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Cogeneration vs. Conventional Thermal Power: Performance Assessment and Rankine Cycle Design at Kipevu III and Rabai

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Abstract

Diesel power plants are vital for Kenya's electricity generation by providing peaking capacity, grid stability and emergency electricity generation. Nonetheless, these heavy fuel plants are associated with relatively low thermal efficiency, high fuel consumption and a great contribution to greenhouse gas emissions. This project proposal aims to deliver a framework for a case-study based assessment that compares the performance of a cogeneration enabled diesel powerplant to that of a conventional diesel plant using Rabai Power and Kipevu III powerplant as examples and also framework that develops a practical waste-heat-recovery (WHR) solution for Kipevu III based on a basic Rankine bottoming cycle. The project will adopt a mixed engineering-analytical methodology. The comparative performance part will use plant operational records which will be obtained during site visits and heat-balance analysis to quantify thermal efficiency, specific fuel consumption, recoverable heat streams among the key parameters. Operational emissions pollutants are to be estimated using fuel-based and stack measurement methods. Economic and environmental assessment will be made. The design section will convert recoverable exhaust heat into more electricity through a Rankine Cycle. The expected deliverables thus include a validated comparative performance analysis for the two plants, the heat-recovery potential and design of a Basic Rankine Cycle for Kipevu III, a techno-economic model that yields LCOE and investment metrics and an integrated recommendation on whether cogeneration retrofit is technically and economically justified for Kipevu III and thus by extension, other Kenyan diesel Plants.

Keywords
Specific Fuel Consumption, Waste Heat Recovery, LCOE, Payback Period.

1. Introduction
The world over, thermal power is unmistakably vital, contributing the major share of electricity generation with coal at 35% and natural gas at 22%. Oil fired power plants contribute about 2.6% of the electricity. The small percentage of oil fired power plants electrical share is also simultaneous in Kenya.((IEA), 2023).

Despite Kenya's electricity generation being dominated by renewable sources like hydro, wind, solar and geothermal, the diesel thermal powerplants play a huge role in stabilizing Kenya's grid. Thermal plants have over the years offered Kenya crucial backup as standby plants that swing into action at a moment's notice during downtimes in geothermal and weather-dependent hydropower, solar-power and wind-power. Diesel generators are flexible enough to be switched on and off and ramped up and down. This flexibility enables them to play a crucial role of matching demand spikes and drops in the national grid, acting as system stabilizers. However, these plants suffer from low thermal efficiency, high fuel costs and significant operational emissions. To analyze these challenges, this propasal proposes a focused, case-study–based investigation that will include:

1. a comparative performance analysis of a cogeneration-capable diesel plant versus a conventional simple-cycle diesel plant (case studies: Rabai Power Plant and Kipevu III Power Plant)
2. The design and techno-economic evaluation of a practical waste-heat-recovery (WHR) solution for Kipevu III (basic Rankine bottoming cycle, including preliminary HRSG and steam-turbine sizing).

The results are intended to inform near-term retrofit decisions and broader policy discussions about improving the efficiency and environmental performance of Kenya's thermal generation sector.

1.1 Problem Statement

It is quite evident that Kenya's reliance on renewable energy sources to produce electricity is higher than ever(Fobi et al., 2018). However, Thermal powerplants however still play an important part in the national grid serving as backups and peaking stations. The operation of these powerplants requires consumption of a lot of fuel and have substantial greenhouse gas emissions which fall short of Kenya's policy targets of considerably reducing carbon emissions by 2030.(Kabeyi & Olanrewaju, 2024) In addition to the above, the plants operate at relatively low thermal efficiencies of around 30% (Heywood, 2018) with a large portion of energy lost to heat yet this energy can potentially be recovered through cogeneration to improve plant efficiency, reduce the specific fuel consumption and emissions per unit of electricity generated.(M. J. B. Kabeyi & O. A. Olanrewaju, 2022) While cogeneration and other waste heat recovery technologies are widely recognized, there is limited plant-specific evidence within the Kenyan context quantifying the real operational performance benefits of diesel power plants that incorporate cogeneration compared to similar plants that do not. Currently, the performance difference between diesel thermal plants operating with cogeneration systems and those that do not is not well documented using consistent performance indicators such as net electrical efficiency, heat rate, specific fuel consumption, auxiliary power consumption and operational availability. This thus provides a limitation to decision-making on whether waste heat recovery retrofits are technically justified for Kenya's existing thermal power plants. Additionally, for plants where cogeneration is feasible, there is a need for a structured engineering design framework to develop a basic waste heat recovery system based on a Simple Rankine bottoming cycle, including the sizing and preliminary design of key components such as the heat recovery steam generator (HRSG), steam turbine, condenser, and feedwater system.

