Preliminary Design of a Cogeneration Plant for a 120 MW Diesel Engine Power Plant

Moses Jeremiah Barasa Kabeyi *

22064693@dut4life.ac.za

Industrial Engineering Department, Durban University of Technology, Durban South Africa

Oludolapo Akanni Olanrewaju

oludolapoo@dut.ac.za

Industrial Engineering Department, Durban University of Technology, Durban South Africa

*Corresponding Author, contacts: 22064693@dut4life.ac.za; mkabeyi@uonbi.ac.ke

ABSTRACT

The conventional method of electric power generation in diesel power plants involves running of a generator directly coupled to an engine which releases exhaust gases at high temperature to the atmosphere. This is wasteful as recoverable heat energy is wasted to the environment through exhaust heat and the engine cooling and lubrication system. In this, a study performance analysis was done to determine the performance of the 120 MW Kipevu III power plant and feasibility of developing a cogeneration plant using a Rankine cycle steam turbine with exhaust gas boiler for waste heat to steam conversion. It was established that about 10 MW extra electric power can be generated by developing a Rankine cycle cogeneration plant from the combined 119.7 MW Kipevu III diesel engine power plant hence 8.4% extra electric power. This will lead to dual benefit more power output and hence revenue, reduced impact on the environment by avoiding use of extra oil to generate up to 8 MW power and reduced cost of power because of lower specific fuel generation and profits on fuel energy consumed. Therefore, cogeneration is a more efficient use of fuel in diesel engine power plants with financial, energy and environmental benefits.

Key Words

Combined heat and power; diesel power plant; exhaust gas boiler; greenhouse gas emissions; Kipevu III power plant.

1. Introduction

The high efficiency of compression-ignition or diesel engines has endeared themselves as a leading power source in transport especially heavy-duty vehicles and in diesel power plants. The engines are also finding themselves in light-duty cars which were dominated by petrol or gasoline engines. The main challenge of diesel engines 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, 2020i).Diesel power plants constitute diesel engines and auxiliary systems of the power plant. Diesel power plants convert fossil fuels to electricity using diesel engines as generator prime movers(Ogunkunle & Ahmed, 2020). The diesel power plants are widely used in off grid electricity generation, emergency power applications and grid electricity supply mainly as peak load and emergency power plants especially in developing countries (Katiraei & Abbey, 2007).

Other than fossil fuel combustion in coal and diesel power plants, there are various generation technologies like cogeneration that can be used to generate electricity cost effectively while reducing carbon emissions (Sims et al., 2003). Diesel power plants are mainly used as standby generating units alongside grid power supply or grid connected units for supply of peak power (IDC Technologies, 2020; Kabeyi & Oludolapo, 2020h). The construction of diesel power plants consists of the diesel engine prime mover, the generator set and supporting auxiliaries and systems(IDC

Technologies, 2020). Because of size limitation of engines and the need to inbuilt flexibility in the power generation capacity and output, a diesel power plant consists of multiple generating units. For the case of Kipevu III power station, 7 engines of 17.1 MW installed capacity are used hence the power plant capacity is 119.7 MW (Kabeyi, 2020a).

Energy efficiency is an increasingly important contributor to climate change while at the same time reducing the cost of energy as well as an opportunity for technological innovation. The conventional method of power production is wasteful in the sense that only 35% of the primary energy that is fed into the power plant is made available to the consumers(Kabeyi & Oludolapo, 2020h). The major source of loss is in the conversion process where heat is rejected to the surrounding environment. This project will focus on cogeneration which is one of the low hanging fruits of energy efficiency and has benefits on electricity supply side(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022a; Kabeyi & Oludolapo, 2020d). The globally electricity sector accounts for over 7700 million tons of CO_2, annually or 2200 Mt C/year which is about 37.5% of total CO_2 emissions. With business as usual scenario, emissions from power generations were projected to surpass 4,000 Mt C/year by the year 2020 (Sims et al., 2003). In diesel power plants, Only 30-40% of fuel energy combusted in an internal combustion engine is converted to useful mechanical work (Hoang, 2018; Senthilkumar & Vivekanandan, 2018). This implies that efficiency of a modern thermal power plant is on average 30% but can reach 40% on the basis of lower calorific value of fuel (LCV) (Sims et al., 2003)

