Diesel to Gas Engine Power Plant Conversion: A Review and Preliminary Design for an Operating Power Plant

Moses Jeremiah Barasa Kabeyi[1, *] **and Oludolapo Akanni Olanrewaju**[2]

[1] *Durban University of Technology, Department of Industrial Engineering, South Africa*
[2] *Durban University of Technology, Department of Industrial Engineering, South Africa*

Manuscript received 30 June, 2021; revised 29 June, 2022; accepted 1 October, 2022. Paper no. JEMT-2106-1312.

The continuous growth in global electricity demand to sustain the ever-growing economy and electrification programs has put pressure on fossil fuels as convenient means of generating electricity. More energy is needed to meet growing industrial energy needs and automotive application in transport with diesel and petrol being the main fuel options. In this study, an operating diesel engine power plant of capacity 119.7 MWe is analysed for potential conversion to a to a natural gas-powered plant with whose main objectives are to reduce total emissions and cost of electricity by substitution of more polluting heavy fuel oil and industrial diesel with cleaner natural gas as fuel. The study showed that the use of natural gas simultaneously reduces the cost of generation per kWh and total emissions. The conversion process involves modification of the fuel injection system to cope with new fuel injection and ignition requirements, new control for fuel injection and reduced air to fuel ratio and lowering of the engines' compression ratios by increasing the clearance volume for the engine cylinder. The conversion requires provision for natural gas storage facilities and supply system where natural gas can be stored as compressed natural gas(CNG) or liquefies natural gas (LNG). The dual fuel mode proposed a diesel/natural gas ratio of 1:4, which reduced the diesel specific fuel consumption (sfc) for diesel by 81.2% with natural gas consumption rate of 2196.72kg/h leading to annual fuel saving of USD 4.5 million computed at power plant load factor of 0.5.

keywords: *Compressed natural gas; Diesel power plants; diesel engine; engine conversion; natural gas power plant*

http://dx.doi.org/10.22109/JEMT.2022.292982.1312

NOMENCLATURE

CI	Compression ignition.
CR	Compression ratio.
DDF	diesel dual fuel.
DG	Diesel generators.
$HCCI$	Homogeneous charge compression ignition.
Hp	Horse power.
HFO	Heavy fuel oil.
$HPDI$	High-pressure direct injection.
IDO	Industrial diesel fuel.
KES	Kenya shilling.
kWh	Kilowatt-hour.
LNG	Liquefied natural gas.
LPG	Liquefied petroleum gas.
NO_x	Nitrogen oxide.
pm	particulate matter.
sfc	Specific fuel consumption.
SI	Spark ignition.
USD	US dollar.

1. INTRODUCTION

The changing climatic conditions, strict environmental regulations, high cost of diesel power generation and general sustainability concerns have created need for cleaner and cheaper fuels for diesel power plants [1]. Power generation stations where diesel engines are the prime movers for generators are known as diesel power plant [2]. Diesel engines remain competitive for power generation because of their high full load and partial load brake thermal efficiency compared to many other prime movers [3]. Conventional diesel power plants are quick to start and stop and have got capacity to burn different types of fuels other than heavy fuel oil and diesel [4–6]. The engine market is large with over 20 manufacturers of piston diesel engines for power generation generally between 10 hp to 140 hp in capacity [7]. For a long time, many developing countries like Kenya rely on hydropower for its bulk electricity generation for grid electricity to meet both base load and peak load power needs[8, 9]. This comes with low power system reliability due to seasonal variability of rainfall hence low hydro power plants availability. The need to meet the deficit occasioned by low rains or drought conditions create demand for thermal power plants [10]. It is because of this challenge that Kenya decided to build the largest diesel engine power plant in East and Central Africa, named Kipevu III in Mombasa, Kenya. The main challenge of diesel power generation is high and fluctuating fuel cost and high cost of plant operation and maintenance per unit power output[11].

Diesel engines, also called compression ignition (CI) engines have wide applications in industrial, transportation and power generation because of their intrinsic fuel efficiency, robustness, and fuel flexibility. However, since most diesel engines run on fossil fuels particularly diesel or heavy fuel oil, they are associated with significant environmental pollution with many countries not allowing diesel power plants due to strict environmental regulations and high cost of power [12, 13]. This has forced manufacturers to look for alternative fuels for higher efficiency, less environmental impact and relatively low costs. Among many options, the conversion of conventional CI engines to dual-fuel (DF) operations using is one of the most measures. The conversion does not need a completely new engine design, except for few modifications like installation of a r gas mixing and injection system on the fuel intake and reduction of compression ratio. [14–17].

Therefore, natural gas has emerged as a leading alternative for power generation as the global community looks for a cheaper, cleaner and sustainable energy options [18]. Natural gas power generation per kWh is significantly lower than the that of industrial diesel (IDO) and heavy fuel oil (HFO), hence its preferred use as an alternative or substitute of oil will significantly reduce the high cost of diesel power plant electricity generation[19]. It also offers a much cleaner power production process since it produces around 20% less pollutants compared to diesel [20]. In the case of Kipevu III power station, power is generated purely using diesel engines running on heavy fuel oil or industrial diesel [21]. Full or partial conversion of these diesel engines ran on natural gas will play a big role in reducing cost of electricity per kWh of the power station and significant reduction of environmental pollution. The use of natural gas (NG) as a fuel for diesel engines with higher Hydrogen/Carbon ratio of 4, theoretically decreases the carbon dioxide emissions by 25% compared to diesel oil which has H/C of about 1.87. With biogas, a high of about 75% reduction can be realised. On the use of natural gas in a compression-ignition (CI) engine as compared to spark ignition leads to higher thermodynamic conversion efficiencies. With high octane number of methane, there is reduced risk of engine knock for higher compression ratio (CR)[22, 23]. Therefore, theoretically, natural gas is a superior fuel for diesel fuel as energy for diesel engines. Natural gas generators are more reliable than diesel generators mainly on the account of higher reliability of natural gas fuel supply compared to diesel[24]. Natural gas can be supplied through pipelines as opposed to diesel which has to be transported and stored onsite. However, natural gas supply is vulnerable to gas network incidents. The relative reliability of natural gas power plants is affected by the frequency of gas disruptions, particularly those coincident with power outages [15, 24].

Combustion of natural gas can take place over a wide range of physical and thermodynamic conditions. They include varying compression ratios with higher compression ratios in compression ignition engines compared to spark ignition, varying overall fuel-air equivalence ratios, different injection strategies e.g. port injection vs. direct injection, homogeneous vs. heterogeneous in-cylinder fuel stratification, and wide range of in-cylinder temperature and pressure conditions. Different ignition systems can also be used for natural gas e.g., laser ignition, spark ignition, turbulent jet ignition with pre-chambers, diesel-ignited dual-fuel combustion, homogeneous charge compression ignition (HCCI), diesel micro-pilot ignition, high-pressure direct injection (HPDI) and diesel leading to stratified diesel-ignited dual-fuel combustion, and reactivity controlled compression ignition (RCCI). In simple gas turbine plants used of natural gas produces 2–3 % more power output compared to oil, its higher hydrogen to carbon ratio (H/C ratio) hence higher specific heat of combustion [14, 25].

Dual fuel engines also called diesel dual fuel (DDF), are engines that work on both diesel and gas. Some pilot injection of diesel oil is usually applied for ignition in an electronically controlled process where a mixture of fuel and air are injected into the intake manifold [26, 27]. An LPG–diesel dual fuel engines is an engine that is designed to use liquefied petroleum gas (LPG) as the primary fuel while the secondary fuel used is diesel[28]. The LPG dual fuel engines have the benefit of high thermal efficiency at high power output, but also characterized by reduced the performance during part load conditions mainly because of poor charge utilization [29, 30].

In this study, the potential of converting a conventional diesel power plant to a dual duel diesel engine power plant is undertaken. The main aim of the conversion is to reduce power generation costs and reduce greenhouse gas emissions from diesel engine power plants. Specifications for converted power plant were developed from design analysis.

2. PROBLEM STATEMENT

Diesel fuel or industrial diesel oil (IDO) is the main fuel for use by diesel engine prime movers in industrial, transport, and in diesel power plants; unfortunately it is polluting and non-renewable [1]. Hence, there is a dual need to reduce emissions and cost of power from diesel engine power plants [4]. Reliance on diesel power especially during low rains contributes to high cost of grid electricity. The current trend of using diesel fuel has a negative impact to consumers in terms of huge electricity bills [10]. The environmental impact of diesel power plants includes emission of SOx and NOX emissions, then SO2 undergoes chemical reactions with moisture in the atmosphere to form sulfuric acid [31, 32]. The emissions also react with the ozone layer leading to its depletion [9]. The greenhouse gases are responsible for the global warming in addition to other health effects to humans like chronic respiratory diseases, lung cancer, heart diseases, and damage to brain, liver and kidneys[3, 11, 33].