Without such assessments and solutions, Kenya faces the risk of continued environmental burdens and the continuous rise of the already high electricity costs.(Oloo, 2020)

1.2 Objectives

The objective of this study is to evaluate the performance benefits of cogeneration in diesel thermal powerplants in Kenya through a comparative case study of Rabai Power which has cogeneration and Kipevu III, a conventional diesel power plant that does not incorporate cogeneration. This would therefore enable the development of an engineering design of a basic Rankine-cycle waste heat recovery system for Kipevu III to produce extra power. The study would then seek to evaluate the feasibility of an integrated Rankine cycle to produce extra electricity. The parameters to be considered are economic feasibility and reduction in the environmental emissions.

1.3 Rationale

Thermal power plants are evidently a very important electricity generator. With more than 50% share in the global production, they cannot be done away with. Oil fired plants are also in the thermal power generation sector and they widely use cogeneration globally to boost efficiency and production. Some Thermal power plants use cogeneration to produce extra electricity.

It is still evident diesel and heavy-fuel-oil (HFO) plants are still important for flexible peaking and reserve capacity at times of high demand or when variable renewables underperform even though official data reveals that Kenya primarily gets its electricity from geothermal, hydro, wind, and solar energy. Thermal generation, comprising mainly diesel and heavy fuel oil continues to be a major contributor to capacity and electricity generation. However, these plants are typically characterized by relatively high specific fuel consumption and operating costs, largely due to limited overall thermal efficiency and significant waste heat losses through exhaust gases and cooling systems (Zhang, 2020). There is therefore strong technical and economic justification to evaluate efficiency-enhancing options within existing thermal power-plants.

Some Kenyan plants (e.g., Rabai and Thika) already incorporate cogeneration features thus demonstrating precedent for bottoming cycles that capture exhaust heat to produce steam and finally use it to produce electricity. Nevertheless, the decision to adopt cogeneration is plant-specific and depends on real operating conditions, load profiles, auxiliary consumption and system integration constraints. In Kenya, there is limited evidence quantifying the performance advantage of cogeneration-enabled diesel plants compared to non-cogeneration plants using consistent key performance indicators such as net electrical efficiency and output. This study therefore provides value by establishing a structured comparison between Rabai (cogeneration-enabled) and Kipevu III (non-cogeneration) as representative case studies. This thus enables an evidence-based assessment of the drivers of performance differences.

In addition to the assessment, a key justification of this study is the development of a preliminary engineering design of a basic Rankine-cycle waste heat recovery system for Kipevu III. Providing a clear design methodology that covers the HRSG sizing, steam conditions selection, turbine to be used, condenser requirements and expected power recovery translates the comparative findings into a practical, replicable framework that can assist in future retrofits of similar diesel thermal plants.

2. Literature Review

2.1 Introduction to Thermal Power Generation in Kenya and its role in the National Energy Mix

Electricity generation is very important to Kenya's economy since it supports industrial growth, digital development and improved living standards. Although thermal power is a non-renewable source that mainly uses HFO and diesel, it remains important because it provides reliable, controllable electricity when renewable sources such as hydropower, wind and solar are affected by the unpredictable weather and climate. HFO, which is the preferred fuel in most Kenyan thermal plants, is a heavier residual fuel oil that requires preheating before use. Thermal power stations are usually located near the coast or load centres to reduce transport and transmission costs. The fuel is treated before being supplied to engines, which drive generators producing electricity at about 11 kV before step-up transformers raise the voltage for grid transmission. Despite contributing a smaller share of Kenya's total installed capacity, thermal power remains vital for grid stability. However, it also increases electricity costs because it is expensive to generate and is affected by global fuel price fluctuations.

