OPTIMIZATION OF ENERGY EFFICIENCY AND INTEGRATION OF RENEWABLE ENERGY OF DATA CENTERS IN KENYA

By

Nicholas Kiptum Rotich

A Thesis Submitted to the School of Engineering, Department of Mechanical &
Production Engineering in Partial Fulfilment of the Requirements of the Award of
the Degree **Master of Science** in Energy Studies
(Renewable Energy Resources Option)

MOI UNIVERSITY

2023

DECLARATION

Declaration by Candidate

I declare that the contents of this thesis report represent my work, and that the report has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Moi University.

Sign:_____________________________ Date:_____________________________

Nicholas Kiptum Rotich

ENG/MES/3982

Declaration by the Supervisors

This thesis has been submitted with our approval as the university supervisors.

Sign:_____________________________ Date:_____________________________

Prof. Zachary Otara Siagi

Department of Mechanical, Production & Energy Engineering

School of Engineering

Moi University

Sign:_____________________________ Date:_____________________________

Dr. Isaiah Muchilwa

Department of Mechanical, Production & Energy Engineering

School of Engineering

Moi University

DEDICATION.

I would like to dedicate this work to my mother Mrs. Dinah Rotich.

ACKNOWLEDGEMENTS

I wish to thank: My supervisor Professor Siagi and Dr. Muchilwa for the guidance they offered me in writing this this proposal. My parents for the financial support they offered me to facilitate my studies. My employers Edmond and Mumali for being accommodative and helpful whenever I approached them for clarifications and discussions pertaining this study.

ABSTRACT

There has been exponential growth of ICT industry such as artificial intelligence (AI), social media (Netflix, Tiktok) and cloud computing which requires enormous amount of data storage, power consumption and cooling. This has become the challenge for the data centers industry which offers this storage, cooling, and power demand for this expanding industry. Moreover, data centers are currently facing a significant energy efficiency problem, which is contributing to an increase in power consumption that directly affects the operation cost. This study sought to optimize energy efficiency and integration of renewable energy for Data centers in Kenya. The methodology involved site survey (with the aim of taking measurement of power usage effectiveness (PUE) parameters for analysis and optimization), numerical simulation using CFD software for thermal environmental optimization and HOMER software for cost benefit analysis of power sources. The findings showed that data center three PUE was improved by 37% when centralized chiller system was used in place of direct expansion units. Similarly, the PUE values for the other two data centers were improved by an average of 28% when modular power conditioning units (UPS equipment) was used in place of fixed frame. Additionally, the selected data center for analysis of integration of renewable energy as alternative source of energy realized a saving of up to Ksh.31,000,000.00 annually with a payback period of 5 years. On thermal environmental analysis using CFD software, tile opening ration of 10% and 70% tile opening ration was analyzed. An optimized design was achieved using 10% tile opening ration which increased the airflow of the cold air. Energy performance in air management system was also analyzed using return temperature index (RTI) index. The RTI for DC1and DC2 was 71.48% and 94.79% respectively, implying the cold air was by-passed without first being properly directed into IT equipment, resulting in wasted energy while that for DC3 was 114.86% implying that air was recirculated, resulting to hot air from the IT equipment mixing with the cold air from the air conditioning equipment. It is recommended that metering and monitoring systems be established for all energy-consuming devices to provide environmental data and data related to energy efficiency, including end-user power breakdown by the various load components, power chain, and infrastructure power usage to enable real time monitoring of PUE parameters to identify gaps for energy efficiency improvements. Data center operator should also consider integrating their power sources with renewable energy sources such as solar photovoltaic system to reduce their operation cost and increase their PUE value, hence the efficiency of the data center.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

GLOSSARY

DC.	Is an infrastructure that houses IT equipment
AC	Alternating Current
IT	Information Technology.
Conventional energy source	These are usually fossil fuels and more greenhouse gas emissions and other negative environmental effects.
DC	Direct Current
Irradiance	It is the power density of the sun, measured in W/m^2
Solar Reflector.	This may be a planar mirror or parabolic arrays of solar mirrors used to achieve a substantial concentration reflection factor for solar energy systems.
Photovoltaic (pv) cells	Is a specialized semiconductor diode that converts visible light into direct current (DC). Some **PV cells** can also convert infrared (IR) or ultraviolet (UV) radiation into DC electricity.
CPU	Computer Central processing unit
PUE	This is a measure of the efficiency of a data center by considering how much energy is used by the computing equipment visa vis the total facility power.
CRAC	Computer Room Air-condition Unit

HVAC	Heating, Ventilation and Air-conditioning
Annualized cost	The price of an item that, if it occurred evenly annually of the project's lifespan, would result in the same net present cost as the component's actual cash flow sequence
Net present cost	Is the present value of all the costs of installing and operating the Component over the project lifetime, minus the present value of all the revenues that it earns over the project lifetime.
Project lifetime	The Project lifetime is the length of time over which the costs of the system occur. HOMER uses the project lifetime to calculate annualized costs from net present costs.
Salvage value	Salvage value is the value remaining in a component of the power system at the end of the project lifetime.
Present value	is the current equivalent value of a set of future cash flows, taking into account the time value of money.

CHAPTER ONE

INTRODUCTION

1.1 Background

Data centers are a fundamental part of Telecommunication services and more widely the cyber-universe. They offer the data storage, power, cooling, and connectivity requirement for the ICT industry (Pärssinen, 2016). With the rapid growth of ICT industry such as artificial intelligence (AI), social media (Netflix, Tiktok, snapchat) and cloud computing requires enormous amount of data storage, power consumption and cooling, resulting in the management of energy efficiency for this increased capacity and size of the data center to be a challenge. Besides energy inefficiency challenges for data center is the exponential rise of carbon emission that impact global warming and climate inconsistencies.

The energy consumption of worlds Data center in 2018 was 205 terawatt-hours of electricity, or about 1 percent of all electricity consumed that year(Sverdlik, 2020), making of data center energy management an important challenge for researchers. According to the business wire magazine, the current capacity of data center industry in Kenya is estimated at 30MW of IT power which translated to 0.26 terawatt-hours of electricity annually. This is projected to grow to 150MW by 2030 which will represent 1.2 terawatt-hour of electricity annually.

Previously, a large amount of research on data centers has been focusing on improving metrics like performance, reliability, and availability. However, due to the rise in data center industry, together with energy costs, the energy efficiency has now been added as a new key metric for data centers with additional of integration of power system with renewable energy to reduce operation costs. Indeed, the prices for electricity are constantly getting higher due to the instabilities experienced across the globe. With the rapid energy demand growth, there is a need to not only significantly increase the adoption of renewable energy sources in coming years but also improve the efficiency of utilization, especially on IT and Cooling systems (Sverdlik, 2020).

1.2 Problem Statement

Data centers are currently facing a significant energy efficient problem, which is contributing to an increase in power consumption that directly affects the operation cost and the addition of carbon footprints to the environment. For the sustainability of data center industry, in reference to the rapid growth of the industry, this study sought to provide recommendation on the solution to be adopted to improve the energy efficiency and reduction of operation cost.

1.3 Overall Objective

This study sought to optimize energy efficiency and integration of renewable energy for Data centers in Kenya.

1.3.1 Specific Objectives

1. To analyze energy efficiency of data centers in Kenya with the aim of reducing and optimizing energy consumption of the Data Centers.
2. To carry out assessment of thermal environment optimization using computer fluid dynamic (CFD) analysis and mathematical formulations.
3. To model the consumption of servers applied for energy prediction and management to realize energy savings for server and cooling systems.
4. To evaluate cost benefit analysis using Homer software of using Solar Photovoltaic hybrid system as compared to diesel generator energy sources to power data centers in Kenya.

1.4 Problem Justification

This study sought to analyze the energy efficiency opportunities to be adopted by the data center stakeholders, acknowledging the rapid growth of data center industry not only in Kenya but across the globe which increases the demand for power and the carbon footprint contribution to the environment.

1.5 Significance and Motivation of Study

Availability and affordability of energy are the foundations and enablers of the transformation and growth of an industry and the same applies to data centers. The high-power requirement that is accompanied by high cost has forced many middle companies to seek collocation services to the already built data center. This is not only costly to them but unsustainable because of the continuous growth of data which requires storage. Therefore, there is a need to effectively optimize data center power consumption and introduce green energy to reduce the cost of power and environmental pollution.

Another factor encouraging the study is the presence of renewable resources in Kenya. The potential of solar and wind energy resources is sufficient to support the possible electricity demand of data centers in Kenya.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction.

2.1.1 Data Center

Data centers are a combination of elements that serve as the backbone for all kinds of IT equipment, including servers, storage subsystems, networking switches, routers, and firewalls. Besides these, it also includes cooling equipment, power equipment, and fire system (IBM Cloud Education, 2020).

The history behind the data centers is a long one going back to the 1940s when the first computers were originally made, and they required large server rooms for the huge computer machinery. This data center was built in the USA in 1946, and it was called ENIAC (Electronic Numerical Integrator and Computer). The American army used it for storing defense codes ((Martin, 2018). This changed in the 1970s when microcomputers were invented and there was no need for such large rooms anymore. In the 1990s more modern servers were created and with the IT bubble servers became popular. Finally, at the start of the 21st century when cloud services became dominant data centers truly became prolific (Martin Pramatarov, 2018)

2.1.2 Data Center Power System

There are many sorts of important equipment that constitute Data Centers. Among the critical ones are the power systems. These are transformers, reserve power systems, batteries, and generators. Power failure in data center can be a huge disaster causing serious impacts. This is because more and more companies are turning to colocation services and cloud solutions. A reliable power supply and distribution system must be considered to keep the efficiency and security of a data center and minimize economic loss (Howard, 2020).

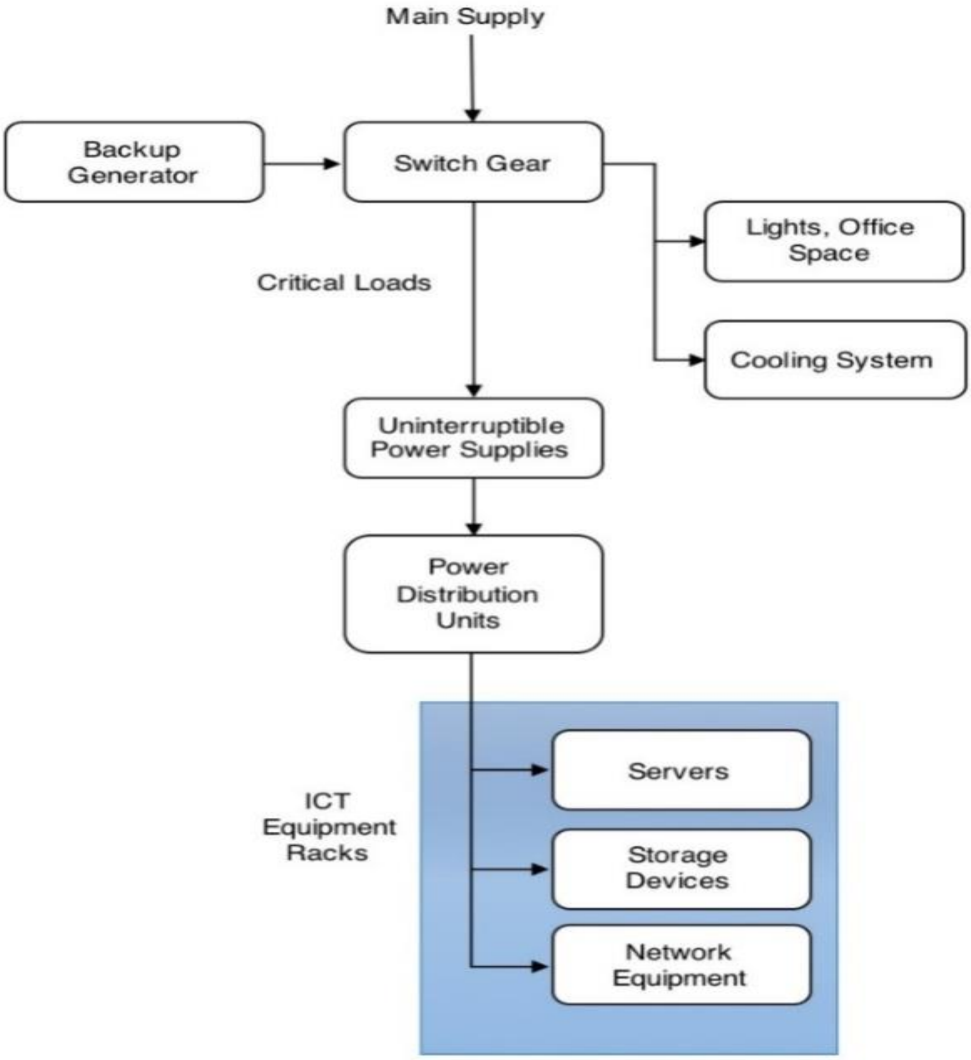


Figure 2.1. Typical Data Center Power Architecture (Howard, 2020)

Commonly the main power comes from national electricity networks and generators are being used for backup power (Howard, 2020).The importance of having backup power is that when something fails there is another one to keep up power. This is redundant and takes some extra expenses but is also very critical to attaining high levels of reliability (Howard, 2020). UPS is the reserve system that makes sure that there are no breaks in power input. This works as a reserve copy for the system. UPS system provides power to IT equipment, especially during the transition period from a utility supply to a generator. There is usually a delay of almost 60 seconds before the generator comes on.

Power distribution in the data center is mainly to computer equipment, cooling systems, fire suppression pumps and auxiliary loads such as lighting and small power. (Raritan, 2016)a leading provider of data center equipment, conducted a series of tests to examine the power distribution and usage from the upstream up to final IT loads, heat, and airflow. The goal was that by knowing more about their real-time operational environment, data center managers would be empowered to manage smarter.

They employed advanced 3-D computational fluid dynamics to determine the heat and airflow in regard to cooling and by using measuring instruments to determine power usage of different capacity components.(Raritan, 2016) were able to monitor temperature and humidity, calculate airflow as well measure power for both the IT and supporting infrastructure load. They considered a data center with 200 racks capacity.

Data center energy consumption can be categorized into two parts, that is, energy use by IT equipment (e.g., servers, networks, storage, etc.) and usage by infrastructure facilities (e.g., cooling and power conditioning systems) (Dayarathna et al., 2016).

Air-conditioning infrastructure consumes a major portion of the data center energy usage followed by IT equipment such as servers and storage, and other infrastructure elements. The amount of energy consumed by cooling and IT infrastructure depends on the design of the data center as well as the efficiency of the equipment.

2.1.3 Data Center Cooling

Cooling equipment is another very critical part of data centers since they constitute the expenses data centers have. It is necessary to cool data centers because heat dissipation is an important factor to be considered for the availability and reliability of the IT equipment (Capozzoli & Primiceri, 2015). The continuous development in the microprocessor industry has caused a continuous growth in the number of transistors for chip and clock rates. This development has caused a rigorous rise in heat dissipation density. High heat density can have an impact on the reliability of computer equipment due to high rise in temperatures.

At the beginning of early 2000, data center designers were concerned by the increasingly server's high-power consumption and how to cool them down. The current power consumption of a single IT cabinet is approaching or exceeding 5 kilowatts (Heslin, 2015)

At some point, the U.S. Congress got involved since they had become aware of data centers and the huge amount of energy they consume.

They then directed the U.S. Environmental Protection Agency (EPA) to submit a report on data center energy consumption (Heslin, 2015). This law also directed the EPA to identify efficiency strategies and drive the market for efficiency and one of the focus points was the cooling system.

A cooling system must be able to achieve full environmental control, and that includes air temperature, humidity, and pollution concentration. There are different types of data center cooling methods, and these include a chilled water system, pumped refrigerant, or containment cooling (Gento, 2017). With the chilled water technique, the Computer Room Air Handling Unit (CRAH) is connected to a chiller. In the process, as the chilled water transverse through coils, it absorbs the heat and deposits it into the chiller. After the water returns to the chiller, it mixes with condenser water flowing through a cooling tower. For the pumped refrigerant, the chilled water is pumped through a heat exchanger and utilizes a cold pumped refrigerant to draw out the heat. The pumped refrigerant technique provides savings since it can transmit energy from servers, and it allows for humidification to be greatly reduced.

For containment cooling, it can either be a hot or cold aisle configuration. Hot and cold aisle management is a common method of maintaining data center temperatures. The hot/cold aisle method is implemented by positioning racks so that the lanes are divided by hot aisles and cold aisles (Gento, 2017).

For decades, computer rooms and data centers utilized raised floor systems to deliver cold air to servers. Cold air from a computer room air conditioner (CRAC) or computer room air handler (CRAH) pressurized the space below the raised floor. Perforated tiles provided a means for the cold air to leave the plenum and enter the main space more specifically in front of server intakes. After passing through the server, the heated air returned to the CRAC/CRAH to be cooled, usually after mixing with the cold air. Very often, the CRAC unit’s return temperature was the set point used to control the cooling system’s operation. Most commonly the CRAC unit fans ran at a constant speed, and the CRAC had a humidifier within the unit that produced steam. The primary benefit of a raised floor, from a cooling standpoint, is to deliver cold air where it is needed, with very little effort, by simply swapping a solid tile for a perforated tile (Gento, 2017).

Data Center Cooling process can be broken down into four distinct processes.

a) **Server Cooling** – IT equipment generates a lot of heat as the electronic component within the IT equipment converts the electrical energy to heat. The air-conditioning system is used to dissipate this heat by blowing cold air the on servers, hence cooling them.

b) **Space Cooling** - In most data center designs, heated air from servers' mixes with other air in the computer room space and eventually makes its way back to a CRAC/CRAH unit. The heated air is transferred via a refrigerant to a CRAC unit with exception of the CRAH unit which uses chilled water as a medium for heat transfer. The refrigerant and chilled water aid the removal of heat from the data center space. The discharge temperature for the incoming air from the air-conditioning equipment is usually between (13-15.5°C). This rather cold air is blown into a raised floor plenum—typically using constant-speed fans to cool the server equipment.

c) **Hot and Cold Aisle Containment** - In a Cold Aisle containment system, cool air from the air-conditioning system is contained, while hot air from the servers is allowed to return freely to the air handlers. For a Hot Aisle containment system, the hot air generated by IT equipment is contained and is returned to the air handlers through a ceiling return plenum.

2.1.4 Data Center Tiers

Another unique system to compare data centers as far as design and construction works is concerned is through tier levels. This is a certification system called TIA-942 standard developed by Uptime Institute to categorize the data centers into four different levels of tiers as described in table 2.1. These four levels categorize data centers based on their reliability and resilience (Andy Lawrence., 2019).

Table 2.1. Data Center Tier Classification (Andy Lawrence., 2019)

	Tier I	Tier II	Tier III	Tier IV
Active Capacity Components to Support IT load	N	N+1	N+1	N After any failure
Distribution Paths	1	1	1 Active and 1 Alternative	2 Simultaneously Active
Concurrently Maintainable	No	No	Yes	Yes
Fault Tolerance	No	No	No	Yes
Compartmentation	No	No	No	Yes
Continuous Cooling	No	No	No	Yes

a) A Tier 1 basic data center denoted by N, has non-redundant capacity components and a single non-redundant distribution path for power and cooling architecture. Due to this, the data center is susceptible to disruption from both planned and unplanned maintenance.

b) A Tier II data center has redundant capacity components and a single non-redundant distribution path serving critical components. This means it is possible to remove redundant capacity components without causing any of the critical components to shut down but removing the non-redundant distribution paths will require a shutdown. A Tier II data center is denoted by N+1 where N denotes the capacity component.

c) A Tier III data center denoted by N+1, consists of redundant capacity components and a redundant distribution path serving critical components. This means it is possible for concurrent maintainability of the data center. It is a requirement for Tier III IT equipment to be dual-powered. This has an impact on the efficiency of power supplies especially UPS as explained below.

d) A Tier four data center is represented by 2(N+1). It has multiple, independent redundant capacity components that provide continuous power and cooling to critical components.

As illustrated in table 2.1, the high the Tier levels the high the reliability. However, the efficiency of capacity components is compromised. This is explained in detail by taking UPS components as illustrated in the example below together with figure 2.2.

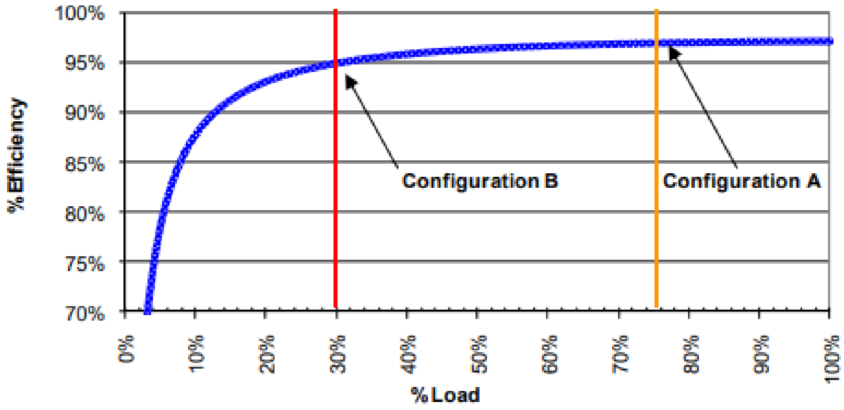


Figure 2.2: Schneider APC UPS efficiency Curve (Sawyer, 2016)

Based on runtime level compliance, a UPS device in a 2N configuration will never operate at 100% load. This is because each side of 'N' must have the capacity to power the critical load at full load if one side fails. In real-world scenarios, 2N systems rarely reach 50% utilization on any system (Sawyer, 2016). Assuming the UPS is operating between 20% and 30%, the graph shows less than 95% efficiency. At this point, it is important to consider the impact of UPS inefficiencies on operating costs. In this example, a typical 225kVA / 180kW UPS operates at 20% load, which corresponds to a 36kW load and operates at approximately 85% efficiency. The annual kWh consumed by the UPS to support this system load is 311,040. Additionally, cooling must be considered, adding an additional 371,011.76 kWh/year. At a power price of $0.10 per kWh, this translates to $59,059.60 per annum.

2.1.5 Power Usage Effectiveness

Power Usage Effectiveness (PUE) is an index that compute the energy efficiency of a computer data. It is a ratio of the total amount of energy used by a computer data center facility to the total facility power. This PUE value is determined on a scale from 1 to 4, with 1 being very efficient and 4 very inefficient. Figure 2.3 shows the relationship between PUE and DCIE.

Other devices that are considered not IT devices such as lighting and cooling system is categorized as facility energy consumption (Development, 2015).

$$PUE = {}^{Total\ Facility\ Power(Kw)}\Big/_{IT\ Equipment\ Power\ (Kw)} \qquad (2.1)$$

The total Facility Power value can be obtained from the power measured at the utility meter, while IT Equipment Energy can be obtained from the UPS display meter since UPS system is only dedicated to IT loads.

Data Center Infrastructure Efficiency (DCIE) can also be used to compute data center energy efficiency. This is a reciprocal of PUE where it calculates total power of the IT equipment to the total facility power and then multiplied by 100.

$$DCIE = \frac{IT\ Equipment\ Power\ (Kw)}{Total\ Facility\ Power\ (Kw)}\ X\ 100 \qquad (2.2)$$

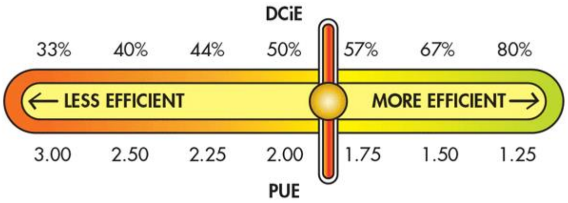


Figure 2.3: Values of PUE and DCIE from the least efficient to the most efficient (Yole, 2015)

2.1.6 Power Usage Effectiveness (PUE) on Data Centers Energy Efficiency.

Power Usage Effectiveness (PUE) is the best metric to use when examining a data center's efficiency. The PUE value, as previously mentioned, is the proportion of IT load power to the total input power of the data center. The efficiency of the data center decreases when the PUE value increases because more energy is used to power other non-critical loads. An energy-inefficient data center with a high PUE rating used more electricity than necessary. A data center is more efficient if it has a low PUE rating since its total power consumption is much closer to the energy requirements of its IT equipment. (Andy Lawrence., 2019).

Measurements of efficiency using PUE allows data centers operators to ascertain their overall operations and identify opportunities to improve their efficiency. An efficient Data center means lower operating costs for both data center operator and the customer.

In 2019, Uptime Institute carried out a global data center energy efficiency survey and for the first time there was no recorded improvement as far as PUE value is concerned (Andy Lawrence., 2019). As a matter of fact, energy efficiency worsens slightly, from an average PUE of 1.58 in 2018 to 1.67 in 2019. Uptime Institute has been carrying out industry average PUE numbers, at intervals, over the past twelve years as shown in the figure 2.4 below.

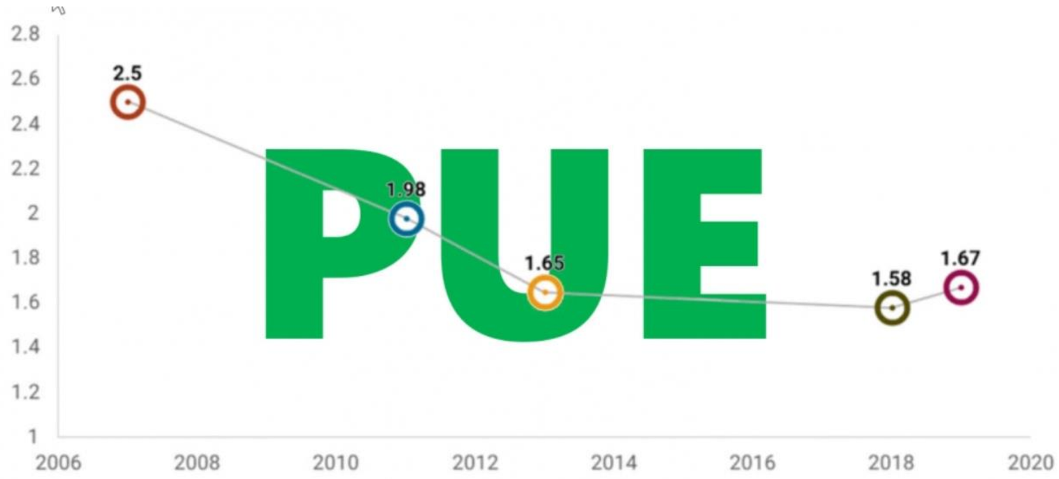


Figure 2.4: PUE Trend of PUE from 2006 to 2020

The explanation given for the slight deterioration of the PUE value was attributed to the higher and extreme temperatures experienced in the last year in many parts of the world where data centers are situated this result to the increased use of cooling which ultimately increased the PUE value (Andy Lawrence., 2019). Another factor is the inefficient utilization of many data centers because of the decreased workload which implies data centers were operating below their optimal design. There is no record of PUE values of data centers in Kenya.

Power electrical efficiency of a data center is rarely planned during the designed stage or managed during operations, and this usually results in wastage of substantial amount of power. Nowadays it is possible to design and improve the electrical efficiency of the data center because of the advancement of monitoring and designed software for data center. In most cases the actual efficiencies of the installations are usually much lower than that designed one.

Factors influencing the electrical efficiency of a data center is listed below: -

a) **IT Load*:*** Critical IT load is the amount of energy consumed by servers and network equipment and it usually varies frequently, hence efficiency varies instantaneously according to the demand. IT equipment generally consumes roughly half of their peak load power when idle and grows with utilization.

b) **Effect of Outdoor Conditions*:*** The most significant factor is the outdoor air temperature. As the outdoor air temperature increases the efficiency of the data center decreases and this is due to heat rejection system consuming more energy as they process data center heat which increases because of sucking in of the outdoor heat into the data center.

c) **User Configurations*:*** There is a significant amount of variation in the PUE value due to the action of the user. This may include change in the environmental parameters set point such as temperature and humidity of Air-conditioning systems, Changes in Venter Floor Tiles, Changes in Plenum and Failure of cleaning air filters.

2.2 Review of Related Studies Literature.

2.2.1 Modern practices towards Achieving Low PUE for Data Centers

Data center can use up to 100-200 times more electricity than standard office spaces. They are ideal targets for energy-efficient design strategies because of their high-power consumption, which can minimize electricity use and save money. The crucial nature of data center loads, however, enhances many design requirements, including energy efficiency is far behind dependability and high-power density capacity. Frequently, brief design cycles leave little it's time to thoroughly evaluate design potential for efficiency. That may lead to designs that are just enlarged versions of typical office space methods as opposed to thought through designs befitting special facilities such as data centers.

