University of Nairobi

Faculty of Engineering

Energy Performance Analysis of Geothermal Drilling Rigs in Menengai, Nakuru

By

Muriga George

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Department of Mechanical and Manufacturing Engineering

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DECLARATION

A. Student's declaration

I confirm that this project is my work and has never been submitted to any other institution for examination or any other purpose.

Muriga George, F56/7533/2017

Signature...... Georg ....

Date.....July 26, 2022...............

B. Supervisor's declaration

I confirm that the above student carried out this project work under my supervision for the entire period of the project.

Dr. R. Kimilu

Signature...

Date........16/11/2022..............................

Dr. A. Aganda

Signature......[illegible] aganda...............

Date........16/11/2022......................

ACKNOWLEDGMENT

To challenge myself for self-actualization in the field of engineering is no mean feat and it would not have been possible without support from academicians, fellow engineers and family.

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ABBREVIATIONS AND ACRONYMS

AC	Alternating Current
BOP	Blow out Preventer
DC	Direct Current
DMM	Digital Multi Meter
GDC	Geothermal Development Company
GHE	Greenhouse gases emissions
HP	Horsepower
Hz	Frequency in Hertz
J, MJ, GJ	Joule, Mega-joule, Giga-joule
KenGen	Kenya Electricity Generating Company
KES	Kenya Shillings
kW_eh	Electrical Kilo Watt Hour
kW	Kilo Watt
kV	Kilo Volt
KP	Kenya Power & Lighting Company ltd.
LED	Light Emitting Diode
MCB	Main Circuit Board
MWe	Mega Watt Electric
PF	Power Factor
ROP	Rate of Penetration
SCR	Silicon Control Rectifier
UNEP	United Nations Environmental Program
USD	United States Dollar
V	Volt
W	Watt
WOB	Weight on Bit

ABSTRACT

Economics of drilling a geothermal well continues to be of great concern to drilling companies worldwide including KenGen and GDC in Kenya. Globally, focus has been placed on climate change, global warming, and the adverse effects of pollution caused by thermal fuels as a source of energy. A major uptake of renewable energy has been noted over the years globally where efforts are being placed in the research of wind, solar, nuclear, and geothermal energy utilization. Geothermal is a resource indigenous to particular regions such as Nakuru in Kenya due to the volcanic nature of the Great Rift Valley. In entirety, cost of utilizing geothermal energy, whose key activities involves exploration, drilling, and then power utilization; drilling is the single most expensive venture undertaken that costs up to six (6) million USD. There are many aspects that lead to the total cost of drilling a geothermal well whose primary source of energy is diesel. Obtaining the energy factor cost per unit well and then identifying measures to reduce this cost may save drilling companies substantial amounts of money spent on purchasing diesel, and further improve drilling efficiencies throughout its drilling time. Drilling companies worldwide have invested in the research of industry best practices. Studies have been made with the objective to increase drilling depth with the same energy input or lowering the energy input while obtaining the same drilling depth. In this study, power requirements necessary for the rig operations were addressed. Data obtained included historical records of the rig output, diesel consumed and depths of the well dug; and on-site real-time measurements. Real-time measuring equipment included rig instrumentation, and a digital multi-meter to compare with historical data. It was determined that a typical 2000HP rig would use about 540MWh per month if powered by electricity. With the current KP electricity tariffs as at 2019, it proved cheaper to continue purchasing diesel than to fuel-switch to electricity. Further, by use of the energy monitoring, targeting, and reporting tool, control limits of $\pm 250 GJ$ would be within reasonable range of drilling using optimum diesel energy supply. Comparison between historical data and real-time measurements resulted to a variation of ≈5%. Rate of return of cashflow economic analysis of the retrofit measures proposed had payback periods of less than or equal to three years with initial capital expenses not exceeding two million Kenya shillings. Simple housekeeping measures of switching lights off during daytime and low-cost periodic rig maintenance activities were also recommended. In addition; bidding for a more competitive diesel fuel supplier may offer a cheaper rate thus realizing savings that would otherwise have been accrued by the taxpayer.

Table of Contents

List of Figures

List of Tables

CHAPTER ONE: INTRODUCTION

1.1 Background

The problem of global warming has transcended to large scale issues such as power generation by burning fuel that cause acid rain, development and land use change, mercury pollution on third world countries, loss of biodiversity, and particularly depletion of earth‟s protective ozone layer that leads to climate change [1]. Environmentalists, scientists, politicians and all concerned stakeholders have formed regulatory international bodies that make policies and resolutions towards mitigating harmful effects caused towards our planet earth. In 1972, UNEP was formed in Stockholm after a conference deliberated on the impact of economic development and environmental degradation. The Earth Summit (Rio-de-Genaro) of 1992 was a historic event where several resolutions mainly involving sustainable utilization of natural resources to reduce pollution were made. The summit proposed several measures such as placing humanity at the center of concern, having minimum forest cover in a country amongst others. Additionally, the Kyoto Protocol of 2005 addressed Green House Emissions (GHE) by industrialized countries and measures to reduce it by 5% by 2012. Penalties if they do not meet their obligation as prescribed by Kyoto Protocol was to pay carbon credits to developing countries. Primary recommendations of these treaties were to promote renewable energy sources and sustainable energy consumption. [2]

In Kenya, energy is one of our major pillars of economic growth. As part of the energy development plan (2017–2037), Kenya has invested heavily in geothermal energy, with an installed capacity of about 663MW as of 2019 [3]. Energy poverty, which is the lack of access to modern fuels, plague parts of rural Kenya despite being endowed with renewable energy resources including wind, solar, and geothermal. Geothermal is poised to lead overall in Kenya‟s base power installed capacity. Geothermal power harnessing in Kenya is undertaken by KenGen and Geothermal Development Corporation (GDC). Drilling is the single most expensive venture in a geothermal project. It uses fossil fuel as energy source contradicting environmental measures by contributing to GHE.

Menengai is a massive shield volcano caldera located in Nakuru County. GDC has embarked on an ambitious strategy of producing 400 MWe of geothermal power in Menengai. This requires drilling about 120 wells[4]. Drilling such numbers of wells is an expensive venture, and any reduction of drilling costs can have a significant cost saving.

1.2 Problem Statement

In order to achieve vision 2030, the energy demand in Kenya is projected to increase at a rate of 7% per annum from current peak demand of 1,912MW as at 2019. According to geological surveys, Kenya"s geothermal resource potential is close to 10,000MW along its Rift Valley. There are about fourteen geothermal potential sites identified in the Kenyan rift valley region. Of these, two sites have already begun commercial utilization which are Olkaria and Menengai. Olkaria field is the single source of all the geothermal energy supplied to the national grid by KenGen translating to 663MWe. Menengai is the second field exploited by GDC whose projected output is 400MWe. From these deductions, geothermal energy is expected to be an essential resource in the future of the Kenyan power system.[3]

For geothermal energy to be utilized in the national grid, it must be mined from the ground through an activity known as drilling. Drilling uses an equipment known as a rig. The outcome of the rig after drilling is a wellbore. Drilling a well is tailored around an allotted budget and targeted depth. The costs of drilling become higher the deeper the well is dug and the number of days a rig spends on a site. Diesel fuel is spent running the generators continuously throughout the duration a rig spends on site.

There has been limited study aimed at obtaining the best possible energy mix between current use of diesel fossil fuel powering the rig and identifying energy measures likely to optimize the usage.

1.3 Objectives of the Study

Information sourced included energy requirements for drilling a single geothermal well then investigating on alternatives to fossil fuel, focusing on electricity obtained from geothermal or from the overall Kenyan grid system.

1.4 Specific Objectives

The following were the specific objectives of this study:

1. Identify and measure the rig energy consumption in terms of GJ per meter depth drilled and compare the data with other rigs on site.
2. Use the Energy Monitoring, Targeting, and Reporting tool to analyze historical trend for energy optimization
3. Identify what opportunities there may be for saving current diesel energy requirements
4. Perform a financial analysis on cost breakdown for the energy intervention measures identified

1.5 Study Limitations

Geothermal research associated with geoscientific exploration, socio-political economic surveys, financial funding, civil infrastructural outlays, commissioning and decommissioning of power plant projects are excluded from this study. Only conventional land rigs of 2000HP capacity were considered for the study. Focus was placed on the actual energy spent from beginning of drilling a well, called spud in, to the last completion day of drilling. All energy intensive activity before, such as rig up mobilization, and after, such as rig down demobilization and rig move to another site are not considered in the study. All historical data is as obtained only from Menengai geothermal field.

CHAPTER TWO: LITERATURE REVIEW

2.1 Drilling Rigs

Drilling is the most expensive venture in geothermal industry. All drilling activities undertaken focus on making the exercise as successful as possible. Drilling is undertaken using a rig. The drilling rig is a sophisticated machinery composed of several equipment performing various roles all connected to the drill bit that bores the ground to reach depths of between 2500 – 3000m as for the case of geothermal wells.

Before commencement of drilling, an advance drilling crew performs reconnaissance of the rig site called the well-pad. Engineers inspect the road and well-pad condition including the cellar where the rig sits a-top. Stability is their top concern followed by access route since the rig components are transported in parts whereby some are oversize, and heavy. Availability of water at the well-pad is also critical before deciding to move a rig to site.

Once a rig is brought to site in pieces, it is assembled in an activity known as rig-up. „Spud in‟ is a term used in drilling which is the moment the drill bit of the rig begins coring the ground. This activity is carried out throughout the drilling period until the target depth as advised by geo-scientists is hit. Afterwards, the rig is demobilized (rig-down) and moved to another site to conduct the same exercise.

The bit is the tool that does the actual drilling using two principles[5];

- Rock removal by exceeding its shear strength
- Removal by exceeding compressive strength

Shear failure involves use of the bit tooth cutting the rock to small pieces so it can be removed from beneath the rock bit. This mechanism is employed while drilling softer formations.

Compressive failure is used where there is hard formation since shearing wears the bit tooth as it is twisted or dragged across the subsurface. This drilling method requires that the load remain on the surface long enough for rock failure to occur, hence high bit weight and low rotary speeds.

Rigs are categorized as either marine or land.

2.1.1 Marine Rigs

Marine rigs are used offshore (in water) and could be anchored to the sea floor or could be on floating vessels. Marine rigs are solely for oil and gas industry and not for geothermal drilling. These offshore rigs have similarities to land rigs but with several additional features to adapt them to marine environment such as a heliport, living quarters, cranes and risers. A heliport, also known as the helipad, is a large deck area that is placed high and to the side of the offshore rig to aid helicopters land and fly off, as they are the main source of transport for rig crew. Living quarters are for the drilling crew inclusive of escape boats located nearby in case of emergency. Accessories such as cranes are used to move equipment and material from work boats onto the rig and also shift loads around the rig. A riser is used to extend the wellhead from the mudline to the surface. Marine rigs are classified into fixed production platform as shown in Figure 2 - 1or a Jack-up rig as shown in Fig 2-1.

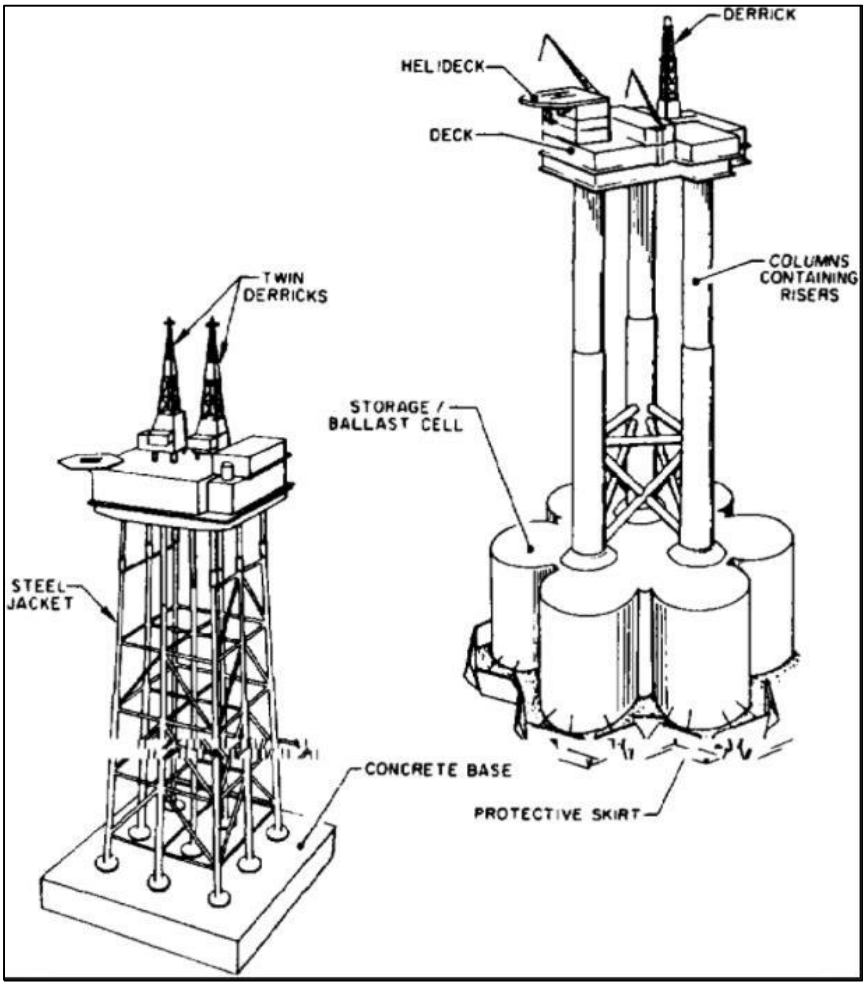


Figure 2 - 1: Fixed production platform [6]

Fixed platforms as shown in Fig. 2-1 are positioned over preset wellheads by jacking across on skid beams. After the wells are drilled, the rig is removed from the platform and transferred elsewhere.

Jack-up platforms as shown in Figure 2 - 2 have their support legs not permanently attached to the sea-floor, the weight of the rig is sufficient to keep it on location. The rig‟s legs can be jacked down to drill and jacked up to move to a new location; when under tow, floating hull buoys the Jack-up.

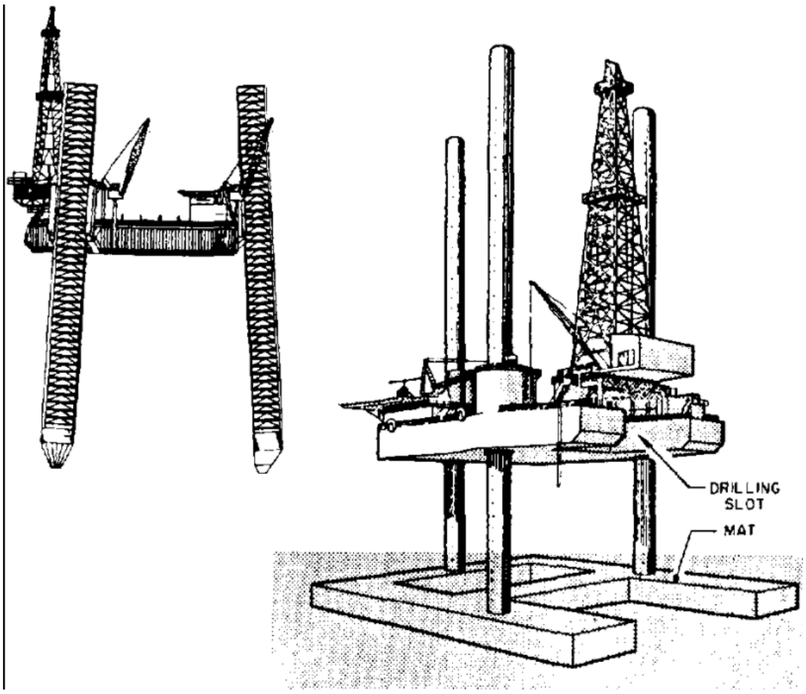


Figure 2 - 2: The Jack-up Marine Rig [6]

Submersible rigs such as shown in Figure 2 - 3 are designed to work in deeper waters and are anchored in place. The Pontoon type require towing while the twin hull types are self-propelled.

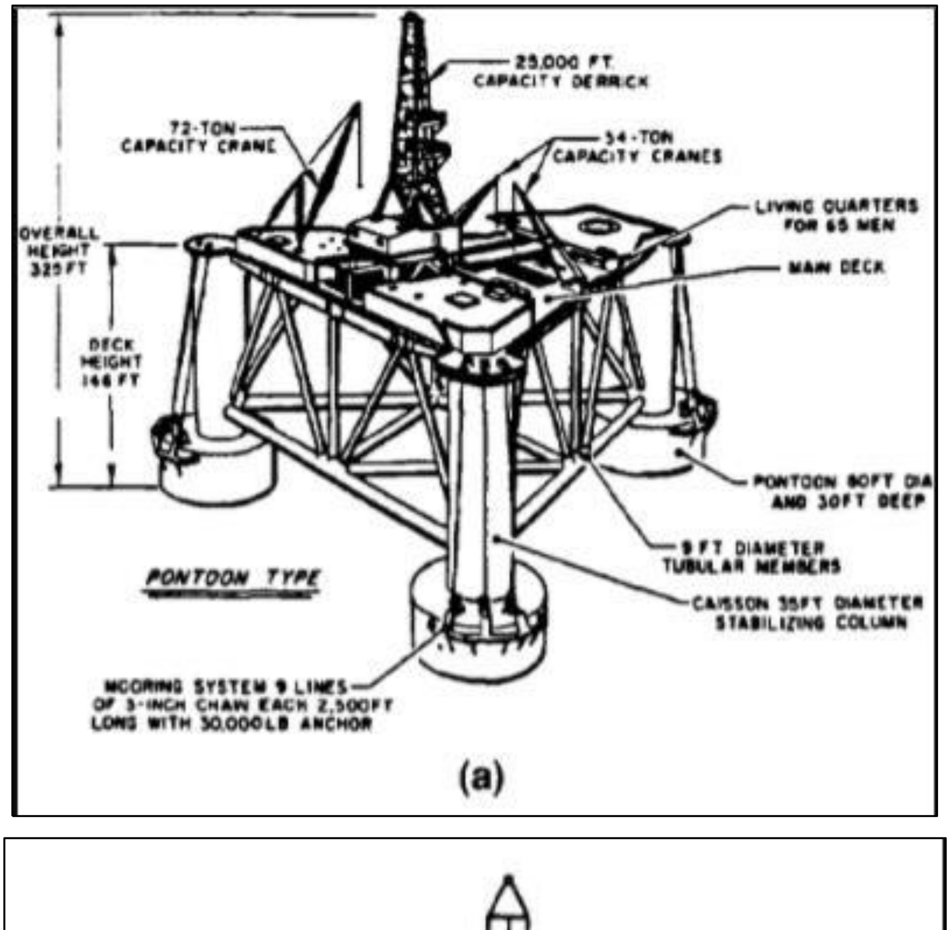


Figure 2 - 3: Semisubmersible rigs (a) Pontoon type (b) Twin hull [6]

Marine rigs can also be mounted on drill ships as shown in Figure 2 - 4. These are amenable for deep-sea drilling where anchoring is not feasible [6].

