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ORIGINAL RESEARCH

The question of thermoelectric devices (TEDs) in/efficiency—A practical research considering thermoelectric generators (TEGs)

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Abstract
Thermoelectricity is a versatile clean energy technology; however, its in/efficiency has been a question of debate. Thus, this practical study focuses on thermoelectric devices' (TEDs') performance when operated as thermoelectric generators (TEGs). Sixteen identical TEDs (TEC-12706 of the same made and model) were operated as TEGs under the same experimental setup and test modalities with a hotside temperature between ∼20°C and ∼100°C and a coldside temperature of ∼20°C, to practically and comparatively examine the TEGs voltage production and energy conversion in/efficiency. The findings revealed that, while it's already common knowledge that a TEG output voltage is proportional to its temperature difference as evident in all the TEGs used in the study; however, as the TEGs temperature difference proportionally increases, some of the TEGs relatively produced less, the same and more output voltages at certain temperature differences compared to others. For example, TEG1 and TEG3 produced almost the same output voltages throughout; however, at ∼100°C hotside temperature, TEG3 produced 3.16 V, whereas TEG1 produced 2.90 V. While such widespread TEGs discrepancies can be mostly attributed to bad manufacturing/poor workmanship, they are usually misconstrued by some as a generic inherent thermoelectricity technology limitations which this study highlights.

1 | INTRODUCTION

Energy insecurity and the transition to renewable/alternative energy sources as the solution of choice are gaining traction [1]. Thermoelectricity or thermoelectric devices (TEDs) are an interesting technological option, as it is clean and versatile and can convert direct current (DC) electricity to cold/heat when operated as thermoelectric coolers/heaters (TECs/TEHs) [2] and can also convert heat to DC electricity when operated as thermoelectric generators (TEGs) [1]. TEGs can be a useful alternative energy source that can be applied to harvest low-grade waste heat into electricity. However, TEG energy conversion in/efficiency has been a subject of concern over the years and several studies have been conducted to provide various highlights and insights. In [3], TEGs were used in hot springs to convert heat to DC electricity and the parameters that determine the efficiency of energy conversion were studied. A TEG model with three possible sources of irreversibilities—that is, the resistance responsible for Joule heating, the heat exchangers thermal conductance and the internal thermal conductance for heat leakage were considered in [4]. Pressure/force and contact resistance affect TEG voltage production [5]. Experiments were conducted with (i) no intermediate substance, (ii) a thermal paste and (iii) thermal pad and were further subjected to different magnitude of forces to study a TEG contact resistance effect on voltage production and efficiency. Their findings disclosed that the worst performance is obtained with no intermediate substance and the best performance is if the intermediate substance is thermal paste. TEG output voltage and efficiency can be increased with solar heat concentrators (magnifying lenses) by focusing heat on the TEG hot side [6]. TEGs material chemistry is central in TEG-generated voltage and efficiency. Using materials that operate at room temperature and with higher electrical conductivity and lower thermal conductivity will enhance TEG's performance [7, 8]. Heat exchangers and especially their shapes are crucial to improve TEGs' performance [9]—a cylindrical shape pipe performs better than square and triangular shape pipes. Many power generation applications often give priority to power output over efficiency [10]. This is however often the case when the

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energy source is abundant. According to [10], the thermoelectric compatibility factor, which is the reduced electric current necessary to attain the highest efficiency determined by the thermoelectric material figure of merit (z), affects the performance of all thermoelectric modules. TEGs find themselves in diverse applications, one of which advanced in [11] is the use of TEG to convert human heat to power a wristwatch (with a conversion efficiency of 5–5.7%) without the need for external charging. Also proffered in [12] is the use of stretchable TEG (STEG), which when attached to an elbow, had a maximum power density of 51.42 and 20 μW/cm^2 under steady-state at an ambient temperature of 17°C. The influence of heat flux—which first increases and then later decreases the output power and efficiency of a commercial Bi_2Te_3-based thermoelectric module was also examined in [13, 14].

From the literature review, TEGs are often reported for being inefficient in energy conversion and this inefficiency or generally poor performance is due to various factors which were researched/reported variously and possible solutions proposed. However, what this study seeks to uniquely investigate and advance is the voltage output and in/efficiency between TEGs (of the same made and model) when subjected to the same test conditions under the same experimental setup. In other words, the question this research undertakes to address/answer is, what are the chances that the gross TEGs inefficiency/poor performance that has been reported is at times from limited practical data and/or which is obtained from defective TEGs and/or from a small sample size, as well as from substandard practical implementations and/or poor workmanship?

The manuscript is structured as follows: TEGs literature is discussed in brief in the introduction, proceeded by the research methodology. Thereafter the research findings are succinctly presented, as well as analysed and lastly closing comments are drawn.

2 | METHODOLOGY

The approach employed to conduct the study is summarily articulated herein. The research setup made used of sixteen TEDs as assembled in [2]; however, it was modified slightly and operated as TEGs with the following dichotomy. The assembly bottom section (hot side) was submerged in hot water (controlled between 20 and 100°C) and monitored with two MAX6675 temperature sensors. The assembly top section (cold side) was cooled with tap water (around 20°C) and each TEG cold side was monitored with a DS18B20 temperature sensor. The TEG cold side water temperature was maintained around 20°C, by repeatedly pumping warm water out and cold water in every 10 s. The temperature sensors were connected to an ESP32 microcontroller. Each of the TEG outputs was connected to an ADC pin of the ESP32 microcontroller. The microcontroller was programmed using the Arduino IDE to iteratively read the TEGs' hot and cold sides temperatures, measure each of the TEGs' output voltage and control the temperatures on the TEGs' hot and cold sides every 10 s. The TEGs' hot and cold sides temperature measurements were calibrated with a

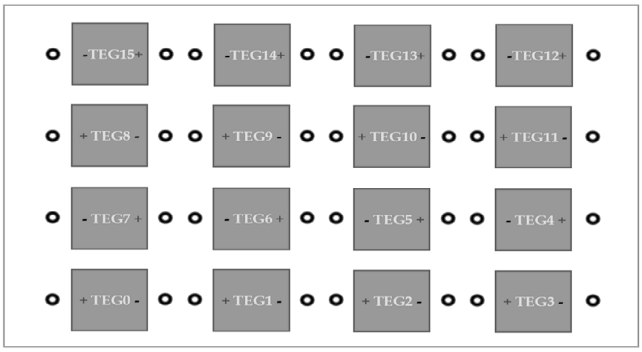

FIGURE 1 TEGs assembly layout.