The following are the recommendations on data center best practices prepared by (Bruschi, 2012) that covers four key areas as listed below:

i. Information Technology (IT) Systems
ii. Environmental Conditions
iii. Cooling Systems
iv. Electrical Systems

2.2.1.1 Information Technology (IT) Systems

IT equipment loads can contribute to more than half of typical data center facility's total energy consumption. The data center's burden on these resources will be greatly reduced using efficient IT equipment, which will lower the size of the cooling equipment required. The best approaches to reduce IT equipment loads in a data center are to buy servers with energy-efficient CPUs, fans, and power supplies, high-efficiency network equipment, consolidate storage devices, consolidate power supplies, and the use of virtualization (VanGeet, 2011).

a) Efficient Servers

Most of the IT energy load in a typical data center is accounted for by rack servers, which frequently waste the most energy. The bulk of servers use 20% or less of their resources on average, but they nonetheless consume all their available power. To reduce this wasted energy, server processors and internal cooling systems have recently undergone significant advances. According to Energy Star (Energy Star, 2016) server’s fans account for about 5-10% of total data center energy use. Servers with constant fans are not able to vary the fan speed to match the data center heat load, which varies depending on the workload. It is therefore advisable to search for new servers that have variable speed fans rather than a typical constant speed fan for the internal cooling component.

Experimental analysis of server fan control strategies was carried out by (Rickard Brännvall, 2016), where it was integrated with a custom-made circuit board that controlled the fans using a proportional, integral and derivative (PID) controller running on the servers operating system. The controller was used to maintain a constant temperature for the server’s, regardless of external environmental factors or workload. To simulate the environmental conditions of a data center, (Rickard Brännvall, 2016)conducted the experiments in a server wind tunnel. To maintain a predetermined pressure-drop over the server and air entering at a specified temperature and humidity, the wind tunnel fan, humidifier, and heater were each controlled by a separate PID controller. While examining the impact on the temperature differential, ΔT, the tests provide server operation temperatures that ideally trade off power losses versus server fan power. Additionally, the findings were theoretically applied to a direct fresh air-cooled data center to examine the effect of server operating temperature, which demonstrated ΔT to be high than in normal circumstance. This ultimately reduces the workload on the air-conditioning equipment hence saving on cooling power.

Increasing ΔT improves the efficiency of the data center cooling equipment. This is because raising the ΔT above the factory setting causes the server to shift out of its ideal operating range. This, ultimately reduces the workload on air-conditioning equipment and hence improves data center energy saving (Rickard Brännvall, 2016).

Variable speed fans enable adequate cooling to be provided while operating more slowly. It is feasible to provide adequate cooling while running slower and using less energy with variable speed fans. Through its recognition of high-efficiency servers, the Energy Star program benefits consumers. On average, servers that adhere to Energy Star efficiency standards will be 30% more efficient than typical servers.

Additionally, a throttle-down drive is a component that lowers the energy consumption of processors when they are not in use, preventing a server from using all its power when it is operating at its average 20% utilization. This is also referred to as "power management" at times. Many IT organizations worry that slowing down servers or turning off inactive servers will reduce server reliability, although technology is built to withstand tens of thousands of on-off cycles.

Servers that have "power cycler" software installed can also have their power draw modified.

The software can instruct certain devices on the rack to turn off when there is no demand. Performance issues and system failure are two major power management hazards that should be considered against the potential energy savings.

2.2.1.2 Energy Efficiency in Air Cooling

There is a need for a global management technique that aggressively deploys a cooling system in a computer room regarding the dynamic heat load distributions, and then dissipates the heat based on the most efficient cooling configuration in the data center room. In 2010, (Brandon A Rubenstein, 2010) proposed a data center cooling system that uses refrigerant system with above ambient properties.(Brandon A Rubenstein, 2010) implemented a cooling solution that takes advantage of a mixture of water and glycol at a temperature range of (40 °C to 50 °C) that is above ambient conditions to cool the heat dissipated IT equipment in place of a chilled liquid with a temperature range of less than 20 °C or chilled forced air. The impact of this is that the energy required for cooling the data center is lowered, significantly eliminating the need for chillers.

Traditional cooling system with liquid provides more dedicated point cooling. The mixture of water and glycol has a specific heat four times greater than air, therefore (Brandon A Rubenstein, 2010)hybrid system can remove heat with a lower mass flow rate than air, hence reducing the load on fluid and the holistic power drawn by the system. The (Brandon A Rubenstein, 2010) cooling system consists of two cooling loops and an ambient air. The first loop is located within the data center building and provides cold water to the racks. The other loop is internal to the rack and provides direct rack cooling.

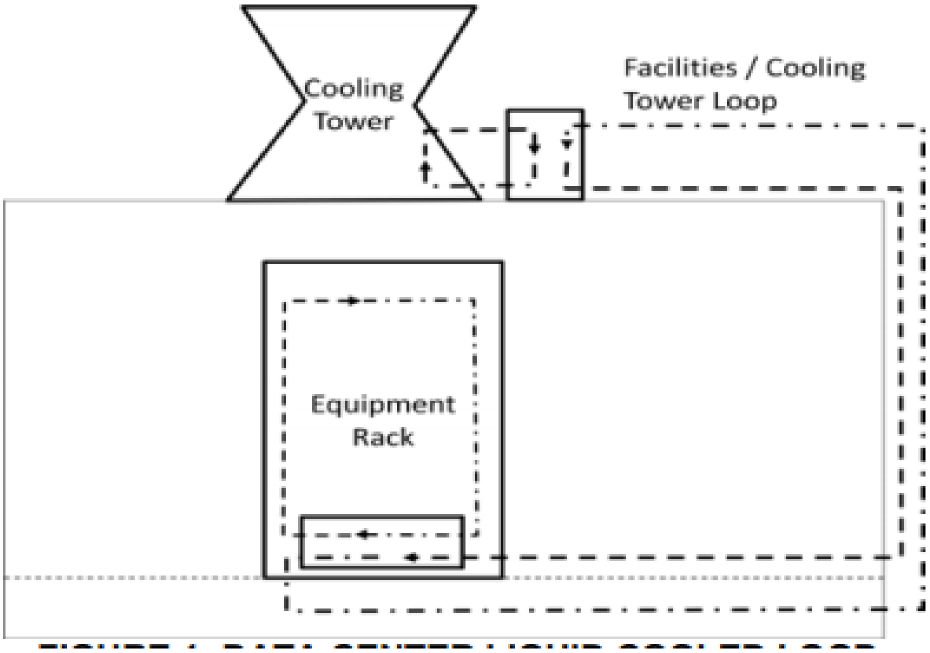


Figure 2.5: Data Center Liquid Cooled Loop (Brandon A Rubenstein, 2010)

Figure above shows the general layout of the liquid cooling system. The heat from the IT equipment is internally carried to a heat exchanger located inside the rack. The heat is delivered to the building water through that heat exchanger. The heat is the carried to the cooling tower where the heat is transferred to the facility cooling tower where it then dissipates the heat through evaporate cooling(Brandon A Rubenstein, 2010).

To evaluate the thermal performance of the hybrid data center, (Brandon A Rubenstein, 2010)developed an analytical model using both the equation of heat transfer and manufacturer’s data. Typical data centers data was considered to evaluate the performance, and this includes the floor area of the IT facility, the power that the facility can support per unit area.

Even though the hybrid data center cooling model can reduce the energy required for cooling, hence lowering the operation cost, it does not address the challenge of humidity control hence leading to the formation of rains cloud in data center room, which can lead to equipment failure.

CFD simulation was used to examine the airflow pattern in a typical data center by (Gao et al., 2015). The targeted model for measurements on the thermal environment and energy consumption was a typical data center located in Beijing China, with a raised floor air supplying system. The observed findings were utilized to validate the simulation results, provide boundary conditions for airflow pattern modeling, and examine the cooling effectiveness of the studied scenario. The efficiency of three actions taken to optimize the airflow pattern was examined by CFD simulation based on the validated model. Sensors was used to measure the boundary conditions.

Three potential actions were made to improve the airflow pattern regarding the issues of the investigated data center (henceforth referred to as case 1), and they are denoted as actions 1 through 3. They are adding vertical partitions to prevent the mixing of cold and hot air at the rack top (measure 1), blanking off the unused racks to prevent the hot air from returning to the cold lanes (measure 2), and partially enclosing the cold aisles (measure 3) (Gao et al., 2015).

From the analysis, it was discovered that the data center under study had potential for energy efficiency. The optimal thermal environment is a result of the CRACs' provision of more than enough cold air. The energy efficiency was increased when the three measures were combined to optimize the airflow pattern. By partially enclosing the cold aisles, the supply temperature could be raised by three degrees while the thermal environment was kept within the acceptable range. This can lead to a commensurate increase in the CRAC system's performance coefficient, which will save data storage's energy (Gao et al., 2015).

Even though the study focused on the methods of improving data center energy, it only focused on one method of cooling, that’s containment method.

2.2.2 Artificial Bee Colony (ABC) Algorithm for Energy Optimization of Servers and Switches

There are three types of business in Fat Tree regarding the server locations of intercommunication, that is, close-range business, medium-distance business and long-distance business (Zhou et al., 2019). The criteria to select the shortest path varies under different type of businesses. Long-distance business implies the server of intercommunication are in different pods. The shortest path for traffic is determine by the serial number of the switches in the core layer. The medium-distance business means the server of interconnection are in the same pods, however, with a unique switch in the edge layer. The closest path is found out by the serial numbers of the switches in the aggregation layer. For a close-range business, the servers for interconnection are in the same pods, with the same switches in the connected layer. This means there exists only one shortest path for this case.

Considering the different type of business in a Fat Tree topology, the determination and selection of the shortest path can be done the ABC. This will reduce the workload hence solving the optimization of energy consumption of a data center network (Zhou et al., 2019).

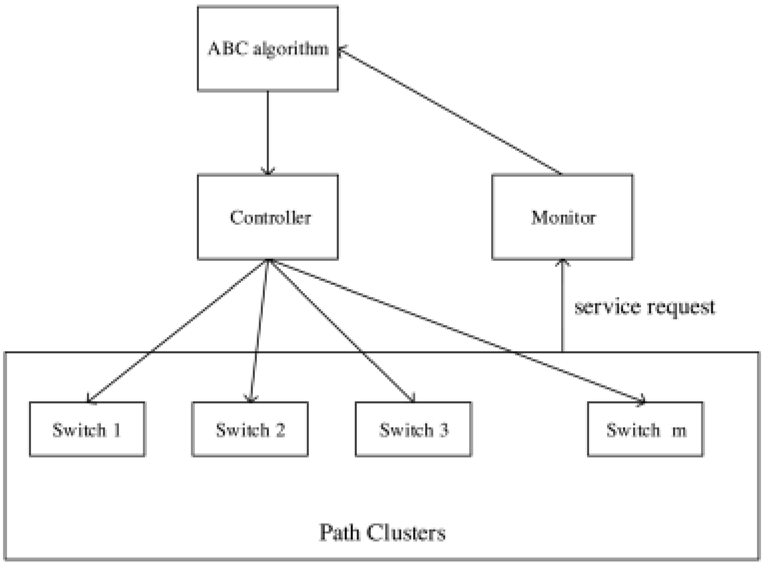


Figure 2.6: Anti Bee Colony (ABC) Structure (Zhou et al., 2019)

To generate a two-dimensional solution space whereby each switch can point to a two-dimensional space, the energy consumption of network in the data center in the underload and overload clusters was considered (Zhou et al., 2019). Each k lookout or scouts are arbitrary freighted to k points to check the increase of the predicted energy consumption. A minimum m points was then selected to explore m global optima target. This is after a comparison was made on the k-values obtained (Zhou et al., 2019).This information was then transferred to the controller, with m optional switches and target path obtained by the proposed ABC. Then, the selected and allocated solution spaces are sent to the controller, responsible for the selection of path. Finally, the target path of the business Ki is determined.

Zhou analyzed the optimization of energy consumption for the data center network based on k (k = 12) core switches. During the simulation, the rates of all the links and ports were 1000 Mbps, and the load rate α of network was defined as the ratio of the traffic to the total number of servers.

$$\alpha = \frac{\Sigma i \Sigma j\ dij}{N} . i\ \neq j; i, j\ \in [1, N] \qquad (2.3)$$

Where N is the total number of servers of Fat Tree.

The algorithm is validated by two different types of traffic where a small-scale task is chosen as input. In this case, less delay and bandwidth are required with a random number between (50 and 100). Another scenario is the use of large-scale task as input. This means for a large traffic, there is low latency and high bandwidth, with a random number between (250, 650) (Zhou et al., 2019). Anti-Bee Colony (ABC was used to simulate the data center network with k=12 and the result was plotted on a graph of energy saving against network load rate. The percentage improvement in energy savings was clearly visible from the graph in figure 2.7 due to the convergence of the algorithm (Zhou et al., 2019)

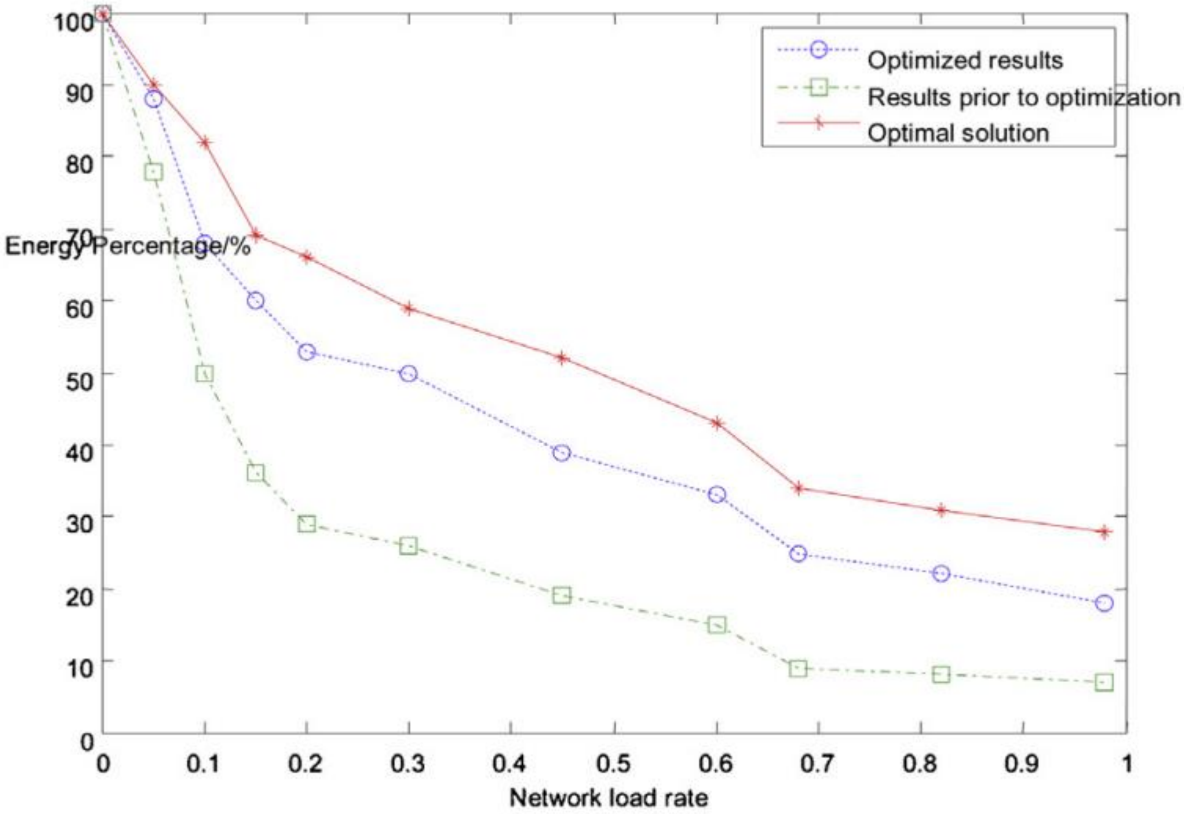


Figure 2.7: Algorithm performance of traffic

Most approaches use traffic as input for simulation of data network without further breaking down.

2.2.3 Analysis of Energy Solution for Sustainable Green Data Center

Renewable energy adoption is another method meant to reduce the data center CO_2 carbon foot, increase data center PUE value, and reduce in the long run the cost of power for the data center. The main challenge is the intermittent nature of the Renewable energy resources, whereas data center requires energy 24 hours per day every day, which needs to be provided even when renewable energy power is not available.

The most problematic issues for new generation data centers are the development of renewable energy and carbon dioxide reduction as the two main climate action initiatives. Reduction of traditional power use and cost of electricity (COE) with higher quality of electricity have also been identified as an intriguing research issue. Furthermore, designing a large-scale, sustainable green data center using stand-alone renewable energy system is difficult because of the intermittent nature of the available renewable solution.

A hybrid system consisting of solar, wind, utility and generator was developed by Rahaman, and economic analysis of the different system was done using HOMER software.

2.2.3.1 System Model

The solution proposed by (Rahaman et al., 2021)assumed various homogeneous servers. The hybrid power supply system for the proposed green data center is shown in Figure 2.8. IT equipment is classified as a DC load, while other equipment such as lights and cooling devices are classified as an AC load.

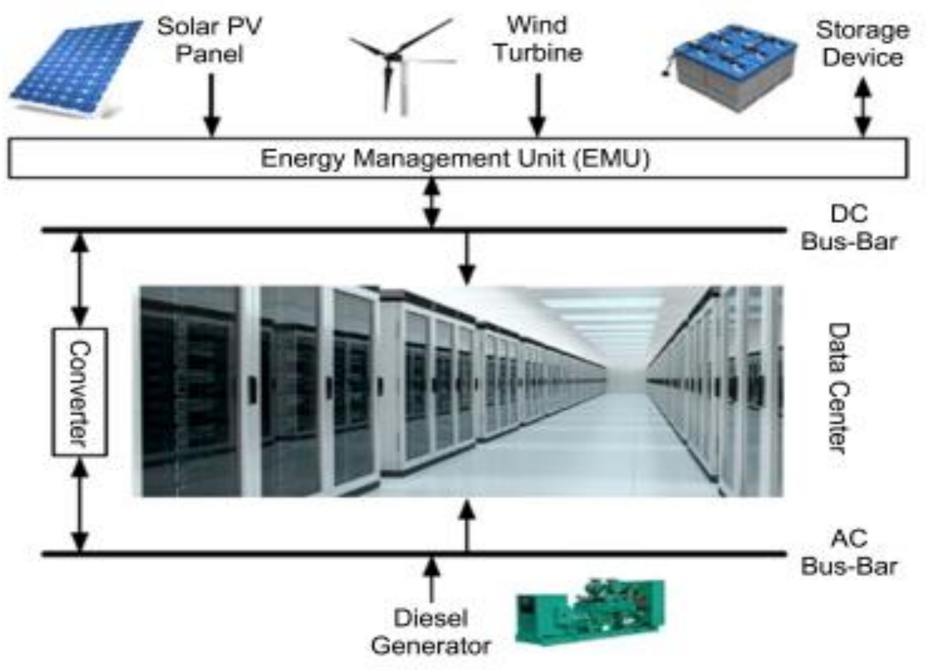


Figure 2.8: Hybrid PV/WT/DG Powered Green Data Center Schematic (Rahaman et al., 2021)

An energy management unit (EMU) was used to connect solar, wind and storage sources to the DC Bus section. A converter was then used to convert the DC power to AC.

HOMER software was used to simulate the economic comparison of the different system. Figure 3.1 shows the intermittent nature of wind resources in Bangladesh. Solar and wind power generation normally fluctuate due to nature and hence it is not desirable to be used as standalone system for data centers.

The diesel generator was employed to supply the data center when renewable energy was not available.

The power model developed by (Rahaman1, 2021) is as shown below.

$$P_{DG}\,[k,\,t] = Q_{DG}\,[k,t] - P_{renew}\,[k,t] \qquad (2.4)$$

$$P_{renew}\,[k,\,t] = P_{PV}\,[k,t] + P_{WT}\,[k,t] \qquad (2.5)$$

$P_{PV}[k,t]$ represents solar energy source, $P_{WT}[k,t]$ represent power generation from wind turbine and $P_{DG}[k,t]$ denotes the generation from the diesel generator.

From the above equation, it is observed that when $P_{renew}[k,t] < Q_{DC}[k,t]$, then the data center will be supplied by $P_{DG}[k,t]$ and when $P_{renew}[k,t] = Q_{DC}[k,t]$, the entire power requirement of the data center will be supplied by renewable energy source.

2.2.3.2 Cost Aware Optimal Framework

The cost modelling included the net percent cost (NPC) which represents the total cost proposed system over its full lifecycle, and includes replacement cost (RC), capital costs (CC), operations and maintenance expenses (OMC), and salvage value (S) across the project's lifespan. This can be calculate using the formula below (Rahaman et al., 2021).

$$NPC = \frac{TAC}{CRF} = CC + RC + OMC - S \qquad (6)$$

The annual and capital cost recovery factor can be calculated using the following equation.

$$TAC = TAC_{CC} + TAC_{RC} + TAC_{OMC} \qquad (7)$$

$$CRF = \frac{i(1+i)^M}{(1+i)^M - 1} \qquad (8)$$

Where, i represent annual real interest rate and M denotes the project duration.

The design consists of homogeneous servers ranging in numbers from 500, 100, 1500, 2000, 2500, 3000, 3500, and 4000. The power consumption for each server was assumed to be 120W. The PUE and utilization factor (U_f) was varied from 0 to 1.0 and 1.3 to 2.0 respectively. The project lifespan was taken as ten years and annual rate of interest as 6.75% (Rahaman et al., 2021).

The power consumption for servers was simulated by varying the number of servers, utilization factor and power usage effectiveness. From the simulation results, the power consumption was observed to increase with the increase of number of servers, utilization factor, number of server requests and power usage effectiveness.

Homer software was used to simulate the energy contribution for energy sources such as wind, solar and generator. The results of the simulation indicate that the solar PV, wind power and generator power increase with increase in the load requirement (increase in the number of servers). It also demonstrates hybrid renewable energy solution as potential to power green data centers.

Even though the study focuses on renewable energy impact on data center, it failed to demonstrated cost benefit analysis of renewable energy compared to other sources of energy powering data center and the impact of renewable energy to PUE and hence the efficiency of data centers.

CHAPTER THREE

METHODOLOGY

3.1 Analyzing the Energy Efficiency of Three Data Centers in Kenya with the Aim of Reducing and Optimizing Energy Consumption of the Data Centers

The data center sector is increasingly becoming the world's largest consumer of electricity (Development, 2015). With an increasing data consumption and an average Power Usage Efficiency (PUE) of 1.8, worldwide data center energy consumption will reach 507.9 TWh by 2022 (Energy Star, 2016). This section will discuss the PUE of selected data centers in Kenya and methods that can be used to improve it. Limited open-source information will be used to compute the PUE of the three data centers. The data obtained will then be used to investigate the sensitivity of the PUE to certain parameters.

Due to the growth of data consumed by different organizations and government institutions, the energy requirement of the IT Racks has increased drastically in the last few years. For this reason, energy efficiency has become more prominent to data center operators not only to reduce operation costs but also to reduce carbon footprint. Power and cooling are the two major factors affecting power efficiency for most data centers. There is a need for data centers operators to take several measures to ensure better power usage effectiveness (PUE) since a better PUE value can achieve both energy efficiency and save costs. The PUE value of 2.0 is considered standard while 1.5 is considered good and 1.0 is the ideal value.

Three data centers were selected for the study where all parameters used for computation of the PUE was measured and recorded. The three were selected based on the size of the data center and the technology adopted. The multimeter was used to measure the power consumption of different equipment used for computation of the PUE values.

Measurement and recording of Energy consumption of IT Equipment was achieved by reading directly from a power distribution unit (PDU) with intelligent meters, while those without PDU with intelligent meters.

A PDU is a power distribution frame with an intelligent meter to measure and indicate the power consumption of each rack. Without adequate information on the power use of the IT equipment, it is difficult to make an accurate energy consumption prediction. This clearly shows inaccuracy that can arise from estimating the energy consumption or PUE for a data center still in the design phase.

Measurement of energy consumption of Air-conditioning equipment was done using multimeter whereby the amount of power drawn by each unit was measured. This result was then compared with the data sheets provided by the data center owners.

There is always inefficiency in a typical data center power distribution system incurred during transmission of energy by different equipment, mainly the transformers, Power Distribution Unit (PDU) and the Uninterruptible Power Supply units (UPSs). The inefficiency due to UPS and transformer were obtained from the data sheets provided while electrical losses due to cable resistance were calculated based on the size of the circuit.

The power usage effectiveness (PUE) was then computed using the following equations.

$$PUE = \frac{Annual\ DC\ electricity\ usage\ (dEC1)}{IT\ Equipment\ usage(dEC2)} \qquad (3.1)$$

Where

$$dEC1 = Power\ drawn\ by, IT + Air - condition + Distribution\ losses + Auxilliary\ loads$$

The figure 3.1 below shows the process for PUE computation and analysis.

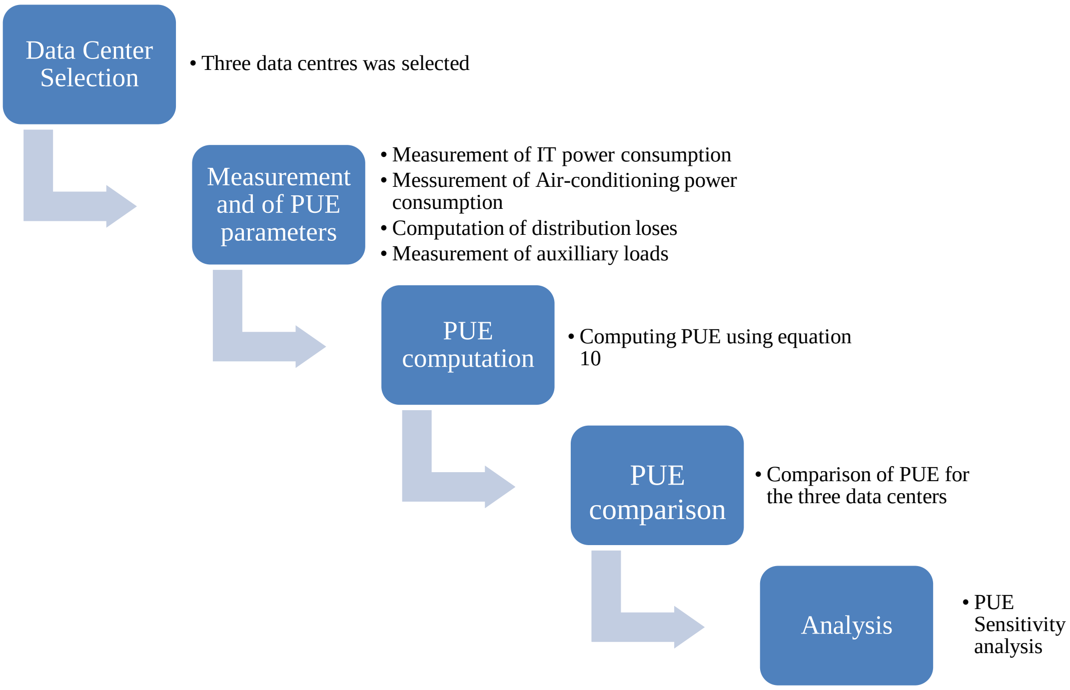


Figure 3.1: Methodology for PUE Computation and Analysis

Data Center selection

Three data centers located in Nairobi were selected for the study. The selection was based on the size of the facility. The owners include government agencies and private entities.

They were built to offer network connectivity, colocation services, data processing, storage, and cloud services. These three selected for the study had high capacity (greater than 1000kw) hence offered a good opportunity for energy efficiency optimization analysis, as compared with the rest which consumed less than 500kW.

Measurement of PUE Parameters

PUE is a ration of data center power and IT power as described in equation 10. The multimeter and power analyzer were used to measure data center power while the IT power was read directly from the display meter of PDU.

PUE Computation and Analysis

The measured values for the three data centers were tabulated and PUE computed using equation 3.1. Further comparison done for the three data centers to compare which was operating efficiently. Finally, sensitivity analysis of different parameters that are used to calculate PUE was carried out by varying the inputs until the optimal level is achieved.

More information about data centers two and three were achieved through material interview with an Engineer at DC II who oversees Mechanical and Electrical system operation and managing director for data center three.

Sensitivity Analysis

Sensity analysis was done through varying of the setpoint temperature of the return air temperature, varying the load factor to understand its effect on the efficiency of the UPS and lastly analysis different cooling technology and its effect on the efficiency of the cooling systems.

3.2 Thermal Environmental Optimization and control

Almost all the electrical power consumed by IT equipment ends up as waste heat and it is vital to remove the heat to prevent high temperature conditional that is unfavorable to the IT equipment (Dunlap & Rasmussen, 2012). Nearly all data center IT equipment is air-cooled, and this implies that every IT equipment absorbs cold air and release hot air as exhaust air.

Generally, data center usually contain many communication devices which generate enormous amount of hot airflow paths that altogether represent the total heat that must be removed (Dunlap & Rasmussen, 2012). The configuration of IT racks and air-conditioning system are vital to ensure that there is enough airflow rate for heat removal and energy saving initiatives by the air-conditioning system to remove the heat.

An ideal environmental condition is important for the smooth operation of a data center. Several factors such as the size of the space, how the racks are arranged, and the surrounding temperature, affect the data center's thermal environment.