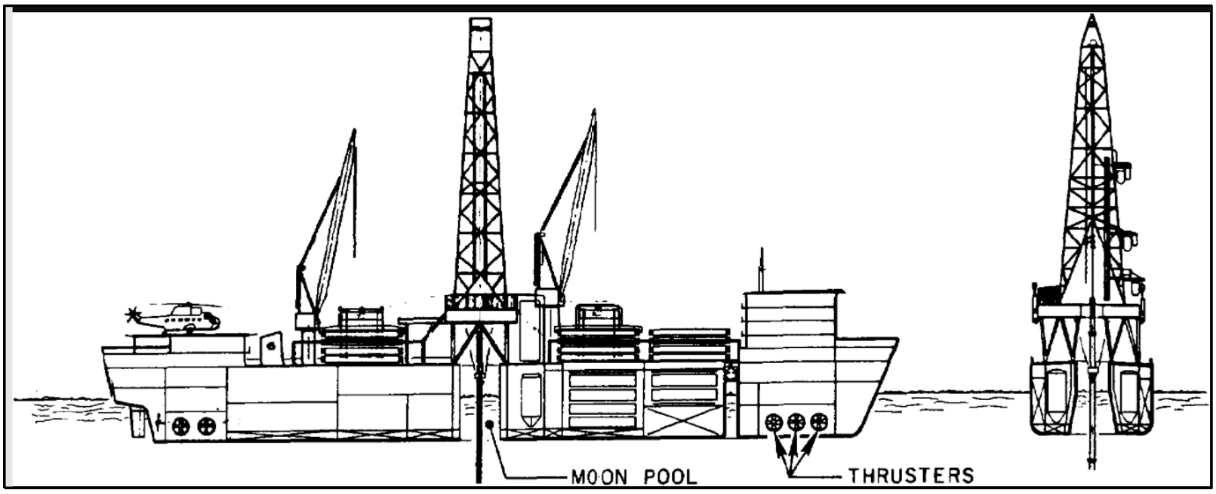


Figure 2 - 4: Dynamic positioning drill ship [6]

2.1.2 Land Rigs

Land rigs unlike their offshore counterparts‟ drill on the earth‟s surface and are the type used for geothermal drilling. They fall under two main categories: the standard derrick, and the portable rig. For the standard derrick type, the mast/ derrick is built on location and dismantled after the drilling process. The others are portable rigs mostly mounted on a truck for low rig up. Figure 2 - 5 show a typical conventional rig where the key components are bulky that they cannot be transported on a single truck bed as in Figure 2 - 6 [7].

Figure 2 - 5: Conventional land rig as found in Menengai

Figure 2 - 6: Truck mounted rig [5]

2.2 Overview of Drilling Process

Drilling is the actual breaking of the ground achieved by use of a rock bit. The bit is rotated under weight of the drill string and the entire bottom-hole assembly. A drill string serves to provide essential requirements for the bit to perform and is the connection between the rig and the bit[5]. The bit both crashes and gouges the rock as it rotates. The broken pieces arising from the bore are lifted by the circulation drilling fluid. This process continues until the well is completed at a targeted depth. For geothermal wells, depths are between 2000 – 3000m. For the rock bit to perform, it requires rotary motion, fluids such as water and/or air, and the force (weight) to crash the rocks.

2.3 Energy Distribution in a Typical Rig Equipment

Typical land rigs have seven distinct systems, which include:

1. Power and lighting system
2. Hoisting system
3. Circulating system
4. Rotary system
5. Blow out Preventer (BOP) system
6. Air drilling system
7. Auxiliary rig equipment

2.3.1 The Power and Lighting System

These consists of a prime mover, primarily diesel engines, and some means of transmitting power to the auxiliary equipment. Transmission may be in the form of mechanical drives like chains, DC generators and motors or AC generators, and Silicon Control Rectifiers (SCR) (Appendix Fig. 1-1), and DC motors.

Typical technical parameters for the main diesel generator found in the market would be;

- The type of generator
- Capacity in kVA

- Voltage, frequency and power factor of the generating set
- Number and power of the auxiliary diesel generating set
- Voltage and frequency of auxiliary diesel generating set
- Number and type of the direct current electrical motor
- Rated power of the direct current electrical motor
- Fuel load consumption

2.3.2 The Hoisting System

This is one of the major rig components responsible to supporting, lifting, and lowering rotating drill-string while drilling is in progress. Additionally, it consists of pneumatic hoisting systems at the rig floor for general equipment lifting. The hoisting system consists of;

I. Supporting structure such as the mast/derrick, the substructure and the rig floor.
II. Hoisting equipment [Figure 2 - 7] consisting the draw-works, crown-block, travelling block, hook, swivel, elevators links, Kelly, Kelly saver subs, and the drilling wire-line.

The draw-works is the major component of the hoisting system with the highest power input. It is used to complete the operation of tripping drill string in and out of the well, running casing with making up and breaking out tubular goods as well as controlling the drilling pressure, handling accidents, taking the core barrel and testing oil. Besides, it is used to complete the operation of raising and lowering the mast and the front and rear drill floors of the substructure during rig up and rig down process[8].

The draw-works as shown in Figure 2 - 8 is comprised of; (1) driller‟s console, (2) spinning cathead, (3) sand reel, (4) main drum, (5) hydromantic brake and, (6) manual brakes. Power consumed by the draw-works can be computed by considering the hook-load and the travelling speed. It is powered from the generator by means of the SCR through a step-down DC transformer.

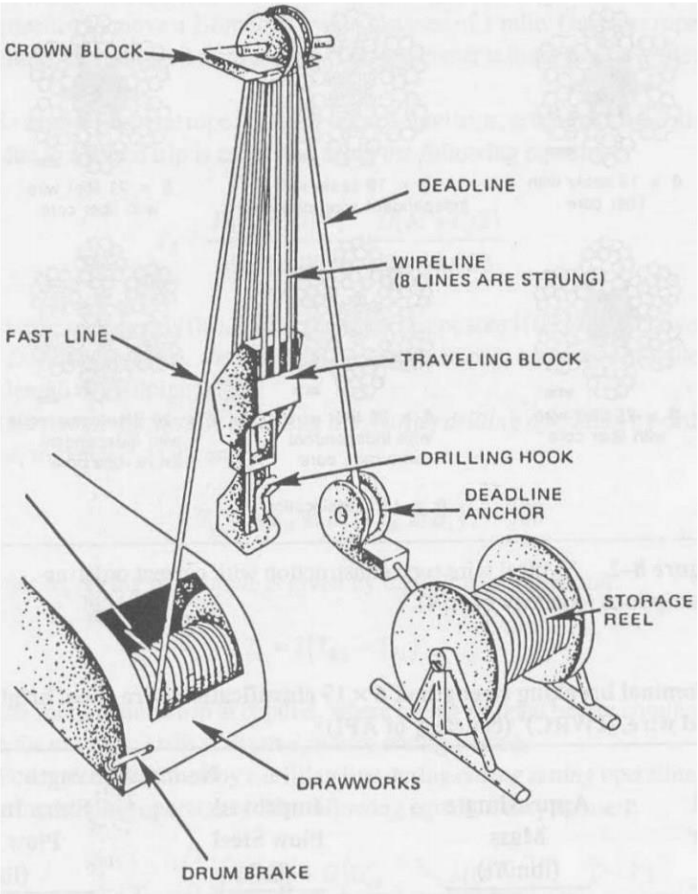


Figure 2 - 7: Hoisting system of a rig [8]

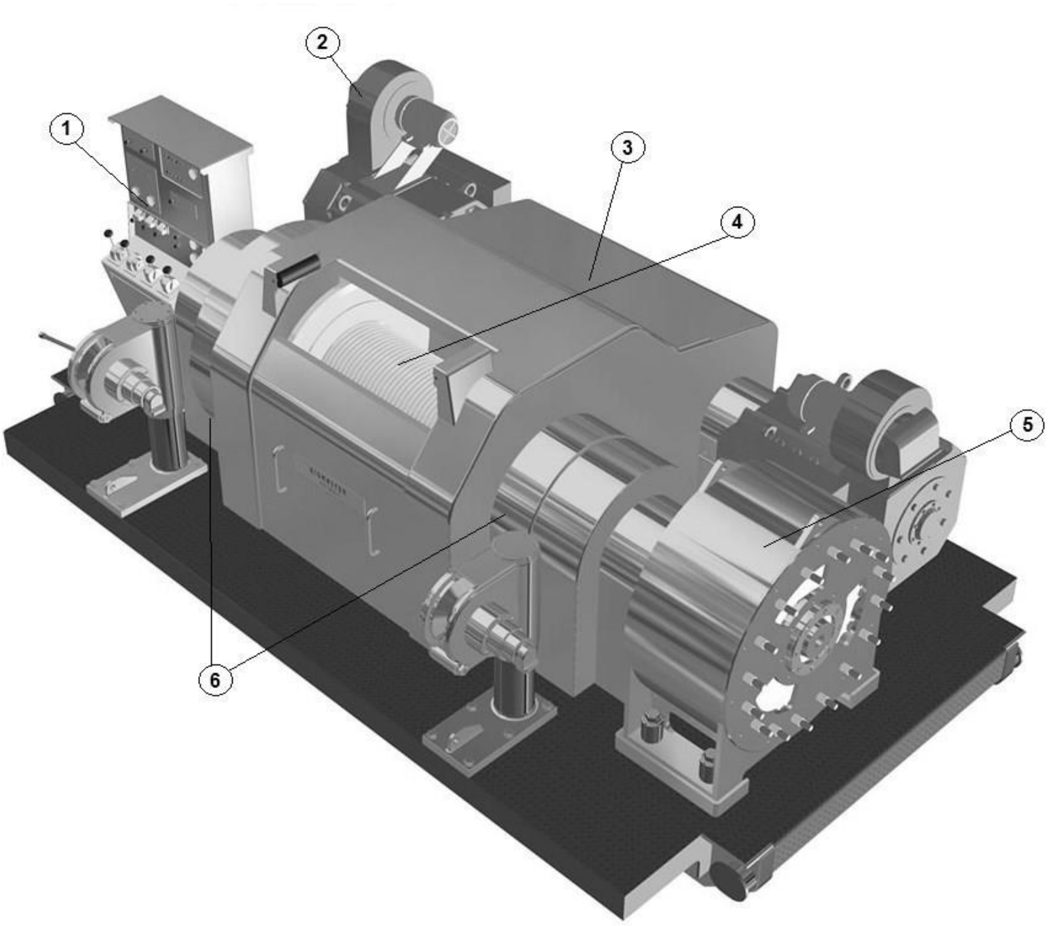


Figure 2 - 8: Draw-works [8]

2.3.3 The Circulation System

The circulation system ensures drilling fluid flows within the wellbore to the bit and back to the surface carrying rock cuttings. Circulation system consists of a set of pumps, standpipes, rotary hose, swivel, Kelly, drill-string, shale shakers, tanks and mud pits all shown in Figure 2 - 9.

The pumps are the critical energy components of the entire circulation system. They typically consist of DC electric motors, belt pulley with shaft, and the V belt transmission.

The shale shaker is a fine screen linear motion sieve. It is used to remove a large percentage of drill cuttings before the mud is circulated through the surface mud system leading to improved performance of downstream solid control equipment. The shale shaker performs two primary jobs: separate drilled solids from the mud and transport the solids rapidly and efficiently off the screens.

Mud pumps are used to pump large volumes of drilling fluid through the drill-string to the wellbore throughout the drilling process. Fluids are circulated using an axial reciprocating piston pump, whereby the driller could increase or decrease the oscillations depending on how much volume of drilling fluid is needed at a specific time of drilling. The axial piston in the pump moves fluid only in one direction, thus there are two parameters to measure the pump‟s performance, displacement and pressure. Figure 2 - 10 shows a set of three mud pumps at a drilling site.

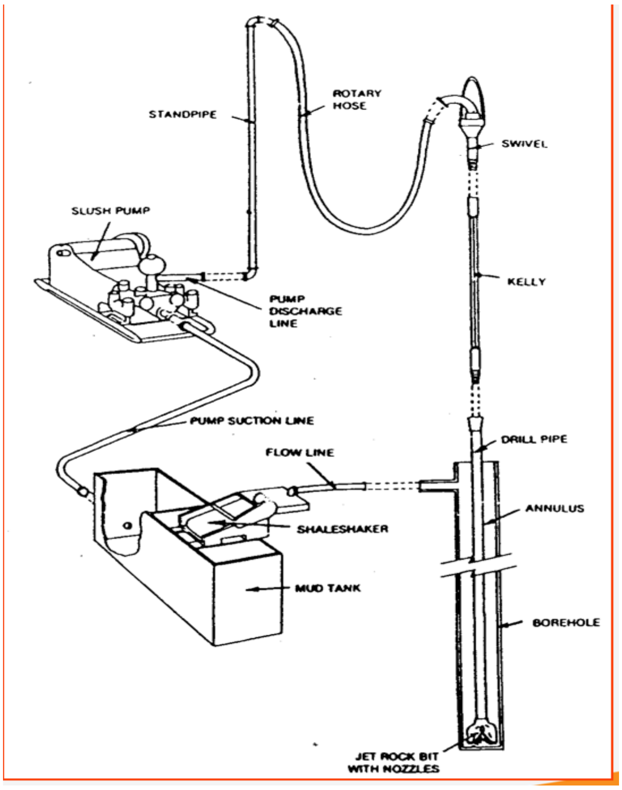


Figure 2 - 9: Circulation system [8]

Figure 2 - 10: Triplex mud pumps [Menengai]

Pump displacement is the volume of fluid which will be removed from the piston during every revolution while pump pressure is a function of the reservoir characteristics encountered in the wellbore during the course of drilling. The overall efficiency of a mud pump is the product of mechanical and the volumetric efficiency. Typical mechanical efficiencies of mud pumps is 90%.

2.3.4 The Rotary System

This system is responsible for the rotating action to the drill-string and bit. The main components are the Kelly, rotary table, and drive bushing, swivel rotary hose and drill-string. When the rotary table is working, it drives the Kelly bushing rotating drilling stem which hangs under the swivel [8]. Figure 2 - 11 shows a typical rotary system.

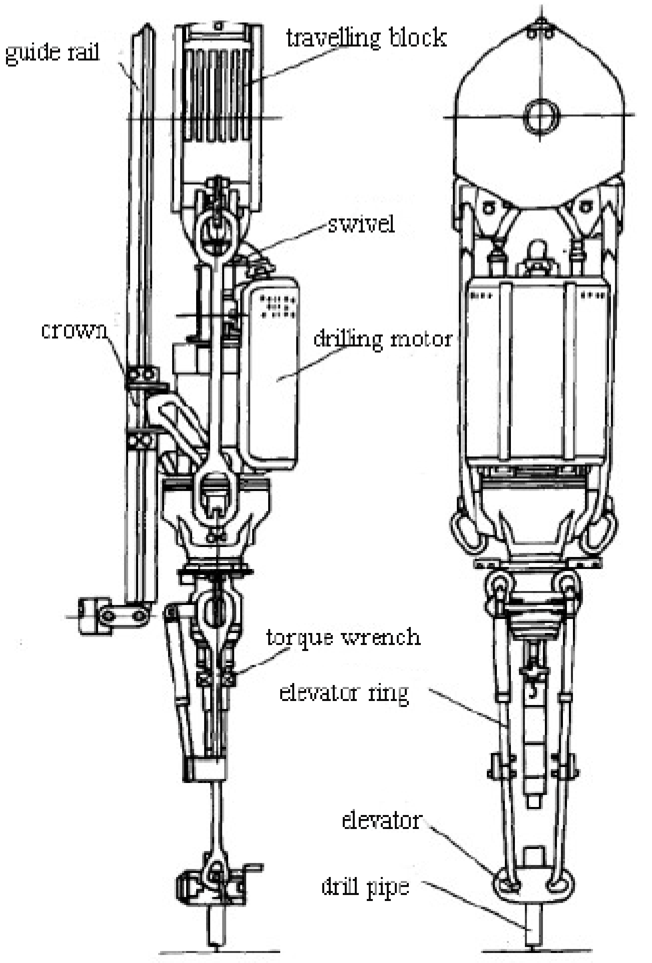


Figure 2 - 11: The rotary system [8]

2.3.5 The Blow out Preventer (BOP) System

The blowout preventer (BOP) is primarily used to seal the well to prevent uncontrolled flow, or blowout, of formation fluids. The system is comprised of drill-pipe or casing ram, blind ram and an accumulator system. It uses compressed hydraulic fluids to operate[8].

