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Abstract

This paper investigates the solar evacuated tube heat pipe system (SEHP) coupled with a thermoelectric generator (TEG) using the internet of things (IoT). The TEGs convert heat energy into electricity through the Seebeck effect that finds application in the waste heat recovery process for the generation of power. The present work deals with the theoretical study on solar evacuated tube heat pipe integrated TEG and it is validated experimentally using with and without parabolic trough concentrating collector. And the carbon credit of the TEG system is determined to find its potential in the environmental aspect. Also, the boost type converter is used to raise the power output by increasing the voltage from the TEG for rural electrifications. However, it is found that the maximum power output due to the influence of the parabolic trough concentrator results in increased efficiency when compared with the non-concentrating SEHP-TEG system. The TEG output power can be boosted up to a maximum of 5.98 V using a power electronic boost converter. Besides, the recorded real sensor data with Arduino is implemented in the experimental process for automatic remote monitoring of the temperature.

Keywords: Solar evacuated tube heat pipe, thermoelectric generator, parabolic trough concentrating collector, Environmental analysis, internet of things, boost converter.

1. Introduction

In today's world, one of the major concerns was to provide clean energy for a hazardous-free environment (Zoui et al. 2020). As of now, in the total energy consumption, about 80% is fossil fuel's contribution and the remaining is from other sources such as nuclear power, hydro, and renewable energy sources like solar, biofuels (Bildirici, 2018), wind, and geothermal energy (Faik Bilgili, 2020). But in the current state, fossil fuels are in the urge of depletion, and in the meantime, it is expected that due to the increase in the global population the electricity demand can be increased by 49% by the year 2040 (CAPP 2018). Furthermore, the use of fossil fuels leads to a rapid increase in greenhouse gas emissions, which has an impact on the world's long-term growth due to global warming, climate change, and other factors (Yousefi et al. 2016, Veronesi et al. 2017). Matching the gap between the depletion of fossil fuels and the growing population will lead us to depend on alternative fuels like renewable energy sources. One such renewable energy is solar which is of clean energy source and is feasible, therefore it has a significant part in reducing the global crisis for energy. In this context, thermoelectric technology would also be a suitable energy source for the future as it directly converts the energy from one form to another without affecting the environment (Karthick et al. 2019). Thermoelectric technology (TE) is an eco-friendly technology that does not pollute any greenhouse gases and also has longer life since it has no moving parts (Ahıska and Mamur 2016). TE uses both the Seebeck (Thermoelectric generators) and Peltier effect (Thermoelectric coolers). In this, thermoelectric generators (TEGs) which work on the Seebeck effect converted to electrical energy from thermal energy (Verma et al. 2021). TEGs have superabundant advantages compared with other renewable energy devices as it is solid-state, clean energy conversion, cost-effective, and environmentally friendly (Enescu 2019). In addition to some conventional heat recovery applications, the heat pipe technology with solar concentrators would efficiently enhance the heat and mass transfer performance for cogeneration and one such is the hybrid solar water heating system with evacuated tube heat pipe along with the TEG and cooling jackets to produce combined heat and power (He et al. 2012; Lv et al. 2017; Ong et al. 2017). Typically, a cogeneration system produces electrical energy of 0.19kWh and 300 liters of hot water in a day at 55°C for solar insolation below 1000W/m². The obtained electrical power output is 64.80W and the efficiency of the collector and electrical efficiency of thermoelectric modules is 47.54% and 1.59% respectively (Zhang et al. 2013). In this regard, the thermoelectric generator may be chosen due to advantages such as improved heat transfer characteristics on both sides of the thermoelectric generator due to

