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A Novel Application of a Parabolic Trough Collector for Solar Cooking, Thermal Storage and Thermoelectric Energy Harvesting

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Abstract. The work here involves designing a solar solution for safe cooking and low-power generation intended for application in rural communities. A system was developed that combines Concentrated Solar Power (CSP) and Thermoelectric Generator (TEG) technologies. The CSP provides heat for clean cooking, and the excess heat is harvested by the TEG and converted into electrical power. A storage tank was integrated into the system, storing excess energy and serving as the medium for indirect cooking and supplying the heat required by the TEG. The Parabolic Trough Collector, having a resulting average thermal efficiency value of 21%, provided the useful energy to store over 4.25kWh of heat in the tank during the initial testing of the system. The TEG developed has four Peltier modules and attained 23W - over 80% of their rated power and a maximum conversion efficiency of 4.14% at a temperature difference of 220°C between the cold and hot surfaces of the generator. During the experiment, the TEG operation was limited to only four hours before subjecting a no-load test to assess the total energy storable from the system. The initial results from the test carried out here show the potential of the hybrid system in storing energy in the tank for an extended period and simultaneous operation of the TEG. Excess energy stored can be utilised further in providing the heat required for cooking or further electrical power generation.

Keywords: Parabolic Trough Collector, Solar Cooking, Thermoelectric Generator, Energy Harvesting, Concentrated Solar Power

1. Introduction

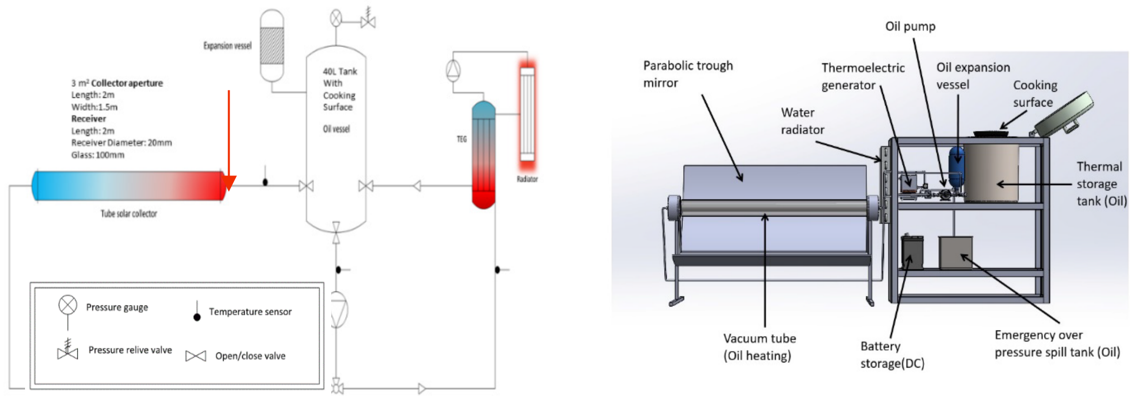
Clean energy options are in high demand as a replacement for depleting and environmentally hazardous fossil fuels. Challenges include rising energy prices, environmental emissions, and global warming [1]. Several waste heat recovery studies have thus been conducted to use various thermoelectric designs to generate electricity, including installing a thermoelectric device directly under a solar concentrator. The work here introduces a design concept of combining Concentrated Solar Power (CSP) and thermoelectrics to generate heat and electricity.

Reducing energy consumption and pollutant emissions has led to significant developments and research on waste heat recovery. Energy recovery is essential because it improves performance [2]. Thermoelectric materials are usually used for energy harvesting in the form of pre-fabricated Peltier modules. Thermoelectric generators (TEGs) have demonstrated their ability to directly transform thermal energy into electrical energy through the Seebeck effect

[3]. The main advantage of thermoelectric generators is their direct energy conversion to electrical energy with no need for an intermediate generation with electro-mechanical alternators. Many rural areas in developing countries have little to no access to electricity due to inadequate power infrastructure. CSP cookers provide a means of safe and affordable cooking while also reducing the cost of cooking fuel [4]. Excess heat can be used to generate energy to meet low-power demands, such as charging phones and running light-emitting diodes (LEDs) [5]. Combining these approaches and incorporating storage would result in a hybrid approach that could provide a long-term solution to the need for safe cooking and access to electricity in developing countries. Using PV modules with thermal storage is not within the scope of this work.