2.3.6 Air Drilling System

Air drilling is suitable for drilling oil and gas, and as well as geothermal wells. Atomized fluid with higher pressure is pumped into the stem and then to well bottom to enclose the fine rock debris generated by the shocking of air hammer. Force is applied at the surface by means of the air compressors through the annulus in order to dislodge the cuttings. The cuttings are guided into the scum handling pipe through the rotary blowout preventer located in the wellhead and finally into the mud pit through air-fluid separator.

Air drilling system has its own special equipment, including ground and wellhead equipment. The ground equipment includes air compressor, air dryer, booster, control valve set, atomizing pump skid, pneumatic pump skid, and ground manifolds, while the wellhead equipment includes rotary scum remover connected with blowout preventer, scum handling pipeline, special air-fluid separator, sampling pipeline and valves etc.

2.3.7 Auxiliary Rig Equipment

These are equipment that boost efficiency of drilling when combined to the draw-works, rotary, Kelly, swivel blocks, drilling line, bits and prime movers as shown in Figure 2 - 12 [5], [8].

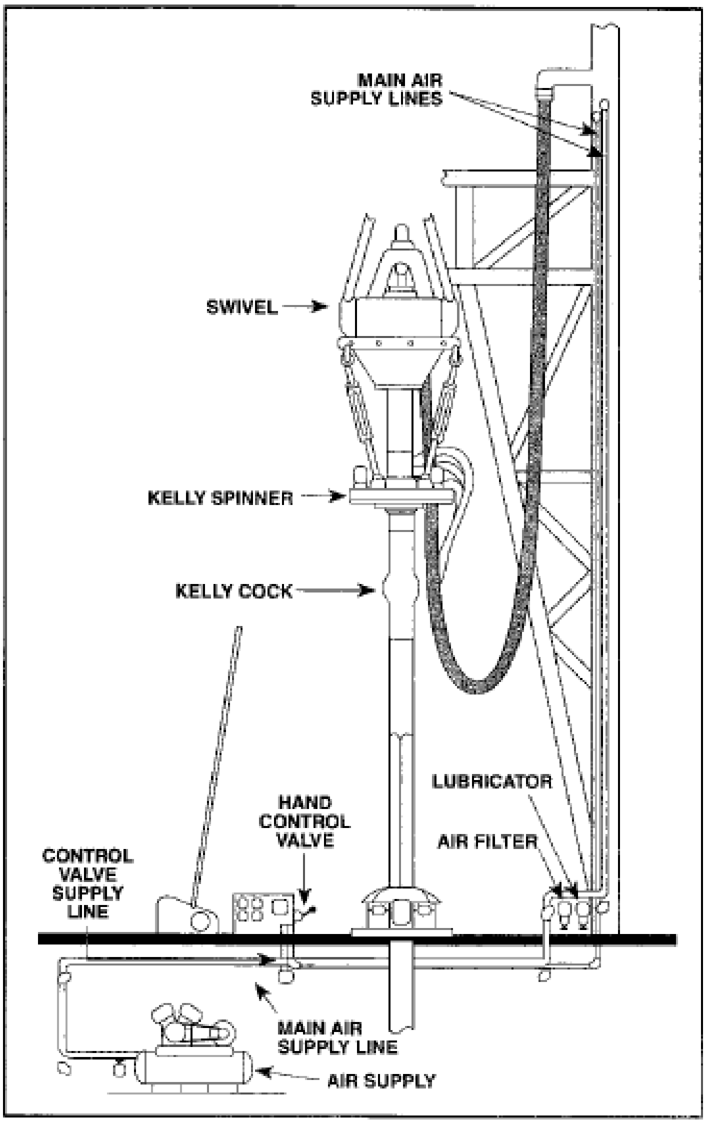


Figure 2 - 12: Typical auxiliary rig equipment [5, 7]

They can be broadly grouped as:

a) Drill-string handling tools; spinning wrenches, power tongs, hydraulic torque wrenches, power slips, automatic drilling, Kelly spinner, and automatic cathead
b) Instrumentation; weight indicators, mud pumps pressure gauges, rotary tachometer, rotary gauge indicator, pump stroke indicator, and rate of penetration recorder
c) Air hoist
d) Rig floor tools such as the choke and choke manifold, analogue and digital instruments, integrated drilling systems, rig clean-up equipment, and the fire detection and suppression system

2.4 Drilling Process

Upon SPUD in, the exercise of coring a geothermal bore begins from the surface to the targeted depths. The various drilling stages, challenges encountered, fuel used, and the costs expected have been discussed.

2.4.1 Drilling Stages

Based on the expected well operation condition and the expected drilling site geology, the casing depths are prescribed and detailed in the drilling program but actual depths are chosen by reference to geology and hole conditions. Typical geothermal wells have targeted depths of up to 3000m[9] and have typical profiles of the form shown in Figure 2 - 13.

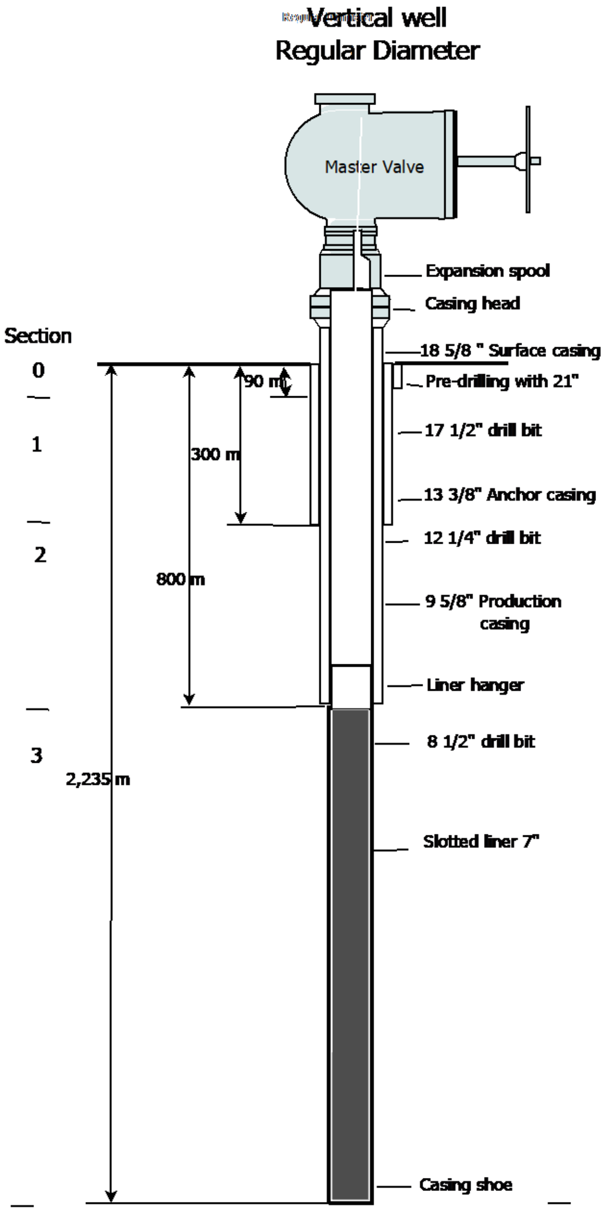


Figure 2 - 13: Typical vertical well profile [9]

Typically, a drilling program is agreed upon by engineers before commencing drilling. However, actual drilling program varies greatly upon encountering numerous challenges during the course of drilling. Figure 2 - 14 represents design versus actual drilling duration, the blue line represents the target drilling program while the green line indicates the actual scenario.

describes the sections of a wellbore profile, expected challenges and mitigation measures employed for each.

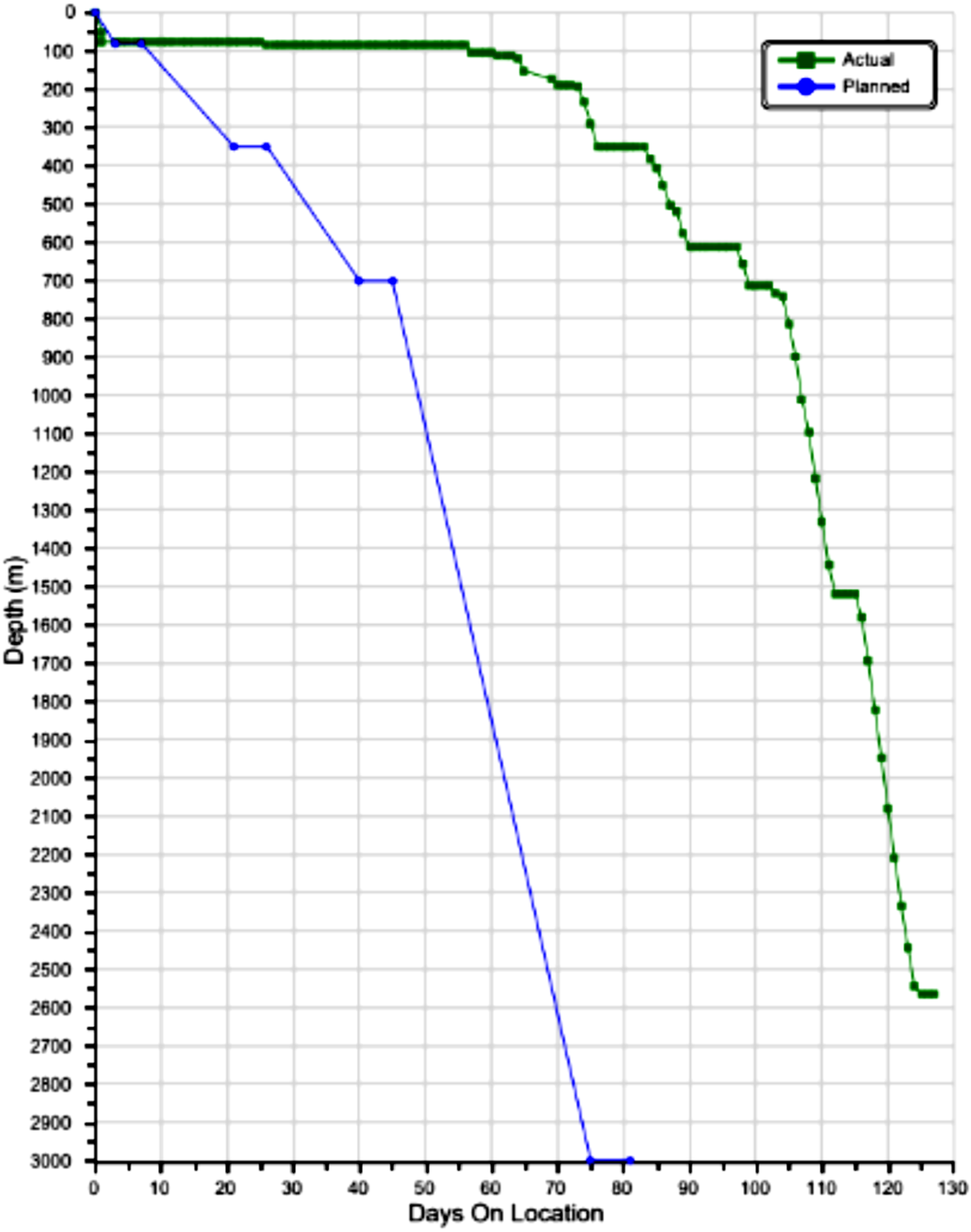


Figure 2 - 14: Typical drilling days trajectory planned vs actual days [9]

Table 2 - 1: Description of well profile, possible challenges and remedies [9]

Section Diameter	Depth (m)	Rate of Penetration m/hr	Duration (days)	Challenges	Remedy Drilling Fluid
26”	0 – 80	0.5 – 0.7	7 – 10	WOB is usually very high causing heavy vibrations	Water
$17^{1}/_{2}$”	80 – 400	1.5 – 2.0	10 – 15	Section is medium rough and tough	Aerated water and foam
$12^{1}/_{4}$”	400-1000	Varied	15 - 70	Medium soft formation	Aerated water, foam, & mud gel
$8^{1}/_{2}$”	1000-Final depth	Varied	20 - 120	Loose formation with tendencies to collapse	Aerated water, foam, & mud gel

2.4.2 Drilling, Energy and Environmental Impact

In drilling a well, the circulation fluid usually used is simple water-based bentonite mud. Additionally, air and aerated water and foam may be used for efficient bore cleaning. Approximately a million liters of water is used to drill a single well to completion. These large volumes of fluid are pumped continuously throughout the drilling process. Maintaining the drill bit rotation which includes the entire length of the drill-string inside the wellbore requires intense power. Power for pumping and running the drill bit is usually from diesel engines[10].

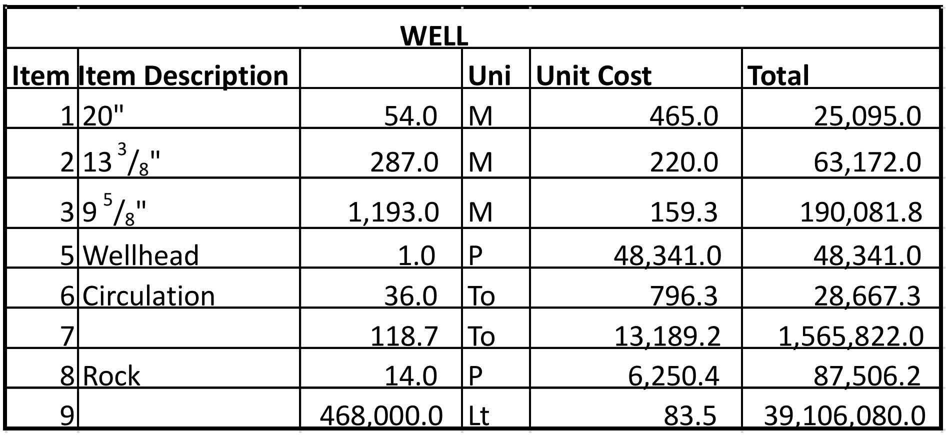
Drilling process is heavily reliant on thermal energy and the target for every drilling program is an optimal process with efficient energy consumption to minimize fuel cost. Potential benefits that could be accrued from minimal use of diesel engines include reduced emission of greenhouse gases, reduced noise pollution, minimized oil spills, and preservation of indigenous wildlife at a drilling site.

2.5 Aggregating Costs of Drilling

2.5.1 Analysis of Typical Costs of Drilling

According to a previous study that sought to quantify the total costs of drilling a well to completion, the following tabulations were obtained [Table 2 - 2][11];

Table 2 - 2: Typical drilling costs in Menengai [10]



WELL					
Item	**Item Description**		**Uni**	**Unit Cost**	**Total**
1	20"	54.0	M	465.0	25,095.0
2	13$^{3}/_{8}$"	287.0	M	220.0	63,172.0
3	9$^{5}/_{8}$"	1,193.0	M	159.3	190,081.8
5	Wellhead	1.0	P	48,341.0	48,341.0
6	Circulation	36.0	To	796.3	28,667.3
7		118.7	To	13,189.2	1,565,822.0
8	Rock	14.0	P	6,250.4	87,506.2
9		468,000.0	Lt	83.5	39,106,080.0

Drilling a geothermal well consists of a succession of steps of drilling and well casing construction until the top of the resource is reached. Once the well penetrates into the geothermal reservoir, the only additional casing that may be required would be an uncemented slotted liner to prevent rocks and debris from falling into the wellbore, however if the formation rock is competent then no additional casing is required. The productivity of the well is influenced by its length in the permeable rock as well as the number of productive fractures it crosses[12].

Drilling costs are highly dependent upon resource characteristics. Other economic parameters may however also influence the total cost of drilling.

2.5.2 Depth of the Resource

The depth of the resource is one of the major parameters influencing the cost of drilling a geothermal well. Along with the rock formation (nature, structure and hardness), which determines the drilling speed, these parameters influence the initial well diameter, the number of casing strings needed and, thereby, the time required to drill the well.

Geothermal reservoirs are typically located between 2000-3000m below the surface of the earth. Consequently, there is a direct relationship between the depth of the resource and the energy related costs to drill to the targeted depth. Energy management of drilling a wellbore requires a delicate balance between minimizing time spent on a single well and utilizing just the sufficient fuel source to reach the depth desired[12], [13].

2.5.3 The Fuel Type

As previously discussed, rigs are categorized either as marine or land. Marine rigs are located offshore and solely drill for oil and gas. Consequently, a mini-refinery is located on rig site, which in turn distills the diesel fuel or fires a gas turbine used to power all of the rig operations.

The land rigs both portable and conventional primarily run on diesel power. However; some land rig manufacturers equip auxiliary equipment such as transformers to enable a rig be connected to an existing electricity grid. A 33kV or the 132kV grid is usually selected depending on the grid type available and the rig equipment to be powered. However; electricity is rarely used since rig sites are mostly located in remotest regions including out in the open sea away from any existing grid lines. Diesel is thus the default primary major source of fuel.

2.6 Geothermal Drilling Challenges

Geothermal drilling has many similarities to oil and gas drilling, but there are many other different variables that make it more challenging. In drilling for oil and gas offshore, the formation encountered is the soft sandy sea floor. For geothermal case, half the cost in well development is directed towards the drilling process. [14].

A significant amount of time is lost while waiting for water supply for drilling the wellbore. It is estimated that drilling consumes approximately a million liters of water necessitating there be a constant supply of it.

In the course of drilling a well, some depths may pose significant challenges due to loose or very tight formations slowing down drilling time and, in the process, increasing the energy consumption.