the greater heat transfer area. TEGs are also used in the waste heat recovery system such as exhaust from the car for electricity generation and this helps in reducing fuel consumption. Heat pipes and TEGs can thus be employed in automobile applications due to their small size and solid-state nature (Orr et al. 2016). With increasing vehicle speed, which raises the hot junction temperature, the TEG's performance improves due to higher exhaust temperature, flow rate, and heat conduction via the TEG leg from the hot junction.(Yu et al. 2015). The nanostructured thermoelectric materials are used in flat-panel thermoelectric generators for achieving high performance (Kraemer et al. 2011). A comparison of the flat plate and annular thermoelectric generators were conducted, in this, the latter has attained higher heat transfer at standard solar radiation, and they have produced 1.92 W power output with an electrical efficiency of 2.63% (Manikandan and Kaushik 2016). While considering the materials for thermoelectric generators, bismuth telluride alloys are a suitable one and can maintain a maximum figure of merit at a temperature of 500 K (Goldsmid 2014) and can produce an electrical power of 14.1W for hot and cold side temperatures of 250°C and 50°C respectively (Karabetoglu et al. 2012). Low convergence efficiency harms the growth of thermoelectric generators in the power generation sector, thus attention must be paid to the geometric configuration. The leg pin of thermoelectric generators can help enhance system efficiency by lowering thermal conductance (Ali et al. 2014). Likewise, if TEG's substrate area increases, then its output also increases as it increases the thermal concentration ratio and this was analyzed using ANSYS v12.0.1 (Chen et al. 2013). And the TEG performance was enhanced by the optimization of heat sink design using finite element numerical method and observed that the frontal area is increased by decreasing the length and this seems to be the best approach (Wang et al. 2012). To monitor the temperature of the cold and hot sides of the TEGs, temperature sensors can be integrated with IoT for accuracy. Nowadays the role of Information and Communication Technology (ICT) has enhanced a lot with the emergence of IoT in every sector (Rozik et al. 2016). The significant thing with IoT is that it can easily collaborate as a part with any domain or application. The thermoelectric generator's progress using the IoT system which helps in providing the sustainable power supply by the integration of wireless sensor networks (Park et al. 2019). The IoT based technology is used for monitoring and controlling double pipe heat exchanger (Sridharan et al. 2018) and observed that the temperature and mass flow can be measured without manpower by the way of creating channels and by collecting, analyzing, and visualizing data, acting on the data according to the required situation. This type of control system helps in continuous and appropriate operation. Since the voltage obtained from the system is low and therefore it finds difficulty in the applications.

And this can be managed by the usage of a DC-DC converter by boosting the output voltage (Park et al. 2019).

Thus, thermoelectric generators can be utilized as an alternative energy source since they are a green energy technology that can produce electricity from waste heat energy, lowering energy costs, reducing environmental impacts, and reducing the usage of fossil fuels. As a result, this technology has been identified as being vital in the heat recovery process as well as a viable alternative to the traditional method. The integration of IoT TEGs leads to a long-term power supply. The present paper investigates the thermoelectric generator's (TEGs) whose role is to convert the heat energy from the solar evacuated tube heat pipe system to electrical energy using with and without a concentrating collector with the output being monitored by an IoT system and further the electrical output is boosted by the boost converter.

2. Experimental Setup

The system comprises an individual evacuated tube heat pipe collector as shown in Fig 1. It is exposed to sunlight equipped with two thermoelectric modules and cooling fans on the condenser part for the production of electricity. Solar evacuated tube heat pipe is exposed to sunlight tends to absorb heat through copper heat pipe having evaporator, adiabatic section, and condenser part filled with low boiling Ammonia as working fluid for repeated evaporation and condensation. The maximum amount of heat is absorbed in the evaporator followed by the adiabatic section is transferred to the condenser part of the heat pipe which is coupled with the aluminium (Al) bars attached with TEG as shown in Fig 1. The heat is then generated across the heat spreader Al bar to the hot junction and ejected at the cold junction of thermoelectric modules. The cold side of the TE module makes close contact with the Al fins cooling jacket which enables the airflow and gets heated up. Due to the difference of temperature across the surfaces of the thermoelectric module, DC power is produced by the Seebeck effect. In addition, the heat energy received by the air is used for preheating, increasing the system's total effectiveness.

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Fig 1. A cross-sectional view of the Evacuated tube heat pipe

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The parabolic trough collector (PTC) system is covered with a high reflective aluminum sheet to achieve high reflectivity for better concentration. The proposed SEHP-TEG system is placed on top of PTC to receive as much radiation reflected as line focus shown in Fig 2.

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Fig 2. Experimental setup of SETHP-TEG

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The SEHP's condenser is equipped with an aluminium block and two TEG modules with Al heat sinks as shown in Fig 2(b). TEG modules are placed between aluminium heat spreader blocks that spread the heat from the condenser and the heat sink Al fins jacket to produce as much of a temperature gradient as possible for maximum TEG module power generation. The non-hardening thermal adhesive paste is used on the surfaces of the Al heat spreader and heat sink to avoid air gaps for better heat transfer and to maintain thermal conductivity.

