphson Methods of Load Flow Study. Available online: https://www.brainkart.com/article/Compare-the-Gauss-Seidel-and-Newton-Raphson-Methods-of-Load-Flow-Study_12416/ Accessed November 2021

[106] https://www.researchgate.net/figure/Flowchart-of-the-Newton-Raphson-method-for-load-flow-solution-of-power-system-network_fig2_332402309 Accessed December 2021

[107] https://www.researchgate.net/figure/Single-line-diagram-for-IEEE-14-bus-system_fig2_322140152 Accessed December 2022.

[108] Metz, D.; Saraiva, J.T. Use of battery storage systems for price arbitrage operations in the 15- and 60-min German intraday markets. *Electr. Power Syst. Res.* 2018, *160*, 27–36.

[109] Y. Zhang, S. Ren, Z. Y. Dong, Y. Xu, K. Meng, and Y. Zheng, “Optimal placement of battery energy storage in distribution networks considering conservation voltage reduction and stochastic load composition,” *IET Gener. Transm. Distrib.*, vol. 11, no. 15, pp. 3862–3870, 2017, doi: 10.1049/iet-gtd.2017.0508.

[110] S. B. Karanki, D. Xu, B. Venkatesh, and B. N. Singh, “Optimal location of battery energy storage systems in power distribution network for integrating renewable energy sources,” *2013 IEEE Energy Convers. Congr. Expo. ECCE 2013*, pp. 4553–4558, 2013, doi: 10.1109/ECCE.2013.6647310.

[111] Hameed, Z., Hashemi Toghroljerdi, S., Ipsen, H. H., & Træholt, C. (Accepted/In press). Placement of Battery Energy Storage for Provision of Grid Services – A Bornholm Case Study. In *Proceedings of 9th International conference in smart energy grid engineering* IEEE.

[112] Hameed, Z., Hashemi Toghroljerdi, S., & Træholt, C. (2020). Site Selection Criteria for Battery Energy Storage in Power Systems. In *Proceedings of 33rdCanadian Conference of Electrical and Computer Engineering* IEEE. https://doi.org/10.1109/CCECE47787.2020.9255678

[113] https://www.power-technology.com/marketdata/meru-county-energy-park-battery-energy-storage-system-kenya/ Accessed March 2022

[114] Africa Energy Market Place (2021). “Country Priority Plan and Diagnostic of the Electricity Sector- Kenya” https://www.afdb.org/sites/default/files/2021/11/22/kenya.pdf Accessed March 2022

[115] Rancilio, G., Lucas, A., Kotsakis, E., Fully, G., Merlo, M., Delfanti, M. and Masera, M. “Modeling a Large-Scale Battery Energy Storage System for Power Grid Application Analysis”. Energies 2019, 12, 3312; doi:10.3390/en12173312

[116] https://www.engineeringenotes.com/electrical-engineering/power-flow/newton-raphson-method-to-solve-power-flow-problem-electrical-engineering/25354 Accessed March 2022.

[117] https://www.digsilent.de/en/load-flow-analysis.html Accessed March 2022.

[118] Kerahroudi S.K., Alamuti M.M., Li F., Taylor G.A., Bradley M.E. (2014) Application and Requirement of DIgSILENT PowerFactory to MATLAB/Simulink Interface. In: Gonzalez-Longatt F., Luis Rueda J. (eds) PowerFactory Applications for Power System Analysis. Power Systems. Springer, Cham. https://doi.org/10.1007/978-3-319-12958-7_13

[119] M. Pedram, N. Chang, Y. Kim and Y. Wang, "Hybrid electrical energy storage systems," 2010 ACM/IEEE International Symposium on Low-Power Electronics and Design (ISLPED), 2010, pp. 363-368, doi: 10.1145/1840845.1840924.

[120] Tobiah Steckel, Alissa Kendall, Hanjiro Ambrose,” Applying levelized cost of storage methodology to utility-scale second-life lithium-ion battery energy storage systems,” Applied Energy, Volume 300,2021, 117309, ISSN 0306-2619.

16/11/2023

16/11/23
DR. MUSAU

APPENDICES

Appendix I: Originality Report

6/19/23, 9:09 AM — Turnitin - Originality Report - ERIC NDETO KYALO MSc. EEE Thesis

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Abstract Eric Ndeto Kyalo. Reg. No: F56/37513/2020 Email: ndeeto@students.uonbi.ac.ke Modelling and Optimized

Placement of a (Li-**Ion battery)-based Grid Scale Energy Storage System** for **the Kenyan Grid** [1]

The study modelled the Kenyan grid based 14-Bus and applied load flow analysis, simulation tools (on DigSilent Power Factory) together with analysis fordifferent test cases to equip policy makers, regulators and investors on the technical and economic limits of GSES and also the interaction between GSES andgrids integrated with RES. From analysis and simulation specific knowledge was gained

