# Conversion from Diesel to Dual Fuel Power Generation and Implications On the Transition

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## Abstract

Diesel is the main fuel for use in industrial, transport, and in diesel power plants; unfortunately, it is polluting and non-renewable. The overall objective of this study is to assess the sustainability of converting diesel power plants to dual fuel power plants which use both diesel or heavy fuel oil and gas. The study showed that the use of natural gas simultaneously reduces the cost of generation per kilowatt hour (kWh) and emissions, particularly $SO_X$. 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 through increase of the engine cylinder clearance volume. These fuel savings will influence renegotiation of the power purchase agreement resulting into lower tariffs, higher load factor and power plant utilization which translates to more revenue and reduced unit cost of power with lower environmental impact as well as better return on investment from the largest grid connected diesel power plant in East and Central Africa. This study showed that dual fuel diesel power plants running on both natural gas and diesel exhibit better 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.

Key Words: Diesel engines; diesel power plants; gas engines; gas power plants; power plant design.

## 1. Introduction

Diesel engines operate at a relatively higher efficiency and with a higher power density than petrol making them the best choice as prime movers in transport especially heavy-duty vehicles and in diesel power generation. The engines are also increasingly finding application in light-duty cars are dominated by petrol or gasoline engines. The main challenge of using diesel engines in power generation is the emissions mainly in the form of carbon dioxide, NOx due to oxidation of nitrogen in the air at high combustion temperatures., particulate matter (PM) and sulphur dioxide from oxidation of sulphur component of the fuel (IEA, 2021; Kabeyi & Oludolapo, 2020a, 2020f).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 (Arefin et al., 2020). In diesel Power generation stations, diesel engines are used as prime movers for generators (Kabeyi & Olanrewaju, 2020b). 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. They are also quick to start and stop and have got capacity to burn different types of fuels (Niemi, 1997). The engine market is large with over 20 manufacturers of piston diesel engines for power generation generally between 10 hp to 140 hp (Andriulli et al., 1999). For a long time, many developing countries like Kenya rely on hydropower for its bulk electricity generation for its grid electricity (Kabeyi, 2020b; Kabeyi & Oludolapo, 2021a). This comes with low reliability due to seasonal variability of rainfall hence power plant availability. The need to meet the deficit occasioned by low rains or drought conditions create demand for expensive and polluting thermal power plants (Andae, 2017). 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 challenges of diesel power plants are high and fluctuating fuel cost and high cost of plant operation and maintenance per unit power output. Therefore, as the global community looks for a cheaper, cleaner and sustainable energy production, natural gas has emerged as an alternative fuel in power production (Munde & Dalu, 2012). The use of natural gas as a fuel in power generation reduces fuel cost of power per unit (Eurostat, 2020), and therefore conversion from use of diesel to natural gas can be used as a strategy to reduce the high cost diesel power generation. It also offers a much cleaner power production process since it produces around 20% less pollutants compared to diesel (Königsson, 2014). In the case of Kipevu III power station, power is generated purely using seven diesel engines using heavy fuel oil as the engine fuel (Kabeyi, 2020a). 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.

Natural gas power plants are used in power generation by natural gas as their fuel mainly in gas turbines.. Natural gas power plants use a gas turbine as the prime movers in a system where natural gas and a stream of air, are combusted and expanded through a turbine which then rotates a generator to produce electricity(Valera-Medina et al., 2015). In some natural gas power plants, the waste heat leaving the prime mover curtesy of the second law of thermodynamics. Is recovered for further use in extra power generation as in combined cycle power plants. Natural gas power plants are cheaper, faster to build, and have higher thermodynamic efficiencies compared to other thermal power plants. The environmental benefit of natural gas power generation is emission of less pollutants like NOx, SOx and particulate matter compared to coal and oil. However, the plants are more polluting than nuclear and renewable sources of energy.

