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COMBINED SOLAR-HEAT PUMP SYSTEMS FOR HEATING DIESEL POWER PLANTS IN STANDBY MODE

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Abstract. *In the context of high penetration of photovoltaic (PV), which is heavily dependent on environmental conditions, dispatchability has become a very important characteristic of energy generation. Diesel power plants have the advantage of operating whenever they're needed. To keep a diesel power plant in standby mode, there needs to be a constant source of heat to keep it at 63°C. This process usually burns diesel in auxiliary boilers. This paper considers the case of a power plant in the semi-arid region of Pernambuco, which uses diesel-fueled steam generators to provide hot water for their diesel engines to keep them in standby mode. This work analyzes the viability of using photovoltaic-thermal solar collectors and a heat pump to warm the engines and keep them in standby mode. Three configurations were modeled in the software TRNSYS. The parameter chosen for comparison was the thermal fraction, which represents the fraction of heat that was generated by the thermal collectors and heat pump. Configuration 1 is an array of photovoltaic-thermal solar collectors used as a source of heat and electricity. The solar panels heat the water from ambient temperature up to about 45°C. Then, the water is transported to a water-water heat pump, which is powered by the electrical energy from photovoltaic-thermal collectors, and is used to heat the water feeding the engine up to 63°C. Configuration 2 is an air-water heat pump used to heat the engine's water up to 63°C. The heat pump is partially powered by PV modules. Configuration 3 is composed of solar thermal collectors used to directly heat the water that is feeding the engine. In all configurations, an auxiliary boiler is used in case the system can't generate enough heat. Solar collectors were chosen as a cost-effective long-term alternative due to the abundance of excellent solar resources in the region and their independence from external fuel requirements. Preliminary solutions show that Configuration 1 offers the best thermal fraction, however, it is the most complex model and with more components. All configurations are viable alternatives to diminish the diesel usage in the power plant, especially in Configurations 1 and 2, which provide estimated yearly savings of US$ 52,731.87 and US$ 47,964.79, respectively. These configurations, however, may have a higher initial cost due to their need for more components.*

Keywords: thermal-photovoltaic systems, diesel consumption reduction, combined solar-heat pump systems, diesel power plant.

1. INTRODUCTION

In the energy sector, especially in electric energy generation, the availability of energy sources is extremely important. Although thermoelectric power plants generate greenhouse-effect gasses, their ability to operate all year with little drawbacks caused by the environment turned them into the go-to power-generating option around the globe, including in certain regions of Brazil. In the scenario of thermoelectric generation, diesel power plants take a significant margin of the total energy generators. However, to be kept on standby, they need to be supplied with constant heat, which adds avoidable energy costs and may generate even more pollutants.

World energy demand in 2021 is also responsible for the second-largest increase in CO_2 emissions (IEA, 2021a, IEA, 2021b). Despite non-renewable sources dominating the global energy supply, the demand for them after 2020 decreased, as renewable sources occupied 3% more space in the energy matrix (IEA, 2021b). Alternatively, renewable sources, such as solar energy, could be used to aid power plants with minimal operational costs and environmental pollution. The choice of an alternative source involves factors such as the environment, financial interests, reliability of energy supply, and tariff policies (Costa et al., 2018).

Brazil is a promising field for the insertion of solar thermal (ST) and photovoltaic (PV) systems, as it has an annual average of daily global radiation of 18 MJ/m²day (Fraidenraich et al., 2022). Despite the climatic and environmental differences of the Brazilian territory, the daily total horizontal global irradiation is reasonably uniform enhancing 6.25 kWh/m² in the Northeast region. The Northeast of Brazil also has the lowest interannual variability of solar irradiation (Pereira et al., 2017).

ST systems are composed of collectors capable of capturing solar radiation that reaches their surface and is absorbed as thermal energy for heating (Allan et al., 2015). Mirrors can be used to enhance the performance of the function of concentrating Direct Normal Irradiance (DNI) (Ferreira, 2018). ST technologies are mainly used in preheating processes, low-temperature steam generation, air conditioning, hot water for domestic use, and drying systems (Weiss and Spörk-Dür, 2020, Mathew and Venugopal, 2021).