The field measurement was undertaken to study the environmental condition of the data centers. Measurements of air flows and temperature at different locations within the data centers were taken including supply and return air temperature of the air-conditioning and IT rack. Then, a program called 6SigmaRoom for computer fluid dynamics was used to model the thermal environment of the data center. The numerical calculation and simulated model were then compared for verification and an optimization design.

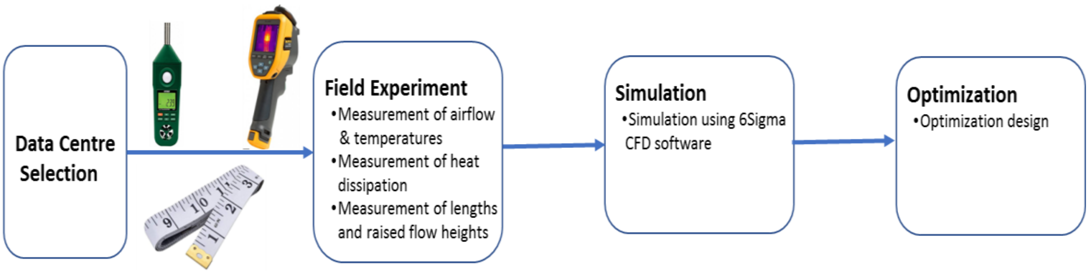


Figure 3.2: Methodology for Data Center Thermal Studies

Table 3.1: Instrument Used for the Field Experiment

NO	INSTRUMNENT	RANGE	ACCURACY	FUNCTION
1	Environmental Meter Model: BESANTEK Serial No.AJ 38522	-20-80^{0}C 0.05-30m/s	±0.01^{0}C ±0.01 m/s	Measure the environmental parameter such as Supply and Return temperature and relative humidity.
2	Thermal Imager Model: Hti Serial No.201911004638)	20-120^{0}C	±0.1 ^{0}C	Measure the heat dissipation within the data center space
3	Tape Measure	0-10 Meters	±0.1M	Measure the length of the data hall and the height of the raised floor.

The experiment was done for three data centers in Nairobi to investigate the thermal environmental parameters and opportunities for their enhancement as described in figure 3.2 and flow chart of figure 3.3.

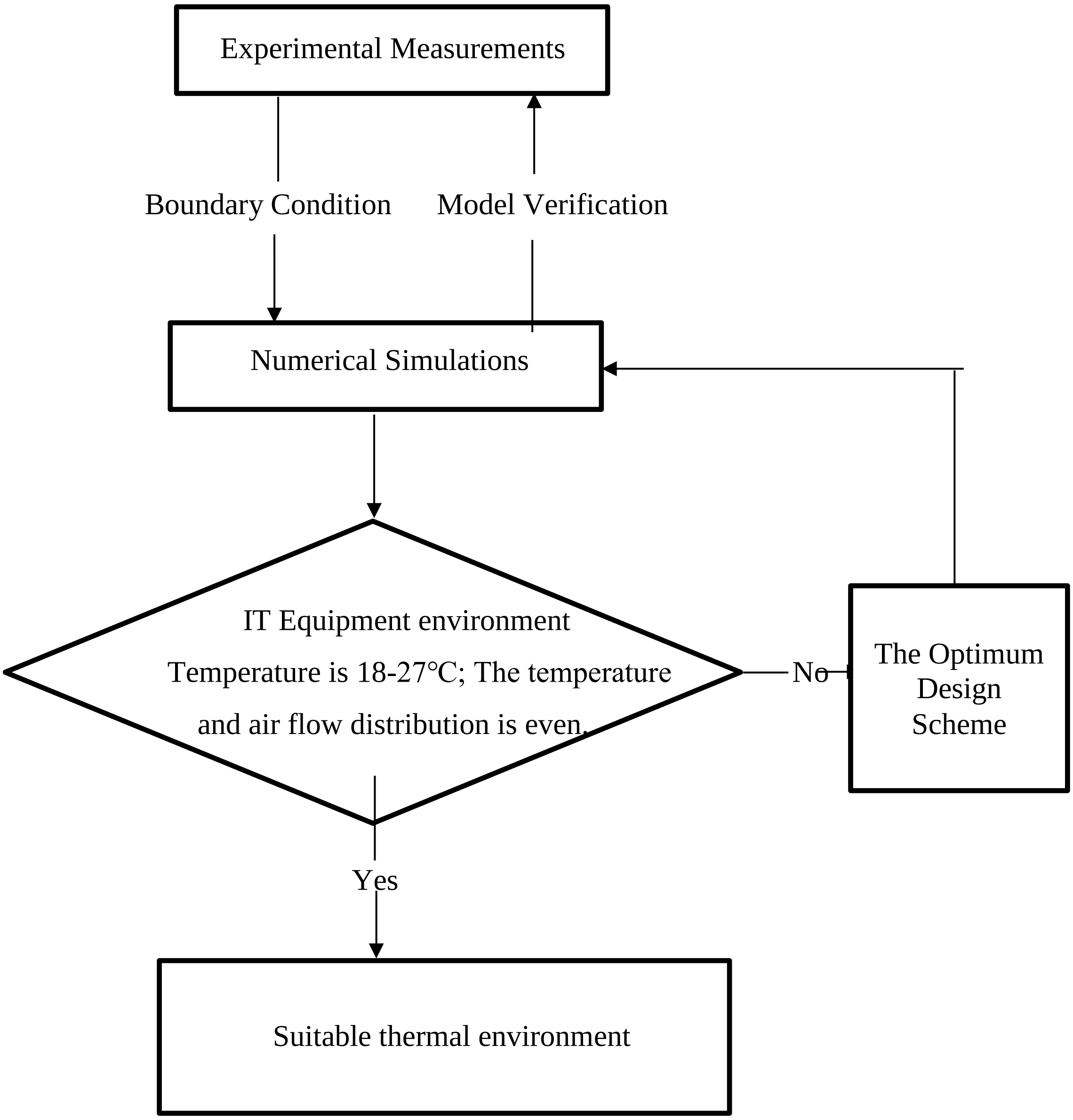


Figure 3.3: Simulation flow chart

3.2.1 Numerical analysis

3.2.1.1 CFD Modelling Geometry

Geometry of the three data center in the CFD model containing the air conditioning equipment and server racks were inserted in the model. During simulation, boundary conditions was applied as the input to the CFD model as described in table 3.2.

3.2.1.2 Boundary Condition

To set up the boundary condition on the CRAC unit, the flow rate and supply temperature were measured. The values of the air flow rates emanating from the front sides of all the CRAC units were measured using the environmental meter. The values were taken on the three locations of the server cabinet, namely, the top, middle and the bottom of the server rack.

Table 3.2: Boundary conditions for the CRAC units

No	Items	Data Center One	Data Center Two	Data Center Three
1.	Server rack rating (Kw)	2.5	3	3
2.	Perforated tile opening ration (%)	50	65	50
3.	Sensible Cooling (Kw)	39.9	37.5	32.8
4.	Flow rate (m^3/s)	2.22	2.4	2.3
5.	Supply & Return temperature (^oC)	18 & 24	18 & 24	18 & 24

3.2.1.3 Physical model and computational settings

Using the computer room layout and dimension, the physical model was established using CFD simulation software 6SigmaRoom. The computer fluid dynamic (CFD) simulation software 6SigmaRoom is capable of numerically calculating and analyzing the thermal environment for existing and new computer room systems. The advantage of 6SigmaRoom simulation software is that the process of modeling is more convenient and quicker since the software contains server modules and air-conditioning equipment within the model.

A dedicated air-cooled direct expansion unit with R410 as a refrigerant was selected in the software model. In the normal operation of the computer room, the air conditioner system absorbs heat from the computer room and transfers it to the outdoor air through an air-cooled heat exchanger.

Due to the continuous operation of data center systems, the calorific value of air conditioner equipment is much less as compared to that of the IT server, which can be neglected in this paper. Hence, the air conditioner cooling load Q is the sum of the IT server load Q_1 and the external load Q_2, as shown in Equation (11).

$$Q = Q_1 + Q_2 \qquad (3.1)$$

The IT equipment load in the computer room can be determined by tabulating the rating of each server's power rating. The external heat load Q2 represents the heat gain through the enclosure structure, personnel, and lighting.

Therefore, the air conditioner cooling load Q is equal to the IT server load Q1 and external heat load Q2.

Alternatively, IT server load can be calculated according to the Equation (3.2).

$$Q1 = Cq_v\rho(T_{in} - T_{out}) \qquad (3.2)$$

where C is the air specific heat capacity at constant pressure, and can be taken as 1.01 kJ/ kg.°C), q_v represents the air flow rate, which was measured using environmental meter, while ρ represents the air density, 1.2 kg/m3 and lastly Tin and Tout constitute the supply temperature and return temperature of the air conditioner respectively. In this case, the experimental results of supply and return temperature of air conditioner was used.

3.2.1.4 Governing Equations

Mathematical equations form the basis of any numerical simulation. In this case, an assumption is made that the flow field in the data center satisfies Bernoulli Hypothesis, which is based on the mass conservation equation, the momentum conservation equation, and the energy conservation equation (A, 2015). Considering an incompressible fluid, the mass conservation equation is:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad (3.3)$$

The momentum conservation equation becomes:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = v(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}) - \frac{1}{\rho}\frac{\partial p}{\partial x} + X \qquad (3.4)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = v(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}) - \frac{1}{\rho}\frac{\partial p}{\partial x} + Y \qquad (3.5)$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = v(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}) - \frac{1}{\rho}\frac{\partial p}{\partial x} + Z \qquad (3.6)$$

The energy conservation equation is:

$$p(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z}) = \frac{\Lambda}{C_p}(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}) + S_T \qquad (3.7)$$

Selection is done for standard k - ε model of turbulence calculation for high Reynolds numbers, which represent the default calculation model of CFD simulation software 6SigmaRoom. It is represented in the following equations.

Turbulent kinetic energy equation is:

$$\rho\frac{\partial k}{\partial t} + \rho u_i\frac{\partial \varepsilon}{\partial x_i} = \frac{\partial\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial x_j}\right]}{\partial x_j} + C_k - \rho\varepsilon \qquad (3.8)$$

The turbulent dissipation rate equation is:

$$\rho\frac{\partial \varepsilon}{\partial t} + \rho u_i\frac{\partial \varepsilon}{\partial x_i} = \frac{\partial\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial x_j}\right]}{\partial x_j} + C_{1\varepsilon}\frac{\varepsilon}{k}G_k - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \qquad (3.9)$$

The kinetic viscosity μ_t can be found from the following equations:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \qquad (3.10)$$

3.2.1.5 Model Validation

Five points within the whitespace were taken for verifying settings of the boundary conditions of the model whether it can meet the engineering practice. Then, airflow and temperature at different heights (500mm, 1000mm, 1500mm, and 2000mm away from the raised floor) of these points were measured and recorded. Finally, simulation was done on 6Sigma software for optimization design.

3.3 Application of the Server Power Consumption Model for Energy Forecasting and Management to Achieve Energy Savings for Servers and Cooling Systems

Power consumption models of servers in data centers can be used for both energy management and thermal management. Typically, heavier workloads emanating from applications and processing can be handled without consuming more energy, and the difference between the peak power and idle power of the servers is not consistent from generation to generation.

Power consumption models of servers is critical in achieving energy efficiencies in data center space. Adoption of actual instruments such as multimeter and power analyze was used get accurate measurements for electrical devices. However, the use of alternative power analyzer approaches that include both hardware and software solutions can be more efficient. This includes:

a) Intelligent power distribution units (PDU). This gives all the power parameters for network devices installed in a rack.
b) The use of data center infrastructure management software/platform that provide interface with integrated sensors, such as Intelligent Platform

> Management Interface (IPMI) and environmental monitoring sensors. In addition, this hardware and software platform can be used for the optimization strategies of data centers, by estimating the power consumption of different data center devices.

A series of tests was run to test the null hypothesis in which different applications were run to the devices under test and evaluated power consumption with a power analyzer tool. The power usage was measured using power analyzer data logger (MODEL PEL 113) which has a 0.5 percent precision. Linear and Polynomial regression model was then used to create models illustrating the relationship between the observed power consumption and the injected traffic.

Compared to (Zhou et al., 2019), this model considered all components related to energy consumptions of servers such as CPU and memory which are major energy consuming components.

A server forms part of the IT equipment that provides computing capability, such as storage and running of software applications. Most servers contain the following major hardware building blocks: processors for running software applications, memory, chipset, input/output devices, storage, peripherals, voltage regulators, power supplies, and cooling systems. Data center servers can generally be divided into rack type, blade type, and tower type based on their configurations. A rack server is a server that is built purposely to be mounted within a server rack. A blade server can be described as a modular server since it enables consolidation of multiple servers. Its advantage is that it can be connected to provide a high-speed network environment, while at the same time share resources between the same user group. A tower server is in form of a computer intended for use as a server and built in an upright cabinet that stands alone.

Rack servers and blade servers are widely deployed in data center environment. Servers can also be classified according to the application scenario as database servers, file servers, mail servers, print servers, web servers, game servers, and application servers.

The methodology comprises the extraction and selection of features, modelling, and evaluation steps. The component extraction and selection step are liable for gathering elements of the assets and applications important to the energy utilization modelling. This can be performed by utilizing either resource monitor or performance monitor. The power model using regression modelling was then used based on the feature extractions.

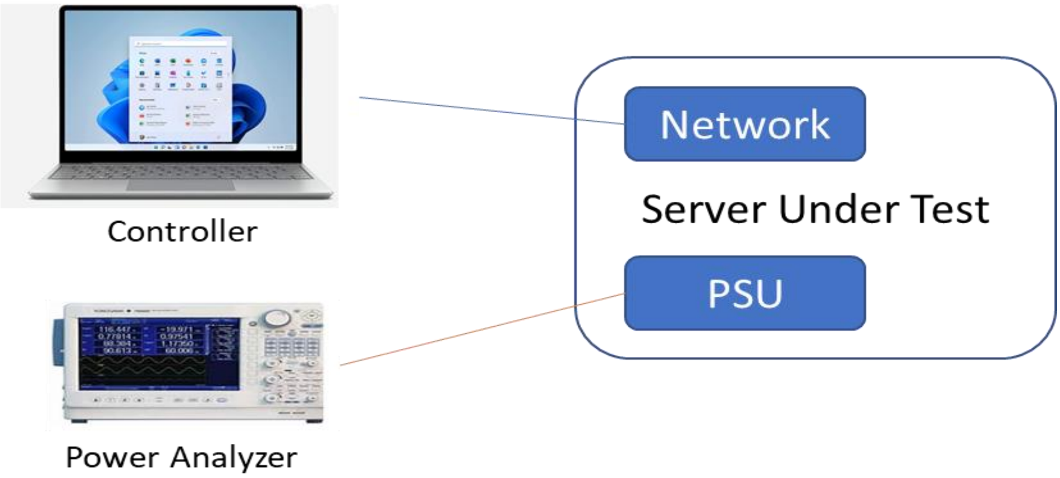


Figure 3.4: System Diagram

The experiment was carried out as depicted in figure 3.4, which primarily consists of three parts: a server, a controller, and a measurement system.

A power analyzer supplied to the server's PSU (power supply unit) was used to measure the server's AC current and power consumption, with a maximum measurement error of less than 1% while the controller was used to inject traffic to the server under test as well as transmit commands to a server over a network wire.

Feature extraction

The proposed power model consists of different subsystems parameters related to energy usage as shown in the equation 21 below.

$$P_{system} = P_{CPU} + P_{memory} + \varepsilon \quad (3.10)$$

Where P_{system}. is the total power of the server, P_{cpu} and P_{memory} are the power usage of CPU and memory while ε represent the power of other subcomponent.

The hypothesis was then used to investigate if network traffic (CPU and memory utilization) has a significant impact on server's power consumption.

Hypothesis

H_1 There is a significant impact of network traffic on server's power consumption.

3.4 Evaluation of Cost Benefit Analysis Using Homer Software of Utilizing Solar-Diesel Hybrid System to Power Data Centers in Kenya

Reliable power supply underpins all aspects of data center development and provides foundation for the development of cheap and reliable data center enterprise. While diesel fuel will continue to play a fundamental role in providing reliable power supply to data centers, solar/diesel hybrid power system has started to provide alternative to least cost electricity service provision for data centers. Over the last decade, the price of solar system components has reduced to the point that solar/diesel hybrid power system has now become economically viable for powering data centers, relative to diesel-only power. Solar photovoltaic system is fast becoming the lowest cost, lowest risk technology option for reducing diesel fuel consumption for data center enterprises.

This section analyzed the feasibility of implementing PV systems in an existing hybrid diesel grid system for data centers two and three. Data center one was not considered because of unavailability of space to implement solar energy. The goal for the implementation of solar PV to power the two data centers is to reduce the consumption of diesel fuel, the working hours of diesel generators, as well as the electricity bills. The optimal system design was realized by as described below through pre-design preparation and system design simulation using Homer Software tool and manual simulation of the power bills. Figure 3.5 below shows the cost analysis process followed during the study.

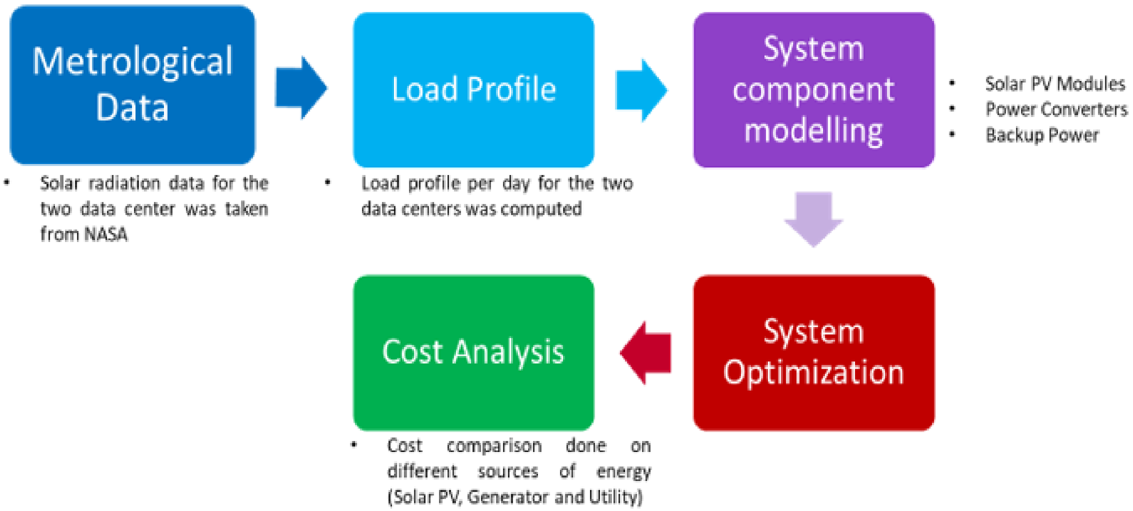


Figure 3.5: Flow diagram for data center renewable energy impact analysis

Meteorological Data Collection: Solar resource data was obtained from NASA data base in Homer software. The readings inputted to the software were the average global horizontal irradiation from NASA. The radiation value was used in the HOMER software to calculate the amount power generated by the solar PV.

Data Center Load Profile: Due to the sensitive nature of the IT equipment, power usage was read directly from the display meter of the power distribution unit (PDU). For the mechanical and other auxiliary loads, power usage was measurement at the distribution board using multimeter. These values were then used together with the daily usage to tabulate the load provide. The daily usage for the two data centers is as shown in table 3.3 below.

Table 3.3: Data Center load usage

No	Load	Usage (Hours)
1.	IT Equipment	24
2.	Air-condition Equipment	24
3.	Pumps	2
4.	Bollards,	5
5.	Mechanical Ventilation	8
6.	Small Power and Lighting	8

The total load (kWhr) was then computed using the following equation:

$$Load\ (kWHr) = Equipment\ load\ (kW)\ X\ Usage\ (Hrs) \qquad (3.12)$$

System Component Modelling: Component information related to their pricing and size was defined. These includes the price and sizes for power inverter, solar PV modules and generator. The HOMER software then used the price of the components to determine the cost of the entire system and simulate cost comparison.

System Optimization: Optimization scenario of the whole system was achieved using sensitivity variable. A sensitivity variable is an input variable for which multiple values can be specified. HOMER performs a separate optimization procedure for each specified value. This sensitivity variables includes diesel fuel price, solar PV efficiency and the electrical load.

Cost Analysis:

A simple payback technique was used to analyze the feasibility of implementing the proposed hybrid system. This method yields the number of years required for the system to pay for itself.

$$Simple\ payback\ time = \frac{Cost\ of\ the\ system}{Annual\ savings}\ , years \quad (3.13)$$

The feasible solutions in HOMER software are presented in an increasing order of the net present cost from the least to the highest NPC. The categorized table presents the least cost-effective combinations from among all components setup, whereas the overall optimization results table displays all of the affordable system combinations based on their NPC. Power systems are selected after simulation based primarily on minimum net present cost. On top of these parameters, the cost of energy, high renewable fraction, low-capacity shortage, low excess electricity generation, and less diesel fuel consumption was used for comparison of power generating schemes to check their technical feasibility.

The following are some of the terms used by Homer software.

Net present cost

The net present cost of a system is the present value of all the costs of installing and operating the system over the project lifetime, minus the present value of all the revenues that it earns over the project lifetime. Costs include capital costs, replacement costs, O&M costs, fuel costs, emissions penalties, and the costs of buying power from the grid. Revenues include salvage value and grid sales revenue.

HOMER calculates the net present cost of each Component in the system, and of the system.

Type: Output Variable

Units: $

Symbol: CNPC

HOMER calculates the total NPC by summing the total discounted cash flows in each year of the project lifetime. The total NPC is HOMER's main economic output, the value by which it ranks all system configurations in the optimization results, and the basis from which it calculates the total annualized cost and the levelized cost of energy.

Levelized Cost of Electricity

HOMER defines the levelized cost of energy (COE) as the average cost per kWh of useful electrical energy produced by the system.

Type: Output Variable

Units: $/kWh

Symbol: COE

To calculate the COE, HOMER divides the annualized cost of producing electricity (the total annualized cost minus the cost of serving the thermal load) by the total electric load served, using the following equation:

$$COE = \frac{C_{ann,tot} - C_{boiler} H_{served}}{E_{served}} \quad (3.14)$$

Where:

$C_{ann,tot}$ = total annualized cost of the system [$/yr]

C_{boiler} = boiler marginal cost [$/kWh]

H_{served} = total thermal load served [kWh/yr]

E_{served} = total electrical load served [kWh/yr]

The second term in the numerator is the portion of the annualized cost that results from serving the thermal load. In systems, such as wind or PV, that do not serve a thermal load ($H_{thermal}$=0), this term is zero. The COE is a convenient metric with which to compare systems, but HOMER does not rank systems based on COE.

CHAPTER FOUR

RESULTS AND DISCUSSION.

4.1 Analysis of Energy Efficiency of Three Data Centers in Kenya with the Aim of Reducing and Optimizing Energy Consumption of the Data Centers

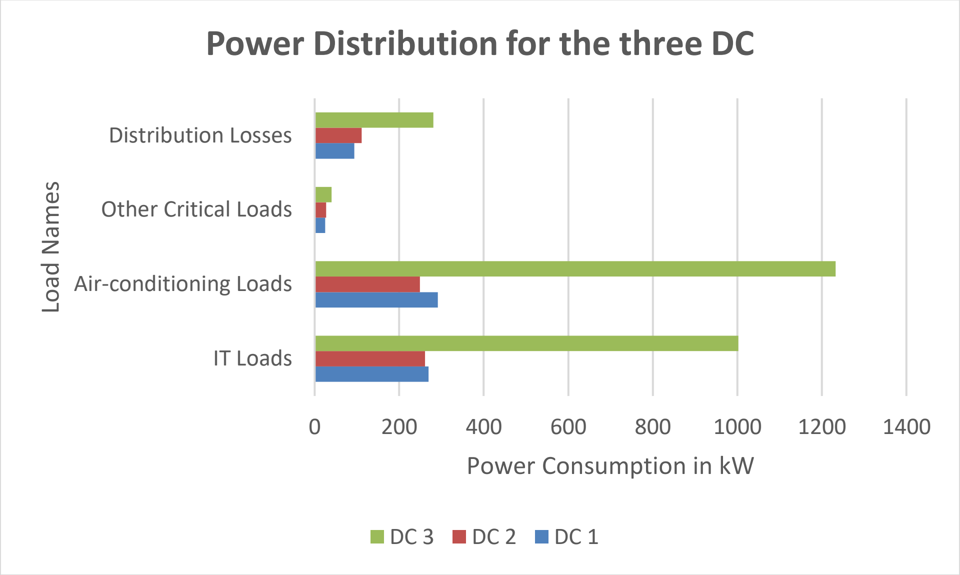
4.1.1 Power Distribution of the three Data Centers

It was observed that the average power consumption of each Telco rack for DC 1 and DC 2 was about 1.5Kw. Computer room hosted server racks which was used for data storage of camera feeds captured across the entire country. It was observed that the average power consumption of each server rack for DC 1 was 3Kw while that for DC 2 was 2.5Kw.

The sizing of the air-conditioning equipment was dependent on the heat load of the room. For instance, the power usage for computer room air-condition for DC 1 was 18.33kW while for telco room was 1.5kW.

On the other hand, data center three is located at Sameer Industrial Park, Nairobi. It consists of floor space of 2,000 square meters of secured space for data servers over four floors. It offers access to carrier networks across Kenya and colocation services for different companies and organizations. The data center was among the first in Kenya to acquire Tier III Uptime certification implying they comply on mission-critical and continuous availability of power, cooling, and connectivity. The IT and air-condition equipment were distributed among three floors from basement to third floor.

Table 4.1: Power Distribution for the three Data Centers



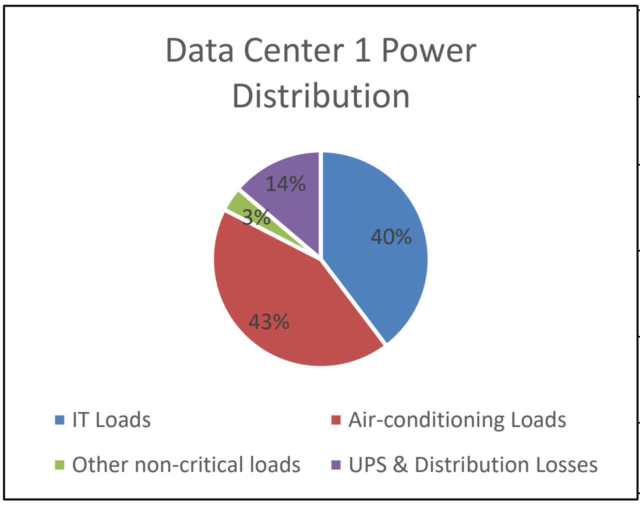
4.1.2 Power Usage Effectiveness (PUE) Computation and Discussion

Data Center I power usage effectiveness was computed as follows.

$$PUE = \frac{Total\ building\ Power\ (Kw)}{IT\ Equipment\ Power\ (Kw)} = \frac{678.84}{269.4} = 2.51 \quad (4.1)$$

Considering Uptime recommended PUE of 1.58 as an average, this PUE for this data center is still poor and this means there is overhead energy consumed by other equipment at the expense of IT loads.

Table 4. 1: Data Center I Overall Power Distribution



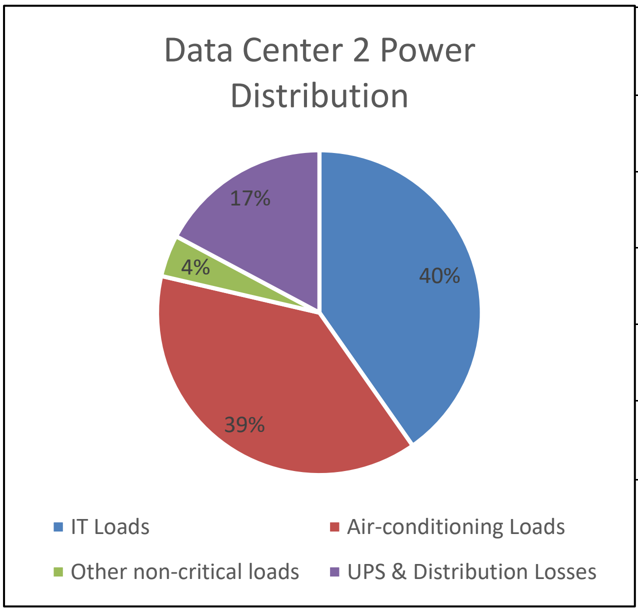
Category	**Power Draw**
IT Loads	269.4kW
Air-conditioning loads	291.04kW
Other non-critical loads	25kW
UPS & Distribution losses	93.4kW
Total	**678.84kW**

Data Center II power usage effectiveness was computed as follows.

$$PUE = \frac{Total\ building\ Power\ (Kw)}{IT\ Equipment\ Power\ (Kw)} = \frac{648.1}{261} = 2.48 \quad (4.2)$$

Considering Uptime recommended PUE of 1.58 as an average, this PUE for this data center is still poor and this means there is overhead energy consumed by other equipment at the expense of computer equipment.