The overall objective of this study was to convert the Kipevu III 120 MW diesel engine power plant to a dual fuel to reduce the cost of power and greenhouse gas emissions associated with diesel engine combustion. The study specified the technically requirements, cost implications and associated financial and environmental benefits of the conversion.

## 2. Problem Statement

Diesel is the main fuel for use in many industrial, transport, and in diesel power plants. However, it is polluting and non-renewable (Arefin et al., 2020). Hence, there is a dual need to reduce emissions and cost of power from diesel engine power plants (Niemi, 1997). The current trend of using diesel fuel has a negative impact to consumers in terms of high electricity tariffs (Andae, 2017).The environmental impact of diesel power plants includes emission of $So_x$, $NO_X$ emissions and oil spills and leakages to the environment (Barasa, 2020; Jeremiah, 2018). The emissions also react with the ozone layer leading to its depletion. 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. On average basis, it costs KES 6.00 (6 US cents) to produce 1 kWh of electricity using natural gas (Eurostat, 2020) which is much lower compared to diesel power generation which costs about ksh. 30 (US cents 30) (Andae, 2017; Kabeyi & Olanrewaju, 2020b). Therefore, conversion to natural gas will reduce the cost of power generation.

## 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 cheaper than diesel (Arefin et al., 2020). 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 when either of the fuels is unavailable. Additionally, natural gas is clean and leads to 20% to 30% reduction in $CO_2$ emissions, 70% to 90% reduction in CO emissions and generally 50% to 87% reduction in NOx emissions (Shasby, 2004). In this conversion approach, the engine compression ratio is maintained high and hence the engine performance is retained upon conversion(Kabeyi, 2019). 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 costs less than doing overhaul of the plant (Königsson, 2014). In many countries around the world, there is growing interest in converting diesel power plants mainly to increase energy security and reduce cost of unit power (Engineering Research Center of Engineering innovation, 2014). 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 (Kabeyi & Olanrewaju, 2020a).

## 4. Diesel Power Generation

### 4.1. Introduction to diesel power plants

Diesel electric power plants vary in sizes for application in central, decentralized, and off grid power generation. They have a wide range of applications which include peak load plants, mobile plants, standby units, emergency plants, nursery plants, black start plants and central power plants (Agrawal, 2006; Kabeyi & Olanrewaju, 2020b; Rajput, 2009).

### 4.2. Diesel Engine Power Plant Design and construction

Diesel electric power plants vary in sizes for application in centralized, decentralized, and off grid power generation(Kabeyi & Oludolapo, 2020a, 2021b). 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 (Agrawal, 2006; Kabeyi & Olanrewaju, 2020b; Rajput, 2009). Diesel engines work on the principle of the diesel thermodynamic cycle which consists of four processes completed in either two or four stroked of the pistons. Most diesel engine power plants use four stroke diesel engines(Kabeyi & Olanrewaju, 2020b). Most diesel engine power plants use four stroke diesel engines. The four strokes that constitute a complete cycle four stroke engine combustion are the suction/Intake, compression, power, and exhaust strokes take place the combustion chamber. These events are completed within two complete cycle s of the crankshaft(Kabeyi & Oludolapo, 2020a, 2020e)

The main components of a diesel power plant includes, the engine, fuel supply system, air intake system, exhaust system, cooling system, lubricating system, engine starting system and governing and control system (Rajput, 2009). A diesel engine can either be four-stroke or two-stroke. Four-stroke engines are mostly used due to their higher efficiency and are more balanced. In diesel engines, air is compressed adiabatically in the cylinder elevating the temperature of air before atomized fuel is injected to the combustion chamber. The high temperature caused by air compression ignites the diesel fuel spontaneously. The products of combustion expand pushing the piston downward which then drives the crankshaft setting the engine into operations(Agrawal, 2006).