Other times, the drill string assembly could be stuck due to numerous reasons mostly wellbore collapse necessitating use of extra energy to try unplug it from the ground or abandon the procedure altogether and deviating from the stuck trajectory.

Environmental pollution is present albeit in low quantities since diesel is the major source of fuel. Heavy fuel oil emits 0.26kg of CO_2per equivalent kWh[15].

2.7 Alternative power sources – grid power (Power Tariffs in

Generally, where there is availability of grid power, it has been shown that the fuel cost element in the drilling operations can be reduced significantly [16]. In the Kenyan situation, it is important to understand the energy price mix from the service provider KPLC. The tariffs are more favorable when consuming power from a higher voltage as shown in the Table 2 - 3 [17]

Table 2 - 3: Schedule of non-fuel tariffs for electrical energy supplied by KP [17]

Tariff	Charges (KES)	
	Energy charge (per kWh)	Demand charge (per kVA)
DC - (Lifeline domestic 1, 240V) DC - (Domestic ordinary 2, 240V)	(0-100kWh) 10.00 (Above 100kWh) 15.80	n.a
SC - (Small Commercial 1, 240V) SC – (Small commercial 2, 240V	(0-100kWh) 10.00 (101-15000kWh) 15.60	n.a
C11 (Commercial, 415V)	(>15,000kWh) 12.00	800.00
C12 (Commercial, 11kV)	10.90	520.00
C13 (Commercial, 33kV)	10.50	270.00
C14 (Commercial, 66kV)	10.30	220.00
C15 (Commercial, 132kV)	10.10	220.00
SL (Street lighting, 240 or 415V)	(11 hours a night) 7.50	n.a

In addition to these, there are additional variable surcharges that add to the total cost of electricity as indicated in Table 2 - 4.

Table 2 - 4: Additional surcharges to electricity billing

Surcharge	Rate / Notes
Fuel cost charge (FCC)	Variable rate per kWh, published monthly by KP. It is supposed to be reflective of the cost to KP of generation electricity during the previous month.
Foreign exchange rate fluctuation adjustment (FERFA)	Variable rate per kWh, published monthly by KP. This includes the "sum of the foreign currency costs incurred by KenGen, the sum of the foreign currency costs incurred by KP other than those costs relating to electric power producers", and the" sum of the foreign currency costs incurred by KenGen".
Inflation adjustment (INFA)	Variable rate per kWh, published monthly by KP. Factors include the "underlying consumer price index as posted by Kenya National Bureau of Statistics", and the "consume price index for all urban consumers".
ERC levy	3 cents per kWh
REP levy	5% of the revenue from unit sales
Warma levy	≅1 cent per kWh
Rounding adjustment	Any cumulative differences from any of the above surcharges between the total costs and actual billed amounts from the previous month
VAT	16% charged to demand charge, foreign exchange fluctuation adjustment, inflation adjustment, fuel cost and non-fuel energy cost

2.8 Previous

A proceeding in Germany in 2007 presented new technology drilling rigs in light of issues to do with climate change and the exigencies to reduce the emission of carbon dioxide. It was named „The Herrenknecht TI-350" drilling rig. The rig proposed was a prototype subject to demand then the manufacturer fabricates it. The rig design borrowed heavily from the marine off-shore rigs such as sound insulation, pipe handling and hands-off technology. The rig design proposed was highly automated and optimized handling as far as possible. It emphasized a smart energy management strategy where only the amount of energy needed is made available to reduce the overall drilling costs. [18]

The Icelanders were amongst the pioneers of geothermal studies. The cost of geothermal wells and field development is about 40% of the total investment cost for new high temperature geothermal plants which makes it unattractive to build than conventional thermal plants. A study in 2012 found that about half of the well cost is related to the time charges of the drilling rig (day rates) and associated equipment and thus ways of reducing the time it takes to drill the well is one way of reducing the overall cost. More importantly, the study noted there was surprisingly little published data available on the breakdown of geothermal drilling costs, because of the competitive nature of the drilling market and confidentiality clauses. [13]

A report on geothermal drilling done in 2013 noted that drilling represents 30% to 50% of the cost of a hydrothermal geothermal electricity project. It focused on research and development to improve geothermal drilling technologies in order to reduce its costs, but the main challenge was to improve market conditions for geothermal deep drilling. It noted the challenge of accessing available geothermal drilling cost data which was very limited. The study suggested use of alternate application of novel technologies like spalling, projectile, chemical drilling and other types being researched. The study showed a co-dependence correlation between costs of drilling in the general oil and gas industry over time as shown in Figure 2 - 15. It further noted that the situation is likely to persist as long as the geothermal drilling sector does not build-up a strong market share of its own compared to the oil and gas industry. [19]

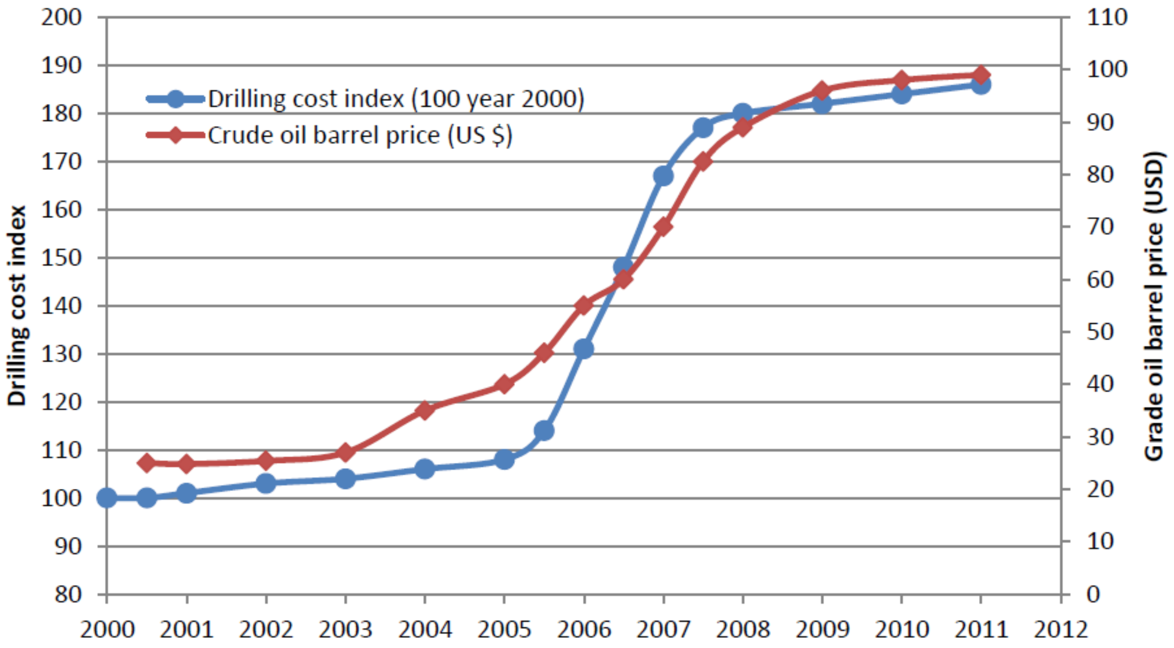


Figure 2 - 15: Drilling cost vs. crude oil prices [19]

More recent studies in 2019 focused on the consumption of energy during the drilling process by focusing on the idle power, cutting power and auxiliary power. The relationship between the cutting power and auxiliary power was analyzed for simple shallow holes. A model was simulated and an equation was derived but was specific to particular prototype machining tools. It concluded that further research was needed on the energy consumption of deep hole drilling. [20]

A study done at the Dedan Kimathi University modelled a process using digital twin for real time monitoring and control for geothermal drilling tools during operations. It proposed reduction of drilling costs by addressing the wear and tear of the tools whereby continuous monitoring may increase drilling efficiency thereby saving on cost. The program used was supplied by Siemens Mechatronics. [14]

CHAPTER THREE: METHODOLOGY

3.1 Introduction

Primary data sought was the amount of diesel fuel used to achieve a completed wellbore successfully. Additionally, electricity tariffs in Kenya would be investigated to contrast against the cost of diesel fuel used. In order to determine this, both descriptive and analytical research strategies were employed in this study.

3.2 Energy Data Collection

Data collected consisted of historical records and on-site real-time measurements. For historical records, energy data usage on previous drilling exercise was obtained. Real time measurements involved determining electrical power consumption of various rig components at the time of their use.

The drilling engineers had logs of delivery of diesel tankers to each rig. The daily drawdown of the fuel was recorded and aggregated in the final drilling completion report. The rig equipment was fitted with various measuring devices of which data was downloaded and analyzed.

A gauge meter and a flow meter at the diesel tank intake and engine generator room measured the consumption of diesel per minute. A Power Analyzer unit was fitted in three modern rigs in Menengai where the power quality was recorded.

A Silicon Control Rectifier [SCR] [Appendix Figure 1 - 1] fitted in all the rigs recorded the AC current from the engine generators being converted to DC current for consumption by the rig equipment.

Power Compensator Units were fitted in three of the rigs to create a provision for future retro-fit measures to switch to electricity, which would compensate for low Power Factor [PF] and provide constant current to the rig equipment.

A Digital Multi-meter [DMM] of model Fluke 179 [Appendix Figure 1 - 2] was used to measure the voltage and current, continuity, resistance, and harmonics of the power supply to the rig equipment.

To measure the adequacy of lighting illuminance at the rig site during night time operations, a Luxmeter HI97500 by HANNA was used. [Appendix Figure 1 - 3]. The findings were compared to internationally acceptable values and recommendations proposed. [

Appendix Table 1 - 3]

3.3 Rig Data Analysis

Historical data was analyzed by use of linear regression tools. Consecutive baselines were determined based on the optimal data sets selected. Eventually, CUSUM was computed to establish the total energy saved. This resulted to creating a new baseline that acted as a prediction tool for optimization of energy. Additionally, energy saving interventions would be determined.

3.4 Energy Saving Opportunities

Energy saving interventions are broadly categorized to three types

1. Housekeeping measures which involve no costs other than changes associated with human behavior. In the process of identification and measurement of energy data at the rigs, observations were noted as simple opportunities for energy savings.
2. Low-cost measures incurring some minor expenses such as regular general maintenance. Use of the Energy Monitoring, Targeting, and Reporting tool compared all the rigs performance by use of linear regression. Consequently, energy saving measures could now be quantified and costs ascribed either as low cost or retrofit.
3. Retrofit measures involving significant capital expenditure.

3.5 Economic Analysis

Attributing costs to the savings realized employed the rate of return of cash flow formula. It is a process of iteration that uses an interest rate which reduces the present worth of cash flow expenditures to zero. For the energy intervention measures identified, the annual equivalent cost of each alternative was computed first. Then the alternative which had the least cost was selected as the best option. This option was termed as capital recovery with return whereby it involved replacement of existing asset with a new asset. [21]

The equations and procedures of engineering economy utilized the following terms and symbols;
P = value or amount of money at a time designated as the present or time 0, also called present worth
A = series of consecutive, equal, end-of-period amounts of money, also called annual worth
n = number of interest periods; years, months, days
i = interest rate per time period; percent per year, percent per month.

The capital recovery factor (CRF) calculated the equivalent uniform annual worth A over n years for a given P in year 0, when the interest rate was I as shown in equation 3.1.

$$A = P[\frac{i(1:\quad)^n}{(1:\quad)^n;}] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

The capital recovery factor (CRF) can further be modified to compute the length of time required for equalizing the net savings and the capital cost of the retrofit measure identified. This is termed as the simple payback period and excluded the internal rate of return as shown in equation 3.2.

$$\eta = \frac{P}{A} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Introduction

The company had seven operational rigs that were deployed out in the field where there was no access to electricity, hence entirely relied on diesel as power source. Evaluation of energy performance was done considering individual components of consuming loads. Trends and patterns for each of the rig compared with the corresponding well output was established.

4.1.1 Rig Energy Applications Inventory

The rig electrical system was a sophisticated, regularized, safe, reliable, and convenient powered from the SCR. It supplied power for various electric equipment of the rig and provided illumination for the derrick area, rig floor area, solid control area, pump area, well site and the auxiliary drillers‟ quarters[8]. Each rig was equipped with lighting gadgets that illuminated the working area both day and night. Importantly, the lights on the rig worked throughout as long as the diesel engines were running; for four to five months.

The Main Diesel Generators

Table 4 - 1 summarizes the diesel generators parameters and output while Table 4 - 2 shows how the power from the generators flows throughout the entire rig system.

Table 4 - 1: Main diesel generators parameters

No.	Item Description	Quantity & Rating
1.	Number of main diesel generating set	4 sets
2.	Type of diesel engine	CAT3512B
3.	Type of generator	SCR4B
4.	Capacity of generating set	1900kVA
5.	Voltage, frequency and power factor of generating set	600V, 50Hz, 0.8-0.9
6.	Number and power of auxiliary diesel generating set	1 set 365kVA, CAR3406
7.	Voltage and frequency of auxiliary diesel generating set	400V/230V, 50Hz,
8.	Number and type of the direct current electrical motor	9 sets, YZD800/-4A/ YZD800/-4
9.	Rated power of the direct current electrical motor	800kW
10.	Fuel load consumption	50%

Table 4 - 2: Distribution of power loads at the rig

Ref.	Item.	Qty & Rating (kW).	Total Rating (kW)
Main power consumers			
1.	Draw-works	1 × 1470	1,470.00
2.	Mud pumps	3 × 400	1,200.00
3.	Rotary table	1 × 440	440.00
Maximum simultaneous power consumption			1,600.00
Secondary power consumers			
4.	Shale shakers	2 × 3	6.00
5.	Degasser motor	1 × 18.5	18.50
6.	Agitator motors	12 × 5.5	66.00
7.	Centrifugal pumps	3 × 55	165.00
8.	BOP control unit	1 × 15	15.00
9.	Hydraulic power unit (emergency)	2 × 110	220.00
10.	Electrical installed lighting	(Appended below)	300.00
Maximum simultaneous power consumption			400.00
List of electrical lighting			
1.	Circulating tank flood lights	2 × 38	76.00
2.	Explosion-proof fluorescent lamp	39 × 3.3	128.70
3.	Standby power	9 × 22.8	205.20
4.	Disc brake hydraulic station	1 × 11.4	11.40
5.	Driller‟s wing room	1 × 22.8	22.80
6.	Driller‟s quarters fluorescent lamps	20 × 3.3	66.00

The power distribution in the rig was as shown in Figure 4 - 1. All loads connected to the SCR DC transformer ran non-stop for the entire drilling period. Loads connected to the AC MCB were operated on a need basis. Figure 4 - 2 shows the power distribution to rig equipment. Figure 4 - 2 depicts the draw-works as being the single most used equipment on the rig due to the nature of drilling operations. Electrical lighting was the second biggest power consumer given the lights operated throughout day and night. The mud pumps were used interchangeably hence accounted for less than 10% energy use during drilling.

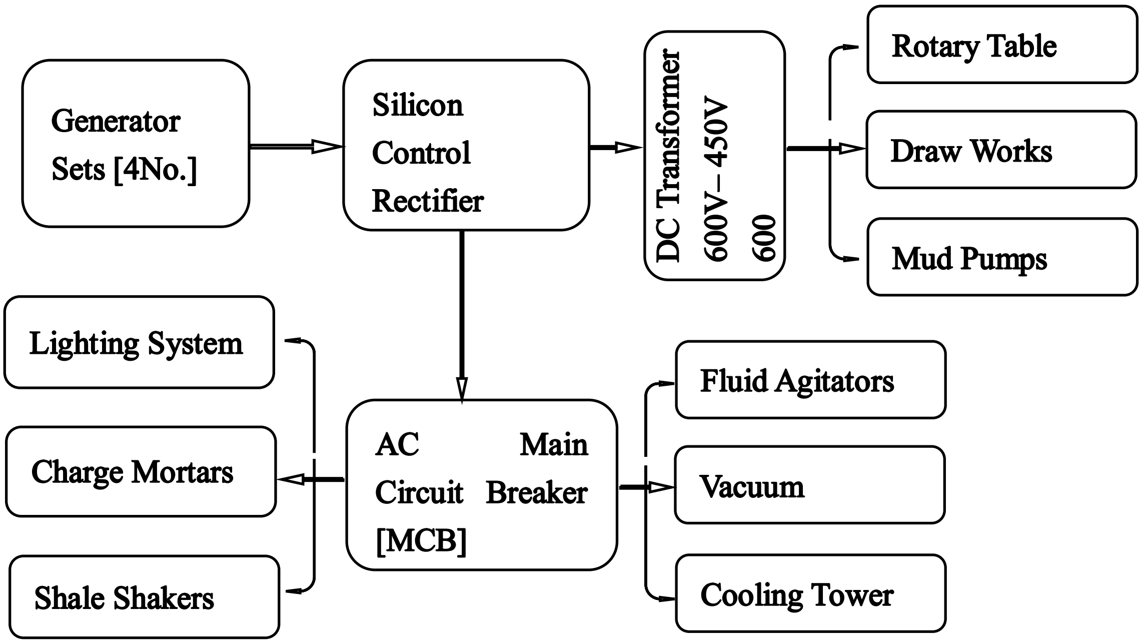


Figure 4 - 1: Power distribution from the generators

Figure 4 - 2: Energy distribution pie chart

Each rig has four diesel powered generators rated 1900kVA, 50Hz. At any given instance, only two of the four generators power the entire rig operations while the other two are on standby. At maximum load, each generator consumes about 313 liters per hour. Typically, there are additional two compressors running with a booster to increase the air pressure whenever air drilling is employed.