Fossil fuels remain widely available, accessible and more competitive in terms of price/cost and conversion efficiency than some renewable energy sources(Jaccard, 2007). The exhaust gas temperature from an engine is 450 - 600ºC the waste heat can recovered leading energy, pollution reduction and reduced consumption and dependence on fossil fuels (Hoang, 2018). The energy demand is growing but the supply of fossil fuels is limited, and finite hence the danger of price fluctuations and increases, pollution from greenhouse gas emissions which are a threat to the global climate stability. These negative trends can therefore be mitigated by using primary energy sources efficiently through cogeneration in diesel power generation (Kabeyi & Oludolapo, 2020b, 2020h). The benefits of cogeneration include increase in cycle efficiency to up to 90%, reduced emissions per unit useful energy, and valuable recognition as well as access to energy efficiency credits available in many countries(Caterpillar, 2021).

The main objective of the study will be to design a diesel engine cogeneration and conduct the performance analysis of Kipevu-III power diesel plant. Cogeneration also known as combined heat and power, CHP) is the use of a heat engine to simultaneously generate both electricity and thermal energy (useful heat) from a single source of primary energy. The useful heat is in the form of high-pressure steam (steam process) or hot water.

2. Diesel Power Plants

In most heat engines, more than 50% of the primary energy in fuel is wasted. Cogeneration makes use of waste heat that would have otherwise been wasted in a conventional power plant then increases efficiency to as high as 80% to 95%, instead of about 40% that can be realized in conventional power plants(Wagner & Brenner, 2016). Diesel engines have the highest thermal efficiency compared to all heat engine prime movers of similar size and capacity. The engines can be classified as two stroke or four stroke engines. Other mode of classifying diesel engines includes the number of cylinders, i.e., single cylinder or multi-cylinder among others(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2021a). Compared to Otto cycle or petrol engines, diesel cycle engines can operate with high compression ration which makes them have higher power density and slower engine specific volume which makes them versatile and compact as well as more efficient than Otto cycle engines(Khattak et al., 2016).

An ideal diesel cycle process follows four thermodynamic processes, i.e., constant pressure combustion, isentropic compression, expansion, and constant volume cooling. The diesel power plants have many advantages which include small area requirements, high thermal efficiency, and simple construction layout of the power plant(M. Kabeyi & O. Olanrewaju, 2022; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2021). On the other hand, the disadvantages of diesel power plant cannot be ignored which as well makes them attractive for many applications like emergency power supply, off grid power supply, standby units, and in some cases, diel power plants are use in base load grid power supply whenever cheaper and cleaner sources become limited. They however have limitations like high cost of fuel and electricity, high emissions of greenhouse gases, high operation and maintenance costs and low reliability of supply (Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2021; Khattak et al., 2016).

Internal combustion engines release about 30-40% of the fuel energy content as waste heat in the exhaust gas and about 30 to 40% is released through the cooling system (Wilson et al., 2017). These waste heat can be recovered for thermal applications and in some cases power generation through a Rankine cycle (Milkov et al., 2012). The recovery of waste engine heat for valuable application reduces the fuel consumption and related negative environmental impact which includes NO_X and SO_2 emissions while producing the same power output (Kabeyi & Oludolapo, 2020e, 2020g). Therefore, engine waste heat recovery is a proven strategy for mitigation against excessive use of fossil fuels hence reduced environmental pollution and can process heating costs and fuel energy costs. Diesel engine exhaust can supply extra mechanical power using the Rankine cycle in which the working fluid is water with about 38% extra power potential through waste heat recovery with optimum pressure of about 30 bars (Bari & Hossain, 2013).

Internal combustion engines consume more than 60% of fossil fuels for their application as prime movers in agriculture machines, fishery, transportation, construction, power generation (Hoang, 2018). While about 60% of air pollution comes from internal combustions engine exhausts (Hoang, 2018; Senthilkumar & Vivekanandan, 2018). . An engines main output is mechanical power which can be used to turn a generator for power generation and waste heat in the exhaust and cooling system which can be recovered for thermal applications (Kabeyi & Oludolapo, 2020b). The mechanical output can also be used for rotation of equipment such as compressors, pumps, and other machinery.