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Appendix II: Line Data

			220kV																	
S/n	From Bus Number	From Bus Name	To Bus Number	To Bus Name	Id	Line R (ohms)	Line X (ohms)	Charging B (uF)	In Service	Rate A	Length	R-Zero (pu)	X-Zero (pu)	B-Zero (pu)	Zero Seq G From (pu)	Zero Seq B From (pu)	Zero Seq G To (pu)	Zero Seq B To (pu)
1	1	ISINYA 220.00	204	SUSWA DUMMY 220.00	2	2.451	27.165	1.346	1	500	100	0.0443	0.2004	0.0915	0	0	0	0
2	2	ATHI RIVER 220.0	201	ISINYA 220.00	1	1.690	11.741	0.666	1	815	46.3	0.0205	0.0928	0.0424	0	0	0	0
3	101	ISINYA 220.00	204	SUSWA DUMMY 220.00	1	2.451	27.165	1.346	1	900	100	0.0443	0.2004	0.0915	0	0	0	0
4	101	ISINYA 220.00	322018	KATHI RIVER2220.00	1	1.690	11.741	0.666	1	815	46.3	0.0205	0.0928	0.0424	0	0	0	0
5	201	ISINYA 220.00	216	MARIAKANI 220.00	2	14.567	101.170	5.740	1	815	398.97	0.1766	0.7994	0.3650	0	0	0	0
6	202	RABAI DUMMY 22	216	MARIAKANI 220.00	2	2.218	12.760	0.243	1	274	29	0.0128	0.0581	0.0265	0	0	0	0
7	203	EMBA DUMMY 2	322019	CABLE-OHL 220.00	1	0.114	1.074	2.154	1	334.2	6.7	0.0030	0.0134	0.0061	0	0	0	0
8	205	EMBA-DUMMY2 2	206	CABLE-OHL2 220.00	1	0.114	1.074	2.154	1	334.2	6.7	0.0030	0.0134	0.0061	0	0	0	0
9	206	CABLE-OHL2 220.	322018	KATHI RIVER2220.00	1	0.918	5.280	0.100	1	274	12	0.0053	0.0240	0.0110	0	0	0	0
10	207	ISINYA3 220.00	209	SUSWA DUMMY2220.00	1	2.451	27.165	1.346	1	900	100	0.0443	0.2004	0.0915	0	0	0	0
11	207	ISINYA3 220.00	215	MARIAKANI 220.00	1	14.567	101.170	5.740	1	815	398.97	0.1766	0.7994	0.3650	0	0	0	0
12	208	RABAI DUMMY22	215	MARIAKANI 220.00	1	2.218	12.760	0.243	1	274	29	0.0128	0.0581	0.0265	0	0	0	0
13	210	KATHI DUMMY 22	322019	CABLE-OHL 220.00	1	0.918	5.280	0.100	1	274	12	0.0053	0.0240	0.0110	0	0	0	0
14	300	LOIY1 220.00	302	SUS1 220.00	1	10.168	113.382	6.323	1	900	430	0.1903	0.8616	0.3933	0	0	0	0
15	301	LOIY2 220.00	303	SUS2 220.00	2	10.168	113.382	6.323	1	900	430	0.1903	0.8616	0.3933	0	0	0	0
16	322004	KDANDORA21 22	322006	KEMBAKASI21 220.00	1	1.258	5.227	0.108	1	250	12.5	0.0055	0.0250	0.0114	0	0	0	0
17	322004	KDANDORA21 22	325001	KKAMBURU21 220.00	1	7.792	46.416	0.897	1	250	107.5	0.0476	0.2154	0.0983	0	0	0	0
18	322004	KDANDORA21 22	325001	KKAMBURU21 220.00	2	7.938	47.287	0.913	1	250	109.5	0.0485	0.2194	0.1002	0	0	0	0
19	322004	KDANDORA21 22	329001	KNBNORTH21 220.00	3	3.678	22.022	0.426	1	250	51	0.0226	0.1022	0.0467	0	0	0	0
20	322004	KDANDORA21 22	329001	KNBNORTH21 220.00	4	3.678	22.022	0.426	1	250	51	0.0226	0.1022	0.0467	0	0	0	0
21	322006	KEMBAKASI21 220	322020	KCBD 220.00	1	0.221	1.791	3.080	1	334	14	0.0062	0.0281	0.0128	0	0	0	0
22	322006	KEMBAKASI21 220	322020	KCBD 220.00	2	0.221	1.791	3.080	1	334	14	0.0062	0.0281	0.0128	0	0	0	0
23	322006	KEMBAKASI21 220	325002	KKIAMBERE21 220.00	2	11.084	65.050	1.263	1	250	151	0.0668	0.3026	0.1381	0	0	0	0
24	324001	KRABAI21 220.0	324004	KMALINDI21 220.00	1	9.313	41.837	0.827	1	236.6	97	0.0429	0.1944	0.0887	0	0	0	0
25	324001	KRABAI21 220.0	324009	TESTBUS 220.00	2	22.385	90.798	1.896	1	210	220	0.0974	0.4408	0.2012	0	0	0	0
26	324004	KMALINDI21 220.	324005	KGARSEN21 220.00	1	11.233	50.463	0.998	1	236.6	117	0.0518	0.2344	0.1070	0	0	0	0
27	324005	KGARSEN21 220.	324006	KLAMU21 220.00	1	10.369	46.581	0.921	1	236.6	108	0.0478	0.2164	0.0988	0	0	0	0
28	324009	TESTBUS 220.00	325002	KKIAMBERE21 220.00	2	22.385	90.798	1.896	1	210	220	0.0974	0.4408	0.2012	0	0	0	0
29	325001	KKAMBURU21 22	325002	KKIAMBERE21 220.00	1	3.582	14.617	0.302	1	210	35	0.0155	0.0701	0.0320	0	0	0	0
30	325001	KKAMBURU21 22	325003	KGITARU21 220.00	1	0.678	3.872	0.075	1	250	9	0.0040	0.0180	0.0082	0	0	0	0
31	326001	KOLKARIAIAU222	326004	KOLKARIA II2220.00	1	0.217	1.295	0.025	1	250	3	0.0013	0.0060	0.0027	0	0	0	0
32	326001	KOLKARIAIAU222	326004	KOLKARIA II2220.00	2	0.217	1.295	0.025	1	250	3	0.0013	0.0060	0.0027	0	0	0	0
33	326001	KOLKARIAIAU222	326005	KSUSWA21 220.00	1	1.812	10.793	0.209	1	250	25	0.0111	0.0501	0.0229	0	0	0	0
34	326001	KOLKARIAIAU222	326005	KSUSWA21 220.00	2	1.812	10.793	0.209	1	250	25	0.0111	0.0501	0.0229	0	0	0	0
35	326003	KOLKARIAIII2220.	326004	KOLKARIA II2220.00	3	0.506	3.020	0.058	1	250	7	0.0031	0.0140	0.0064	0	0	0	0
36	326004	KOLKARIA II2220.	326005	KSUSWA21 220.00	1	2.167	12.942	0.250	1	250	30	0.0133	0.0601	0.0274	0	0	0	0
37	326004	KOLKARIA II2220.	326005	KSUSWA21 220.00	2	2.167	12.942	0.250	1	250	30	0.0133	0.0601	0.0274	0	0	0	0
38	326005	KSUSWA21 220.	326010	KOLKARIA IV 220.00	1	1.450	8.635	0.167	1	250	20	0.0089	0.0401	0.0183	0	0	0	0
39	326005	KSUSWA21 220.	326010	KOLKARIA IV 220.00	2	1.450	8.635	0.167	1	250	20	0.0089	0.0401	0.0183	0	0	0	0
40	326005	KSUSWA21 220.	329001	KNBNORTH21 220.00	1	2.818	16.824	0.325	1	250	39	0.0173	0.0781	0.0357	0	0	0	0