The manufacturer‟s rated average fuel consumption for a day of drilling is about 5,500 liters translating to about 165,000 liters of fuel per rig in a single month. In monetary terms, this is about KES. 17,166,600 in monthly fuel consumption as at November 2019 when fuel sold was retailing at about KES 104.04. [17] Current fuel consumption from the rigs indicates that generators were operating at roughly 50% load as shown in Table 4 - 3;

Table 4 - 3: Total fuel consumption against generator loads

1492 kW$_e$, 1900 kVA		
24-hour operation		
Fuel Consumption	Total fuel/ day consumed (liters)	Generated kW$_e$h
100% load	313.0 liters/hr	1,074,240.00
75% load	238.2 liters/hr	805,680.00
50% load	161.9 liters/hr	537,120.00

Power factor (PF) determines the relationship between true power and apparent power. True power is also known as active power. Apparent power is also called kVA. True power (kW) is the work that is done on the load by the engine. True power determines the amount of power that is available for the load to do work. The apparent power (kVA) is the total power that is produced by the generator. Power factor can be calculated by using the following formulae PF = kW / kVA. Determination of the power requirements in kW was found by multiplying the power factor by the kVA that is supplied to the system. As the power factor increases, the total current that is supplied to a constant power demand will decrease. With equal loads, a lower power factor will draw more current. A high-power factor will result in full engine load that is less than the generator‟s rated amperage. A lower power factor will increase the possibility of overloading the generator. For the Caterpillar generator listed in Table 4 - 1, it has been designed for a power factor of 0.8 lagging. [15]

The total electrical energy output in an ideal scenario free of drilling challenges by a typical rig fueled by diesel in a month can be determined by;

$$E_{(kWh/Month)} = \frac{P_W \times T_{(h/} \times D_{mont}}{100_{(W/kW)}} \times 0.5 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.1)$$

Where: P_w is the total power rating of the equipment i.e., 2000HP

$T_{h/da}$ are the hours worked that is 24 hours per day

D_{mont} are the 30 working days in a month

0.5 is the operating capacity of the generators; (two out of four are always on standby)

Substituting in the values;

$$P_W = 2000HP \times 746W = 1492\ kW_e \text{..................................(4.2)}$$

$$E_{(MWh/Month)} = \frac{149\ _{(kW}\ \times 2\ _{(hours\ per}\ \times 3\ _{(days\ /\ )}}{1\times 1\ ^{3}{}_{(kW/MW)}} \times 0.5\ _{capacit} = 537.12\ MW_e \text{ 4.3)}$$

Maximum kVA demand computed using the manufacturer"s power factor of 0.8 becomes;

$$190\ _{kVA} \times 0.8\ _{PF} \times 0.5_{capacit} = \quad _{kVA} \qquad \text{..............................(4.4)}$$

The Air Drilling System

The air drilling system consisted of the primary compressed air at 2.0MPa supplied by five air compressor units (4 for use and 1 standby). The air entered into a 4" low pressure pipeline, before finally being delivered to three sets of boosters (2 for use and 1 standby) via air dryer. The final maximum air discharge was about 120m ^{3}/min and maximum air exhaust pressure, of about 15MPa as shown in Table 4 - 4. Two sets of atomizing plunger pumps with maximum discharge of 180L/ min and maximum operating pressure of 16 MPa were installed between boosters and high-pressure mud standpipe to pump foaming agent into the wellbore thus lifting and expunging the cuttings to the surface.

Table 4 - 4: Compressors and booster's parameters

Description	Rating	5. No. Compressors	3. No. Boosters
Manufacturer		Atlas Copco	Atlas Copco
Model		XRHS1096Cd	B18-62/2500
Air delivery		508l/s	500-1000l/s
Discharge pressure	Bar	20	36-150bar
Parameters of Diesel Engines			
Manufacturer		Caterpillar C13 T3	Caterpillar CAT C18 – Tier 3
Motor Rating	kW	328	429
75% load oil consumption		47.2 l/h	78 l/h
Specific power	KW/l/h	6.95	5.5

The total electrical energy output for a typical compressor fueled by diesel in a month was determined by;

$$E_{(MWh/Month)} = \frac{6.9\ _{(kW}\ \times 47.\ \ _{l/h}\ \times 2\ \ _{(hours\ per}\ \ \times 3\ \ _{(days\ /\ )}}{1\times 1\ \ ^{3}{}_{(kW/MW)}} \times 0.75\ \ _{capacit} =$$

$$177.14M\ \ _{e} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.5)$$

The total electrical energy output for a typical booster fueled by diesel in a month was determined by;

$$E_{(MWh/Month)} = \frac{5.\ \ _{(kW}\ \times 7\ \ _{l/h}\ \times 2\ \ _{(hours\ per}\ \ \times 3\ \ _{(days\ /\ )}}{1\times 1\ \ ^{3}{}_{(kW/MW)}} \times 0.75\ \ _{capacit} =$$

$$231.66\ E_{MWh} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.6)$$

This gives a combined power of 408.8MWh$_e$from the compressors and boosters.
Maximum kVA demand computed using manufacturers rating of 0.75 capacity becomes;

$$190\ \ _{kVA} \times 0.8\ \ _{PF} \times 0.75_{capacit} = \qquad _{kVA} \ldots\ldots\ldots\ldots\ldots\ldots(4.7)$$

<u>Simulated Power Bill by Kenya Power</u>

Total electrical wattage is the summation of values computed in Equations 4.3, 4.5, and 4.6 while maximum demand is the summation of values computed in Equations 4.4 and 4.7. These translates to 945,920kW$_e$and 1900 kVA respectively.
If this energy were to be extracted from the grid, and based on the C15 tariff listed in Table 2 - 3, the costs would work out as follows as shown in Table 4 - 5.

Table 4 - 5: Simulated electricity bill from KP

Surcharge	Cost (KES)
Energy charge @ KES 10.10 per kWh	9,553,792.00
Demand charge @ KES 220 per kVA	418,000.00
FCC @ KES 5.73 per kWh	5,420,121.60
Forex @ KES 1.92 per kWh	1,816,166.40
Inflation @ KES 0.3 per kWh	283,776.00
ERC @ KES 3 cents per kWh	28,377.6
REP @ 5% of energy charge sales	477,689.60
WARMA @ ≈ 1 cent per kWh	9,459.20
VAT @ 16%	2,881,181.00
TOTAL BILL	20,888,563.40

Compared to the monthly cost of diesel of KES. 17,166,600, it is evident that KP costs would be more expensive than purchasing diesel per given month unless the energy charge by KP becomes cheaper. Consequently, energy saving interventions can only be undertaken by focusing on the rig equipment and optimizing the diesel fuel purchased.

4.1.2 Historical Energy Data Collection

Historical data of the wells drilled using these rigs over a span of eight financial years from 2012 to 2019 was collected. Focus was placed on the drilling depth, number of days taken for drilling, and cumulative diesel purchased per each well drilled.

Fifty-two (52) wells were dug during the 8-year period using seven (7) rigs. All seven rigs are similar in configuration and energy output. Differences in diesel oil consumption arose depending on the sub-surface formation encountered during drilling; whereby the more challenging the formation, more days were spent drilling and consequently more energy was consumed.

Raw data was analyzed and has been presented in Table 4 - 6. The raw data consisted of an individual rig identification and the well it dug, the total purchased volume of diesel fuel in liters for each well, the depth dug by the rig, and the duration the rig dug the well. The Rate of Penetration (R.o.P) which is an average ratio of drilled depth per day was computed, and also the diesel oil consumed per day. The volume of diesel oil was converted to gigajoules energy to enable computations for ratio of total energy per day and specific energy per depth.

Table 4 - 6: Historical raw data analysis

Wel	Ri	Purchased Oil	Depth (m	Day	Dat		Depth/Day (R.o.P) (m/day	Oil/Day (lt/day	Total Energy (GJ	Specific Energy (GJ/day	Energy Intensity (GJ/depth
1	1	31367	270	12	2-Mar-	4-Jul-	21.7	2529.6	1141	92.0	4.2
2	2	29894	250	106	10-Mar-	24-Jun-	23.5	2820.2	1088	102.6	4.3
3	3	32748	300	13	17-Apr-	27-Aug-	22.7	2480.9	1192	90.3	3.9
9	4	11456	140	8	18-Jun-	14-Sep-	15.9	1301.9	417	47.3	2.9
6	3	31745	300	13	13-Sep-	30-Jan-	21.5	2283.8	1155	83.1	3.8
1	2	36436	310	13	30-Oct-	14-Mar-	22.9	2699.0	1326	98.2	4.2
7	1	26542	280	9	15-Dec-	24-Mar-	28.2	2681.0	966	97.5	3.4
1	4	30672	260	12	6-Mar-	11-Jul-	20.4	2415.1	1116	87.9	4.2
8	5	24356	240	10	6-Mar-	20-Jun-	22.6	2297.7	886	83.6	3.6
4	6	28975	280	11	4-Apr-	28-Jul-	24.3	2519.5	1054	91.7	3.7
1	1	25163	250	12	4-May-	3-Sep-	20.4	2062.5	916	75.0	3.6
1	2	26731	250	10	9-Jul-	25-Oct-	23.1	2475.1	973	90.0	3.8
1	3	22342	240	114	26-Aug-	18-Dec-	21.0	1959.8	813	71.3	3.3
1	5	32342	300	12	2-Oct-	1-Feb-	24.5	2651.0	1177	96.5	3.9
2	2	18735	190	10	12-Dec-	24-Mar-	18.6	1836.8	682	66.8	3.5
1	6	25618	270	12	6-May-	4-Sep-	22.3	2117.2	932	77.0	3.4
1	1	27171	240	10	2-Jul-	10-Oct-	24.0	2717.1	989	98.9	4.1
1	3	21118	250	12	9-Jul-	9-Nov-	20.3	1716.9	768	62.5	3.0
5	7	26909	260	12	5-Aug-	9-Dec-	20.6	2135.6	979	77.7	3.7
2	2	24352	240	12	6-Oct-	11-Feb-	18.7	1902.5	886	69.2	3.6
2	4	24052	240	12	8-Oct-	8-Feb-	19.5	1955.4	875	71.1	3.6
2	1	26757	250	11	9-Jan-	4-May-	21.7	2326.7	974	84.6	3.9
2	3	22332	190	10	31-Jan-15	18-May-	17.7	2087.1	812	75.9	4.2
3	2	26235	250	12	5-May-	6-Sep-	20.1	2115.7	955	77.0	3.8
2	5	28926	250	12	7-Jun-	5-Oct-	20.8	2410.5	1052	87.7	4.2
3	2	35423	290	13	10-Jun-	27-Oct-	20.8	2548.4	1289	92.7	4.4
2	6	32211	290	13	1-Jul-	8-Nov-	22.3	2477.7	1172	90.1	4.0
3	1	24633	250	12	3-Aug-	1-Dec-	20.8	2052.7	896	74.7	3.5
2	4	30032	300	130	23-Aug-	31-Dec-	23.0	2310.1	1093	84.0	3.6
3	3	31626	260	13	7-Sep-	22-Jan-	18.9	2308.5	1151	84.0	4.4
1	7	32452	300	13	9-Nov-	19-Mar-	22.9	2477.2	1181	90.1	3.9
4	1	19034	190	10	26-Jun-	5-Oct-	18.8	1884.6	692	68.6	3.6
2	4	19852	170	9	9-Jul-	14-Oct-	17.5	2046.6	722	74.5	4.2
2	6	33165	300	14	7-Aug-	27-Dec-	21.1	2335.5	1207	85.0	4.0
3	5	25673	240	119	10-Aug-	7-Dec-	20.1	2157.4	934	78.5	3.8
4	3	31983	290	13	9-Sep-	19-Jan-	21.9	2422.9	1164	88.2	4.0
4	2	22326	190	111	17-Nov-	8-Mar-	17.1	2011.4	812	73.2	4.2
3	7	21455	210	10	28-Dec-	10-Apr-	20.3	2083.0	781	75.8	3.7
4	1	25434	260	12	1-Feb-	4-Jun-	21.1	2067.8	925	75.2	3.5
3	4	26782	280	12	3-Feb-	8-Jun-	22.4	2142.6	974	77.9	3.4
3	6	26753	280	12	6-May-	6-Sep-	22.7	2175.0	973	79.1	3.4
4	5	32321	300	13	15-Sep-	1-Feb-	21.5	2325.2	1176	84.6	3.9
5	3	20633	220	11	28-Oct-	21-Feb-	18.9	1778.7	751	64.7	3.4
3	4	24235	250	12	8-Nov-	12-Mar-	20.1	1954.4	882	71.1	3.5
4	1	38763	260	14	24-Dec-17	14-May-	18.4	2749.1	1411	100.0	5.4
4	2	22115	190	10	8-Jan-	27-Apr-	17.4	2028.9	805	73.8	4.2
3	6	32156	250	12	4-Feb-	11-Jun-	19.6	2532.0	1170	92.1	4.6
4	7	26543	250	12	3-Apr-	1-Aug-	20.8	2211.9	966	80.5	3.8
5	3	22993	240	12	7-Jul-	4-Nov-	20.0	1916.1	837	69.7	3.4
4	2	20021	250	11	1-Oct-	23-Jan-	21.9	1756.2	728	63.9	2.9
5	5	18293	210	11	4-Nov-	22-Feb-	19.0	1663.0	665	60.5	3.1
4	6	26732	250	12	20-Dec-	24-Apr-	20.0	2138.5	973	77.8	3.8
5	7	21876	240	11	9-Jul-	30-Oct-	21.2	1935.9	796	70.4	3.3

Analysis considered how the energy use vary with depth, and further the relation between energy use and how drilled depth changed with time as computed in Appendix Table 1 - 1. A functional relationship between diesel oil consumed and drilled depth was determined by means of the linear regression tool as shown in Figure 4 - 3.

A trend line on the scatter plot shows the algebraic expression that defines the line whereby the energy performance model for the entire data set was;

$y = 3.9124x - 141.14$ ……………………………………………………….(4.5)

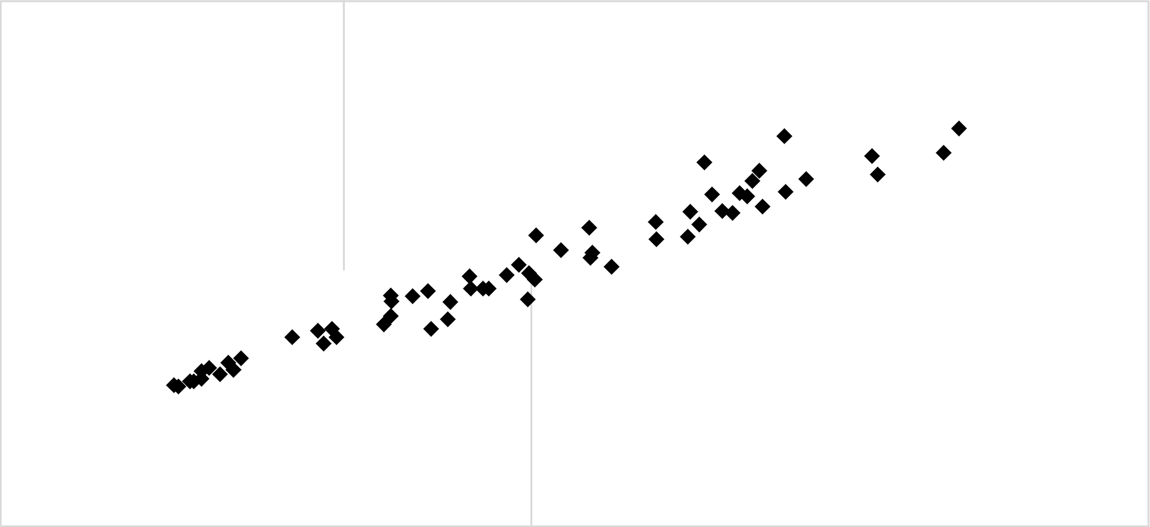


Figure 4 - 3: Linear regression of baseline

There are three parameters in the model expressed in equation (4.5)

- The slope, 3.9124 GJ/m, represents the incremental energy required to drill one meter depth of a well
- The y-intercept, -141.14 GJ, is a negative value and should be interpreted to mean economically viable energy was already being expended before actual drilling began with zero depths recorded.
- The R^2 parameter is a measure of how well the trend line fits the data points whereby 0.9657 gives us a high degree of confidence in the energy performance model generated.

A time series plot in Figure 4 - 4 as derived from Appendix Table 1 - 1 plots the energy consumed over the entire period of study and shows variations in energy used.

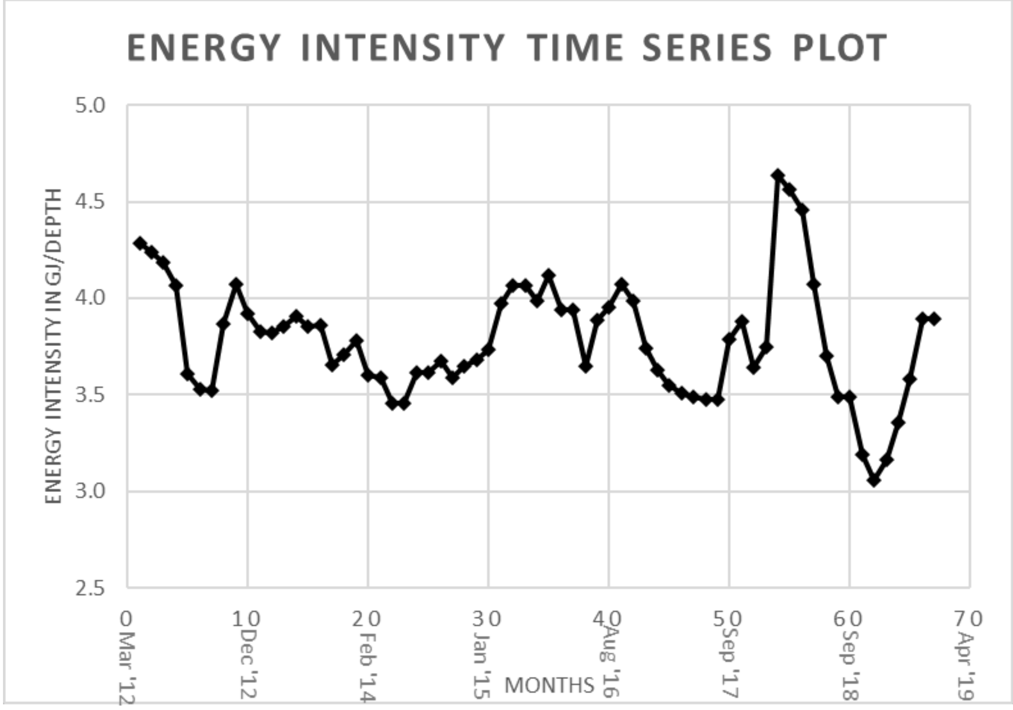


Figure 4 - 4: Time series energy intensity plot

Analyzing the time series in Figure 4 - 4, it can be noted that between the months 43 to 53 corresponding to February to December 2017, a consistent rate of drilled depth was achieved with adequate purchased fuel, whereby it shall be selected as the baseline.