3. Cogeneration

3.1. Benefits of cogeneration

Cogeneration also called combined heat and power (CHP) generation of heat and electricity at the same time from the same fuel source. In combined heat and power (CHP) plants, waste heat is recovered and put to useful use for thermal applications like heating which in this case is referred to as combined heat and power district heating. Waste heat recovered can also be used in absorption refrigerators for cooling applications(Onovwiona et al., 2007). In cogeneration systems, the heat energy may be used to generate steam, hot air for dryers or chilled water for process cooling. With over 60% of fuel energy being lost to exhaust and cooling systems, cogeneration is an attractive measure to improve an engines overall thermal efficiency (AL-Hawaja & AL-Mutairi, 2007). Cogeneration, otherwise known as combined heat and power is simultaneous generation of heat and electricity from the same energy source. Cogeneration involves various concepts and technologies through which heat, and electric are power jointly produced by a system. There is a potential to generate more electricity than needed for internal use with excess electricity being exported to the grid to earn an extra revenue stream(Kabeyi, 2020b). with the option of the excess energy being fed into the public grid could help in saving this energy. Cogeneration results to high levels of efficiency of about 85%, because of using waste energy as a co-product of electricity generation(Kabeyi & Oludolapo, 2020g, 2020h).

Cogeneration systems for diesel power plants make use of different devices, but the basic elements are the electric generator, Rankine cycle steam turbine, the engine, heat recovery equipment like exhaust gas boilers, super heaters, and system control devices. The steam turbines are the prime movers with various options whose performance and application may also vary e.g., condensing turbines, back pressure turbines and extraction turbines(Kabeyi, 2020b; Urbonienė, 2019). Based on the lower heating value of fuel used, cogeneration systems, have efficiency greater than 80% compared to an average of 30–35% in conventional thermal systems generation systems and up to 55% for the case of combined cycle power plant systems like in gas turbine combined cycle gas turbine(Moses Jeremiah B. Kabeyi & O. A. Olanrewaju, 2021; M. J. Barasa Kabeyi & O. A. Olanrewaju, 2021; Kabeyi & Olenwaraju, 2021; Kabeyi & Oludolapo, 2020g, 2020h). The main benefit of the increased energy efficiency is low energy expenditure and reduction in generation related greenhouse gas (Onovwiona et al., 2007).

3.2. Types of Cogenerations

Based on usage, cogeneration can be classified into three types, namely i.) Industrial cogeneration

Industrial cogeneration is applied in industries that require both heat and electrical energy. These industries use the dual demand opportunity to generate steam in boilers for generation of electricity and heat for own consumption and they can export the excess of these forms of energy (Mysiakowski, 2021). In some cases, a plant may need coolness in addition to heat and electricity which leads to trigeneration by installation absorption chillers. A typical example of industrial cogeneration is the sugarcane industry where sugarcane factories use bagasse to generate steam in boilers to run steam turbines for power generation with the exhaust steam being used for process heating(Kabeyi, 2020b; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2021b). Another example is of industrial cogeneration is a modern sewage plant which produce biogas for process heating purpose and generation of electricity for use and export(Kabeyi & Oludolapo, 2020c, 2020f).

ii.) Heating cogeneration.

Heating cogeneration is applied where there is substantial demand for heat which is the main product of interest but in the process, some generation of electricity is done as a by-product. An example of this is district heating systems which usually produce heat at temperatures between 40°C and 140°C.

iii.) Agricultural cogeneration

This cogeneration is used mainly in rural processes like agriculture which need heat of between 15°C and 40°C for processes like cereals drying and horticulture in green houses. Agricultural cogeneration systems aim at producing useful heat and in the process generate electricity for own use and sell of excess (Mysiakowski, 2021). Cogeneration cycles can be classified as toping cycle plants or bottoming cycle plants. Topping cycle plants have a primary objective of producing electricity from a steam turbine and the exhaust steam or partly expanded steam then used for heating at appropriate temperature and state for use in district heating, water desalination and other thermal applications. Bottoming cogeneration cycles produce high temperature heat for process use and then the waste is recovered in waste heat recovery boiler to generate steam for power generation. The Bottoming cycle plants are found in high temperature industrial processes like furnaces for glass and metal manufacturing.