Table 4.3: Data Center II Power Distribution



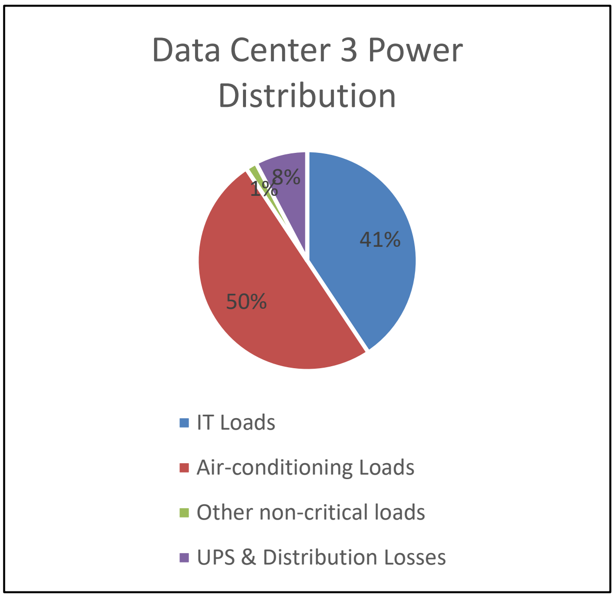
Category	**Power Draw**
IT Loads	261kW
Air-conditioning loads	248.6kW
Other non-critical loads	27kW
UPS & Distribution losses	111.5kW
Total	**648.1kW**

Data Center III power usage effectiveness was computed as follows.

$$PUE = \frac{Total\ building\ Power\ (Kw)}{IT\ Equipment\ Power\ (Kw)} = \frac{2{,}555.92}{1002.00} = 2.55 \quad (4.3)$$

Considering Uptime recommended PUE of 1.58 as an average, this PUE for this data centers are still poor, and this means there is an overhead energy consumed by other equipment at the expense of computer equipment.

Table 4. 2: Data Center III Total Power Distribution



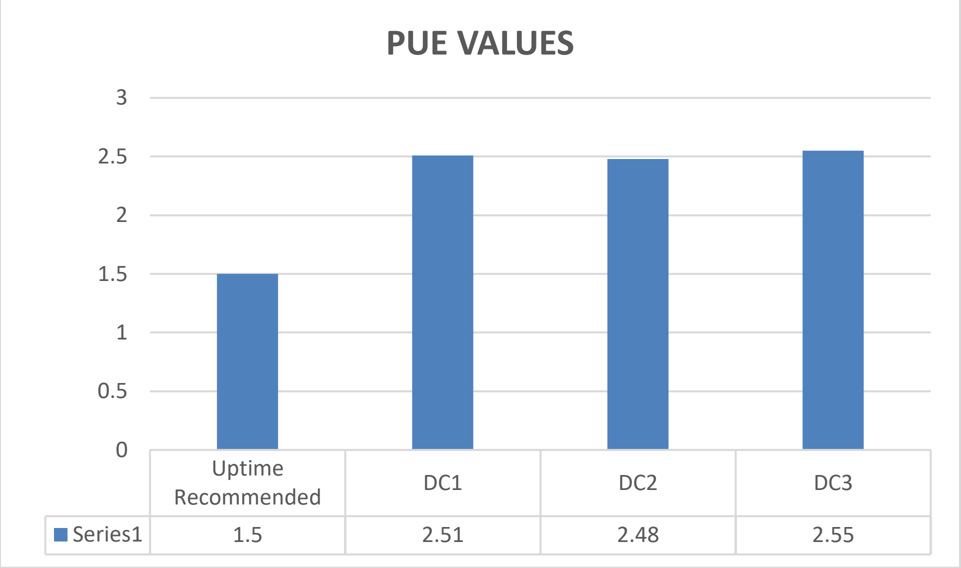
Category	**Power Draw**
IT Loads	1002.0kW
Air-conditioning loads	1232.92kW
Other non-critical loads	40kW
UPS & Distribution losses	281kW
Total	**2,555.92kW**

From the above computation, it was observed that data center 3 had the highest PUE value while data center one had the least. This is due to the cooling technology employed for the three data centers.

The reason for this is that data center 3 employed the traditional room method for data center cooling also known as the perimeter cooling system. This system distributes cold air under a raised floor system while the return air which is warm air (from the IT equipment) is consumed from the top of each AC unit. The process of moving hot air from the rear of the IT racks to the tops of the AC units leads to the mixing of hot and cold air and therefore reduces the efficiency, capacity and liability of the AC units. This usually amounts to hot spots, air-conditioning equipment oversizing and unpredictable environments, especially with a higher rack power consumption.

Data center 1 and 2 adopted in-row cooling where the air-conditionig equipment are close coupled with the IT racks in a hot asile containment system. This is to ensure that the IT racks receive the coldest air possible while the air-condition equipment consume the warmest return air possible.Table 4.5 below shows the PUE comparison of the three data centers

Table 4.5: PUE Values



4.1.3 Optimal Design

Effect of Cooling on PUE

Guidelines for the temperatures at which a data center can be operated reliably are published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) which recommends for operating temperatures between 18 and 27 degrees Celsius (°C), a dew point (DP) of -9 to 15 degrees Celsius (°C), and a relative humidity (RH) of 60 percent for the majority of classes of information technology (IT) equipment. The equipment under those recommendations falls within the ASHRAE classifications A1 to A4. The design for the three data centers followed ASHRAE class A1. Without data centers operators following this measure will result in cooling systems consuming a lot of electricity.

The IT equipment and HVAC are the main data center power consuming equipment. The ratio of yearly IT equipment energy to annual HVAC system energy is used to measure HVAC system effectiveness:

$$HVAC\text{ Effectiveness}= \frac{kWh/yr_{IT}}{kWh/yr_{HVAC}} \tag{4.4}$$

Standard	**Good**	**Better**
0.7	1.4	2.5

The optimization design can be achieved through the following measures.

1. **Use of Modular Power Equipment such as UPS to Increase Load Factor**

   The table below shows the relationship between the UPS loading and its impact on efficiency using the graph in figure 2.2.

Table 4.6: Comparison of a Typical UPS Loading with its corresponding efficiency.

UPS Loading (%)	**Efficiency (%)**
20	92
40	95.5
50	96
60	96.5
80	97.5
100	98

   When the load factor is increased from 50% to 100% will save up to 2% of the total power for each UPS.

2. **Use of Centralized Chiller system as opposed to Direct expansion system as currently implemented.**

   A central chilled water plant will be more effective in large data centers where cooling requirements are on the scale of hundreds of tons of refrigeration. In a system of this kind:

   i. The cooling coils in a building are fed with chilled water from a central chiller plant.

ii. CRAHs (computer room air handlers) located close to the conditioned space.

iii. The remote chiller plant, which is either outside in the open or inside a mechanical room, houses the refrigeration system.

iv. Indoor CRAHs are equipped with fans, filters, humidifiers, reheat, chilled-water coils, and chilled-water control valves which eventually consume less amount of power because the units will not have compressors.

v. To ensure a high level of cooling, chilled water temperature is kept as high as feasible (at least 47°F / 8.33°C)

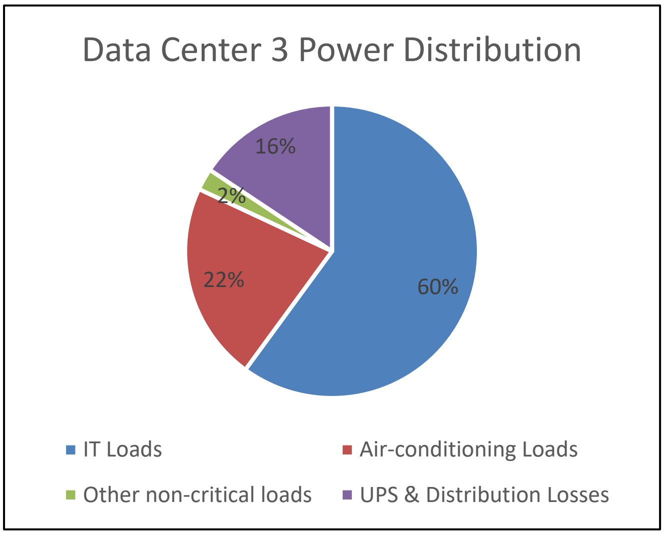
For instance, let’s consider data center three where the current total cooling load requirement is 1232.92kW which accounts to fifty percent of the total energy consumption. Data center best practice demands that the total power consumption of cooling unit should not exceed 40% of total data center power. From the table in appendix c-1, the IT load for data center three is 1002Kw meaning the net sensible cooling requirement is 1002kW. From the above equation 28, the maximum net sensible cooling should be:

$$HVAC_{(kW)} = \frac{1002.0}{2.5} = 400.8kW \qquad (4.5)$$

This can be achieved using a chiller system. The power consumption of the air-conditioning equipment can reduce to 365.7Kw as seen in the attached data sheets in appendix d-3 where two chillers of model Vertiv FH4065 was selected with total power requirement of 156Kw each and ten Chilled Water Perimeter Unit of 120.6kw Net Sensible Cooling Capacity and 5.37Kw power input requirement.

With the adoption of centralized chilled water system and the use of modular UPS system, the power distribution, and the PUE for data center three becomes:

Table 4.7: Data Center 3 Power Distribution



Category	Power Draw
IT Loads	1002.0kW
Air-conditioning loads	365.7kW
Other non-critical loads	40kW
UPS & Distribution losses	261kW
Total	**1,668.7kW**

Data Center III power usage effectiveness now changes to:

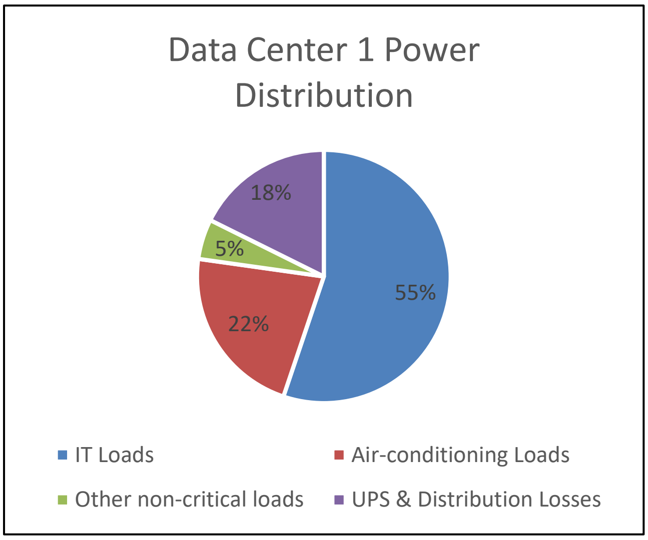
$$PUE = \frac{Total\ building\ Power\ (Kw)}{IT\ Equipment\ Power\ (Kw)} = \frac{1668.7}{1002} = 1.66 \quad (4.6)$$

For data center one and two, the UPS load factor can also be increased to realize the best efficiency and correct setting made on the air-conditioning equipment. Considering their IT load, it is not recommended to adopt centralized chiller system. The optimum design parameters for data center one should be:

$$HVAC_{(kW)\ DC1} = \frac{269.4}{2.5} = 107.76kW \qquad (4.7)$$

The value in equation 4.7 should be the maximum power requirement for air-conditioning equipment for data center one.

Table 4.8: Data Center I Overall Power Distribution



Category	**Power Draw**
IT Loads	269.4kW
Air-conditioning loads	107.76kW
Other non-critical loads	25kW
UPS & Distribution losses	86.2kW
Total	**488.3kW**

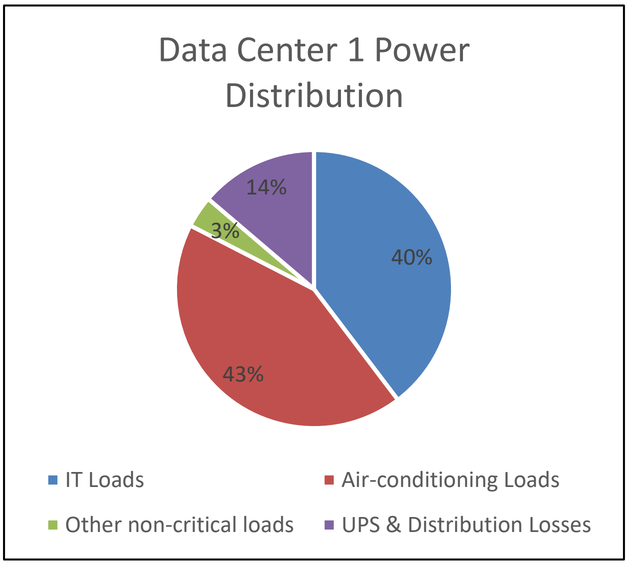
Data Center I power usage effectiveness now changes to:

$$PUE = \frac{Total\ building\ Power\ (Kw)}{IT\ Equipment\ Power\ (Kw)} = \frac{488.3}{269.4} = 1.8 \quad (4.8)$$

The optimum design parameters for data centers III should be:

$$HVAC_{(kW)\ DC1} = \frac{261}{2.5} = 104.4kW \qquad (4.9)$$

Table 4.9: PUE Sensitivity Analysis



Category	**Power Draw**
IT Loads	261kW
Air-conditioning loads	104.4kW
Other non-critical loads	27kW
UPS & Distribution losses	95.5kW
Total	**487.9kW**

Data Center II power usage effectiveness now changes to:

$$PUE = \frac{Total\ building\ Power\ (Kw)}{IT\ Equipment\ Power\ (Kw)} = \frac{487.9}{261} = 1.86 \quad (4.10)$$

4.1.4 Tweakable parameters for better power usage effectiveness

a) Location of Data Center

As indicated above, PUE value is impacted by cooling and power losses hence if improvement can be made on these two components, better PUE value can be achieved. Better cooling for data centers can be achieved depending on the location of your data centers. For instance, a data center located in Mombasa, where the ambient temperature and humidity is high, will require greater levels of cooling leading to high power consumption of air-conditioning equipment. Data centers in this location renders the combination of free cooling and liquid cooling options very difficult to implement. On the other hand, a data center located in Limuru where the ambient temperature is low will require less cooling and hence free cooling can be implemented.

b) Overall Infrastructure

When building data centers from a green field, implementation and adherence to the Leadership in Energy and Environmental Design (LEED) norms can help reduce overall power consumption. LEED is a national certification system developed by the U.S Green Building Council to promote the construction of energy and resource-efficient building (Vettier, 2017). Assessment of self-sustaining solutions, where the architectural model allows the ambient light to enter while keeping out the heat can reduce the amount of cooling required within the data center space.

c) UPS Selection and their Loading

It is vital to match the UPS load to the system load for better PUE. UPS system tend to operate optimally when fully loaded and vice versa. The use of Modular UPS system can help data center operators to plug in UPS as and when required. If you have a load requirement of 200Kva currently and look forward to having an ultimate load of 500 KVA, you can buy a UPS with a frame of 500Kva and plug in two modules of 100 KVA UPS to make it 200Kva instead of buying a chassis of 500Kva UPS.

All the three data centers used on-line double conversions UPS system with a standard frame UPS system as opposed to modular. However, in this type of system, some of the electrical energy is wasted as losses due to inefficiency and conversion during the process of charging batteries and current transforms.

In data center I, the load factor measured ranged from 40% to 50%, and the efficiencies were relatively poor (80–90%). For data center II, the load factor was 24%, and the efficiency was 85%. In comparison to data center III, the load factor was varying mainly due existence of four distinct four data hall but an average of 40% to 60% was noted. The table 4.10 below shows the relationship between load factor and efficiency for the three data centers.

Table 4.10: UPS Load factor and efficiency

Data Center	**UPS Capacity (Kw)**	**Load Factor(%)**	**Efficiency**
Data Center I	500	56	0.964
Data Center II	360	24	0.95
Data Center III	500	50	0.94

It was also noted that all the three data center had redundant UPS employed to fulfill the requirement of contingency planning. The configuration of the UPS and the generator system was N + 1, where N represent the need and then +1 is the redundancy. N+1 topology provides minimal reliability by adding a component to support a single failure or requirement of that component. The architecture configuration is as shown in figure 4.14, 4.15 and 4.16 below.

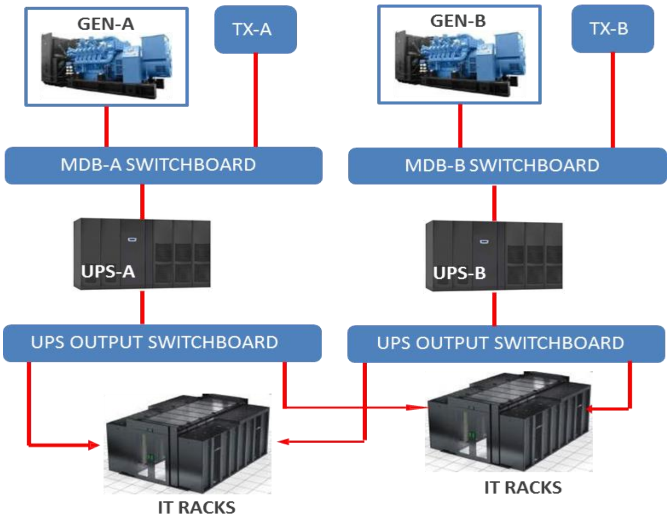


Figure 4.1: Data center I power architecture.

Data center I has two generators and UPS equipment arranged in an N+1 configuration to take care of the redundancy requirement by Uptime.

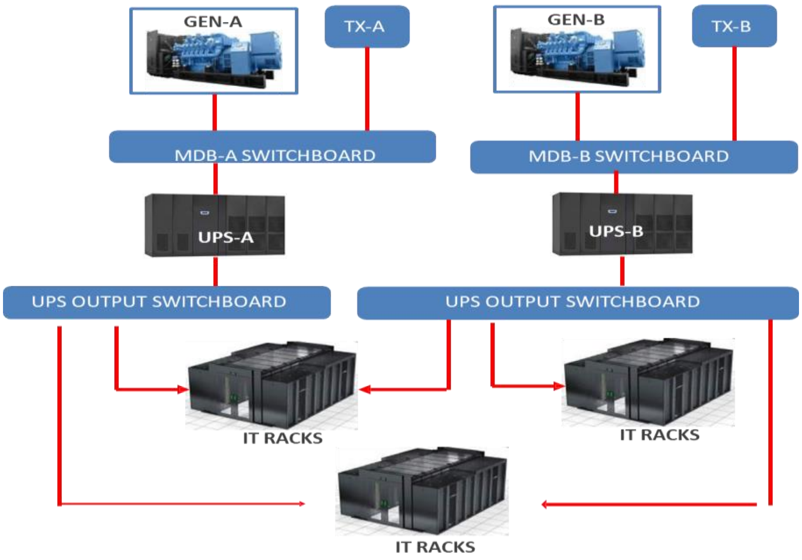


Figure 4.2: Data Center II power architecture

Data center II has distributed redundancy which offers better power system topology that allows better way of load management as shown in the figure below.

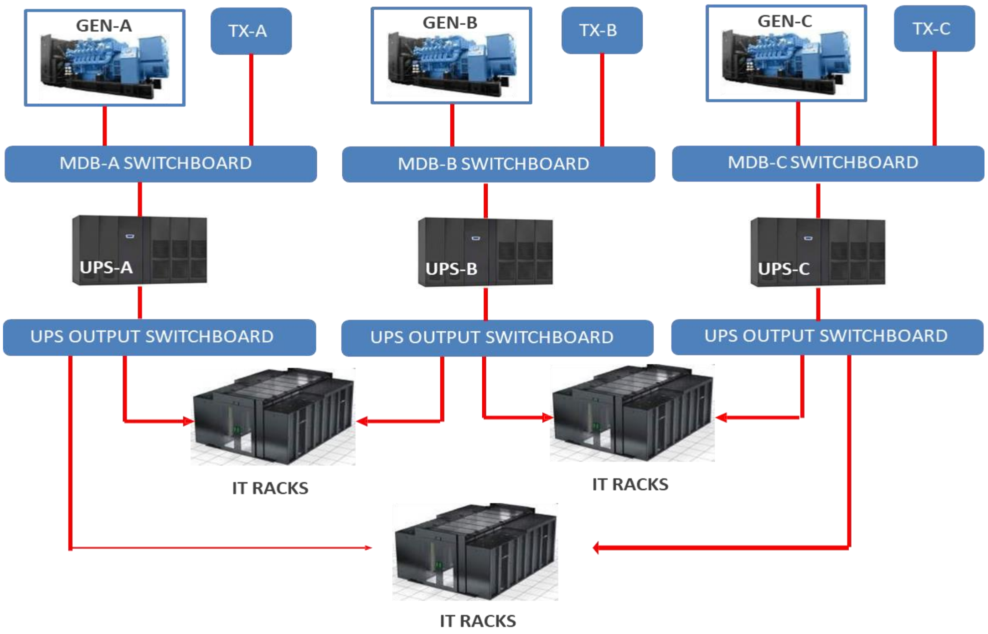


Figure 4.3: Data center III power architecture

The architecture for Data center III is like Data center II only that Data center III has three generators and UPS equipment to cater for additional data hall.

Considering UPS load factor in the table 4.11 above and comparing it to its respective efficiency using the graph given by figure 2.2, the following table 4.12 is obtained.

Table 4.11: Data Center I, II and III Efficiency and Load factor

Data Center	Load Factor(%)	Efficiency
Data Center I	56	0.96
Data Center II	24	0.92
Data Center III	50	0.955

Using the above efficiency and the overall capacity of the UPS, the total loss was calculated and tabulated in the table 4.12 below.

Table 4.123: Data Center I, II and III Total Losses

Data Center	**UPS Capacity (Kw)**	**Efficiency**	**Losses (Kw)**
Data Center I	500 x 2	0.96	2 x 0.04 x 500 = 40
Data Center II	360 x 2	0.92	2 x 0.08 x 360 = 57.6
Data Center III	500 x 6	0.955	6 x 0.045 x 500 = 135

Cost analysis

This section covers the operation costs incurred due to the UPS losses for a year. 2018 Schedule of tariffs for Kenya Power was used to compute bill simulation which is KSh.10.90 per unit consumed.

Table 4.13: Cost Incurred due to UPS losses for the three data centers.

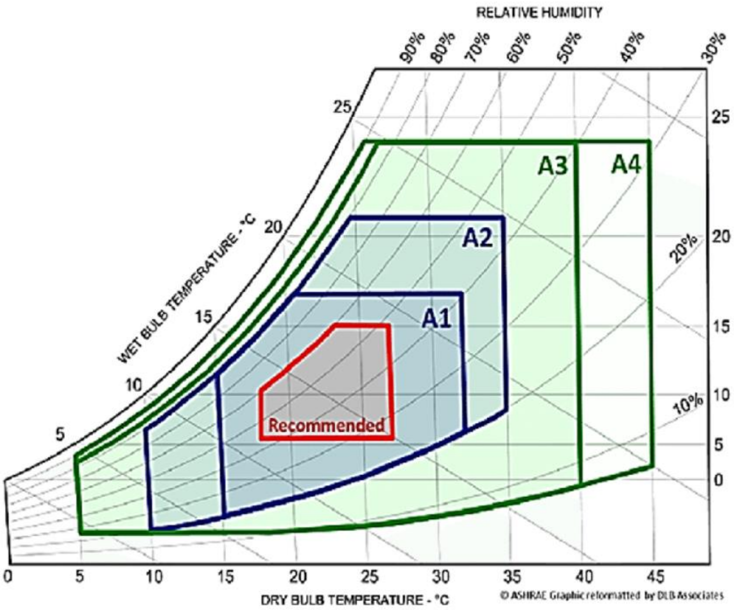
Data Center	**Units (kWhr)**	**Energy Charge**	**Total Cost/Year**
Data Center I	40x24x30 = 28,800	KSh.10.9x28,800	KSh.313,920.00
Data Center II	57.6x24x30 = 41,472	KSh.10.9x41,472	KSh.452,044.80
Data Center III	135x24x30 = 97,200	KSh.10.9x97,200	KSh.1,059,480.00

The cost as computed in table 4.13 above is incurred by the respective data centers as result of operating the UPS at low load factor which ultimately affects the UPS efficiency and hence the operation cost.

d) Configuration and Setting of Air-Conditioning Equipment

The design, placement and setting of air-conditioning equipment has a direct impact on the PUE of your data center.

The measured values taken for the environmental conditions of the three data centers are as shown in the Table 4.14. The measured room dry-bulb temperatures for data center I was 22.2 ^{o}C data center II was 20.7^{0}C, and data center III was 23.8^{+}. These values are within the allowable temperature range set by ASHRAE of 18^{o}C to 27^{o}C as shown in figure 4.17. Any deviation beyond these values will have an impact to energy saving and efficiency of HVAC equipment. This is shown in the next section and the potential of energy saving achieved by raising room temperature.



© ASHRAE Graphic reformatted by DLB Associates

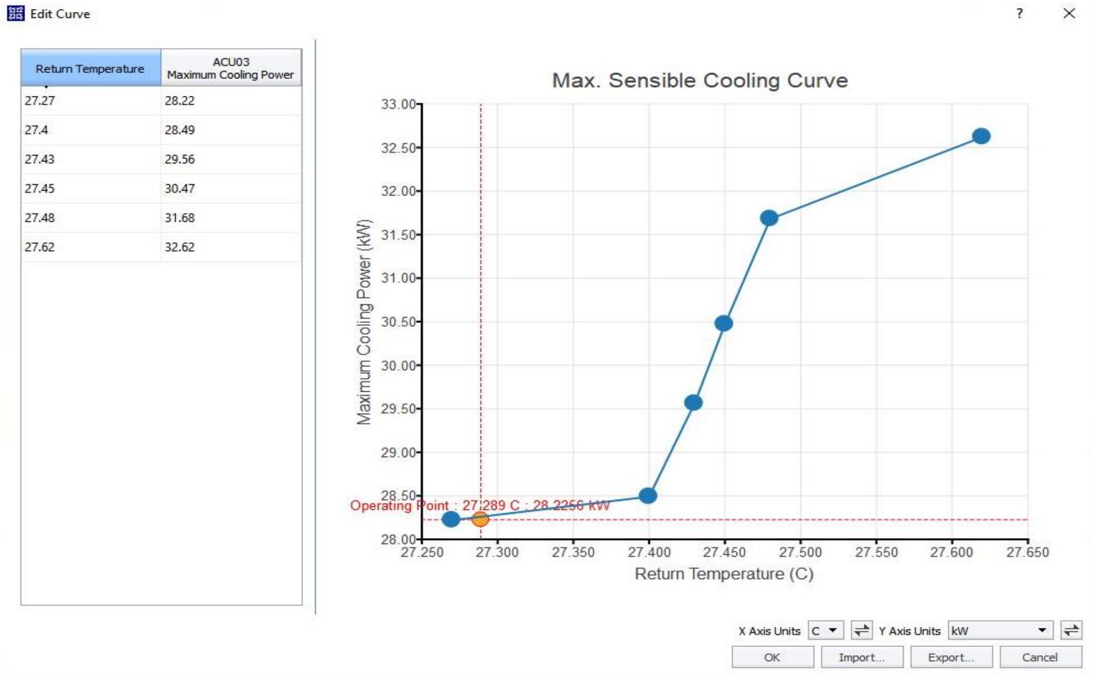
Figure 4.4: ASHRAE Guidelines

In addition, too much humidity in data centers poses the risk of having condensation form which can lead to formation of corrosion which can slowly damage the IT equipment. The recommended ASHRAE guidelines on the relative humidity ranges from 40% to 60% as shown in figure 32 above. However, from the measurements done as shown in table 4.14 below, all the three data centers had breached the threshold. This affects the performance of the Air-condition equipment because low humidity makes the Air-condition equipment to work more to generate cool air while high humidity levels can cause growth of algae and mold inside the supply air ducts. This can greatly reduce the quality of indoor air.

Table 4.14: Data Center I, II and III Environmental Condition in comparison to ASHRAE 2008

Environmental Condition	**ASHRAE 2008**	**Data Center I**	**Data Center II**	**Data Center III**
Temperature: Low End	18°C	22.2°C	20.7°C	23.8°C
Temperature: High End	32°C	28.0°C	27.0°C	29.6°C
Moisture: Low End	40% RH and 41.9°F DP (5.5°C)	72.8% RH	67% RH	68% RH
Moisture: High End	60% RH and 59°F DP (15°C)	72.8% RH	65% RH	65% RH

A graph of change of cooling power of the air-conditioning system against return air temperature for data center II was plotted on 6Sigma CFD software as illustrated in figure 4.5.



Return Temperature	ACU03 Maximum Cooling Power
27.27	28.22
27.4	28.49
27.43	29.56
27.45	30.47
27.48	31.68
27.62	32.62

Operating Point : 27.289 C : 28.2256 kW

X Axis Units: C

Y Axis Units: kW

Figure 4. 5: Relationship between Cooling Power and Return Air Temperature

From figure 4.5, an increase in the return air temperature resulted to the increase in cooling power and hence efficiency of the cooling system.