Natural gas engines are either bi-fuel or dedicated natural gas engines. The bi-fuel engines run on natural gas or gasoline, and they work on the Otto cycle which is used by spark ignition engines. These engines maintain both natural gas and gasoline fuel supply systems which makes them flexible and efficient. The dedicated natural gas engines also work on the Otto cycle, hence are spark ignited engines fueled by natural gas as the only fuel source. The dedicated natural gas engines are optimized in terms of compression ratio to take the benefit of high octane rating of natural gas (Group of Experts on Pollution & Energy (GRPE), 2001). Unlike the bi-fuel engines which are based on the Otto cycle, the dual fuel natural gas engines are based on the diesel cycle technology, which is the operating cycle for diesel engines, but they use natural gas as the primary fuel. The dual engines are designed to operate smoothly with diesel interchangeably mainly a 'pilot' ignition source. The dual fuel engines can also operate on 100% diesel fuel especially when they are idling or on low loads. These engines admit more natural gas as the load increases usually to 80% or more natural gas. The benefits of natural gas use in dual and bi-fuel engines is better fuel economy and cleaner combustion with lower emissions (Group of Experts on Pollution & Energy (GRPE), 2001).

### 4.3. Natural Gas Fuel for diesel power plants

Natural gas mainly consists of methane ($CH_4$) and trace amounts of ethane, propane, nitrogen, helium, hydrogen sulfide, carbon oxide and water vapor. The principal component is methane which is normally above 90% (Shasby, 2004). 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 options namely:

- Spark-ignition reciprocating internal combustion engine,
- Gas-fired turbines and
- Dual fuel gas engines.

The main features which make natural gas attractive as a fuel for power generation and hence increased interest in its application are; wide availability, environmental friendliness, compatibility with the conventional spark ignition and compression ignition engine and low operational cost compared to other fossil fuels (Khan et al., 2015). The advantages of natural gas power plants include efficient combustion, low cost, complies with environmental regulations, high availability and supply, cleaner power.

### 4.4. 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.

Table 1. Typical composition of compressed natural gas in Vol% (Munde & Dalu, 2012).

| | Element | Symbol/Formulae | Volumetric % |
|---|---|---|---|
| 1 | Methane | $CH_4$ | 94.42 |
| 2 | Ethane | $C_2H_6$ | 2.27 |
| 3 | Propane | $C_3H_8$ | 0.03 |
| 4 | Butane | $C_4H_{10}$ | 0.25 |
| 5 | Nitrogen | $N_2$ | 0.44 |
| 6 | Carbon dioxide | $CO_2$ | 0.57 |
| 7 | Others | - | 2.00 |
| | Total | | 100% |

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.

## 4.7. Conversion of Diesel Engine to Dual-Fuel Engine

The main components and systems to be modified are; the fuel Injection System, fuel gas system, air and Exhaust System, Combustion Chamber and Control System (Engineering Research Center of Engineering innovation, 2014). For gas diesel engines, the electric efficiency varies with the power required for gas compression. A gas diesel (GD) engine like the Wärtsilä V46GD can realize optimum shaft efficiency of 49.6% in gas operation at about 85% to 90% loading. Energy consumed during compression is about 2.5% shaft power output, for inlet pressure of 16 bar. However, if the gas is delivered in liquefied form, the compression work consumes about 0.8% of shaft power output. In another case, at the gas-driven Ringgold Cogen power station, the plant heat rate is about 9,300 kJ/kWh which corresponds to an efficiency of around 39% with plant availability of about 90.1% after over 48 months of operation (O'Keefe, 1995). The gas diesel engines of the plant run on natural gas compressed to 250 bars for injection with pilot oil amount of about 5% of fuel intake. The power plant has specific lubricating oil consumption averages about 0.8 g/kWh (Niemi, 1997).The main challenge with gas engine is that the NOx emissions level is higher. As a result of this; in a natural gas engine, a catalytic exhaust purification system may be necessary to reduce the NOx emissions from a level of 1300 mg/MJ(fuel) to a target level of 200 mg/MJ as it is in an existing plant in Finland which emits from small gas turbines plant (Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022c; Niemi, 1997).