Fig 3. Aluminium block and its dimensions

The Al block is 12.5 mm in width, 50 mm in length, and a 25 mm blind diameter hole is bored fit on the heat pipe's condenser section as shown in Fig 3. Two Laird Technologies thermoelectric (TE) modules (Model - TEC-12706) each have a dimension of 40x40x3.3 mm are attached to the two sides of the Al block. The generated voltage and current across each module are measured using a digital multimeter with an uncertainty of $\pm 3\%$. The product of voltage and current is used to calculate the power generated by each TE module. The inclination angle of the SEHP with and without PTC is kept at 13° throughout the experimentation. Solar radiation was recorded using Kipp and Zonen pyranometer with an uncertainty of $\pm 3\%$. A 12 V DC cooling fan is used to evacuate the temperature of the cold side to maximize ΔT of the TEG. After fixing the heat source, heat sink, and Al plate with SEHP, the experiment is conducted in a specified interval for with and without PTC and observations have been tabulated.

A pilot experiment was undertaken for analyzing the performance of the SETHP-TEG system based on the thermodynamic relations. The temperature was measured using thermocouples affixed to various surfaces, which were obtained via the IoT logger. This arrangement has the benefit of providing electrical power output and avoidance of manpower with the help of IoT technology. The temperature was measured using thermocouples affixed to various surfaces, which were obtained via the IoT logger. The TE module's output was connected to an electronic load with variable resistance.

3. Thermodynamic Modelling of SETHP- TEG

The following assumptions were considered for the thermodynamic modeling and SEHP-TEG analysis:

- a. One Dimensional steady-state conductive heat transfer is considered for the analysis.
- b. The thickness (d) of the thermoelectric (TE) module is kept constant.
- c. The losses due to convection and radiation from the sides of the TE module are neglected.
- d. The cold side temperature of the TE module is assumed to be constant.

Heat energy supplied from the condenser part of SEHP is absorbed by the Al bars at the hot junction (Q_h) and can be obtained by doing the energy balance at the hot junction of the TEG as,

$$Q_h = \alpha I T_h - \frac{I^2 R}{2} + K(T_h - T_c) - \frac{\tau I (T_h - T_c)}{2} \times n \quad (1)$$

The heat rejection at the TEG's cold side is utilized to heat the air circulated by the fan, and it's written as:

$$Q_c = \alpha I T_c + \frac{I^2 R}{2} + K(T_h - T_c) + \frac{\tau I (T_h - T_c)}{2} \times n \quad (2)$$

3.2 Power and efficiency analysis

The power output, electrical energy efficiency, electrical exergy efficiency, and the thermal efficiency of the SEHP-TEG system can be written as,

The maximum output power is calculated as

$$P_{max} = V_{max} \times I_{max} \quad (3)$$

The maximum voltage and current expression as

$$V_{max} = V_{oc}/2 \quad (4)$$

$$I_{max} = I_{sc}/2 \quad (5)$$

The open circuit and voltage are calculated as

$$V_{oc} = 2\alpha \times N \times \Delta T \quad (6)$$

$$I_{sc} = (\alpha/\rho) \times (A/L) \times \Delta T \quad (7)$$

The electrical and thermal efficiencies of the TE module can be expressed as

$$\eta_{el} = \frac{P_{max}}{Q_{in}} = \frac{P_{max}}{G \times A_{abs} \times a_{tube-in} \times t_{tube-out}} \times n \quad (8)$$

4. Environmental Analysis

For a low-carbon society, life cycle CO₂ emission assessment has been chosen as a parameter for environmental analysis. And here the main focus is on carbon dioxide emission since it has a greater impact compared to other greenhouse gases. As a result, scenario analysis is formalized for TEGs alone in the context of solar thermal systems. The reason for choosing TEG is that it has the potential of changing waste heat energy into useful electricity in various sectors and there is a need for analyzing its environmental impact as it is an emerging technology for power generation. Since solar thermal system (Concentrating technology) is of renewable energy source which has lower emission compared to other conventional system and many analyses has been carried out in this aspect. Hence coupling this technology with the TEGs is for greater technological feasibility as well as in economical aspect, since it is the mere future.