132kV																		
S/n	From Bus Number	From Bus Name	To Bus Number	To Bus Name	Id	Line R (ohms)	Line X (ohms)	Charging B (uF)	In Service	Rate A	Length	R-Zero (pu)	X-Zero (pu)	B-Zero (pu)	Zero Seq G From (pu)	Zero Seq B From (pu)	Zero Seq G To (pu)	Zero Seq B To (pu)
1	312001	KULU11 132.00	312010	KKONZA 132.00	1	0.950	2.153	0.043	1	97	5	0.0175	0.0349	0.0018	0	0	0	0
2	312001	KULU11 132.00	312013	NEW SULTAN 132.00	1	7.028	15.934	0.317	1	97	37	0.1298	0.2586	0.0135	0	0	0	0
3	312002	KJUJA RD11 132.00	312003	KDANDORA11 132.00	1	0.139	0.836	0.016	1	190	2	0.0070	0.0140	0.0007	0	0	0	0
4	312002	KJUJA RD11 132.00	312003	KDANDORA11 132.00	2	0.139	0.836	0.016	1	190	2	0.0070	0.0140	0.0007	0	0	0	0
5	312002	KJUJA RD11 132.00	312007	KRUARAK TE11132.00	1	1.011	2.091	0.042	1	73	5	0.0175	0.0349	0.0018	0	0	0	0
6	312002	KJUJA RD11 132.00	312010	KKONZA 132.00	1	14.246	32.299	0.642	1	97	75	0.2630	0.5242	0.0273	0	0	0	0
7	312002	KJUJA RD11 132.00	312012	KRUARAKAT12 132.00	2	1.011	2.091	0.042	1	73	5	0.0175	0.0349	0.0018	0	0	0	0
8	312002	KJUJA RD11 132.00	319012	KTHIKA11 132.00	1	8.277	19.688	0.395	1	73	46	0.1613	0.3215	0.0168	0	0	0	0
9	312004	KSULTAN HA11132.00	312005	KKIBOKO11 132.00	1	7.218	16.365	0.325	1	97	38	0.1333	0.2656	0.0138	0	0	0	0
10	312004	KSULTAN HA11132.00	312013	NEW SULTAN 132.00	1	0.570	1.292	0.026	1	97	3	0.0105	0.0210	0.0011	0	0	0	0
11	312005	KKIBOKO11 132.00	312009	KMAKINDU 132.00	1	3.799	8.613	0.171	1	97	20	0.0701	0.1398	0.0073	0	0	0	0
12	312006	KMTITO AND11132.00	312009	KMAKINDU 132.00	1	13.106	29.715	0.591	1	97	69	0.2420	0.4823	0.0251	0	0	0	0
13	312006	KMTITO AND11132.00	314005	KMANYANI11 132.00	1	10.447	23.686	0.471	1	97	55	0.1929	0.3844	0.0200	0	0	0	0
14	312007	KRUARAK TE11132.00	312008	KRUARAKA11 132.00	1	0.314	0.627	0.013	1	81	1.5	0.0053	0.0105	0.0005	0	0	0	0
15	312007	KRUARAK TE11132.00	316002	NAIVASHA11 132.00	1	14.427	30.056	0.590	1	73	71.2	0.2497	0.4977	0.0259	0	0	0	0
16	312008	KRUARAKA11 132.00	312012	KRUARAKAT12 132.00	2	0.314	0.627	0.013	1	81	1.5	0.0053	0.0105	0.0005	0	0	0	0
17	312010	KKONZA 132.00	312011	KMACHAKOS11 132.00	1	3.799	8.613	0.171	1	97	20	0.0701	0.1398	0.0073	0	0	0	0
18	312012	KRUARAKAT12 132.00	316002	NAIVASHA11 132.00	3	14.427	30.056	0.590	1	73	71.2	0.2497	0.4977	0.0259	0	0	0	0
19	312013	NEW SULTAN 132.00	319008	KWOTE11 132.00	1	4.005	15.272	0.331	1	97	37	0.1298	0.2586	0.0135	0	0	0	0
20	314003	KKIPEVU11 132.00	314007	KKIPEVUDII11132.00	1	0.057	0.129	0.003	1	97	0.3	0.0011	0.0021	0.0001	0	0	0	0
21	314003	KKIPEVU11 132.00	314010	KRABAI11 132.00	2	3.229	7.321	0.146	1	97	17	0.0596	0.1188	0.0062	0	0	0	0
22	314003	KKIPEVU11 132.00	314010	KRABAI11 132.00	3	1.840	7.017	0.152	1	97	17	0.0596	0.1188	0.0062	0	0	0	0
23	314003	KKIPEVU11 132.00	314036	KJOMVU 132.00	1	0.649	2.477	0.054	1	135	5.94	0.0208	0.0415	0.0022	0	0	0	0
24	314005	KMANYANI11 132.00	314013	KVOI11 132.00	1	6.838	15.504	0.308	1	97	36	0.1263	0.2516	0.0131	0	0	0	0
25	314006	KSAMBURU11 132.00	334029	KTOP STEEL 132.00	1	4.559	10.336	0.206	1	97	24	0.0842	0.1678	0.0087	0	0	0	0
26	314006	KSAMBURU11 132.00	334030	KNEWMAUNGU 132.00	1	8.927	20.241	0.402	1	97	47.025	0.1649	0.3287	0.0171	0	0	0	0
27	314007	KKIPEVUDII11132.00	314010	KRABAI11 132.00	1	3.419	7.752	0.154	1	97	18	0.0631	0.1258	0.0066	0	0	0	0
28	314008	KKOKOTONI11 132.00	314010	KRABAI11 132.00	1	0.950	2.153	0.043	1	97	5	0.0175	0.0349	0.0018	0	0	0	0
29	314008	KKOKOTONI11 132.00	314016	KMARIAKANI11132.00	1	2.469	5.599	0.111	1	97	13	0.0456	0.0909	0.0047	0	0	0	0
30	314010	KRABAI11 132.00	314017	KGALU11 132.00	1	9.497	21.533	0.428	1	97	50	0.1754	0.3495	0.0182	0	0	0	0
31	314010	KRABAI11 132.00	314029	KRABAITRF11 132.00	2	0.523	0.871	0.000	1	150	0	0.0000	0.0000	0.0000	0	0	0	0
32	314010	KRABAI11 132.00	314030	KRABTRF12 132.00	1	0.523	0.871	0.000	1	150	0	0.0000	0.0000	0.0000	0	0	0	0
33	314010	KRABAI11 132.00	314037	TEE OFF 132.00	1	0.649	2.476	0.054	1	135	6.03	0.0211	0.0421	0.0022	0	0	0	0
34	314010	KRABAI11 132.00	314038	BAMB TEE 132.00	1	5.140	10.355	0.209	1	73	24.6	0.0863	0.1719	0.0090	0	0	0	0
35	314011	KKILIFI11 132.00	314034	KMSACEMTEE32132.00	1	3.791	7.637	0.154	1	73	18.139	0.0636	0.1268	0.0066	0	0	0	0
36	314012	KBAMBURI11 132.00	314037	TEE OFF 132.00	1	1.615	3.661	0.073	1	81	9	0.0316	0.0629	0.0033	0	0	0	0
37	314013	KVOI11 132.00	314015	KMAUNGU11 132.00	1	5.698	12.920	0.257	1	97	30	0.1052	0.2097	0.0109	0	0	0	0
38	314015	KMAUNGU11 132.00	334030	KNEWMAUNGU 132.00	1	1.895	4.296	0.085	1	97	9.975	0.0350	0.0697	0.0036	0	0	0	0
39	314016	KMARIAKANI11132.00	334029	KTOP STEEL 132.00	1	1.140	2.584	0.051	1	97	6	0.0210	0.0419	0.0022	0	0	0	0
40	314017	KGALU11 132.00	314035	TITANIUM11 132.00	1	2.659	6.029	0.120	1	97	14	0.0491	0.0979	0.0051	0	0	0	0
41	314029	KRABAITRF11 132.00	314030	KRABTRF12 132.00	1	0.000	0.017	0.000	1	0	0	0.0000	0.0000	0.0000	0	0	0	0
42	314029	KRABAITRF11 132.00	314039	KRABAITR 13 132.00	1	0.000	0.017	0.000	1	0	0	0.0000	0.0000	0.0000	0	0	0	0