In conclusion, environmental setting of air-condition equipment and load factor of power supply equipment have drastic impact on energy efficiency as seen in the above analysis. Among the three data centers, data center three was observed to be less energy conservative. This is because data center three employed perimeter wall cooling, an old and inefficient method of cooling. The problem of using this method of cooling is that the servers at the bottom of the rack get the coolest air first, while on the other hand the servers at the top usually have the warmer inlet temperature. In case the airflow is increased to solve the issue, efficiency will decrease since air now flows past the face of the server rack and mixes with hot return air.

6Sigma CFD software was used to investigate the importance of the environmental setting especially the supply and return air temperature settings on cooling efficiency. Higher return air temperature equals higher capacity and efficiency of the cooling system.

Generally, the simulated value was lower compared to the measured value because of the following reasons:

1. The aging of air-conditioning equipment implying most of the individual components were not operating optimally. Different alarms for maintenance requirement were displayed on some of the CRAC units such as changing air filters. Replacement of air filters is the most crucial maintenance task for any CRAC unit. Otherwise, if not replaced the dirty filters will overwork motors, hence reducing cooling capacity.
2. The three data centers were observed to contain doors that might allow heat gain or loss. The losses impact the internal temperature and relative humidity by allowing outside air infiltration and moisture migration to and from the data center space.
3. It was observed that some CARC units had different environmental settings. CRAC equipment housed in the same computer room should ideally carry out the same

task. It will be exceedingly inefficient to have two CRAC units in opposition to or complimentary to one another, such as having one execute heating and the other cooling duties. This phenomenon is known as "demand fighting." It is by far the biggest cause of energy inefficiency.

4.2 Thermal Environmental Optimization and Discussion

From the field experiment and one on one interview with the data center owners, the following are discussions of the three data center in terms of thermal environmental performance.

a) Data Center I

This data center is located in Ruaraka constituency, Nairobi County and has two floors where the ground floor houses the power room, and the first floor houses the computer room.

Our interest is the computer room since it is the room that houses IT racks and air-conditioning equipment. The computer room dimensions are 33.6 x 19.2 x 3.5m (LXWH). It adopts an air distribution form of hot aisle containment that consists of a physical barrier that guides hot exhaust airflow back to the air-condition return.

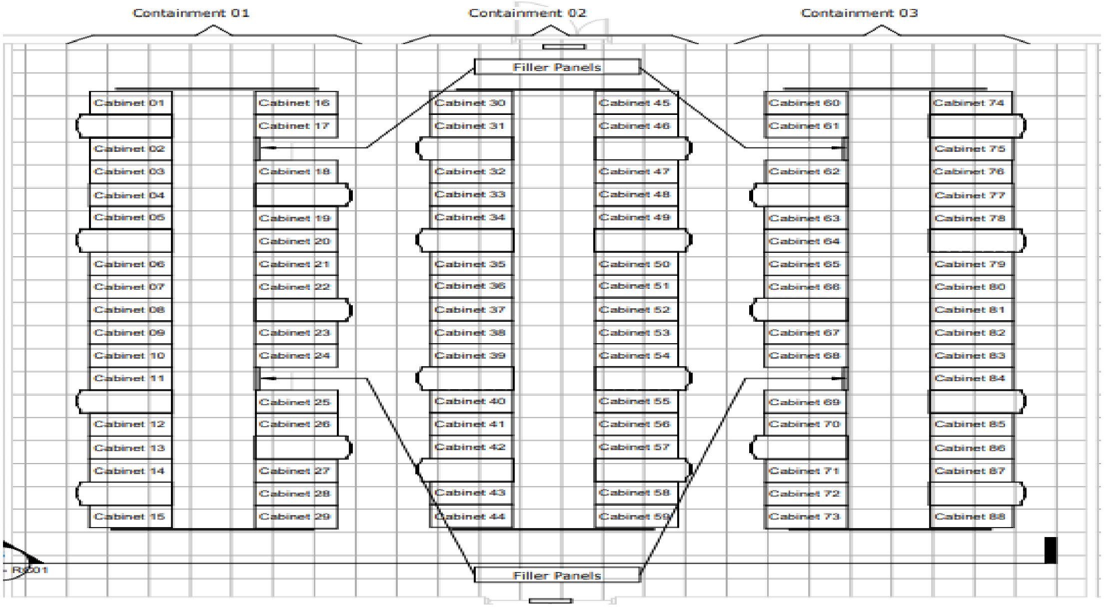


Figure 4.6: Data Center II IT and Air-conditioning arrangement

Figure 4.6 above shows the arrangement of the air-conditioning equipment and the computer equipment arranged in a hot aisle containment system. The air -conditioning equipment is twenty-one while the computer equipment (server racks) is eighty-two.

The computer room has a raised floor of height 0.45 m high. The hot aisle containment is enclosed in a frame of width of 1.3m.

There are 228 perforated tiles, whose size is 0.6x0.6m and aperture rate is 39%. Perimeter blowing air conditioning was installed with the following dimensions: 2172x 866 x 1960mm, air outlet size of 100 x 1920 mm, refrigerating capacity of 48 kW, and air flow rate of 16030 m3 /h. There are 88 racks with a size of 800 x 1060 x 1950 mm, which are divided phases one and two with phase one currently implemented. The airflow and temperature distribution were measured at different locations within the computer room. The thermal imager was then used to measure and record the heat distribution on the surface of the equipment in the data center.

b) Data Center II

This data center is located in Karen, Nairobi County and has only one floor but is subdivided into different rooms including power rooms and computer rooms.

Our focus was the computer room since it is the room that houses IT racks and air-conditioning equipment. The computer room dimensions were 20 x 10 x 3m (LXWH). It adopts an air distribution form of hot aisle containment that consists of a physical barrier that guides hot exhaust airflow back to the air-condition return.

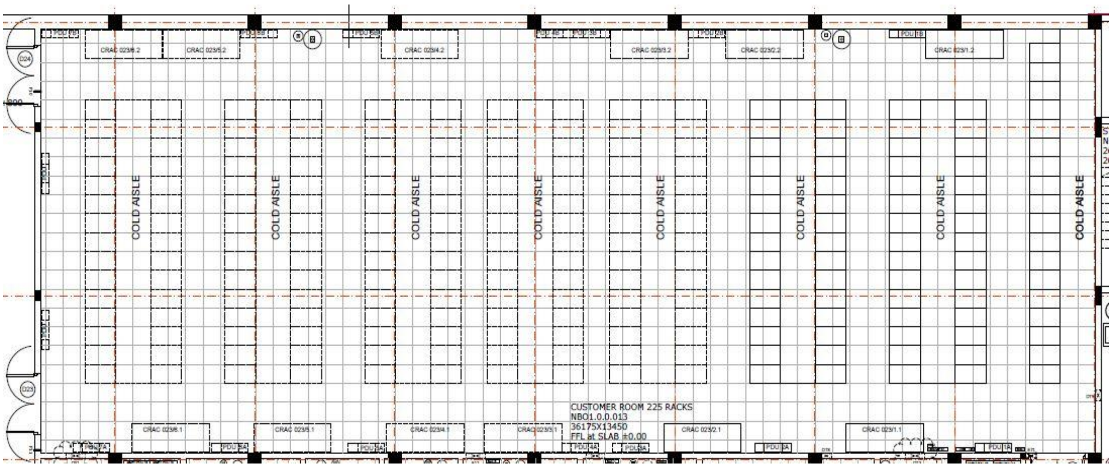


Figure 4.7: Data Center I IT and Air-conditioning arrangement

The figure 4.7 above shows the arrangement of the air-conditioning equipment and the computer equipment arranged in a hot aisle containment system. The air -conditioning equipment is twenty-two while the computer equipment (server racks) is eighty-eight.

Hot aisle containment works in the principles of the natural properties of warm air rising. The air-conditioning system directs the upward airflow to an AC return system such as a drop-ceiling void. The computer room contains a raised floor of height 0.5 m high, and the cable rack is overhead. The hot aisle containment is enclosed in a frame with a width of 1.2 m. There are 15 perforated tiles, whose size is 0.6x0.6m and aperture rate is 39%.

Side blowing air conditioning was installed with the following dimensions: 2172x 866 x 1960mm, air outlet size of 100 x 1920 mm, refrigerating capacity of 48 kW, and air flow rate of 16030 m3 /h. There are 88 racks with a size of 800 x 1060 x 1950 mm, which are divided from phase one and two with phase one currently implemented. The airflow and temperature distribution were measured at different locations within the computer room. The thermal imager was then used to measure and record the heat distribution on the surface of the equipment in the data center.

c) Data Center III

Data Center III is located at Sameer Industrial Park, Nairobi. The cooling system implemented is perimeter cooling units that distribute cold air under raised floor to data center space. In this design, one or more HVAC units, working in-tandem, push cold air into the data center while drawing out warm air exhausted by IT equipment.

The basic approach of this method is that the HVAC systems not only provide raw cooling capacity to IT equipment, but they also serve as a large mixer, periodically stirring and mixing the air in the data center space to bring it to a homogeneous average temperature, preventing hot spots from occurring. This approach is viable only as long as the power needed to mix the air is a small percentage of the total data center power consumption. The total number of AC units serving each floor was nineteen. Figure 4.8 below shows the arrangement of the AC equipment with respect to IT equipment.

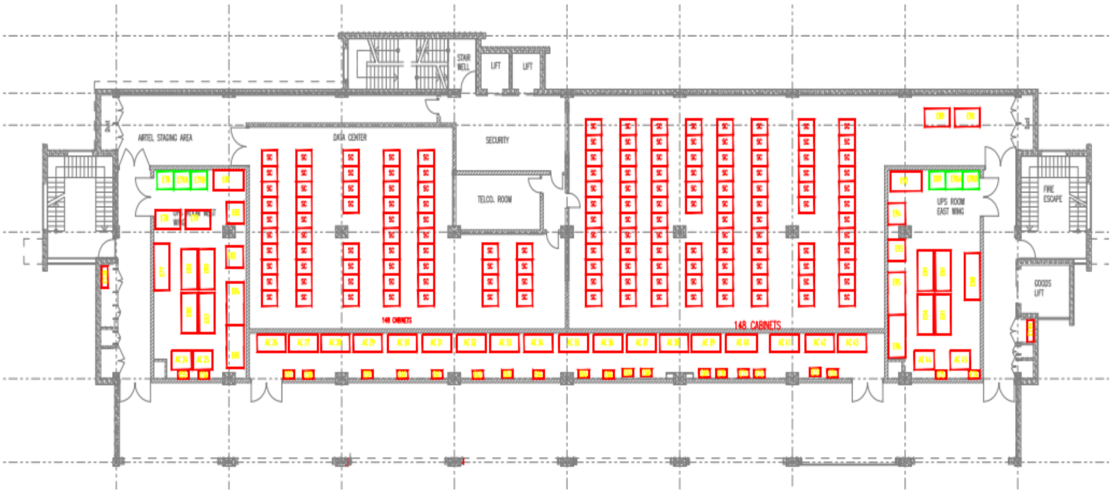


Figure 4.8: Data Center III Typical Equipment Layout

The data for the three data center was then tabulated as shown in the table below.

The air flow rate, temperature and relative humidity of several racks were measured at different locations including upper, middle and lower parts of the racks and result tabulated as shown in table 4.15 below. An average of this was used as an input to CFD model.

Table 4.154: Data center I, II and III environmental parameters

Average IT Environment			**Air temperature (°C)**		**Relative humidity (%)**		**Air Flow (m3/s)**	
			Simulated	Measured	Simulated	Measured	Simulated	Measured
Data Center I	Inlet (upper/lower)	T#01	17.5	22.2	55	72.8	2.2	1.1
		T#02	18.5	21.0	60	72.8		
	Outlet (upper/lower)	T#03	31.9	41.7	43	43.4		
		T#04	31.0	29.2	45	47.8		
Return air temperature		T#05	24.0	33.5	45	47.8		
Supply Air from CRAC		T#06	17.3	19.5	60	72.8		
Data Center II	Inlet (upper/lower)	T#01	15.8	20.7	54	67	2.2	2.3
		T#02	16.2	19.8	54	65		
	Outlet (upper/lower)	T#03	29.5	39.9	60	45		
		T#04	27.5	37.8	60	45		
Return air temperature		T#05	24.0	36.8	36.0	45		
Supply Air from CRAC		T#06	15.6	18.6	70.7	67		
Data Center III	Inlet (upper/lower)	T#01	20.8	23.8	56.0	68	2.3	1.6
		T#02	19.7	21.5	55	65		
	Outlet (upper/lower)	T#03	33.1	38.6	45	39		
		T#04	32.2	36.0	40	47		
Return air temperature		T#05	24.0	36.8	45	47		
Supply Air from CRAC		T#06	14.2	19.8	56	68		

4.2.1 Analysis of Key Performance Parameters Indices for the Data Centers

Return temperature index (RTI) was used as the key performance parameters indices for the data centers. Any data center cooling component can be characterized by inlet and outlet temperature.

The RTI is a measure of energy performance in air management system. The index is defined by:

$$RTI = \frac{T_{return} - T_{supply}}{\Delta T_{equipment}} x100\% \qquad (4.12)$$

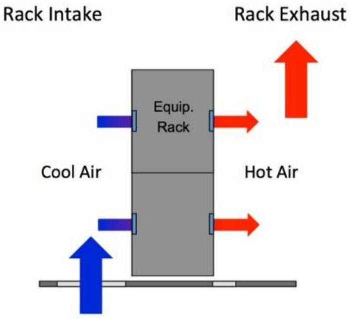


Figure 4.9: Air flow Distribution

The *RTI* can also be described as the ratio of total airflow through the air-conditioning equipment and the IT equipment. The target value of RTI as a measure of the energy performance is 100 %. RTI of more than 100% indicates re-circulation and less than 100%, the flow is bypassed. In an ideal case, an optimized data center would have an RTI metric value of 100% but some amount of by-pass air and re-circulation air will always exist. The main goal is to minimize these conditions to increase the efficiency of the data center air-conditioning system.

Table 4.16: Return temperature index

Rating	**RTI**
Target	100%
Recirculation	$> 100\%$
By-pass	$< 100\%$

$$RTI_{DC\ I} = \frac{33.5-19.56}{19.5}\ x100\% = 71.48\% \quad (4.13)$$

Since this value is below 100%, this indicates that the flow is bypassed implying that the cold air is recycled without first being properly directed into IT equipment that is supposed to be cooled, resulting in wasted energy.

$$RTI_{DC\ II} = \frac{36.8-18.6}{19.2}\ x100\% = 94.79\% \quad (4.14)$$

Similarly, this value is below 100%, and this indicates that the flow is bypassed.

$$RTI_{DC\ III} = \frac{36.8-19.8}{14.8}\ x100\% = 114.86\% \quad (4.15)$$

Since this value is above 100%, this indicates that air is repeatedly circulated through IT equipment without being adequately cooled, endangering equipment and increasing the risk of downtime.

4.2.2 CFD Modelling

Simulation analysis was conducted for different perforated tile opening ratios, rack power densities, different geometric arrangements of CRACs locations and different arrangements of aisle containments. In each experiment, air flow and temperature distributions in the data center are obtained and analyzed. In the following sections the effects of the different operating and geometric parameters on the flow and temperature distribution and on the data center performance indices are analyzed and discussed.

Data center II was considered for CFD simulation for the analysis of the effect of power density, tile opening ration and location of air-conditioning unit with respect to rack equipment. This data center was selected since the CFD software contained the library for the air-conditioning equipment used. The total area of this data center is 65.4 m2 (704 sq.ft.) with a 0.91 m (3 ft) deep plenum and 4.37 m (14.3 ft) ceiling height. A total of 153 perforated floor tiles, each measuring 0.60 m × 0.60 m, were distributed in the aisle in rows. The aisle had two rows of cabinets arranged in 15 cabinets per row giving a total of 30racks per containment. However, there were two independent rows of 18 and 15 cabinet racks.

The overall dimensions of the racks were 710 mm × 1065 mm × 2114 mm. Each of the racks was populated by five Cisco 2 RU servers and one network switch. The power consumption of the servers was obtained from the reading on the power distribution frame display that fluctuated between 2100W and 2500W. For the purposes of simulation, 2500W was taken as the input to the CFD model.

a) Effect of percentage of opening area of floor tiles

In data centers, the proportion of floor tiles that is open has a significant impact on air flow, temperature distribution, and rack cooling. Larger open area perforated tiles give lower average flow velocity for the same air flow rate (i.e. power density). The homogeneity of the pressure distribution in the plenum determines the local air flow rate in each tile. Plenum impediments such as cables, ducts, pipes, and tiles frequently cause the plenum pressure to be unevenly distributed. The regularity of the pressure distribution in the plenum is also affected by the placement and distribution of the CRACs that discharge the cold air to the plenum. The imbalanced distribution of cooled air is caused by the non-uniformity of the pressure distribution.

Different values of the percentage of tile opening area were assumed in the CFD model and simulation was done to determine its effect on airflow distributions. These values ranged from 10% to 70% at a constant power density of 2500kw. The performance indices RTI was then computed to compare the results. The figures 4.10 and 4.11 below shows the temperature distribution for different tile floor opening ratio.

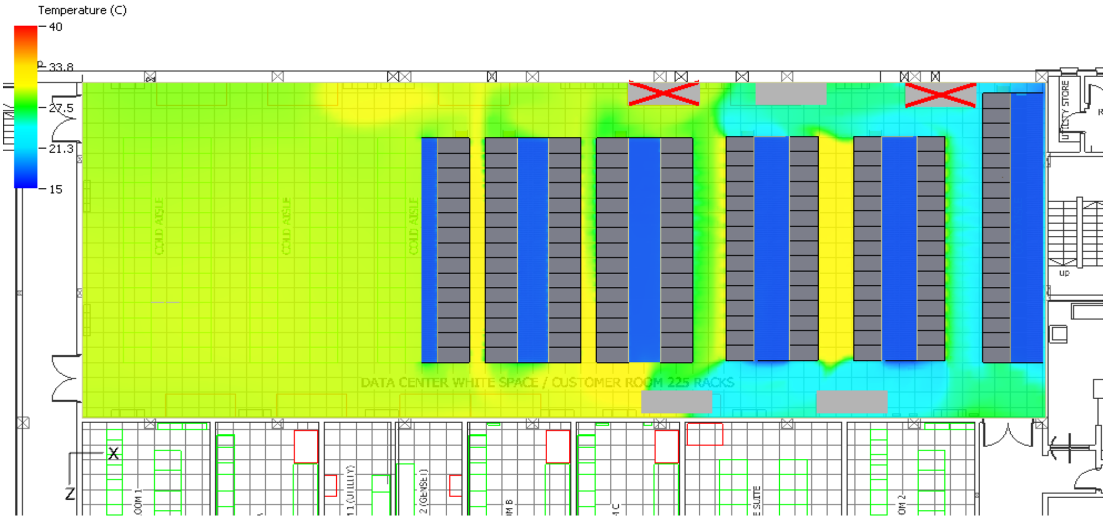


Figure 4.101: 10% of floor tile opening area

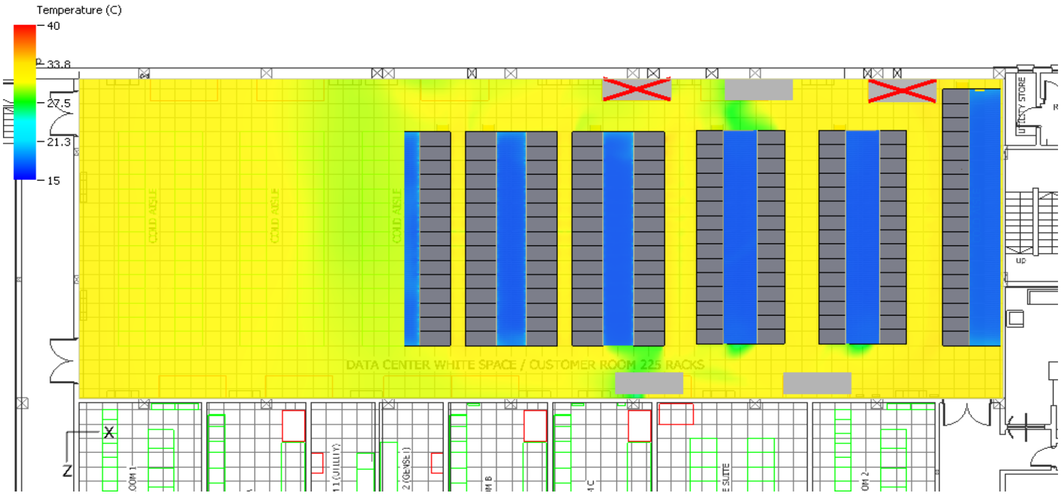


Figure 4.11: 70% of floor tile opening area.

As shown in the figures above, at a low opening ration (10%), the temperature ranges from 27.5 ° C to 33.6 ° C while for opening ratio of (70%), the temperature ranges from 21.3 ° C to 30 ° C. Increasing the tile opening from 10% to 70% increases the tile flow area, and this resulted in the reduction of the velocity of cold air stream entering the aisle through the vent tiles. This reduction in the cold air velocity causes an increase in the static pressure at the cold aisle and hence prevents hot air from flowing into the aisle and as result, leads to reduction in recirculation and heat infiltration.

b) Effect of rack power density

The sizing of the air-conditioning equipment for data centers is dependent on the rack power density. If either of this is not gotten right, will have a profound impact thermal management of the data center. The figure below shows the thermal performance of data centers with rack power densities of 2500W and 5000W at a similar air-conditioning equipment selection.

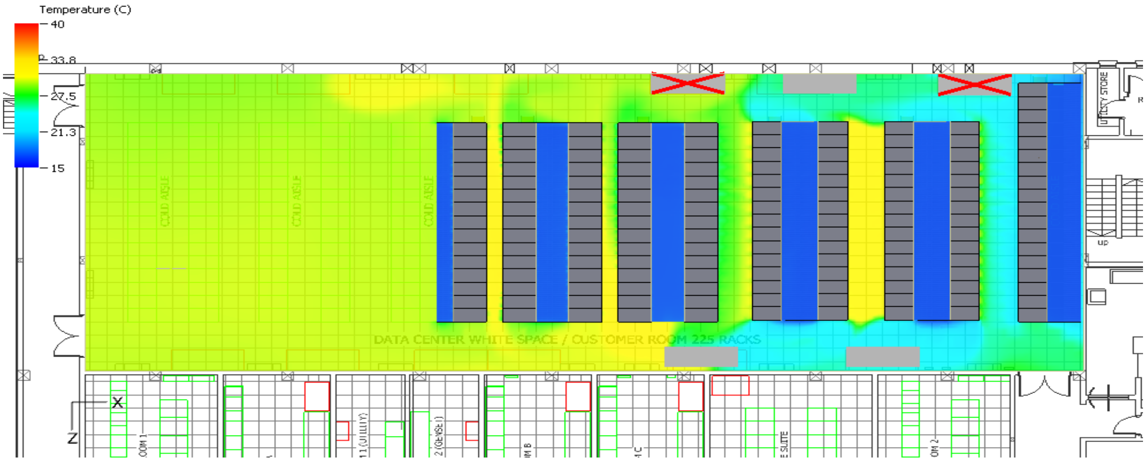


Figure 4.12: Data center with a rack density of 2.5kW

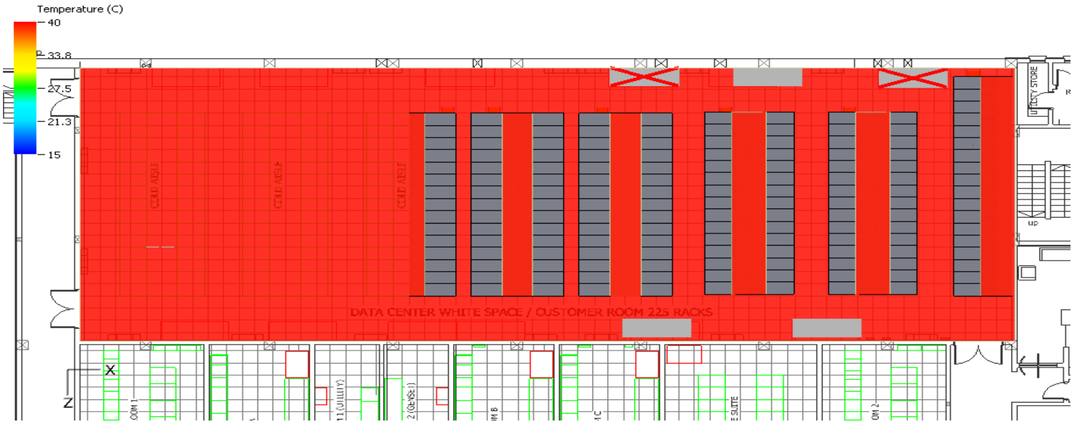


Figure 4.13: Data center with a rack density of 5Kw

For racks in figure 4.13, shows the temperature distribution of between 21.3° C to 30 °C which is within the recommended ASHRAE operating temperature while for racks in figure 4.8, the temperature distribution is around 40 ° C. This is beyond ASHRAE maximum recommended operating of 32 ° C and, hence, the working of the IT equipment would not be possible.

The increase in the power density increases the requirements of the cooling and air velocity as shown in the equation below.

$$Q = \rho \; x \; V \; x \; c_p \; x \; \Delta T \qquad (4.16)$$

$$V = \frac{Q}{\rho \; x \; c_p \; x \; \Delta T} \qquad (4.17)$$

Where Q = Heat load (kJ/hour)

ρ = Density of air (1.2kg/m^3)

c_p = specific heat of air at constant pressure (1.005kJ/kg ^{0}C)

ΔT = Change in temperature (13.97 ^{0}C)

V = Velocity

Taking the rack power density as the heat load generated by the IT load.

For power rack density of 2.5Kw, the required velocity is;

$$V\ =\ \frac{2.5\ x\ 3600}{1.2\ x\ \ 1.005\ x\ 13.97} = 534.19m3/hour\ \approx 8.9m^3\ \ /min \qquad (4.18)$$

For power rack density of 5.0Kw, the required velocity is;

$$V\ =\ \frac{5\ x3600}{1.2\ x\ \ 1.005\ x\ 13.97} = 1068.38m3/hour\ \ \approx 17.8m^3\ \ /min \qquad (4.9)$$

This calculation shows that the required velocity doubles when the power density increases from 2.5kw to 5.kw, hence air velocity is directly proportion to rack power density.

The cooling load for 2.5kw power rack density

$$Cooling\ load = \frac{12000\ x\ 2.5}{3.157}\ 8530\ BTU/Hour \qquad (4.10)$$

The cooling load for 5kw power rack density

$$Cooling\ load = \frac{12000\ x\ 25}{3.157}\ 17{,}060\ BTU/Hour \qquad (4.11)$$

1 ton cooling = 3.157Kw

1 ton cooling = 12000 BTU/Hour

This also shows that the required cooling loads doubles when the power density increases from 2.5kw to 5.kw, hence cooling load is directly proportion to rack power density.

c) Effect of racks locations w.r.t. Computer Room Air-conditioning Equipment

The location of an air conditioning unit can have a dramatic effect on the data center thermal performance as shown in the figure below.

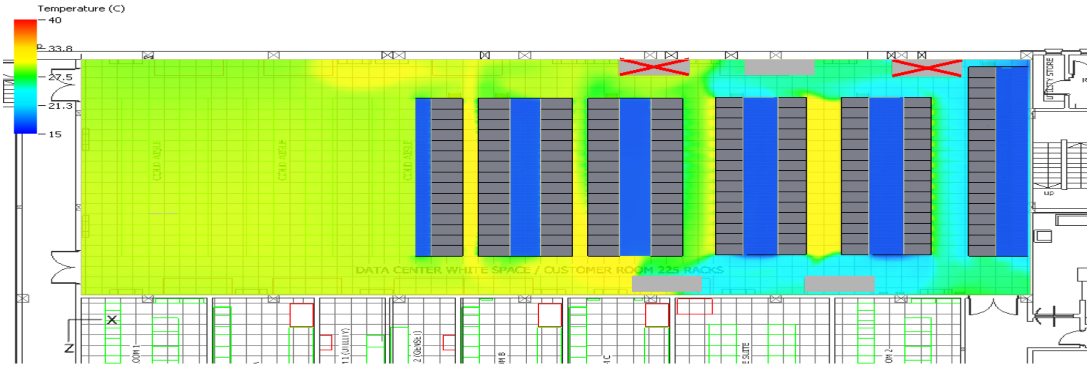


Figure 4.14: Three air-condition (One on the upper side and two on lower side)

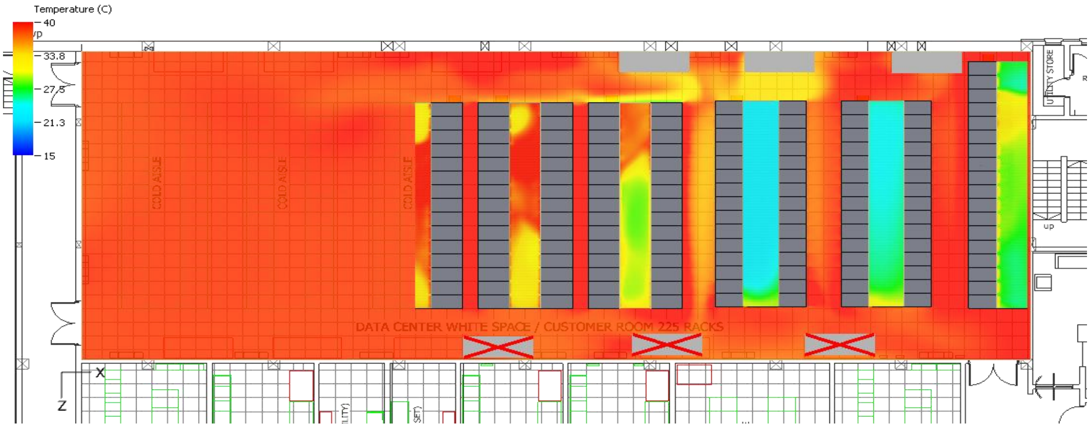


Figure 4.15: Three air-condition (All located on the upper side)

Figure 4.15 shows the temperature distribution of between 21.3° C to 30 °C which is within the recommended ASHRAE operating temperature while for racks on figure 4.10, the temperature distribution is around 27.6 ° C to 40 ° C. This is a result of uneven pressure and air distribution within the plenum to reach each section of the data center space.