2. Setup of designed system

The project involves designing and developing a CSP Parabolic Trough Collector (PTC) system with an integrated high-temperature oil energy storage tank serving as an indirect cooking unit. The stored energy is also used to transfer the heat to the TEG unit for low-grade electric power generation. The TEG unit uses four units of Peltier modules, each rated at a power output of 6.99W [6]. The high-temperature pump feeds the storage tank and the TEG unit via the collector. The Heat Transfer Fluid (HTF) is continually recirculated through the system via the collector until desired temperatures are reached, where the energy can either be stored or used. Figure 1a&b shows the system's piping diagram and the layout showing the various components.



a. b.

Figure 1 a. PID for the Designed System b.Layout showing designed components

The following section is divided into three units describing a significant component of the designed system.

2.1 The thermoelectric generator

Thermoelectric power generation has been implemented in the cooker system to utilise the unused heat by the cooker to generate electricity for use in other applications. Commercially available bismuth telluride thermoelectric modules or Pelter modules having a working temperature range of 30°C - 250°C are used. The thermoelectric generator uses a water-cooling system and the heated thermal oil circulation to achieve a constant heat differential that produces a D.C. output of around 6.99 Watts per module. Using an array of TEG modules to convert thermal energy to D.C. electrical energy, a max-power-point-tracking system (MPPT) is incorporated to adjust the resistance modules to achieve optimum power output. The TEG unit is shown in Figure 2.

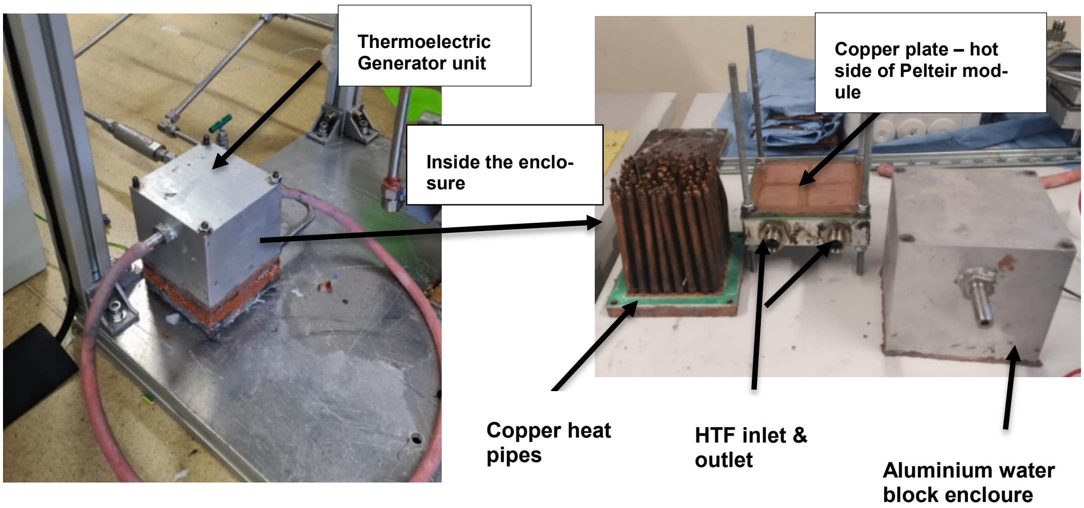


Figure 2. Thermoelectric Generator unit (TEG)

Four units of the Peltier modules are included in the design of the harvester (Figure 3). Each module has a matched load output of 1.38A and a load output voltage of 5.05V. Each module requires a heat flow of 138.9W to reach the matched load output power.