Thermal power plants are basically primarily peaking and back up units. They can only play this role since they offer the flexibility of being ramped up and down by the touch of a button to exactly match the demand at the time. These power plants are usually dispatched when renewable generation is insufficient or when the grid requires stabilization. For example when there are dry spells that reduce hydroelectric output from dams such as Masinga, Turkwell, Gitaru(Surwase & Farkade, 2016) etc. Economically, Thermal power has greatly influenced the prices of electricity in the country. The cost of production is typically around 20-35 Kenya Shillings per kWh. Eventually when this power is sold to the off taker, it could be even priced at around 50 Kenya shillings per kWh, by the IPPs, and around 30 Kenya shillings per kWh by KenGen. This is much more expensive by several fold as compared to the cost per kWh of electricity generated by renewable sources. The cost of production per kWh by renewable sources could be as low as 3-7 Kenya shillings. This therefore generally means that thermal power plants serve to increase the price of electricity in the country.(Oloo, 2020) This is even inescapable due to the fact that long PPAs were signed spanning decades of the Take or Pay nature. Thermal power plants are therefore relied on by KPLC and the general country and population to supplement regional grids and the national grid such as in Coastal Grid and Nairobi Grid which experience high industrial and commercial loads due to heavy industrialization around these areas and high population. This makes the thermal power plants to occupy a vital niche that cannot be easily filled hence the necessity of making them as efficient as possible so as to improve and reduce the specific fuel consumption per kWh and a dual cycle is one of these ways. This would see reduced emissions and reduced electricity costs.

2.2 Performance Assessment of Typical Power Plants with Cogeneration (Rabai) And without Cogeneration (Kipevu III)

There are several Key parameters to be considered when carrying out a performance assessment of a thermal power plant. These include but are not limited to;

1. Specific Fuel Consumption
2. Cost per unit of electricity produced, often per KWh
3. Operational and Maintenance costs

Both of These Power plants use the Wartsilla 18V46 engines. Kipevu III, a 120MW rated plant has seven of these engines while Rabai, a 90MW rated plant has five of these engines. For a good representation of Performance of the two power plants, we shall use the specific fuel consumption when the plants are running at full load to show how much fuel is required to produce one unit of electricity. This value gives a lot of information as fuel costs are among the main costs if not the main one when it comes to operational costs. This also informs to some degree the maintenance of major equipment such as fuel separators, pumps and fuel tanks. The engines have specific fuel consumption (sfc) of 3400 kg/h at design conditions

A. Kipevu III

$$SFC = 120000KWh \div (3400 \times 7)kg/h$$

$$SFC = 5.042KW/kg$$

This means for every KWh of electricity produced, the amount of fuel needed is the reciprocal of the sfc which is 0.1983kg or, assuming density of HFO is 0.9558kg/m^3 at 15°C, approximately 0.2075 m^3 (207.5 liters)

B. Rabai

$$SFC = 90000KWh \div (3400 \times 5)kg/h$$

$$SFC = 5.294KW/kg$$

This means for every KWh of electricity produced, the amount of fuel needed is the reciprocal of the sfc which is 0.1889kg or, assuming density of HFO is 0.9558kg/m^3 at 15°C, approximately 0.1976 m^3 (197.6 liters)

It is thus very clear that the plant with cogeneration would have a lower SFC thus it would need less fuel to produce the same amount of electricity as the plant without cogeneration hence we can directly deduce that the plant with cogeneration has less operational costs and less maintenance costs on equipment that deal with fuel such as fuel separators and pumps

2.3 The Cogeneration Potential of Kipevu III

The Exhaust Gasses that are released to the environment after combustion by the engine posses a lot of energy which can be harnessed to be used in a cogeneration plant.

According to Kabeyi & Olanrewaju (2022), *"Preliminary Design of a Cogeneration Plant for a 120 MW Diesel Engine Power Plant,".* The total thermal power present in the exhaust stream will be calculated as:

$$\dot{Q}_{exh,total} = \dot{m}_{exh} \; c_p \; (T_{exh,in} - T_{ref})$$

Where:

m_{exh}- mass flow rate of the exhaust steam

c_p- Specific heat capacity of exhaust gas

This power however will not all be recoverable due to losses and temperature constraints.

