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Optimization of heat conversion from candle flame into electrical energy using a thermoelectric generator

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Abstract: Indonesia is still heavily reliant on fossil fuels, which has become an obstacle to integrating renewable energy into the national energy supply. This dependency also slows down the achievement of the NDC target to reduce emissions by 26%. Meanwhile, renewable energy continues to grow rapidly worldwide, with consumption increasing by around 3% per year. The purpose of this study is to maximize the conversion of heat energy from candle flames into electrical energy using thermoelectric generators (TEG). TEG works by utilizing the temperature difference between the hot side and the cold side to generate electricity through the Seebeck effect. In this research, four TEG modules were installed on candles and arranged in series to test the effectiveness of two types of cooling systems: a heatsink with a fan and a heatsink with water. Data collection was carried out by measuring the temperature and the performance of the cooling systems in generating electricity, which was evaluated based on the voltage, current, and power produced during the candle-burning process. The results showed that the water-cooled heatsink produced higher voltage and power compared to the fan-cooled heatsink. However, the fan-cooled heatsink was more effective in maintaining a stable temperature difference between the hot and cold sides, making it more suitable for long-term use. This study highlights the significant potential of TEG as an environmentally friendly and cost-effective alternative energy solution, particularly in utilizing everyday waste heat.

Keywords: Waste heat; candle flame; TEG; cooling system

1. INTRODUCTION

Electrical energy in Indonesia continues to experience rapid development, in line with significant economic growth and increasing industrial activity [1][2]. Currently, Indonesia faces at least two main challenges in providing electricity. The first challenge is to balance between optimizing commercial objectives while still supporting development [3]. Despite efforts to address energy poverty, about 25 million people in Indonesia still do not have access to electricity, which shows that energy justice has not been fully achieved [4]. The second challenge is Indonesia's dependence on fossil fuels, which hinders the integration of renewable energy into the energy supply, thus hindering the achievement of the NDC target to reduce emissions by 26% [5]. Meanwhile, renewable energy is now the fastest-growing energy source in the world, with consumption increasing by around 3% per year [6].

To address this problem, scientists are focusing on the development of alternative energy sources, such as thermoelectric generators (TEGs) capable of converting direct heat energy into electricity through the Seebeck effect [7][8][9][10]. The working principle of TEG is to generate electricity from the temperature difference on the two sides of the device [11][12][13][14]. One of the main advantages of TEG is the absence of pollution, parts that need to be replaced, low maintenance costs, as well as long service life [15]. TEG has been used in a variety of applications, but the use of heat from a candle flame to generate electricity is still rare, although it is potentially environmentally friendly and cost-effective [16][17]. The electrical power generated by the TEG depends on the amount of heat absorbed and the temperature difference on both sides of the device [18]. To maintain an optimal temperature difference, an effective cooling method is required, as the heat on one side of the TEG can affect the temperature on the other. Two main cooling methods can be used in TEG technology, namely: forced air cooling system, and water cooling system [19][20].

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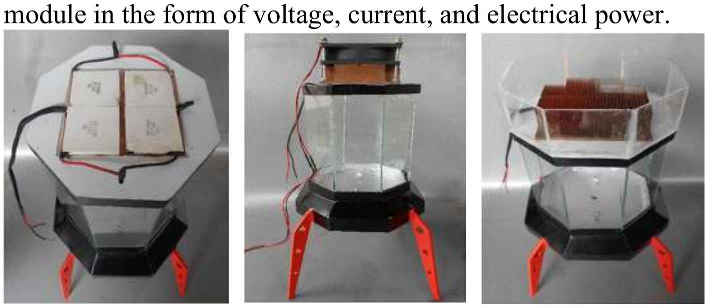
This study aims to evaluate the performance of TEG that utilizes heat from candle flames and determine the most effective cooling system for maintaining the stability of TEG output, specifically voltage, current, and power [21]. In addition, this research also designs a device in the form of a candle tube that can be used as an alternative energy source for daily needs, such as lighting lights. Previously, there was no research on the use of waste heat from candle flames with thermoelectric generator type SP 1848 27145 SA that was commercially available in Indonesia.