Photovoltaic (PV) modules convert concentrated and scattered solar radiation into direct current by direct collision in semiconductor material (Pinho and Galdino, 2014; Preet, 2018). However, only part of the incident radiation is converted into electric current. The part that is not converted is accumulated as heat and it rises the PV operating temperature (Busson et al., 2021; Dimri et al., 2017; Guarracino et al., 2016).

Methods to cool PV modules can be carried out with or without forced circulation of the cooling fluid. Photovoltaic-thermal (PVT) modules are an example of forced circulation utilizing pump (Busson et al., 2021), then the fluid withdraws heat from the rear module surface, reducing operating temperature and improving electricity generation (Huide et al., 2017). When PVT modules use water as a circulating fluid, they combine the electrical generation from PV modules with the supply of heated water from ST collectors (Sultan and Efzan, 2018).

Unlike solar systems that are intermittent, diesel power plants have the advantage of operating whenever they're needed. To keep a diesel power plant in standby mode, there needs to be a constant source of heat to keep it at 63°C. This process usually burns diesel in auxiliary boilers.

The present paper considers the case of a power plant in the semi-arid region of Pernambuco, which uses diesel-fueled steam generators to provide hot water for their diesel engines to keep them in standby mode. The main goal is to compare, through simulations in the software TRNSYS, three configurations combining PVT, ST collectors, PV modules, and heat pumps to maintain thermoelectric diesel engines heated in standby mode. The solar fraction (thermal and electrical) parameter obtained in simulations is used for the determination of total solar fraction.

2. METHODS AND MATERIALS

Four different configurations (the original setup of the power plant plus the three alternative configurations) were considered for the present paper. In all the alternative configurations it's desired to minimize the use of the boiler from the original configuration since the main goal is to analyze which of these scenarios provides the best thermal and electrical fractions, as well as the biggest diesel savings for the power plant. To analyze the thermal and electrical fractions, the different configurations were modeled on TRNSYS. In this software, different "boxes" (called "Types") are used to emulate each component and simulate their transient performance across the year, using weather data to simulate the different conditions.

In the original setup, as in Figure 1, a boiler heats water that is fed to a heat exchanger; then the heat exchanger supplies thermal energy to a dedicated water circuit that feeds the generator. For the basic configuration, Type138 was used to simulate the main boiler, heat exchanger, and their basic components, with the same thermal power output as the system. The water setpoint temperature was set for 63°C, which is the temperature needed to keep the generator on standby. For the generator, Type158 was used. Its parameters, such as volume, number of nodes, and energy loss coefficients were estimated such as to give it the same thermal power loss and consumption as the real generator. Type114 was used to emulate a pump used to move the water around the loop, with an idealized heat loss of zero and a water flow rate of 13 m³/h, the same flow rate as the real system. To use the external weather data of Petrolina on TRNSYS Type15 was used, as it functions as an interface that reads these external files and translates them into workable variables inside the simulation.
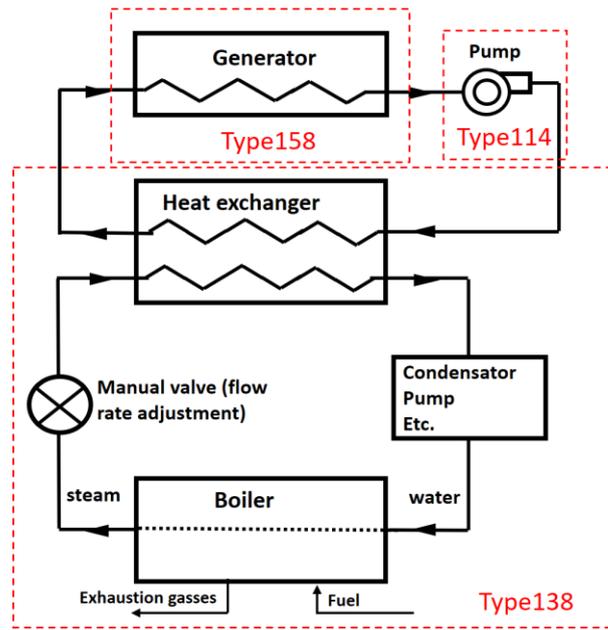
Figure 1 - Representation of the original setup of the power plant.