3.3. Steam Turbines-Based Cogeneration

Steam turbine cogeneration systems work on the Rankine's cycle and are quite flexible when it comes to fuel used. There are two types of steam turbines used in cogeneration. The turbines used are the Back-Pressure Turbine and extraction condensing turbine. In back pressure turbines, steam exits the turbine at its exhaust at a pressure higher than atmospheric for process use. In Extraction-Condensing Turbines, process steam is extracted at a pressure higher than exhaust pressure between the turbine stages while the remaining steam is allowed to expand through to the turbine exhaust into the condenser. Although back pressure turbines are simple in construction and cheaper than the extraction-condensing steam turbine type, they are less efficient and hence generate less power than the condensing type (Kabeyi, 2020b; Mysiakowski, 2021).

3.4. Gas Turbine Cogeneration System

This cogeneration system is applied on gas turbine plants where the turbine exhaust which has high energy content is used for thermal applications(Mysiakowski, 2021). The system can also be used to generate extra power by means of a steam turbine by using the turbine exhaust gases to generate steam for the Rankine cycle turbine. Cogeneration can be applied on the steam turbine using the two modes i.e., back pressure system or the extraction-condensing turbine. In some cases, only electricity is needed, so a pure condensing turbine is the best option for maximum power generation(Kabeyi, 2020b; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2021).

3.5. Recuperating Engine Cogeneration System (RECS)

This system uses an internal combustion engine to provide mechanical power and heat at a higher efficiency than in steam and gas turbines systems. In recuperating engine cogeneration system (RECS), heat is recovered from four sources, namely the exhaust gasses, lubrication oil, the engine jacket-cooling water and turbocharger cooling systems. Recuperating engine cogeneration system is an ideal cogeneration system for off-grid, low and medium power systems, and distributed generation systems. The advantage of RECS is that it is flexible and is quick to stop and start hence ideal as a standby unit. However, it is expensive to maintain(Mysiakowski, 2021).

3.6. Environmental Impact of Diesel Power Plants

The society energy needs are predominantly met buy fossil fuels sources including diesel power plants for grid and off grid power production. The fossil fuels are also used to power, boilers and air-conditioning systems and other heat applications (Kabeyi & Oludolapo, 2020e). Fossil fuels have a significant contribution to global primary energy supply, and their overall consumption has increased over the years (Kabeyi & Oludolapo, 2020h). The global increase in fossil fuels consumption worldwide is a threat to the environment due to increased CO_2 and hence the danger of global warming besides accelerated depletion of the fossil fuel reserves (Intergovernmental Panel on Climate Change, 2001). Cogeneration in diesel power generation is attractive due to the growing need to reduces consumption through efficient use of resources. Through cogeneration and other technologies, the global energy sector can reduce carbon emissions by between 8.7-18.7% (Sims et al., 2003).

4. Material and Methods

The contract for construction of Kipevu III diesel engine power plant was signed on November 27, 2009, with the project contractor being Wartsilla. Kipevu III diesel engine power plant is located at Kipevu in Mombasa and was commissioned in the 2011., with the commissioned plant being handed over on March 6, 2011, to Kenya Electricity Generating Company (KenGen)(Kabeyi, 2020a). The power plant is the largest grid connected diesel engine power plant in East and Central Africa, having installed capacity of 119.7 MW connected to the Kenyan national grid through a 132KV switch yard extension (Kenya Electricity Generating Company Plc, 1999). The power plant is equipped with seven Wärtsilä 18V46 turbocharged diesel engines(Kabeyi, 2020a). The power station on average has effective of 117 MW with auxiliary equipment consuming part of the 119.7 MW installed generation capacity(Global Energy Observatory, 2016). The plant employs the latest technology in plant operations monitoring and supervision, plant safety, sound attenuation and exhaust gas dispersion control and efficient treatment to ensure environmental protection (Global Energy Observatory, 2016; Kenya Electricity Generating Company Plc, 1999).

The design of a diesel engine power plant involves optimal sizing of the various units that constitute a power plant. This includes a careful consideration of daily and seasonal load fluctuations, electricity demand growth, incorporation of practical constraints to ensure flexibility and reliability of the plant and economic operation and maintenance. To avoid oversizing of the power plants, the individual units should not be sized based on peak and/or average load values alone. Consideration should be made for some safety margins and future demand and capacity based on projections made. A practical approach in the design of a power plant is use multiple units, like a set of two, three or four engines with varying sizes. For maximum fuel efficiency, engines should be loaded in a way that maximizes cycle efficiency and use a dispatch strategy that optimizes the power plant performance(Katiraei & Abbey, 2007).

