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DEPLOYMENT OF A SMALL-SCALE MODEL FOR EVALUATION OF A THERMAL POWER PLANT ENGINE HEATING SOLUTION USING HYBRID THERMAL-PHOTOVOLTAIC COLLECTORS.
27TH COBEM

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Abstract.
In recent decades, several policies have been adopted to reduce fossil fuel consumption and increase renewable energy production. In Brazil, due to the imminent risk of energy rationing in the 2000s, a plan was developed to build thermoelectric power plants in strategic locations throughout the country. In this study, a laboratory-scale prototype was developed to validate an alternative solution for heating engines in a thermal power plant using an innovative heat exchanger model. The aim was to reduce the thermal demand for engine heating, which is currently done through a steam boiler heated with diesel oil. This reduction would be achieved by obtaining water heated to approximately 45°C from thermal-photovoltaic collectors. The water then undergoes a second heating stage, which involves a heat pump raising the temperature to 60°C, the engine's operating temperature. The heat pump is powered by the electricity generated by the hybrid collectors. The results confirmed the hypothesis that it is possible to use thermal-photovoltaic hybrid systems to heat an equivalent model of a thermal power plant engine.

Keywords: *thermal-photovoltaic collectors, fossil fuel, solar energy, thermal power plant.*

1. INTRODUCTION

In recent decades, several policies have been adopted to reduce the consumption of fossil fuels and increase renewable energy production (Demolli et al., 2019). In Brazil, the use of oil-fired thermal power plants has been usual for several decades. However, in the early 2000s, due to the imminent risk of energy rationing, a plan was developed to construct thermal power plants in strategic locations throughout the country. Thermal power generation was chosen due to factors such as its low implementation complexity, fast construction, and its ability to quickly respond to short-term load variations in the power system. (Rodrigues & Sauer, 2015).

Thermal power plants utilize internal combustion engines due to their high energy efficiency (Ramírez et al., 2019). However, one of the negative aspects of thermal power plants is the atmospheric emissions that pollute the environment with harmful substances such as carbon monoxide, carbon dioxide, nitrogen dioxide, and others (Bhattacharjee et al., 2014).

Over the years, studies have been conducted on the application of solar energy for industrial purposes, such as in the work of Kalougirou (2003), where the application of solar water heating systems in industrial processes was studied, offering various feasible possibilities for different temperature levels: low, medium, and medium-high. There are some limitations for usage at the beginning of the day or late at night, as well as for operations across several shifts. According to the study, the most effective and cost-efficient systems are those for preheating, utilizing low-tech systems such as flat plate collectors, where the supply rate does not need to exceed the demanded rate of hot water (Kalogirou, 2003).

In the work of Junior et al., a literature review is conducted on the possibilities of using solar water heating in industrial processes. One of the evaluated studies considers that electrical energy is an important industrial resource, and its scarcity, negative environmental impacts, and high costs have led the industry to seek effective and economical methods to capture, store, and convert solar energy into useful energy. This work points out that solar energy is advantageous for industrial heating applications, even though in some cases, water heated by the solar system may require additional heating from another energy source. The study concludes that the use of solar water for heating in industries in Brazil is possible and represents an alternative that can contribute to a 30% to 40% reduction in cost and energy consumption for low-temperature heating processes, especially in the food, beverage, textile, and chemical sectors (Junior et al., 2014).

In the work of Cavalcante et al., photovoltaic modules were used in conjunction with diesel engines in the Amazon region with the aim of reducing electricity costs. These systems have high costs due to the complex and unreliable fuel supply chain for this specific application. The inclusion of large-scale photovoltaic installations in these isolated grids has the potential to increase reliability and reduce electricity costs. It was concluded that the use of PV (photovoltaic) modules can achieve an annual reduction in fuel consumption of over 1 million liters, helping to reduce the cost of electricity in this locality (Cavalcante et al., 2021).

Thermal-photovoltaic collectors, also known by the acronym PVT (Photovoltaic Thermal), are devices capable of generating electricity and thermal energy in a single module (Sultan & Ervina Efzan, 2018). In solar thermal systems, collectors are used for water heating, which, through the absorption of solar radiation, transfers energy to water in the form of heat. This system is known by the acronym ST (Solar Thermal) (Filho et al., 2020). Solar photovoltaic energy consists of generating electricity from photons through the photovoltaic effect, which is a phenomenon exhibited by certain semiconductor materials that, when exposed to solar radiation, generate electricity (Esposito & Fuchs, 2013).