Toptronic T235H multimeter to be accurate within +/−2°C and the TEGs output voltage measurements were calibrated with a Techgear TG411DP multimeter to be accurate within +/−0.075 V. The experiments were conducted for about 50 min—from when the TEGs hot side temperature was ∼20°C till when it reached ∼100°C. During this period, the TEGs' hot and cold side temperatures and the generated voltages were measured and logged to a text file every 10 s (see Data Availability Statement). The lab ambient temperature was measured using a Fluke Ti20 thermal imager. Figure 1 illustrates the TEGs assembly layout and Figure 2 depicts the test setup.

3 | RESULTS AND ANALYSIS

This section presents and discusses the research findings. The experiment measurements were logged every 10 s and took ∼50 min—from when the TEGs hot side temperature was ∼20°C till when it reached ∼100°C. The entire measurements logged are found in the Google Drive link provided in the Data Availability Statement/Supporting Information Sections. Due to the large amount of data collected, the entire measurements logged could not be presented here and are abridged. As a result, only the measurements logged at the TEGs hot side mean temperatures of ∼20°C, ∼40°C, ∼60°C, ∼80°C and ∼100°C are presented. The measurements presented are for TEG0 to TEG15. The parameters measured, computed and presented are as follows: (i) the TEGs hot side heat sink (HS) water temperatures using two MAX6675 temperature sensors; (ii) the calculated hot side HS water temperatures average value; (iii) the TEGs cold side HS water temperature using sixteen DS18B20 temperature sensors (one per TEG); (iv) the calculated temperature difference (TD); and (v) the voltages generated. The following insightful parameters were also computed: (i) TEG0-TEG15 output voltages mean value at the TEGs hot side HS water mean temperatures of ∼20°C, ∼40°C, ∼60°C, ∼80°C and ∼100°C; (ii) TEG0-TEG15 cold side temperatures mean value at the TEGs hot side HS water mean temperatures of ∼20°C, ∼40°C, ∼60°C, ∼80°C and ∼100°C; (iii) TEG0-TEG15 TD mean value at the TEGs hot side HS mean temperatures of ∼20°C, ∼40°C, ∼60°C, ∼80°C and ∼100°C; (iv) TEG0-TEG15 output voltage rank and the output voltage mean rank

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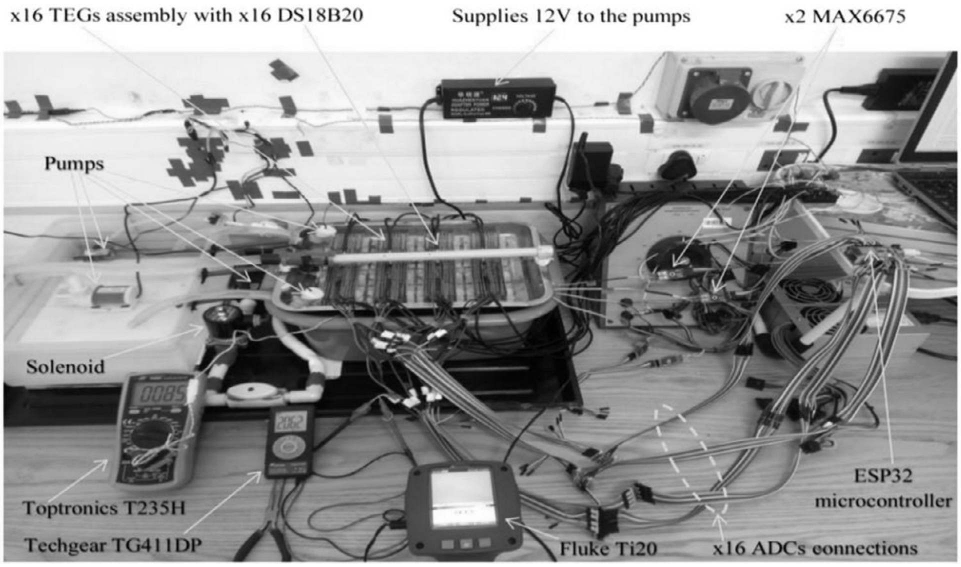

FIGURE 2 TEGs test setup.

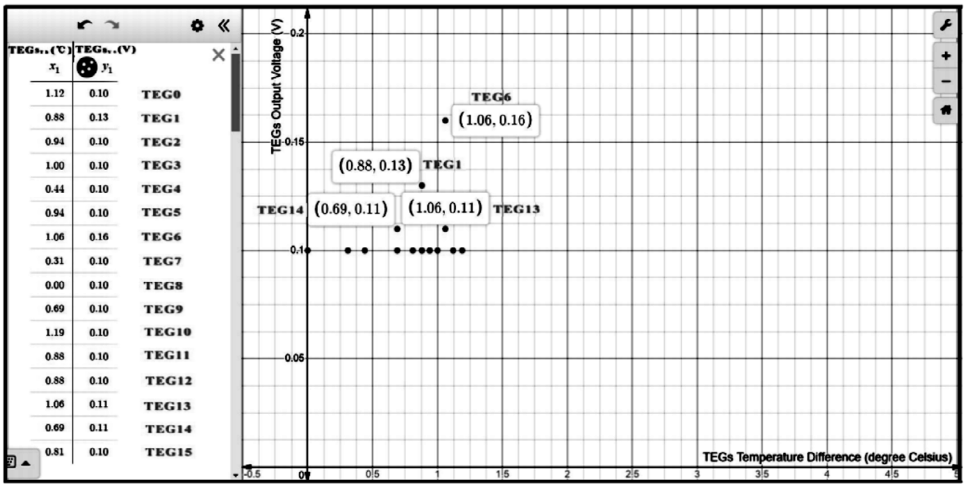

FIGURE 3 TEG0–TEG15 V_{out} (V) versus TD (°C) at TEGs ∼20°C (mean) hot side HS water temperature.

at the TEGs hot side HS mean temperatures of ∼20°C, ∼40°C, ∼60°C, ∼80°C and ∼100°C, (v) TEG0-TEG15 TD rank as well as the TD mean rank at the TEGs hot side HS mean temperatures of ∼20°C, ∼40°C, ∼60°C, ∼80°C and ∼100°C and (vi) TEG0-TEG15 Carnot efficiency at the TEGs hot side HS mean temperatures of ∼20°C, ∼40°C, ∼60°C, ∼80°C and ∼100°C. Since the TEGs used had no parameters datasheet for use to compute their conversion efficiency, the Carnot efficiency was used to infer the maximum ideal efficiency limit. The results crux is summarised in the tables and figures that follow.