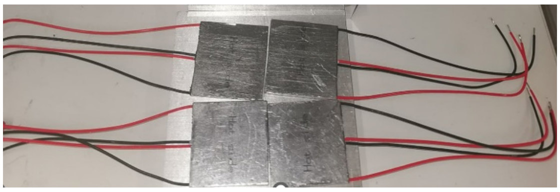


Figure 3. Peltier modules (40mm × 40mm with Prak Power Output of 6.99W)

The TEG has an inlet and outlet connector fitted with pipes that conduct the heated oil onto the Peltier modules via copper plate. An aluminium block encloses copper pipes where water is pumped through to the cooling system. The copper pipes and the cooling system from the water enclosure and radiator are used to maintain the temperature of the Peltier module's cold side to 30°C. The copper heat pipes with sintered wicks have enclosed de-ionised water as working fluid. The copper heat pipes are bonded to the cold face of the Peltier modules. As the HTF from the PTC heats up, the liquid in the heat pipes is turned to vapour and travels to an area of lower pressure towards the cooling water enclosure, where the absorbed heat is expended, making the liquid return to the heat source. A total of 64 heat pipes is included in the TEG design. Each heat pipe is 6mm in diameter and has a maximum power carrying capacity of 10W, totaling 640W, capable of evacuating the complete heating input.

2.1.1 Setup for Indoor testing of the energy harvester

An initial indoor testing of the energy harvesting unit was conducted to record its output in standard lab conditions. The experimental testing of the harvester was made using a Huber Chili system. The Chili system is a heating circulator for closed systems with a maximum operating temperature of 300°C. A chiller was added to the setup to maintain the cold side temperature at 30°C. Figure 4 shows the setup used for indoor testing.

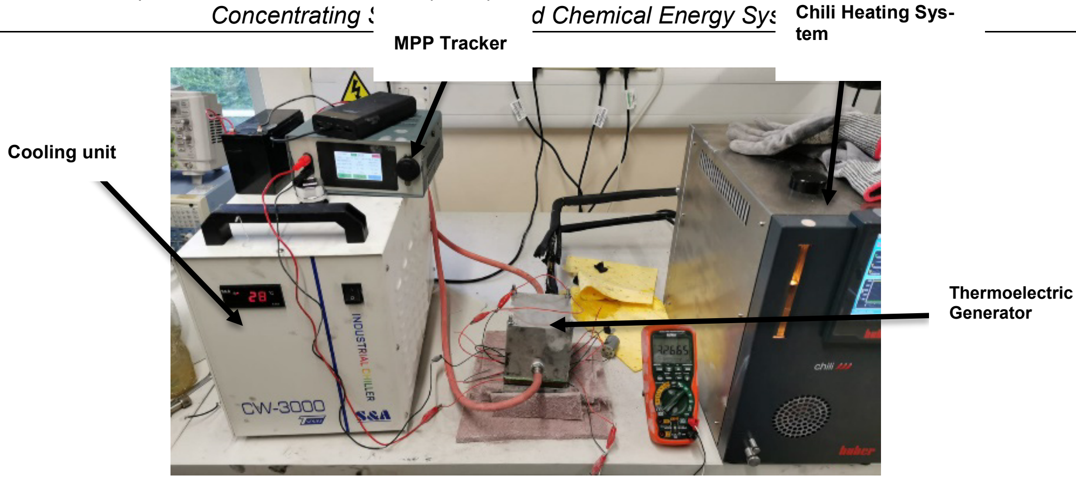


Figure 4. TEG experimental testiing of TEG unit using Huber's Chili Systyem.

2.2 The cooling system

Cooling is vital in the TEG system to keep the temperature differential conditions producing maximum power. The water cooling system adopted here is a relatively simple concept of running water through radiators with large surface areas to disperse heat to the ambient air. The advantage of water radiators is that the water pumping and airflow can be adjusted to increase water-to-air energy transfer. An aluminum radiator with an estimated surface area of 2.5m^2 is adopted as the cooling medium. 20L of water is stored for pumping through the radiator.