S/n	From Bus Number	From Bus Name	To Bus Number	To Bus Name	Id	Line R (ohms)	Line X (ohms)	Charging B (uF)	In Service	Rate A	Length	R-Zero (pu)	X-Zero (pu)	B-Zero (pu)	Zero Seq G From (pu)	Zero Seq B From (pu)	Zero Seq G To (pu)	Zero Seq B To (pu)
43	314031	KVIPINGO31 132.00	314032	KMSCEMTEE31 132.00	1	1.706	3.436	0.069	1	73	8.16	0.0286	0.0570	0.0030	0	0	0	0
44	314031	KVIPINGO31 132.00	314038	BAMB TEE 132.00	1	2.743	5.525	0.112	1	73	13.122	0.0460	0.0917	0.0048	0	0	0	0
45	314032	KMSCEMTEE31 132.00	314033	KMSACEM31 132.00	1	0.971	1.955	0.040	1	73	4.644	0.0163	0.0325	0.0017	0	0	0	0
46	314033	KMSACEM31 132.00	314034	KMSACEMTEE32132.00	1	0.948	1.909	0.039	1	73	4.535	0.0159	0.0317	0.0017	0	0	0	0
47	314036	KJOMVU 132.00	314037	TEE OFF 132.00	4	0.649	2.476	0.054	1	135	6.03	0.0211	0.0421	0.0022	0	0	0	0
48	315001	KKINDARUMA11132.00	315003	KKAMBURU11 132.00	1	3.311	7.876	0.157	1	81	18.4	0.0645	0.1286	0.0067	0	0	0	0
49	315001	KKINDARUMA11132.00	319007	KMWINGI11 132.00	1	6.078	13.781	0.274	1	97	32	0.1122	0.2237	0.0117	0	0	0	0
50	315001	KKINDARUMA11132.00	319012	KTHIKA11 132.00	1	19.254	45.796	0.918	1	73	107	0.3753	0.7479	0.0390	0	0	0	0
51	315002	KGITARU11 132.00	315003	KKAMBURU11 132.00	1	1.394	3.241	0.066	1	126	7.7	0.0270	0.0538	0.0028	0	0	0	0
52	315002	KGITARU11 132.00	315003	KKAMBURU11 132.00	2	1.359	3.241	0.066	1	126	7.7	0.0270	0.0538	0.0028	0	0	0	0
53	315003	KKAMBURU11 132.00	315004	KMASINGA11 132.00	1	1.324	7.945	0.153	1	150	18.4	0.0645	0.1286	0.0067	0	0	0	0
54	315003	KKAMBURU11 132.00	315009	KISHIARA11 132.00	1	2.231	13.386	0.259	1	150	31	0.1087	0.2167	0.0113	0	0	0	0
55	315003	KKAMBURU11 132.00	315019	KKAMBTRF11 132.00	1	0.139	-0.523	0.000	1	150	0	0.0000	0.0000	0.0000	0	0	0	0
56	315003	KKAMBURU11 132.00	315019	KKAMBTRF11 132.00	2	0.139	-0.523	0.000	1	150	0	0.0000	0.0000	0.0000	0	0	0	0
57	315004	KMASINGA11 132.00	315022	KKUTUSTEE2 132.00	1	11.447	22.637	0.440	1	73	52	0.1824	0.3635	0.0189	0	0	0	0
58	315005	KNANYUKI11 132.00	315018	KKIGANJO11 132.00	1	10.751	21.710	0.442	1	73	51.5	0.1806	0.3600	0.0188	0	0	0	0
59	315008	KKYENI11 132.00	315009	KISHIARA11 132.00	1	2.699	6.415	0.126	1	81	15	0.0526	0.1048	0.0055	0	0	0	0
60	315009	KISHIARA11 132.00	315010	KMERU11 132.00	1	6.693	40.159	0.776	1	150	93	0.3262	0.6500	0.0339	0	0	0	0
61	315010	KMERU11 132.00	319010	KISIOLO11 132.00	1	5.399	12.830	0.252	1	81	30	0.1052	0.2097	0.0109	0	0	0	0
62	315011	KGITHAMBO11 132.00	319012	KTHIKA11 132.00	1	7.737	18.404	0.369	1	73	43	0.1508	0.3006	0.0157	0	0	0	0
63	315018	KKIGANJO11 132.00	315021	KKUTUSTEE1 132.00	2	8.145	16.107	0.313	1	73	37	0.1298	0.2586	0.0135	0	0	0	0
64	315020	KEMBU11 132.00	315021	KKUTUSTEE1 132.00	1	4.623	9.142	0.178	1	73	21	0.0737	0.1468	0.0076	0	0	0	0
65	315020	KEMBU11 132.00	315022	KKUTUSTEE2 132.00	1	4.623	9.142	0.178	1	73	21	0.0737	0.1468	0.0076	0	0	0	0
66	316001	KOLKARIA1 11132.00	316003	KOLKARIAIAU1132.00	1	0.073	0.422	0.009	1	150	1.1	0.0039	0.0077	0.0004	0	0	0	0
67	316001	KOLKARIA1 11132.00	316007	KOLKARIA II1132.00	1	0.219	1.265	0.026	1	150	3	0.0105	0.0210	0.0011	0	0	0	0
68	316001	KOLKARIA1 11132.00	316011	KNAROK11 132.00	1	12.916	29.285	0.582	1	97	68	0.2385	0.4753	0.0248	0	0	0	0
69	316001	KOLKARIA1 11132.00	316011	KNAROK11 132.00	2	12.916	29.285	0.582	1	97	68	0.2385	0.4753	0.0248	0	0	0	0
70	316001	KOLKARIA1 11132.00	316017	KWELLHED37-1132.00	1	0.570	1.292	0.026	1	97	3	0.0105	0.0210	0.0011	0	0	0	0
71	316002	NAIVASHA11 132.00	316003	KOLKARIAIAU1132.00	3	1.610	9.276	0.188	1	150	22	0.0772	0.1538	0.0080	0	0	0	0
72	316002	NAIVASHA11 132.00	316005	KLANET11 132.00	1	13.991	28.331	0.575	1	73	67	0.2350	0.4683	0.0244	0	0	0	0
73	316002	NAIVASHA11 132.00	316005	KLANET11 132.00	2	13.991	28.331	0.575	1	73	67	0.2350	0.4683	0.0244	0	0	0	0
74	316005	KLANET11 132.00	316006	KSOILO11 132.00	2	2.865	6.363	0.130	1	73	15.12	0.0530	0.1057	0.0055	0	0	0	0
75	316005	KLANET11 132.00	316010	KMAKUTANO11 132.00	1	12.948	28.757	0.586	1	73	68.342	0.2397	0.4777	0.0249	0	0	0	0
76	316006	KSOILO11 132.00	316018	KMAKUTEE12 132.00	2	10.083	22.396	0.457	1	73	53.222	0.1867	0.3720	0.0194	0	0	0	0
77	316010	KMAKUTANO11 132.00	318003	KLESSOS11 132.00	2	10.923	24.263	0.495	1	73	57.658	0.2022	0.4030	0.0210	0	0	0	0
78	316011	KNAROK11 132.00	317012	KBOMET11 132.00	1	16.715	37.898	0.754	1	97	88	0.3086	0.6151	0.0320	0	0	0	0
79	316011	KNAROK11 132.00	317012	KBOMET11 132.00	2	16.715	37.898	0.754	1	97	88	0.3086	0.6151	0.0320	0	0	0	0
80	316018	KMAKUTEE12 132.00	318003	KLESSOS11 132.00	1	10.923	24.263	0.495	1	73	57.658	0.2022	0.4030	0.0210	0	0	0	0
81	317004	KMUHORONI11 132.00	317005	KKISUMU11 132.00	1	10.123	20.508	0.411	1	73	48.5	0.1701	0.3390	0.0177	0	0	0	0
82	317004	KMUHORONI11 132.00	317006	KCHEMOSIT11 132.00	1	6.412	12.981	0.261	1	73	30.7	0.1077	0.2146	0.0112	0	0	0	0
83	317004	KMUHORONI11 132.00	318003	KLESSOS11 132.00	1	11.848	23.975	0.486	1	73	56.7	0.1989	0.3963	0.0206	0	0	0	0
84	317005	KKISUMU11 132.00	317010	KSONDU11 132.00	1	7.260	20.860	0.431	1	150	50	0.1754	0.3495	0.0182	0	0	0	0
85	317006	KCHEMOSIT11 132.00	317014	KSOTIK 132.00	1	4.356	12.516	0.259	1	150	30	0.1052	0.2097	0.0109	0	0	0	0
86	317007	KWEBUYE11 132.00	317008	KMUSAGA11 132.00	1	3.764	7.614	0.153	1	73	18	0.0631	0.1258	0.0066	0	0	0	0
87	317008	KMUSAGA11 132.00	317009	KMUMIAS11 132.00	1	5.645	11.291	0.247	1	81	27	0.0947	0.1887	0.0098	0	0	0	0
88	317008	KMUSAGA11 132.00	318003	KLESSOS11 132.00	2	13.660	27.617	0.563	1	73	66	0.2315	0.4613	0.0240	0	0	0	0