Presented in Table 1 and Figure 3 are summary of the results when TEG0 to TEG15 were subjected to a hot side mean temperature of 20.87°C and to a cold side mean temperature of 20.07°C. A mean TD of 0.806°C was attained with a mean Carnot efficiency of 0.274%, which produced a mean voltage of 0.107 V. There was no significant output voltage difference between the TEGs, with TEG6 producing the most output voltage of 0.16 V with a TD of 1.06°C and Carnot efficiency of 0.361%; followed by TEG1 output voltage of 0.13 V with a TD of 0.88°C and Carnot efficiency of 0.299%.

Depicted in Table 2 and Figure 4 are summary of the results when TEG0 to TEG15 were subjected to a hot side mean temperature of 40.50°C and to a cold side mean temperature of 20.866°C. A mean TD of 19.632°C was attained with a mean Carnot efficiency of 6.259%, which produced a mean voltage of 0.706 V. TEG5 had a TD of 20.19°C and produced the highest output voltage of 0.85 V with a Carnot efficiency of 6.437%. TEG15 had a TD of 19.56°C and produced the lowest voltage of 0.53 V with a Carnot efficiency of 6.236%.

Presented in Table 3 and Figure 5 are summary of the results when TEG0 to TEG15 were subjected to a hot side mean temperature of 60.88°C and to a cold side mean temperature of 19.955°C. A mean TD of 40.919°C was attained with a mean Carnot efficiency of 12.250%, which produced a mean voltage

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TABLE 1 Measurements of TEG0–TEG15 at ∼20°C (mean) hot side HS water temperature.

Measurements of TEG0–TEG15 at ∼20°C (mean) Hot-side heatsink water temperature

TEG0 to TEG15	TEGs hotside HS-water temperatures with MAX6675_A (°C)	TEGs hotside HS-water temperatures with MAX6675_B (°C)	TEGs hotside HS-water temperatures mean (°C/K)	TEGs coldside HS-water temperature using DS18B20 (°C)	Temperature difference (TD) (°C/K)	TEGs Carnot efficiency [TD/$T_{\text{hotside mean}}$]	Voltages generated (V)
TEG0	19.25	22.5	20.87/294.02	T0 = 19.75	1.12	0.381%	0.10
TEG1	19.25	22.5	20.87/294.02	T1 = 20.00	0.88	0.299%	0.13
TEG2	19.25	22.5	20.87/294.02	T2 = 19.94	0.94	0.319%	0.10
TEG3	19.25	22.5	20.87/294.02	T3 = 19.87	1.00	0.340%	0.10
TEG4	19.25	22.5	20.87/294.02	T4 = 20.44	0.44	0.149%	0.10
TEG5	19.25	22.5	20.87/294.02	T5 = 19.94	0.94	0.319%	0.10
TEG6	19.25	22.5	20.87/294.02	T6 = 19.81	1.06	0.361%	0.16
TEG7	19.25	22.5	20.87/294.02	T7 = 20.56	0.31	0.105%	0.10
TEG8	19.25	22.5	20.87/294.02	T8 = 20.87	0.00	0.000%	0.10
TEG9	19.25	22.5	20.87/294.02	T9 = 20.19	0.69	0.235%	0.10
TEG10	19.25	22.5	20.87/294.02	T10 = 19.69	1.19	0.405%	0.10
TEG11	19.25	22.5	20.87/294.02	T11 = 20.00	0.88	0.299%	0.10
TEG12	19.25	22.5	20.87/294.02	T12 = 20.00	0.88	0.299%	0.10
TEG13	19.25	22.5	20.87/294.02	T13 = 19.81	1.06	0.361%	0.11
TEG14	19.25	22.5	20.87/294.02	T14 = 20.19	0.69	0.235%	0.11
TEG15	19.25	22.5	20.87/294.02	T15 = 20.06	0.81	0.275%	0.10
TEG_{mean}	19.25	22.5	20.87/294.02	20.07	0.806	0.274%	0.107

TABLE 2 Measurements of TEG0–TEG15 at ∼40°C (mean) hot side HS water temperature.

Measurements of TEG0–TEG15 at ∼40°C (mean) hot-side heatsink water temperature

TEG0 to TEG15	TEGs hotside HS-water temperatures with MAX6675_A (°C)	TEGs hotside HS-water temperatures with MAX6675_B (°C)	TEGs hotside HS-water temperatures mean (°C/K)	TEGs coldside HS-water temperature using DS18B20 (°C)	Temperature difference (TD) (°C/K)	TEGs Carnot efficiency [TD/$T_{\text{hotside mean}}$]	Voltages generated (V)
TEG0	40.25	40.75	40.5/313.65	T0 = 20.37	20.12	6.415%	0.64
TEG1	40.25	40.75	40.5/313.65	T1 = 21.69	18.81	5.997%	0.77
TEG2	40.25	40.75	40.5/313.65	T2 = 21.12	19.37	6.176%	0.71
TEG3	40.25	40.75	40.5/313.65	T3 = 20.81	19.69	6.277%	0.78
TEG4	40.25	40.75	40.5/313.65	T4 = 20.75	19.75	6.297%	0.64
TEG5	40.25	40.75	40.5/313.65	T5 = 20.31	20.19	6.437%	0.85
TEG6	40.25	40.75	40.5/313.65	T6 = 20.31	20.19	6.437%	0.83
TEG7	40.25	40.75	40.5/313.65	T7 = 20.50	20.00	6.376%	0.70
TEG8	40.25	40.75	40.5/313.65	T8 = 21.00	19.50	6.217%	0.63
TEG9	40.25	40.75	40.5/313.65	T9 = 20.94	19.56	6.236%	0.64
TEG10	40.25	40.75	40.5/313.65	T10 = 20.50	20.00	6.376%	0.79
TEG11	40.25	40.75	40.5/313.65	T11 = 20.62	19.87	6.335%	0.70
TEG12	40.25	40.75	40.5/313.65	T12 = 21.19	19.31	6.156%	0.58
TEG13	40.25	40.75	40.5/313.65	T13 = 21.25	19.25	6.137%	0.69
TEG14	40.25	40.75	40.5/313.65	T14 = 21.56	18.94	6.038%	0.81
TEG15	40.25	40.75	40.5/313.65	T15 = 20.94	19.56	6.236%	0.53
TEG_{mean}	40.25	40.75	40.5/313.65	20.866	19.632	6.259%	0.706