2. METHOD

This study applies a conversion system that utilizes wax as a heat source for the TEG module, with a candle tube design as shown in Figure 1. The design was carried out by making a candle tube followed by the installation of a plate made of copper right above the surrounding fire source, namely one candle as a conductor of waste heat that can be converted into electrical energy using a TEG module. The installation of four TEGs are assembled in series and placed on the outside of the copper plate. In this study, the TEG module used type SP 1848 27145 SA. Table 1 shows the specifications and dimensions of the TEG module type SP 1848 27145 SA. On TEG surfaces that are cold to the environment two methods are used: heatsink with fan, heatsink with water. The method of the heatsink cooling system with a fan, a DC fan with a voltage of 12 Volt with 0.18 Ampere is used to dissipate heat from the TEG, while in the heatsink cooling system with water, a volume of 600 ml water is used. The process of collecting data for this research was carried out at the working temperature of the output of the TEG module in the form of voltage, current, and electrical power.



(A) (B)

Figure 1. A) Installation of TEG, and B) Installation of cooling system on candle tubes

The thermoelectric generator module made of bismuth telluride (Bi_2Te_3) type SP 1848 27145 SA was used as the research subject shown in Figure 2. This TEG has an operating temperature of 150°C and a maximum temperature of up to 300°C, however for continuous use, the recommended maximum temperature is 135°C. The TEG module has been modified to generate DC power while retaining the cable, where the increased temperature difference between the two sides of the module will result in greater DC power, as well as improve the efficiency of thermoelectric conversion. The full specifications of thermoelectric type SP 1848 27145 SA can be shown in Table 1.

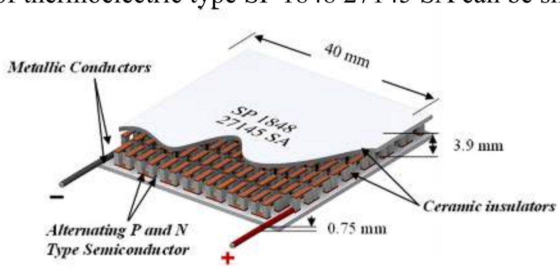


Figure 2. Thermoelectric generator [22].

Table 1. Specification of TEG SP 1848 27145 SA module [23][24][25].

No.	Parameters	Specifications
1.	Dimension:	
	a. Long	40 mm
	b. Wide	40 mm
	c. Thick	3.9 mm

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No.	Parameters	Specifications
	d. Heavy	25 grams
2.	Composition Material:	
	a. TEG hot side and cold side material	Ceramic
	b. Positive conductor (p-leg)	Bi2Te3
	c. Negative semi-conductor (n-leg)	Bi2Te3
3.	Physical parameters:	
	a. Seebeck coefficient	0.054 V/K
	b. Electric conductivity	0.6 W/m.K
	c. Number of semiconductor materials	220
	d. Operating temperature	150°C
	e. Maximum operating temperature	300°C
4.	Manufacturing by	SRT (Shenzen Ruised Technology Co., Ltd)

The research scheme for data collection is shown in Figure 4. The data collection process is carried out in stages. In the first stage, the data was taken using a candle flame with a heatsink cooling method equipped with a fan. In the second stage, the data was obtained by cooling the heatsink with water.

Data collection begins when the candle is lit, with a copper plate used to transfer and flatten the heat from the energy source to the hot side of the TEG. The cold side of TEG uses a heatsink to absorb heat, which is then released into the surrounding air, with the addition of a cooling system in the form of a fan and water. At each measurement point, a type K thermocouple cable is used to measure TEG hot surface temperature, TEG cold surface temperature, ambient temperature, heatsink temperature, and water temperature. Temperature measurement is carried out with a data acquisition tool in the form of an Arduino MEGA2560 microcontroller connected to the Max6675 sensor so that the temperature data (°C) is immediately read digitally. The results of signal processing by the Arduino MEGA2560 are displayed in real time on the laptop. The block diagram of the measurement system can be seen in Figure 3.