Table 1. TEGs performance, CO₂ emissions, and cost (Kishita et al. 2014, 2016)

Item	Value	Reference
Conversion efficiency	7.2% 17.72%	The conversion efficiency is 7.2% in 2013; 17.7% by 2030 according to (Kishita et al. 2014).
Maximum electric output	184 W	Estimated by the author considering 2 modules in usage.
TEG Cost	\$6.20	TGE unit price is \$3.10 (Full Battery). And here 2 TEG modules are considered. Likewise, other accompanying costs are not considered.
CO ₂ emissions of producing thermoelectric materials - Bi-Te	14.78 kg of CO ₂ /module	Likewise, the TEG unit has 2 modules. The CO ₂ emission of producing thermoelectric materials Bi-Te is 7.39 kg of CO ₂ / module.
CO ₂ emissions of producing the housing Aluminium part	4 kg of CO ₂ /kg	(Hydro 2018b)
CO ₂ emissions of producing from casing – cast iron	1.51 kg of CO ₂ /kg	(Winnipeg)

The following CO₂ emission per watt, CO₂ mitigation, and carbon credits are described below, and the equations are as follows -Eqn. 9 to 11 (Garud et al. 2021)

(i) CO₂ emission per Watt of power generation:

$$\text{CO}_2 \text{ emission per } W \text{ power generated} = \frac{\text{Mass of the carbon dioxide (g)}}{\text{Power generated from TEG (W)}} \quad (9)$$

CO₂ emission of power generated for each configuration of TGS is presented in g/W.

(ii) Net CO₂ mitigation:

CO₂ emissions will be reduced as a result of TGE waste heat to power conversion. As a result, in this case, net CO₂ mitigation is well-defined as the total power produced (net decrease in CO₂ emissions) by each TGE design throughout its life.

$$\text{Net CO}_2 \text{ mitigation} = E_{\text{out}} \cdot n \cdot \frac{1}{1-L_a} \cdot \frac{1}{1-L_t} \cdot 0.98 \quad (10)$$

Where,

E_{out} = Annual energy output (kWh/year),

L_a and L_t = 0.2 and 0.4, respectively. (Assumption values -domestic appliance loss and transmission appliance loss)

(iii) Carbon credit:

Carbon credit refers to the maximum amount of carbon dioxide or other greenhouse gases that can be released. One credit entitles one tonne of carbon dioxide to be released into the atmosphere. For each configuration of TGS, the net CO₂ mitigation in tones can be changed to carbon credit in USD dollars by considering CO₂ emission is dealt at 24.85 \$/tones of CO₂ emission.

$$\text{Carbon credit} = \text{Net CO}_2 \text{ mitigation} \times \text{cost per tone of CO}_2 \text{ mitigation} \quad (11)$$

5. IoT based temperature monitoring system:

Automatic remote temperature monitoring is enabled by integrating the system with IoT technology to improve the proposed system's effectiveness. The hot and cold side temperatures of the TE module could be remotely measured and monitored using the system setup outlined in Fig 4.

Fig 4. Block diagram of IoT integrated solar evacuated tube TEG

Table 2 Specification of IoT System

The description and specifications of the IoT systems are listed in Table 2.

S. No	Resources Required	Description	Specification
1	Arduino Board (Uno)	It is ATmega328P based microcontroller. It has 14 digital and 3 analog input/output pins. This board is programmable through Arduino IDE software.	8-bit ATmega328P microcontroller, operating voltage 5V (Arduino UNO).
2	Blynk	This software is specially designed for IoT data collection, remote control, data storage, and visualization. Three main components of Blynk- Blynk libraries, Server, App.	Works well with iOS and Android (Blynk).
3	Arduino software (IDE)	It contains space for several components like a text editor, console, serial monitor, and several other menus. It provides an environment to upload code into the hardware and to communicate with it.	Can be installed with Windows, Linux, and Mac OS (Arduino Software (IDE)).
4	Sensor- LM35	Its output voltage is linearly proportional to the Centigrade temperature. It draws only 60 μ A from the supply. It is rated to operate over a -55°C to 150°C temperature range	$\pm 0.5^{\circ}\text{C}$, 4V-30V, Temperature sensor with analog output (Texas Instruments).
5	Wi-Fi Shield- ESP8266	This is a Wi-Fi MCU, have the capability of a 32-bit microcontroller	Power- 3.3 V, 16 GPIO pins (Espressif Systems; Sparkfun ALC) .
6	Jumper Wires	This is to make interconnections between Arduino, breadboard, sensors, and other components	150 mm length