A linear regression on the 11 months of 2017 yielded Figure 4 - 5 and a new energy performance model:

$$y = 3.6803x - 64.892 \qquad (4\text{-}6)$$

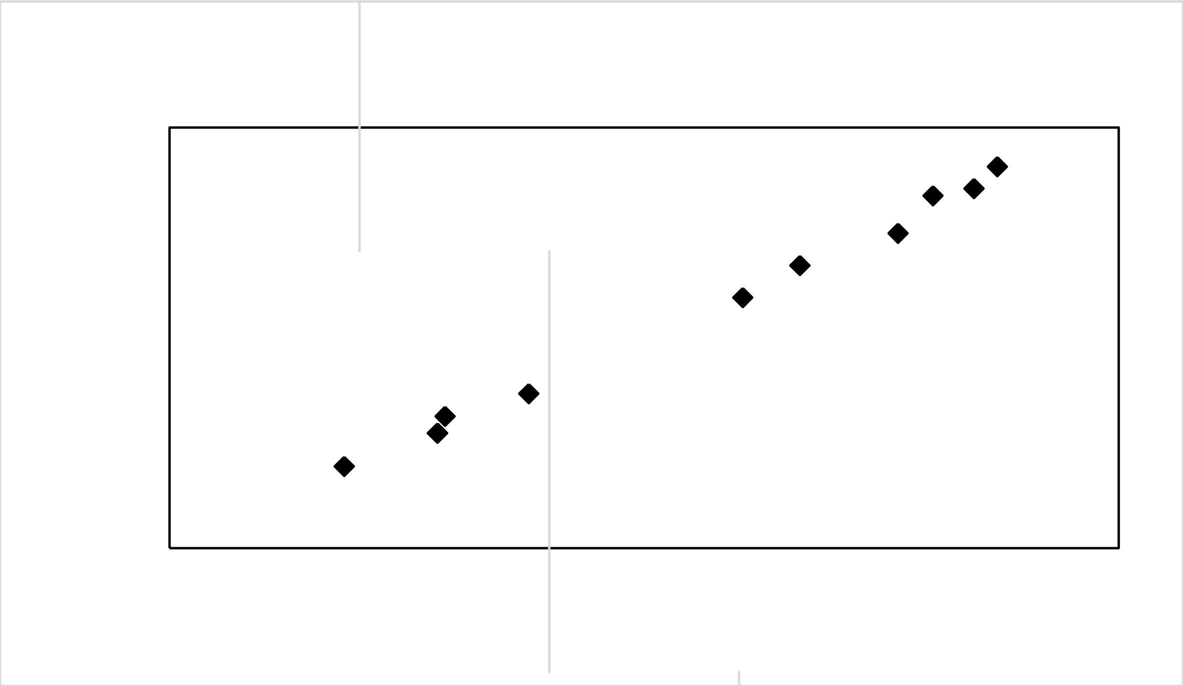


Figure 4 - 5: Linear regression of baseline

Table 4 - 7: Comparative of energy performance models - total and baseline

Model	Incremental load (GJ/Depth)	Base load (GJ)
Total data set	3.9124	-141.14
Baseline data	3.6803	-64.892

It can be noted from Table 4 - 7 that the incremental load for the baseline data is lower than the total data set but its base load was higher suggesting some favorable drilling practices were performed that saved on fuel.

CUSUM was performed in this analysis as per Appendix Table 1 - 2 which brought out critical points in form of change in slope of the line as shown in Figure 4 - 6. CUSUM stands for „CUmulative SUM of differences", and refers to differences between actual consumption and predicted consumption.

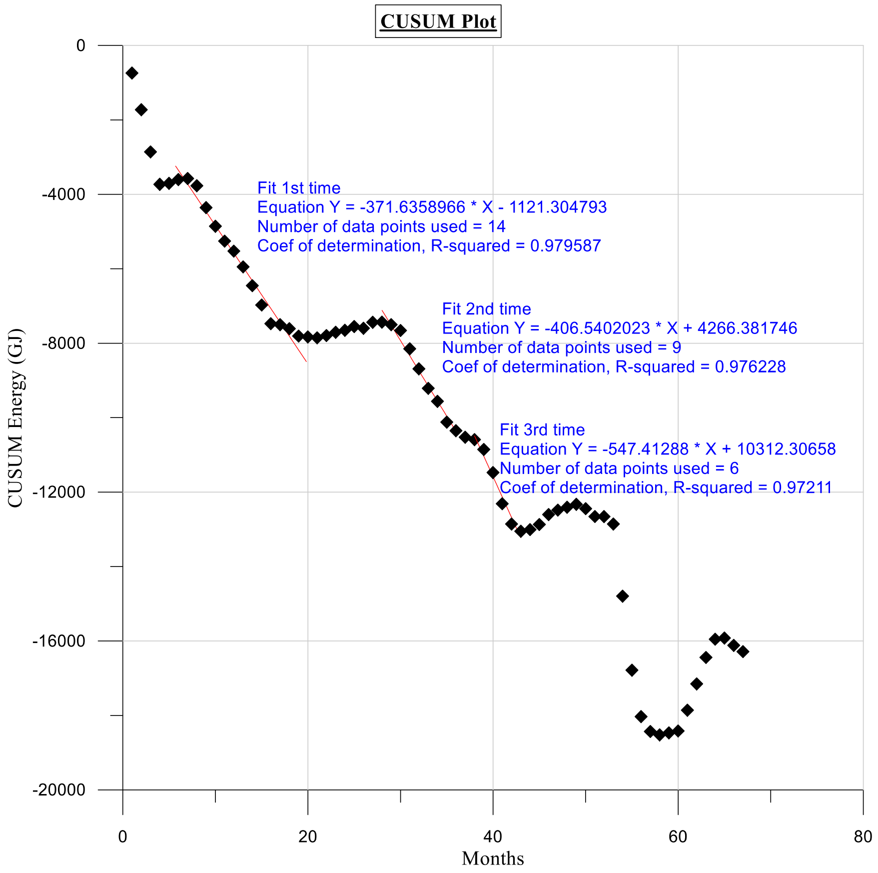


Figure 4 - 6: CUSUM plot for drilling energy use

Considering the majority of the well depths ranged between 2500m to 3000m, and the typical duration the rig took to drill to such a targeted depth was between 4 to 5 months, further considering that all seven rigs are of similar configuration; the differences in energy consumption would be determined by the formation challenge of the well being dug.

It can be observed that over the years, drilling efficiency improved since the first well that was dug, until the 50th month September of 2017 through 2018 to the 64th month January 2019 where drilling operations heightened causing a breakdown in energy conservation measures.

4.2 Maximizing system efficiencies – control measures

From the CUSUM plot in Figure 4 - 6, the period between the 29 th month December 2014 to the 36th month February 2016 was chosen since it performed better to set a target for future control measures. A new trendline to form the baseline for control from the regression plot in Figure 4 - 7, thus becomes;

$$y = 3.6151x + 378.17 \qquad (4\text{-}7)$$

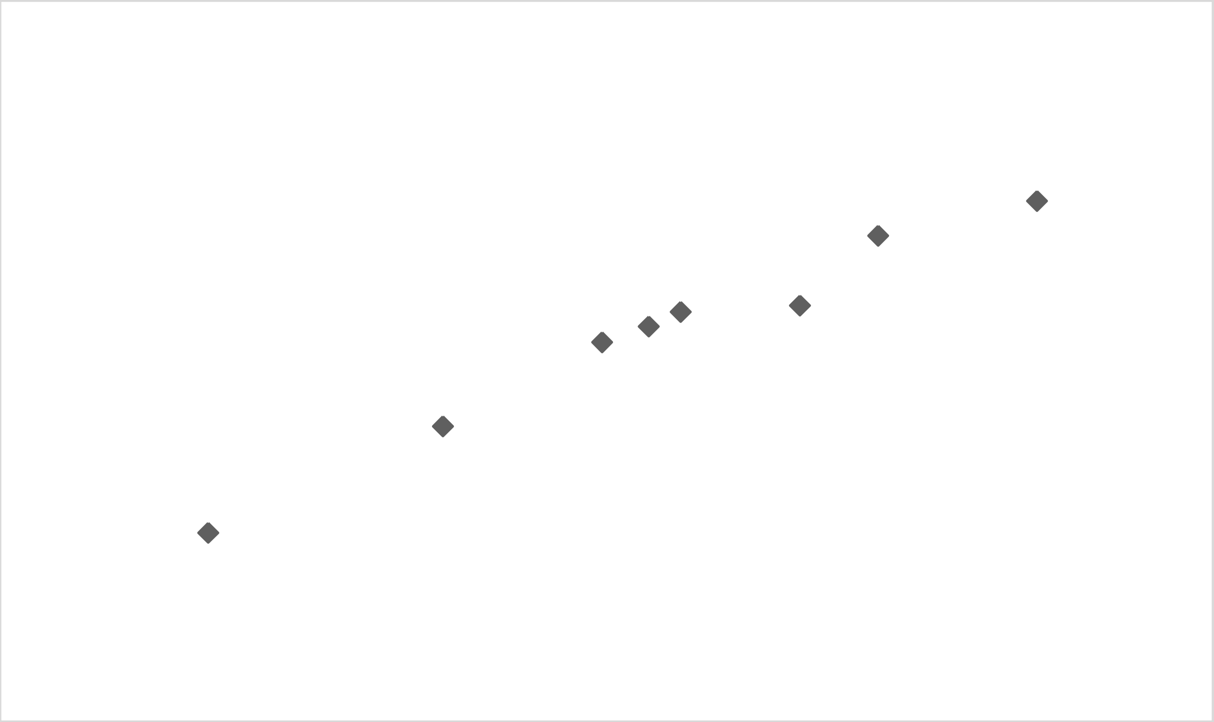


Figure 4 - 7: Regression line for targeting

Table 4 - 7 can thus be revised to obtain ideal target conditions for energy usage;

Model	Incremental Load (GJ/Depth)	Base Load (GJ)
Total data set	3.9124	-141.14
Baseline data	3.6803	-64.892
Target	3.6151	378.17

The difference between the control data predicted energy use and the actual used energy was plotted as a time series in months presented in Figure 4 - 8. Controls were denoted by an energy band within whose desired limits are to be maintained. A good value for control level is 1.4 times the average of the differences within the months chosen, with the signs being ignored. From the Appendix Table 1 - 2, the average difference in the period between the 29 th month Dec 2014 and 36 th month Feb 2016 is 167.136, and 1.4 times this is 234 GJ. Control limits of $\pm 250GJ$ would be within reasonable range of drilling using optimum diesel energy supply.

Analysis of the control chart indicated that apart from the months chosen for suitability of control purposes above, the only other period performance was desirable were between the 9th month of November 2012 to the 14th month April 2013. From the Appendix Table 1 - 1, this translates to an average of about 75000 liters of diesel per month per rig for drilling operations to perform optimally within the control band.

In the subsequent years of March to April 2018 and October 2018 to January 2019 as seen in the Figure 4 - 8 below, the parameters encountered during drilling, maybe in form of a very hard surface, or extended periods of drilling caused the energy demand to exceed normal consumption.

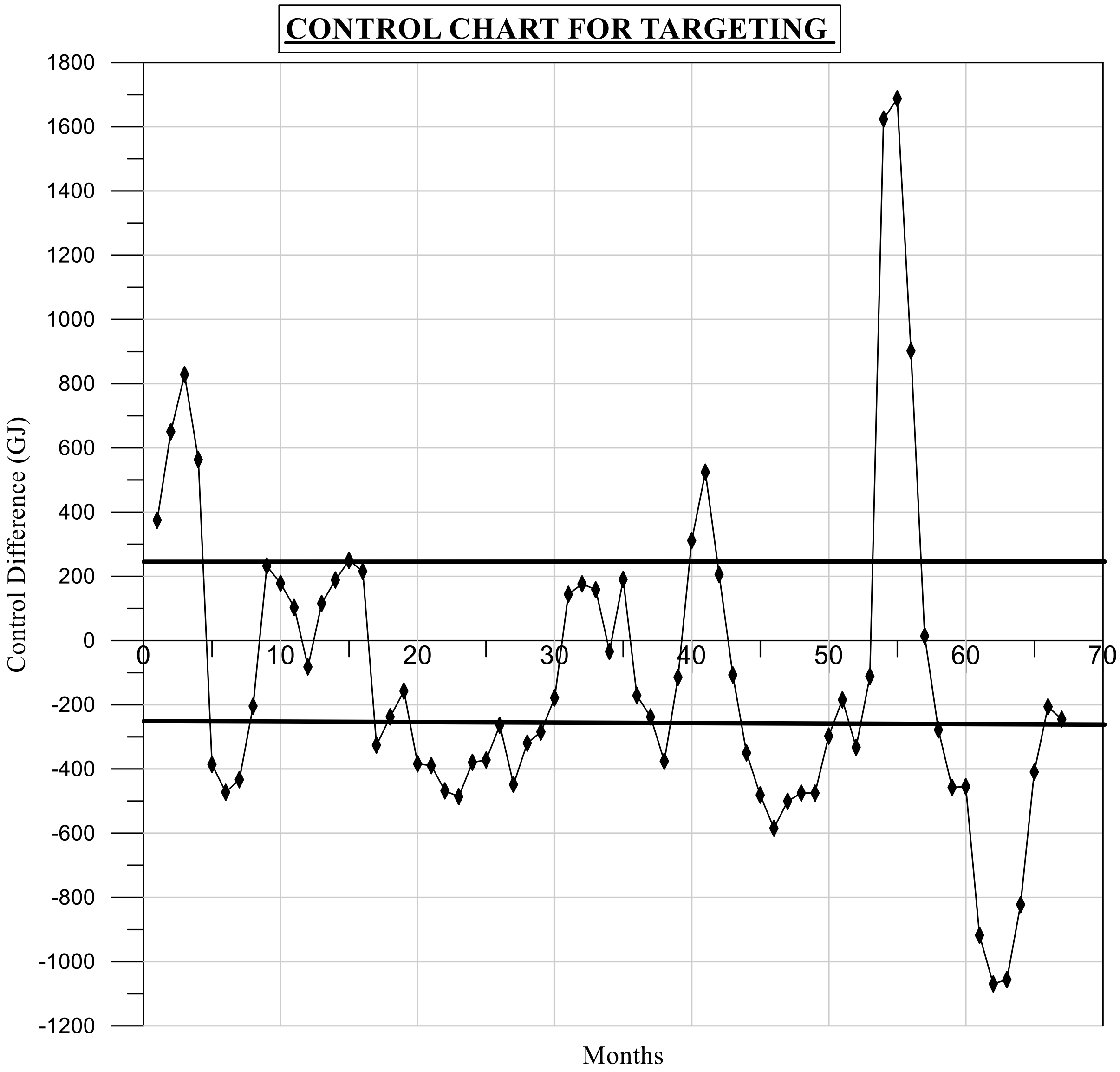


Figure 4 - 8: Control chart for targeting

4.3 Real-time Electrical Loads Measurements

During the course of drilling in one well, measurements were taken using the rig equipment‟s SCR and a digital fluke at the MCB as elaborated in Section 3.3. Parameters measured on March 5th, 2018 from Rig 3 were the power factor, the power distributed to the draw-works, and the mud pump 2 in use. Real time measurements were analyzed in Table 4 - 8, where the digital fluke was connected at the MCD from midday. It recorded measurements at a one-minute interval for 24 hours thus the table presented is part of the whole data.