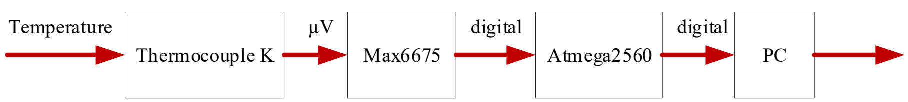
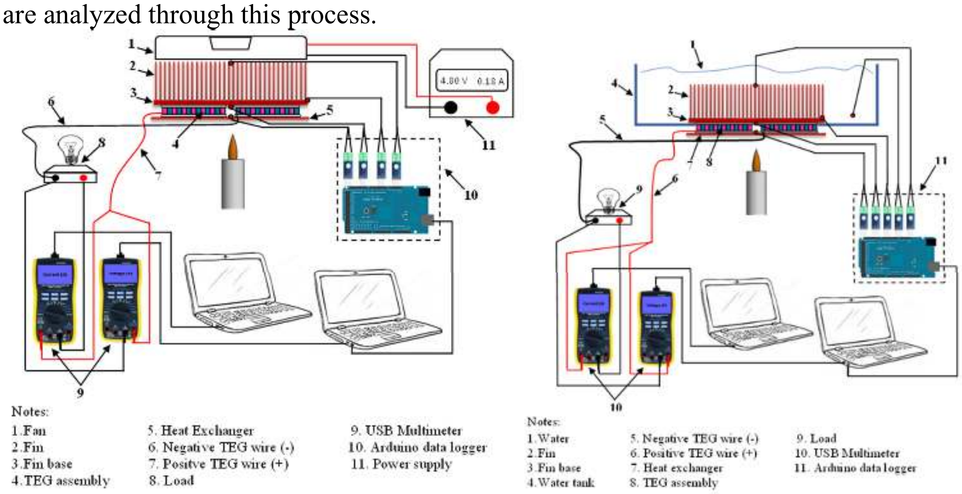


Figure 3. Temperature measurement system block diagram

Subsequently, the data is collected by applying the same load to each predetermined cooling method, using LED lights. This load aims to measure the output of the TEG, including voltage, current, and power generated, using *a* USB multimeter and also connected to a laptop. The results of the TEG are analyzed through this process.



(A) (B)

Figure 4. Research scheme of TEG cooling system. A) heatsink with fan, B) heatsink with water

3. RESULTS AND DISCUSSION

TEG hot side and cold side temperature profiles

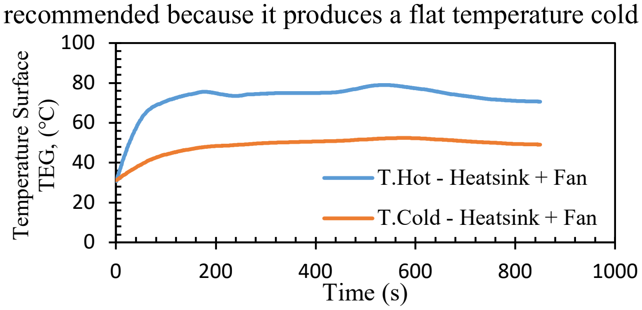
Temperature measurements on the hot and cold sides of the TEG are taken during candle lighting. This measurement aims to evaluate the impact of changes in the cooling system on the heat absorbed and the performance of TEG electrical output.

Figure 5. shows the results of the temperature measurements of the hot side and the cold side during the ignition time of one candle with two types of cooling systems tested: a heatsink with a fan and a heatsink with water. The results show that the temperature profile of the hot side and the cold side of TEG with two types of coolers shows the same tendency where at the beginning of the candle ignition, the temperature will rise rapidly until a certain time and then the temperature tends to be stable both on the hot side temperature and the cold side temperature.

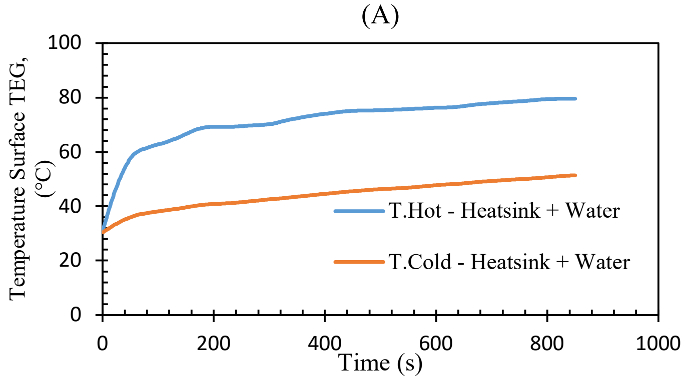
The second period of change, the temperature is called the initial phase of warming and the stable phase. Temperature changes in the stable phase for cooling system variations show a different pattern where the heatsink cooling system with a temperature fan will tend to slope, while in the heatsink cooling system with water, the temperature increases slowly. The difference can be seen in Table 2.