## 4.8. Environmental Impact of Natural gas

Natural gas possesses generally low-emission characteristics that uplifts its status as a relatively clean fuel among fossil fuels, although this does not necessarily give gas a clean bill of health (Gould & McGlade, 2017). Today, the atmospheric concentration of methane is about 2.5 times greater than pre-industrial concentration levels with 2012, global methane emissions estimated to be around 570 million tons (Mt). These emissions are from natural sources at about 40% of emissions, while the remaining 60% of these emissions were from anthropogenic sources. Of these anthropogenic methane emissions, agriculture accounted for ¼ followed by emissions coming from the energy sector like coal, oil, natural gas, and biofuels(Gould & McGlade, 2017; Kabeyi & Oludolapo, 2020e, 2020f). In 2015, there were about 76 Mt methane emissions from oil and gas operations from a wide variety of sources along the oil and gas value chains. Some of these emissions are accidental like leakages while others are deliberate like for safety reasons or due to the design of the facility or equipment. About 42 Mt of natural gas emissions in 2015 came from the natural gas chain which translates into an emission intensity for gas of 1.7%. This implies that on average 1.7% of natural gas produced is lost to the atmosphere before it reaches consumption or user points (Gould & McGlade, 2017). This is quite significant based on the high global warming potential of methane.

Based on global warming potential, methane stores more heat than carbon dioxide per unit of mass although it stays in the atmosphere for a shorter time. One ton of methane is equivalent to between 84 to 87 tons of $CO_2$ based on a 20-year timeframe (GWP20) and between 28 and 36 tons on basis of 100-year timeframe (GWP100). The benefit of conversion of natural gas to electricity is that the conversion efficiency is higher than that for coal and diesel hence emission yield is lower for natural gas in terms of electricity produced instead of heat. All generation scenarios show that gas produces fewer greenhouse-gas emissions than coal and oil when generating heat or electricity, regardless of the timeframe considered(Gould & McGlade, 2017; Kabeyi & Oludolapo, 2020a).

Natural gas is the cleanest fossil fuel compared to coal and oil. Coal and oil consist of complex molecules with higher carbon ratios and higher composition of pollutant forming Sulphur and nitrogen compared with natural gas. These leads to higher emissions of Sulphur dioxide and nitrogen oxides ($NO_x$) in addition to ash. On the other hand, natural gas produces minimal amounts of Sulphur dioxide, nitrogen oxides and almost no ash or particulate matter and emits lower levels of carbon dioxide ($CO_2$), carbon monoxide (CO) and other reactive hydrocarbons. This makes natural gas an environmentally superior fossil fuel compared to coal and oil(Gould & McGlade, 2017; NaturalGas.org, 2013).

Since natural gas is the cleanest fossil fuel, it can be used in many applications to reduce the negative environmental impact of fossil fuel combustion. The use of natural gas in power generation reduces cases of fog since it leads to less NOx emissions which is the main cause of smog. Acid rain whose principal sources $SO_2$ and $NO_x$ is also reduced by use of natural gas in place of oil and coal since natural gas emits almost no $SO_2$ and emits up to 80% less NOx than coal(Weber et al., 2000). A shift from coal and oil to natural gas will significantly reduce pollution from power plants since power generation is a leader in greenhouse gas emissions, example in 2002, power generation accounted for 67% of Sulphur dioxide emissions, 40% of $CO_2$ emissions, 25% of NOx emissions, and 34% of mercury emissions in the US because coal fired power plants have a significant contribution to generation capacity. It can also be noted that natural gas combined cycle power plant emit about 50% as much $CO_2$ as modern super critical coal power plant(NaturalGas.org, 2013).