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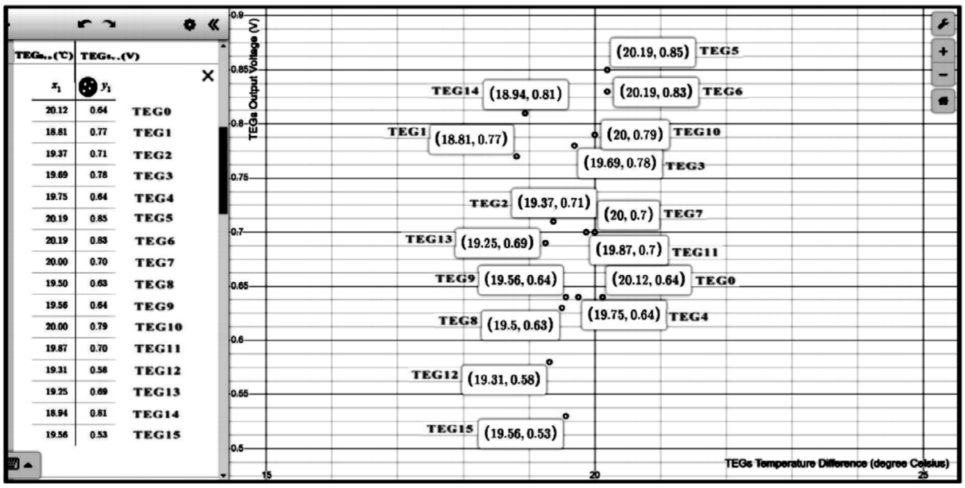

FIGURE 4 TEG0–TEG15 V_{out} (V) versus TD (°C) at TEGs ~40°C (mean) hot side HS water temperature.

TABLE 3 Measurements of TEG0–TEG15 at ~60°C (mean) hot side HS water temperature.

Measurements of TEG0–TEG15 at ~60°C (mean) hot-side heatsink water temperature

TEG0 to TEG15	TEGs hotside HS-water temperatures with MAX6675_A (°C)	TEGs hotside HS-water temperatures with MAX6675_B (°C)	TEGs hotside HS-water temperatures mean (°C/K)	TEGs coldside HS-water temperature using DS18B20 (°C)	Temperature difference (TD) (°C/K)	TEGs Carnot efficiency [$TD/T_{hotside\ mean}$]	Voltages generated (V)
TEG0	59.25	62.50	60.88/334.03	T0 = 19.25	41.63	12.463%	1.25
TEG1	59.25	62.50	60.88/334.03	T1 = 21.31	39.56	11.843%	1.47
TEG2	59.25	62.50	60.88/334.03	T2 = 20.37	40.50	12.125%	1.40
TEG3	59.25	62.50	60.88/334.03	T3 = 20.81	40.06	11.993%	1.46
TEG4	59.25	62.50	60.88/334.03	T4 = 19.81	41.06	12.292%	1.25
TEG5	59.25	62.50	60.88/334.03	T5 = 18.81	42.06	12.592%	1.62
TEG6	59.25	62.50	60.88/334.03	T6 = 18.75	42.13	12.613%	1.59
TEG7	59.25	62.50	60.88/334.03	T7 = 18.50	42.38	12.687%	1.45
TEG8	59.25	62.50	60.88/334.03	T8 = 19.00	41.88	12.538%	1.33
TEG9	59.25	62.50	60.88/334.03	T9 = 19.69	41.19	12.331%	1.17
TEG10	59.25	62.50	60.88/334.03	T10 = 19.37	41.50	12.424%	1.52
TEG11	59.25	62.50	60.88/334.03	T11 = 20.06	40.81	12.217%	1.41
TEG12	59.25	62.50	60.88/334.03	T12 = 21.37	39.50	11,825%	1.13
TEG13	59.25	62.50	60.88/334.03	T13 = 20.81	40.06	11.993%	1.33
TEG14	59.25	62.50	60.88/334.03	T14 = 20.87	40.00	11.975%	1.57
TEG15	59.25	62.50	60.88/334.03	T15 = 20.50	40.38	12.089%	0.98
TEG_{mean}	59.25	62.50	60.88/334.03	19.955	40.919	12.250%	1.371

of 1.371 V. The highest output voltage of 1.62 V was produced again by TEG5 with a TD of 42.06°C and a Carnot efficiency of 12.592%, whereas the lowest output voltage of 0.98 V was again produced by TEG15 with a TD of 40.38°C and a Carnot efficiency of 12.089%.

Portrayed in Table 4 and Figure 6 are summary of the results when TEG0 to TEG15 were subjected to a hot side mean temperature of 80.75°C and to a cold side mean temperature of 21.811°C. A mean TD of 58.939°C was attained, which produced a mean voltage of 2.018 V with a mean Carnot efficiency of 16.654%. The highest output voltage of 2.38 V was once more produced by TEG5 with a TD of 60.06°C and a Carnot efficiency of 16.971%, whereas TEG15 as well produced the lowest output voltage of 1.33 V with a TD of 58.63°C and a Carnot efficiency of 16.567%.

Presented in Table 5 and Figure 7 are summary of the results when TEG0 to TEG15 were subjected to a hot side mean temperature of 100°C and to a cold side mean temperature

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TABLE 4 Measurements of TEG0–TEG15 at ~80°C (mean) hot side HS water temperature.

Measurements of TEG0–TEG15 at ~80°C (mean) hot-side heatsink water temperature							
TEG0 to TEG15	**TEGs hotside HS-water temperatures with MAX6675_A (°C)**	**TEGs hotside HS-water temperatures with MAX6675_B (°C)**	**TEGs hotside HS-water temperatures mean (°C/K)**	**TEGs coldside HS-water temperature using DS18B20 (°C)**	**Temperature difference (TD) (°C/K)**	**TEGs Carnot efficiency [TD/$T_{\text{hotside mean}}$]**	**Voltages generated (V)**
TEG0	80.25	81.25	80.75/353.900	T0 = 20.56	60.19	17.007%	1.93
TEG1	80.25	81.25	80.75/353.900	T1 = 23.31	57.44	16.231%	2.20
TEG2	80.25	81.25	80.75/353.900	T2 = 22.56	58.19	16.442%	2.09
TEG3	80.25	81.25	80.75/353.900	T3 = 23.25	57.50	16.247%	2.20
TEG4	80.25	81.25	80.75/353.900	T4 = 22.00	58.75	16.601%	1.79
TEG5	80.25	81.25	80.75/353.900	T5 = 20.69	60.06	16.971%	2.38
TEG6	80.25	81.25	80.75/353.900	T6 = 20.44	60.31	17.041%	2.31
TEG7	80.25	81.25	80.75/353.900	T7 = 19.37	61.38	17.344%	2.18
TEG8	80.25	81.25	80.75/353.900	T8 = 20.06	60.69	17.149%	1.99
TEG9	80.25	81.25	80.75/353.900	T9 = 21.56	59.19	16.725%	1.61
TEG10	80.25	81.25	80.75/353.900	T10 = 21.25	59.50	16.813%	2.23
TEG11	80.25	81.25	80.75/353.900	T11 = 22.37	58.38	16.496%	2.08
TEG12	80.25	81.25	80.75/353.900	T12 = 23.87	56.88	16.072%	1.68
TEG13	80.25	81.25	80.75/353.900	T13 = 22.75	58.00	16.389%	2.00
TEG14	80.25	81.25	80.75/353.900	T14 = 22.81	57.94	16.372%	2.29
TEG15	80.25	81.25	80.75/353.900	T15 = 22.12	58.63	16.567%	1.33
TEG_{mean}	80.25	81.25	80.75/353.900	21.811	58.939	16.654%	2.018