Kipevu III power station is a diesel engine power plant located at Kipevu in Mombasa County that was commissioned in the year 2011(Kabeyi, 2020a). The construction of the power plant officially started with the signing of a construction on November 27, 2009, between the Kenya Electricity Generating Company Plc. (KenGen) as the owner or employer and Wartsila Finland as the contractor. The power plant was constructed, commissioned, and handed over to KenGen for operation and maintenance on March 6, 2011. The power plant so far the largest diesel engine power plant in East and Central Africa with 119.7 MW connected to the national grid through a new 132KV switch yard extension (Kenya Electricity Generating Company Plc, 1999). The power plant is owned by Kenya Electricity Generating Company Limited (KenGen) who have a 20-year power purchase agreement with the grid electricity utility company, the Kenya Power Plc(Kabeyi, 2020a). The power plant has a total of 7 Wärtsilä 18V46 turbocharged diesel engines individually exhausting the products of combustion as exhaust gases to the atmosphere via a turbocharger (Kabeyi, 2020a). The effective capacity of the power plant is 117 MW with the auxiliary units consuming about 2.7 MW electric power (Global Energy Observatory, 2016). The power plant (Kipevu III) employs the latest technology in plant monitoring and supervision, safety, sound, emission monitoring and provisions emission treatment to ensure environmental protection and compliance (Global Energy Observatory, 2016; Kenya Electricity Generating Company Plc, 1999).

A cogeneration power plant design requires the selection of most economic combination of equipment and technology from the many available alternatives. This technology is chosen based on the energy forms required by the user which may include Heat Recovery Steam Generator (HRSG). The important factors that play a key role in determining the plant configuration is the available fuel and the ratio of heat demand to power demand. The proposed cogeneration plant has one exhaust gas recovery boiler that gets exhaust gas supply through connection to the exhaust ducts of the 7 diesel engines. Steam generated is directed to the Rankine cycle steam turbine to which rotates a synchronous electric generator for grid connected electricity generation.

5. Results and Discussion

Kipevu III diesel power plant has 7 similar diesel engines and generators. The engine specifications are summarized in table 1 below.

Table 1: Kipevu III Engine Specifications (Kabeyi, 2020a)

Manufacturer	Wärtsilä
Type of engine (operating strokes & orientation)	18V46
Bore	460mm
Stroke	580mm
Number Of Pistons	18
Compression ratio	22:1
Power output	17.1 MW
No of generating units	7
Speed (RPM)	500 RPM
Cooling system	Water Cooled
Exhaust Gas Temperature	360 °C
Compression Pressure	190 bars
Specific Fuel Consumption	0.1818 kg/kWh
Swept Volume Capacity	96,390 cc
Mean Effective Pressure	24 bars

Mean Torque	318.946kNm

Table 1 summarizes the specifications of the engines and the power plant. It is noted the power plant has got seven engines are which 18 cylinder V-engines with specific fuel consumption of 0.1818 kg/kWh and swept volume capacity of 96,390 cm^3 .The engine exhaust temperature is 360ºC at engine torque of 318.946 kNm

4.1. Power Plant Performance Analysis

i.) Availability and load factor for the power plant

The performance of the power plant in terms of load factor and availability is summarized in table 2 below.

Table 2: Kipevu III power plant performance Indicators

FACTOR/YEAR	2017/2018	2016/2017	2015/2016	AVERAGE
1.Load factor	58.93	50.84	17.66	42.48
2.Availability	89.6	93.05	97.84	93.50

From table 2, it is noted that between 2017/18 and 2015/2016 financial years, average availability was 93.5% while average load factor was 42.48% while. This implies that although the plant was available most of the time, its demand was low.

ii.) Indicated Power

$$Indicated\ Power\ (IP) = \frac{\text{Imep x Ac x L x N x n}}{2\ x\ 60} = \approx 17\ 350.236\ \text{kW}$$

Therefore, the indicated power which corresponds to fuel power is about 17.35 MW

iii.) Brake Power

Engine brake power is the actual power output of an engine and is measured by means of a dynamometer on the test bench.

$$Break\ Power = \frac{2\pi NT}{60} \text{ Where N is engine speed, T engine torque} = 16699.973\ \text{kW}$$

iv.) Efficiency

Mechanical efficiency of an engine is the ratio of brake power to indicated power and it is a measure of energy conversion to useful power from the power developed in the cylinder.