It costs about KES. 6.00 to produce 1 kWh of electricity using natural gas [19] which is much lower compared to diesel power generation which costs about KES. 30 [2, 10]. Therefore, conversion to natural gas will reduce the cost of power generation. Diesel generators (DG) are economically cheaper to purchase, but technically more y expensive to operate and maintain especially during partial load conditions which are less efficient as a result of high fuel cost delivered to the power plant from far away. Diesel engines also have many moving parts leading to high rates of failure and increased cost of operation and maintenance [5, 6]. As a double coincidence, diesel fuel is often delivered to remote power station by tracks and rail powered by diesel engines. Thus, since the price of diesel fuel is very dependent on the of diesel is high, this further increases the cost of diesel power produced. On the contrary large scale gas supply is often delivered by gas pipelines which are cheaper to operate and maintain. For cites which can only be conveniently accessed by air instead of road or rail for fuel delivery, the of power is higher than that power produced in those accessible by boat or by land [30, 34].

As far as the environment is concerned, the diesel power plants have significant environmental impacts besides the power plants being non-optimal and expensive to operate and maintain. Operation of diesel engines contaminates local air and soil and emit significant amounts of greenhouse gases. Since the use of these diesel generators is not optimal and is additionally very expensive, there is growing need to identify alternative fuels and means of power generation to reduce the cost of power and mitigate environmental impact of diesel power plants [27, 35, 36].

3. RATIONALE OF THE STUDY

As an alternative fuel, natural gas can be produced by purification of biogas, also called bio methanation. Natural gas is also abundant in supply, is cleaner and is cheaper than diesel and heavy fuel oil l [1]. Conversion to dual-fuel engines also called diesel dual fuel has an added advantage over full conversion to natural gas since they can run on either natural gas or diesel mode when either of the fuels is unavailable. Additionally, natural gas is clean and leads to 20% to 30% reduction in CO2 emissions, 70% to 90% reduction in CO emissions and generally 50% to 87% reduction in NOx emissions [8, 37]. In this conversion approach, the engine compression ratio is maintained relatively high and hence the engine performance is retained upon conversion [38]. Another benefit is the additional degree of freedom needed to control combustion like the homogeneous charge compression ignition (HCCI) and the partly premixed compression ignition (PPCI). This means reduction in pollution tariffs and less impact on environment. Converting the existing diesel engines through modification cost less than doing overhaul of the plant [20]. In many countries around the world, there is interest in converting diesel power plants mainly to increase energy security and reduce cost of unit power [39, 40]. Engine modification and proper use of natural gas can lead to better system efficiency, reduction in greenhouse gas emissions and lower electricity costs leading to competitive economies and a cleaner environment for humanity [40–42].

Conventional diesel engines produce significant amounts of carbon dioxide, particulate matter and unburnt fuel to the environment and Nitrogen Oxides (NOx). After treatment can be applied to reduce both particulate (PM) and NOx emissions making the process expensive. The diesel –LNG, diesel-CNG, diesel-LPG engines take advantage of the diesel engines high power density, high conversion efficiency and high power density with low emissions density of natural gas to improve the performance of diesel power plants. LNG can be used as a fuel for heavy duty commercial vehicles as well as light duty vehicles [43]. By using a fuel with low carbon content like natural gas which is reach in methane, either in liquid r gaseous form leads to significant reduction of carbon dioxide emissions as compared to use of diesel as the only fuel. With ese of vaporization there are additional benefits in terms of engine-out PM emissions, and thus indirectly of engine-out NOx emissions hence less. CO2 is produced for same power output at almost similar fuel conversion efficiency. Although LPG is liquid in normal conditions, it vaporizes much more easily and faster than diesel which is equally in liquid form which effectively reduces the reduces to zero the PM emissions except for those coming from the pilot oil used [43].

Dual fuel engines may be a good alternative for many diesel engine applications like trucks, boats, commercial vehicles, industrial applications and power generation, off-road vehicles and tractors, whose modification to install additional fuel system elements is not limited by significant constraints. Some further modifications that may be quite appealing are on after-treatment system leading to very low concentration of soot in the exhaust flow, and reduction in NOx reduction by undertaking minor modifications. Other benefits of natural gas substitution of diesel are lower CO2 emissions, increased plant availability, easy of substituting natural gas with biomethane and hydrogen which are renewable, smoother combustion hence reduced noise and less diesel fuel injection hence reduced compression needs and energy consumption [44, 45].

4. DIESEL POWER GENERATION

A. Introduction to diesel power plants

Diesel power generators vary in size and applications ranging from centralized, decentralized, and off grid applications in power generation [46, 47]. The power plants have a wide range of applications which include use as peak load plants, mobile power plants in various field applications, standby power plant units, emergency power plants, nursery plants, black start plants and central power plants [2, 48, 49].

B. Design and construction of Diesel Engine power plant

The overall performance of a diesel engine power plant is a function of many factors with efficiency being influenced by the size, load profile, state of the engine and mode of operation and maintenance of the engine and the power plant which affect the engine performance [2, 34]. The best design strategy for diesel engine power plants is to have a generator whose rating is equal to the prevailing demand. However, since the demand is dynamic, it is recommended to select many generator sets of varying sizes corresponding to both peak load, base load and the load profile [7].

Diesel engines are mainly used as prime movers for the diesel power plants where they rotate electric generators/alternators coupled to them to generate electricity [49]. The diesel engine drives an alternator which converts mechanical energy into electrical energy [28]. The main components of a diesel power plant includes, the engine, the fuel storage supply system, engine charge air intake system, engine exhaust system, engine cooling system, Lubricating System, Engine Starting System and speed governing and control system, engine start system, instrument and control air system [49]. A diesel engine can either be four-stroke or two-stroke, V-engines or inline engines among other designs [47]. Four-stroke engines are mostly used due to their higher efficiency and are more balanced compared to two stroke engines. In diesel engines, air is compressed adiabatically in the cylinder which causes elevation of the temperature of air before atomized fuel is injected to the combustion chamber to initiate combustion. The high temperatures due to the air compression ignite the diesel spontaneously with hot expanding products of combustion causing the movement of the piston connecting rod and hence crank shaft rotation [48–51]. When combustion is complete, the combustion gases expand pushing the piston downward which then drives the crankshaft [48, 52].

B.1. Natural Gas Fuel for diesel power plants

Different types of gaseous fuels can be used in power plants as fuels. Examples of the gaseous power plant fuels are natural gas, oil-associated gas extracted during oil production, blast furnace and coke oven gases released in a metallurgical process, synthetic gases from solid fuel gasification process, biogas, biomethane etc. Natural gas is the most dominant gaseous fuel from the primary energy category [15, 40]. Natural gas exists as a mixture of several gaseous carbohydrates CnH2n+2, having methane (CH4.) as the main constituent element Natural gas is a fossil fuel developed over the millions of years from biomass being subjected to intense pressure and heat which turns it to kerogen first then upon further heating kerogen first forms oil and then turns into NGL, and followed by natural gas formation. For this reason, natural gas is found only in the deep underground reservoirs together with oil reserves since they were formed basically by the same process. Natural gas can be trapped under high pressure within the reservoir in sedimentary rocks where it cannot easily migrate. Natural gas can also be found in the gas-rich shale layers as shale gas, coal as coal-bed gas, or in sand layers. The shale layers are highly impermeable and need special production technology which for now is not economically feasible [53].

Raw natural gas is often extracted through the vertical gas wells located beyond one thousand meters deep in most conventional reservoirs. Due to the high pressure of natural gas underground, the gas naturally flows up to the well head, for piping to gas processing facility where higher hydrocarbons are extracted and purification done to remove contaminants like carbon dioxide, hydrogen sulfide, water, SO2, mercury, and a few others. The composition of natural gas mainly depends on the type and location of the gas field, and the geology of the area. The main component remains methane varying between 70 and 98% by volume. The contaminants like Sulphur dioxide (SO2) , higher hydrocarbons, and other valuable products can be removed and further processed in a value added products in petrochemical plants and used in chemical production [52, 54]. Natural gas is a naturally occurring mixture of hydrocarbons often found in petroleum, coal fields and as a hydrate on the seabed. It is formed by composition of organic matters [55]. Liquid natural gas is formed by cooling natural gas to a temperature of -162oC at atmospheric pressure [56]. Natural gas is mainly made of methane (CH4) and smaller amounts of hydrogen sulfide, ethane, nitrogen propane, helium, carbon oxide (CO2) and moisture or water vapor. The main constituent CH4 which is normally about 90% [37]. A natural gas engine is a mechanical engine that uses natural gas as a fuel to produce power (mechanical or electrical). There are three natural gas engine modes based on fuel namely: Spark-ignition reciprocating internal combustion engine, Gas-fired turbines, and Dual fuel gas engines [45, 57, 58].

The main characteristics which make natural gas attractive as a fuel for power generation and other engine application include affordability, wide availability, environmental friendliness, compatibility with the conventional spark ignition and compression ignition engine and low operational cost compared to other fossil fuels [59]. The advantages of natural gas power plants include efficient combustion, low cost, complies with environmental regulations, high availability and supply, cleaner power [8].