In the first configuration, as in Figure 2, PVT modules were added to heat the water which is then transported to a thermal reservoir, and then transported to a water-water heat pump, which uses it as a heat source to further heat the water in the main loop from the base configuration. The electric energy produced by the PVT modules is used to partially power the heat pump.
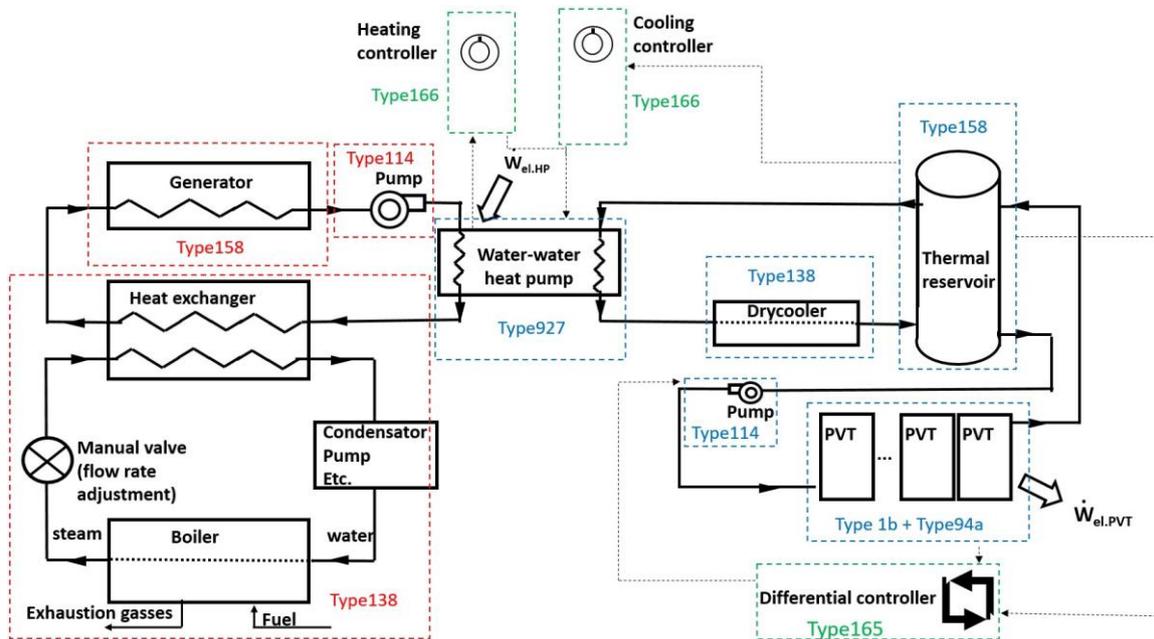

[1] $\dot{W}_{el,HP}$ is the consumed power of heat pump
[2] $\dot{W}_{el,PVT}$ is the PVT generated power

Figure 2 – Representation of configuration 1 (HP + PVT).