The cold side temperature profile of a flat fan heatsink cooling system indicates that the airflow from the fan can cool or absorb the heat in the heatsink stably. Meanwhile, the temperature profile of the heatsink cooling system with water indicates that the water temperature is not able to absorb heat from the increase in the heatsink temperature.

Data for the heating rate in the initial heating phase and the stable phase, the average temperature of the hot side and the cold side of TEG, and the difference between the average temperature in the stable phase can be seen in Table 2. It can be seen that the TEG cooling system using a heatsink with water is 29°C will produce a higher temperature difference between the hot and cold sides of TEG than using a TEG heatsink cooling system with a fan which is 27°C. A higher TEG temperature difference in the heatsink cooling system with a fan will result in higher electrical output. This is because the heatsink cooling system with water can produce higher electrical output than the heatsink cooling system with a fan. But by looking at the temperature curve of the cold side of the heatsink cooling system with rising water, it can reduce the TEG temperature difference for longer candle lighting so that it will reduce the output of the voltage difference produced. Thus, a heatsink cooling system with a fan is recommended because it produces a flat temperature cold side profile.



(A)



(B)

Figure 5. TEG hot side and cold side temperature profiles with cooling system; A) heatsink with fan, B) heatsink with water.

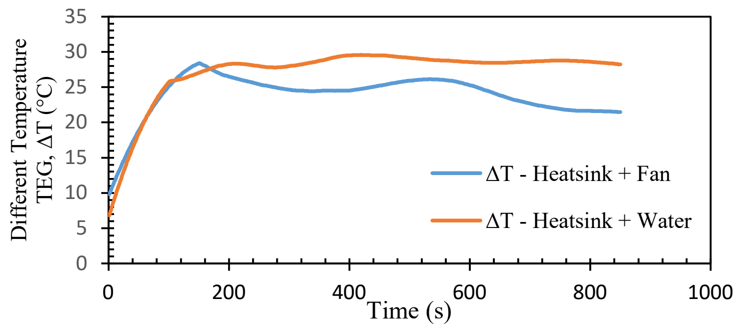


Figure 6. Temperature difference profile on hot and cold surface TEG modules.

Table 2. Heat energy flow rate, average hot and cold surface temperature, TEG surface temperature difference.

TEG cooling system	Heating rate of the beginning of heating (C/s)	Stable phase heating rate (C/s)	Average temperature of the hot side (°C)	Average temperature of the cold side (°C)	Average temperature difference ΔT (°C)
Heatsink + fan	2.7	7.6	79	52	27
Heatsink + water	2.8	0.61	75	46	29

TEG module performance

Voltage measurement: Voltage measurements are needed to determine the potential difference produced by the temperature difference between the hot and cold sides of the TEG system. Figure *7*. shows the results of voltage measurements during the ignition time of one candle, each with two types of cooling systems, namely a heatsink with a fan and a heatsink with water.

The results of the study show that the voltage profile on the ignition of one candle with two types of cooling systems shows the same tendency where the beginning of the ignition of the candle the voltage will rise rapidly until a certain time, then the voltage shows a stable tendency until the candle goes out. For different cooling system methods, the change in the steady and horizontal phases reveals a different curve pattern for candle ignition with a heatsink cooling system with higher water voltage generated by the TEG output.

The difference in data can be seen in Table *3*. This is possible because the voltage profile generated by the TEG output is directly related to the TEG temperature difference in Figure 6. previously. Where is Figure *6*. The highest temperature difference between the candle lighting and the water heatsink cooling system. This is appropriate if the higher the heat absorbed by the hot side of the TEG and conversely the lower the temperature of the cold side of the TEG, the difference in TEG temperature will be larger so that the output of the TEG will also be larger.

The data for the average voltage in the stable phase in Table *3* can be seen that the ignition of the candle with the heatsink cooling system with water produces a voltage of 2.74 Volt and the heatsink cooling system with a fan of 2.82 Volt. The average output data of the thermoelectric generator in the form of voltage can be seen in Table 3.