Only the temperature drop from HRSG inlet to the minimum allowable stack temperature is recoverable thus the recoverable heat is as shown below:

$$\dot{Q}_{rec} = \dot{m}_{exh} \, c_p \, (T_{exh,in} - T_{exh,out})$$

Minimum stack temperature is selected to avoid sulphuric acid dew point corrosion: typically, ≥ 150–180°C for HFO exhaust.(M. J. B. Kabeyi & O. A. Olanrewaju, 2022)

Mass flowrate of the exhaust gasses 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.

$m_{exh} = m_{fuel} + m_{air} = 0.8433 + 5.3 = 6.144\ kg/s$

Then;

$\dot{Q_{rec}}$ = 6.144 kg/s × 1.008 KJ/kgK × (360−170) = 1176.69KW per engine

Taking the entire plant;

$$1176.69\text{KW} \times 7 = 8236.83\text{KW}$$

Thus, the plant has a potential of producing an extra 8.236MW from cogeneration alone

2.4 The Rankine Cycle

Principle of Waste Heat Recovery in Diesel Engines

In typical diesel power plants, only about 40-45% of the chemical energy in fuel is converted to useful mechanical energy used to run the engine and eventually utilized in power generation. The remaining 60-65% energy is dissipated as waste heat. The losses are approximately as follows;

1. In exhaust gasses, approximately 35% 6.
2. In cooling water, approximately 20%
3. Radiation losses and to the ambient air around the engines, approximately 5%

This then presents a huge thermal potential that can be tapped into to do all sorts of tasks around the plant, apart from just producing steam to run a steam turbine coupled to a generator to produce more electricity. The quantity of heat contained in both the exhaust and the coolant is a function of both the temperature and the mass flow rates (Surwase & Farkade, 2016)

The total thermal power present in the exhaust stream will be calculated as:

$$\dot{Q}_{exh,total} = \dot{m}_{exh}\ c_p\ \left(T_{exh,in} - T_{ref}\right)$$

Where:

m_{exh}- mass flow rate of the exhaust steam

c_p- Specific heat capacity of exhaust gas

This power however will not all be recoverable due to losses and temperature constraints.

Only the temperature drop from HRSG inlet to the minimum allowable stack temperature is recoverable thus the recoverable heat is as shown below:

$$\dot{Q}_{rec} = \dot{m}_{exh}\, c_p\left(T_{exh,in} - T_{exh,out}\right)$$

The Rankine cycle as a Bottoming Cycle

The Rankine power cycle is an ideal vapor power cycle. It differs from the other power cycles in that its working fluid goes from vapor to liquid and back depending on the stage of the cycle it is at while the other cycles use gasses as their working fluids. The Rankine cycle is an ideal process that is used for studies but for analysis purposes, there are some factors that have to be taken into consideration. Both the organic and basic Rankine cycles employ these processes, with the only difference being in the working fluid The Rankine cycle involves four major processes (Moran et al., 2010)

The Figure 1 Below shows the four major processes of the Rankine cycle and the major components used to carry out these processes. These Components are the Boiler, the turbine, the condenser and finally a pump. The line 3 to 4 shows the process if there was no superheating in the boiler. 3a to 4a is the superheated path, as in turbines.