S/n	From Bus Number	From Bus Name	To Bus Number	To Bus Name	Id	Line R (ohms)	Line X (ohms)	Charging B (uF)	In Service	Rate A	Length	R-Zero (pu)	X-Zero (pu)	B-Zero (pu)	Zero Seq G From (pu)	Zero Seq B From (pu)	Zero Seq G To (pu)	Zero Seq B To (pu)
89	317008	KMUSAGA11 132.00	603026	UTORO11 132.00	2	14.723	29.795	0.601	1	73	70.5	0.2473	0.4928	0.0257	0	0	0	0
90	317009	KMUMIAS11 132.00	317016	KRANGALA11 132.00	1	2.488	14.336	0.290	1	150	34	0.1192	0.2376	0.0124	0	0	0	0
91	317010	KSONDU11 132.00	317011	KSANGORO11 132.00	1	1.044	2.114	0.043	1	73	5	0.0175	0.0349	0.0018	0	0	0	0
92	317010	KSONDU11 132.00	317018	KNDHIWA11 132.00	1	12.597	29.936	0.588	1	73	70	0.2455	0.4893	0.0255	0	0	0	0
93	317012	KBOMET11 132.00	317014	KSOTIK 132.00	1	6.268	12.628	0.255	1	73	30	0.1052	0.2097	0.0109	0	0	0	0
94	317013	KKISII11 132.00	317014	KSOTIK 132.00	1	4.356	12.516	0.259	1	150	30	0.1052	0.2097	0.0109	0	0	0	0
95	317013	KKISII11 132.00	317015	KAWENDO11 132.00	1	9.194	18.521	0.374	1	73	44	0.1543	0.3075	0.0160	0	0	0	0
96	317015	KAWENDO11 132.00	317018	KNDHIWA11 132.00	1	5.888	13.350	0.265	1	97	31	0.1087	0.2167	0.0113	0	0	0	0
97	317020	MUSAGATEE 132.00	318003	KLESSOS11 132.00	1	14.681	29.709	0.599	1	73	70.297	0.2465	0.4914	0.0256	0	0	0	0
98	317020	MUSAGATEE 132.00	603026	UTORO11 132.00	1	13.826	27.979	0.564	1	73	66.203	0.2322	0.4627	0.0241	0	0	0	0
99	318002	KELDORET11 132.00	318003	KLESSOS11 132.00	1	6.708	13.573	0.274	1	73	32.1	0.1126	0.2244	0.0117	0	0	0	0
100	318002	KELDORET11 132.00	318007	KKITALE11 132.00	1	10.797	25.659	0.504	1	81	60	0.2104	0.4194	0.0219	0	0	0	0
101	318003	KLESSOS11 132.00	318004	KKAPSABET11 132.00	1	6.269	12.685	0.256	1	73	30	0.1052	0.2097	0.0109	0	0	0	0
102	318003	KLESSOS11 132.00	318008	KLESSTRF11 132.00	1	0.000	0.017	0.000	1	150	0	0.0000	0.0000	0.0000	0	0	0	0
103	318003	KLESSOS11 132.00	318008	KLESSTRF11 132.00	2	0.000	0.017	0.000	1	0	0	0.0000	0.0000	0.0000	0	0	0	0
104	319006	KGATUNDU11 132.00	319012	KTHIKA11 132.00	1	3.599	8.560	0.172	1	73	20	0.0701	0.1398	0.0073	0	0	0	0
105	319007	KMWINGI11 132.00	319009	KGARISSA11 132.00	1	36.468	82.686	1.644	1	97	192	0.6734	1.3420	0.0699	0	0	0	0
106	319009	KGARISSA11 132.00	319014	GARISA PV132132.00	1	1.330	3.015	0.060	1	97	7	0.0246	0.0489	0.0025	0	0	0	0
107	319012	KTHIKA11 132.00	319013	KTHIKA12 132.00	1	0.038	0.086	0.002	1	97.2	0.2	0.0007	0.0014	0.0001	0	0	0	0

Appendix III: Demand Data

MONTH	90/91	91/92	92/93	93/94	94/95	95/96	96/97	97/98	98/99	99/2000	00/01	01/02	02/03	03/04	04/05	05/06	06/07
JULY	505	542	555	597	602	569	648	689	658	701	534	722	758	780	827	885	934
AUGUST	508	531	554	588	605	610	652	696	665	708	522	719	765	784	836	889	933
SEPTEMBER	520	536	568	603	599	592	644	701	691	695	597	737	774	802	840	898	966
OCTOBER	547	553	572	598	591	594	599	719	700	704	581	746	780	818	852	903	965
NOVEMBER	539	565	585	607	583	561	601	721	712	692	676	745	779	807	864	908	971
DECEMBER	515	544	568	597	589	582	629	710	707	683	638	748	772	812	872	916	947
JANUARY	528	560	577	623	562	633	615	702	681	680	703	753	774	821	878	916	974
FEBRUARY	517	562	594	606	562	647	599	711	721	679	724	753	778	821	873	901	968
MARCH	518	537	589	598	560	648	591	718	734	688	700	733	769	817	884	911	978
APRIL	521	539	589	585	556	640	642	669	705	687	711	757	786	819	864	895	976
MAY	544	544	596	595	577	603	665	678	718	700	716	752	767	815	868	894	971
JUNE	534	553	587	601	593	643	680	674	721	549	718	760	765	830	878	916	979
AVERAGE	525	547	578	600	582	610	630	699	701	680	652	744	772	810	861	903	964
Fiscal Year MD	547	565	596	623	605	648	680	721	734	708	724	760	786	830	884	916	979
Annual growth rate		3.3%	5.5%	4.5%	-2.9%	7.1%	4.9%	5.9%	1.8%	-3.5%	2.2%	5.0%	3.4%	5.7%	6.5%	3.7%	6.8%
CALENDER YEAR	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
PLANT CAPACITY MW	661	661	661	661	767	762	853	853	853	1,009	1,113	1,151	1,223	1,180	1,090	1,186	1,178
Calendar Year MD	565	585	607	623	610	652	721	718	734	700	748	780	818	872	916	971	979
Annual growth rate		3.5%	3.8%	2.6%	-2.1%	6.9%	10.5%	-0.4%	2.2%	-4.6%	6.9%	4.2%	4.9%	6.6%	5.1%	6.0%	0.7%