One of the challenges in developing a thermally balanced hybrid system is optimizing both electrical and thermal efficiencies (Shyam et al., 2015). Indeed, in heat exchangers, higher working temperatures generally lead to higher efficiency. This is different from photovoltaic systems, which need to operate at lower temperatures to maintain their efficiency. (Suman et al., 2015).

In the context of a thermal power plant, preheating the diesel engine is vital to ensure efficient operation. When the engine is turned off, its components gradually cool down, increasing the risk of wear and long-term issues such as high emissions and lack of lubrication. Preheating involves warming critical components like cylinders and glow plugs, ensuring the engine is ready for heavy-duty operations. Keeping the engines on standby during idle periods helps prevent these problems, ensuring they remain at ideal operating temperature conditions for a fast generation response.

This study developed a laboratory-scale prototype to validate an alternative solution for heating engines in a thermal power plant using an innovative heat exchanger model. The heat exchanger used can be coupled with any type of photovoltaic module, transforming a regular PV module into a hybrid thermal-photovoltaic collector (or simply a thermal-photovoltaic collector). This collector reduces the heat of the photovoltaic module, increasing electricity production and producing hot water. With this application in a thermal power plant, the aim is to reduce the thermal demand for engine heating, which is currently supplied by a steam boiler heated by burning diesel oil.

The proposed solution, illustrated in Figure *1*, aims to reduce the consumption of diesel fuel used in the boiler for engine heating in a thermal power plant. To achieve this, the solution incorporates thermal-photovoltaic collectors (photovoltaic modules with heat exchangers) that enable the generation of electrical energy while harnessing the thermal energy from solar radiation in the PV modules for water heating. Simultaneously, the collectors cool the modules, increasing electricity production. The proposed solution includes a heat pump to raise the temperature of the water leaving the heat exchangers to the desired level for engine heating. Additionally, the thermal-photovoltaic collectors also generate electrical energy used by the heat pump.

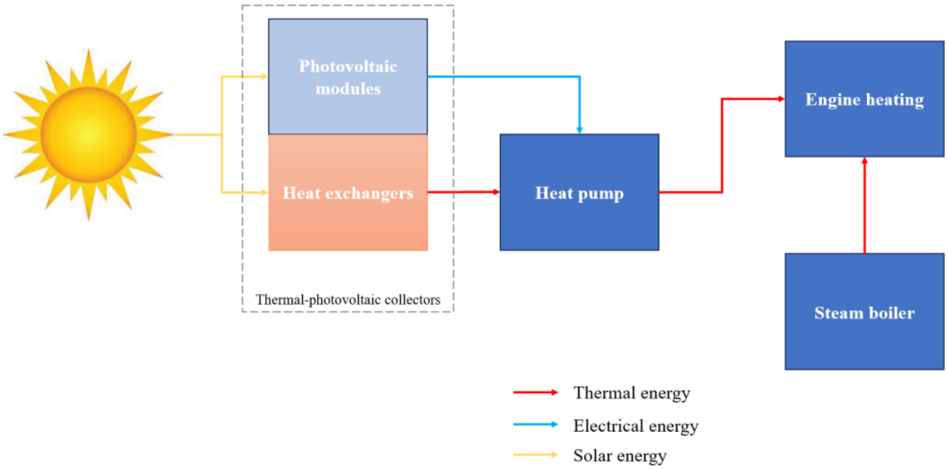

Figure 1 - Basic diagram of the proposed solution for engine heating using thermal-photovoltaic collectors.

Due to the impossibility of implementing the above-mentioned proposed solution at a 1:1 scale, a reduced-scale laboratory prototype was developed for proof of concept. For this purpose, for equipment such as the heat pump, engine, and steam boiler that could not be found on a reduced scale on the market, equivalent models were developed to emulate this equipment in the laboratory prototype of the solution.

The article is divided as follows: Section 1 presents the introduction with the contextualization and presentation of the proposed solution. Section 2 presents the requirements of the engine heating application. Section 3 covers the design and construction of the laboratory prototype. Section 4 describes the testing process. Section 5 provides an analysis and discussion of the results. Finally, Section 6 presents the conclusion.

2. REQUIREMENTS OF THE ENGINE HEATING APPLICATION

In this section, the requirements and sizing of the proposed solution and the laboratory prototype will be presented.