2.3 The parabolic trough collector

Solar cookers come under different categories that depend on the technology deployed. These technologies include concentrating and non-concentrating technologies. Concentrating technologies include parabolic trough concentrator, parabolic dish, linear Fresnel reflector (IFR) and central receiver tower [7]. Among these, PTC has found better and more feasible solutions due to the rapid achievement of high temperatures of 60°C–400 °C and storage integration[8][9]. This formed the basis of the selection of the PTC for the thermal energy collector. The PTC includes a reflector and an absorber tube (See Figures 4a&b). The reflector comprises of curved reflective mirror surface that collects the solar radiation falling on its aperture and concentrates it on the receiver tube. For the reflecting mirror, two units of acrylic mirror sheets, each sized 1.5m by 1m, are placed across the frame of the concentrator. The frame provides the shape of the parabola via curved shaped ribs. The receiver is a linear coated absorber tube covered by a glass surface and vacuumed to reduce the convective heat loss from the absorber surface. The receiver is also linear and omnidirectional, designed to accept concentrated flux from any direction. Full specifications of the PTC are highlighted in Table 1.

Table 1. PTC Design specification

Description	Value
Focal length	0.44m
Length of parabola	2.00m
Aperture width	1.50m
Parabola height	0.32m
Rim angle	81.39°
Absorber tube material	Steel
Steel tube diameter	40mm
Glass tube diameter	100mm
Collector reflectivity	0.80

PTCs are meant to orient themselves to follow the sun's movement during the day. A high degree of accuracy is therefore required from the tracking system. There are two distinct types of tracking; mechanical and electronic/electrical tracking [10],[11]. The electronic/electrical tracking system has greater reliability and accuracy at a higher cost [10]. A simple mechanical tracking is hence adopted, which ensures minimal tracking. A cylindrical groove supports the rib's structure where it can rotate 45° in either direction. East-West axis orientation (North-South tracking) is used here. In this chosen orientation, minimal adjustment is needed; only once a day at noon according to normal solar radiation [12].

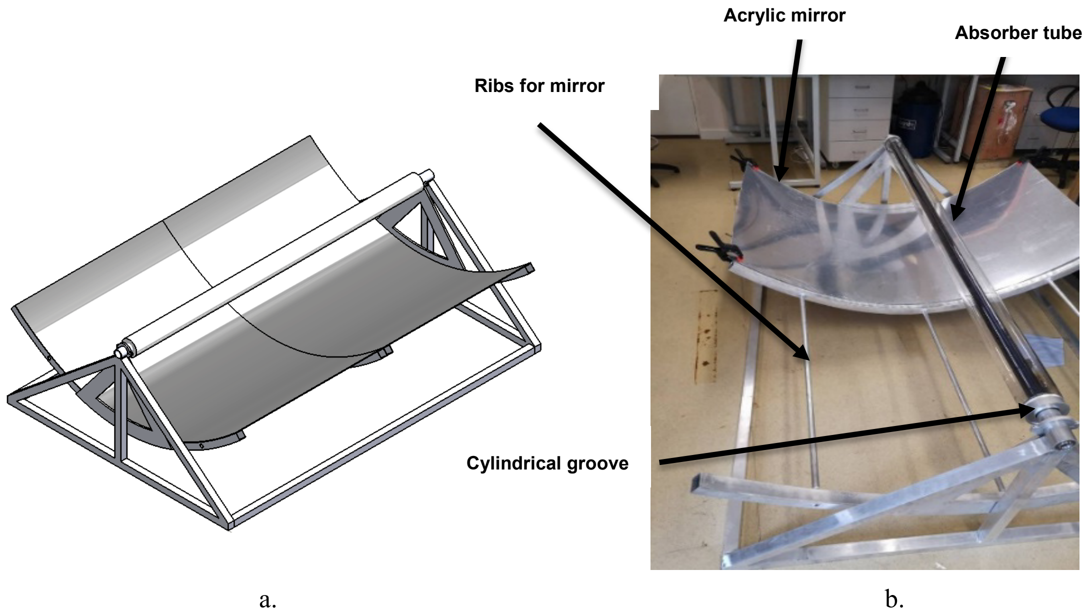


Figure 5 a. PTC layout design b. Assembly of PTC

Heat Transfer Fluid is one of the essential components in the plant itself and has a contributing factor to the overall system's efficiency. Choosing a HTF fluid for an application thus becomes necessary. High operating temperature, thermal stability, high energy content, low corrosion, low vapour pressure and low cost are some of the desired characteristics of the HTF in this application. The HTF selected for the work is the mineral oil Shell Thermal B. Shell Thermia Oil B is a paraffinic heat transfer fluid that operates at 320°C bulk temperatures in closed heat transfer systems. The oil was selected due to its non-hazardous and non-toxic nature. It has an operating temperature of 310°C [13], which corresponds well with the temperature range requirements for the TEG operation.