7	Power supply	Constant power is to be supplied for prolonged functioning of Arduino, LM35, and ESP8266	Power is supplied by a USB link connected with PC
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Fig 5. Circuit diagram of the proposed IoT system components

The circuit connections for the IoT-based temperature monitoring system are depicted in Fig 5. The following are the procedures adopted for the implementation of the IoT system with the SEHP-TEG system:

- **Interfacing of sensors with Arduino** - Temperature sensor LM35 is used to remotely monitor the temperature on the sides of the TE module. The sensor's output voltage is proportional to the temperature it measures.
- **Interfacing of Wi-Fi module with Arduino** - The Arduino board was connected with the Internet through ESP8266 Wi-Fi module (other modes such as GSM, Ethernet, Bluetooth, USB (Serial), etc.) with proper AT (ATtention) commands for controlling (Espressif Systems) and to ensure whether the system is working or not (the communication between the device and its application).
- **Programming in Arduino** - Arduino software is an IDE for writing and uploading the programs into Arduino software. In the proposed system, Analog pin A1 is connected to the V_{out} pin of LM35 to collect the output.

- **Channel creation for Linking the Arduino and Blynk** - After the successful creation of the channel in Blynk, the corresponding token will be sent to the registered Blynk mail-id. The Blynk server and Arduino device are connected using this auto-generated token. The correspondence is to be inserted into the program in the Arduino IDE.
- **Monitoring the data in real-time** - Eventually, with the help of Blynk libraries, the collected data has been stored in the Blynk server and it is accessed through the Blynk App.

6. Boost converter for rural applications

As the name implies, a boost converter is one of the most basic forms of the switch-mode converter. Its purpose is to increase the input voltage. An inductor, a semiconductor switch, a diode, and a capacitor with a source for a periodic square wave are the main components of the proposed boost converters. Modern high-frequency switching power supplies are built on the foundation of DC-DC converters. However, maintaining a constant DC output voltage level for diverse DC input voltage levels is critical. In the power converter, a control circuit is employed to calculate the voltage output against the internal reference voltage. (Eydi et al. 2019). When the output deviates from its predetermined value, output control is used to offer smooth acceleration control, high efficiency, and quick dynamic response.

Fig 6. Boost converter block diagram

$$\frac{V_o}{V_{in}} = \frac{1}{1-D} \quad (12)$$

Equation 12 gives the boosted output voltage considering the output voltage as an input.

7. Results and Discussion

From the standpoint of the application, the combined performance of the solar heat pipe and TEGs is significant. The temperature gradient has a significant impact on TEG output performance because of the heat flux distribution from side to side across the hot and cold

connections of the TE module. The temperature distribution rate at the hot side of the TE module hinge on the heat transfer capacity of the solar heat pipe, the connectivity with the Al block and the condenser part. Similarly, temperature distributions on the Al blocks coupled with the hot side of the TE module affect the electrical power generated from the TE module. Meanwhile, due to the low thermal conductivity of the TE modules, the heat transfer performance of TEG affects the heat transfer performance of heat pipes. As a result, investigating the heat transfer coupling performance between heat pipes and TEGs is critical for further promoting and optimizing SEHP-TEG performance.

The effect of the ambient temperature is substantial for the SEHP-TEG system, and the output power fluctuations among the various temperature in the environment became evident with the different temperature gradients. Ambient temperature forced at the cold junction of the TE module can affect the output performance, hence the ambient temperature of 30°C was considered for the theoretical analysis to obtain the electrical power. The hot and cold side temperatures of the TE module were found to be significantly high when the ambient temperature was raised. The output power was observed to be low for the high temperature at the cold side of the TEG. If the connectivity between the Al block and hot side of TEG is kept proper, the losses can be reduced. Furthermore, the TEGs are connected in series on four sides of the Al blocks, the output power produced varies little depending on the ambient temperature is comparatively small.