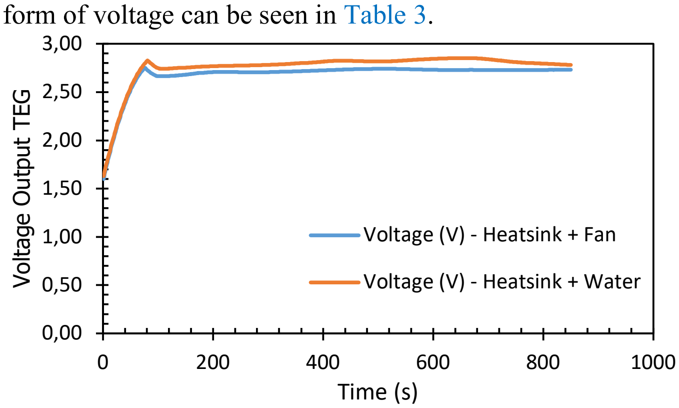


Figure 7. The electrical voltage generated by TEG

Current measurement.

Current measurements are carried out to determine the flow of electricity in a closed-circuit system when two LED lights are installed. Figure 8. It shows the results of current measurements during the ignition time of one candle using the method of two different types of cooling systems, namely heatsink with fan and heatsink with water.

The results showed that the current profile fluctuated during candle ignition, with the current increasing slowly, steadily, then decreasing, and again increasing. The rise and fall of the current in the ignition of the candle with different cooling methods is influenced by the resistant load of the lamp while the highest current is reached when using the heatsink cooling system with water. This is by the voltage profile where at the ignition of this candle the voltage is higher with the heatsink cooling system with water. The data for the average current in the stable phase is in Table 3. It can be seen that lighting one candle using a heatsink cooling system with water produces a current of 0.11 A.

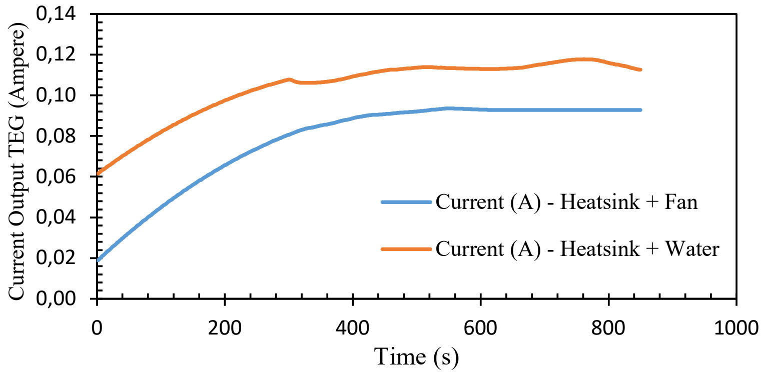


Figure 8. The electrical current generated by TEG.

Power measurement.

Power calculations are used to determine the electrical output of the TEG system Figure 9. It shows the results of power measurement during the ignition time of one candle using different cooling system methods, namely a heatsink cooling system with a fan and a heatsink with water. The results show that the power produced also fluctuates, with the highest power being generated when using a heatsink cooling system with water. This is by the voltage and current profile where at the ignition of one higher voltage candle with a heatsink cooling system with water. The average data of stable phase power is in Table 3. It is known that lighting one candle with *a* heatsink cooling system with water produces a power of 0.32 Watts. The average data of TEG output in the form of power can be seen in Table 3.

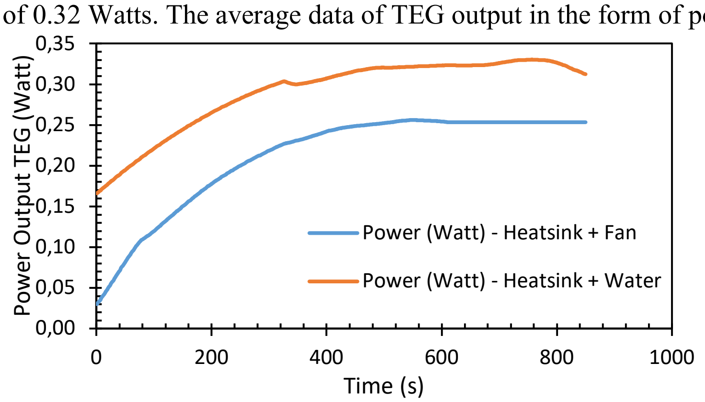


Figure 9. Electrical power generated by TEG.