TABLE 5 Measurements of TEG0–TEG15 at ~100°C (mean) hot side HS water temperature.

Measurements of TEG0–TEG15 at ~100°C (mean) hot-side heatsink water temperature							
TEG0 to TEG15	**TEGs hotside HS-water temperatures with MAX6675_A (°C)**	**TEGs hotside HS-water temperatures with MAX6675_B (°C)**	**TEGs hotside HS-water temperatures mean (°C/K)**	**TEGs coldside HS-water temperature using DS18B20 (°C)**	**Temperature difference (TD) (°C/K)**	**TEGs Carnot efficiency [TD/$T_{\text{hotside mean}}$]**	**Voltages generated (V)**
TEG0	102.00	98.00	100.00/373.15	T0 = 20.62	79.37	21.270%	2.55
TEG1	102.00	98.00	100.00/373.15	T1 = 24.25	75.75	20.300%	2.90
TEG2	102.00	98.00	100.00/373.15	T2 = 23.75	76.25	20.434%	2.82
TEG3	102.00	98.00	100.00/373.15	T3 = 23.94	76.06	20.384%	3.16
TEG4	102.00	98.00	100.00/373.15	T4 = 21.75	78.25	20.970%	2.32
TEG5	102.00	98.00	100.00/373.15	T5 = 21.06	78.94	21.155%	3.38
TEG6	102.00	98.00	100.00/373.15	T6 = 20.56	78.44	21.021%	3.22
TEG7	102.00	98.00	100.00/373.15	T7 = 18.75	81.25	21.774%	2.96
TEG8	102.00	98.00	100.00/373.15	T8 = 19.50	80.50	21.573%	2.57
TEG9	102.00	98.00	100.00/373.15	T9 = 22.12	77.87	20.868%	2.04
TEG10	102.00	98.00	100.00/373.15	T10 = 21.62	78.37	21.002%	3.15
TEG11	102.00	98.00	100.00/373.15	T11 = 22.25	77.75	20.836%	2.78
TEG12	102.00	98.00	100.00/373.15	T12 = 24.31	75.69	20.284%	2.16
TEG13	102.00	98.00	100.00/373.15	T13 = 23.75	76.25	20.434%	2.58
TEG14	102.00	98.00	100.00/373.15	T14 = 23.81	76.19	20.418%	3.16
TEG15	102.00	98.00	100.00/373.15	T15 = 21.94	78.06	20.919%	1.62
TEG_{mean}	102.00	98.00	100.00/373.15	22.124	77.812	20.853%	2.711

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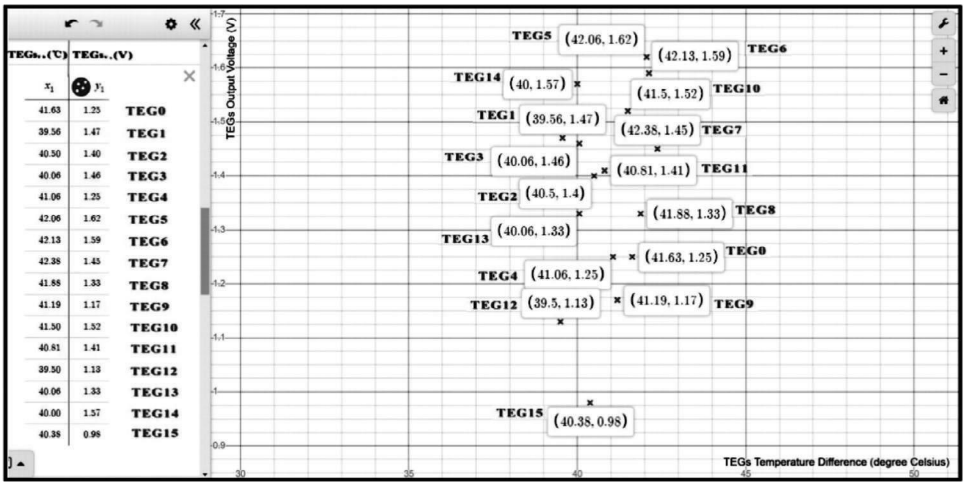

FIGURE 5 TEG0–TEG15 V_{out} (V) versus TD (°C) at TEGs ~60°C (mean) hot side HS water temperature.

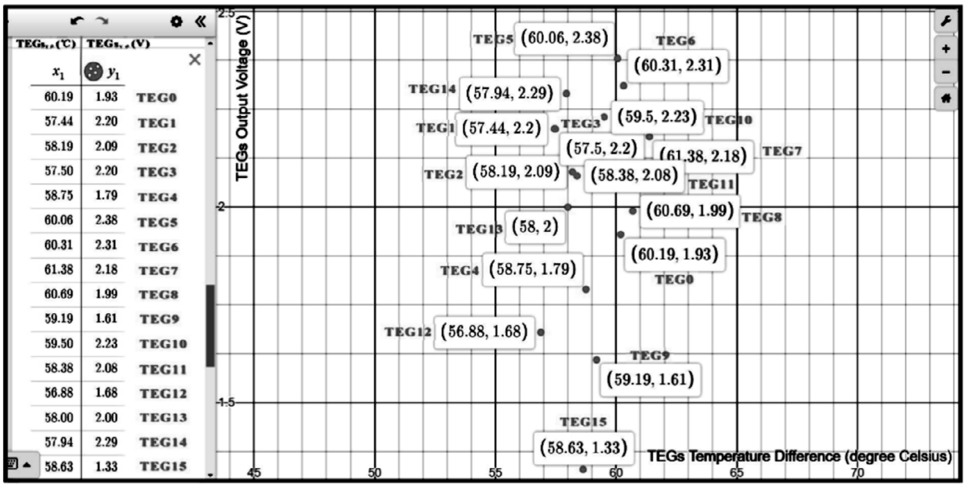

FIGURE 6 TEG0–TEG15 V_{out} (V) versus TD (°C) at TEGs ~80°C (mean) hot side HS water temperature.