Whereas liquefied natural gas (LNG) as a fuel has got lower carbon per unit energy compared to diesel and heavy fuel oil, its use might not reduce greenhouse gas emissions on a life-cycle basis. A study by (Sui et al., 2020) analyzed the life-cycle GHG emissions of marine gas oil (MGO), liquefied natural gas ( LNG), low sulfur industrial diesel fuel, and heavy fuel oil in internal combustion engines suitable for international application and found out that over a 100 year basis the maximum life cycle greenhouse gas emission reduction by use of LNG is 15% compared to marine gas oil (MGO) but if a high pressure dual fuel (HPDF) injection is used as well as upstream methane emissions. The control of upstream methane leaks is however not easy which further reduces the benefit of using LNG in place of diesel. The situation is worse if natural gas is derived from shale gas as this is bound to lead to more upstream leakages. The analysis based on a 20-year GWP showed some 4% more life cycle GHG emissions from LNG compared to MGO when upstream leakages are considered. The study also showed that technology choice has a significant impact on the lifecycle emissions from LNG. For example, use of LNG leads to about 70% more life-cycle GHGs emissions when LNG is used in place of MGO and about 82% more than MGO when used in medium-speed diesel engines(MSD) engine(Pavlenko et al., 2020).

A shift to natural gas will also lead to more use of shale resources which have significant water requirement. This may put pressure on water resource use and water pollution in the process of natural gas recovery. Water used in natural gas extraction is wastewater and needs treatment on the positive side, although natural gas production consumes water, the demand is considerably less water per unit of energy delivered compared to coal production, manufacture of ethanol production, tar (oil) sands, or oil shale. All the same, natural gas production from shale resources needs more water than conventional natural gas production and hence more demand for natural gas will lead to increased demand and use of water from available resources. (Pavlenko et al., 2020).

## 5. Materials and Methods

### 5.1. Introduction

Natural gas engines differ in the ignition methods, range of the air-fuel ratio, compression ratio, and which influence performance and emissions characteristics. With its high-octane rating, natural gas allows an increase in power for Otto cycle engines. As a gas, natural gas needs a larger volume in the engine combustion cylinder than diesel and other liquid fuels, which will effectively reduce power output of the engine. To compensate for this volume requirements, natural gas needs to be stored and used in compressed form. Even in compressed form, the storage space remains higher for natural gas compared to diesel and other liquid fuels(Werpy et al., 2010). Conversion from diesel to natural gas requires design and construction of gas storage, handling, and supply systems. Engine compression ratios may also need some adjustment and in some applications, there is need for exhaust gas treatment to limit NOx emissions.

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 2.

Table 2. Engine Technical Specifications (Kabeyi, 2020a).

| | 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 |

From table 2, it is noted that the engines used are V-engines with 18 cylinders and swept volume of 96.4 $dm^3$. The combined installed capacity of the 8 engines is 119.7 MWe.

## 6. Modification of the Fuel Injection System

For successful conversion of the injection system, a D-GID® Electronic Control Unit is introduced just before the natural gas and diesel are injected into the engine. The D-GID® system is the first technological platform developed by Ecomotive Solutions. Innovative system allowing the fuel diesel engines with a mixture of diesel oil and natural gas (CNG compressed natural gas, LNG liquefied natural gas, Bio methane, Syngas, etc.). D-GID® Control Unit determines the amount of diesel fuel injected and air/gas mixture dosage dynamically, modifying it in real time according to the feedback provided by the engine to guarantee perfect operational conditions (Kumar & Gaddipati, 2017).

### 6.1. Reduction of the Compression Ratio

Natural gas requires lower compression ratio compared to diesel, therefore a modification to facilitate this is required. A plate is added between the piston head and the cylinder block and act as a seal between the engine block and the piston head which increases the clearance volume. The shape of the plate will follow the shape of the top of the piston head (Kumar & Gaddipati, 2017). This plate is a gasket plate that normally exists in every engine block and acts as a seal between the piston head and the engine block.