$$\eta = \frac{\text{Brake Power}}{\text{Indicated Power}} x100\% = \frac{16{,}699.973}{17{,}350.236} = 96.25\ \%$$

v.) mass flow rate of exhaust gases

Mass flowrate is the rate of flow of the flue gases in kg/sec. the total mass of flue gases for a closed system is the sum of combustion air and the fuel supplied to the furnace. Therefore.

$$m_{ex} = m_{fl} + m_{ar} = m_{ex} = 0.8433 + 5.3 = 6.144\ \text{kg/s}$$

vi.) Heat loss by the exhaust gases (One engine unit)

This refers to technically recoverable waste heat or exhaust heat. Hence the exhaust contains Sulphur dioxide, the recommended minimum exhaust temperature is 170ºC.

$$Q_{ex} = m_{ex}\ x\ Cp\ x\ \Delta T$$

Where ΔT *is the temperature difference i.e.* $(360 - 170) = 120$. This represents technically recoverable heat energy in exhaust gases. $\Delta T = Thermal\ gradient, Cp = Heat\ capacity\ of\ flue\ gases$

$$Q_{ex} = m_{ex}\ x\ Cp\ x\ (Tsource - T\ sink),\ Q_{ex} = \frac{6.144kg}{s}\ x\ \frac{1.008KJ}{kgK}\ X\ (360 - 170) = 1176.69\ \text{Kw}$$

4.2: Heat Recovery Steam Generator (HRSG)

A shell and tube heat exchanger are proposed for the heat recovery steam generator to extract heat from the engine exhaust. It receives exhaust gases from all the 7 engines.

Heat Transfer area and tube numbers

1 shell and 2 tube passes

1´´ OD tubes (*do*) (14 BWG) on 1¼´´ square pitch (*PT*)
Outer diameter of tube= 1, Tube length (*Lt*) =16, Tube ID (*d*i) = 0.834´´

Heat transfer Area

$$\text{A} = \frac{\text{Q}}{U_0\ (\text{LMTD})F_T} = \frac{\text{mex Cpex(Thi} - \text{Tho)}}{U_0\ (\text{LMTD})F_T}$$

$$(\text{LMTD}) = Logarithmic\ mean\ temperature\ difference$$

Where LMTD is logarithmic mean temperature difference, $U_0 = Overall\ heat\ transfer\ coefficient,$
Thi and Tho is temperature at inlet and outlet for hot flluid

$$A = \frac{1.394\ \text{x}10^3\ \text{x}\ 7\ \text{x}\ 6.144\ \ (360 - 220)}{60\ (225.94)0.98} = 631.78m^3$$

Figure 1 below demonstrates the counterflow heat exchanger proposed for this design.

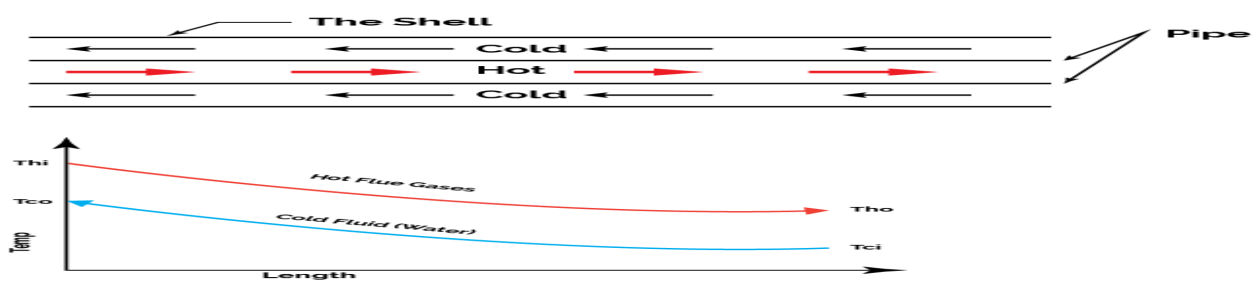

Figure 1: Temperature Distribution for Counter Flow Heat Exchanger (Authors Conception)

Figure 1 shows the temperature distribution for the two fluids i.e., flue gases as hot fluid and water/steam as the low temperature fluid in the heat exchanger. The flow gases flow in the tube side while the water flows through the shell side towards opposite directions.

i.) Shell diameter (Ds)

For a 1-shell and 2-pass heat exchanger, according to TEMA standards, for 1300 tubes, the minimum recommended shell diameter is 84 inches. $DS = 84\ inches = 84\ x\ 25.4 = 2133.6\ mm$

ii.) Baffle Spacing and baffle cut.