The heat added to the HTF is used to evaluate the collector's thermal energy output rate. The useful energy output, Qu, from the collector, expressed in heat absorbed by the HTF, is expressed by [14]:

$$Q_u = \dot{m}\, C_p\, (T_{out} - T_{in}) \tag{1}$$

Where $\dot{m}$ is the mass flow rate, Cp is the fluid's specific heat capacity, and Tin and Tout are the HTF's outlet and inlet temperature. PTC's thermal efficiency can be expressed by:

$$\eta = \frac{Q_u}{A_a H_b} \tag{2}$$

H_b is the Direct Normal Irradiance (DNI) and A_a is the collector's aperture area.

2.4 The Storage Tank

The storage system is built as an insulated mild steel tank with a capacity of 40L and can store 29MJ of energy in the HTF operating at peak operating temperature of the HTF. The tank stores the energy collected from the PTC. An indirect solar cooking method is adopted here where the cooking plate is displaced from the collector and integrated with the tank, and heat is supplied via the HTF in the tank. The tank is insulated using fiberglass of 2inch thickness to reduce heat loss, maintaining usable temperatures for using the solar cooker and use of TEG during evenings.

The developed system was set up in the U.K. at the University of Cranfield, where a full-day test was conducted (see Figure 6).

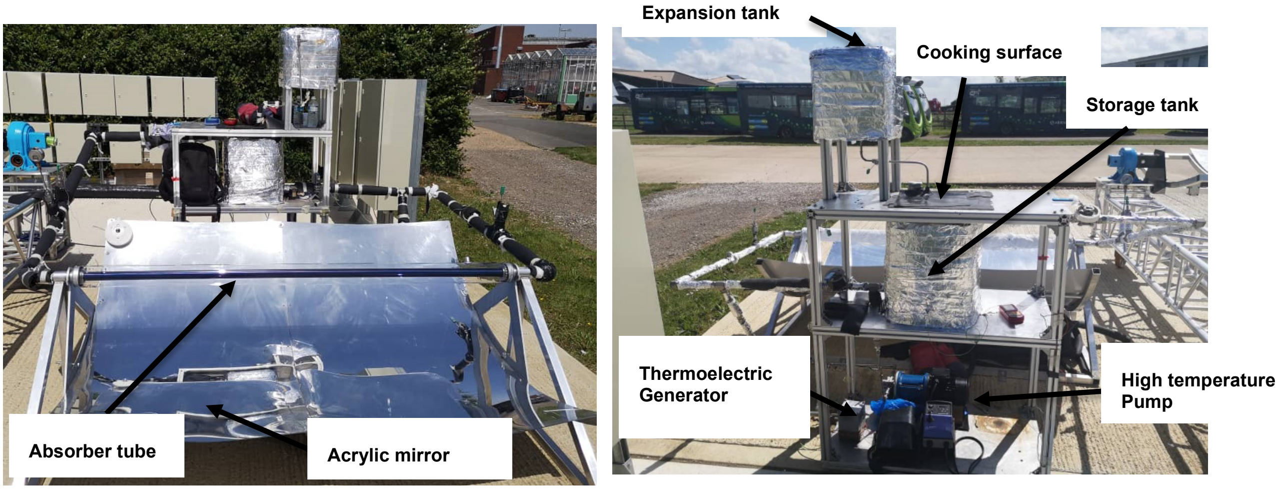


Figure 6. Complete setup of hybrid PTC system showing the parabolic torugh (Left) and the storage unit with cooking surface on the storage tank (Right).

3. Results

In Figure 7, the result obtained from the experimental lab test of the TEG is presented.