Natural gas has got wide application across industries, e.g. on average about 38% the global consumption was used by the industrial sector, 30% for residential applications, 7% was used in transportation, the commercial sector used 13% while non-energy sector like fishing and agriculture used 12% of the total natural gas consumption which implies that the energy sector is the largest consumer of natural gas. Storage and handling natural gas is the main challenge natural gas application. The gas can be stored as compressed natural gas (CNG) form at about 3600 psig or 250 bar or as liquefied natural gas (LNG) at t 260 $^\circ F$ or 160 $^\circ C$)). Cryogenic natural gas storage as LNG is technically more complicated and economically more demanding, has the benefit of lower storage space and weight requirements [14].

B.2. Composition of compressed natural gas

Compressed natural gas has the following typical properties which may be slightly different from the uncompressed natural gas. These properties are summarized in Table 1 below. From Table 1, it is noted that CNG as a fuel is a mixture of several organic gases with the highest component being methane. Other common constituents of CNG are ethane, butane, propane, Nitrogen, and carbon dioxide.

Table 1. Typical composition of compressed natural gas in Vol% [18]

	Element	Symbol/Formulae	Volumetric %
1	Methane	CH4	94.42
2	Ethane	C2H6	2.27
3	Propane	C3H8	0.03
4	Butane	C4H10	0.25
5	Nitrogen	N2	0.44
6	Carbon dioxide	CO2	0.57
7	Others	-	2
	Total		100%

B.3. Thermodynamic properties of natural gas

The thermodynamic properties of compressed natural gas, diesel and gasoline are presented in Table 2 below.

From table 2, it can be noted that CNG, diesel and gasoline have differences in thermodynamic properties with diesel being denser and hence heavier with the highest molecular weight among the three fuels, CHG has got higher auto ignition point and is more flammable. With highest octane number, CNG is more ideal for spark ignition applications than compression ignition engines.

B.4. Converting Diesel engines to gas engines

It is possible to convert a diesel engine to a full gas engine but for this to work, several modifications should be done [62]. They include the following changes are necessary:

Table 2. Thermodynamic properties of compressed natural gas [18, 60, 61]

	Property	Unit	Gasoline	Diesel	CNG
1	Stoichiometric Ratio	Ratio	14.2	15	15.7
2	Cetane number	Unit	N/A	40-55	N/A
3	Octane number	Unit	96	N/A	120-130
4	Lower calorific value	Mj/kg	42.2	43.5	45.9
5	Higher calorific value	Mj/kg	45	45.6	50.3
6	Density at 25°C (DIN 51757)	Kg/m^3	749	837	2.52
7	Molecular weight	Kg/kmol	106.2	186	16
8	Minimum ignition energy	Mj	0.33	0.5	0.26
9	Lamilar flame speed	cm/sec	30	-	37.5
10	Flammability unit	Vol% in air	5.2	1	15.6
11	Adiabatic flame temp	K	2227	-	2266
12	Vaporization energy	Mj/m^2	293	192	215-276
13	Flash point	K	266	325	124
14	Combustion Energy	Kj/m^3	32.6	36	24.6
15	Auto ignition point	K	505-755	477-533	900

i.) Remove the engine fuel injector pump and fuel injection nozzles.

ii.) Reduce the design compression ratio to prevent fuel pre-ignition by increasing the stroke volume.

   a. Exchange the piston for one that effects a lower compression ratio.

   b. Cut off o material from the piston top and modify the piston groove.

   c. Machine off some material from the combustion chamber side on the cylinder head.

   d. The piston is modified by use of thicker cylinder gasket [62].

iii.) Modification also involves the introduction of an ignition system with distributor, ignition coil, and spark plugs for ignition. The ignition system chosen is a function of the number of cylinders for the engine. For single cylinder engine, a transistor type system may be required and often a magnet is installed on the flywheel. But the multi-cylinder engines require installation an ignition distributor. [62].

iv.) Installation of electric supply (alternator), Modification also requires the introduction of an ignition system for conversion to a spark ignition system with an alternator and storages device in form of batteries with a charge regulator. Some diesel engines already have alternators and batteries for the stator which can serve the purpose.

v.) installation of a mixing device This is needed to mix the air and fuel for supply to the combustion chamber. This may consist of a venturi mixer, a simple mixing tank or pneumatic control valve [62].

vi.) The engine speed control is achieved by variation of the supply of the air/fuel mixture.

B.5. Conversion of Diesel Engine to Dual-Fuel Engine

By 31 July 2019, the world had 27,765,376 natural gas vehicles using engines running on natural gas as compression ignition or spark ignition engine modes. The compression ignition natural gas engines are more popular because of their higher reliability and fuel efficiency [56]. In the conversion of a diesel engine to dual engine, the main engine components and systems that should be modified include the fuel system, its fuel injection system, the fuel gas system, air intake or charging system, the engine exhaust System, the combustion chamber, and Control System. Overall, the air fuel ration has to be reduced [39]. On engine performance, the efficiency varies with the power required for gas compression, hence the more the power requirement, the less the engine efficiency. For a gas engine optimum shaft thermal efficiency of 49.6% in gas operation at about 85% to 90% loading can be realized upon conversion. The compression energy is about 2.5% of shaft power shaft power output, at inlet pressure of 16 bar. If the gas is delivered as a liquid, the compression work consumes about 0.8% of engine shaft power output.

In a study at the gas powered Ringgold Cogen power station, the plant heat rate is about 9300 kJ/kWh which corresponds to an efficiency of around 39% with plant availability of about 90.1% over five years (12 months) of operation [63]. In this plant, the diesel engines ran on natural gas compressed to 250 bars. The injection was with pilot oil amount of about 5% of total fuel intake. The Ringgold Cogen Power plant's average specific lubricating oil consumption was about 0.8 g/kWh [4].The main limitation with gas engines is higher NOx emissions compared to 100% diesel engine fuel mode. As a control measure, a catalytic exhaust purification system may be is recommended to reduce NOx emissions from a realized level of 1300 mg/MJ(fuel) to a desirable level of 200 mg/MJ or less as in a case of existing natural gas power plant in Finland [4].

The conversion of diesel engine to dual-fuel engine using natural gas in this study involves the following proposed modifications to the diesel engines in Kipevu III power station.

i.) Introduction of Dual-Fuel Electronic Control Unit (ECU). The role of the ECU is to send high speed pulse-modulated signals to natural gas and diesel fuel injectors and hence control amount of fuel injected. This control unit determines and controls the supply of dual fuel to the engine ensuring optimum fuel control which is usually 8% diesel combined with 92% natural gas under steady conditions.

ii.) Turbo-Charger Air Bypass (TAB). This controls the amount of air provided by the turbocharger by use of bypass valve usually of a butterfly design.

iii.) Pistons and combustion chamber modification The overall objective is to change the compression ratio and are re-designed the combustion chamber to influence combustion characteristics including flame flow. The piston groove may be modified as well as the bowl while the length of the connecting rod may also need modification [64].

The conversion to CNG for CIE (compression ignition engines) leads to better engine performance with reduction in engine emissions which are mainly in the form of nitrogen oxides (NOx), (HC) hydrocarbons, and carbon dioxide (CO2). However, other studies have shown that the use of CNG diesel engines ultimately leads to an increase in NOx emissions in the engine exhaust [65]. In another study, a performance analysis was done for a diesel-CNG (dual fuel) engine of specifications 2.5-liter (cc) cylinder with 4-cylinders and a common rail direct injection diesel engine. The engine performance and exhaust gas emissions of several diesel-CNG dual fuel blend ratios, i.e., 100:0, 90:10, 80:20, 70:30, 60:40 and 50:50 was analyzed. In this study, it was observed that for engine loading of 100%, 75%, 50%, the engine brake torque and brake power at engine at a speed between 2000 and 3000 rpm was higher compared with 100% diesel only engine mode. However, it was at 50:50 diesel-CNG ration that the highest brake torque and brake power were achieved but with the highest brake specific fuel consumption, meaning that more fuel was consumed. Emissions for the dual fuel mode in this study showed that as more and more CNG was added to the dual fuel mode, there was an increase in the unburned hydrocarbons and carbon dioxide emission, but CO emission decreased. The study further showed that NOx emission concentration is generally remains unaffected by the changes in the natural gas-diesel fuel ratio in the engine [30, 44, 65]. Therefore, this implies that the conversion to CNG leads to increase in power output and reduction in emissions except for NOx.

5. MATERIALS AND METHODS

A. Introduction

This study targeted the largest diesel power plant in East and Central Africa, namely Kipevu III 120 MW power plant which is equipped with 7 Wärtsilä W18V46 of capacity 17.1 MW running on heavy fuel oil. The engine specifications are specified in Table 3 below. From Table 3, it is established that the power plant has got seven V-engines of weight 237 tones and run at a constant 500 revolutions per minute (RPM). Figure 1 below illustrates the external appearance of Kipevu III 120 MW power station. Figure 1 above shows Kipevu III power station at final stage of construction with main features being the power plant structure, chimneys, fuel tanks and other equipment with the Indian Ocean at the background.