For the first configuration, Type1b was used to simulate a thermal collector, with 100 modules with an area of 2 m² each. Type94a was added to simulate a PV module and, despite being separate boxes, in the simulation, they are supposed to work as a PVT module. Their other properties were obtained from the product datasheet. Then, a pump (Type114) feeds the water towards a thermal reservoir (Type158) with a volume of 16 m³ at a rate of 30 m³/h. To emulate the water-

water heat pump, Type927 was used with a flow rate of 13 m³/h on both the source and load sides. Its parameters were based on the EW-HT-Y-0152 model from Climaveneta, which was used to interpolate its operation range. A dry cooler, simulated by Type138, was added to cool the water before it circles back to the thermal reservoir. Its power is 20 kW and it activates once the temperature in the water is within 4°C of ambient temperature. Type165 was used as a differential controller to control the pump from the "thermal reservoir, pump, thermal module" loop, monitoring the cold outlet temperature from the reservoir and the thermal module outlet temperature, turning the pump on once the upper-temperature dead band is 1°C and turning it off once the temperatures are equal. Finally, two Type166 were used to control the heat pump. The heat pump is turned on once its load outlet temperature is below 63°C and the cold outlet thermal reservoir temperature is above 25°C.

In the second configuration, shown in Figure 3, an air-water heat pump is used to heat the water in the main loop of the original configuration; the heat pump is partially powered by PV modules. For the second configuration, Type94a was again used as a PV module powering an air-water heat pump, which was modeled using Type941, and its parameters were derived from the AW-HT-0152 model from Climaveneta. In the simulated model, the heat pump was placed in the main loop right before the water-heating main boiler. Type 166 was used to control the heat pump signal, turning it on once the temperature reaches 63°C, with a 1°C temperature dead band.
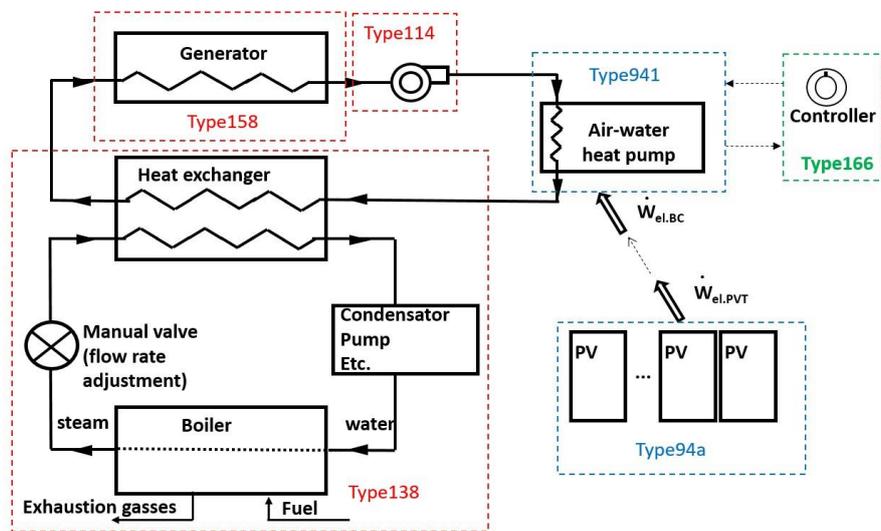
[1] $\dot{W}_{el,BC}$ is the electrical power consumed by the heat pump
[2] $\dot{W}_{el,PVT}$ is the PV generated power

Figure 3 – Illustration of configuration 2 (HP + PV).