Table 4 - 8: Real Time Measurements - Digital Fluke Readings

Voltage Units: kV		**Gauge Series Number: DMM179**			**Date of Measurement: 03/05/2018**			
Current Units: A		**Gauge model: FLUKE USA**			**Maximum Recorder Range: 5000**			**60 sec**
Ite	**Rig 3**	**PF**	**kW**	**A**	**kVA**	**Depth(m)**	**Trend_Period**	**Avg**
Pump_		0.9623	110.967	27.127	0	112.98	60	969.
D	MCD = 2770M	0.971	110.967	27.127	718	113.47	60	920.
D	CS = 1182M	0.971	110.966	29.475	0	113.95	60	920.
D	TL = 1157M	0.971	110.933	27.718	0	114.44	60	920.
D	3/5/2018 12:24	0.971	110.921	27.129	0	114.93	60	920.
Pump_	3/5/2018 12:25	0.971	110.912	29.477	0	115.43	60	969
MC	3/5/2018 12:26	0.971	110.899	27.129	0	115.91	60	461.
MC	3/5/2018 12:27	0.971	110.915	27.127	718	116.4	60	459.
MC	3/5/2018 12:28	0.971	110.902	29.478	0	116.9	60	460.
MC	3/5/2018 12:29	0.971	110.871	27.132	0	117.39	60	460.
Pump_	3/5/2018 12:30	0.971	110.859	27.13	0	117.87	60	969.
D	3/5/2018 12:31	0.971	110.871	27.131	0	118.36	60	920.
D	3/5/2018 12:32	0.971	110.839	27.13	0	118.85	60	920.
D	3/5/2018 12:33	0.971	110.828	27.131	0	119.34	60	920.
Pump_	3/5/2018 12:34	0.971	110.818	27.132	0	119.82	60	969.
D	3/5/2018 12:35	0.971	110.812	27.13	0	120.31	60	920.
D	3/5/2018 12:36	0.971	110.804	27.131	0	120.81	60	920.
D	3/5/2018 12:37	0.971	110.795	27.131	0	121.29	60	920.
D	3/5/2018 12:38	0.971	110.815	27.132	0	121.78	60	920.
Pump_	3/5/2018 12:39	0.971	110.81	31.855	0	122.27	60	969
MC	3/5/2018 12:40	0.971	110.804	27.133	718	122.75	60	461.
MC	3/5/2018 12:41	0.971	110.773	27.133	0	123.24	60	459.
MC	3/5/2018 12:42	0.971	110.769	27.133	0	123.73	60	460.
MC	3/5/2018 12:43	0.971	110.763	27.135	0	124.22	60	460.
Pump_	3/5/2018 12:44	0.971	110.755	27.133	0	124.71	60	969.
D	3/5/2018 12:45	0.971	110.749	27.135	0	125.2	60	920.
D	3/5/2018 12:46	0.971	110.765	27.152	0	125.69	60	920.
D	3/5/2018 12:47	0.971	110.73	27.133	0	126.18	60	920.
Pump_	3/5/2018 12:48	0.971	110.72	27.135	0	126.67	60	969.
D	3/5/2018 12:49	0.971	110.722	27.155	0	127.15	60	920.

Figure 4 - 9 shows the power consumption over the day from the time there was a shift crew

change midday of 3/5/2018. The crew at the rig site operate on a 12-hour basis; one shift from midnight to midday, then switch the next half day throughout the drilling program. At the beginning of recording, operations had slowed down and the power supplied was majorly consumed at the two mud pumps and lighting at night.

The sudden increase at about the 7 thhour occurred when the driller engaged the draw-works to perform a trip in activity to drill ahead. Subsequent variations are expected since drilling is a function of erratic unexpected sub surface formations requiring constant power adjustment of the draw-works drill-string, and pumps for wellbore lubrication. Overall, the trend showed that power use fluctuated depending on the equipment being used at a particular time during the course of drilling.

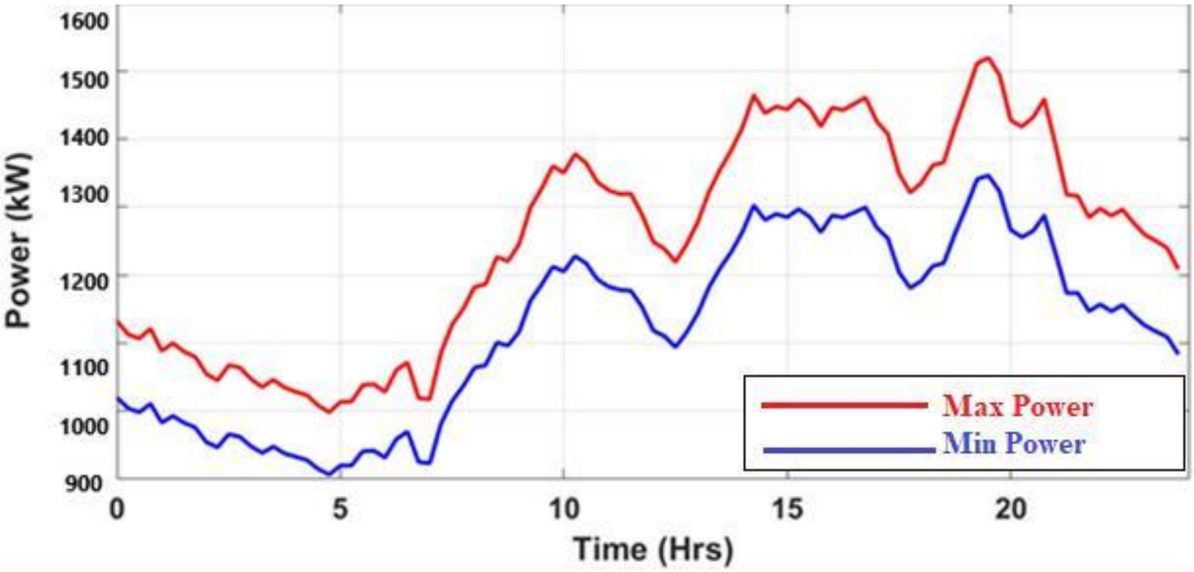


Figure 4 - 9: SCR power data logger for power in 24 hours

Figure 4 - 10 shows the real time fluctuation of the power factor as was measured from the SCR room which is a containerized capacitor bank. This gave an indication of the quality of power supplied to the rig equipment via the SCR. The rig personnel hardly modify its settings as it is highly automated. During the 24-hour period of data collection, the fluctuation was consistent with the power usage at the rig. It was noted that the SCR was capable of maintaining a consistent quality over time for higher loads used for the draw-works at about 96% efficiency. The mud pumps derive a lower power factor due to their nature of being required online at irregular intervals.

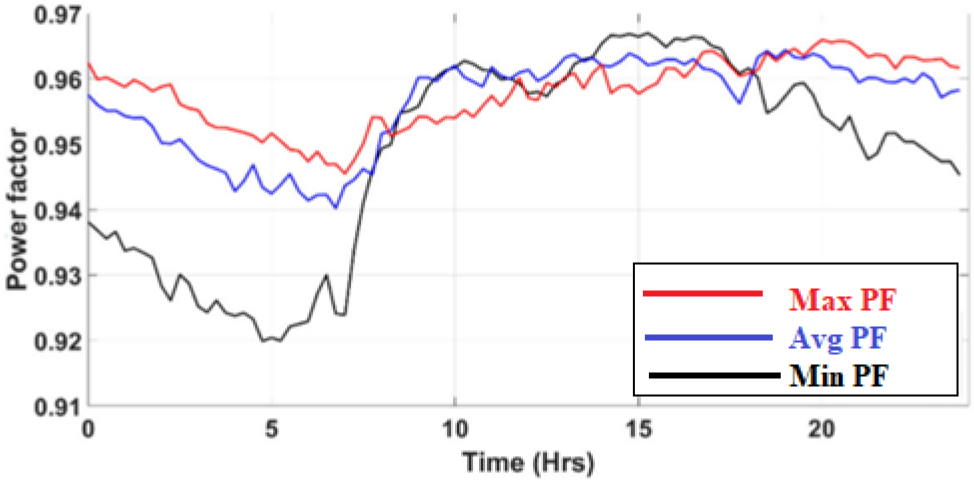


Figure 4 - 10: Power factor for 24-hour load curve

There is a resemblance of the curve patterns of the energy supply and power factor to the draw-works and the pumps. In both, they increase when the loads were engaged as shown in Figure 4 - 11. Information obtained was useful for kVA demand management in a scenario where electricity may be the cheaper option to power the rig.

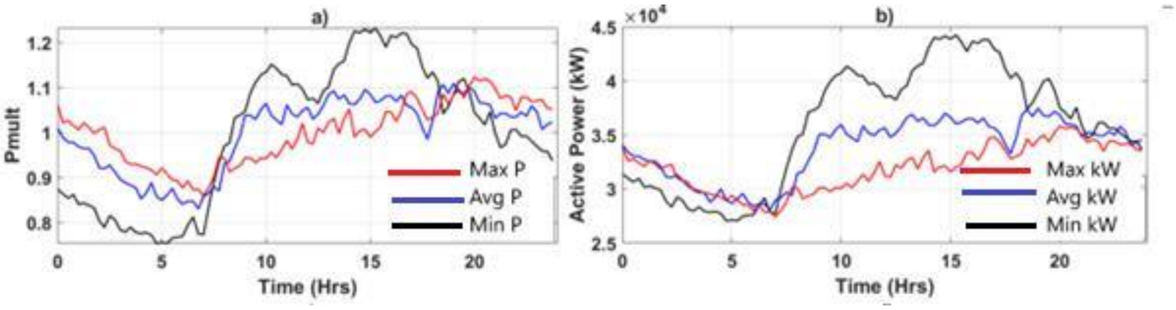


Figure 4 - 11: Mud pump 2 power factor and load curve

A comparison between the actual measurements and calculated measurements was done for March 5 th, 2018 shown in Table 4 - 9 whereby differences occurred due to the inferred drilling conditions which may not have been encountered.

Table 4 - 9: Comparison of real time and calculated values

Sn.	Description	kW - Demand	kVA - Demand
1.	Real time measurement	1429.33	718.08
3.	Calculated values	1492.00	760.00
Variation		4.20%	5.51%

Analyzing these outcomes showed that the equipment was being used optimally at near recommended manufacturer"s rating though there was still potential to save on kVA and kWh. Simple housekeeping measures like switching off lights to retrofit measures were identified and discussed for recommendation. This is assuming the SCR continues to perform as efficiently as possible.

4.4 Adequacy of Rig Illuminance at Night

With the consideration that the rig works continuously day and night, it became apparent to determine whether the rig lighting at night was adequate and safe for operations. It was noted that apart from the confined spaces of the operation rooms and the staff quarters, the entire of the rig equipment is out in the open sky susceptible to all weather patterns day and night. To this end, a Luxmeter [Appendix Figure 1 - 3] was used to measure the illuminance on May 10th 2022 at Rig 3 at night from 21:05hrs. The crew were drilling ahead and at that time were at a depth of 430m after 17 days since SPUD in. Table 4 - 10 shows the values obtained at the various locations within the rig site. These values were contrasted against acceptable standards according to

Appendix Table 1 - 3.

Table 4 - 10: Measured illuminance values at Rig 3 at night

Area	Measured Illuminance (Lux) at 21:05hrs	Activity Type/ Work Area/ Movement Area	Recommended Level of night Illuminance	Finding
Mess dining area	36 - 39	Level 3	20 lux	Adequate
Barracks / offices	469 - 485	Level 6	200 lux	Exceeded
Workshop	44 - 52	Level 4	50 lux	Adequate
Generators	101 - 103	Level 5	100 lux	Adequate
SCR	189 - 239	Level 6	200 lux	Adequate
Mud pumps	409 - 652	Level 6	200 lux	Exceeded
Shale shakers	68 - 69	Level 4	50 lux	Adequate
Draw works	54 - 65	Level 4	50 lux	Adequate
Drillers cabin	235 -265	Level 6	200 lux	Adequate
BOP	24 - 27	Level 3	20 lux	Adequate
Cellar	543 - 546	Level 6	200 lux	Adequate
Boosters & compressors	95 - 97	Level 5	100 lux	Adequate
Pipe rack / Cat walk	19 - 22	Level 3	20 lux	Adequate

The safety association for Canada‟s upstream oil and gas industry had published lease lighting guidelines for illumination at night at the rigs [22]. Since oil and gas drilling operations use rigs that are similar in nature to those of geothermal, these guidelines were adopted in this study to contrast against the data collected. Findings showed that the rig lighting at night was adequate and safe for operations.

4.5 Energy Saving Opportunities at Rig Site

From the onset of data acquisition, it was evident that rig personnel were not particularly concerned about energy saving intervention measures provided that they accomplish the target depth. Actual amount of energy consumed is immaterial to the project provided the wellbore is completed. It is only when the project is incapable of fulfill its task, because of lack of sufficient energy supply or because energy becomes too costly, that a critical look into energy use is proposed. [16]

4.5.1 Housekeeping Measures

1. Using the lights only during a night of 12hrs for one-month resulted in savings of 850 liters of diesel. From Table 4-2, 300kW was installed capacity for lighting. Keeping the lights on 24hrs a day for a month translated to 216,000kWh of energy consumed. This is equivalent to 60GJ which is powered by diesel, about 1700 liters. Assuming drilling takes place for 5 months, expected savings can be 4,250 liters at KES. 107 becomes about KES 450,000. Carbon emission saved for 108,000kWh at 0.26kg per equivalent kWh is 28 tons.

2. Regular cleaning of work-area surfaces such as the rig-floor, the generator SCR room, mud pumps, rotary table, draw-works, boosters and the compressors. Keeping rotating parts clean and greased improved the overall efficiency of the equipment and kept the working area safe.

4.5.2 Low-Cost Measures

1. Analyzing the CUSUM plot Figure 4 - 6, from the 8 th month October 2012 to the 36th month February 2016, 5553GJ of energy was saved, translating to about 153000 liters of diesel. By the end of the data series, the combined measures had saved 16,285 GJ of energy equivalent to 447,390 liters of diesel, adequate to drill about three wells to completion.

2. Scheduled maintenance of the rig equipment comprising the draw-works, mud pumps, rotary table, air boosters, and the compressors. Replacing worn out consumables such as air filters, bearings, frail wire-ropes, gaskets, and other low-cost accessories not only extended the lifetime of the equipment but also maintained safety and efficiency.

3. Further, whenever there is a down-time being experienced on site due to wait of drilling supplies, the main engines could be shut down and the auxiliary engine engaged to power small utilities.

4.5.3 Retrofit Measures

1. Replacing existing lights with LED technology which is compliant to the harsh environment of working in external terrain has been analyzed in Table 4 - 11. The energy flow proportion in Figure 4 - 2 shows that electrical lighting consumes about 13% of the energy. Lighting is crucial for drilling operations as the safety, and health of the staff is dependent on adequate sufficient lighting especially at night. Adequate lighting saves energy, and money and poor or bright light affects worker"s productivity. [23]

Table 4 - 11: Electrical lighting costs analysis

Item	Lamp type	Qty	Existing		Retrofit		Expected Investment (KES)
			Rating (W)	Total (kW)	Rating (W)	Saving (kW)	
1.	Circulating tank flood light	2	38,000	76.0	25,000	26.0	150,000
2.	Fluorescent lamps	59	3,300	194.7	2,000	76.7	2,950,000
3.	Flood light	1	22,800	22.8	15,000	7.8	90,000
Total		62		293.5		110.5	3,190,000

From Table 4-11, the energy savings projected were 110.5 kW

Given that the rig may operate for five months continuous, equation 4.3 was applied to obtain;

$kWh = 110.5_{(kW} \times 24_{(hours\ per} \times 30_{(days\ per} {}_{)} \times 5_{(months} = {}_{(kWh}$
(4.8)

Using equation 3.2, the simple payback period of 3 years was established.

Expected carbon saved was obtained as shown in equation 4.9 as summarized in Table 4 - 12.

$$Carbon\ saved\ (tn) = \frac{110.\ {}_{kW} \times 2\ {}_{hrs\ per} \times 3\ {}_{days\ per} \times 0.2\ {}_{kg/kW}}{100\ {}_{kg/t}} = 21_{t} \quad \ldots(4.9)$$

Table 4 - 12: Retrofit for rig lighting

Energy savings	397,800 kWh
Expected cost savings	KES 450,000
Expected investment	KES 3,190,000
Payback period	3 years
Carbon saved	21 tons/month

2. Motion sensors installed in the drillers‟‟ quarters has the potential to control 33 fluorescent lights whenever the quarters are unoccupied. The sensors can work automatically or can be switched off if preferred. A robust motion sensor has been quoted at KES 25,000 per item whereby there 15 are needed for each driller‟‟s cabin. Assuming a derating factor of 60% occupancy, and governed by equations 4.3, 4.8, and 4.9, the costs work out as in Table 4 - 13;

Table 4 - 13: Retrofit for motion sensors

Energy savings	235,224 kWh
Expected cost savings	KES 266,090
Expected investment	KES 375,000
Payback period	1 year
Carbon saved	17 tons/month

3. Use of solar lighting at night may replace the 30 explosive proof fluorescents lights currently installed. The panels themselves can be placed at the derrick top away from interference and exposed to sunlight. These can be used intermittently with the diesel-powered lights in the eventuality that the weather conditions may not sufficiently power the solar lamps.

A 500W solar lamp with its accessories; panels, cabling, and truss mounting, has been quoted at KES 55,000 a package. For the required illumination at night, 30 units have been analyzed governed by equations 4.3, 4.8, and 4.9 in; shown in Table 4 - 14.

Table 4 - 14: Retrofit for use of solar lighting

Energy savings	356,400 kWh
Expected cost savings	KES 403,167
Expected investment	KES 1,650,000
Payback period	2 years
Carbon saved	19 tons/month

4. Bidding for a competitive fuel supplier and signing a long-term agreement to purchase the fuel at a constant fixed price per year considering price hikes are inevitable.

5. An energy monitoring, targeting, and reporting program could be implemented by senior drilling engineers in collaboration with management. This tool would require constant logging of energy data from the SCR apart from the usual daily recording of diesel fuel levels of consumption. This way, a target band can be maintained and when exceeded, management is alerted. In geothermal drilling practice, it has been noted that whenever the subsurface is challenging to drill, the wellbore is invariably tight, and therefore no steam is harnessed, leading to economic loss. Best drilling practices recommend strict adherence to maintenance of equipment which if performed continuously and meticulously, has the indirect benefit of improving efficiency and lifetime of the equipment. [7]

Since more load is needed to the draw-works when drilling a challenging formation, it leads to longer drilling time invariably more energy consumed, only to hit a dry, non-productive wellbore. Interdependency of hard formations and energy use can be quantified via an elaborate monitoring system hence can raise the alarm and stop drilling on that site thereby saving energy.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

5.1 Conclusions

This study proposed to review the energy requirements as used for a typical drilling rig during the entire drilling program, then conduct the energy monitoring, targeting, and reporting tool to investigate energy saving opportunities. The study identified that the main components that consumed the most power output were the draw-works, the mud-pumps and general lighting. Electrical power output supplied by the diesel engines was contrasted against current KP customer rates and found to be expensive to fuel switch to electricity.