Table 3. Engine Technical Specifications [21]

	PARAMETER	SPECIFICATIONS
1	Configuration	V-Engine
2	Number of Cylinders	18
3	Cylinder bore	460 mm
4	Stroke	500 mm
5	Speed	500 rpm
6	Mean piston speed	9.67 m/s
7	Mean Effective Pressure	24.3 Bar
9	Swept Volume per cylinder	96.4 dm^3
10	Number of Inlet Valves	2 Per cylinder
11	Number of outlet Valves	2 per Cylinder
12	Direction of Rotation	Clockwise
13	Engine Length	13.580 m
14	Width	5.347 m
15	Height	5.488 m
16	Weight	237,000 Kg

Fig. 1. Kipevu III 120 MW diesel engine power plant (Photo taken by 1st Author During Plant Construction).

B. Methods and Procedure

For a successful conversion of a diesel engine power plant to a dual-fuel natural gas the following procedure is applied:

i. Obtain existing design specifications of the diesel engine.

ii. Modification and addition of parts of the engine.

iii. Reduction of the compression ratio.

iv. Identify the appropriate Gas Storage and Gas Supply System.

v. Draw a layout design of the Dual-Fuel Power Plant.

C. Overview of the Design

In the design of a dual-fuel engine power plant, the following modifications and additions need to be done on the existing diesel power plant.

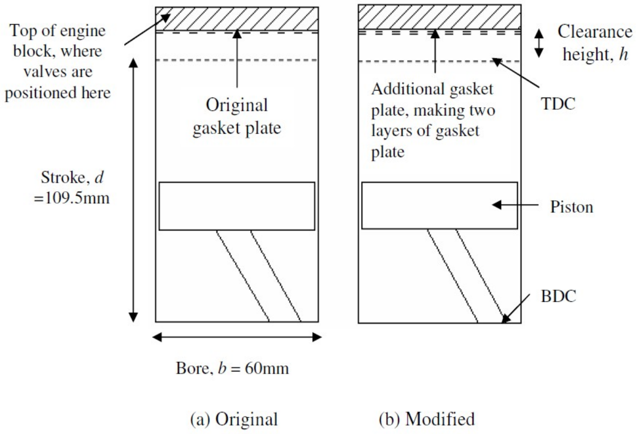

Fig. 2. Additional Plate to Increase Clearance Volume [61].

6. MODIFICATION OF THE FUEL INJECTION SYSTEM

For successful conversion of the injection system, a D-GID® Electronic Control Unit is introduced before the natural gas and diesel are supplied to the combustion chamber or the cylinder. In this study, a D-GID® control unit is used. This is the system is the first technological platform developed by Ecomotive Solutions. The control units allow proper and adequate mixing of the fuel based on the engine condition and need. D-GID® Control Unit helps to determine correct amount of diesel fuel injected and air/gas mixture dosage dynamically, modifying it in real time based on determined need [66]. Overall performance of a converted engine is a function of the load conditions, fuel mixture homogeneity, and combustion chamber design which affects flame speed and fuel mixing [67, 68].

A. Reduction of the Compression Ratio

Natural gas use as a fuel for diesel engines requires a lower compression ratio (CR) as compared to pure diesel fuel. Therefore, the engine design must be modified to enable it to have a lower compression engine than designed [64]. For this, a plate is added s added between the piston head and the engine cylinder block just like a seal between the engine block and the piston head to increase the clearance volume between the piston top dead center (TDC) and the cylinder head. The plate shape should be similar to the shape of the top face of the engine piston head [66]. The plate added as in form of gasket plate which normally exists for all engine blocks and acts as a seal between the piston head and the engine block. In the cylinder assembly, a gasket is placed between the top of the engine block and piston acts as a seal between the piston head and the engine block [61, 66]. Figure 2 below demonstrates the place for the extra plate to added in the modification Figure 2 demonstrates the proposed modifications for the combustion chamber aimed at reducing compression ratio. An additional gasket is introduced effectively reducing the clearance volume along the cylinder axis.
For one cylinder:
Swept volume $V_s = \frac{\pi \times b^2 \times l}{4}$
b- bore diameter.
l- stroke length
V$_c - Clearancevolume$
$Compressionratio$C, R=V$_s + V_c \frac{}{V_c}$
Additional plate creates an extra volume V$_{plate}$
V$_{plate} = \frac{\pi}{4} \times b^2 \times t$
Where t – plate thickness
The new $C, R = \frac{V_s + V_c + V_{plate}}{V_c + V_{plate}}$

B. Gas Piping and Supply System

A gas supply system is required to supply natural gas from storage tank to the dual-fuel engine [1, 60, 66]. It includes: an industrial gas filter, a pressure regulator, a gas shut-off valve and pipes.

C. Gas Storage System

Natural gas is typically stored in underground or above ground based on quantities, state, and application. Where the gas is stored above the ground, specially fabricated tanks that limit access is used. Transportable or mobile tanks can also be used for natural gas storage. This system makes loading and transportation easy and cheaper in many applications [55]. Natural gas can be stored as CNG (Compressed Natural Gas) or LNG (Liquefied Natural Gas). LNG takes up about 1/600th the volume of natural gas in the gaseous state. The natural gas liquefaction process involves removal of certain undesirable components, such as dust, acid gases, helium, water, and heavy hydrocarbons. The natural gas is then condensed upon cooling to form a liquid. This is at approximately -162$^{\circ}C$ and maximum pressure about 25kPa. The choice of the storage facilities depends on the consumption rate of the fuel. For large volumes of natural gas, it is easier and convenient to store natural gas in liquid state. Other equipment is needed for the process of regasification of LNG, which converts LNG from liquid state to gaseous state before use. This needs a heat exchanger using ambient air or sea water as the source of heat. Other required equipment includes an LNG pump, vaporizer, and a compressor. On the other hand, in selecting CNG tanks, the most important parameter is the storage pressure for the natural gas [55, 56].

D. Conversion of injection system

There is need to convert the injection system to handle both natural gas and diesel fuel. In this study, a D-GID® Electronic Control Unit is installed, as shown in Figure 3 just before the natural gas and diesel are injected into the engine. The D-GID® system was a developed of Ecomotive Solutions. It facilitates the injection of both diesel oil and natural gas in form CNG, liquefied natural gas (LNG), Syngas, bio-methane, and other gases to the engine cylinder. The D-GID® Control Unit establishes the quantity of diesel oil and natural gas to inject and air/gas mixture dosage through modification in real time based on engine load conditions and requirements [69, 70]. Figure 3 below illustrates the new injection system to facilitate dual fuel operation of the power plant engines Figure 3 above illustrates the injection system for the proposed dual fuel system with related elements like the CAN-BUS systems, LNG storage and injection dynamic adjuster.
The control system manages and controls the quantity of diesel fuel injected, which can be reduced to as high 80-90% during in steady conditions. However, the average diesel oil substitution rate under dynamic load conditions is generally 40-50%. This D-GID® ECU manipulates the fuel ratios to maintain engine proper performance under dual fuel mode.

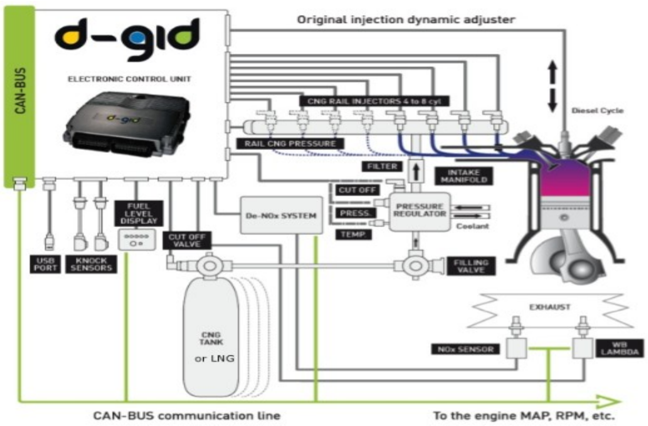

Fig. 3. D-gid® electronic control unit injection system [69, 70].

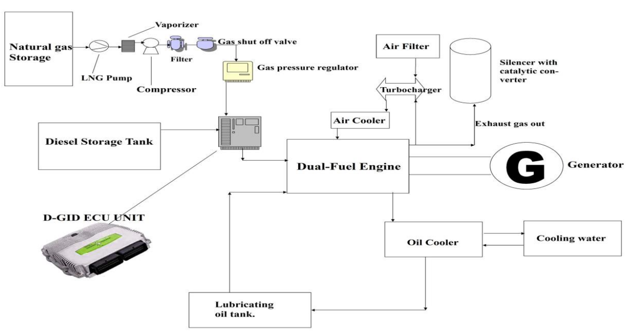

Fig. 4. The Dual fuel system mode.

E. Converted system

Figure 4 below illustrates the proposed dual diesel-CNG system for conversion of the diesel power plant to dual fuel power plant. From figure 4 above, the main elements of the proposed system are the D-Gid ECU unit, natural gas storage and handling facilities, and engine prime mover with all the necessary systems charge air system, fuel system, generator, engine units, and cooling system.

7. RESULTS AND DISCUSSION

A. Parameters before and after conversion

Table 4 highlights the before and after conversion of the parameters From table 4, it is noted that the conversion involves reduced compression ratio from 22:1 to 17:1, the specific fuel consumption reduced by 15.3% and fuel cost per unit reduced by 27.9% while load factor was maintained at 0.5 for the purpose of performance analysis.