Table 3. TEG output in the form of voltage, current, and power.

TEG cooling system	Average voltage (V)	Average current (A)	Average power (W)
Heatsink + fan	2.74	0.09	0.25
Heatsink + water	2.82	0.11	0.32

4. CONCLUSION

This research proves that a thermoelectric generator (TEG) can be used effectively to convert heat from candle flames into electrical energy. The two cooling systems tested, the fanned heatsink system proved to be more stable in maintaining the temperature difference between the hot and cold sides of the TEG, although the heatsink with water was able to produce higher voltages. However, the less stable temperature profile of the heatsink with water indicates that the system is less efficient for long-term applications. Therefore, heatsinks with fans are more recommended for optimizing TEG performance in generating electricity from low-heat sources such as candle flames. This research shows the potential of TEG as an environmentally friendly and cost-effective alternative energy solution, especially in utilizing daily waste heat sources.

REFERENCE

[1] M. A. McNeil, N. Karali, and V. Letschert, "Forecasting Indonesia's electricity load through 2030 and peak demand reductions from appliance and lighting efficiency," *Energy for Sustainable Development*, vol. 49, pp. 65–77, Apr. 2019, doi: 10.1016/j.esd.2019.01.001.

[2] Erdiansyah, "Solar energy utilization in desalination power plan," *Journal of Applied Mechanical Engineering (JTTM)*, vol. 4, no. Vol 4 No 1 (2023): JTTM: Journal of Applied Mechanical Engineering, pp. 119–126, Apr. 2023.

[3] M. Siyaranamual, M. Amalia, A. Yusuf, and A. Alisjahbana, "Consumers' willingness to pay for electricity service attributes: A discrete choice experiment in urban Indonesia," *Energy Reports*, vol. 6, pp. 562–571, Nov. 2020, doi: 10.1016/j.egyr.2020.02.018.

[4] A. B. Setyowati, "Mitigating inequality with emissions? Exploring energy justice and financing transitions to low carbon energy in Indonesia," *Energy Res Soc Sci*, vol. 71, Jan. 2021, doi: 10.1016/j.erss.2020.101817.

[5] M. Silaen *et al.*, "Lessons from Bali for small-scale biogas development in Indonesia," *Environ Innov Soc Transit*, vol. 35, pp. 445–459, Jun. 2020, doi: 10.1016/j.eist.2019.09.003.

[6] A. Afful-Dadzie, A. Mallett, and E. Afful-Dadzie, "The challenge of energy transition in the Global South: The case of electricity generation planning in Ghana," *Renewable and Sustainable Energy Reviews*, vol. 126, Jul. 2020, doi: 10.1016/j.rser.2020.109830.

[7] N. Jaziri, A. Boughamoura, J. Müller, B. Mezghani, F. Tounsi, and M. Ismail, "A comprehensive review of Thermoelectric Generators: Technologies and common applications," Dec. 01, 2020, *Elsevier Ltd*. doi: 10.1016/j.egyr.2019.12.011.

[8] S. LeBlanc, "Thermoelectric generators: Linking material properties and systems engineering for waste heat recovery applications," *Sustainable Materials and Technologies*, vol. 1, pp. 26–35, Dec. 2014, doi: 10.1016/j.susmat.2014.11.002.

[9] D. Champier, "Thermoelectric generators: A review of applications," 2017, *Elsevier Ltd*. doi: 10.1016/j.enconman.2017.02.070.

[10] Triwahyudin Rohman, "Arduino performance in control systems for converting air-to-water," *Journal of Applied Mechanical Engineering (JTTM*, vol. 5, no. Vol 5 No 2 (2024): JTTM: Journal of Applied Mechanical Engineering, pp. 244–252, Oct. 2024.

[11] M. Hamid Elsheikh *et al.*, "A review on thermoelectric renewable energy: Principle parameters that affect their performance," 2014. doi: 10.1016/j.rser.2013.10.027.