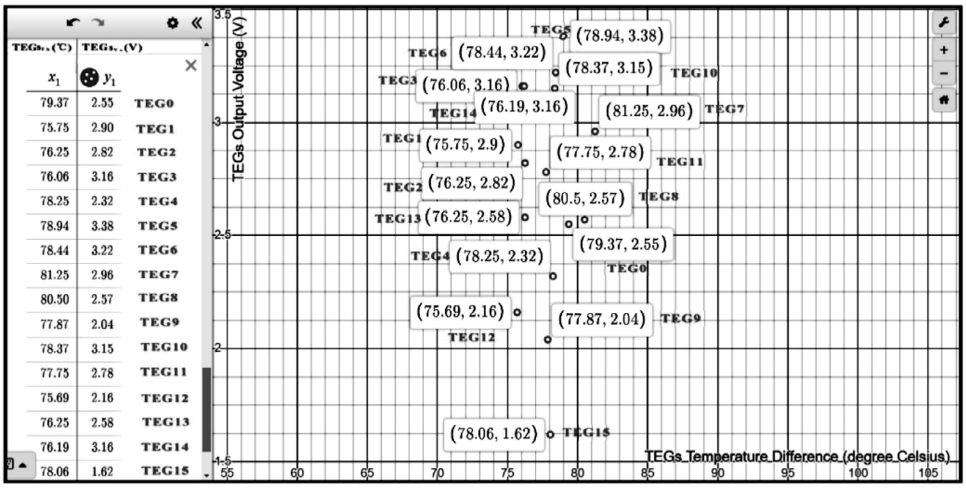

FIGURE 7 TEG0–TEG15 V_{out} (V) versus TD (°C) at TEGs ~100°C (mean) hot side HS water temperature.

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TABLE 6 TEG0–TEG15 voltage measurements summary at ~20°C, ~40°C, ~60°C, ~80°C and ~100°C (mean) hot-side heatsink water temperature (T_h).

TEG0–TEG15 voltage measurements summary at ~20°C, ~40°C, ~60°C, ~80°C and ~100°C (mean) hot-side heatsink water temperature (T_h)												
TEGs 0–15	V_{out} @T_h ~20°C (V)		V_{out} @T_h ~40°C (V)		V_{out} @T_h ~60°C (V)		V_{out} @T_h ~80°C (V)		V_{out} @T_h ~100°C (V)		$V_{out\ mean}$ (V)	$V_{out\ rank}$ (overall)
TEG0	0.10	4	0.64	10	1.25	11	1.93	11	2.55	11	1.294	12
TEG1	0.13	2	0.77	6	1.47	5	2.20	5	2.90	6	1.494	6
TEG2	0.10	4	0.71	7	1.40	9	2.09	7	2.82	7	1.424	8
TEG3	0.10	4	0.78	5	1.46	6	2.20	5	3.16	3	1.540	5
TEG4	0.10	4	0.64	10	1.25	11	1.79	12	2.32	12	1.220	13
TEG5	0.10	4	0.85	1	1.62	1	2.38	1	3.38	1	1.666	1
TEG6	0.16	1	0.83	2	1.59	2	2.31	2	3.22	2	1.622	2
TEG7	0.10	4	0.70	8	1.45	7	2.18	6	2.96	5	1.478	7
TEG8	0.10	4	0.63	11	1.33	10	1.99	10	2.57	10	1.324	11
TEG9	0.10	4	0.64	10	1.17	12	1.61	14	2.04	14	1.112	15
TEG10	0.10	4	0.79	4	1.52	4	2.23	4	3.15	4	1.558	4
TEG11	0.10	4	0.70	8	1.41	8	2.08	8	2.78	8	1.414	9
TEG12	0.10	4	0.58	12	1.13	13	1.68	13	2.16	13	1.130	14
TEG13	0.11	3	0.69	9	1.33	10	2.00	9	2.58	9	1.342	10
TEG14	0.11	3	0.81	3	1.57	3	2.29	3	3.16	3	1.588	3
TEG15	0.10	4	0.53	13	0.98	14	1.33	15	1.62	15	0.912	16
$TEGv_{out\ mean}$	0.107		0.706		1.371		2.018		2.711		1.382	

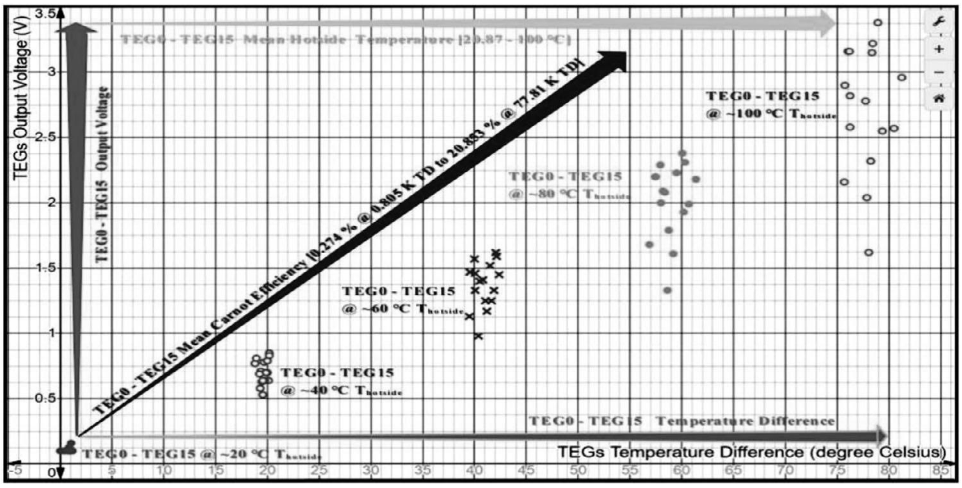

FIGURE 8 TEG0–TEG15 V_{out} (V) versus TD (°C) summary at TEGs ~20°C, ~40°C, ~60°C, ~80°C and ~100°C (mean) hot side HS water temperature.

of 22.124°C. A mean TD of 77.812°C was attained with a mean Carnot efficiency of 20.853%, producing a mean voltage of 2.711 V. TEG5 again yielded the highest output voltage of 3.38 V with a TD of 78.94°C and a Carnot efficiency of 21.155%, whereas TEG15 as expected had the lowest output voltage of 1.62 V with a TD of 78.06°C and a Carnot efficiency of 20.919%. It was also noticed that (see also Tables 6 and 7), though TEG7 had the highest TD of 81.25°C, it could only produce the fifth-highest output voltage of 2.96 V.