Due to the influence of the external environment and usage, the heat dissipation of equipment in the computer room has characteristics of dynamic changes, which had been regarded as a steady state process in the simulation. Moreover, in the numerical simulation, the influence of external environment and heat dissipation of air conditioner were neglected.

In the field experiment, the results were also affected by the interference of the activities of the surveyors and the errors of the measuring instrument system. These are the main reasons for deviation between simulated results and measured. Nevertheless, the trend of variation between simulated and measured values is basically the same, and the relative deviation is small. Therefore, it can be concluded that the physic model, the boundary conditions settings, and the calculated method are reasonable, and it can meet the needs of an engineering.

4.3 Modelling Energy Consumption of Servers with Regressions Methods

4.3.1 Multiple Linear Method

The use of regression analysis and the subset features described below in table 4.17 was used to construct the power model. The subset mentioned is as shown in the table below.

Table 4.175: Power Model Subset

Parameter	**Description**
Y	Energy consumption
X_1	CPU utilization
X_2	Memory Utilization

The linear regression model is then represented by the following equation.

$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \varepsilon$ (4.12)

$E(\varepsilon) = 0,$

$D(\varepsilon) = \sigma^2 < +\infty$

where y represent the observed energy consumption, and xi $(1 \leq i \leq m)$ represent observation of utilization of each component, βi $(0 \leq i \leq m)$ is the coefficient of regression model, and ε is the random error that cannot be observed. For random error ε, an assumption is made that its expectation and variance are 0 and σ^2 respectively.

Power consumption of the server was measured using power analyzer logger (Model

PEL 103) and at the same time the subset features at that instant recorded from the task manager, resource monitor and performance monitor.

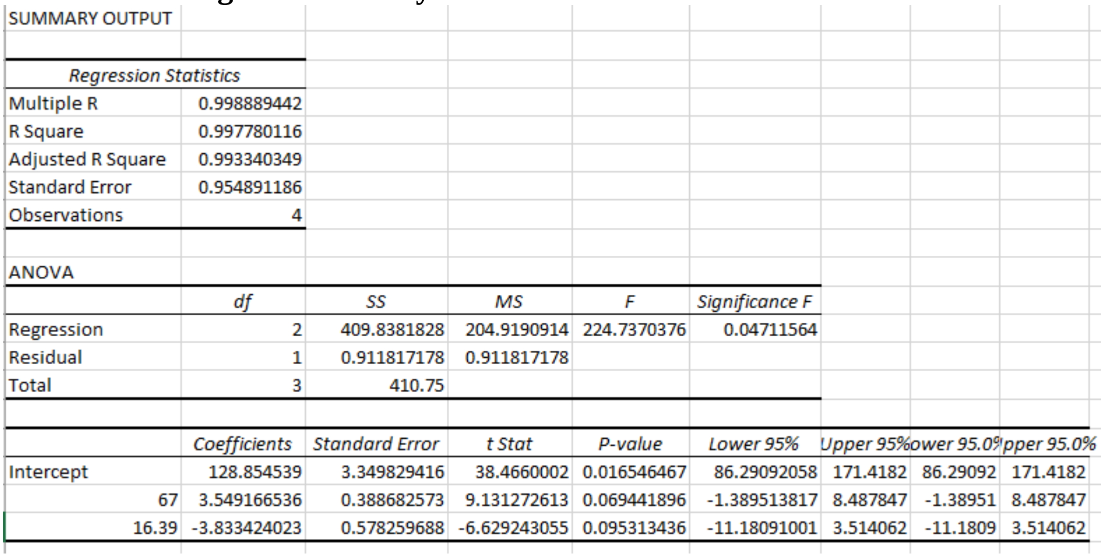
The data of power consumption of server verses CPU and memory utilization was tabulated as shown in table 4.18 and exported to excel file and regression analysis performed as indicated in table 4.19.

Table 4.186: Power consumption of servers

Energy Consumption	**CPU Utilization (%)**	**Memory Utilization (%)**
209	67	16.39
211	76	48.88
206	63	38.23
192	56	35.56
186	50	31.23

The hypothesis was then used to test if network traffic carries a significant impact on server's power consumption. The dependent variable (server's power consumption) was regressed on predicting variable (network traffic) to test the hypothesis H1|NT significantly predicts server's power consumption. The value of $p<0.05$ which indicates that network traffic can play a significant role in shaping server's power consumption. SPC ($\beta = 128.85, p<0.05$). These results clearly direct the positive effect of the network traffic. Moreover, the R sq = 0.997 depicts that the model explains 99.78% of the variance in server's power consumption. The table 4.19 below summarizes the findings.

Table 4.197: Regressions Analysis



SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.998889442
R Square	0.997780116
Adjusted R Square	0.993340349
Standard Error	0.954891186
Observations	4

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	409.8381828	204.9190914	224.7370376	0.04711564
Residual	1	0.911817178	0.911817178		
Total	3	410.75			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*ower 95.0%*	*pper 95.0%*
Intercept	128.854539	3.349829416	38.4660002	0.016546467	86.29092058	171.4182	86.29092	171.4182
67	3.549166536	0.388682573	9.131272613	0.069441896	-1.389513817	8.487847	-1.38951	8.487847
16.39	-3.833424023	0.578259688	-6.629243055	0.095313436	-11.18091001	3.514062	-11.1809	3.514062

The equation now becomes:

$Y = 128.85 + 3.55X_1 - 3.83X_2 + \varepsilon$ (4.13)

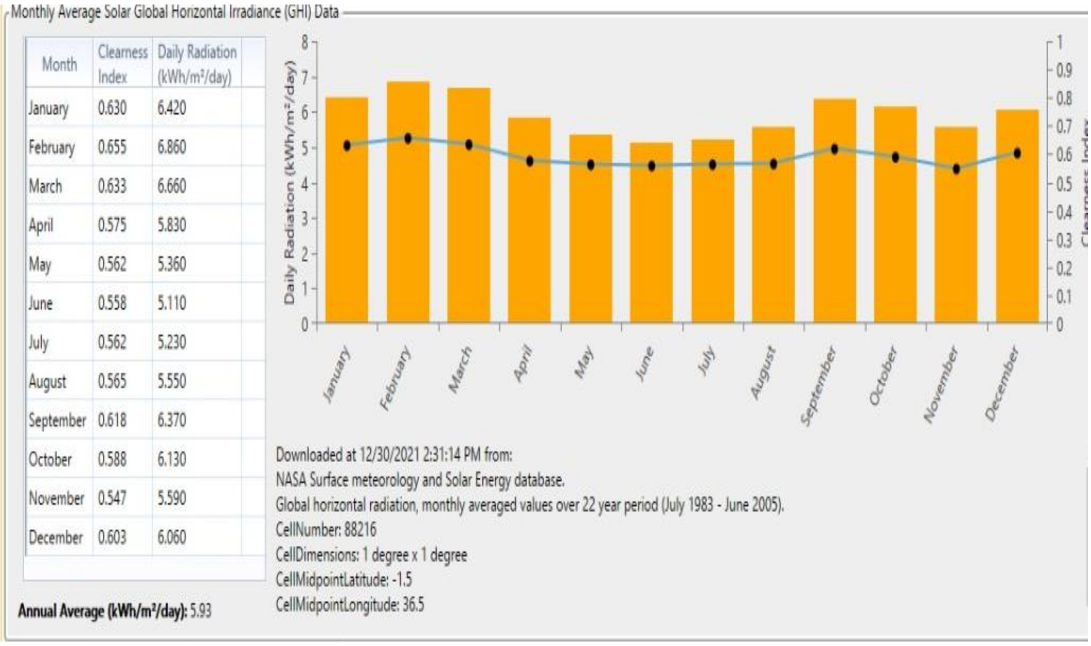
The goal of the regression approach, which is a useful tool for modeling the connection between factors, is to forecast how the target variable will change in response to changes in the decision variables. In more specific terms, we consider energy to be the target variable (y) while CPU and memory utilization as the decision vector (x). From table 4.19, it is observed that an increase in workload (CPU and memory utilization) causes an increase in power usage by the server.

This therefore means the next generation network design should concentrate on developing a virtual memory system that can manage physical memory resources while running to enhance energy efficiency.

4.4 Evaluation of Cost Benefit Analysis Using Homer Software of Utilizing Solar-Diesel Hybrid System to Power Data Centers in Kenya

4.4.1 Solar energy resource

Kenya receives an average of 5.5kWh/m2 /day to 6.5kWh/m2 /day of solar insolation. As there are seasonal variations but not as extreme cases during the year the insolation also varies from 4.55kWh/m2 per day in July to maximum of 5.55kWh/m2 per day in February and March. The figure 4.16 below shows the daily radiation from the month of January to December.



Monthly Average Solar Global Horizontal Irradiance (GHI) Data

Month	Clearness Index	Daily Radiation (kWh/m²/day)
January	0.630	6.420
February	0.655	6.860
March	0.633	6.660
April	0.575	5.830
May	0.562	5.360
June	0.558	5.110
July	0.562	5.230
August	0.565	5.550
September	0.618	6.370
October	0.588	6.130
November	0.547	5.590
December	0.603	6.060

Annual Average (kWh/m²/day): 5.93

Downloaded at 12/30/2021 2:31:14 PM from:
NASA Surface meteorology and Solar Energy database.
Global horizontal radiation, monthly averaged values over 22 year period (July 1983 - June 2005).
CellNumber: 88216
CellDimensions: 1 degree x 1 degree
CellMidpointLatitude: -1.5
CellMidpointLongitude: 36.5

Figure 4.162: Solar Resources of Nairobi, Kenya

4.4.2 Load Profile

Data center two has an installed solar PV system capacity of 100KW but have a potential to produce additional 200KW considering the available space they have. This can total up to 300KW of solar energy. This value was considered as the maximum amount this data center can produce and hence our simulation was based on this maximum value.

The tabulated load profile for a period of 24hrs is attached at the appendixes.

Data center three on the other hand has an already installed solar PV system capacity of 1000KW integrated with grid and thermal (generator power). Due to high power demand, the facility has its own 66/33KV substation with two lines from the utility.

In our simulation, the installed capacity of 1000KW was used as the maximum solar

PV energy that can be generated.

The tabulated load profile for a period of 24hrs is attached at the appendixes.

4.4.3 Hybrid Modelling and Optimization of DC II using Homer Software

The results are provided in accordance with the least cost of energy (COE) or any other criterion chosen after the optimization models are run by the Homer program. The sensitivity analysis enables the modeler to investigate numerous scenarios while considering every potential variable that might be present during the power system's lifetime. To determine the best- and worst-case scenarios in which the project would be possible, any parameters that lead to doubt can be changed.

For data center II, it has an installed solar PV system capacity of 100Kw but has the potential to produce an additional 200KW considering the available space they have. This can total up to 300kw of solar energy. This value was considered as the maximum amount this data center can produce and hence our simulation was based on this maximum value.

4.4.3.1 Homer Schematic Setup

The configuration shown in Figure 4.17 consists of a 2X550Kva diesel generator, Grid and PV system without back up batteries.

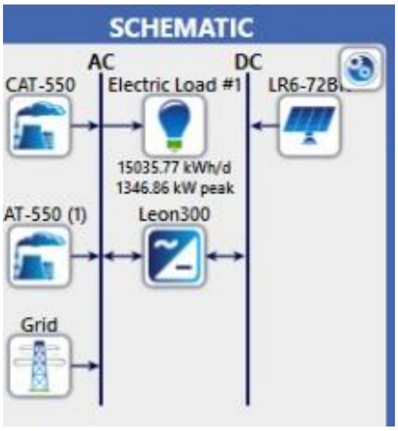


Figure 4.17: Homer power architecture

4.4.3.2 Load Profile

The data center II load was the first value to be introduced to the software. This helped to select the equipment necessary to meet the load. HOMER can determine whether the equipment is sufficient to meet the load or not. The primary load needs to be described on an hourly basis, so that the software can model the peak load and low consumption hours. This helps in selecting the most economical power source according to power consumption.

Name: Electric Load #1

January Profile

Hour	Load (kW)
0	606.820
1	624.180
2	621.150
3	630.240
4	612.060
5	613.660
6	615.780
7	630.450
8	636.300
9	630.000
10	625.780

Time Step Size: **60** minutes

Random Variability
Day-to-day (%): 10
Timestep (%): 20

Peak Month: **None**

Metric	Baseline	Scaled
Average (kWh/d)	15,035.	15,035.
Average (kW)	626.49	626.49
Peak (kW)	1,125.0	1,125.0
Load Factor	.56	.56

Load Type: ● AC ○ DC

☐ Efficiency (Advanced)
Efficiency multiplier: 1
Capital cost ($): 0
Lifetime (yr): 10

Scaled Annual Average (kWh/d): 15,035.77

Figure 4.18: Data center II load Homer load profile

4.4.3.3 Hybrid System Components

In this section the various components necessary for the system's design are expounded on. Information related to their pricing and size is given since the price of the components is what homer software uses to determine the cost of the entire system.

The solar PV cells.

The solar panel considered was Generic flat plate PV system. It has efficiency of 19.4 %. Installation cost was taken as 60% of the PV price and the operation and maintenance cost is 1% of the total cost per year.

Considering the maximum solar PV system of about 300Kw that can be produced, the following cost can be realized.

1. Capital cost Ksh.64,000 /KW
2. Replacement cost Ksh.64,000 /KW
3. PV life 25 year

Name: Peimar SG315M (BF)

Properties
Name: **Peimar SG315M (BF)**
Abbreviation: **SG315M (BF)**
Panel Type: **Flat plate**
Rated Capacity (kW): **315**
Temperature Coefficient: **-0.4**
Operating Temperature (°C): **25**
Efficiency (%): **19.4**
Manufacturer: **Peimar Inc.**
www.peimar.com
Notes:
18 kg. Footprint: 1.627 m2

Figure 4.19: Solar PV module specification

There is not any tracking system considered in this research, thus the system is modeled as fixed tracking mount at ground. The derating factor is a term accounted for both PV systems efficiency. The derating factor was taken as 80%, ground reflectance was also considered as 20%, slope 14.46 (latitude of the location) and azimuth 0 (south orientation).

Power Converter Size and Cost

A converter is needed to maintain the flow of energy between AC and DC power system components.

1. Capital cost of converter is taken as (Ksh) 60,000/kw.
2. Replacement cost (Ksh) 60,000/kw
3. Efficiency of converter is around 96%
4. Converter sizes considered 300Kw.

Diesel Generator Size and Cost

The load ration for the generator was taken as 25%. Since this is an existing site, the size of the generator is therefore predetermined and is 2NOX500Kva. The operation's lifetime was taken as 90000hrs. The initial cost of the generator was tabulated as follows following the inputs gotten from the site visit.

1. Capital cost was taken as (Ksh) 10,400,000.00.
2. Replacement cost (Ksh) 10,400,000.00.
3. The size of Gen set considered is 2No X 500kVA.
4. The minimum load ratio of 25% of rated load was accounted.

4.4.3.4 Cost Analysis of Solar PV and Utility Power

2018 Schedule of tariffs for Kenya Power was used to compute bill simulation. This premises was being metered at 11kV hence Method C12 applicable to commercial and industrial consumers metered at 11,000 volts billing was used which is as follows.

a) Energy charges of KSh.10.90 per unit consumed.
b) Energy charge of KSh.5.45 per unit consumed for supply metered during off-peak hours.
c) Demand charge of KSh.520.00 per Kva

Average load demand in kW= 606.82Kw

Taking p.f of 0.9, total load in kVA= $606.82/_{0.9} = 674.24$kVA

Total number of units based on the load schedule above is 18,085.04Units.

Total number of units in a month is;

18,085.04 X 30 = 542,551.20 Units

Energy Charge = 542,551.20 X KSh.10.90 = KSh.5,913,808.08

Demand charge = KSh.520 X 674.24 = KSh.350,604.80

Total Bill per month = KSh.5,913,808.08 + KSh.350,604.80= KSh.6,264,412.88

Considering the energy contribution of solar PV system that can amount to 300kW and insolation data of 5.93kWh/m2/day from homer software.

Total daily energy capacity = 300Kw x 5.93 = 1,779 Units

The energy demand from the grid therefore reduces to.

= 18,085.04 – 1,779 = 16,306.04 Units

Total KW also reduces to.

= 606.82 – 300 = 306.82Kw

Taking p.f of 0.9, total Kva =$306.82/_{0.9} = 340.91$Kva

Total number of units in a month is.

16,306.04 X 30 = 489,181.20 Units

Energy charge = 489,181.2 X KSh.10.90 = KSh.5,332,075.08

Demand charge = KSh.520 X 340.91 = KSh.177,273.2

Total Bill per month = KSh.5,332,075.08+ KSh.177,273.2= KSh.5,509,348.28

Total savings per month = KSh.6,264,412.88- KSh.5,332,075.08 = KSh.755,064.6

Total savings per year = KSh.755,064.6 X 12 = KSh.9,060,775.2

4.4.3.5 Simple Payback Analysis

The total Cost of the PV system was taken as Ksh.180,000 /Kw

Total cost = Ksh.180,000 X 300Kw = Ksh.54,000,000.00

$$Payback\ time = \frac{54{,}000{,}000}{9{,}060{,}775.20} = 5.96\ yrs\ \cong 6\ yrs \qquad (4.14)$$

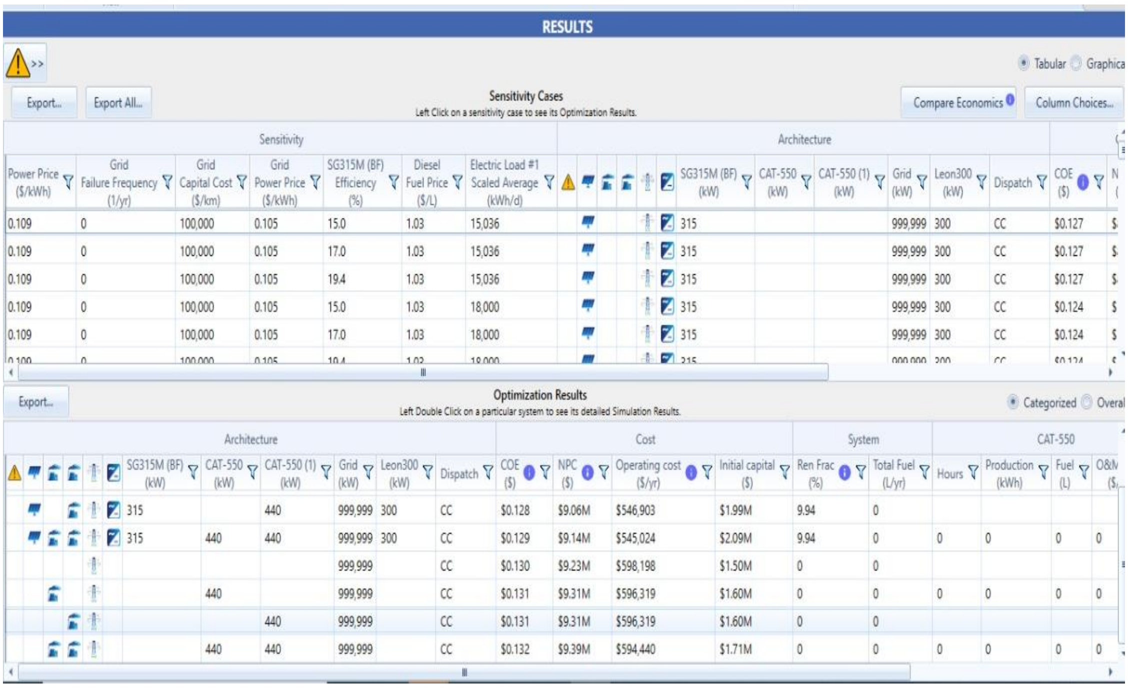
4.4.3.6 System Optimization

Optimization scenario of the whole system was achieved using sensitivity variable. A sensitivity variable is an input variable for which multiple values can be specified. HOMER performs a separate optimization procedure for each specified value.

These sensitivity variables include diesel fuel price, solar PV efficiency and the electrical load.

HOMER Pro has two optimization algorithms. The original grid search algorithm simulates all the feasible system configurations defined by Search Space. HOMER then displays a list of configurations, sorted by net present cost (sometimes called life-cycle cost), that you can use to compare system design options. The Optimization Results table lists all the feasible simulations for the selected sensitivity case (non-feasible systems are not shown.)

Our result shows that the least cost (feasible system) is the Grid – solar PV combination while the least feasible is the is the grid – thermal(generator) combination. The ranking as shown in figure 4.20 is based on the initial capital cost, operating cost, and total net present cost.



Sensitivity Cases
Left Click on a sensitivity case to see its Optimization Results.

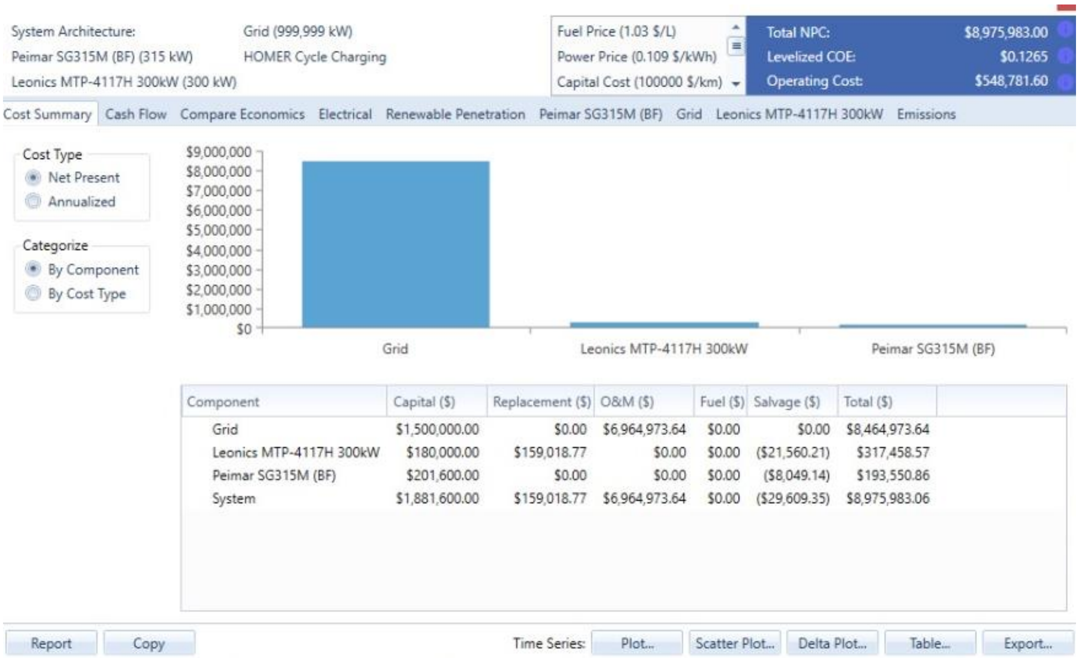
Sensitivity							Architecture						
Power Price ($/kWh)	Grid Failure Frequency (1/yr)	Grid Capital Cost ($/km)	Grid Power Price ($/kWh)	SG315M (BF) Efficiency (%)	Diesel Fuel Price ($/L)	Electric Load #1 Scaled Average (kWh/d)	SG315M (BF) (kW)	CAT-550 (kW)	CAT-550 (1) (kW)	Grid (kW)	Leon300 (kW)	Dispatch	COE ($)
0.109	0	100,000	0.105	15.0	1.03	15,036	315			999,999	300	CC	$0.127
0.109	0	100,000	0.105	17.0	1.03	15,036	315			999,999	300	CC	$0.127
0.109	0	100,000	0.105	19.4	1.03	15,036	315			999,999	300	CC	$0.127
0.109	0	100,000	0.105	15.0	1.03	18,000	315			999,999	300	CC	$0.124
0.109	0	100,000	0.105	17.0	1.03	18,000	315			999,999	300	CC	$0.124
0.109	0	100,000	0.105	19.4	1.03	18,000	315			999,999	300	CC	$0.124

Optimization Results
Left Double Click on a particular system to see its detailed Simulation Results.

Architecture						Cost				System		CAT-550			
SG315M (BF) (kW)	CAT-550 (kW)	CAT-550 (1) (kW)	Grid (kW)	Leon300 (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)	Hours	Production (kWh)	Fuel (L)	O&M ($
315		440	999,999	300	CC	$0.128	$9.06M	$546,903	$1.99M	9.94	0				
315	440	440	999,999	300	CC	$0.129	$9.14M	$545,024	$2.09M	9.94	0	0	0	0	0
			999,999		CC	$0.130	$9.23M	$598,198	$1.50M	0	0				
	440		999,999		CC	$0.131	$9.31M	$596,319	$1.60M	0	0	0	0	0	0
		440	999,999		CC	$0.131	$9.31M	$596,319	$1.60M	0	0				
	440	440	999,999		CC	$0.132	$9.39M	$594,440	$1.71M	0	0	0	0	0	0

Figure 4.20: Data Center II optimization results

Double clicking on the least cost desired system in the optimization results displays the simulation results corresponding to that system case. For our case the feasible system was found to be grid-solar combination and its simulation results as shown in figure 4.21.


System Architecture: Grid (999,999 kW)
Peimar SG315M (BF) (315 kW) HOMER Cycle Charging
Leonics MTP-4117H 300kW (300 kW)

Fuel Price (1.03 $/L)
Power Price (0.109 $/kWh)
Capital Cost (100000 $/km)

Total NPC: $8,975,983.00
Levelized COE: $0.1265
Operating Cost: $548,781.60

Cost Type: ● Net Present ○ Annualized

Categorize: ● By Component ○ By Cost Type

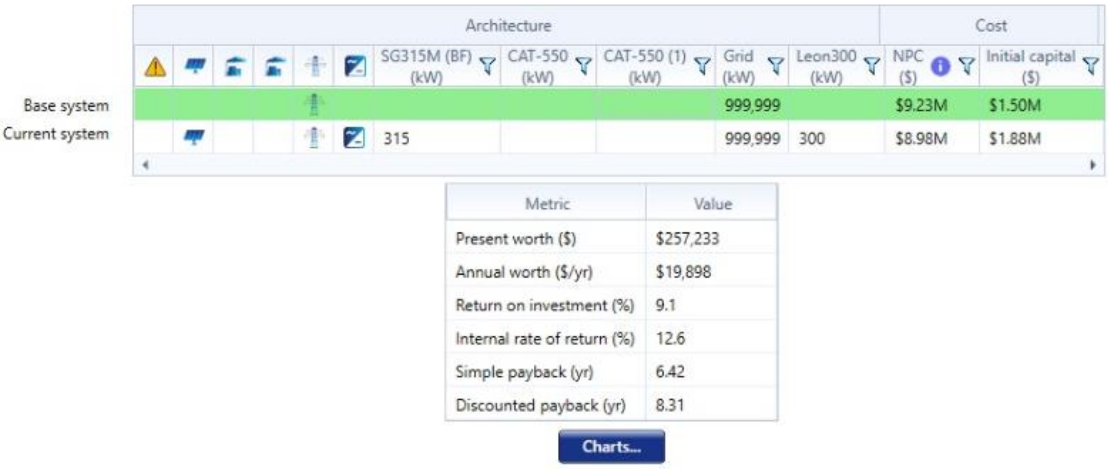
Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Grid	$1,500,000.00	$0.00	$6,964,973.64	$0.00	$0.00	$8,464,973.64
Leonics MTP-4117H 300kW	$180,000.00	$159,018.77	$0.00	$0.00	($21,560.21)	$317,458.57
Peimar SG315M (BF)	$201,600.00	$0.00	$0.00	$0.00	($8,049.14)	$193,550.86
System	$1,881,600.00	$159,018.77	$6,964,973.64	$0.00	($29,609.35)	$8,975,983.06

Figure 4.21: Results for the Optimal option

4.4.3.7 The economics of the system (payback, return on investment and other economic metrics)

HOMER calculates payback by comparing one system with another. In general, payback tells you how many years it takes to recover an investment. You invest a certain amount of money initially, then earn income from that investment. The payback is the number of years it takes for the cumulative income to equal the value of the initial investment. HOMER can also calculate other economic metrics such as Internal Rate of Return (IRR), present worth, and return on investment.