Natural gas with compression ratio lower than diesel requires modification in the cylinder to facilitate this is required. A plate is added between the piston head and the cylinder block and acts as a seal between the engine block and the piston head which increases the clearance volume. The shape of the plate will follow the shape of the top of the piston head. The plate is a gasket plate that normally exists in every engine block and acts as a seal between the piston head and the engine block (Kumar & Gaddipati, 2017; Li, 2004).

### 6.2. Gas Piping and Supply System

A gas supply system is required to supply natural gas from storage tank to the dual-fuel engine (Arefin et al., 2020; Boretti, 2020; Kumar & Gaddipati, 2017). It includes: an industrial gas filter, a pressure regulator, a gas shut-off valve and pipes.

### 6.3. Gas Storage System

Natural gas can be stored as CNG (Compressed Natural Gas) or LNG (Liquefied Natural Gas). LNG takes up about 1/600$^{th}$ the volume of natural gas in the gaseous state. The liquefaction process involves removal of certain components, such as dust, acid gases, helium, water, and heavy hydrocarbons. The natural gas is condensed into a liquid as low as close to atmospheric pressure by cooling to approximately -162$^{o}$C and maximum pressure around 25kPa. The choice of the storage tanks depends on the consumption rate of the fuel. When dealing with large volumes, it is easier and convenient to store natural gas as a liquid. When selecting LNG tanks, other equipment must be accounted for. This is due to the process of regasification of LNG, which converts LNG from liquid state to gaseous state using a heat exchanger using ambient air or sea water. This 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.

### 6.4. Conversion of injection system

For conversion of the injection system, a D-GID® Electronic Control Unit is proposed just before the natural gas and diesel are injected into the engine. The D-GID® system is the first technological platform developed by Ecomotive Solutions. The system facilitates a mixture of diesel oil and natural gas (CNG compressed natural gas, LNG liquefied natural gas, Biomethane, Syngas, etc.) injection to the engine cylinder. D-GID® Control Unit determines the amount of diesel fuel injected and air/gas mixture dosage by dynamically modifying it in real time according to the feedback provided by the engine to guarantee perfect operational conditions (Ecomotive Solutions S.r.l, 2020a, 2020b).

## 7. Results and Discussion

It is noted from this study that a dual fuel diesel engine runs on both gas and diesel or heavy fuel oil. Natural gas is a cleaner fuel than diesel and heavy fuel. Although natural gas is nonrenewable, it can be substituted with biogas and biomethane which are renewable sources of energy with similar properties, especially biomethane. This study further established that natural gas produces the least total emissions compares to other fossil fuels followed by oil and coal respectively. Emissions coming from natural gas combustion include nitrogen oxides (NOx), carbon monoxide (CO), and carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), volatile organic compounds (VOCs), and trace amounts of sulfur dioxide ($SO_2$), and particulate matter (PM).

### 7.1. Benefits of Natural Gas Power Generation

Comparatively, natural gas produces 82.7% less total emissions than coal and 44.4% less total emission than oil. Since natural gas is the cleanest fossil fuel, it can be used in many applications to reduce the negative environmental impact of fossil fuel combustion. Use natural gas in power plants in place of diesel and coal, reduces cases of fog since it leads to less NOx emissions which is the main cause of smog. Acid rain whose principal sources $SO_2$ and NOx is also reduced by use of natural gas in place of oil and coal since natural gas emits almost no $SO_2$ and emits up to 80% less NOx than coal. Because of the clean combustion properties, natural gas use in power generation and transport has increased in countries like the US. Whereas it is not in dispute that natural gas as a fuel yield less emissions compared to diesel, there are legitimate concerns about natural gas leakages during handling and combustion given that methane is a more potent greenhouse gas, and this leads to uncertainty over the actual extent of the climate benefits from the use of natural gas as a fuel substitute to diesel power generation. Natural gas has high hydrogen/carbon (H/C) ratio compared to the other fossil fuels sources of energy which implies that $CO_2$ emissions are significantly lower while the mass per unit energy is also lower hence leads to lower specific fuel consumption. Additionally, combustion of natural gas leads to formation of water vapor and carbon dioxide as main products. These products have less environmental impact hence more preference for natural gas as a fuel(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022a; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022).