Appendix IV: Results Data

Time	National Gen. Demand	Nairobi Region	Coast Region	West Region	Mt. Kenya Region
00.30	1614.80	700.00	260.00	285.00	160.00
01.00	1535.00	630.00	257.00	285.00	153.00
01.30	*1495.80*	*624.00*	*258.00*	*254.00*	*150.00*
02.00	1508.60	620.00	258.00	274.00	147.00
02.30	1494.80	616.00	254.00	271.00	144.00
03.00	1487.00	612.00	251.00	272.00	142.00
03.30	1476.80	602.00	248.00	273.00	144.00
04.00	1466.80	597.00	250.00	265.00	145.00
04.30	1487.60	600.00	254.00	276.00	148.00
05.00	1502.80	608.00	257.00	280.00	148.00
05.30	1340.96	494.51	256.00	229.46	151.00
06.00	1268.56	517.27	208.56	234.92	98.02
06.30	1352.12	582.87	207.69	247.03	104.94
07.00	1383.74	601.43	208.68	246.34	117.50
07.30	1429.49	624.61	213.13	252.65	129.10
08.00	1512.56	671.31	220.00	270.43	141.02
08.30	1574.64	701.95	228.40	290.41	143.88
09.00	1655.56	756.65	245.70	295.63	147.78
09.30	1683.00	783.71	249.11	290.00	150.58
10.00	1686.49	788.79	243.02	294.06	150.82
10.30	1684.11	783.43	248.29	292.26	150.14
11.00	1707.10	800.11	251.32	296.67	149.20
11.30	1680.77	784.89	255.91	281.37	149.00
12.00	1700.08	782.03	256.83	302.38	149.04
12.30	1666.15	774.47	251.68	299.03	148.58
13.00	1648.96	773.49	246.63	299.78	145.46
13.30	1612.76	760.77	244.86	289.81	140.52
14.00	1588.67	754.79	234.17	290.56	142.56
14.30	1582.29	758.59	239.29	296.20	144.42
15.00	1559.09	751.41	237.82	294.02	143.44
15.30	1557.85	753.17	236.86	291.07	145.16
16.00	1527.05	738.37	234.14	281.36	144.98
16.30	1531.55	737.17	233.58	290.64	143.76
17.00	1533.66	741.29	231.03	289.12	142.62
17.30	1546.16	727.93	231.09	306.56	143.58
18.00	1564.55	735.91	230.65	312.79	143.20
18.30	1647.19	752.59	230.88	359.05	154.28
19.00	1556.80	750.00	226.00	313.00	118.00

19.30	1586.80	759.00	228.00	312.00	140.00
20.00	1581.80	752.00	230.00	302.00	142.00
20.30	1571.40	750.00	234.00	290.00	138.00
21.00	1535.80	745.00	215.00	282.00	131.00
21.30	1579.11	775.31	212.00	281.00	125.00
22.00	1547.79	733.99	214.00	273.00	117.00
22.30	1611.27	689.13	252.87	297.49	162.18
23.00	1511.44	644.05	242.33	266.88	148.38
23.30	1428.84	601.01	234.27	251.21	132.36
24.00	1644.80	685.00	275.00	295.00	180.00

Appendix V: Generation Data

Bus Numb	Bus Name	Id	Code	VSched (p	Remote B	In Service	Pgen (MW)	Pmax (MW)	Mbase (MVA)	R Source (pu)	X Source (pu)
1001	KINDARUMA 11.000	1	2	1.05	0	1	40.0	48	60	0	0.14
1001	KINDARUMA 11.000	2	2	1.05	0	1	24.0	24	30	0	0.14
1002	GITARU 1&2 15.000	1	3	1.05	0	1	80.2	144	171	0	0.13
1003	KAMBURU 11.000	1	2	1.05	0	1	70.0	90	111	0	0.17
1004	MASINGA 11.000	1	2	1.05	0	1	30.0	40	47	0	0.17
1005	KIAMBERE 11.000	1	2	1.05	0	1	120.0	164	170	0	0.17
1007	TURKWEL 11.000	1	2	1.05	0	1	52.5	52	58	0	0.18
1007	TURKWEL 11.000	2	2	1.05	0	1	52.5	52	58	0	0.18
1008	OLKARIA 1 11.000	1	-2	1.05	0	1	44.0	45	56	0	0.12
1009	GITARU3 15.000	1	2	1.05	0	1	55.0	80	85	0	0.13
1014	EMBAKASIGT1 11.000	1	-2	1.05	0	1	27.0	30	38	0	0.16
1015	EMBAKASIGT2 11.000	1	-2	1.05	0	1	27.0	30	38	0	0.16
1016	1KIPD I 11.000	1	-2	1.05	0	1	10.0	12	14.4	0	0.192
1016	1KIPD I 11.000	2	-2	1.05	0	1	10.0	12	14.4	0	0.192
1017	2KIP DI 11.000	3	2	1.05	0	1	10.0	12	14.4	0	0.192
1017	2KIP DI 11.000	4	2	1.05	0	1	8.0	12	14.4	0	0.192
1018	3KIP DI 11.000	5	-2	1.05	0	0	10.0	12	14.4	0	0.192
1018	3KIP DI 11.000	6	-2	1.05	0	0	10.0	12	14.4	0	0.192
1019	1KIP DII 11.000	5	-2	1.05	0	1	11.0	11.6	13.57	0	0.117
1019	1KIP DII 11.000	6	-2	1.05	0	1	11.0	11.6	13.57	0	0.117
1019	1KIP DII 11.000	7	-2	1.05	0	1	9.0	11.6	13.57	0	0.117
1020	2KIP DII 11.000	1	-2	1.05	0	1	11.0	11.6	13.57	0	0.117
1020	2KIP DII 11.000	2	-2	1.05	0	1	11.0	11.6	13.57	0	0.117
1020	2KIP DII 11.000	3	-2	1.05	0	1	11.0	11.6	13.57	0	0.117
1020	2KIP DII 11.000	4	-2	1.05	0	0	11.0	11.6	13.57	0	0.117
1023	KIP DIII 11.000	1	-2	1.05	0	1	57.5	60	72	0	0.16
1024	KIP DIII 11.000	1	-2	1.05	0	1	57.5	60	72	0	0.16
1032	IBERAG1 11.000	1	-2	1.05	0	1	10.5	12.372	13.75	0	0.19
1032	IBERAG1 11.000	2	-2	1.05	0	1	20.0	23.1	25.4	0	0.16
1032	IBERAG1 11.000	3	-2	1.05	0	1	20.0	22.868	25.4	0	0.195
1033	IBERAG2 11.000	1	2	1.05	0	1	15.0	22.868	25.4	0	0.195
1033	IBERAG2 11.000	2	2	1.05	0	1	30.0	30.8	38.5	0	0.16
1040	OLKNEG1 11.000	1	2	1.05	0	1	28.0	35	44.3	0	0.18
1041	OLKNEG2 11.000	2	-2	1.05	0	1	30.0	35	44.3	0	0.18
1043	OLKNEG3 11.000	1	-2	1.05	0	1	30.0	35	44.3	0	0.18
1045	OLK III 2 11.000	1	-2	1.05	0	1	19.5	19.5	42	0	0.18
1045	OLK III 2 11.000	2	-2	1.05	0	1	19.5	19.5	22.5	0	0.18
1046	OLKAIII 11.000	1	-2	1.05	0	1	13.0	13	15	0	0.18
1046	OLKAIII 11.000	2	-2	1.05	0	1	13.0	13	15.4	0	0.18
1046	OLKAIII 11.000	3	-2	1.05	0	1	13.0	13	15.4	0	0.18
1046	OLKAIII 11.000	4	-2	1.05	0	1	13.0	13	15.4	0	0.18
1051	OLKARIA III 11.000	1	2	1	0	1	18.0	18	22.5	0	0.18
1055	MUMIAS 11.000	1	-2	1.05	0	1	14.0	26	42.75	0	0.16
1056	RABAI POWER 11.000	1	-2	1.05	0	1	18.0	18	21.34	0	0.16
1056	RABAI POWER 11.000	2	-2	1.05	0	1	18.0	18	21.34	0	0.16
1057	RABAI POWER 11.000	1	-2	1.05	0	1	18.0	18	21.34	0	0.16
1057	RABAI POWER 11.000	2	-2	1.05	0	1	18.0	18	21.34	0	0.16
1057	RABAI POWER 11.000	3	-2	1.05	0	1	18.0	18	21.34	0	0.16
1059	SONDU 11.000	1	2	1.05	0	1	20.0	30	38	0	0.16
1060	SONDU 11.000	2	2	1.05	0	1	20.0	30	38	0	0.16
1061	SANGORO 11.000	1	2	1.05	0	1	6.6	12	14.4	0	0.192
1061	SANGORO 11.000	2	2	1.05	0	1	6.6	12	14.4	0	0.192
1078	MUHORONI MSD11.000	1	-2	1.05	0	1	30.0	30	37.5	0	0.18
1080	TANGEN1 11.000	1	2	1.03	0	1	5.7	12	15.85	0	0.2
1080	TANGEN1 11.000	2	2	1.03	0	1	5.7	12	15.85	0	0.2
1085	THIKA PP 11.000	1	2	1.05	0	1	43.5	43.5	47	0	0.192
1086	THIKA PP 11.000	2	2	1.05	0	1	43.5	43.5	47	0	1
1090	NGONG WIND 11.000	1	-2	1.05	0	1	3.0	5.1	5.3	0	0.16