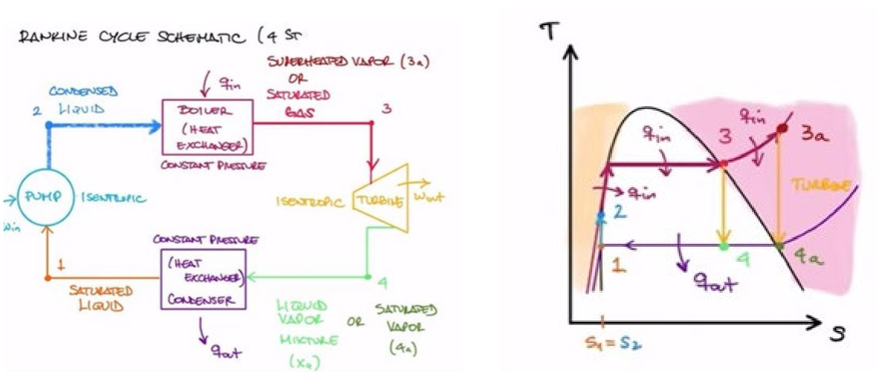

Figure 1. The Rankine cycle Schematic and TS diagram of The Process

2.5 Preliminary Design of a Rankine Cycle System for Kipevu III

In diesel power plants, the most common method of producing electricity is to run a generator that is directly connected to an engine and discharges high-temperature exhaust fumes into the atmosphere. This is quite wasteful since the engine cooling, lubrication system as well as exhaust heat release heat energy into the environment. The performance of Kipevu III power plant and the viability of building a cogeneration plant with a Simple Rankine cycle steam turbine and exhaust gas boiler for waste heat to steam conversion is assessed.

The proposed cogeneration system for the Kipevu III power plant is based on a Rankine cycle steam power plant that recovers waste heat from the exhaust gases of the plant's seven Wärtsilä 18V46 turbocharged diesel engines. Each engine produces 17.1 MW of electrical power, giving a combined installed capacity of 119.7 MW. Rather than releasing exhaust gases directly to the atmosphere, the system channels them through a waste heat recovery train to generate superheated steam, which drives a condensing steam turbine coupled to a synchronous generator. Data, equations, and design specifications presented in this section are drawn from Kabeyi & Olanrewaju (2022), *"Preliminary Design of a Cogeneration Plant for a 120 MW Diesel Engine Power Plant,"*.

System configuration overview:

Heat Recovery Steam Generator (HRSG)

Rather than a single shared HRSG collecting exhaust from all seven engines through a common duct manifold, this redesign assigns one dedicated HRSG and one dedicated superheater to each of the seven Wärtsilä 18V46 engines. Superheated steam from each unit is collected in a common steam header before being fed into a single condensing steam turbine-generator set. This configuration improves reliability, allows independent maintenance per engine unit, and provides better thermal matching between each engine's exhaust and its corresponding heat exchanger.

The process flow for each engine unit is:

Engine Exhaust (360°C) → Individual HRSG (wet steam) → Individual Superheater (dry superheated steam) → Common Steam Header → Condensing Steam Turbine (10 MW) → Condenser → Feed Water Pump → Back to HRSG

Heat Transfer Area Per HRSG:

The HRSG cools exhaust gas from 360°C to 220°C (the remaining 220°C to 170°C is extracted in the superheater). For a single engine unit:

$$A_i = \frac{Q_i}{U_0 \cdot (LMTD) \cdot F_T} = \frac{1.008 \times 10^3 \times 1 \times 6.2 \times (360 - 220)}{60 \times 225.94 \times 0.98}$$

$$A_i = \frac{1{,}199{,}247.36}{13{,}285.5} = 65.86\ m\text{^}2\ per \text{ HRSG}$$

Where:

LMTD = Logarithmic Mean Temperature Difference

U_0 = Overall heat transfer coefficient

F_T = Correction Factor This adjusts the LMTD for the fact that the heat exchanger is not a perfect counter-flow arrangement. It accounts for the shell and tube pass configuration.

The number of tubes per HRSG given $d_o = 1$ inch $= 0.0254$ m, tube length $L_t = 16$ ft $= 4.877$ m:, now becomes:

$n_i = \frac{A_i}{\pi \cdot d_o \times L_t} = \frac{65.86}{\pi \times 0.0254 \times 4.877} = 170$ tubes per HRSG (rounding off to the nearest whole number)

For approximately 170 tubes on 1¼ inch square pitch in a 1-shell, 2-pass configuration, TEMA standards recommend a shell diameter of 23.25 inches:

$$D_{s,i} = 23.25 \text{ inches} = 23.25 \times 25.4 = 590.6mm$$

Baffle Spacing Per HRSG: $B_i = 0.4 \times D_{s,i} = 0.4 \times 590.6 = 236.24\ mm$

Shell Thickness Per HRSG: $\frac{t_{s,structural}}{R_s} = \frac{2.21}{1{,}066.8} = 0.002072 \quad t_{s,i} = \frac{PR_{s,i}}{\sigma J - 0.6P} + \text{Corrosion Allowance}$

$$t_{s,i} = (0.002072 \times 295.3) + 1.5 = 0.61 + 1.5 = 2.11 \text{ mm per unit}$$