For diesel engines to run on both natural gas and diesel, the compression ratio must be reduced by increasing the engine cylinder clearance volume. It is easier to convert a diesel engine to a dual fuel engine relatively easily because the engine doesn't need changes on compression ratio, engine cylinder heads, or basic engine operation. The converted diesel engines are easier to install, operate and maintain. Two thicknesses of 10 mm and 5 mm were proposed for analysis, which gave compression ratios of 13.4 and 17.1, respectively. For a dual-fuel engine, a compression ratio of 16-18 is required. Therefore, the 5 mm thickness is chosen for the engine modification. The specific fuel consumption (sfc) of Kipevu III is 3400 kg/hr assuming full load optimum conditions. 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. With more natural gas displacement of diesel at the rate of 1 to 4, a cleaner combustion is expected and less unit cost of generation per unit power output(Kabeyi & Oludolapo, 2020b).

The total cost of the dual fuel is calculated based on assumed average 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) can be realized in fuel cost savings at average load factor of 0.5. 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; however, this estimated direct cost shows that the investment makes economic and financial sense as the payback on estimated direct cost is just 4.06 months. More accurate figures can be established by carrying out a detailed design and feasibility study for the project(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022a).

A sustainable electricity transition calls for eventual transition of the 62% of the global electricity production which comes from fossil fuels to low carbon and renewable energy sources. In the short and to some extend middle term, natural gas can substitute oil and coal although with the risk of delaying the zero emissions transition and creating transition related carbon lock-in and stranded assets by developing natural gas infrastructure. Since countries with huge coal and oil reserves may find it unsustainable to make immediate transition, increase in the share of natural gas and investment in efficient technologies like cogeneration and clean coal technology can reduce the carbon footprint. Based on global warming potential, methane stores more heat than carbon dioxide per unit of mass although it stays in the atmosphere for a shorter time. One ton of methane is equivalent to between 84 to 87 tons of CO2 based on a 20-year timeframe (GWP20) and between 28 and 36 tons on basis of 100-year timeframe (GWP100). The benefit of conversion of natural gas to electricity is that the conversion efficiency is higher than that for coal and diesel hence emission yield is lower for natural gas in terms of electricity produced instead of heat. All generation scenarios show that gas produces fewer greenhouse-gas emissions than coal and oil when generating heat or electricity, regardless of the timeframe considered(Gould & McGlade, 2017; Kabeyi

& Oludolapo, 2020a).

Natural gas is a cleaner fuel compared to coal and oil. Coal and oil consist of complex molecules with higher carbon ratios and higher composition of pollutant forming sulfur and nitrogen compared with natural gas. These leads to higher emissions of sulfur dioxide and nitrogen oxides (NOx) in addition to ash. On the other hand, natural gas produces minimal amounts of sulfur dioxide, nitrogen oxides and almost no ash or particulate matter and emits lower levels of carbon dioxide ($CO_2$), carbon monoxide (CO) and other reactive hydrocarbons. This makes natural gas an environmentally superior fossil fuel compared to coal and oil(Gould & McGlade, 2017; NaturalGas.org, 2013). Table 6 below shows the emission levels from natural gas, oil, and coal(M. kabeyi & O. Olanrewaju, 2022; Kabeyi & Oludolapo, 2020c, 2020d).The emissions from natural gas, oil and coal are summarized in table 3.