Historical data of the diesel consumed against drilled depth collected was analyzed using the energy monitoring, targeting and reporting tool. Analyzing the time series, it was noted that between the months of February and December 2017, a consistent rate of drilled depth was achieved with adequate purchased fuel, whereby it was selected as the baseline. The CUSUM plot revealed that over the years, drilling efficiency improved since the first well that was dug, until 2018 to January 2019 where drilling operations heightened causing a breakdown in energy conservation measures. By the end of the data series, the combined measures had saved 16,285 GJ of energy equivalent to 447,390 liters of diesel, adequate to drill about three wells to completion.

The targeting regression function when plotted against the time series identified an optimum energy band of 250GJ per month per rig within which when exceeded, an alarm should be sent to management. When the rigs with the highest total energy consumption per well were contrasted to their output, it was noted that majority of them hit dry wells or low-quality wells. Consequently, alerting management to make a prudent decision to terminate drilling when the 250GJ mark has been exceeded within two consecutive months can save three months“ worth of diesel fuel.

Real time measurements were conducted and contrasted against calculated values as provided by the manufacturer whereby the kW demand varied by 4.20% while the kVA varied by 5.51%. This indicated that the draw-works and the mud-pumps, which consume the highest energy within the rig, were operating optimally whereby energy intervention measures would depend on sub-surface formation encountered. Housekeeping activities majorly switching off unnecessary lights, and retrofit measures such as solar lighting and LED replacement of fluorescent lights were identified as capable of achieving significant energy intervention measures.

Illuminance at the rig was found to be adequate and safe for operations at night. In all the locations that the drilling crew access at night, the lighting installed proved to be sufficient inasmuch as retrofit measures could be introduced to obtain more modern efficient lights.

Retrofit measures included replacement to LED lights at an initial investment of Kes 3.1M and a payback period of 3 years. Installation of sensors were proposed at a cost of Kes 375,000 with a year"s payback period. External solar lighting was proposed at a cost of Kes 1.6M with two years payback period.

5.2 Recommendations

The study recommended the following measures which could be implemented to realize savings in diesel oil consumption for drilling.

5.2.1 Housekeeping measures

Unused unnecessary lighting during the day could be turned off. These lights include all the external lights at the rigs such as circulating flood lights, and the explosion proof fluorescent lamps. Further, the crew quarters have the fluorescent lamps that could also be switched off if not required both during day or night.

Regular cleaning of work-area surfaces could be undertaken. These include the rig-floor, the generator SCR room, mud pumps, rotary table, draw-works, boosters and the compressors. Keeping rotating parts clean and greased improved the overall efficiency of the equipment and kept the working area safe.

5.2.2 Low-cost measures

Scheduled maintenance of the rig equipment comprising the draw-works, mud pumps, rotary table, air boosters, and the compressors. Replacing worn out consumables such as air filters, bearings, frail wire-ropes, gaskets, and other low-cost accessories

The smaller auxiliary engine could be used whenever the rig is not using the draw-works, or mud-pumps for an extended period of time.

5.2.3 Retrofit measures

Purchasing of energy efficient LED lights compatible with the harsh environment the rigs are exposed to all year round can be done. These would cost about Kes. 4 million but has a payback period of 3 years and further has a carbon saving of 21 tons per month.

Purchasing motion sensors to automatically regulate lighting in driller‟s quarters. These would cost about Kes. 400,000 and a payback of a year, with a carbon saving of 17 tons per month.

The use of solar lamps with related accessories of solar panels and battery pack to substitute the explosion proof fluorescent bulbs at night together with the circulating tanks flood lights. The investment would cost about Kes. 1.6 million and a payback period of 2 years with a carbon saving of 19 tons per month.

Bidding for a more competitive diesel fuel supplier could be considered. This would be contrary to the single sourced supplier of diesel thus would open the market for competition and access the same diesel at a competitive rate.

Proposing an energy monitoring and targeting management program for a rig in line with ISO 9001:2015 which the company is a signatory to.

5.2.4 Further study recommendations

Collection of real-time data could be considered for all the rig equipment present in the rig whereby use of more digital fluke gadgets would be employed. This would give a more range of data analysis for monitoring and reporting.

This study can be escalated further in the field of energy automation in distribution, fault detection with preventive maintenance, or control systems automation of the rig equipment.

A study to investigate the possibility of storing idle power generated by the diesel engines in batteries that would power external lights could be undertaken.

Further, a study that would combine energy management and wear and tear of tools maintenance could be undertaken. Combined measures would result to adaptive measures to reduce drilling costs.

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APPENDICES

Appendix Table 1 - 1: Processed diesel oil raw data

Year	Month	Month	Depth (m)	Oil (ltrs)	Total Energy (GJ)	Specific Energy (GJ/Depth)
2012	1	Mar	1127	132585	4826	4.28
	2	Apr	1656	192749	7016	4.24
	3	May	2111	242756	8836	4.19
	4	Jun	2092	233627	8504	4.07
	5	Jul	1285	127387	4637	3.61
	6	Aug	1107	107344	3907	3.53
	7	Sep	590	57052	2077	3.52
	8	Oct	692	73498	2675	3.87
	9	Nov	1336	149485	5441	4.07
	10	Dec	1833	197365	7184	3.92
2013	11	Jan	2236	235298	8565	3.83
	12	Feb	1435	150642	5483	3.82
	13	Mar	2078	219954	8006	3.85
	14	Apr	1926	206895	7531	3.91
	15	May	2645	279896	10188	3.85
	16	Jun	2412	255873	9314	3.86
	17	Jul	4451	459068	16710	3.75
	18	Aug	6858	746940	27189	3.96
	19	Sep	1387	139236	5068	3.65
	20	Oct	4444	451147	16422	3.69
	21	Nov	3869	405637	14765	3.82
	22	Dec	1495	152357	5546	3.71
2014	23	Jan	1340	139122	5064	3.78
	24	Feb	546	54082	1969	3.60
	25	Mar	447	44084	1605	3.59
	26	Apr	0	0	0	0.00
	27	May	558	52930	1927	3.45
	28	Jun	669	63516	2312	3.45
	29	Jul	1835	182203	6632	3.61
	30	Aug	2602	258618	9414	3.62
	31	Sep	2038	205562	7482	3.67

	32	Oct	2427	239142	8705	3.59
	33	Nov	1950	195263	7108	3.65
	34	Dec	1372	138819	5053	3.68
2015	35	Jan	1664	170786	6217	3.74
	36	Feb	1468	160160	5830	3.97
	37	Mar	1224	136830	4981	4.07
	38	Apr	1185	132416	4820	4.07
	39	May	931	101885	3709	3.98
	40	Jun	37123	555267	126590	3.41
	41	Jul	61948	67573	232926	3.76
	42	Aug	68187	68341	308886	4.53
	43	Sep	98680	16369	407549	4.13
	44	Oct	94304	265642	371559	3.94
	45	Nov	68445	2569	274466	4.01
	46	Dec	60170	2034	222027	3.69
2016	47	Jan	1127	127582	4644	4.12
	48	Feb	641	69363	2525	3.94
	49	Mar	435	47068	1713	3.94
	50	Apr	0	0	0	0.00
	51	May	0	0	0	0.00
	52	Jun	75	7538	274	3.65
	53	Jul	969	103449	3766	3.89
	54	Aug	2057	223229	8126	3.95
	55	Sep	2790	303611	11051	3.96
	56	Oct	2301	252472	9190	3.99
	57	Nov	5720	622499	22659	3.96
	58	Dec	1984	221878	8076	4.07
2017	59	Jan	1580	172965	6296	3.98
	60	Feb	2181	224042	8155	3.74
	61	Mar	2119	211190	7687	3.63
	62	Apr	1510	147144	5356	3.55
	63	May	1919	184900	6730	3.51
	64	Jun	947	90664	3300	3.49
	65	Jul	706	67427	2454	3.48
	66	Aug	706	67427	2454	3.48
	67	Sep	460	47929	1745	3.79
	68	Oct	726	77419	2818	3.88

	69	Nov	1660	166118	6047	3.64
	70	Dec	2011	207056	7537	3.75
2018	71	Jan	2855	319702	11637	4.08
	72	Feb	2461	288959	10518	4.27
	73	Mar	1964	250067	9102	4.63
	74	Apr	2177	272939	9935	4.56
	75	May	1514	185551	6754	4.46
	76	Jun	862	96422	3510	4.07
	77	Jul	1126	114557	4170	3.70
	78	Aug	620	59400	2162	3.49
	79	Sep	600	57484	2092	3.49
	80	Oct	1278	112087	4080	3.19
	81	Nov	1234	103591	3771	3.06
	82	Dec	1492	129522	4715	3.16
2019	83	Jan	1716	158243	5760	3.36
	84	Feb	980	96467	3511	3.58
	85	Mar	620	66296	2413	3.89
	86	Apr	480	51326	1868	3.89

Appendix 1B：CUSUM Control Data

Appendix Table 1 - 2: CUSUM Control Data

Month	Raw Data		Baseline (CUSUM) Data		Control Data	
	Depth (m)	Total Energy (GJ)	Predicted Energy (GJ)	CUSUM (GJ)	Predicted Energy (kWh)	Difference (kWh)
1	1126.735	4826.099	4081.829465	-744	4451.4284	374.67037
2	1656.228	7016.072	6030.522148	-1729.55	6365.5981	650.47367
3	2110.678	8836.324	7703.034514	-2862.84	8008.4803	827.84415
4	2091.991	8504.011	7634.261797	-3732.59	7940.926	563.08519
5	1284.824	4636.881	4663.64594	-3705.82	5022.9374	-386.05677
6	1106.818	3907.336	4008.530955	-3604.63	4379.4284	-472.09233
7	589.6337	2076.684	2105.137081	-3576.18	2509.755	-433.07107
8	692.0277	2675.323	2481.977585	-3769.52	2879.9194	-204.59635
9	1336.371	5441.271	4853.353835	-4357.44	5209.2845	231.98703
10	1833.442	7184.103	6682.72405	-4858.82	7006.2456	177.85714
11	2236.102	8564.836	8164.632509	-5259.02	8461.9007	102.93512
12	1434.882	5483.383	5215.904795	-5526.5	5565.4125	-82.029314
13	2078.118	8006.314	7583.206116	-5949.61	7890.7748	115.53936
14	1926.462	7530.98	7025.06606	-6455.52	7342.5227	188.45744
15	2644.594	10188.2	9668.006411	-6975.71	9938.6409	249.5558
16	2412.192	9313.79	8812.699314	-7476.8	9098.4864	215.30399
17	1387.499	5068.193	5041.51984	-7503.48	5394.1169	-325.92363
18	1495.164	5545.812	5437.760139	-7611.53	5783.3374	-237.52587
19	1339.746	5064.049	4865.775433	-7809.8	5221.486	-157.43698
20	546.1588	1968.577	1945.1362	-7833.24	2352.5886	-384.0117
21	447.0588	1604.64	1580.418588	-7857.46	1994.3324	-389.69188
22	557.8512	1926.658	1988.167917	-7795.95	2394.858	-468.2
23	669.4215	2311.99	2398.779901	-7709.16	2798.1956	-486.206
24	1834.89	6632.199	6688.053699	-7653.31	7011.4809	-379.28234
25	2602.325	9413.688	9512.443868	-7554.55	9785.8343	-372.14648
26	2038.06	7482.453	7435.779905	-7601.23	7745.9604	-263.50718
27	2427.294	8704.755	8868.279316	-7437.7	9153.0817	-448.32647
28	1949.84	7107.575	7111.105263	-7434.17	7427.0377	-319.46275
29	1371.842	5053.022	4983.899344	-7503.29	5337.5172	-284.49539

30	1664.389	6216.615	6060.558536	-7659.35	6395.1024	-178.48701
31	1468.239	5829.816	5338.669739	-8150.5	5686.0025	143.81323
32	1224.38	4980.601	4441.19494	-8689.9	4804.4273	176.17372
33	1184.884	4819.937	4295.837297	-9214	4661.6448	158.29167
34	930.7762	3708.629	3360.64379	-9561.99	3743.0192	-34.390404
35	1127.442	4644.001	4084.43247	-10121.6	4453.9853	190.01582
36	641.2214	2524.823	2294.995023	-10351.4	2696.2494	-171.42646
37	435.1145	1713.273	1536.459908	-10528.2	1951.1524	-237.87974
38	75.24752	274.3983	212.0414653	-10590.6	650.19733	-375.79899
39	968.7353	3765.552	3500.344624	-10855.8	3880.2451	-114.69281
40	2057.039	8125.536	7505.628452	-11475.7	7814.5715	310.96484
41	1984.455	8076.356	7238.498808	-12313.5	7552.1743	524.18201
42	1580.094	6295.935	5750.326874	-12859.1	6090.3668	205.56806
43	2180.885	8155.132	7961.41823	-13052.8	8262.2865	-107.1547
44	2118.66	7687.322	7732.413593	-13007.8	8037.3389	-350.01706
45	1510.03	5356.043	5492.470808	-12871.3	5837.0789	-481.03561
46	1918.79	6730.376	6996.831735	-12604.9	7314.7886	-584.41269
47	946.6797	3300.174	3419.173207	-12485.9	3800.5117	-500.33724
48	705.6911	2454.343	2532.262797	-12408	2929.3137	-474.97035
49	705.6911	2454.343	2532.262797	-12330	2929.3137	-474.97035
50	460.3264	1744.626	1629.247151	-12445.4	2042.2959	-297.67026
51	725.9613	2818.06	2606.863372	-12656.6	3002.5927	-184.53283
52	1659.996	6046.697	6044.39098	-12658.9	6379.2212	-332.52449
53	2011.074	7536.854	7336.462895	-12859.3	7648.4029	-111.54862
54	1964.17	9102.454	7163.842419	-14797.9	7478.8405	1623.6138
55	2176.885	9934.99	7946.697396	-16786.2	8247.8265	1687.1633
56	1514.226	6754.05	5507.91241	-18032.3	5852.2469	901.8029
57	862.3688	3509.771	3108.883771	-18433.2	3495.7193	14.051602
58	1125.833	4169.874	4078.512417	-18524.6	4448.1701	-278.29559
59	620	2162.146	2216.894	-18469.9	2619.532	-457.38595
60	600	2092.399	2143.288	-18419	2547.23	-454.8306
61	1277.895	4079.957	4638.144	-17860.8	4997.8873	-917.93058
62	1234.258	3770.695	4477.549091	-17153.9	4840.1374	-1069.4426
63	1491.643	4714.594	5424.800788	-16443.7	5770.6077	-1056.014
64	1716.204	5760.061	6251.254121	-15952.5	6582.4196	-822.35874
65	980	3511.396	3541.802	-15922.1	3920.968	-409.57182
66	620	2413.169	2216.894	-16118.4	2619.532	-206.36284

67	480	1868.26	1701.652	-16285	2113.418	-245.15801

Appendix Figure 1 - 1: The SCR Room data collection

Appendix Figure 1 - 2: Digital Fluke Model 179 Multi-meter with specifications

Digital Fluke 179 Multi-meter	
AC volts DC mV	600 mV to 1000V 600mV
Accuracy	1.0% + 3
Frequency range	45Hz to 500Hz
MIN MAX AVERAGE	±12 counts for changes longer than 275minutes in duration

Appendix Table 1 - 3: Light levels for oil and gas lease sites at night

Activity Type/ Work Area/ Movement Area	Average Level of Illuminance
Level 1 Areas used infrequently, activities requiring minimal visual acuity, and pedestrian traffic areas Examples: • Walking from shacks to task site • Moving between task sites • Staging areas accessed infrequently at night	5 lux
Level 2 Areas accessed semi-regularly during a typical shift, and activities and tasks requiring minimal to moderate visual acuity Examples: • Walkways, stairs, and ladders used infrequently • Areas in which piping is laid (e.g. flare lines, steam lines, wellhead plumbing, flow lines) • Tank farms • Tasks requiring the ability to read larger labels • Manual loading and unloading • Single unit unloading and loading a load • Egress routes	10 lux
Level 3 Areas accessed multiple times during a typical shift, and activities and tasks requiring moderate visual acuity Examples: • Walkways and stairs used regularly • Walkways above mud tanks • Tasks requiring the ability to read smaller labels • Tasks requiring ongoing inspections of pipes or fittings for leakage • Loading and unloading with front-end loader • Multiple units loading or unloading simultaneously • Moving and spotting large equipment	20 lux

Activity Type/ Work Area/ Movement Area	Average Level of Illuminance
Level 4 High movement areas, and activities and tasks requiring high levels of visual acuity Examples: • Wellhead (immediate vicinity area) • Any tasks requiring the reading of gauges/ digital displays • Tasks requiring more detailed inspections of pipes or fittings • Positioning, assembly, and disassembly of large equipment on location • Lifting and lowering of loads with crane/ boom truck	50 lux
Level 5 Activities or tasks requiring ability to see fine details Examples: • Mechanical repair tasks • Makeup or teardown of equipment with small parts • Fixed control panels	100 lux
Level 6 Activities or tasks requiring ability to see very fine details Examples: • Repairing electrical motor (i.e. fine coil wiring, etc) • Repairing electric circuitry	200 lux

Appendix Figure 1 - 3: Luxmeter HI 97500 with specifications

Energy Performance Analysis of Geothermal Drilling Rigs in Menengai, Nakuru - 2

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