Superheater Design

The superheater extracts additional heat from the exhaust gases to convert the saturated wet steam from the HRSG into dry superheated steam before it enters the turbine. Key design parameters are:

i) Specific heat capacity of steam = 2.01KJ/kgK
ii) Specific heat capacity of flue gases = 1.008KJ/KgK
iii) Mass flow rate of steam = 2.36Kg/s per HRSG.
iv) Heating surface area = 436.43 m^2 per HRSG
v) Desired super heater efficiency = 0.9

Heating surface area per superheater

$$A_{SH,i} = \frac{A_{SH,total}}{N_{engines}} = \frac{3{,}055}{7} = 436.43 \text{ m}^2 \text{ per engine}$$

Number of Tubes Per Superheater given 1.5 inch OD, 4 m length

$n_{SH,i} = \frac{A_{SH,i}}{\pi \cdot D_o \times L} \quad n_{SH,i} = \frac{436.43}{\pi \times 0.0584 \times 6} = \frac{436.43}{1.1012} \approx 396$ tubes per superheater

Total tubes = $n_{SH,total} = 396 \times 7 = 2{,}772$ tubes $\approx 2{,}775$ tubes

Steam Turbine

An impulse-type condensing steam turbine is selected. The blade speed and shaft work are determined as follows:

Blade tip speed:

$$U = \omega R_m = \frac{15{,}000 \times 2\pi \times 0.71}{60} = 111.53 \text{ m /s}$$

Shaft work per unit mass:

$$W_{shaft} = -(2U^2) = 2 \times 111.53^2 = -24{,}876.34 \text{ Nm}$$

Condenser and Feed Water Pump

Turbine exhaust steam at a condenser pressure of about 0.25 bar is condensed back to liquid water. The condensate, along with any make-up water, is returned to the HRSG via a feed water pump, completing the closed Rankine cycle. The feed water pump raises the liquid pressure from condenser pressure back to the boiler operating pressure of up to 110 bars

The complete Rankine cycle system follows this process sequence:Exhaust gas (360 °C) → HRSG (wet steam generation) → Superheater (dry superheated steam at ~520 °C, 110 bar) → Condensing Steam Turbine (mechanical work) → Synchronous Generator (~10 MW electrical output) → Condenser (steam → condensate at 0.25 bar) → Feed Water Pump → HRSG (cycle repeats)

The system is projected to generate approximately 8–10 MW of additional electricity from the same fuel consumed by the diesel engines, representing a 6.7–8.4% gain in plant output with no additional fuel cost while also simultaneously reducing the specific fuel consumption and greenhouse gas emissions per unit of electricity generated.

3. Methodology

The study adopts a comparative engineering and analytical approach centered on two case-study plants: Rabai Power Plant and Kipevu III Power Plant. The methodology is structured into two integrated phases:

Phase I: Comparative Performance Assessment

The first phase involves a detailed comparison between Rabai Power Plant which utilizes a simple Rankine cycle for cogeneration and Kipevu III which currently operates as a simple-cycle plant. Both facilities use the same Wärtsilä 18V46 medium-speed engines, providing a controlled baseline for analysis.

- Thermodynamic Analysis: Evaluation of thermal efficiency(Elkelawy et al., 2025), Specific Fuel Consumption (SFC) and plant availability.
- Economic Evaluation: Assessment of Capital Expenditure (CAPEX), Operational and Maintenance (O&M) costs, and the Levelized Cost of Electricity (LCOE).(Kabeyi & Olanrewaju, 2023)
- Environmental Impact: Quantification of air emissions and calculation of Greenhouse Gas (GHG) intensity.(Elkelawy et al., 2025).

Phase II: Design and Modeling of the Rankine Cycle

The second phase focuses on designing a basic Rankine bottoming cycle tailored for Kipevu III to capture waste heat from engine exhaust.