7.1 Experimental Performance parameters of SETHP-TEG without concentrating collector

Fig 7. Power output of SEHTP-TEG

The electrical power generation capability of the TE module can be calculated based on its open-circuit voltage and current intensity. Thus, the maximum obtained power from the Thermoelectric module is the product of voltage and current. The electrical efficiency is too low when compared to other direct energy conversion systems. As a result, using a succession of SEHP to achieve improved electrical efficiency is recommended. As shown in Fig. 7, the produced power is too small at the beginning and the end of the day because of lower solar radiation, lowering the temperature on the TE module's hot side. The TE module's hot side temperature rises as sun radiation rise until it reaches its maximum value of 0.163W at 13:40 hours. The generated electric power eventually rises as the temperature difference amid the hot and cold sides of the TE module widens.

The maximum electrical energy measured during the experiment was 0.163W, which was recorded at 13:40 on August 24, 2020, while the cold side temperature of the TEG was sustained at 30°C. The experimental results show the power output of the TE module between 9:30 and 16:30 hours varies as the heat pipe is subjected to different solar radiation intensity.

The experimental data is collected using an IoT-connected LM35 temperature sensor mounted on the TE module's hot and cold sides. The changes of the predicted and experimental power output of the TEG at various hot side temperatures are plotted in Fig. 7. The output power of the TEG grows as the temperature gradient increases.

Fig 8. Electrical Energy Efficiency of SETHP-TEG

The experiment represents the electrical energy efficiency of TEG from 9:30 hr to 16:30 hr. The electrical efficiency produced from each thermoelectric module varies as they are subjected to different radiation intensities at different times. The radiation, on the other hand, peaked at 15:30 hr and then gradually fell as the evening progressed. The electrical energy efficiency varies in the afternoon due to the system's lag time response to radiation, as seen in Fig 8.

7.2 Experimental Performance parameters of SETHP-TEG with concentrating collector

Fig 9. Power Output of SETHP-TEG

The experiment represents the power output of TEG from 10.30 hr to 16.30 hr. The power output produced from each thermoelectric module varies as they are subjected to different radiation intensities at different times. The power production fluctuated throughout the afternoon due to the system's lag time response to radiation, as seen in Fig 9. and the output power produced is maximum when compared to the SETHP-TEG system without concentrating collector.

The higher the hot side temperature, the higher the electrical efficiency of TE modules. When PTC is integrated with the SEHP the cold side of the TEG operates at 60°C due to the higher heat dissipation, the electrical efficiency of the TE module peaks at 0.16%, which is a lesser value compared to the theoretical efficiency of 0.68% for static thermoelectric conversion. Due to the thermal resistance of the adhesive substance employed and contact resistance, the temperature gradient across the TEG modules inserted between the Al bars and the cooling fins is smaller than the recorded values at the condenser of the heat pipe and cold

junction of the TEG. Furthermore, measuring the temperature difference between the cold and hot sides of the TE module is difficult to precise values.

The contrasts of theoretical and experimental results with effective real-time data obtained are shown in Figures 9 and 10. The experimental findings and theoretical values are in good agreement. However, the theoretical results with the experimental results of the thermoelectric performance are considerable due to the factors such as contact thermal resistance, thermal resistances of Al blocks, copper condenser and adhesive material, and heat loss resulting from the air supply.

Fig 10. Electrical Energy Efficiency of SETHP-TEG

7.3 Environmental analysis

The study was carried out for sustainable development by analyzing the TEGs performance in environmental aspects such as the CO₂ emission for the power generated, net CO₂ mitigation, and carbon credits for the application of power generation from the solar evacuated tube heat pipe with and without concentrator. TEG converts the most waste heat into electricity, resulting in the maximum CO₂ emission of about 2.34×10^{-3} g/W, net CO₂ reduction of 0.027 tones. The highest quantity of net CO₂ mitigation translates to the highest carbon credit value, which is roughly 0.681 dollars by assuming CO₂ emission at 24.85 \$/tones of CO₂ emission (Garud et al. 2021). Further, when the TEG output is boosted, the power output would be higher which in turn adds to the carbon mitigation and will also increase the carbon credit. Thus, the TEG helps in the reduction of carbon emissions.