The third configuration, presented in Figure 4, uses ST collectors to heat the water up to 60°C, which is then transported to a thermal reservoir and used as a heat source in a heat exchanger to increase the temperature of the water in the main loop. Similarly to the first configuration, the third configuration has a loop with a pump (Type114), a thermal collector (Type1b), and a thermal reservoir (Type158), as well as a differential controller (Type165) controlling the pump. The pump has a flow rate of 40 m³/h, the thermal collectors have a total area of 200 m² and the thermal reservoir has a volume of 50 m³. Its second loop has a pump (Type114; named "pump-2") with a flow rate of 3 m³/h feeding water to a counter-flow heat exchanger (Type5) with a heat transfer coefficient of 25,000 W/K, as well as two controllers (Type166) controlling pump-2, that turn it on once both the temperature coming out of the load side of the heat exchanger is below 62.5°C and the temperature of the water coming out of the thermal reservoir's load side is above 63°C.
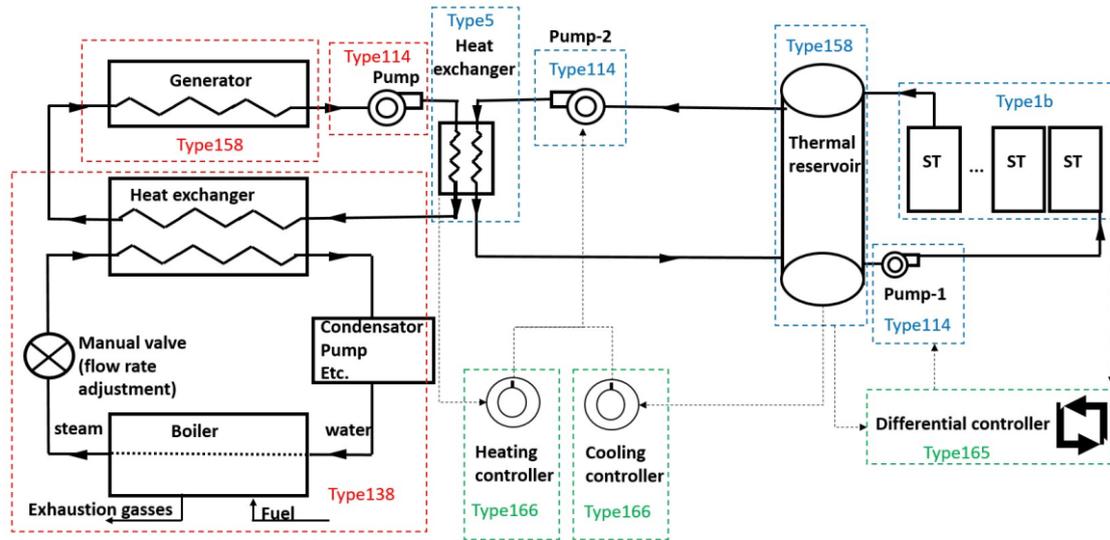
Figure 4 – Representation of configuration 3 (HE + ST).

For the first and second configurations, to quantify the amount of thermal energy produced by heat pumps a thermal fraction was defined. Its value is equal to the amount of heat generated by the heat pump divided by heat loss caused by the generator's operation. To quantify the amount of electrical energy supplied to the heat pumps, an electrical fraction was defined. Its value is equal to the electrical energy generated by the PV modules divided by the amount of electrical energy used by the heat pumps. For the third configuration, since it doesn't use heat pumps or photovoltaic energy, only the thermal fraction was considered, with its value being calculated as the heat provided by the heat exchanger divided by the heat loss from the generator.

A few different parameters were considered when studying each configuration. For configuration 1, the drycooler power, when increased, provided higher diesel savings, at the cost of lowering the electrical fraction, while the drycooler activation temperature was shown to reduce diesel consumption when closer to ambient temperature, but reducing the electrical fraction as well. Another parameter analyzed was the lower working temperature of the heat pump: lowering this value provides higher diesel savings, but lowers the electrical fraction. Finally, the last parameter analyzed for the first configuration was the volume of the thermal reservoir, where bigger volumes provided a minor increase in the diesel savings and a small reduction of the electrical fraction.

For the second configuration, the temperature dead band was analyzed, with lower values presenting lower diesel consumption and higher electrical fraction.

For the third configuration, the flowrate of pump-2 was studied, with higher values providing a slight increase in diesel savings. Another parameter studied was the volume of the thermal reservoir, which shows that higher volumes provide higher diesel consumption. Lastly, how closer the temperature in the controllers is to the temperature of the engine, more frequently pump-2 was activated and lower the fuel consumption is.