Appendix VI: Transformer Data

From Bus	From Bus Name	To Bus Nu	To Bus Name	Id	In Service	Specified R (pu or	Specified X (pu)	Rate A (MVA	Wnd 1 Nominal kV	Wnd 2 Nominal kV
1103	KAMBURU 132.00	1304	KAMBURU 33.000	1	1	0.011	0.11	23	132	33
1109	OLKARIA II 132.00	1210	OLKARIA II 220.00	1	1	0.003376	0.09992	90	220	132
1114	KIPEVU 132.00	1314	1KIP33 33.000	1	1	0.00534	0.121	60	132	33
1114	KIPEVU 132.00	1314	1KIP33 33.000	2	1	0.00534	0.121	30	132	33
1114	KIPEVU 132.00	1314	1KIP33 33.000	3	1	0.00534	0.121	60	132	33
1116	MANGU 132.00	1673	MANGU 1 66.000	1	1	0	0.12198	60	132	66
1116	MANGU 132.00	1686	MANGU2 66.000	1	1	0	0.12198	60	132	66
1117	JUJA RD 132.00	1617	JUJA RD 66.000	4	1	0	0.128748	60	132	66
1117	JUJA RD 132.00	1617	JUJA RD 66.000	5	1	0	0.129	15	132	66
1117	JUJA RD 132.00	1617	JUJA RD 66.000	6	1	0	0.128349	30	132	66
1117	JUJA RD 132.00	1617	JUJA RD 66.000	7	1	0	0.129	15	132	66
1117	JUJA RD 132.00	1668	JUJA RD 66.000	1	1	0	0.12618	60	132	66
1117	JUJA RD 132.00	1668	JUJA RD 66.000	2	1	0	0.129	15	132	66
1117	JUJA RD 132.00	1668	JUJA RD 66.000	3	1	0	0.12618	60	132	66
1121	DANDORA 132.00	1221	DANDORA 220.00	1	1	0.0002	0.105	200	220	132
1121	DANDORA 132.00	1221	DANDORA 220.00	2	1	0.0002	0.105	200	220	132
1121	DANDORA 132.00	1921	1DAND11 11.000	1	1	0.004	0.106	23	132	11
1121	DANDORA 132.00	1921	1DAND11 11.000	2	1	0.004	0.106	23	132	11
1126	RABAI 132.00	1325	RABAI33 33.000	1	1	0.0138	0.099	23	132	33
1126	RABAI 132.00	1326	RABAI33 33.000	1	1	0.0138	0.099	23	132	33
1127	ELDORET 132.00	1327	ELD33 33.000	1	1	0.0138	0.1196	23	132	33
1127	ELDORET 132.00	1328	ELD33 33.000	1	1	0.0138	0.1196	23	132	33
1128	MUHORONI 132.00	1375	MUHORONI 33.000	1	1	0	0.1	23	132	33
1129	KISUMU 132.00	1329	KISU33 33.000	1	1	0.0138	0.13	45	132	33
1129	KISUMU 132.00	1330	KISU33 33.000	1	1	0.0138	0.13	45	132	33
1130	CHEMOSIT 132.00	1350	CHEMO33 33.000	1	1	0.0138	0.1196	23	132	33
1130	CHEMOSIT 132.00	1351	CHEMO33 33.000	1	1	0.0138	0.1196	23	132	33
1132	KIGANJO 132.00	1352	KIGA33 33.000	1	1	0.0138	0.1196	23	132	33
1132	KIGANJO 132.00	1352	KIGA33 33.000	2	1	0.0138	0.1196	23	132	33
1133	NANYUKI 132.00	1353	NANYU33 33.000	1	1	0.0138	0.1196	23	132	33
1134	KILIFI 132.00	1345	KILIFI 33.000	1	1	0.0138	0.104	23	132	33
1134	KILIFI 132.00	1345	KILIFI 33.000	2	1	0.0138	0.104	15	132	33
1136	BAMBURI 132.00	1364	BAMBURI 33.000	1	1	0.0138	0.1196	45	132	33
1139	MUSAGA 132.00	1339	MUSAGA 33.000	1	1	0.015	0.099	15	132	33
1139	MUSAGA 132.00	1339	MUSAGA 33.000	2	1	0.0138	0.097	23	132	33
1140	LESSOS 132.00	1340	LESSO33 33.000	1	1	0.015	0.12	23	132	33
1141	LANET 132.00	1341	LANET33 33.000	1	1	0.0138	0.097	23	132	33
1141	LANET 132.00	1341	LANET33 33.000	2	1	0.0138	0.0978	23	132	33
1141	LANET 132.00	1342	LANET33 33.000	1	1	0.0138	0.0981	23	132	33
1142	NAIVASHA 132.00	1343	NAIVA33 33.000	1	1	0.015	0.12	15	132	33
1142	NAIVASHA 132.00	1344	NAIVA33 33.000	1	1	0.015	0.12	15	132	33
1149	SOILO 132.00	1359	SOILO 33.000	1	1	0.0138	0.097	23	132	33
1151	RUARAKA 132.00	1601	RUARAKA 66.000	1	1	0	0.12198	60	132	66
1151	RUARAKA 132.00	1601	RUARAKA 66.000	2	1	0	0.12198	60	132	66
1156	GALU 132.00	1346	GALU 33.000	1	1	0.0138	0.104	23	132	33
1156	GALU 132.00	1346	GALU 33.000	2	1	0.0138	0.104	15	132	33
1163	MERU 132.00	1360	MERU 33.000	1	1	0.0138	0.1196	23	132	33
1167	KISII 132.00	1356	KISII33 33.000	1	1	0.0138	0.1196	23	132	33
1167	KISII 132.00	1356	KISII33 33.000	2	1	0.0138	0.1196	23	132	33
1178	RANGALA 132.00	1376	RANGALA 33.000	1	1	0.0138	0.1196	23	132	33
1183	MAKUTANO 132.00	1316	MAKUTANO 33.000	1	1	0.0138	0.1196	23	132	33
1203	KAMBURU 220.00	1703	KAMBTRF 132.00	1	1	0.002403	0.11205	270	220	132
1203	KAMBURU 220.00	1703	KAMBTRF 132.00	2	1	0.002403	0.11205	270	220	132
1223	EMBAKASI 220.00	1625	EMBAKASI 66.000	2	1	0.003087	0.161	90	220	66
1223	EMBAKASI 220.00	1672	EMBAKASI 66.000	1	1	0.003087	0.161	90	220	66
1223	EMBAKASI 220.00	1672	EMBAKASI 66.000	2	1	0.003087	0.161	90	220	66
1224	NBNORTH220 220.00	1640	NBNORTH66 66.000	1	1	0.003087	0.161	90	220	66
1224	NBNORTH220 220.00	1640	NBNORTH66 66.000	2	1	0.003087	0.161	90	220	66
1224	NBNORTH220 220.00	1640	NBNORTH66 66.000	3	1	0.003087	0.161	90	220	66
1226	RABAI 220.00	1726	1RABTRF 132.00	1	1	0.003141	0.106893	90	220	132
1226	RABAI 220.00	1727	RABAITRF 132.00	2	1	0.003141	0.106893	90	220	132
1240	LESSOS 220.00	1740	LESSTRF 132.00	1	1	0.032775	0.09999	75	220	132
1240	LESSOS 220.00	1740	LESSTRF 132.00	2	1	0.032775	0.09999	75	220	132
1254	MALINDI 220.00	1378	MALINDI 33.000	1	1	0	0.092499	23	220	33
1255	GARSEN 220.00	1379	GARSEN 33.000	1	0	0	0.092499	23	220	33
1256	LAMU 220.00	1380	LAMU 33.000	1	0	0	0.092499	23	220	33