2.1 Requirements of the proposed solution

To define the solution, the thermal energy demand of one engine was calculated. The thermal energy demand is calculated using equation (1), where $\dot{Q}$ [W] is the thermal power consumed by the engine; $\dot{m}$ [kg/s] is the mass flow rate of water; Cp [J/kg/°C] is the specific heat capacity of water, and T_{in} e T_{out} are the inlet and outlet temperatures of water in the engine.

$$\dot{Q} = \dot{m} * C_p * (T_{in} - T_{out}) \qquad (1)$$

Considering the following values as nominal design conditions: $\dot{m} = 3.89 \frac{Kg}{s} = \left[14 \frac{m^3}{h}\right]$, $C_p = 4.180 \frac{J}{kg*°C}$, $T_{in} = 66°\text{C}$ e $T_{out} = 65°\text{C}$, obtains the thermal demand of the 16.26 kW engine. Considering the total thermal demand calculated for one engine, it was estimated that the proposed solution could use 93 thermal-photovoltaic collectors and a heat pump that consumes an average of 45 MWh to supply the remaining heat demand. Therefore, the proposed solution would require a total area of 205.6 m^2 for the deployment of the proposed solution on a full scale, considering an area of 2.21 m^2 needed for each collector.

2.2 Sizing of the laboratory prototype

For the construction of the laboratory prototype, which is a scaled-down version of the proposed solution, equivalent models were developed for the engine, Steam boiler, and heat pump.

The equivalent engine model consists of a radiator and a coolant tank. To dissipate the heat, a radiator capable of dissipating approximately 2.1 kW was specified, considering a $\dot{m} = 0{,}1\ kg/s$ for a $\Delta T = 5°C$ using equation (1). The coolant tank used is responsible to simulate the heating ramp of the engine from ambient temperature to the desired temperature, which is above 60°C.

For the equivalent model of the heat pump, an electrical resistance of 15 kW and a radiator were defined to dissipate the heat. The 15 kW electrical resistance was specified to provide a certain amount of heat to the engine based on a mass flow rate of $\dot{m} = 0{,}2\ kg/s$, which is a higher flow rate than that used in the equivalent model of the engine.

This is necessary to ensure that the resistance is always immersed in water for its proper functioning. The electrical power of the resistance was also considered to achieve a ΔT of approximately 18ºC within 1 second using its maximum power. This takes into account that the thermal collectors raise the temperature at least to 42ºC during periods of good solar radiation, allowing the thermal-photovoltaic collectors and heat pump system to provide enough heat to the engine so that the inlet engine model temperature is at least 60ºC. The radiator was designed to simulate the heat loss of one of the sides of the heat pump and maintain, a heat dissipated ratio equivalent to a heat pump with a Coefficient of Performance (COP) of 4.5.

For the equivalent model of the steam boiler, a 5 kW electrical resistance was used. In the resistance sizing, the same mass flow rate as the one used in the equivalent model of the heat pump was utilized due to the inclusion of the resistance in this model. The temperature variation considered was 5°C, considering that temperature may decrease by up to 5°C at the engine model outlet compared to its inlet. By using Equation 1 to calculate the amount of heat provided for engine model heating, a value of 4.18 kW was obtained. Thermal losses in the pipelines and heat transfers through the exchangers were also considered.

3. DESIGN AND CONSTRUCTION OF THE LABORATORY PROTOTYPE

For the design and construction phase, the laboratory prototype was divided into five circuits: (1) Standby engine simulator; (2) High Temperature (HT) circuit simulator; (3) Boiler simulator; (4) Heat pump simulator; and (5) Solar heating. The objective of this division was to evaluate the contribution of each source and validate the concept of the proposed solution using thermal-photovoltaic collectors. Figure 2 illustrates the circuits in prototype, and Figure 3 shows a photo of the laboratory prototype built for the tests.