B. Cost Analysis

Table 5 the estimated cost of investment, savings and payback period for the project. From table 5, the annual cost of savings is higher than the cost of investment meaing that the payback period is less than a year, i.e. 4.06 months.

The relationship between savings in fuel cost and time duration is presented in figure 5 below. Figure 5 shows a graph of cumulative fuel cost savings against period in months with the payback being about 4.06 months. This is very encouraging and attractive payback period for potential investors and financiers.

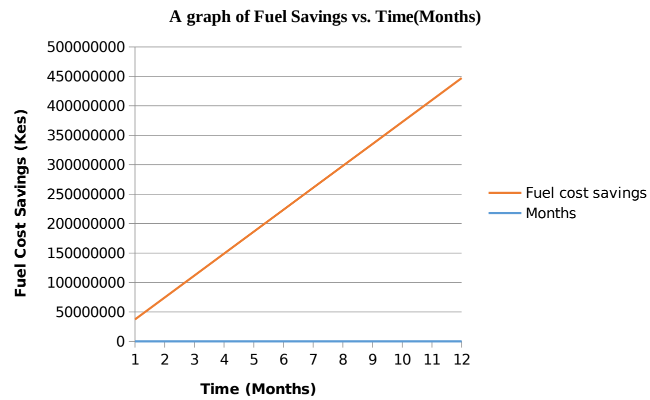

Fig. 5. A graph of Fuel Savings vs. Time (Months).

C. Discussion

C.1. Global trend

Growing world population, economic growth, industrialization, electrification of industrial and commercial operations, rural electrification, and modernization have combined to accelerate energy demand particularly in form of electricity [71–73]. Energy consumption is further expected to increase significantly while the energy diversity is also widening. Global energy consumption is expected to grow from about 575 quadrillion British Thermal Units (BTUs) in 2015 to 739 quadrillion BTU by the year 2040, with natural gas expected to account for a significant portion. Natural gas is stored mainly in form of LNG which is technically more complicated and economically more demanding, but has less space requirements for storage.

C.2. Benefits of conversion

Notable advantages of dual fuel engines over standard diesel combustion include elimination of smoke, 25% reduction of carbon dioxide emissions, from 40 to 80% reduction in carbon monoxide emissions, improved fuel economy by over 8% improvement, elimination or reduction of chances of engine knock even at high loads and high compression ratios of 17.5 and even more [25].

Natural gas is increasingly being attractive for use as a transportation and power generation fuel with many benefits like high resistance to auto ignition due to high octane number, that allows use of higher compression ratios, it has lower carbon-to-hydrogen ratio (hence less post-combustion carbon dioxide emissions, the gas is suitable for lean combustion (leading to higher combustion efficiency and with well-established infrastructure for production and in many countries globally compared to diesel [14, 45, 74]. The many advantages of natural gas make it an ideal fuel for transportation, industrial power generation, and residential applications. Therefore, the use of natural gas as a combustion fuel for internal combustion (IC) engines will remain an attractive energy conversion strategy within foreseeable future [14, 28, 75].

C.3. Challenges of conversion

On the negative side, the conversion requires that the charge composition is carefully controlled, to avoid misfiring or knocking. Injection must be optimized to achieve the best trade-off between engine performance and pollutant emissions; hence oxidation catalyst must be designed from scratch for the exhaust gas recirculation system as a result of higher concentration

Table 4. Parameters before and after conversion

	Parameter	Units	Original parameter	Parameter after conversion
1	Compression ratio	Ratio	22:01	17.1
2	Specific fuel consumption	Ratio	3,400	2,878.70
3	Fuel cost per hour	KES	189,190.50	134,164.00
4	Load factor	Ratio	0.5	0.5
5	Fuel cost per kWh	KES	11	7.9

Table 5. Cost Analysis Table.

	Item	Cost (KES)
1	Total cost of investment	153, 492,500.0
2	Annual savings in fuel cost	453,407,867.6
3	Payback period	4.06 months

of HC and CO, and presence of traces of methane gas in the exhaust flow [14–16].// With the use of natural gas as the fuel, generators can fail to start, or in some cases fail to run a result of lack of fuel supply leading to lower system reliability. Start failure has highest impact on short outages, but failure to run and failure of fuel supply strongly effect on long outages. Natural gas power plants face the risk of gas pressure loss, while diesel engine power plants are affected by the greater risk of running out of fuel supply. Many power outages are generally short, but long outages do happen especially for areas prone to natural disasters like tornados, hurricanes, and wildfires. With respect to long outages, the natural gas supply has higher reliability compared to that of diesel fuel making natural gas power plants more reliable than diesel power plants based on estimates from small data sets and significant assumptions. For regions prone to long outages, natural gas power plants have higher reliability than diesel power plants [24, 40–42].

Limitations of dual fuel engines include poor utilization of the fuel at low and intermediate loads leading to poor engine performance and efficiency reduction. Other are high levels of hydrocarbon (HC), carbon monoxide (CO) emissions and higher incidents misfiring at higher gas inducted levels. The main reason for poor part load performance of natural gas engines is incomplete combustion leading to low thermal efficiency and higher unburnt hydrocarbons engine exhaust [15, 42, 74]. The main challenge with use of LNG, CNG and LPG is the high octane rating and low cetane rating making it difficult apply it alone in a compression a compression ignition engine hence the need for dual fuel operation or use of a pilot fuel to initiate combustion and application for low loads. Under this arrangement, the LNG, CNG or LPG is injected prior or after the diesel injection and ignition which may then burn premixed or gas supplied by diffusion. The initial combustion phase generates a rapid pressure build-up hence the rate of combustion of the second phase is highly influenced by the rate of injection of LNG, CNG, or LPG with the objective of maintaining pressure during the expansion stroke [43, 76].

Another issue with LNG or CNG is the high specific volume of the fuel, hence low fuel density at normal operating conditions which necessitates use of injectors with larger cross-sectional areas making it difficult for fast actuation, limit multiple injection capabilities, and need for non-standardized injectors which complicate and make designs expensive. The low density also means that fuel storage space requirements are increased and hence higher storage and handling costs. Although LNG has hire volumetric density, it requires a cryogenic system to maintain low temperature of the fuel. The CNG also has lower volumetric density and additionally needs pressurized tanks which increases handling and storage costs [43].

C.4. Impact of the conversion of operating power plant

Kipevu III diesel power plant is the largest diesel power plant in East and central Africa. The power plant is equipped with seven Wartsila W18V46 engines used in the power plant have a compression ratio of 22:1 is ideal for use with diesel and heavy fuel oil. The compression ratio of the dual fuel engine must be reduced for the engine to run on gas as the fuel by increasing the clearance volume. Two thicknesses of 10mm and 5mm are used for analysis, which give compression ratios of 13.4 and 17.1, respectively. For a dual-fuel engine, a compression ratio of 16-18 is required. Therefore, the 5mm thickness is chosen for these engines. The specific fuel consumption (sfc) of Kipevu III is 3400 kg/h. From this sfc, for one engine unit the cost of diesel fuel is calculated per hour. A diesel to natural gas ratio of 1:4 is chosen in our conversion. This ratio reduces the amount of diesel fuel used significantly and replacing it with natural gas. Natural gas has a higher calorific value of 52,000 kJ/kg compared to diesel 42,000 kJ/kg, which means it takes less natural gas to produce same power with diesel [15, 17].

Using the diesel to natural gas ratio and the specific fuel consumption (sfc), the volume of diesel consumed after conversion is calculated and using the prevailing average cost of diesel per liter, the cost of diesel fuel (after conversion) is determined. For natural gas, the consumption and cost of natural gas is used to determine costs involved. Therefore, very important for analysis of both fuels is the ratios and their calorific value which helps in quantifying consumption in form of, the mass of natural gas consumed is calculated and the diesel oil used. The total cost of the dual fuel is calculated based on diesel cost of ksh 46/liter (US$0.46/liter) of oil and natural gas cost of $605/ton. Using a diesel/natural gas ratio of 1:4, the diesel sfc reduces to 640kg/h from 3400kg/h and the sfc of natural gas is 2196.72kg/h. The total sfc reduces to 2,836.72kg/h of natural gas based on the analytical calorific value of 52,000 kJ/kg of natural gas with average cost of natural gas taken as $605/ton. This fuel combination leads to lower cost of the dual fuel compared to the cost of diesel oil when used alone. For the 7 engines, a total of ksh 453,407,867.60 (US$ 4,534,079.00) in savings at average load factor of 0.5 is realized. Considering all the additions to the existing design and all costs incurred during conversion, the total direct cost of investment amounts to ksh 153,492,500.00 (US$ 1, 534,925.00). The actual project cost is expected to be more than this value.

Based on the total annual fuel cost savings and the cost of investment, the payback period for the whole project is estimated at 4.06 months. This payback period looks too short and too attractive, but the analysis is based on prevailing price of oil and natural gas not actual costs which must capture the indirect costs like handling, transport, and storage costs as well as initial capital investment costs which will have a bearing on total cost of the conversion as well as the cost of system operation and maintenance.