Appendix VII: Dispatch Data

Masinga	20	20	20	10	15	10	10	20	20	20	20	20	20	20	20	20	20	20	20	2
Kamburu	40	40	40	40	40	40	40	40	50	60	60	60	60	60	60	30	30	30	30	3
Gitaru	60	0	0	0	0	0	0	0	0	0	50	50	110	110	110	130	130	165	170	17
Kindaruma	0	0	0	0	0	0	0	0	0	20	10	20	25	25	25	35	25	25	35	3
Kiambere	120	140	115	120	120	120	120	120	120	140	160	164	164	164	164	164	164	164	164	16
Turkwel	40	40	40	40	40	40	40	40	40	40	40	40	80	80	80	80	80	80	80	9
Sondu	10	10	10	10	10	10	10	10	10	10	30	30	30	30	30	30	30	30	30	3
Total main hydro	***290***	***250***	***225***	***220***	***225***	***220***	***220***	***230***	***240***	***290***	***370***	***384***	***489***	***489***	***489***	***489***	***479***	***514***	***529***	***54***
Baseload	***640***	***645***	***643***	***637***	***633***	***620***	***621***	***618***	***626***	***623***	***627***	***747***	***725***	***758***	***721***	***770***	***854***	***858***	***853***	***86***
UETCL Import	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	
OlKaria 1	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	3
OrPower4	20	30	30	30	30	30	30	30	30	30	30	63	63	63	63	63	63	63	63	6
OrPower 4 Plant 2	20	18	18	18	18	18	18	18	18	18	18	39	39	39	39	39	39	39	39	3
OrPower 4 Plant 3	10	10	10	10	10	10	10	10	10	10	10	18	18	18	18	18	18	18	18	1
OrPower 4 Plant 4	10	10	10	10	10	10	10	10	10	10	10	29	29	29	29	29	29	29	29	2
Iberafrica	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.
Iberafrica -2	0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Thika Power	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Gulf Power	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
MUHORONI KVN GT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Rabai Power	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
KDP1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
KDP3	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	1
OlKaria 2	80	80	80	80	80	70	70	70	80	80	80	101	101	101	101	101	101	101	101	10
OlKaria 1 AU	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	140	140	140	14
OlKaria 4	80	80	80	80	80	80	80	80	80	80	80	100	80	115	80	120	140	140	140	14
Triumph Power	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Tsavo	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.
LTWP	194.0	191.0	189.0	186.0	182.0	179.0	177.0	174.0	172.0	169.0	166.0	164.0	163.0	161.0	159.0	158.0	157.0	156.0	151.0	147.
Solar Garrissa	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.0	15.0	20.0	20.0	30.
Export to UETCL	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	
Forecast Dem (No UETC)	929	894	869	858	857	843	844	849	868	912	994	1132	1216	1248	1207	1258	1331	1371	1382	141
Forecast Dem (With UETC)	***929***	***894***	***869***	***858***	***857***	***843***	***844***	***849***	***868***	***912***	***994***	***1132***	***1216***	***1248***	***1207***	***1258***	***1331***	***1371***	***1382***	***141***
G. TOTAL Generation	***930***	***895***	***868***	***857***	***858***	***840***	***841***	***848***	***866***	***913***	***997***	***1131***	***1214***	***1247***	***1210***	***1259***	***1333***	***1372***	***1382***	***141***
OverGeneration	*1*	*1*	*-1*	*-2*	*1*	*-3*	*-3*	*0*	*-2*	*2*	*2*	*-1*	*-2*	*-1*	*3*	*1*	*2*	*1*	*0*	*-*
Actual Total Generation																				
Hydro Spinning Reserve	***108***	***78***	***91***	***79***	***74***	***79***	***79***	***88***	***78***	***62***	***72***	***70***	***104***	***104***	***104***	***74***	***84***	***112***	***97***	***7***
Estimated																				
Coast Generation, Total	**16**	**16**	**16**	**16**	**16**	**16**	**16**	**16**	**16**	**16**	**16**	**16**	**16**	**16**	**16**	**16**	**16**	**16**	**16**	**2**
Coast Demand on 2016-01-27	190	189	187	177	178	177	173	172	171	171	174	180	177	180	173	181	191	194	202	20
Coast export	-174	-173	-171	-161	-162	-161	-157	-156	-155	-155	-158	-164	-161	-164	-157	-165	-175	-178	-186	-17