Finally, to quantify the savings, the amount of diesel used during a year in each configuration was calculated in an Excel spreadsheet using the total energy produced by the boiler (obtained through the simulations), as well as the Low Heat Value (LHV) of diesel to obtain the total volume and mass of fuel used and converting this value to a monetary number, assuming an LHV of 9,300 kcal/kg, a density of 835.4 kg/m³ and a price of 1.48 US$/liter.

3. RESULTS AND DISCUSSION

According to the results, all three alternative configurations provide significant diesel savings over the basic configuration. In this context, the first configuration provides the biggest diesel savings, followed closely by the second configuration and then by the third configuration, which provides the least savings. Figures 5, 6 and 7 show graphs with the results obtained from TRNSYS simulations.
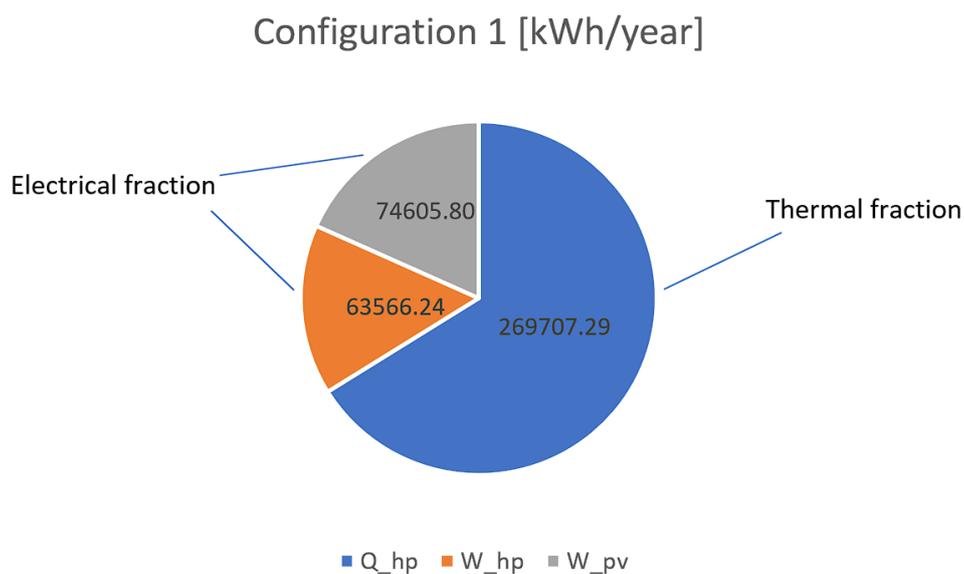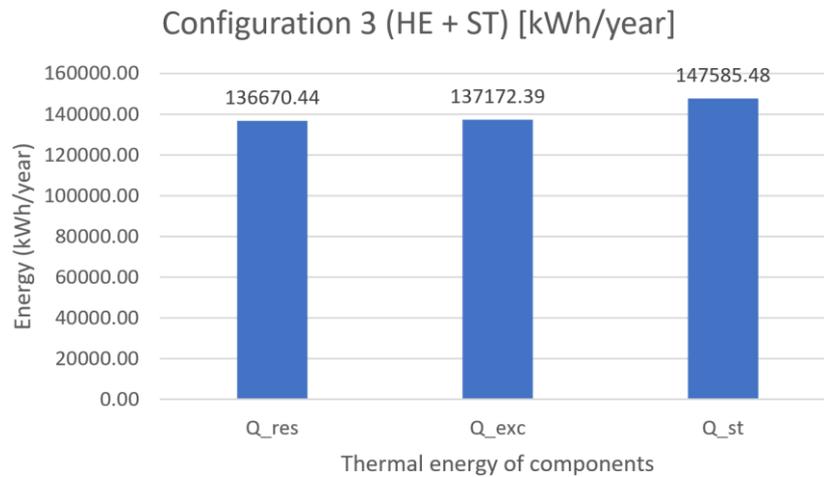
Configuration 1 [kWh/year]