The proposed partial conversion to dual fuel mode is faster, cheaper, and more feasible as it requires less modifications and allows for more fuel diversity and flexibility in the diesel power plant operation and maintenance. Modification of the injection system proposed involved introduction of a D-GID® Electronic Unit which controls the amount and ratios of diesel and natural gas injected in the engines while compression ratio was also reduced to cope with new fuel characteristics. The conversion will reduce specific fuel consumption reduces by 523.28kg/h which influences the cost of fuel. The two values of fuel cost i.e., before and after were compared, to get the fuel savings after converting to dual-fuel engines which was very important to this research. These savings show that it is cheaper to produce power using a dual-fuel power plant using diesel and natural gas instead of diesel or heavy fuel oil alone. Fuel cost influences unit cost of power generation and is a major factor in the power purchase agreement between the power plant and the utility company. Reduction of fuel cost, therefore, will greatly reduce the purchase price of electricity from Kipevu III power station.

8. CONCLUSION

Several approaches can be applied to improve the performance of a gas engines at idling and low loads which are associated with low efficiency. Performance can be enhanced optimizing engine parameters like engine load, speed, pilot fuel quantity, intake manifold condition, modification of injection timing and control of fuel quality. The conversion of conventional diesel power plants to gas and dual fuel engines promise to improve the performance of diesel power plants in terms of higher fuel conversion efficiencies and much lower greenhouse gas emissions. However, the main threat includes cyclic combustion variations and high hydrocarbon and carbon monoxide as a result the cyclic variations being the inconsistent local diesel fuel–air mixing hence inconsistent ignition quality from one cycle to another.

This study demonstrated that diesel power plants can be converted to dual fuel engine power plants running on both natural gas and diesel or heavy fuel oil with better power plant performance indicators in terms of engine specific fuel consumption, engine brake thermal efficiency, diesel engine indicated thermal efficiency, the power plant electricity generating unit cost of power, the total engine emissions and hence leading to less environmental impact. The conversion from conventional diesel power plant to dual fuel will lead to reduced cost of power generation, reduction in total emissions and total amount of other pollutants associated with conventional diesel power generation. Economically, the conversion will lead to better return on investment of the plant because of reduction in fuel related costs and overall unit cost of power. Conversion from diesel fuel powered engines to full gas and dual fuel mode is both technically and financially feasible whole eventual impact will be reflected in reduced electricity bills for the consumers. However, the actual project costs may be higher due to indirect and direct execution costs hence increasing the payback period. The plant usage will also increase due to lower cost of power hence more revenue and profits for investors. Therefore, conversion from pure diesel to due fuel diesel engine power plants is a sustainable way of generating electricity for sustained economic growth and development in a cleaner environment.

RECOMMENDATIONS

This study considered conversion of diesel engine power plants to dual fuel plants which shows an undertaking that is technically feasible, full conversion of the power plant to a full gas power plant. With the average load factor of the power plant being just 0.5, about 50% of the total capacity remains un-utilized as the utility limits generation from of expensive power to cushion consumers from high electricity bills. Therefore, conversion to dual fuel will reduce cost and increase power plant demand leading to higher load factor and power plant utilization which translates to higher revenue and efficiency of operations and thus reduction in unit cost of power. Since the research targeted Kipevu III power station alone, it is recommended that similar studies be carried out for other diesel power plants to facilitate a possible industry wide policy shift and conversions to gas as a fuel.

DISCLOSURES

Funding

No funding was provided for this research and the whole exercise was fully funded by the researchers.

Availability of Data

The research has provided all the data and information used and did not use any undeclared data and information. Moreover, any datasets used and/or analysed during the current study are available from the authors on reasonable request.

Acknowledgements

The authors wish to express their appreciation to the reviewers, researchers, and scholars in the field of geothermal energy and electricity for providing readily accessible, significant, credible, and reliable information in all aspects of geothermal energy. This made the production of this study successful.

Conflict of Interest

The authors declare that they have no conflict of interest in this research.

Ethical Approval and Consent to Participate

Not applicable.

Consent for Publication

The authors have the authority to publish the research work in any publication.

Authors' Contribution

The first author drafted the manuscript without any third-party assistance under guidance of the second author. Considerable insight into the application of cogeneration in advancing sustainability of diesel engine power plants. The first author was also guided by his own experience as an engineer in the discussed power plant. The second author reviewed the manuscript and made improvements and additional theoretical contributions including coordination of editing and other publishing related expenditures.

REFERENCES

1. A. Arefin, N. Nabi, W. Akram, M. T. Islam, and W. Chowdhury, "A review on liquefied natural gas as fuels for dual fuel engines: Opportunities, challenges and responses," Energies, vol. 13, no. 22, pp. 1-19, 2020, Art no. 6127, doi: https://doi.org/10.3390/en13226127.
2. Kabeyi and O. A. Olanrewaju, "Performance analysis of diesel engine powerplants for grid electricity supply," presented at the SAIIE31 Proceedings, Virtual Event, South Africa, 5th – 7th October 2020, 2020, Virtual Conference, 4423. [Online]. Available: https://www.saiie.co.za/cms/content/853-saiie31-conference-proceedings.
3. M. J. B. Kabeyi and A. O. Oludolapo, "The Potential of Power Generation from Municipal Solid Waste," presented at the 2nd African International Conference on Industrial Engineering and Operations Management, Harare, Zimbabwe, 5-7 December 2020, 2020, 081 [Online]. Available: http://ieomsociety.org/harare2020/papers/81.pdf.
4. S. Niemi, "Survey of modern power plantsdriven by diesel and gas engines," Turku Polytechnic, Finland, 1860, 1997. [Online]. Available: https://www.vttresearch.com/sites/default/files/pdf/tiedotteet/1997/T1860.pdf.
5. M. J. B. Kabeyi and O. A. Olanrewaju, "Development of a cereal grain drying system using internal combustion engine waste heat," presented at the 11th Annual International Conference on Industrial Engineering and Operations Management Singapore, March 7-11, 2021, 2021. [Online]. Available: http://www.ieomsociety.org/singapore2021/papers/188.pdf.
6. M. J. B. Kabeyi and O. A. Olanrewaju, "Fuel from plastic wastes for sustainable energy transition," presented at the 11th Annual International Conference on Industrial Engineering and Operations Management, Singapore, March 7-11, 2021, 2021. [Online]. Available: http://www.ieomsociety.org/singapore2021/papers/199.pdf.
7. J. B. Andriulli et al., "Advanced Power Generation Systemsfor the 21st Century: Market Survey and Recommendationsfor a Design philosophy," U.S. Department of Energy, Fort Belvoir, VA, November 1999 1999. [Online]. Available: https://www.osti.gov/servlets/purl/752077.
8. M. J. B. Kabeyi, "Investigating the challenges of bagasse cogeneration in the kenyan Sugar Industry," International Journal of Engineering Sciences Research Technology, vol. 9, no. 5, pp. 7-64, May 2020 2020, doi: 10.5281/zenodo.3828855.
9. M. J. B. Kabeyi and A. O. Oludolapo, "Central versus wellhead power plants in geothermal grid electricity generation," Energy, Sustainability and Society 2021, Art no. ESSO-D-20-00011R4. [Online]. Available: https://energsustainsoc.biomedcentral.com/.
10. G. Andae, "Why electricity bills are still increasing," Daily Nation. [Online]. Available: http://www.nation.co.ke/business/Why-electricity-bills-are-still-increasing/996-4234320-kidepf/index.html.
11. M. J. B. Kabeyi and A. O. Oludolapo, "Characteristics and applications of geothermal wellhead powerplants in electricity generation," in SAIIE31 Proceedings, South Africa, H. Teresa, Ed., 5th – 7th October 2020 2020, vol. 2020, no. 31, South Africa: South African Institution of Industrial Engineers, pp. 222-235. [Online]. Available: https://www.dropbox.com/s/o0sj1l08v8n9sgh/SAIIE31%20Conference%20Proceedings.pdf?dl=.[Online].Available: https://www.dropbox.com/s/o0sj1l08v8n9sgh/SAIIE31%20Conference%20Proceedings.pdf?dl=.
12. M. J. B. Kabeyi and O. A. Olanrewaju, "Conversion of a Flash Power Plant to Organic Rankine System for Olkaria Geothermal Power Plants," in 2021 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME), 7-8 Oct. 2021 2021: IEEE, pp. 1-8, doi: 10.1109/ICECCME52200.2021.9591048. [Online]. Available: https://ieeexplore.ieee.org/document/9591048.
13. M. J. B. Kabeyi and A. O. Olanrewaju, "Performance analysis and evaluation of Muhoroni 60 MW gas turbine power plant," in 2021 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME), 7-8 Oct. 2021 2021, pp. 1-8, doi: 10.1109/ICECCME52200.2021.9591134. [Online]. Available: https://ieeexplore.ieee.org/document/9591134.
14. K. K. Srinivasan, A. K. Agarwal, S. R. Krishnan, and V. Mulone, Natural gas engines s for transportation and power generation (Energy, Environment, and Sustainability). Gateway East, Singapore: Springer Nature Singapore Pte Ltd., 2019.
15. M. J. B. Kabeyi and O. A. Olanrewaju, "Performance evaluation of Kipevu-III 120 MW power station and conversion to dual-fuel power plant," Energy Reports, vol. 8, pp. 800-814, 2022/12/01/ 2022, doi: https://doi.org/10.1016/j.egyr.2022.11.064.
16. M. J. B. Kabeyi and O. A. Olanrewaju, "Technologies for biogas to electricity conversion," Energy Reports, vol. 8, no. Supplement 16, pp. 774-786, 2022/12/01/ 2022, doi: https://doi.org/10.1016/j.egyr.2022.11.007.
17. M. J. B. Kabeyi and O. A. Olanrewaju, "Cogeneration potential of an operating diesel engine power plant," Energy Reports, vol. 8, 16, pp. 744-754, 2022/12/01 2022, doi: https://doi.org/10.1016/j.egyr.2022.10.447.
18. G. G. Munde and R. S. Dalu, "Compressed natural gas as an alternative Fuel for Spark Ignition Engine: A Review," International Journal of Engineering and Innovative Technology (IJEIT), vol. 2, no. 6, pp. 92-95, 2012. [Online]. Available: https://www.ijeit.com/vol%202/Issue%206/IJEIT1412201212_16.pdf.
19. Eurostat. "Natural gas price statistics." Europa. https://ec.europa.eu/eurostat/statistics-explained/index.php/Natural_gas_price_statistics(accessed12December2020,2020).
20. F. Königsson, "Combustion Modes in a Diesel-CNG Dual Fuel Engine 2011-01-1962," presented at the 2011 JSAE Powertrains, Fuels and Lubes, Kyoto Japan, 2014, 2011-01-1962. [Online]. Available: https://www.sae.org/publications/technical-papers/content/2011-01-1962/.
21. M. J. B. Kabeyi, "Challenges of implimenting thermal power plant projects in Kenya: The case of Kipevu III 120 MW Diesel Engine Power Station, Mombasa Kenya," Masters Thesis, Project Planning and Managemet, University of Nairobi, Nairobi, Kenya, 2020.
22. G. Di Blasio, G. Belgiorno, and C. Beatrice, "Effects on performances, emissions and particle size distributions of a dual fuel (methane-diesel) light-duty engine varying the compression ratio," Applied Energy, vol. 204, pp. 726-740, 2017/10/15/ 2017, doi: https://doi.org/10.1016/j.apenergy.2017.07.103.
23. M. V. Barros, R. Salvador, C. M. Piekarski, A. C. de Francisco, and F. M. C. S. Freire, "Life cycle assessment of electricity generation: a review of the characteristics of existing literature," The International Journal of Life Cycle Assessment, vol. 25, no. 1, pp. 36-54, 2020/01/01 2020, doi: 10.1007/s11367-019-01652-4.
24. S. Ericson and D. Olis, "A Comparison of Fuel Choice for Backup Generators " National Renewable Energy Laboratory, USA, 2019. [Online]. Available: https://www.nrel.gov/docs/fy19osti/72509.pdf.
25. R. K. Hegde, Power plant engineering. Uttar Pradesh, India: Pearson India Education Services Pvt. Ltd., 2015.
26. M. J. B. Kabeyi and O. A. Olanrewaju, "Conversion of diesel and petrol engines to biogas engines as an energy transition strategy," presented at the 4th African International Conference on Industrial Engineering and Operations Management, Nsukka, Nigeria, April 5-7, 2022, 2022, 448. [Online]. Available: https://ieomsociety.org/proceedings/2022nigeria/448.pdf.
27. M. J. B. Kabeyi and O. A. Olanrewaju, "Performance analysis and electricity potential for Nzoia sugar factory," Energy Reports, vol. 8, 16, pp. 755-764, 2022/12/01/ 2022, doi: https://doi.org/10.1016/j.egyr.2022.10.432.