From the simulations result our system thus has a simple payback of about 6.5 years and a return on investment of about 9.1% as indicated in figure 4.22.



	Architecture										Cost	
	⚠						SG315M (BF) (kW)	CAT-550 (kW)	CAT-550 (1) (kW)	Grid (kW)	Leon300 (kW)	NPC ($)	Initial capital ($)
Base system					✓					999,999		$9.23M	$1.50M
Current system		✓			✓	✓	315			999,999	300	$8.98M	$1.88M

Metric	Value
Present worth ($)	$257,233
Annual worth ($/yr)	$19,898
Return on investment (%)	9.1
Internal rate of return (%)	12.6
Simple payback (yr)	6.42
Discounted payback (yr)	8.31

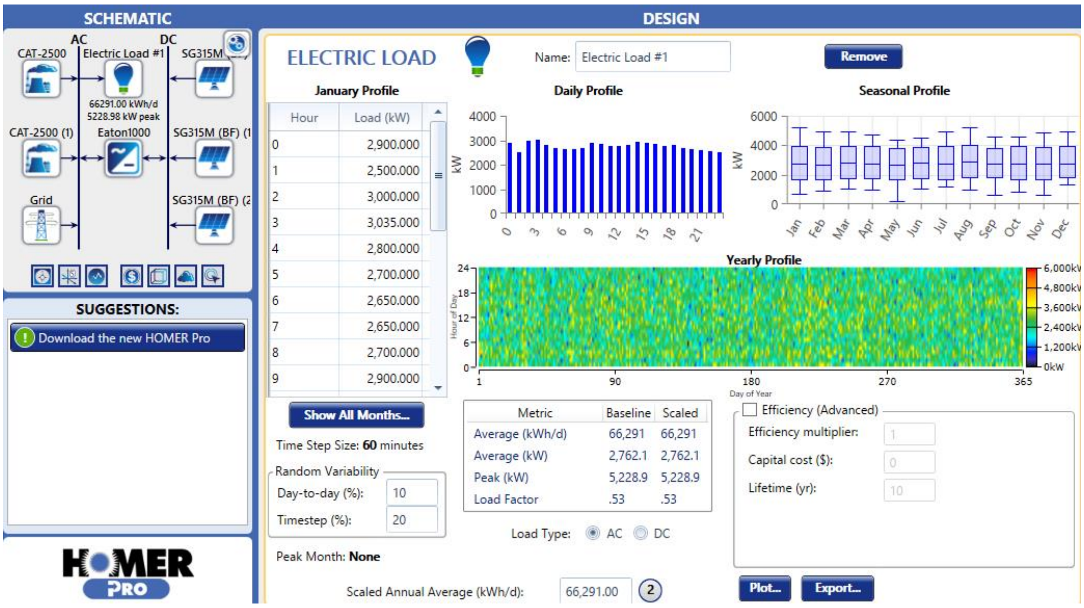
Figure 4.22: Simple pay back and return on investment results

4.4.4 Hybrid Modelling and Optimization of DC III using Homer Software

4.4.4.1 Load Profile

This data center has an already installed solar PV system capacity of 1000KW integrated with grid and thermal (generator power). Due to high power demand, the facility has its own 66/33KV substation with two lines from the utility. In our simulation, the installed capacity of 1000Kva was used as the maximum solar PV energy that can be generated.

The data center III load was inserted to the software as shown in the figure 4.23 below. The load was categorized on an hourly basis, so that the software can model the peak load and low consumption hours. This helps in selecting the most economical power source according to power consumption.



Name: Electric Load #1

January Profile

Hour	Load (kW)
0	2,900.000
1	2,500.000
2	3,000.000
3	3,035.000
4	2,800.000
5	2,700.000
6	2,650.000
7	2,650.000
8	2,700.000
9	2,900.000

Time Step Size: **60** minutes

Random Variability

Day-to-day (%): 10

Timestep (%): 20

Peak Month: **None**

Metric	Baseline	Scaled
Average (kWh/d)	66,291	66,291
Average (kW)	2,762.1	2,762.1
Peak (kW)	5,228.9	5,228.9
Load Factor	.53	.53

Load Type: ● AC ○ DC

☐ Efficiency (Advanced)

Efficiency multiplier: 1

Capital cost ($): 0

Lifetime (yr): 10

Scaled Annual Average (kWh/d): 66,291.00

Figure 4.23: Data center III load Homer load profile

4.4.4.2 Hybrid System Components

In this section the various components necessary for the system's design were expounded on. Information related to their pricing and size were given since the price of the components is what homer software uses to determine the cost of the entire system.

The solar PV cells

The solar panel considered was 315KW Generic flat plate PV system. The efficiency the PV panels was19.4 %, the price of PV modules was taken as Ksh.64/watt. Installation cost is taken as 60% of the PV price and the operation and maintenance cost is 1% of the total cost per year, therefore the cost breakdown will be.

1. Capital cost Ksh.64,000 /Kw
2. Replacement cost Ksh.64,000 /Kw
3. PV life 25 year

Name: Peimar SG315M (BF)

Properties
Name: **Peimar SG315M (BF)**
Abbreviation: **SG315M (BF)**
Panel Type: **Flat plate**
Rated Capacity (kW): **315**
Temperature Coefficient: **-0.4**
Operating Temperature (°C): **25**
Efficiency (%): **19.4**
Manufacturer: **Peimar Inc.**
www.peimar.com
Notes:
18 kg. Footprint: 1.627 m2

Figure 4.24: Solar PV module specification

There was not any tracking system considered in this research, thus the system is modeled as fixed tracking mount at ground. Derating factor is a term accounted for both PV systems efficiency. The derating factor was taken as 80%, ground reflectance was also considered as 20%, slope 14.46 (latitude of the location) and azimuth 0 (south orientation).

Power Converter Size and Cost

A converter is needed to maintain the flow of energy between AC and DC power system components. The rated power of the inverter should be equal to or larger than the maximum solar energy generated by the PV modules.

1. Capital cost of converter is taken as (Ksh) 60,000/kw.
2. Replacement cost (Ksh) 60,000/kw
3. Efficiency of converter is around 96%
4. The converter size of 1000kw.

Diesel Generator Size and Cost

As shown on the schematic, there was two generators of 2x2500Kw. The load ration for the generator was taken as 25%. The operations lifetime was taken as 90000hrs. The initial cost of the generator was tabulated as follows following the inputs gotten from the site visit.

1. Capital cost was taken as (Ksh) 45,500,000.00.
2. Replacement cost (Ksh) 45,500,000.00.
3. The size of Gen set considered is 2No X 2500kVA.
4. The minimum load ratio of 25% of rated load was accounted.

Solar photovoltaic systems can help data center industries in their energy policy goals for secure, reliable and affordable energy to expand electricity access and promote development. This section will cover the operation costs and performance of solar PV system on data center industry.

4.4.4.3 Cost Analysis of Solar PV and Utility Power

This section will cover the operation costs and performance of solar PV system on data center three. 2018 Schedule of tariffs for Kenya Power was used to compute bill simulation. This premises was being metered at 11kV hence Method C12 applicable to commercial and industrial consumers metered at 11,000 volts billing was used which is as follows.

1. Energy charges of KSh.10.90 per unit consumed.
2. Energy charge of KSh.5.45 per unit consumed for supply metered during off-peak hours.
3. Demand charge of KSh.520.00 per Kva

Average load = 2900kW

Taking p.f of 0.9, total load in kVA= ${}^{2900}/_{0.9} = 3{,}222.22$kVA

Total number of units based on the load schedule above is 68,542.48Units.

Total number of units in a month is.

68,542.48X 30 = 2,056,274.4 Units

Energy Charge = 2,056,274.4 X KSh.10.90 = KSh.22,413,390.96

Demand charge = KSh.520 X 3,222.22 = KSh.1,675,554.40

Total Bill per month = KSh.22,413,390.96+ KSh.1,675,554.40 = KSh.24,088,945.36

Considering the installed energy contribution of solar PV of 1000kW and insolation data of 5.93kWh/m2/day from homer software

Total daily energy capacity in kWh = 1000Kw x 5.93 = 5,930 Units

The energy demand from the grid therefore reduces to;

= 68,542.48 – 5,930 = 62,612.48 Units

Total KW also reduces to;

= 29000 – 1000 = 1,900Kw

Taking p.f of 0.9, total Kva =${}^{1{,}900}/_{0.9} = 2{,}111.11$Kva

Total number of units in a month is.

62,612.48 X 30 = 1,878,374.4 Units

Energy charge = 1,878,374.4 X KSh.10.90 = KSh.20,474,280.96

Demand charge = KSh.520 X 1,900 = KSh.988,000.00

Total Bill per month = KSh.20,474,280.96+ KSh.988,000.00= KSh.21,462,280.96

Total savings per month = KSh.24,088,945.36- KSh.21,462,280.96= KSh.2,626,664.40

Total savings per year = KSh.2,626,664.40 X 12 = KSh.31,519,972.8

4.4.4.4 Simple Payback Analysis

A simplified form of cost/benefit analysis is the simple payback technique. This method yields the number of years required for the improvement to pay for itself.

$$Simple\ payback\ time = \frac{Cost\ of\ the\ system}{Annual\ savings}\ , years \quad (4.16)$$

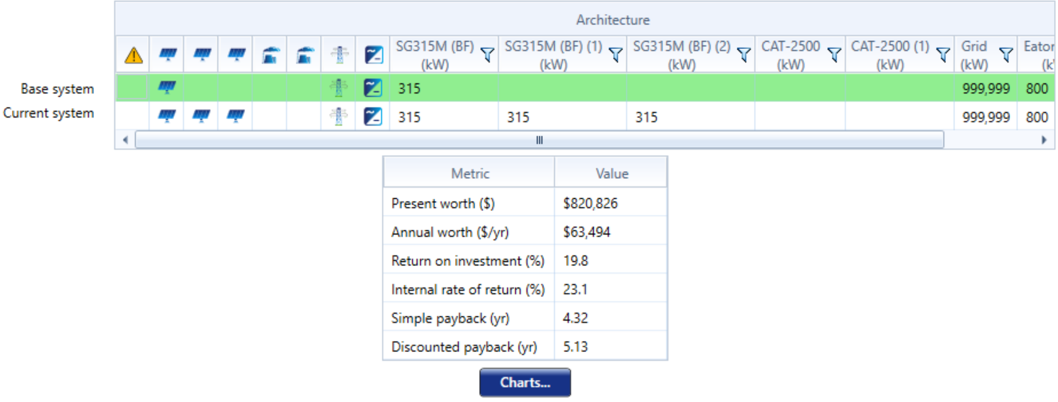
The total Cost of the PV system was taken as Ksh.180,000 /Kw.

Total cost = Ksh.180,000 X 1000Kw = Ksh.180,000,000.00

$$Payback\ time = \frac{180{,}000{,}000}{31{,}519{,}972.8} = 5.7\ yrs \quad (4.17)$$

4.4.4.5 The Economics of the System

Using HOMER software payback period and return on investment was calculated by comparing different system. From the simulations result our system has a simple payback of about 4.32 years and a return on investment of about 19.8%



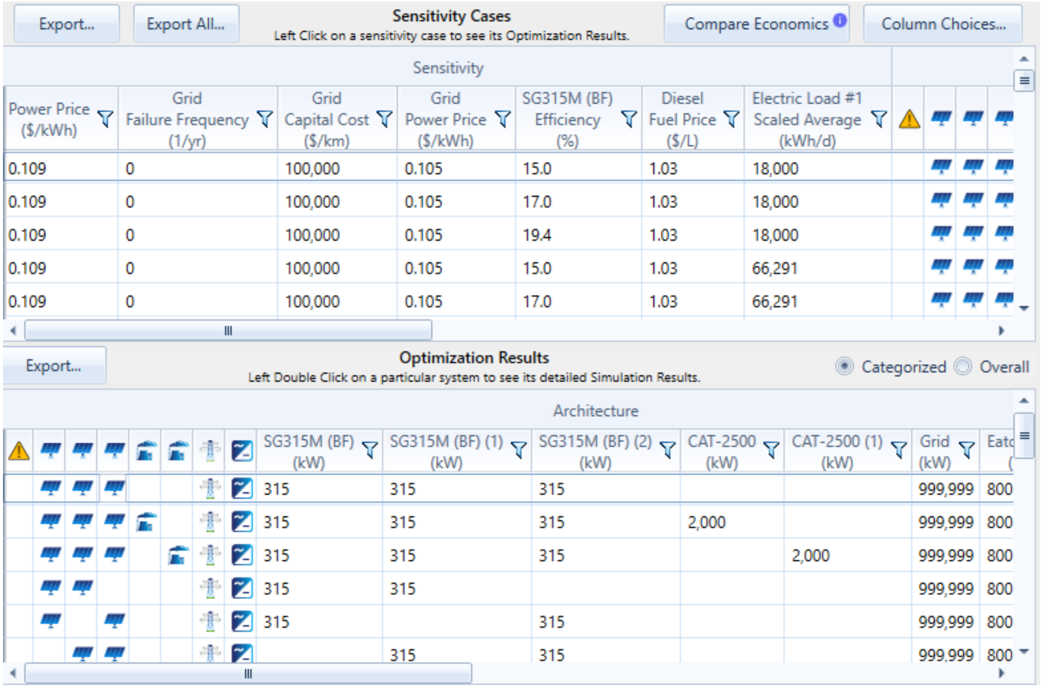
	Architecture						
	SG315M (BF) (kW)	SG315M (BF) (1) (kW)	SG315M (BF) (2) (kW)	CAT-2500 (kW)	CAT-2500 (1) (kW)	Grid (kW)	Eator (k
Base system	315					999,999	800
Current system	315	315	315			999,999	800

Metric	Value
Present worth ($)	$820,826
Annual worth ($/yr)	$63,494
Return on investment (%)	19.8
Internal rate of return (%)	23.1
Simple payback (yr)	4.32
Discounted payback (yr)	5.13

Figure 4.25: The Economics of the Solar PV, Grid Hybrid System

4.4.4.6 Sensitivity Analysis

The result in figure 4.26 shows that the least cost (feasible system) is the Grid – solar PV combination while the least feasible is the is the grid – thermal (generator) combination. The ranking is based on the initial capital cost, operating cost, and total net present cost.



Sensitivity Cases

Left Click on a sensitivity case to see its Optimization Results.

Sensitivity

Power Price ($/kWh)	Grid Failure Frequency (1/yr)	Grid Capital Cost ($/km)	Grid Power Price ($/kWh)	SG315M (BF) Efficiency (%)	Diesel Fuel Price ($/L)	Electric Load #1 Scaled Average (kWh/d)
0.109	0	100,000	0.105	15.0	1.03	18,000
0.109	0	100,000	0.105	17.0	1.03	18,000
0.109	0	100,000	0.105	19.4	1.03	18,000
0.109	0	100,000	0.105	15.0	1.03	66,291
0.109	0	100,000	0.105	17.0	1.03	66,291

Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

Architecture

SG315M (BF) (kW)	SG315M (BF) (1) (kW)	SG315M (BF) (2) (kW)	CAT-2500 (kW)	CAT-2500 (1) (kW)	Grid (kW)	Eat
315	315	315			999,999	800
315	315	315	2,000		999,999	800
315	315	315		2,000	999,999	800
315	315				999,999	800
315		315			999,999	800
	315	315			999,999	800

Figure 4.26: Sensitivity Analysis

4.4.4.7 Simple Payback Analysis

A simplified form of cost/benefit analysis is the simple payback technique. This method yields the number of years required for the improvement to pay for itself.

$$Simple\ payback\ time = \frac{Cost\ of\ the\ system}{Annual\ savings}\ , years \qquad (4.18)$$

The total Cost of the PV system was taken as Ksh.180,000 /Kw

Total cost = Ksh.180,000 X 1000Kw = Ksh.180,000,000.00

$$Payback\ time = \frac{180{,}000{,}000}{30{,}202{,}588.8} = 5.95\ yrs \qquad (4.19)$$

As shown above, the HOMER Pro was used extensively as a tool for simulating and optimizing different energy systems in the two data centers. The software allows more flexibility in defining loads, system architectures, energy sources and delivery strategies. HOMER software makes simulation and optimization relatively straightforward, but designers must consider data and logical assumptions to get meaningful results. Cost results can be significantly improved when designers obtain component costs from manufacturers and suppliers.

4.4.4.8 Impact of Renewable Energy on PUE

Data Center III was used to investigate the impact of renewable energy on PUE and hence the data center efficiency. For instance, the building power demand for data center three from the previous computation was 2555.92kW. With the introduction of 1000kW of solar energy reduces the power to 1555.92kW. Hence, the new PUE now becomes:

$$PUE = \frac{Total\ building\ Power\ (Kw)}{IT\ Equipment\ Power\ (Kw)} = \frac{1555.92}{1002.00} = 1.55 \quad (4.10)$$

Equation 45 shows PUE that the PUE for data center three has reduced from 2.55 to 1.55.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

This study analyzed several recently developed and readily accessible data center technologies for cooling and power. It was observed that different technologies adopted for cooling and power have significant impact on PUE and hence energy efficiency of the data center under the study. Thermal environmental performance was also investigated. Several factors such as floor tile opening ration, rack power density and rack location with respect to air-conditioning equipment were observed to significant affect the thermal performance of the data centers.

Enhancing energy efficiency is essential to lowering operating expenses as well as enabling a growth of data center industry. This can be achieved by reducing energy consumption of servers which was observed to have a linear relationship with CPU and memory utilization by designing next generation networks on virtual memory system that can manage physical memory resources while running to enhance energy efficiency of the servers.

In a nutshell, data center energy use optimization involves getting it right during the initial stage of planning, designing and implementation. As described above, the PUE values can drastically be improved if the correct solution for both power and cooling is selected. For instance, data center three PUE was improved from 2.55 to 1.6 when centralized chiller system was used in place of direct expansion units. Similarly, the PUE values for data center one and two was improved from 2.51 and 2.48 to 1.8 and 1.86 respectively, when modular UPS system was selected with a loading factor of 100%.

In addition, the use of renewable energy as an alternative source of energy has a huge impact not only on the operation cost but also on the energy efficiency as shown in the above analysis. This can be supported by the fact that Kenya has sufficient renewable resources that can support the possible electricity demand of data centers in Kenya

The study will be very useful to current and upcoming data center industries on the opportunities and ways to achieve optimal performance, reduction of operation cost and carbon footprint contribution to the environment hence compacting the climate change and achieving the environmental, social and governance (ESG) requirement.

It is advised that metering and monitoring systems be established for all energy-consuming devices coupled with a thorough dashboard to provide environmental data and data related to energy efficiency, including end-user power breakdown by the various IT components, power chain, and infrastructure power usage. Data center operator should also consider integrating their power sources with renewable energy sources such as solar photovoltaic system to reduce their operation cost and increase their PUE. Simulation of the cost benefit for the RES was done as illustrated in chapter four. However, the cost results can be improved greatly if the designer obtains the cost of components from the manufacturers and suppliers.

REFERENCES

Andy L. (2019, May 15). *Is PUE actually going UP?* Uptime Institute. https://journal.uptimeinstitute.com/is-pue-actually-going-up/

Brandon A R. (2010). *Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), 2010 12th IEEE Intersociety Conference on : date, 2-5 June 2010.* IEEE.

Capozzoli, A., & Primiceri, G. (2015). Cooling systems in data centers: State of art and emerging technologies. *Energy Procedia*, *83*, 484–493. https://doi.org/10.1016/j.egypro.2015.12.168

Dayarathna, M., Wen, Y., & Fan, R. (2016). Data center energy consumption modeling: A survey. *IEEE Communications Surveys and Tutorials*, *18*(1), 732–794. https://doi.org/10.1109/COMST.2015.2481183

Dunlap, K., & Rasmussen, N. (2012). *Choosing Between Room, Row, and Rack-based Cooling for Data Centers Revision 2*.

Energy Star. (2016). *Replace Standard Fans with Variable Speed Fans*.

Gao, C., Yu, Z., & Wu, J. (2015). Investigation of airflow pattern of a typical data center by CFD simulation. *Energy Procedia*, *78*, 2687–2693. https://doi.org/10.1016/j.egypro.2015.11.350

Gento. (2017, October 31). *Types of Data Center Cooling Techniques*. https://www.raritan.com/ap/blog/detail/types-of-data-center-cooling-techniques

Howard. (2020, May 27). *Things You Should Know About Data Center Power System*. FS Community. https://community.fs.com/blog/things-you-should-know-about-data-center-power-system.html

IBM Cloud Education. (2020, January 24). *Data Centers*. https://www.ibm.com/cloud/learn/data-centers?mhsrc=ibmsearch_a&mhq=data%20center

Kevin H. (2015, July 30). *A Look at Data Center Cooling Technologies*. Uptime Institute. https://journal.uptimeinstitute.com/a-look-at-data-center-cooling-technologies/

Martin, P. (2018, August 14). *The History of Data Centers*. Neterra Cloud. https://blog.neterra.cloud/en/the-history-of-data-centers/comment-page-1/

Pärssinen, M. (2016). *Analysis and Forming of Energy Efficiency and GreenIT Metrics Framework for Sonera Helsinki Data Center HDC*. www.aalto.fi

Rahaman, A., Noor, K. N., Abir, T. A., Rana, S., & Ali, M. (2021). Design and Analysis of Sustainable Green Data Center with Hybrid Energy Sources. *Journal of Power and Energy Engineering*, *09*(07), 76–88. https://doi.org/10.4236/jpee.2021.97006

Raritan. (2016). *Data Center Power Distribution and Capacity Planning: Understanding Power Usage in Your Data Center*.

Rickard Brännvall, J. S. (2016). *Proceedings of the Nineteenth InterSociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems : ITherm 2020 : ITherm virtual conference, July 21-23, 2020 (originally scheduled for May 26-29, 2020), Walt Disney World, Orlando, FL, USA*.

Sawyer, R. L. (2016). *Making Large UPS Systems More Efficient Revision 3*.

Sverdlik. (2020, February 27). *Study: Data Centers Responsible for 1 Percent of All Electricity Consumed Worldwide*. Data Center Knowledge. https://www.datacenterknowledge.com/energy/study-data-centers-responsible-1-percent-all-electricity-consumed-worldwide

VanGeet, O. (2011). *Best Practices Guide for Energy-Efficient Data Center Design: Revised March 2011, Federal Energy Management Program (FEMP) (Brochure)*. http://www.thegreengrid.org/en/Global/Content/white-papers/ERE.

Yole. (2015). *From Technologies to Market Sample From Technologies to Market New technologies & architectures for efficient Data Centers*. www.yole.fr

Zhou, Q., Lou, J., & Jiang, Y. (2019). Optimization of energy consumption of green data center in e-commerce. *Sustainable Computing: Informatics and Systems*, *23*, 103–110. https://doi.org/10.1016/j.suscom.2019.07.008

APPENDICES

Appendix A

Table A-1: Power Distribution of DC1 IT Equipment

Location	**Sub-System**	**Equipment**	**Power Density**	**Quantity**	**Sub-Total (KW)**
Telco Room A	N/A	Telco Racks	1.2KW	1	1.2
Telco Room B	N/A	Telco Racks	1.5KW	2	3
Customer Room	POD 1	Server Racks	3KW	22	66
	POD 2	Server Racks	3KW	22	66
	POD 3	Server Racks	3KW	22	66
	POD 4	Server Racks	3KW	22	66
Total (KW)					269.4

Table A-2: Power Distribution of DC1 Air-condition Equipment

Location	**Equipment**	**Power Density**	**Quantity**	**Sub-Total (KW)**
Telco Room A	Split Unit Air-Con	1.5KW	1	1.5
Telco Room B	Split Unit Aircon	1.5KW	1	1.5
UPS Room A	Close Control In-row Unit	18.33KW	1	18.33
UPS Room B	Close Control In-row Unit	18.33KW	1	18.33
Voltage Stabilizer Room A	Close Control In-row Unit	24.87KW	1	24.87

Voltage Stabilizer Room A	Close Control In-row Unit	24.87KW	1	24.87
Whitespace Room	Close Control In-row Unit	18.3KW	11	201.64
Sub-Total				**291.04KW**

Table A-3: Power Distribution of DC1 Other Critical Loads

Location	**Equipment**	**Consumption**	**Quantity**	**Sub-Total (KW)**
Generator	Generator Control Panel	5KW	1	5
Generator	Main Control Panel	5KW	1	5
Offices	Small Power and Lighting	15Kw	1	15
Sub-Total				**25KW**

Table A-4: DC1 Distribution Losses

Location	**Equipment**	**Consumption**	**Quantity**	**Sub-Total (KW)**
Others	UPS Inefficiency (@96%)	$\frac{4}{100} X\ 360Kw = 14.4$	1	14.4
	UPS Recharge Load (As indicated in UPS Data Sheet)	54KW	1	54
	Non-Critical Loads	10KW	1	10
	Distribution Losses	15W	1	15
Sub-Total for C				**93.4KW**

Appendix B

Table B-1: Power Distribution of DC 2 IT Equipment

Location	**Sub-System**	**Equipment**	**Power Density**	**Quantity**	**Sub-Total (KW)**
Meet Me Room A	N/A	Telco Racks	1.5KW	7	10.5
Meet Me Room B	N/A	Telco Racks	1.5KW	7	10.5
Customer Room	POD 1	Server Racks	2.5KW	18	45
	POD 2	Server Racks	2.5KW	30	75
	POD 3	Server Racks	2.5KW	30	75
Private Suite	N/A	Server Racks	2.5KW	18	45
Total (KW)					**261**

Table B-2: Power Distribution of AC Equipment

Location	**Equipment**	**Power Density**	**Quantity**	**Sub-Total (KW)**
Meet Me Room A	Uniflair TDAV0921A Air-Con	11.8KW	1	11.8
Meet Me Room B	Uniflair TDAV0921A Air-Con	11.8KW	1	11.8
UPS ROOM A	Uniflair TDAV0921A Air-Con	11.8KW	2	23.6
LV Room 1	Uniflair SDAV0351A Air-Con	4.5KW	1	4.5
LV Room 2	Uniflair SDAV0351A Air-Con	4.5KW	1	4.5
Customer Room	Uniflair IDAV3822A Air-Con	39.9KW	4	159.6
Private Suite	Uniflair TDAV1321A Air-Con	16.4KW	2	32.8
Sub-Total				**248.6KW**

Table B-3: Power Distribution of Other Critical Loads

Location	Equipment	Consumption	Quantity	Sub-Total (KW)
Generator	Generator Control Panel	5KW	1	5
Generator	Main Control Panel	5KW	1	5
Generator	MCP Rooms Air-conditioning Units	1KW	2	2
Offices	Small Power and Lighting	15Kw	1	15
Sub-Total				**27KW**

Table B-4: Distribution Losses for DC 2

Location	Equipment	Consumption	Quantity	Sub-Total (KW)
Others	UPS Inefficiency (@95.5%)	$\frac{4.5}{100} X\ 400Kw =$ 18	1	18
	UPS Recharge Load (As indicated in UPS Data Sheet)	60KW	1	60
	Non-Critical Loads	20KW	1	20
	Distribution Losses (Taking 3% as an Assumption)	13.5W	1	13.5
Sub-Total				**111.5KW**

Appendix C

Table C-1: Power Distribution of IT Equipment for DC 3

Location	**Sub-System**	**Equipment**	**Power Density**	**Quantity**	**Sub-Total (KW)**
Meet Me Room A	N/A	Telco Racks	1.5KW	8	12
Customer Room	Basement Floor	Server Racks	3 KW	50	150
	First Floor	Server Racks	3 KW	100	300
	Second Floor	Server Racks	3 KW	110	330
	Third Floor	Server Racks	3 KW	70	210
Total (KW)					1,002.00

Table C-2: Power Distribution for other critical loads

Location	**Equipment**	**Consumption**	**Quantity**	**Sub-Total (KW)**
Generator	Generator Auxilliary	10KW	2	20
Offices	Small Power and Lighting	20Kw	1	20
Sub-Total				**40KW**

Table C-3: Power Distribution for air-conditioning equipment for DC 3

Location	Equipment		Power Density	Quantity	Sub-Total (KW)
Meet Me Rooms	1BF	Split Unit Air-Con	1.5KW	2	3
	1SF	Split Unit Aircon	1.5KW	2	3
	2ND	Split Unit Aircon	1.5KW	2	3
	3RD	Split Unit Aircon	1.5KW	2	3
UPS Rooms	1BF	Close Control DX Unit	22.8KW	2	45.6
	1SF	Close Control DX Unit	19.2KW	2	38.4
	2ND	Close Control DX Unit	14.1KW	2	28.2
	3RD	Close Control DX Unit	22.8KW	2	45.6
Stabilizer Rooms	A	Split Unit	1.5KW	2	3
	B	Split Unit	1.5KW	2	3
Whitespace Room	1BF	Close Control DX Unit	30KW	8	240
	1SF	Close Control DX Unit	30KW	8	240
	2ND	Close Control DX Unit	32.8KW	7	229.6
	3RD	Close Control DX Unit	35.04KW	8	280.32
Mechanical Ventilations	Ground Floor	VRF System	3	22.4	67.2
Sub-Total					**1232.92KW**