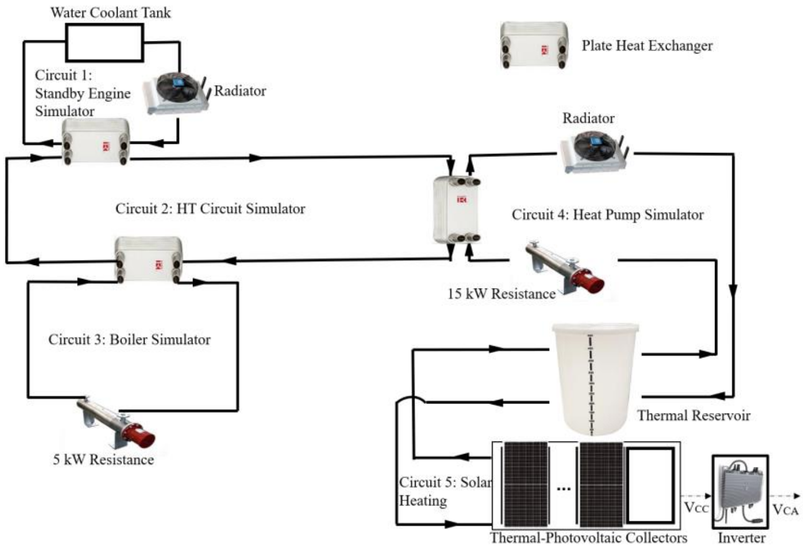

Figure 2 - Illustration of the laboratory prototype circuits.

Figure 3 - A photo of the laboratory prototype.

3.1 Laboratory prototype circuits

Using Figure 2 as a reference, this section describes the function of each circuit in the laboratory prototype. The heat exchangers used between the circuits were designed to facilitate the exchange of heat between them. Circuit 1 is designed to simulate the thermal loss in the engine. To achieve this, the water flow rate is manually adjusted using a valve and kept at a fixed value of $\dot{m} = 0{,}1\ kg/s$. This mass flow rate was determined based on the amount of heat that the engine consumes. A radiator is used to cool the water, simulating the thermal energy consumption during the engine heating process. To simulate a thermal energy consumption equivalent to a temperature decrease of 5°C in a given timelapse, a PID controller was designed to control the radiator to reach the setpoint temperature. The water coolant tank allows the simulation of the heating dynamics of the engine on a reduced scale, from ambient temperature to operating temperature, emulating the heating ramp.

In Circuit 2, which simulates the operation of the HT circuit, the goal is to transfer the heat generated by the different sources such as the boiler, heat pump, and thermal-photovoltaic collectors to the engine. The most critical temperature to control throughout the setup is the inlet engine temperature. For this reason, solenoid valves are used to switch the hydraulic circuit, allowing the system to operate with the different heat sources (steam boiler and solar) either isolated or combined. Figure 4 shows the valve scheme.

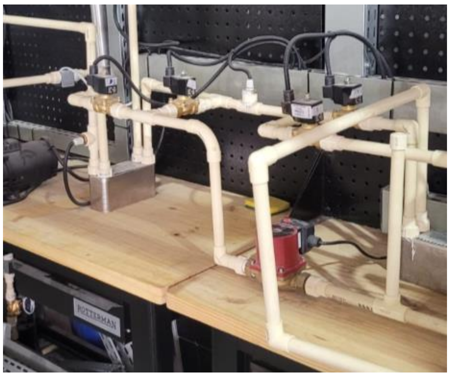

Figure 4. Photo of the valve scheme.

The steam boiler of the power plant, which has the aim of supplying a controlled heat to Circuit 2, is simulated in Circuit 3. A PID controller is used to control the heating ramp of the 5 kW resistance to set the water temperature to a desired temperature. The setpoint temperature is configured at the PID controller to approximately 66°C at the inlet of the plate heat exchanger in Circuit 3, and it will remain constant throughout all tests (simulating the nearly constant steam temperature in the power plant). The PID controller activates the electric heater through a solid-state relay. A flow switch is used as a safety measure to prevent the electric heater from being activated without water flow in the pipeline. The pump is equipped with a frequency inverter that makes possible to adjust manually the water flow ensuring that the temperature at the inlet of the engine will remain above 60°C.

In Circuit 4, the heat pump is responsible for taking the heat from the cold source (thermal reservoir) and delivering it to the hot source in Circuit 2 through the plate heat exchanger. The heat pump was simulated using an 15 kW electric resistance and a radiator, and the control was performed by a Programmable Logic Controller (PLC) which was used to activate the resistance through a solid-state relay. As in Circuit 3, a flow switch was used as a safety measure to prevent the resistance from being activated without a minimum water flow in the pipeline. The desired cooling power was managed by the PLC which controls the operation of the radiator.