- Resource Quantification: Measuring exhaust gas mass flow and temperature to determine the recoverable thermal power.
- System Sizing: Modeling and sizing key components, including the Heat Recovery Steam Generator (HRSG), steam turbine, condenser, and feedwater pump.(Kareem et al., 2018)
- Integration Modeling: Estimating the potential increase in net power output and the resulting improvement in overall plant efficiency without additional fuel consumption,

Data Collection & Technical Framework

The study utilizes a multi-tiered data gathering approach:

1. Sourcing key parameters and metrics from operational manuals from manufacturers such as wätsilä.
2. Conducting a survey with the use of questionnaires to obtain data from employees of the two plants under case study.
3. Historical Review: Analysis of daily log sheets, heat balance diagrams, and statutory environmental audits.

A techno-economic assessment for the Basic Rankine Cycle design for Kipevu III will also be conducted by estimating capital and operating costs of the WHR system and calculating key indicators such as LCOE, NPV, IRR and payback period.(Ramírez-Quintero et al., 2024; Sazdovski & Fushtikj, 2004; Zhou, 2017)

Ultimately, the methodology aims to integrate plant data analysis, thermodynamic modelling, environmental quantification and economic evaluation to determine the technical feasibility and investment viability of cogeneration retrofit for diesel power plants in Kenya.

4. Expected Results

4.1 Assessment of Typical Power Plants With Cogeneration vs Without Cogeneration.

The comparative performance assessment of the thermal power plants relies on calculating expected parameters across three main categories: Thermodynamic, Economic, and Environmental.

Here is a brief note on the key parameters expected to be calculated, why they are important, and how to judge plant performance based on their values:

1. Thermodynamic and Availability Parameters

- **Thermal Efficiency:** This is the ratio of useful electrical work produced to the total chemical energy available in the fuel. It is a critical parameter because it shows how effectively the plant converts fuel into electricity. A higher value is better, indicating that the plant is extracting more useful energy from the same amount of fuel and wasting less as heat.
- **Specific Fuel Consumption (SFC):** This measures the amount of fuel consumed to produce one kilowatt-hour of electricity (kg/kWh). It is vital for evaluating fuel efficiency, which directly impacts operational costs and overall profitability. A lower value is better, signifying that the plant burns less fuel to generate the same amount of power.
- **Plant Availability Factor (AF):** This calculates the percentage of time the plant is capable of providing service, accounting for maintenance and outages. It is important because it measures the plant's reliability and readiness to dispatch power to the grid. A higher value is better, indicating greater reliability.
- **Capacity Factor (CF):** This represents the ratio of the actual energy output over a specific period to its potential output if it operated constantly at full capacity. It is important to show how well the plant is being utilized. A higher value generally means better performance and utilization of the asset.(Bhangu et al., 2019)

2. Economic Assessment Parameters

- **Levelized Cost of Electricity (LCOE):** This parameter represents the average total cost of building, operating, and maintaining a power plant per unit of electricity produced over its entire expected lifetime. It is important because it normalizes costs, allowing for an objective, apples-to-apples economic comparison between different plant configurations. A lower value is better, as it means the plant produces electricity more cheaply.(Ramírez-Quintero et al., 2024)
- **Payback Period (PP):** This is the length of time required for the plant to recover its initial capital investment from its operating cash inflows. It is primarily a measure of financial risk and liquidity. A lower (shorter) value is better because recovering costs faster makes the project less vulnerable to long-term market volatility like fuel price spikes.(Sazdovski & Fushtikj, 2004)
- **Return on Investment (ROI):** This percentage evaluates the total profitability and financial efficiency of the capital invested over the plant's life. It is the ultimate indicator of long-term economic success. A higher value is better, proving the plant is a genuinely profitable venture.(Sazdovski & Fushtikj, 2004)

3. Environmental Parameters

- **Greenhouse Gas (GHG) Intensity (CO_2e per MWh):** This parameter calculates the mass of emissions (like CO_2, NO_x, and SO_2) released per unit of net electricity produced and quantifies the effect of the gasses in terms of a unit mass of CO_2. It is crucial for assessing the environmental footprint, regulatory compliance, and public health impact of the plant. A lower value is better, indicating a cleaner plant that produces less pollution for every megawatt-hour of power it sends to the grid.(Zhou, 2017)

In summary, when comparing a cogeneration-enabled plant to a conventional single-cycle plant, the one that achieves higher efficiency and availability, alongside lower SFC, LCOE, Payback Period, and emission intensity, is performing better across all technical, economic, and environmental metrics.