28. M. J. B. Kabeyi and A. O. Oludolapo, "Performance analysis of diesel engine power plants for grid electricity supply," in 31ST Annual Southern African Institution for Industrial Engineering Conference, South Africa, H. Teresa, Ed., 5th – 7th October 2020 2020, vol. 2020, no. 31, South Africa: South African Journal of Industrial Engineering, 2020, pp. 236-250. [Online]. Available: https://www.saiie.co.za/system/files/2021-11/SAIIE31%20Conference%20Proceedings.pdf. [Online]. Available: https://www.saiie.co.za/system/files/2021-11/SAIIE31
29. B. Ashok, S. Denis Ashok, and C. Ramesh Kumar, "LPG diesel dual fuel engine – A critical review," Alexandria Engineering Journal, vol. 54, no. 2, pp. 105-126, 2015/06/01/ 2015, doi: https://doi.org/10.1016/j.aej.2015.03.002.
30. M. J. B. Kabeyi and O. A. Olanrewaju, "Performance analysis of a sugarcane bagasse cogeneration power plant in grid electricity generation," presented at the 11th Annual International Conference on Industrial Engineering and Operations Management Singapore, March 7-11, 2021, 2021. [Online]. Available: http://www.ieomsociety.org/singapore2021/papers/201.pdf.
31. M. J. K. Barasa, "Corporate Governance in Manufacturing and Management with Analysis of Governance Failures at Enron and Volkswagen Corporations," American Journal of Operations, vol. 4, no. 4, pp. 109-123, 2020, doi: 10.11648/j.ajomis.20190404.11.
32. M. B. K. Jeremiah, "Ethical and unethical leadership issues, cases, and dilemmas with case Studies " International Journal of Applied Research, vol. 4, no. 7, pp. 373-379, 2018, doi: 10.22271/allresearch.2018.v4.i7f.5153.
33. M. J. B. Kabeyi and A. O. Olanrewaju, "Feasibility of Wellhead Technology Power Plants for Electricity Generation," International Journal of Computer Engineering in Research Trends, vol. 7, no. 2, pp. 1-16, 2020, doi: https://doi.org/10.22362/ijcert/2020/v7/i02/v7i0201.
34. M. J. B. Kabeyi and A. O. Oludolapo, "Performance Analysis of an Open Cycle Gas Turbine Power Plant in Grid Electricity Generation," presented at the 2020 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Singapore, Singapore, 14-17 December 2020, 2020, IEEM20-P-0438 [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9309840.
35. M. Issa, H. Ibrahim, R. Lepage, and A. Ilinca, "A Review and Comparison on Recent Optimization Methodologies for Diesel Engines and Diesel Power Generators," Journal of Power and Energy Engineering vol. 7, no. 6, pp. 31-56, 2019, doi: 10.4236/jpee.2019.76003.
36. M. J. B. Kabeyi and O. A. Olanrewaju, "Performance analysis and evaluation of ethanol potential of Nzoia Sugar Company Ltd," Energy Reports, vol. 8, 16, pp. 787-799, 2022/12/01/ 2022, doi: https://doi.org/10.1016/j.egyr.2022.11.006.
37. B. M. Shasby, "Alternative fuels: Incompletely addressing the problems of the automobile," Masters Thesis, Urban and Regional Planning, Virginia Polytechnic Institute and State University, Alexandria, Virginia, 2004. [Online]. Available: http://hdl.handle.net/10919/9976.
38. M. J. B. Kabeyi, "Geothermal electricity generation, challenges, opportunities and recommendations," International Journal of Advances in Scientific Research and Engineering (ijasre), vol. 5, no. 8, pp. 53-95, 2019, doi: 10.31695/IJASRE.2019.33408.
39. Engineering Research Center of Engineering innovation, "Dual fuel engine gas fuel conversion technology," in "New Products Technologies," JFE Engineering, March 2014 2014. [Online]. Available: https://www.jfe-steel.co.jp/en/research/report/019/pdf/019-17.pdf.
40. M. J. B. Kabeyi, "Challenges of implementing thermal powerplant projects in Kenya,the case of Kipevu III 120MW power station,Mombasa Kenya," Masters, Department of Education Management, University of Nairobi, Nairobi, 5866, 2012. [Online]. Available: http://erepository.uonbi.ac.ke:8080/xmlui/handle/123456789/11023.
41. M. J. B. Kabeyi, "Organizational Strategic Diversification with Case Studies of Successful and Unsuccessful Diversification," International Journal of Scientific Engineering Research., vol. 9, no. 9, pp. 871-886., 2018, doi: 10.13140/RG.2.2.12388.01922.
42. M. J. B. Kabeyi and O. A. Olanrewaju, "A Techno-economic assessment of diesel to Gas power plant conversion " presented at the 12th Annual Istanbul International Conference on Industrial Engineering and Operations Management, Istanbul, Turkey, March 7-10, 2022, 2022, 406. [Online]. Available: https://ieomsociety.org/proceedings/2022istanbul/406.pdf.
43. A. Boretti, "Advantages and Disadvantages of Diesel Single and Dual-Fuel Engines," (in English), Frontiers in Mechanical Engineering, Review vol. 5, 2019-December-03 2019, doi: https://doi.org/10.3389/fmech.2019.00064.
44. M. Kabeyi and O. Olanrewaju, "Slaughterhouse waste to energy in the energy transition with performance analysis and design of slaughterhouse biodigestor," (in en), Journal of Energy Management and Technology, vol. 6, no. 3, pp. 188-208, 2022, doi: http://dx.doi.org/10.22109/jemt.2021.292954.1309.
45. M. J. B. Kabeyi and O. A. Olanrewaju, "Biogas Production and Applications in the Sustainable Energy Transition," Journal of Energy, vol. 2022, no. 8750221, p. 43, 2022/07/09 2022, doi: https://doi.org/10.1155/2022/8750221.
46. M. J. B. Kabeyi and A. O. Oludolapo, "Preliminary Design of a Bagasse Based Firm Power Plant for a Sugar Factory," presented at the South African Universities Power Engineering Conference (SAUPEC), Nortn West University, South Africa, 27-28 January 2021, 2021, 104. [Online]. Available: https://easychair.org/cfp/SRP2021.
47. M. J. B. Kabeyi and A. O. Oludolapo, "Design and Modelling of a Waste Heat Recovery System for a 250KW Diesel Engine for Cereal Drying," presented at the 2nd African International Conference on Industrial Engineering and Operations Management, Harare, Zimbabwe, 5-7 December 2020, 2020, 078 [Online]. Available: http://ieomsociety.org/harare2020/papers/78.pdf.
48. S. K. Agrawal, Internal combustion engines. New Delhi, India: New Age International (P) Ltd, 2006.
49. R. Rajput, 4, Ed. A text book of power plant engineering. New Delhi, India: Laxmi Publications (P) Ltd., 2009.
50. R. K. Rajput, Power plant engineering. . New Delhi, India: Laxami Publications, 2010.
51. A. K. Raja, A. P. Srivastava, and M. Dwivedi, Power plant engineering. New Delhi, India: New Age International Publishers Ltd, 2006.
52. A. Androniceanu and O. M. Sabie, "Overview of Green Energy as a Real Strategic Option for Sustainable Development," Energies, vol. 15, no. 22, p. 8573, 2022. [Online]. Available: https://www.mdpi.com/1996-1073/15/22/8573.
53. C. R. Kumar. J and M. A. Majid, "Renewable energy for sustainable development in India: current status, future prospects, challenges, employment, and investment opportunities," Energy, Sustainability and Society, vol. 10, no. 1, p. 2, 2020/01/07 2020, doi: https://doi.org/10.1186/s13705-019-0232-1.
54. I. Iddrisu and S. C. Bhattacharyya, "Sustainable Energy Development Index: A multi-dimensional indicator for measuring sustainable energy development," Renewable and Sustainable Energy Reviews, vol. 50, pp. 513-530, 2015/10/01/ 2015, doi: https://doi.org/10.1016/j.rser.2015.05.032.
55. J. G. Speight, "5 - Recovery, storage, and transportation," in Natural Gas (Second Edition), J. G. Speight Ed. Boston: Gulf Professional Publishing, 2019, pp. 149-186.
56. A. Boretti, "Advances in Diesel-LNG Internal Combustion Engines," Applied Sciences, vol. 10, no. 4, p. 1296, 2020. [Online]. Available: https://www.mdpi.com/2076-3417/10/4/1296.
57. M. J. B. Kabeyi and A. O. Oludolapo, "Optimization of Biogas Production for Optimal Abattoir Waste Treatment with Bio-Methanation as Solution to Nairobi Slaughterhouses Waste Disposal," presented at the 2nd African International Conference