The solar heating was implemented in Circuit 5. The water that was initially stored at ambient temperature was forced to circulate between the thermal reservoir and the thermal-photovoltaic collectors, increasing its temperature up to approximately 42°C. Figure 5 shows a photo of the back side of thermal-photovoltaic collector used in the prototype. In this figure, it can be seen the back side of a monofacial solar panel attached with the innovative solution of heat exchanger which is capable to transform a regular PV module into a thermal-photovoltaic collector, generating hot water and increasing electrical energy generation. To measure the solar thermal generation at the thermal-photovoltaic collectors, a flow meter and temperature sensors were used at the inlet and outlet. A power meter was used to measure the electrical generation. Solenoid valves were also employed to prevent fluid circulation by natural convection when the pump is turned off.

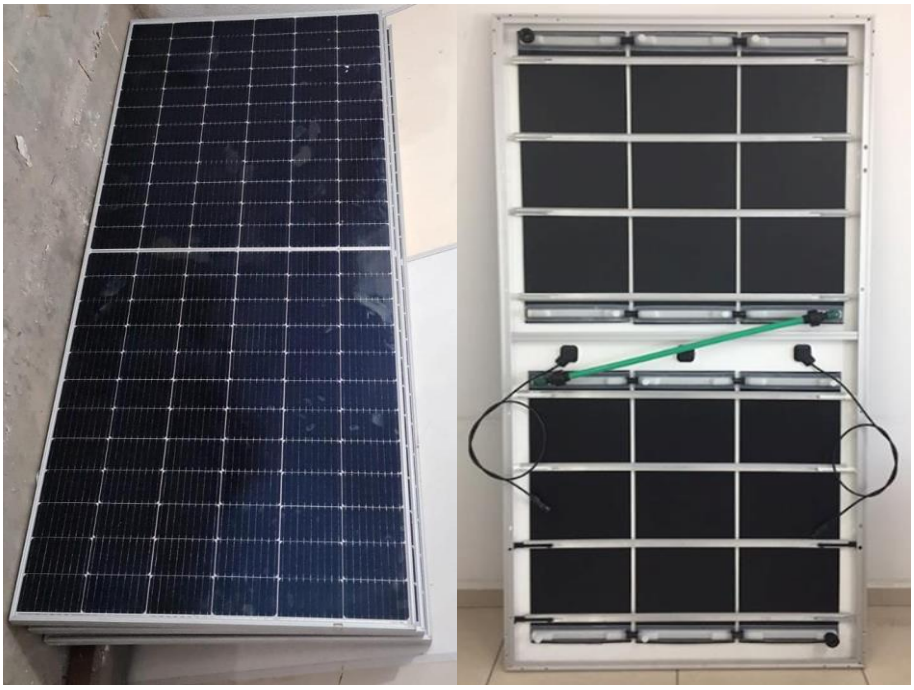

Figure 5 - Photo of the thermal-photovoltaic collector.

4. TESTS

Two primary tests were carried out on the laboratory prototype. The first test aimed to analyze the thermal contribution of the thermal-photovoltaic collector in Circuit 5. It lasted 210 minutes and involved heating 250 liters of water stored in the thermal reservoir during a single morning session. Temperature sensors were used at the inlet and outlet pipes of the thermal collector to determine the maximum thermal contribution to the laboratory prototype.

The second test, lasting 30 minutes, simulated the engine in stand-by mode, with the inlet temperature of the plate heat exchanger in Circuit 1 above 60°C. Its objective was to evaluate the combined contribution of the heat pump in Circuit 4 and the thermal-photovoltaic collectors in Circuit 5 to reduce the usage of the boiler in Circuit 3. The test aimed to assess their capacity to maintain the engine model under stand-by conditions.

5. ANALYSIS AND DISCUSSION OF RESULTS

In Figure 6, the graph displays two temperature curves: one for the inlet (orange) and another for the outlet (blue) of the thermal-photovoltaic collector over the time. It can be observed that the collector raises the temperature of the water in the thermal reservoir from 31°C to 55°C, resulting in a temperature increase of $\Delta T = 24°C$. After 120 minutes from the start of the test, the curves show a slight decline, which can be explained by the decrease in solar radiation on the collectors during that period. The curve then begins to rise again, but with a lower slope, indicating that the collectors tend to stabilize once they reach a certain temperature.