[12] R. Mal, R. Prasad, V. K. Vijay, and A. R. Verma, "The design, development and performance evaluation of thermoelectric generator (TEG) integrated forced draft biomass cookstove," in *Procedia Computer Science*, Elsevier B.V., 2015, pp. 723–729. doi: 10.1016/j.procs.2015.05.085.

[13] M. E. Demir and I. Dincer, "Development of an integrated hybrid solar thermal power system with thermoelectric generator for desalination and power production," *Desalination*, vol. 404, pp. 59–71, Feb. 2017, doi: 10.1016/j.desal.2016.10.016.

[14] J. Sladek, V. Sladek, M. Repka, and E. Pan, "A novel gradient theory for thermoelectric material structures," *Int J Solids Struct*, vol. 206, pp. 292–303, Dec. 2020, doi: 10.1016/j.ijsolstr.2020.09.023.

[15] D. Luo, R. Wang, W. Yu, and W. Zhou, "A novel optimization method for thermoelectric module used in waste heat recovery," *Energy Convers Manag*, vol. 209, Apr. 2020, doi: 10.1016/j.enconman.2020.112645.

[16] S. Mahmoudinezhad, P. A. Cotfas, D. T. Cotfas, A. Rezania, and L. A. Rosendah, "Performance evaluation of a high-temperature thermoelectric generator under different solar concentrations," in *Energy Procedia*, Elsevier Ltd, 2018, pp. 624–630. doi: 10.1016/j.egypro.2018.07.080.

[17] A. Arkundato, G. Jatisukamto, W. Maulina, and K. Ardian Syah, "Thermoelectric Generator Module as An Alternative Source of Electrical Energy in Rural Areas", doi: 10.15294/rekayasa.v8i1.23691.

[18] J. Siviter, A. Montecucco, and A. Knox, "Experimental Application of Thermoelectric Devices to the Rankine Cycle," in *Energy Procedia*, Elsevier Ltd, 2015, pp. 627–632. doi: 10.1016/j.egypro.2015.07.472.

[19] H. B. Gao, G. H. Huang, H. J. Li, Z. G. Qu, and Y. J. Zhang, "Development of stove-powered thermoelectric generators: A review," Mar. 05, 2016, *Elsevier Ltd*. doi: 10.1016/j.applthermaleng.2015.11.032.

[20] A. Elghool, F. Basrawi, T. K. Ibrahim, K. Habib, H. Ibrahim, and D. M. N. D. Idris, "A review on heat sink for thermo-electric power generation: Classifications and parameters affecting performance," 2017, *Elsevier Ltd*. doi: 10.1016/j.enconman.2016.12.046.

[21] Tianur, "Design of a 20 wp solar panel DC power monitoring system based on the internet of things," *Journal of Applied Mechanical Engineering (JTTM)*, vol. 4, no. Vol 4 No 2 (2023): JTTM: Journal of Applied Mechanical Engineering, pp. 231–243, Oct. 2023.

[22] R. Merienne, J. Lynn, E. McSweeney, and S. M. O'Shaughnessy, "Thermal cycling of thermoelectric generators: The effect of heating rate," *Appl Energy*, vol. 237, pp. 671–681, Mar. 2019, doi: 10.1016/j.apenergy.2019.01.041.

[23] N. T. Atmoko, T. W. B. Riyadi, Haikal, Amarulloh, and H. L. Wijayanto, "The Experimental Investigation of Heating Rate Variant Method to Produce Power Output Generated by Thermoelectric Generator SP1848-SA," in *Journal of Physics: Conference Series*, Institute of Physics, 2022. doi: 10.1088/1742-6596/2406/1/012008.

[24] N. T. Atmoko, A. Jamaldi, and T. W. B. Riyadi, "An Experimental Study of the TEG Performance using Cooling Systems of Waterblock and Heatsink-Fan," *Automotive Experiences*, vol. 5, no. 3, pp. 361–367, Apr. 2022, doi: 10.31603/ae.6250.

[25] N. T. Atmoko, I. Veza, and T. W. B. Riyadi, "Study on the energy conversion in the thermoelectric liquefied petroleum gas cooking stove with different cooling methods," *International Journal of Engineering Trends and Technology*, vol. 69, no. 1, pp. 185–193, Jan. 2021, doi: 10.14445/22315381/IJETT-V69I1P228.