on Industrial Engineering and Operations Management, Harare, Zimbabwe, 5- 7 December 2020, 2020, 083 [Online]. Available: http://ieomsociety.org/harare2020/papers/83.pdf.
58. M. kabeyi and O. Olanrewaju, "Optimum biodigestor design and operations," presented at the Fifth European Conference on Industrial Engineering and Operations Management, Rome, Italy, , July 26-28, 2022, 2022, 424.
59. M. I. Khan, T. Yasmin, and A. Shakoor, "Technical overview of compressed natural gas (CNG) as a transportation fuel," Renewable and Sustainable Energy Reviews, vol. 2015, pp. 785-797, 2015, doi: https://doi.org/10.1016/j.rser.2015.06.053.
60. A. Boretti, "Advances in diesel-LNG internal cmbustion engines," Applied Sciences, vol. 10, no. 4, pp. 1-28, 2020, doi: https://doi.org/10.3390/app10041296.
61. L. P. Li, "The effect of compression ratio on the CNG-Diesel engine," Bachelor of Engineering, Mechatronic Engineering, University of Southern Queensland, Australia, 2004. [Online]. Available: https://core.ac.uk/download/pdf/11034520.pdf.
62. K. Mitzlaff, "Engines for biogas," Vieweg Sohn Verlagsgesellschaft mbH, Eschborn, Germany, 1988. [Online]. Available: https://biogas.ifas.ufl.edu/ad_development/documents/Engines%20for%20biogas.pdf.
63. W. O'Keefe, "Engine/generators reconfigured to compete in the next century," Power, vol. 139, no. 10, pp. 52-62, 1995.
64. R. S. Krishna, "CONVERSION OF DIESEL ENGINE TO CNG ENGINE OF COMMERCIAL VEHICLES AND EMISSION CONTROL," International Journal of Mechanical and Production Engineering, vol. 6, no. 11, pp. 2321-2071, 2018. [Online]. Available: http://www.iraj.in/journal/journal_file/journal_pdf/2-518-154951837571-76.pdf.
65. P. A. Azman, M. Fawzi, M. M. Ismail, and S. A. Osman, "One dimensional modeling of a diesel-CNG dual fuel engine," presented at the 7th International Conference on Mechanical and Manufacturing Engineering 21 April 2017, 2017, 020036. [Online]. Available: https://aip.scitation.org/doi/abs/10.1063/1.4981177.
66. M. A. Kumar and A. Gaddipati, "Conversion of Diesel Engine to CNG Engine and Emission Control," International Journal of Science and Research (IJSR), vol. 6, no. 2, pp. 874 - 877, 2017, Art no. ART2017870, doi: 10.21275/ART2017870..
67. S. Bari and S. N. Hossain, "Performance of a diesel engine run on diesel and natural gas in dual-fuel mode of operation," Energy Procedia, vol. 160, pp. 215-222, 2019/02/01/ 2019, doi: https://doi.org/10.1016/j.egypro.2019.02.139.
68. A. Yousefi, H. Guo, M. Birouk, and B. Liko, "On greenhouse gas emissions and thermal efficiency of natural gas/diesel dual-fuel engine at low load conditions: Coupled effect of injector rail pressure and split injection," Applied Energy, vol. 242, pp. 216-231, 2019/05/15/ 2019, doi: https://doi.org/10.1016/j.apenergy.2019.03.093.
69. Ecomotive Solutions S.r.l. "What is D-GID?" Ecomotive Solutions S.r.l. https://www.ecomotive-solutions.com/en/what-is-d-gid (accessed 28 December 2020, 2020).
70. Ecomotive Solutions S.r.l. "How it works." Ecomotive Solutions S.r.l. https://www.ecomotive-solutions.com/en/how-it-works/ (accessed 28 December 2020, 2020).
71. M. J. B. Kabeyi and O. A. Olanrewaju, "Relationship Between Electricity Consumption and Economic Development," presented at the International Conference on Electrical, Computer and Energy Technologies (ICECET), Cape Town-South Africa, 9-10 December 2021, 2022. [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9698413.
72. M. J. B. Kabeyi and O. A. Olanrewaju, "The Use of Smart Grids in the Energy Transition," in 2022 30th Southern African Universities Power Engineering Conference (SAUPEC), 25-27 Jan. 2022 2022: IEEE, pp. 1-8, doi: https://doi.org/10.1109/SAUPEC55179.2022.9730635. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/9730635.
73. M. J. B. Kabeyi and O. A. olanrewaju, "Electricity and Gas Potential of Abattoir Waste," presented at the 12th Annual Istanbul International Conference on Industrial Engineering and Operations Management Istanbul, Turkey, March 7-10, 2022, 2022, 403. [Online]. Available: https://ieomsociety.org/proceedings/2022istanbul/403.pdf.
74. M. J. B. Kabeyi and a. O. Olanrewaju, "Feasibility of Conversion from Diesel Engine to Natural Gas Power Plants," presented at the IECON 2022 – 48th Annual Conference of the IEEE Industrial Electronics Society, Brussels, Belgium, 17-20 Oct. 2022, 2022. [Online]. Available: https://ieeexplore.ieee.org/document/9968428.
75. M. J. B. Kabeyi, "Project and Program Evaluation Consultancy With Terms of Reference, Challenges, Opportunities, and Recommendations," International Journal of Project Management and Productivity Assessment (IJPMPA), vol. 8, no. 2, pp. 47-68, 2020, doi: 10.4018/IJPMPA.2020070103..
76. M. J. B. Kabeyi and O. A. Olanrewaju, "Conversion from diesel to dual fuel power generation and implications on the transition " presented at the 7th North American International Conference on Industrial Engineering and Operations Management Orlando, Florida, USA June 12-14, 2022, 2022, Conference paper, 356. [Online]. Available: https://ieomsociety.org/proceedings/2022orlando/356.pdf.