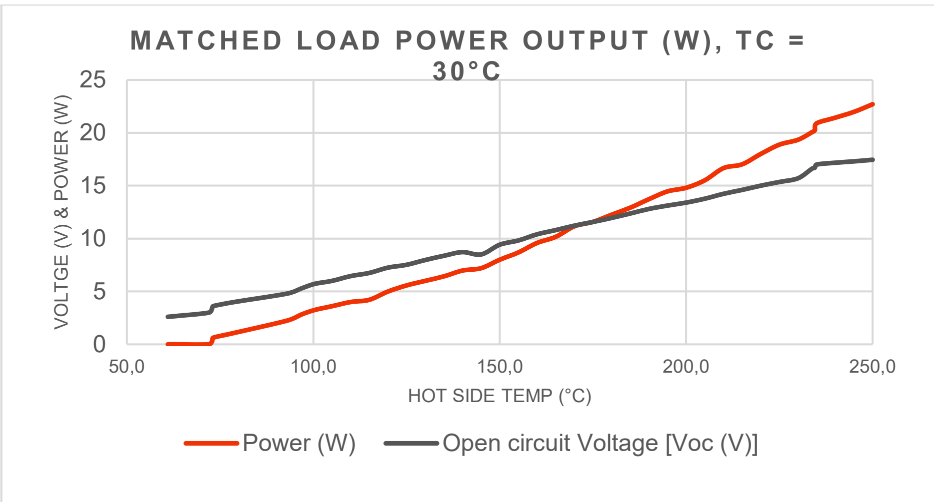


Figure 7. TEG Unit test results

Using the Chili system to supply a steady heat of 560W to the HTF through the entire process, with the cold side of the TEG maintained at a constant temperature of 30°C, a peak power of 23W was extracted from the developed harvester. The harvester's performance was found to be within 80% of the module's specification in all recorded temperatures and a maximum conversion efficiency of 4.14% was achieved at a temperature difference of 220°C between the cold and hot surfaces of the generator.

An SMP10A pyranometer was used to collect the GHI and DHI (Global Horizontal Irradiation and Diffuse Horizontal Irradiation) at the site. The DNI at the site was then calculated and tracked against the system's performance of the PTC. The solar irradiation at the site and the collector's thermal efficiency are shown in Figure 8. A peak thermal efficiency of 37% is recorded on the PTC's conversion efficiency.

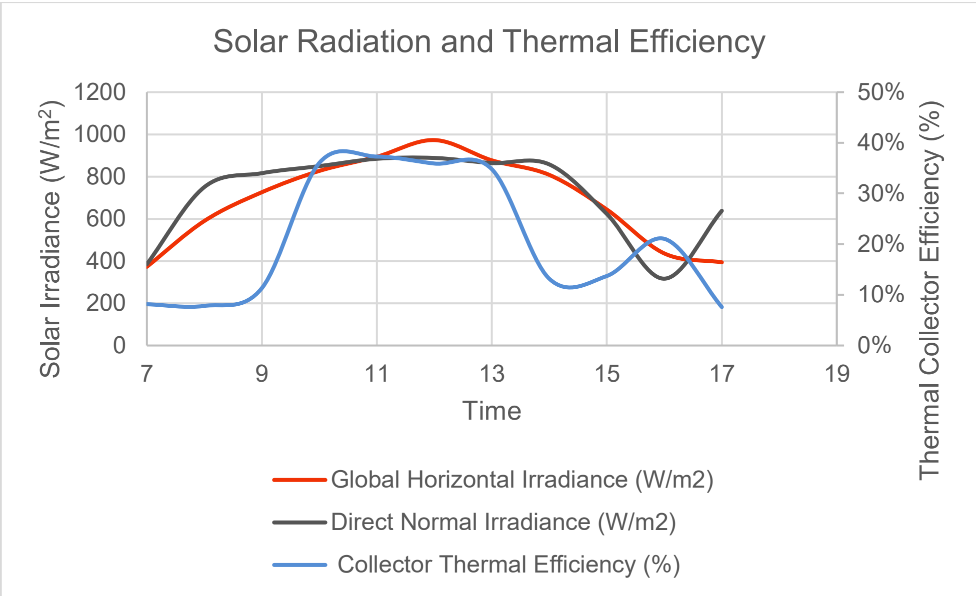


Figure 8. The solar irradiation at the site and the collector's thermal efficiency