7.4 Boost converter

The maximum output obtained from the TEG would be 2.99 V, 0.18 A, and 0.544 W from one side of the AI block were considered for the analysis. The input to the boost converter is 2.99 V and according to equation (11), it is raised to 5.98V as the boosted voltage from the converter. This would be directly used for both mobile charging as well as lighting applications at remote areas and at military camps where the community does not have the proper access to electricity.

Fig 11. Boost converter with 15V output from MATLAB Simulink model

Fig 12. Boost converter with 30 V output from MATLAB Simulink model

If 5 tubes were connected in series, which gives 15 voltage supply with 2.72 watts will be obtained from the thermoelectric generator. This 15V will be input to boost the converter which can be boosted to a 30V supply that can be utilized for higher loads. This part was analyzed using the MATLAB Simulink model to demonstrate and validate the results. Fig. 11 shows the boosted 15V output voltage concerning time and Fig. 12 shows the boosted 30V output from the boost converter. Hence the boost converter model in MATLAB Simulink was analyzed and results were displayed in Fig 11. The MATLAB Simulink model result proves the proposed method's accuracy as plotted in Fig 12.

8. Conclusions

To generate electricity and heat power, a new cogeneration system was tested using a solar evacuated tube system and thermoelectric modules. The performance parameters of the solar evacuated tube thermoelectric generator were studied for varied hot and cold side temperatures using thermodynamic relations. The performance of thermoelectric power generation systems can be improved by using them in hybrid systems. It is recommended to use at least 6 lenses to attain maximum electrical power (approximately 6 W) from one TE module, according to recorded statistics and technical data in the TE module's user guide. The collected results demonstrated that the proposed arrangement can be used in a variety of applications that require thermal and electrical power to diminish fossil fuel usage and CO₂ emissions.

In the experimental investigation, the total electrical efficiency of thermoelectric modules fluctuated according to the radiation pattern. The maximum voltage, output power, and electrical energy efficiency of the thermoelectric generator are 1.02V, 0.152W, and 0.311% respectively for the SETHP-TEG system without concentrating Collector and 2.99V, 0.544W, and 0.16% respectively for SETHP-TEG system with concentrating collector. With an atmospheric air temperature of 300 K, solar radiation between 400 W/m² and 2000 W/m² has been considered. The output power generated from the thermoelectric generator per tube was maximum up to 2.99V according to the fluctuations from solar power and using boost converter it was raised to 5.98V. Power output can be improved by using a thermoelectric module with a higher temperature resistance and a better generator design. The TEG power increases with temperature gradient and it is further improved with using of a power converter. Therefore, the power can be distributed to electrical loads in remote areas where the electrical network does not reach. For further analysis, it is recommended that data obtained from the real-time IoT-

based TE model will be preferred for forecasting the desired results. Also, the environmental analysis was carried out for the TEG module for analyzing the carbon emission per Watt, carbon mitigation, and carbon credit and its results are 2.34×10^{-3} g/W, 0.027 tonnes, and 0.681dollars respectively for a TEG module and if it boosted carbon credits would increases. Thus, the TEG involves in the reduction of carbon emission and this would be more effective when it is coupled with the solar evacuated tube heat pipe since it is a renewable energy system.

The theoretical analysis reported in this study may aid in the design of solar energy power generation. Although the thermoelectric generator's power output and Combined Efficiency are low, with new thermoelectric materials with a higher figure of merit and a boost converter, these types of systems will become more important in the future. Because there is a large market for evacuated glass tube solar collectors in China, and it is simple to manufacture the SHP-TEG system technically based on a solar evacuated tube solar collector system, the SHP-TEG system will be cost-effective in the near forthcoming, especially with the decreasing price of thermoelectric materials.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author's contribution

Sakthivadivel Duraisamy and Sung Chul Kim – These are the corresponding authors who equally contributed in the preparation of the Manuscript. Conceptualization, Methodology, Resources, Formal analysis.

SakthiPriya Manivannan, DivyaLaxmi Gunasekaran, Gowthami Jaganathan, Shanthi Natesan, SabariMuthu Muthusamy, – Data Collection, Writing - original draft preparation, review and editing, Formal analysis.

Balaji Kumar and GaneshKumar Poongavanam - Writing - original draft preparation, review and editing, Supervision and investigation.

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