(1) Q_{hp} is the heat generated by the heat pump in one year
(2) W_{hp} is the electrical energy consumed by the heat pump in one year
(3) W_{pv} is the electrical energy generated by the PV modules in one year

Figure 5 - Thermal and electrical contributions of configuration 1 (HP + PVT).
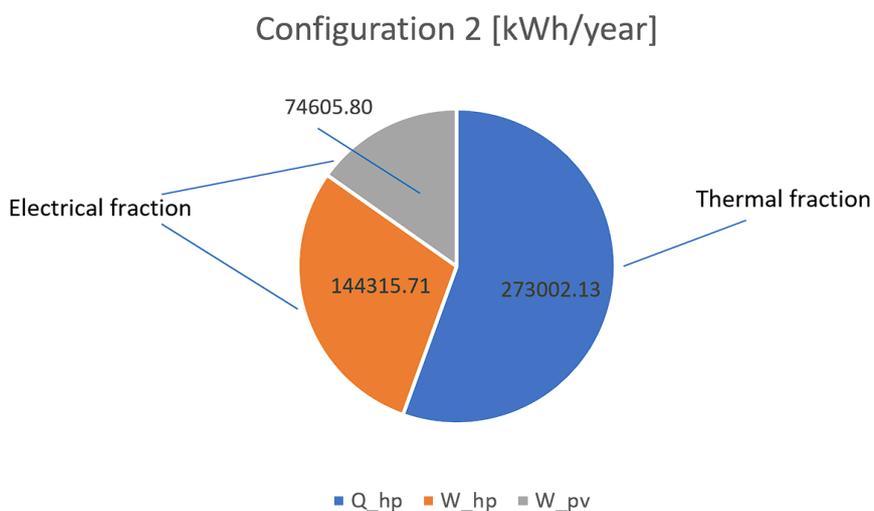
Configuration 2 [kWh/year]

(1) Q_{hp} is the heat generated by the heat pump in one year
(2) W_{hp} is the electrical energy consumed by the heat pump in one year
(3) W_{pv} is the electrical energy generated by the PV modules in one year

Figure 6 - Thermal and electrical results from configuration 2 (HP + PV).

(1) Q_{res} is the thermal energy delivered by the thermal reservoir in the load side in a year
(2) Q_{exc} is the heat delivered by the heat exchanger in a year
(3) Q_{st} is the heat generated by the ST modules in a year

Figure 7 - Thermal results of configuration 3 (HE +ST).

In monetary terms, the original configuration has an expected yearly diesel cost of US$ 144,866.37, while the first configuration predicts a yearly cost of US$ 92,134.44, the second configuration a yearly cost of US$ 96,901.52 and the third configuration a cost of US$ 119,307.24 per year, which translates to a decrease of 36.40%, 33.11%, and 17.65% respectively in diesel spending.

Configuration 1 is associated with the highest Capital Expenditure (CAPEX) compared to the other two configurations. Configuration 2 presents a lower initial investment, amounting to 39% of the CAPEX of Configuration 1, while Configuration 3 requires only 60% of that amount. The higher CAPEX of Configuration 1 is attributed to the need for additional equipment, such as the heat pump and Drycooler.

Although the first and second configurations are close in the energy metric, the first configuration uses significantly less electrical power, being reflected in a better electrical fraction of 1.17 compared to the fraction of 0.52 of the second configuration. This means that, on top of using less diesel, the first configuration is also self-sufficient, as the photovoltaic modules can power the heat pump on their own. However, it's important to mention that this setup is also more complex with more components needed, resulting in a larger initial cost.

Overall, the results are aligned with the initial hypothesis that alternative sources could be used to supply heat to the generator with more effective results than the current setup. Table 1 shows the annual heat consumed by the generator in each configuration, as well as the heat produced by the original boiler and its diesel consumption.

Table 1 - Energy consumption and heat produced.