Tables 6 and 7, as well as Figures 8 and 9, entirely summarised the research results with a unique perspective. As evident, all the TEGs performed differently, with TEG5 having the best performance across (besides when the TD was ~20°C), while TEG15 performed the worst across. Interesting to note also is TEG10—which had a higher TD than TEG14, but TEG14 performed better than TEG10 across all the stated temperature ranges. Further findings showed that at hot side temperatures of ~20°C and ~60°C, TEG1 slightly performed better than

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TABLE 7 TEG0–TEG15 TD measurements summary at ~20°C, ~40°C, ~60°C, ~80°C and ~100°C (mean) hot-side heatsink water temperature (T_h).

TEG0–TEG15 TD measurements summary at ~20, ~40, ~60, ~80 and ~100°C (mean) hot-side heatsink water temperature (T_h)												
TEGs 0–15	**TD @T_h ~20°C (°C)**		**TD @T_h ~40°C (°C)**		**TD @T_h ~60°C (°C)**		**TD @T_h ~80°C (°C)**		**TD @T_h ~100°C (°C)**		**TD_{mean} (°C)**	**TD_{rank} (overall)**
TEG0	1.12	2	20.12	2	41.63	5	60.19	4	79.37	3	40.486	3
TEG1	0.88	6	18.81	13	39.56	14	57.44	15	75.75	14	38.488	15
TEG2	0.94	5	19.37	9	40.50	10	58.19	11	76.25	11	39.050	11
TEG3	1.00	4	19.69	6	40.06	12	57.50	14	76.06	13	38.862	13
TEG4	0.44	9	19.75	5	41.06	8	58.75	8	78.25	7	39.650	8
TEG5	0.94	5	20.19	1	42.06	3	60.06	5	78.94	4	40.438	4
TEG6	1.06	3	20.19	1	42.13	2	60.31	3	78.44	5	40.426	5
TEG7	0.31	10	20.00	3	42.38	1	61.38	1	81.25	1	41.064	1
TEG8	0.00	11	19.50	8	41.88	4	60.69	2	80.50	2	40.514	2
TEG9	0.69	8	19.56	7	41.19	7	59.19	7	77.87	9	39.700	7
TEG10	1.19	1	20.00	3	41.50	6	59.50	6	78.37	6	40.112	6
TEG11	0.88	6	19.87	4	40.81	9	58.38	10	77.75	10	39.538	9
TEG12	0.88	6	19.31	10	39.50	15	56.88	16	75.69	15	38.452	16
TEG13	1.06	3	19.25	11	40.06	12	58.00	12	76.25	11	38.924	12
TEG14	0.69	8	18.94	12	40.00	13	57.94	13	76.19	12	38.752	14
TEG15	0.81	7	19.56	7	40.38	11	58.63	9	78.06	8	39.488	10
$TEG_{TD\ mean}$	0.806		19.632		40.919		58.939		77.812		39.622	

TEG3; however, at 100°C, TEG3 interestingly performed better than TEG1 with respective output voltages of 3.16 and 2.90 V. It is also apparent in Figure 8 that the TEGs output voltage is proportional to their TD as expected; however, at specific TDs, each of the sixteen TEGs generated different amount of output voltages, though with some slightly the same at some TD instances. It is also worth mentioning that TEG3 performed the best when operated as a TEC in [2], but intriguingly not the case when now operated as a TEG in this study.

As a result, the reported TEGs' inconsistent/poor performance might not wholly be due to the well-known intrinsic thermoelectricity technology limitations, but certainly the bad engineering and everything after that. Therefore, our research findings/contributions are simply to practically highlight and succinctly give insights to a new audience on what to bear in mind when considering/employing thermoelectricity, in this case as TEGs. The take-home message to the audience is that thermoelectricity is not really a dismal technology as it is perceived and portrayed to be by some with limited knowledge of it. While TEGs' chemistry is central to its performance and there is ongoing research to advance it, Figure 9 depicts that it is further worsened by other human factors at various levels, which if eliminated/improved will make thermoelectricity very auspicious.

The Figure 9 in/efficiency contributing factors overview are holistically explained as follows:

1. TEGs hot and cold sides temperature: A TEG $T_{hotside}$ and $T_{coldside}$, as well as its temperature difference, determine or limit its ideal maximum efficiency (the Carnot efficiency)/performance, irrespective of any other contributing factor/s involved.
2. TEGs figure of merit (Z): A TEG type of material chemistry is the heart of a TEG, which when employed together with other supporting components during manufacturing, will further degrade the Carnot efficiency—which depends on the hot and cold sides temperature. The hope is to ensure the thermoelectric material used produces the very best performance without affecting further its Carnot efficiency. Unfortunately, once this choice is made, there is nothing the user can do to improve it.
3. TEGs quality of manufacturing: During TEG manufacturing (assembly and production), a lot could go wrong—from a bad solder joint to a broken connection, as well as other substandard components/processes that will affect its performance and efficiency. Unfortunately, also, once it is made, the user can do nothing to enhance it.
4. TEGs applications design: The concept design, layout and components choice to be employed play a vital role. Each application must be designed accordingly from the source (TEG/s) to the load and also take into account maximum power transfer.
5. TEGs design implementation: This pertains to how well the conceptual design is implemented. In practice, there will be challenges that restrict how well the concept design is executed and realised. The environmental/operating conditions, heat flux, as well as contact resistance between the TEGs and the heatsinks, will further affect the TEGs' performance. It is also prudent to add sensors to read/monitor the TEGs' output voltage and control the TEGs temperatures.