Table 3: Fossil fuel emissions (pounds/per Billion Btu of energy output(NaturalGas.org, 2013)

| | Pollutant | Natural gas | Oil | Coal | Remarks |
|---|---|---|---|---|---|
| 1 | Carbon dioxide | 117,000 | 164,000 | 208,000 | Natural gas has least CO2 emissions |
| 2 | Carbon monoxide | 40 | 33 | 208 | Oil produces least CO emissions |
| 3 | Nitrogen oxides | 92 | 448 | 457 | Natural gas emits the least amounts of nitrogen oxides |
| 4 | Sulfur dioxide | 1 | 1,122 | 2,591 | Natural gas emits insignificant amount of sulfur dioxide |
| 5 | Particulates | 7 | 84 | 2,744 | Natural gas emits negligible amounts of particulates |
| 6 | Mercury | 0.000 | 0.007 | 0.016 | Natural gas does not emit mercury to the environment |
| 7 | Total emissions | 117,140 | 165,687 | 214,000 | |

From table 3 above, it is noted that between natural gas, oil and coal, natural gas produces the least total emissions followed by oil and coal respectively. It produces 82.7% less total emissions than coal and 44.4% less total emission than oil.
Using natural gas in power generation reduces cases of fog since NOx emissions are the main cause of smog. Acid rain whose principal sources $SO_2$ and NOx is also reduced by use of natural gas as a substitute fuel for coal and diesel. It can also be noted that natural gas combined cycle power plant emit about 50% as much $CO_2$ as modern super critical coal power plant(NaturalGas.org, 2013). However, if natural gas is derived from shale gas as this is bound to lead to more upstream leakages. The analysis based on a 20-year GWP showed some 4% more life cycle GHG emissions from LNG compared to MGO when upstream leakages are considered. The study also showed that technology choice has a significant impact on the lifecycle emissions from LNG. For example, use of LNG leads to about 70% more life-cycle GHGs emissions when LNG is used in place of MGO and about 82% more than MGO when used in medium-speed diesel engines(MSD) engine(Pavlenko et al., 2020). Additionally, natural gas production from shale resources needs more water than conventional natural gas production and hence more demand for natural gas will lead to increased demand and use of water from available resources(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022b).

### 7.2. Limitations of conversion

Although natural gas power generation reduce pollution, they significantly contribute to the global climate change because of the greenhouse gases emitted. The gas combustion produces carbon dioxide, but in limited quantities. Natural gas mining and handling also leads to significant leakages leading to considerable release of highly potent methane to the atmosphere and thus electricity production using natural will continue adding to the greenhouse effect and global warming (Valera-Medina et al., 2015). Therefore, conversion from diesel to natural gas has threats and opportunities, advantages and disadvantages. The short-term benefits are clear, but we have long term risks to the sustainable energy transition with respect to methane related environmental risks and delay in the transition to zero carbon economy and energy mix.

## 8. Conclusions

Conversion of diesel engine power plants to dual fuel power plants leads to better performance indicators in terms of specific fuel consumption, brake thermal efficiency, indicated thermal efficiency, unit cost of generated power and total emissions and hence less environmental impact. Therefore, conversion will reduce the cost of electricity generation and amount of pollutants associated with diesel in power generation. The conversion will also lead better return on investment of the plant because of reduction in fuel related costs. Conversion from diesel fuel powered engines to full gas and dual fuel (gas and diesel) is both technically and financially feasible. Partial conversion to dual fuel mode is faster, cheaper, and more feasible as it requires less modifications and allows for more fuel diversity. The main engine modification done in the conversion process to dual fuel is the reduction in compression ratio. The main challenge of conversion of an operating power plant is generation interruption and extra investment in gas storage and handling infrastructure as well as renegotiation of the existing power purchase agreements to capture change in fuel and related costs and generation indicators. The long impact on the energy transition is delay in the achievement of zero carbon emissions. And the risk of creating transition related carbon lock-in and stranded assets by developing natural gas infrastructure during the global energy transition.

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