A complete experiment was conducted on a particularly hot and sunny day on the 17th of June, 2022. 40 litres of Shell Thermia B oil was pumped through the system, and the temperatures were recorded at the inlet and outlet of the collector and the storage tank (See Figure 9). The temperature of the HTF at the bottom of storage tank is observed at the start of the experiment until 10 pm. The performance of the PTC was calculated by measuring the HTF's inlet and outlet temperature as shown in equation (1).

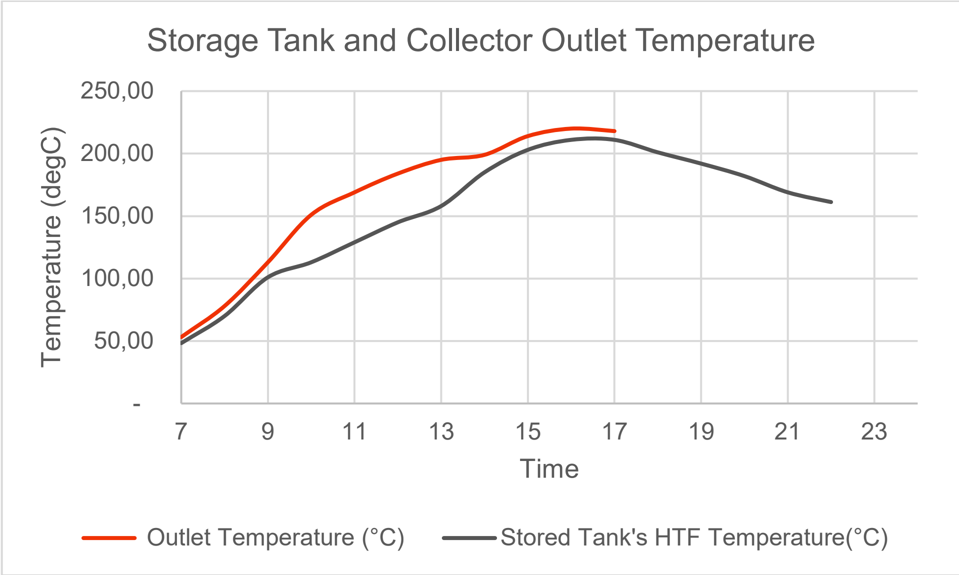


Figure 9. Storage tank and collector outlet temperature readings over time

The output temperature recording from the collector was discontinued at 5 pm when HTF circulation was halted. However, continuous hourly monitoring of the storage tank using an immersion thermocouple shows a HTF temperature of 161°C during the night at 10 pm.

TEG operation during the experiment was limited to four hours when the tank's temperature reached a reasonable value of 150°C. This ensured the system had a reasonably high-temperature output and stored energy by the experiment's end to allow enough energy stored in the tank for night-time use (cooking and TEG operation). During that short operation of the TEG, 25Wh was drawn out from the harvester. At 10 pm, when the last reading was recorded, a net output of 3.60kWh is calculated to be stored in the tank (from a total storable of 5.90kWh, lower end temperatures of 40°C are deemed unusable). This is enough energy for an additional 148Wh extractable from the TEG. See Figure 10 for an illustration of the net energy stored in the tank.