According to the Tubular Exchanger Manufacturers Association (TEMA), the recommended baffle spacing is 0.2 to 1 time the inside shell diameter. $Baffle\ Spacing = 0.4\ x\ 2133.6\ mm = 853.44\ mm$

iii.) Shell thickness: $\boldsymbol{t_s} = \frac{\boldsymbol{PR_s}}{\boldsymbol{\sigma j - 0.6P}} + \boldsymbol{Corrosion\ Allowance}$

J is the efficiency of the joint, J for butt weld joint is 0.8., $t_s = 2.21 + 1.5\ mm = 3.71\ mm$

4.3. Design of A Super Heater (Interface II)

The super heater is a heat exchanger that extracts heat from exhaust gases to heat wet steam with the objective of generating superheated steam.

i.) Specific heat capacity of steam (Cp_s– 2.01 *kJ/kgK)*
ii.) Specific heat capacity of the flue gases (Cp_f= 1.1394 *kJ/kgK)*
iii.) Mass flow rate of steam = 18 kg/s
iv.) Mass flow of flue gases = 43.008 kg/s
v.) Diameter(outer) of the tubes = 1.5 inch (38.1mm)
vi.) Length of the tubes = 4 meters
vii.) The heating surface area, (LTSH) =3055m^2
viii.) Desired efficiency of the super heater = 0.9

4.4. The Number of Tubes for The Heat Exchanger.

$n = \frac{A_O}{\pi\ x\ \ x\ D_O\ X\ L}$, $n = \frac{3055}{\pi\ x\ 0.0584\ X\ 6} =\ 2775\ tubes$

Therefore, the exhaust gas heat recovery system will have 2775 tubes.

4.5. The Steam Turbine

Steam velocity exiting the nozzle= 15000 rpm; Tangential component of velocity out of nozzle is twice the blade speed; Tangential component of absolute velocity out of rotor is zero, High head of about 100m since it's an impulse turbine; Mass flow rate of steam, 18 kg/s (unit)

U = $\omega R_{m,}$ $U = \frac{15000\ \mathrm{x}\ 2\pi\ \mathrm{x}\ 0.71}{60} = 111.53\frac{m}{s}$; $Wshaft = \ -(2U^2) =\ 2x111.53^2 = -24{,}876.34\ Nm$

4.6. Steam Turbo- Generator Design Selection

The turbine selected for the cogeneration application in this design is summarized in table 3 below.

Table 3: Steam Turbo- Generator Selection

Type	SST-200, Single-casing, geared
Application	Industrial use
Model	Multivalve Multistage (MVMS)
Turbine Design	Condensing turbine
Generator type	Synchronous
Power Output	Up to 10MW
Inlet Pressure	Up to 110 bars
Inlet Temperature	Up to 520ºC
Exhaust Pressure (condensing)	Up to 0.25 bar
Exhaust area	0.17 – 0.34 m^2

From table 3 above, it is noted that for optimum design and operation, the turbine will be multistage condensing type with condenser pressure of 0.25 bars, design inlet steam temperature is 520^{0}C, inlet steam pressure is 110 bars, power rating is 10 MW, generator type is synchronous for constant frequency generation,

4.7. Summary of The Proposed Plant

The proposed extension plant recovers heat from the exhaust of the diesel engines to generate superheated steam to run a steam turbine which rotates an electric generator to produce extra elecricity for supply to the grid. This requires the water treatment system for treatment of boiler water for steam generation, the heat recovery steam generator (HRSG) which recoveres heat from flue gases for generation of wet saturated steam from water, a superheater for generation of sry steam by heating saturated steam from the HRSG, a steam turbine for conversion of energy in steam to mechanical power, a generator which is coupled to the steam turbine for power generation, and a condensor for condensing turbine exhaust to water which is recovered andstored in a water tank or feed water tank. A feed water pump is used to ump the condensate and any make up water to the HRSG for another cycle of steam generation.

The main elements of the proposed Rankine cycle plant for extra electricity generation include the already existing 7 engines which supply exhaust gas, the heat Recovery Steam Generator (HRSG), super heater, the condenser, feed water pump impulse steam turbine interconnected with various pipelines and electric generator which is coupled to the steam turbine for conversion of mechanical power to electricity. This will be additional power generated from waste exhaust gases using same amount of fuel used in the diesel engines for primary or main power generation.