Parameters	Basic configuration	Configuration 1 (HP + PVT)	Configuration 2 (HP + PV)	Configuration 3 (HE + ST)
$Q_{generator}$ (kWh)	719,030	719,030	719,030	719,030
Q_{boiler} (kWh)	719,030	449,335	472,586	581,855
Diesel consumption (liters)	99,618	62,253	65,474	80,613

Despite Configuration 3 has lower initial investment, Table 1 indicates that HE + ST shows lower annual diesel savings, totalizing $26,817.15. It is estimated that in relation to Configurations 1, 2, and 3, the payback period is approximately 8, 6, and 7 years, respectively. As a suggestion for future research, a more in-depth analysis of payback and the Levelized Cost of Electricity (LCOE) is proposed as additional metrics to assess the feasibility of these configurations.

Each liter of diesel emits an average of 2.6 kg of CO_2 in the combustion process. As diesel is a non-renewable source and contributes to CO_2 emissions when consumed, the reduction of diesel consumption is shown to be a potential reducer of the environmental impacts of the systems. So, configuration 1 shows lower footprint related to the other configurations.

4. CONCLUSIONS

All three configurations provided a reduction in boiler usage. In the basic configuration, the boiler generated 719,030 kWh of heat, meanwhile in configuration 3 it generated 581,855 kWh, in configuration 2 it generated 472,586 kWh, and in configuration 1 it generated 449,335 kWh of thermal energy. Configuration 1 presented the least need of boiler usage (around 62,5% of the basic configuration), therefore being the configuration with the most energy saving capacity.

Diesel power plants use non-renewable sources but have the advantage of operating whenever they're needed. Despite solar systems being intermittent, they can be utilized as auxiliary systems.

The three configurations presented represent economically viable alternatives for reducing diesel consumption in the power plant, particularly Configurations 1 and 2, which yield annual savings of $52,731.87 and $47,964.79, respectively. Although configuration 3 is not as impactful as the others, it still shows promise in this regard.

However, Configuration 1 is associated with the highest Capital Expenditure (CAPEX) compared to the other two configurations. Configuration 2, on the other hand, features a lower initial investment, amounting to 39% of the CAPEX of Configuration 1, while Configuration 3 requires only 60% of that amount. The higher CAPEX of Configuration 1 is attributed to the need for additional equipment, such as the heat pump and Drycooler.

It is worth noting that Configuration 3, despite having a lower initial investment, results in lower annual diesel savings, totaling $26,817.15. It is estimated that in relation to Configurations 1, 2, and 3, the payback period is approximately 8, 6, and 7 years, respectively. As a suggestion for future research, a more in-depth analysis of payback and the Levelized Cost of Electricity (LCOE) is proposed as additional metrics to assess the feasibility of these configurations.

Configurations 1 and 3 stand out as the ones posing the greatest challenges in terms of their effective implementation, primarily due to the need for additional space allocation for the installation of thermal reservoirs. However, it is worth noting that Configuration 1 faces even more significant difficulties, Given the considerable difficulty associated with procuring the specific water-to-water heat pump required for this arrangement in the market, due to a limitation in the available options. Furthermore, all configurations require the availability of suitable space for the installation of solar panels, as well as meticulous attention to the thermal insulation of the piping to mitigate potential heat losses that could adversely affect system overall performance.

The parameters used for the simulations (set point temperatures for the thermostats and dry cooler, the volume of the thermal reservoir, etc.) were kept constant. They could be optimized to find better results and provide even more reduction in diesel consumption.

Finally, the configurations have significant diesel savings, with configuration 3 providing the least savings and configuration 1 the most. Diesel is a non-renewable resource that emits CO_2 when consumed, and the reduction in diesel consumption reduces these emissions. Therefore, as promising as the monetary savings are, the decrease in diesel usage is also important to lower gas emissions to the environment, especially considering the use of renewable resources as alternatives for heat generation. Although this paper doesn't focus on its environmental impact, future research could use these results as a basis to study the viability of the use of solar energy in countries with a similar climate to Brazil.

5. ACKNOWLEDGEMENTS

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