4.2 Design of a Basic Rankine Cycle for Kipevu III

Based on the methodology detailed in Chapter 3, the design of a basic Rankine cycle for the Kipevu III power plant aims to practically demonstrate how waste heat can be converted into useful electricity.

1. Sizing and Selecting Rankine Cycle Components

The primary design deliverables involve thermodynamic modeling to size and select the appropriate components for the bottoming cycle. The expected outputs include:

- **Waste Heat Potential Assessment:** Calculating the recoverable thermal power from the engine's exhaust gases based on mass flow rates, temperatures, and specific heat capacities. This establishes how much steam can be produced.
- **Component Sizing:** Sizing the four main steady-flow devices of the Rankine cycle using steady-flow energy equations:
  - **Heat Recovery Steam Generator (HRSG) / Boiler:** Sized to effectively transfer the recovered exhaust heat to the feedwater to produce steam.
  - **Steam Turbine:** The prime mover. Defining inlet pressure and temperature, steam mass flow, condenser exhaust pressure and calculating the isentropic enthalpy drop would be the concern here to estimate the gross mechanical power and net electrical output.
  - **Condenser:** Sized to efficiently reject heat at a constant pressure and convert the expanded steam back into a saturated liquid.
  - **Feedwater Pump:** Sized to isentropically compress the liquid water back to the boiler's operating pressure.

2. Assessment of the Added Rankine Cycle (Determining Benefits)

Once the system is theoretically designed, the next major deliverable is a techno-economic and environmental assessment to determine whether integrating this cogeneration system is actually beneficial and justified across the three major valuation parameters:

- **Technical and Efficiency Gains:** Calculating the new, improved Specific Fuel Consumption to demonstrate that the plant can produce more total power (Base Engine and a steam turbine) using the exact same amount of fuel. The Fuel Energy Savings Ratio (FESR) will also be calculated to show primary energy savings.
- **Environmental Impact Reduction:** Quantifying the emission intensity reduction. Because the steam turbine generates extra electricity from waste heat without burning additional fuel, the overall emissions (like CO_2) per megawatt-hour of electricity generated will decrease.
- **Economic Viability (Cost-Benefit Analysis):** Delivering a techno-economic model that evaluates the financial feasibility of the investment. This involves:
  - Computing the Levelized Cost of Electricity (LCOE) for the extra power generated, factoring in the capital expenditure (CAPEX) of the new components and operations/maintenance costs.
  - Calculating core economic indicators such as Free Cash Flow (FCF), Net Present Value (NPV), and Internal Rate of Return (IRR). A positive NPV will be the primary indicator that the cogeneration investment adds financial value.(Ramírez-Quintero et al., 2024)

Thus, the ultimate deliverable of this design and assessment phase is an integrated recommendation—backed by thermodynamic calculations and financial metrics—on whether retrofitting Kipevu III with a waste-heat recovery Rankine cycle is technically feasible, environmentally advantageous, and economically profitable.

5. Conclusion

Thermal power plants play an indispensable role in stabilizing Kenya's renewable-heavy electricity grid by providing crucial backup and peaking capacity. However, with them having low thermal efficiencies, high operating fuel costs and substantial greenhouse gas emissions highlight there is an urgent need for optimization. This proposed project addresses these operational challenges by delivering a structured and comparative performance assessment between a cogeneration-enabled plant, Rabai Power and a conventional simple-cycle plant, Kipevu III. By documenting the specific thermodynamic, economic, and environmental differences, the study aims to provide much-needed, plant-specific evidence regarding the true benefits of waste heat recovery. In addition, by engineering a preliminary Rankine-cycle waste heat recovery system tailored for Kipevu III, the study will translate theoretical efficiency gains into a practical, replicable framework. At the end, the expected technical and financial evaluations including metrics like the Levelized Cost of Electricity (LCOE), Net Present Value (NPV) and emission intensity to yield an evidence-based recommendation on whether cogeneration retrofits are technically feasible and economically profitable. These insights will be very useful in guiding future policy discussions and investment decisions aimed at reducing environmental burdens and lowering electricity generation costs within Kenya's thermal energy sector.

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