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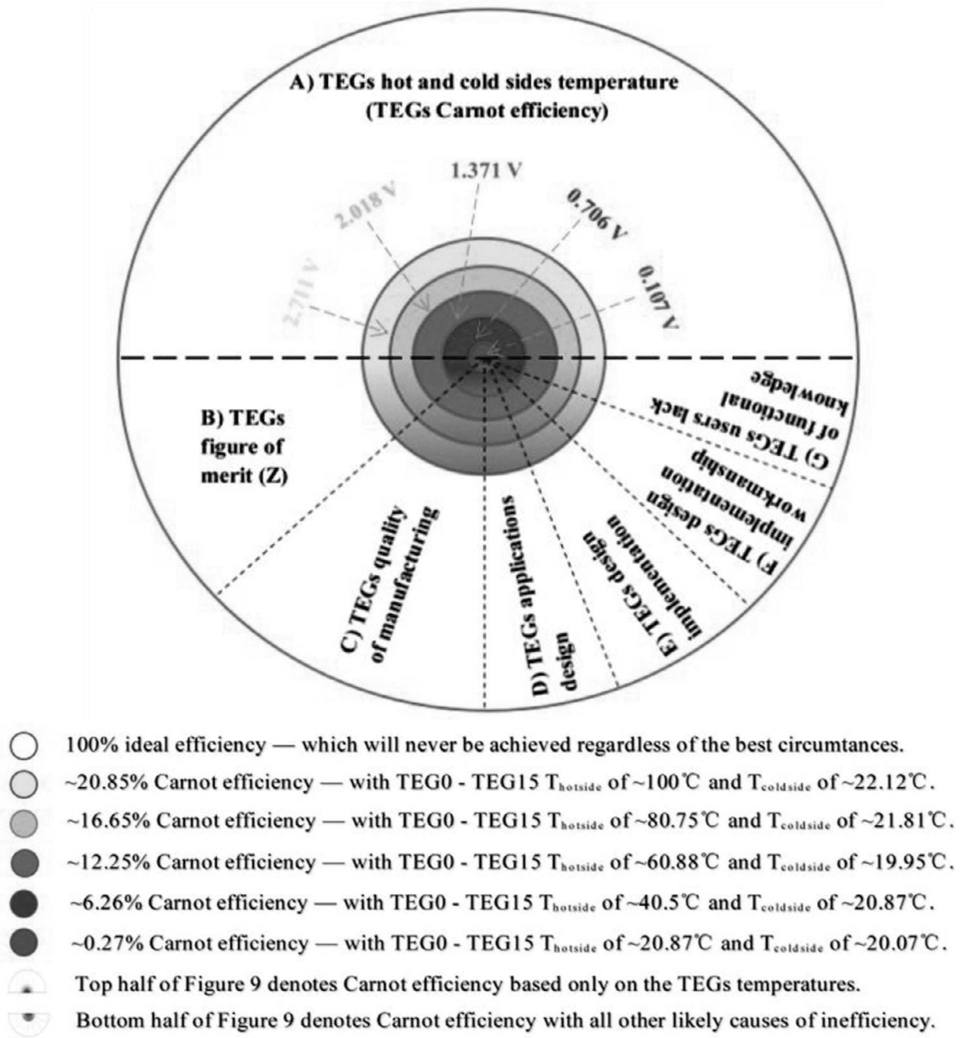

FIGURE 9 Summary of TEG0–TEG15 in/efficiency with associated mean output voltages.

6. TEGs design implementation workmanship: The overall components handling to avoid malfunction during implementation and testing is critical. Discretely checking each TEG and its associated components functionality before, during and after implementation is vital. However, ensuring the components, especially the fragile TEGs do not get damaged or degrade after everything is done, is most crucial.
7. TEG users' lack of functional knowledge: Understanding properly the physics of thermoelectricity, its parameters and operational limits, are some factors that are most often overlooked by some users or audiences. It is often assumed that it is a matter of just buying and using TEGs like other electrical devices, without knowing TEGs are non-linear/temperature-dependent devices that also require lots of extra conditioning.

It is obvious that Figure 9 bottom half factors must not degrade; or else, the TEG overall efficiency and performance will further drop; as it is clearly evident that the product of the TEG Carnot efficiency and all the other inefficiencies will give the actual TEG in/efficiency. While there is nothing that can be done by a user to improve factors B and C once manufacturing is done; factors A, D to G can be innovatively improved by the user to increase the TEGs' efficiency, notwithstanding the constraints.

4 | CONCLUSION

Thermoelectricity lends itself to various applications due to its versatility and most importantly with it being a clean technology. In this study, sixteen TEDs of the same made and model (TEC-12706) were operated as TEGs, whereby they were all subjected to approximately the same hot (between ∼20 and ∼100°C) and cold sides temperatures (∼20°C) to practically and relatively investigate their voltage production and energy conversion in/efficiency—which has been a question of debate. It was observed that while all the TEGs output voltages produced were proportional to their temperature differences, as well as their Carnot efficiencies as expected, some TEGs however produced more output voltage and consequently were more energy efficient relative to others. For example, TEG5 with

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an overall mean TD of 40.438°C, produced the highest overall mean output voltage of 1.666 V; whereas TEG15 with an overall TD of 39.488°C, produced the lowest overall mean output voltage of 0.912 V. Furthermore, while some TEGs performances were slightly the same throughout the same TD, some TEGs relatively performed better than others at certain TDs. For example, at 100°C hot side temperature, TEG3 interestingly performed better than TEG1 with respective output voltages of 3.16 and 2.90 V; whereas at other hot side temperatures, both TEGs' output voltages were approximately the same. Moreover, as noticeable between TEG10 and TEG14, TEG10 had a higher TD throughout, but TEG14 produced a relatively higher output voltage throughout. Ultimately, the Carnot efficiencies show the maximum ideal limits of the TEGs conversion efficiency at the corresponding temperature differences. In sum, TEGs by extension TEDs' chemistry, is very paramount for proper performance; however, TEGs' physics and engineering are pivotal, as TEGs' inferior manufacturing/production quality, lack of decent data, substandard implementation, poor workmanship, small sample size and inadequate knowledge during research/design/construction/application/use, have further exacerbated the general poor performance (inconsistent low output voltages and low energy conversions) biases attributed and reported in TEGs and in general TEDs.

AUTHOR CONTRIBUTIONS

Nganyang Paul Bayendang: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; software; validation; visualization; writing—original draft; writing—review and editing. **Vipin Balyan**: Data curation; formal analysis; funding acquisition; project administration; resources; supervision; visualization; writing—review and editing. **Mohamed Tariq Kahn**: Data curation; formal analysis; funding acquisition; project administration; resources; supervision; validation; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The author declares no conflicts of interest.

DATA AVAILABILITY STATEMENT

Access the TEGs supplementary material (research raw data) using the below enclosed link. https://drive.google.com/drive/folders/1SyuCVpIygg1FzsrBWQRzLHkBlL1RQEam?usp=sharing

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SUPPORTING INFORMATION

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