5. Results and Discussion

Cogeneration or CHP (Combined Heat and Power) solutions can generate heat and power simultaneously effectively increasing the overall efficiency of the system up to 90% and even more based on the lower calorific value. This is high compared to the average of 30–35% for conventional fossil fuel fired power plants and 55% for the combined cycle power plants like the combined cycle gas turbine power plants. Higher energy efficiency can result in lower energy expenditures and lower greenhouse gas emissions per unit generation. This potentially reduces the overall energy expenditures and unit cost of power generation which can be passed to consumers. Cogeneration can be applied on various prime movers other than diesel engines. They include gas turbines, Stirling engines, fuel cells, and geothermal power plant systems(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022b, 2022c; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022d).

Cogeneration's systems can be designed or sized for various plants based on the thermal and electrical needs and thermodynamic conditions. Cogeneration is also a leading source of distributed generation which can enhance power system reliability and help reduce transmission losses because there is no need to transport power over long distances. Cogeneration also reduces electricity load or demand for heating purposes hence reduced need for polluting generation. Through cogeneration, less primary energy resources are c consumed to deliver the same amount of useful energy and hence less pollution from reduced energy consumption to do same work. Therefore, cogeneration has an important contribution to climate change mitigation while offering economic and social benefits to society.

6. Conclusion

Engines account for about 60% of fossil fuels for their application as prime movers in and 60% of air pollution. Kipevu III power plant has installed capacity of 119.7 MW consisting of 7 engines with effective electricity capacity of 17.1 MW from the installed generation capacity of 119.7 MW The engines exhaust recoverable waste heat of about 1,176.69 KW per engine and a total of about 8,236.83 KW for the 7 engines. Therefore, about 8 MW extra electric power can be realized by developing a Rankine cycle cogeneration plant from the combined 119.7 MW Kipevu III diesel engine power plant hence 6.7 % extra electric power. This will lead to triple benefit more power output and hence revenue, reduced impact on the environment by avoiding use of extra oil to generate 8 MW power and reduced cost of power because of lower specific fuel generation. More power can be achieved by optimization of the design and adoption of more efficient cycles like the organic Rankine cycle. Diesel power plants can reduce power cost by exploring the best power producing practices such as cogeneration which increases the power output from same fuel leading to lower specific fuel cost and lower cost of produced power. The payback period for direct investment is as low as 1 year although indirect project cost may increase the period. The analysis shows that the development of a cogeneration plant on the existing power plant is both technically and economically feasible.

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Moses Jeremiah Barasa Kabeyi is currently pursuing his D.Eng. In Industrial Engineering in the Department of Industrial Engineering at Durban University of Technology. He earned his B.Eng. degree in Production Engineering and MSC in Mechanical and Production Engineering (Energy) from Moi University, in Kenya, MA in Project planning and Management from University of Nairobi, in Kenya and Diplomas in Project management, Business management and NGO management respectively from The Kenya Institute of Management. He has worked in various factories including sugar manufacturing at Nzoia Sugar Company Ltd, pulp and paper at Pan African Paper Mills EA Ltd, and power generation at the Kenya Electricity Generating Company (KenGen) in Kenya, in an industrial career of 16 years before moving into teaching. He has taught in various universities in Kenya including University of Nairobi, Technical University of Mombasa, and Egerton University and currently on study leave. His research interests are power generation, fuels and combustion, internal combustion engines and project management and sustainability. He is registered with the Engineers Board of Kenya (EBK) and Institution of Engineers of Kenya (IEK) and has published several journal papers.

Oludolapo Akanni Olanrewaju is currently a Senior Lecturer and Head of Department of Industrial Engineering, Durban University of Technology, South Africa. He earned his BSc in Electrical Electronics Engineering and MSc in Industrial Engineering from the University of Ibadan, Nigeria and his Doctorate in Industrial Engineering from the Tshwane University of Technology, South Africa. He has published journal and conference papers. His research interests are not limited to energy/greenhouse gas analysis/management, life cycle assessment, application of artificial intelligence techniques and 3D Modelling. He is an associate member of the Southern African Institute of Industrial Engineering (SAIIE) and NRF rated researcher in South Africa.