Table C-4: Distribution Losses for DC 3

Location	Equipment	Consumption	Quantity	Sub-Total (KW)
Others	UPS Inefficiency (@96%)	$\frac{4}{100} X\ 500Kw = 20$	2	40
	UPS Recharge Load (As indicated in UPS Data Sheet)	60KW	2	120
	Non-Critical Loads	10KW	1	10
	Distribution Losses	15W	1	15
	Horse Rail and Water Pumps	96KW	1	96
Sub-Total				**281KW**

Appendix D

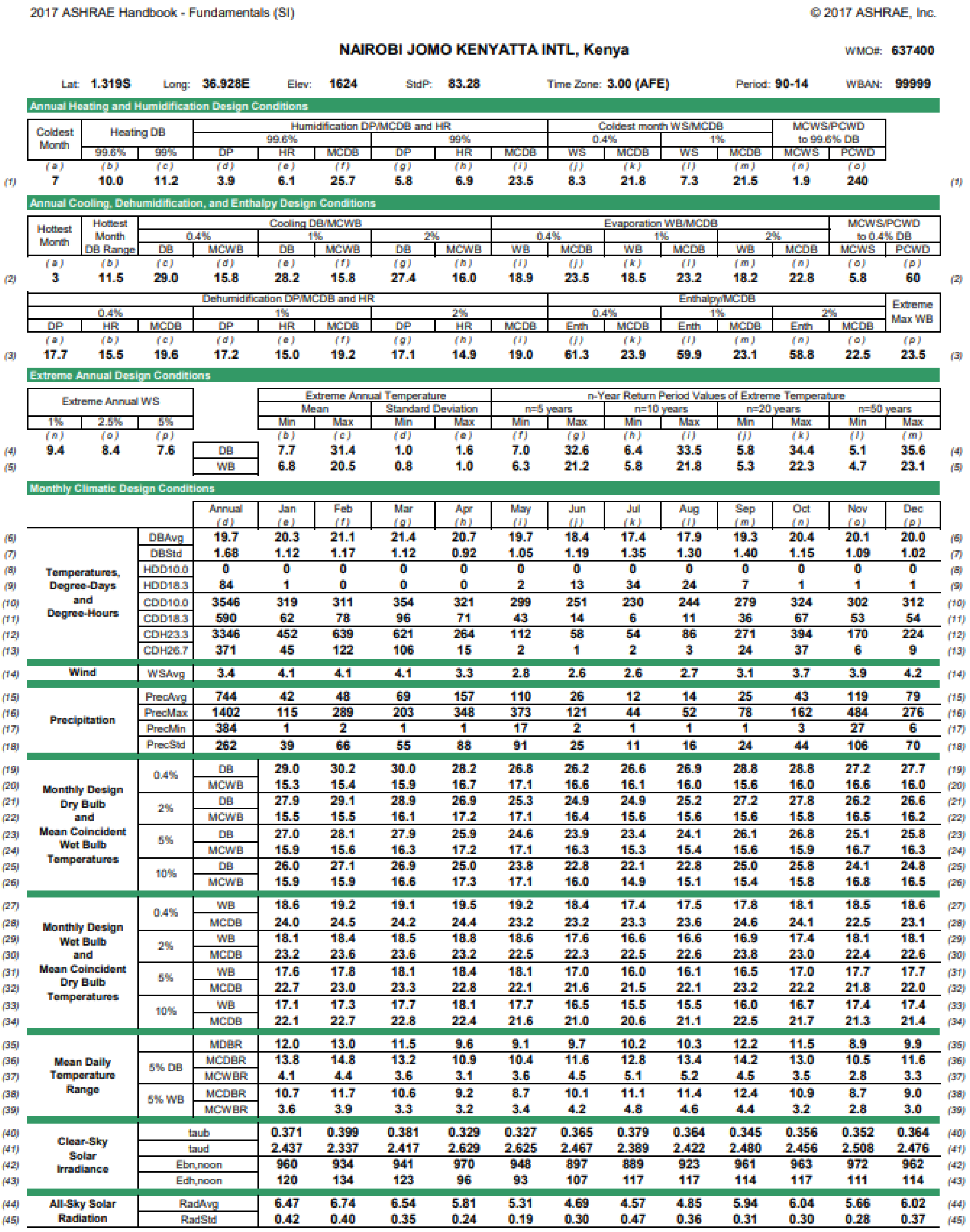
Table D-1: Load Profile for Data Center 2

Equipment	**Number**	**Load (Kw)**	**Total Load (Kw)**	**Usage (Hrs)**	**Total (kWhr)**
Telco Rack	4	1.5	6	24	144
Server Rack	88	3	264	24	6,336
UPS Losses & Recharge	N/A	136.8	136.8	24	3,283.2
Office Load (Lighting & Sockets)	N/A	15	15	8	120
Indoor Aircon Units	N/A	334.66	334.66	24	8,031.84
Mechanical Ventilation	N/A	15	15	8	120
Hydrant Pumps	1	7.5	7.5	2	15
Bollards	2	2.5	5	5	25
Borehole Pump	1	4.5	4.5	2	10
TOTAL					18,085.04

Table D-2: Load Profile for Data Center 3

Equipment	**Number**	**Load (Kw)**	**Total Load (Kw)**	**Usage (Hrs)**	**Total (kWhr)**
Network Rack	8	1.5	12	24	288
Server Rack	330	3	990	24	23,760
UPS Losses & Recharge	8	80	640	24	15,360
Office Load (Lighting & Sockets)	N/A	20	20	8	160
Indoor Aircon Units	N/A	1,165.72	1,165.72	24	27,977.28
Mechanical Ventilation	N/A	22.4	22.4	8	179.2
Hydrant Pumps & Water pumps	N/A	96	96	3	288
Bollards	2	5	10	5	50
Critical loads	N/A	20	20	24	480
TOTAL					68,542.48

Table D-3: ASHRAE Environmental Parameters



2017 ASHRAE Handbook - Fundamentals (SI)

NAIROBI JOMO KENYATTA INTL, Kenya

WMO#: **637400**

Lat: **1.319S** Long: **36.928E** Elev: **1624** StdP: **83.28** Time Zone: **3.00 (AFE)** Period: **90-14** WBAN: **99999**

Annual Heating and Humidification Design Conditions

	Coldest Month	Heating DB		Humidification DP/MCDB and HR						Coldest month WS/MCDB				MCWS/PCWD to 99.6% DB		
				99.6%			99%			0.4%		1%				
		99.6%	99%	DP	HR	MCDB	DP	HR	MCDB	WS	MCDB	WS	MCDB	MCWS	PCWD	
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	
(1)	7	10.0	11.2	3.9	6.1	25.7	5.8	6.9	23.5	8.3	21.8	7.3	21.5	1.9	240	(1)

Annual Cooling, Dehumidification, and Enthalpy Design Conditions

	Hottest Month	Hottest Month DB Range	Cooling DB/MCWB						Evaporation WB/MCDB						MCWS/PCWD to 0.4% DB		
			0.4%		1%		2%		0.4%		1%		2%				
			DB	MCWB	DB	MCWB	DB	MCWB	WB	MCDB	WB	MCDB	WB	MCDB	MCWS	PCWD	
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)	
(2)	3	11.5	29.0	15.8	28.2	15.8	27.4	16.0	18.9	23.5	18.5	23.2	18.2	22.8	5.8	60	(2)

	Dehumidification DP/MCDB and HR									Enthalpy/MCDB						Extreme Max WB	
	0.4%			1%			2%			0.4%		1%		2%			
	DP	HR	MCDB	DP	HR	MCDB	DP	HR	MCDB	Enth	MCDB	Enth	MCDB	Enth	MCDB		
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)	
(3)	17.7	15.5	19.6	17.2	15.0	19.2	17.1	14.9	19.0	61.3	23.9	59.9	23.1	58.8	22.5	23.5	(3)

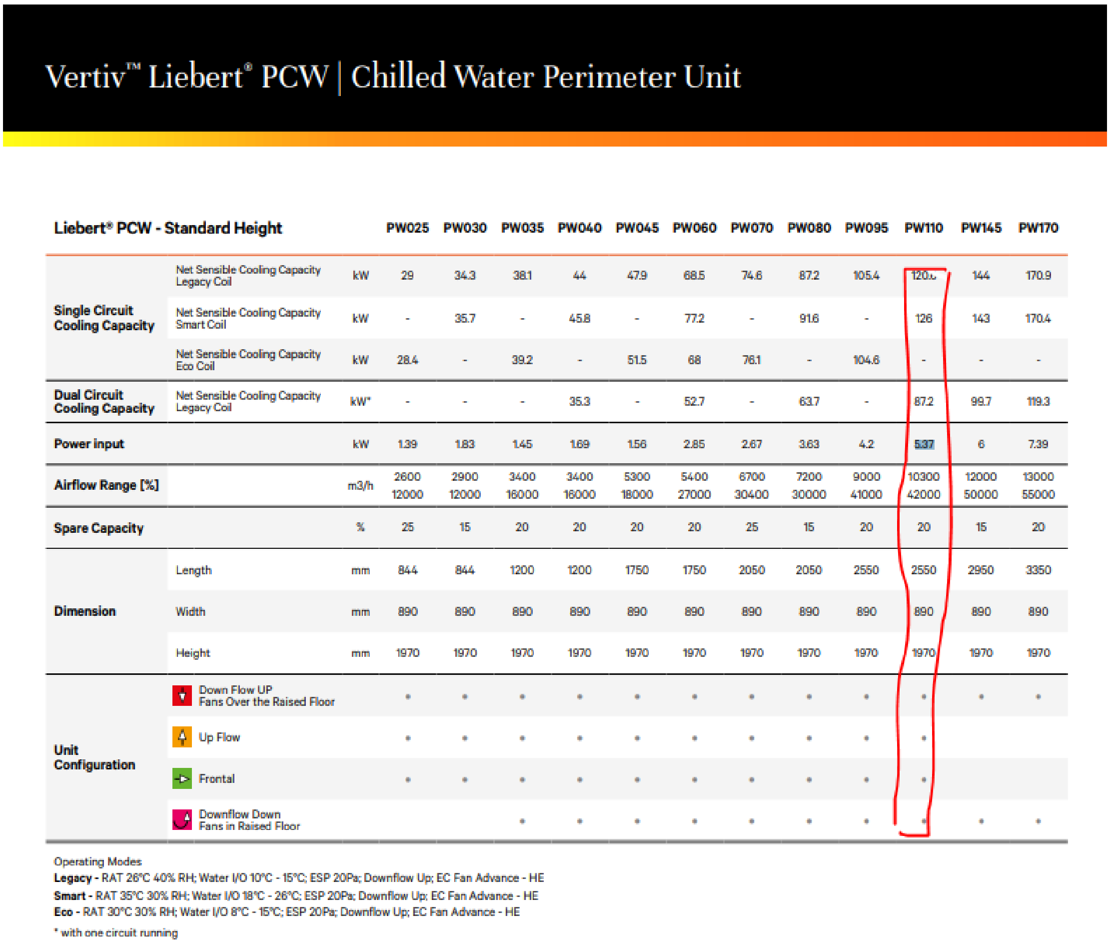
Extreme Annual Design Conditions

	Extreme Annual WS				Extreme Annual Temperature				n-Year Return Period Values of Extreme Temperature								
					Mean		Standard Deviation		n=5 years		n=10 years		n=20 years		n=50 years		
	1%	2.5%	5%		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	
	(n)	(o)	(p)		(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	
(4)	9.4	8.4	7.6	DB	7.7	31.4	1.0	1.6	7.0	32.6	6.4	33.5	5.8	34.4	5.1	35.6	(4)
(5)				WB	6.8	20.5	0.8	1.0	6.3	21.2	5.8	21.8	5.3	22.3	4.7	23.1	(5)

Monthly Climatic Design Conditions

			Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
			(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)	
(6)	**Temperatures, Degree-Days and Degree-Hours**	DBAvg	19.7	20.3	21.1	21.4	20.7	19.7	18.4	17.4	17.9	19.3	20.4	20.1	20.0	(6)
(7)		DBStd	1.68	1.12	1.17	1.12	0.92	1.05	1.19	1.35	1.30	1.40	1.15	1.09	1.02	(7)
(8)		HDD10.0	0	0	0	0	0	0	0	0	0	0	0	0	0	(8)
(9)		HDD18.3	84	1	0	0	0	2	13	34	24	7	1	1	1	(9)
(10)		CDD10.0	3546	319	311	354	321	299	251	230	244	279	324	302	312	(10)
(11)		CDD18.3	590	62	78	96	71	43	14	6	11	36	67	53	54	(11)
(12)		CDH23.3	3346	452	639	621	264	112	58	54	86	271	394	170	224	(12)
(13)		CDH26.7	371	45	122	106	15	2	1	2	3	24	37	6	9	(13)
(14)	**Wind**	WSAvg	3.4	4.1	4.1	4.1	3.3	2.8	2.6	2.6	2.7	3.1	3.7	3.9	4.2	(14)
(15)	**Precipitation**	PrecAvg	744	42	48	69	157	110	26	12	14	25	43	119	79	(15)
(16)		PrecMax	1402	115	289	203	348	373	121	44	52	78	162	484	276	(16)
(17)		PrecMin	384	1	2	1	1	17	2	1	1	1	3	27	6	(17)
(18)		PrecStd	262	39	66	55	88	91	25	11	16	24	44	106	70	(18)
(19)	**Monthly Design Dry Bulb and Mean Coincident Wet Bulb Temperatures**	0.4%	DB	29.0	30.2	30.0	28.2	26.8	26.2	26.6	26.9	28.8	28.8	27.2	27.7	(19)
(20)			MCWB	15.3	15.4	15.9	16.7	17.1	16.6	16.1	16.0	15.6	16.0	16.6	16.0	(20)
(21)		2%	DB	27.9	29.1	28.9	26.9	25.3	24.9	24.9	25.2	27.2	27.8	26.2	26.6	(21)
(22)			MCWB	15.5	15.5	16.1	17.2	17.1	16.4	15.6	15.6	15.6	15.8	16.5	16.2	(22)
(23)		5%	DB	27.0	28.1	27.9	25.9	24.6	23.9	23.4	24.1	26.1	26.8	25.1	25.8	(23)
(24)			MCWB	15.9	15.6	16.3	17.2	17.1	16.3	15.3	15.4	15.6	15.9	16.7	16.3	(24)
(25)		10%	DB	26.0	27.1	26.9	25.0	23.8	22.8	22.1	22.8	25.0	25.8	24.1	24.8	(25)
(26)			MCWB	15.9	15.9	16.6	17.3	17.1	16.0	14.9	15.1	15.4	15.8	16.8	16.5	(26)
(27)	**Monthly Design Wet Bulb and Mean Coincident Dry Bulb Temperatures**	0.4%	WB	18.6	19.2	19.1	19.5	19.2	18.4	17.4	17.5	17.8	18.1	18.5	18.6	(27)
(28)			MCDB	24.0	24.5	24.2	24.4	23.2	23.2	23.3	23.6	24.6	24.1	22.5	23.1	(28)
(29)		2%	WB	18.1	18.4	18.5	18.8	18.6	17.6	16.6	16.6	16.9	17.4	18.1	18.1	(29)
(30)			MCDB	23.2	23.6	23.6	23.2	22.5	22.3	22.5	22.6	23.8	23.0	22.4	22.6	(30)
(31)		5%	WB	17.6	17.8	18.1	18.4	18.1	17.0	16.0	16.1	16.5	17.0	17.7	17.7	(31)
(32)			MCDB	22.7	23.0	23.3	22.8	22.1	21.6	21.5	22.1	23.2	22.2	21.8	22.0	(32)
(33)		10%	WB	17.1	17.3	17.7	18.1	17.7	16.5	15.5	15.5	16.0	16.7	17.4	17.4	(33)
(34)			MCDB	22.1	22.7	22.8	22.4	21.6	21.0	20.6	21.1	22.5	21.7	21.3	21.4	(34)
(35)	**Mean Daily Temperature Range**		MDBR	12.0	13.0	11.5	9.6	9.1	9.7	10.2	10.3	12.2	11.5	8.9	9.9	(35)
(36)		5% DB	MCDBR	13.8	14.8	13.2	10.9	10.4	11.6	12.8	13.4	14.2	13.0	10.5	11.6	(36)
(37)			MCWBR	4.1	4.4	3.6	3.1	3.6	4.5	5.1	5.2	4.5	3.5	2.8	3.3	(37)
(38)		5% WB	MCDBR	10.7	11.7	10.6	9.2	8.7	10.1	11.1	11.4	12.4	10.9	8.7	9.0	(38)
(39)			MCWBR	3.6	3.9	3.3	3.2	3.4	4.2	4.8	4.6	4.4	3.2	2.8	3.0	(39)
(40)	**Clear-Sky Solar Irradiance**	taub		0.371	0.399	0.381	0.329	0.327	0.365	0.379	0.364	0.345	0.356	0.352	0.364	(40)
(41)		taud		2.437	2.337	2.417	2.629	2.625	2.467	2.389	2.422	2.480	2.456	2.508	2.476	(41)
(42)		Ebn,noon		960	934	941	970	948	897	889	923	961	963	972	962	(42)
(43)		Edh,noon		120	134	123	96	93	107	117	117	114	117	111	114	(43)
(44)	**All-Sky Solar Radiation**	RadAvg		6.47	6.74	6.54	5.81	5.31	4.69	4.57	4.85	5.94	6.04	5.66	6.02	(44)
(45)		RadStd		0.42	0.40	0.35	0.24	0.19	0.30	0.47	0.36	0.31	0.30	0.28	0.37	(45)

Table D-4: Chilled Water Perimeter Unit



Vertiv™ Liebert® PCW | Chilled Water Perimeter Unit

Liebert® PCW - Standard Height			PW025	PW030	PW035	PW040	PW045	PW060	PW070	PW080	PW095	PW110	PW145	PW170
Single Circuit Cooling Capacity	Net Sensible Cooling Capacity Legacy Coil	kW	29	34.3	38.1	44	47.9	68.5	74.6	87.2	105.4	120.[illegible]	144	170.9
	Net Sensible Cooling Capacity Smart Coil	kW	-	35.7	-	45.8	-	77.2	-	91.6	-	126	143	170.4
	Net Sensible Cooling Capacity Eco Coil	kW	28.4	-	39.2	-	51.5	68	76.1	-	104.6	-	-	-
Dual Circuit Cooling Capacity	Net Sensible Cooling Capacity Legacy Coil	kW*	-	-	-	35.3	-	52.7	-	63.7	-	87.2	99.7	119.3
Power input		kW	1.39	1.83	1.45	1.69	1.56	2.85	2.67	3.63	4.2	5.37	6	7.39
Airflow Range [%]		m3/h	2600 12000	2900 12000	3400 16000	3400 16000	5300 18000	5400 27000	6700 30400	7200 30000	9000 41000	10300 42000	12000 50000	13000 55000
Spare Capacity		%	25	15	20	20	20	20	25	15	20	20	15	20
Dimension	Length	mm	844	844	1200	1200	1750	1750	2050	2050	2550	2550	2950	3350
	Width	mm	890	890	890	890	890	890	890	890	890	890	890	890
	Height	mm	1970	1970	1970	1970	1970	1970	1970	1970	1970	1970	1970	1970
Unit Configuration	Down Flow UP Fans Over the Raised Floor		•	•	•	•	•	•	•	•	•	•	•	•
	Up Flow		•	•	•	•	•	•	•	•	•	•		
	Frontal		•	•	•	•	•	•	•	•	•	•		
	Downflow Down Fans in Raised Floor				•	•	•	•	•	•	•	•	•	•

Operating Modes

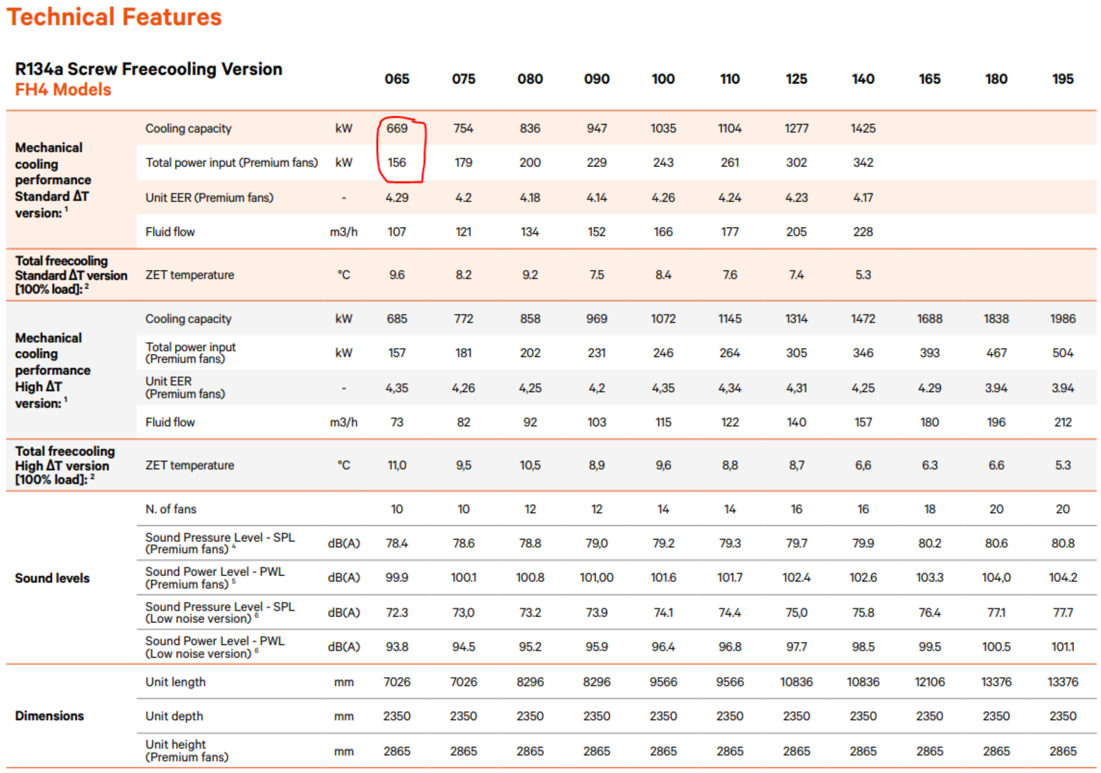
Legacy - RAT 26°C 40% RH; Water I/O 10°C - 15°C; ESP 20Pa; Downflow Up; EC Fan Advance - HE

Smart - RAT 35°C 30% RH; Water I/O 18°C - 26°C; ESP 20Pa; Downflow Up; EC Fan Advance - HE

Eco - RAT 30°C 30% RH; Water I/O 8°C - 15°C; ESP 20Pa; Downflow Up; EC Fan Advance - HE

* with one circuit running

Table D-5: Technical Data Sheets for the Centralized Chilled Water System.



Technical Features

R134a Screw Freecooling Version **FH4 Models**			**065**	**075**	**080**	**090**	**100**	**110**	**125**	**140**	**165**	**180**	**195**
Mechanical cooling performance Standard ΔT version: [1]	Cooling capacity	kW	669	754	836	947	1035	1104	1277	1425			
	Total power input (Premium fans)	kW	156	179	200	229	243	261	302	342			
	Unit EER (Premium fans)	-	4.29	4.2	4.18	4.14	4.26	4.24	4.23	4.17			
	Fluid flow	m3/h	107	121	134	152	166	177	205	228			
Total freecooling Standard ΔT version [100% load]: [2]	ZET temperature	°C	9.6	8.2	9.2	7.5	8.4	7.6	7.4	5.3			
Mechanical cooling performance High ΔT version: [1]	Cooling capacity	kW	685	772	858	969	1072	1145	1314	1472	1688	1838	1986
	Total power input (Premium fans)	kW	157	181	202	231	246	264	305	346	393	467	504
	Unit EER (Premium fans)	-	4,35	4,26	4,25	4,2	4,35	4,34	4,31	4,25	4.29	3.94	3.94
	Fluid flow	m3/h	73	82	92	103	115	122	140	157	180	196	212
Total freecooling High ΔT version [100% load]: [2]	ZET temperature	°C	11,0	9,5	10,5	8,9	9,6	8,8	8,7	6,6	6.3	6.6	5.3
Sound levels	N. of fans		10	10	12	12	14	14	16	16	18	20	20
	Sound Pressure Level - SPL (Premium fans) [4]	dB(A)	78.4	78.6	78.8	79,0	79.2	79.3	79.7	79.9	80.2	80.6	80.8
	Sound Power Level - PWL (Premium fans) [5]	dB(A)	99.9	100.1	100.8	101,00	101.6	101.7	102.4	102.6	103.3	104,0	104.2
	Sound Pressure Level - SPL (Low noise version) [6]	dB(A)	72.3	73,0	73.2	73.9	74.1	74.4	75,0	75.8	76.4	77.1	77.7
	Sound Power Level - PWL (Low noise version) [6]	dB(A)	93.8	94.5	95.2	95.9	96.4	96.8	97.7	98.5	99.5	100.5	101.1
Dimensions	Unit length	mm	7026	7026	8296	8296	9566	9566	10836	10836	12106	13376	13376
	Unit depth	mm	2350	2350	2350	2350	2350	2350	2350	2350	2350	2350	2350
	Unit height (Premium fans)	mm	2865	2865	2865	2865	2865	2865	2865	2865	2865	2865	2865

Appendix E

Interview Questions.

The following are interview questions for the data centre operators on the efficiency values and the capacity of their facility:

Q. What is the capacity of your campus?

Q. What is your current PUE value?

Q. You have plenty of cooling capacity, so why is your file-server area unevenly hot?
Q. Do you have any challenges in airflow movement through equipment racks?

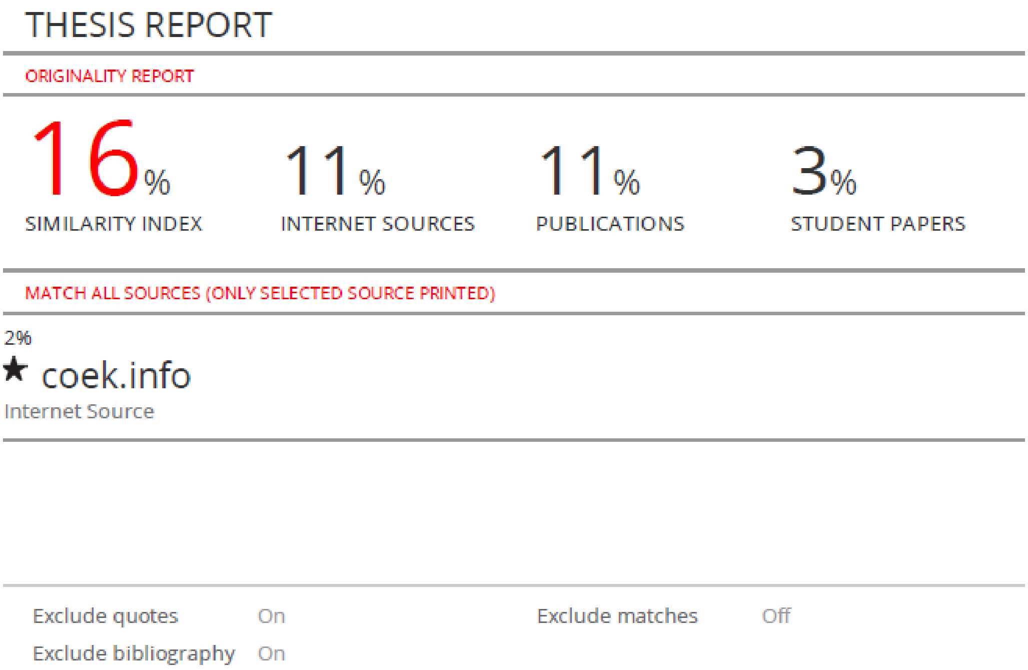
Q. Blade servers consume unprecedented amounts of power, all of which is converted to heat and must be managed. What impact will this new generation of products have ondata center?
Q. Does any particular arrangement of the equipment racks have a positive or negative effect on equipment reliability?

Q. Does your data centre have computational fluid dynamics (CFD) model analysis data?

Q. What is your arrangement and opening ration of your perforated floor tiles?

.

Appendix F: Similarity Index



THESIS REPORT

ORIGINALITY REPORT

16%	11%	11%	3%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

MATCH ALL SOURCES (ONLY SELECTED SOURCE PRINTED)

2%

★ coek.info

Internet Source

Exclude quotes	On	Exclude matches	Off
Exclude bibliography	On		