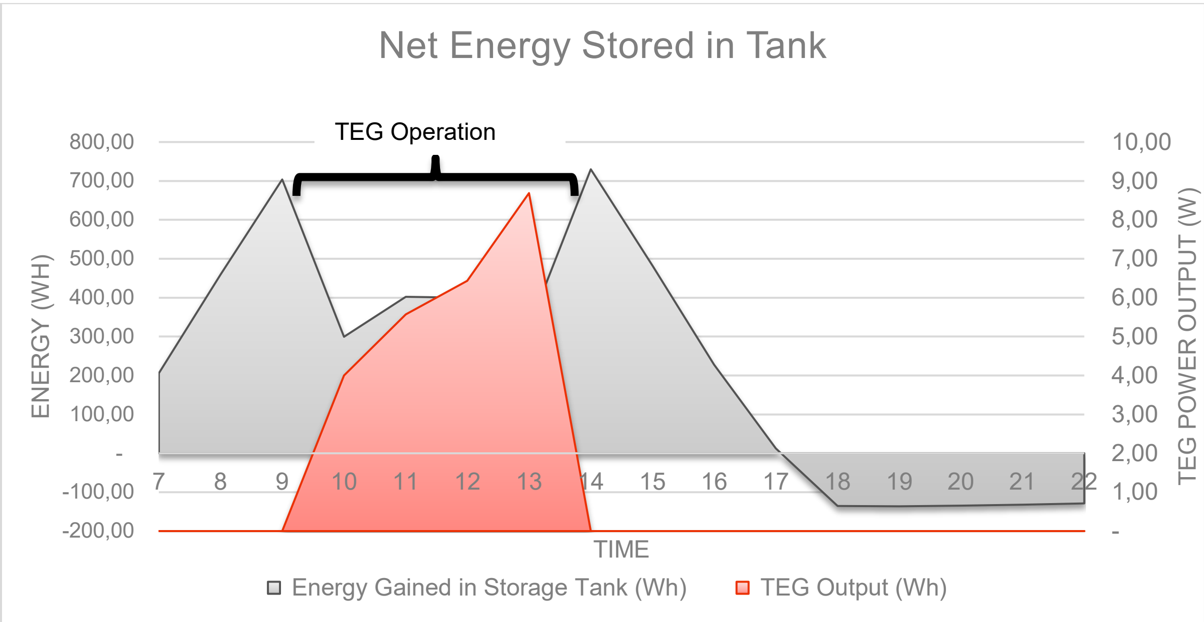


Figure 10. Net energy stored in the tank

At the current stage of the experimental testing, a field test of the system has not been conducted with simultaneous cooking integrated. However, indicative energy usage during cooking is used to estimate the system's performance. For instance, the energy required for cooking rice is 0.10 KWh/kg [15]. The energy balance of the storage tank had 4.25kWh of stored energy when the experiment was halted at 5 pm. That is enough stored heat for over 40kg of rice.

4. Conclusion

A hybrid PTC and thermoelectric generator (TEG) system was developed to store energy and provide access to an affordable smoke free cooking and electrical power for low-grade power applications. The system setup involved designing an energy harvester capable of extracting heat from pre-fabricated Peltier modules. The TEG is then combined with a PTC designed to provide cooking energy and store the excess energy in an integrated storage tank.

Over a period of fifteen hours, the system was able to collect and store a net 3.60kWh of energy in the tank. During that time, 25Wh of D.C electrical output was extracted from the system via the TEG. The excess energy stored is sufficient to provide the required heat to over 40kg of rice or extract an additional 148kWh D.C. power output from the TEG. Results from an initial laboratory test of the TEG show that over 80% of the rated power from the Peltier modules can be extracted at a temperature difference of 220°C between the hot and cold surfaces of the generator.

The initial results from the test carried out here show the potential of the hybrid system in storing energy in the tank for an extended period that can be utilised for cooking or electrical power generation. Further tests on the hybrid system are required to analyse the system's performance with simultaneous TEG operation and cooking under different conditions so the excess storable energy in the tank can be assessed. Further work on the system would also include implementing natural circulation and using surface-to-surface contact directly on the storage tank when using the TEG.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article. Additional information on data can be made available upon reasonable request from the corresponding author.

Author contributions

Zaharaddeen Ali Hussaini: Conceptualization; writing – original draft; formal analysis; Investigation. Fergus Crawley: Conceptualization; formal analysis; investigation; writing – review and editing. Zhenhua Luo: Funding acquisition; project administration; writing – review and editing; Investigation. Christopher Sansom: Funding acquisition; supervision; writing – review and editing. Peter King: Investigation. Adriana Stawiarska: Investigation; resources.

Competing interests

The authors declare that they have no competing interests.

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