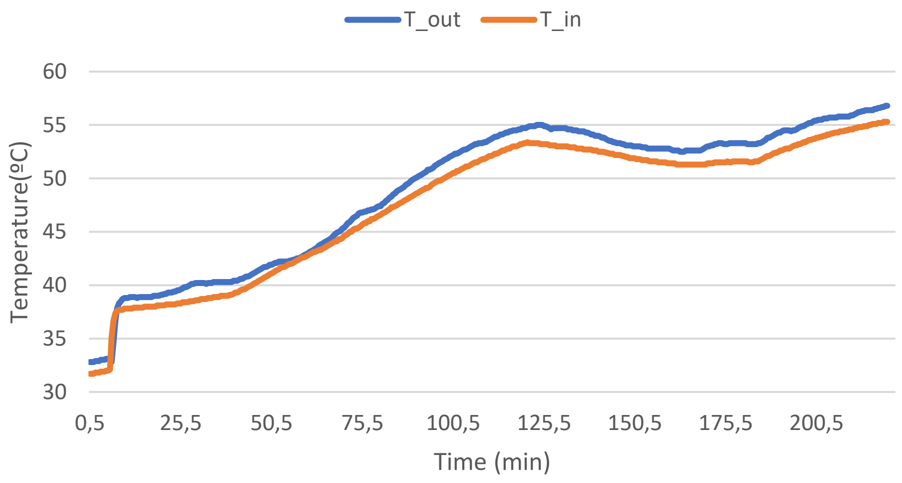

Figure 6 - Temperature behavior at the thermal-photovoltaic collector.

Figure 7 illustrates the behavior of the heat sources over time. Based on data, it can be seen that the average heat consumption by the motor, based on the conducted test, was 2.01 kW. The boiler provided an average of 0.86 kW, while the heat pump and thermal-photovoltaic collectors supplied 1.15 kW of this thermal energy. Thus, it can be observed that the implementation of the solution composed by a thermal-photovoltaic collectors and a heat pump allows a reduction in boiler usage. When considering this system on a larger scale, it becomes true the possibility of decreasing the consumption of energy from fossil fuel sources in this sort of application. This is significant because steam boilers typically rely on these sources for energy generation.

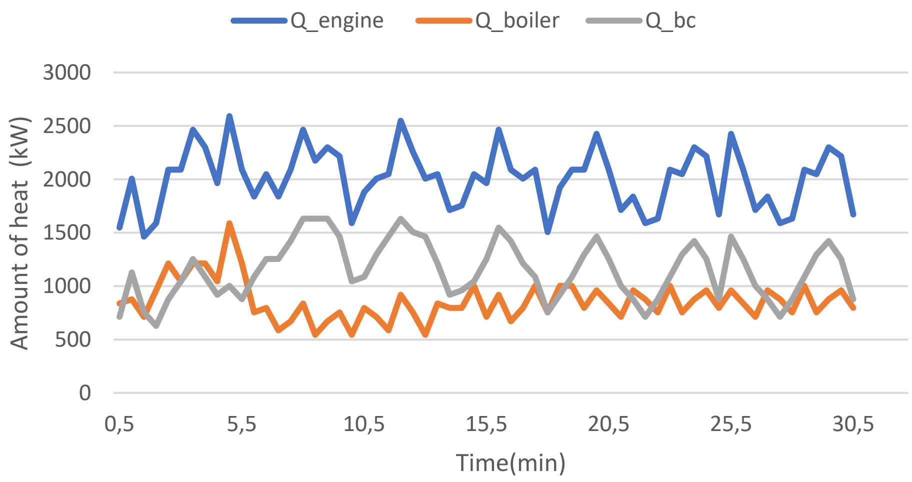

Figure 7 - Behavior of heat sources over time.

6. CONCLUSIONS

The objective of this project was to develop a downscaled laboratory prototype to validate a proposed solution: the reduction of diesel oil consumption in the boiler used to heat the engine of a thermal power plant. The laboratory prototype successfully implemented the proposed solution, utilizing thermal-photovoltaic collectors and a dedicated heat pump designed for thermal power plant applications. The results obtained demonstrated the potential of thermal-photovoltaic collectors in effectively reducing diesel oil consumption while optimizing solar energy production. These collectors significantly contributed to the required heat for the engine, raising the water temperature from ambient to over 55°C. Additionally, the use of the heat pump model showed a potential reduction in boiler consumption of 57.21%. In conclusion, the proposed solution in this study offers significant advantages, including a substantial reduction in diesel oil usage, resulting in cost savings associated with fuel procurement. Moreover, it contributes to the reduction of CO2 emissions, aligning with the global objective of mitigating the environmental impact of fossil fuel-based energy sources.

7. ACKNOWLEDGEMENTS

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