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The Question of Thermoelectric Devices (TEDs) In/Efficiency—A Practical Investigation Considering Thermoelectric Heaters (TEHs)

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ABSTRACT

Thermoelectricity is a promising technology; however, though clean and versatile, its efficiency has been questionable and consequently limiting its extensive utilization. Many published research on thermoelectricity have been on power generation and cooling applications, with few publications on heating, especially practically. Thus, this article practically focuses on thermoelectric devices (TEDs) when used as thermoelectric heaters (TEHs). Sixteen identical TEDs (TEC-12706) were operated as TEHs under similar test modalities and powered in succession with 12, 10, 8, 6, and 4 V, to practically examine TEHs energy dynamics and in/efficiency. It was found that all the TEHs used in the research performed relatively inconsistent with each other with the worst-performed TEH (TEH0) having a mean hot-side temperature of 30.276°C with a mean power consumption of 13.826 W; whereas the best-performed TEH (TEH3) had a mean hot-side temperature of 40.4°C with a mean power consumption of 20.822 W. Furthermore, all the TEHs hot-side temperature increased proportionately with the input voltage; though at the specified voltages, the TEHs hot-side temperature increased while its input power decreased over time. The concepts of TEH hot-side mean temperature and TEH mean input power were also introduced.

1 | Introduction

Heat energy is vital and it is used and produced variously and one way is through thermoelectricity. Thermoelectric devices (TEDs) poor performance has been variously reported and debated, at times it is not clear where the inefficiency lies or whether it is only due to mostly intrinsic limitations in the TEDs chemistry choice and or perhaps its physics and engineering or simply exacerbated by end users factors—which among others could be due to faulty devices, bad designs, poor implementation, bad workmanship and general lack of good theoretical and practical knowledge of TEDs operation. In/efficiency has been used herein to mean both inefficiency and efficiency—which both are measured in this study by how the TEHs relatively respond in terms of the input power consumed and the corresponding TEHs hot-side temperature, when all the TEHs are subjected to identical test conditions. Miscellaneous studies have been conducted on thermoelectricity but with a focus mostly on thermoelectric generators (TEGs) and or thermoelectric coolers (TECs), with little attention on thermoelectric heaters (TEHs). In [1], an extensive study on combined cold, heat, and power (CCHP) systems was presented, whereby TEDs were operated as TEGs to harvest and convert fuel cells waste heat to power. In addition, TEDs were operated as TECs to provide cooling. Operating TEDs as thermoelectric heaters (TEH) was not considered, akin to most scholarly works published on thermoelectricity. TEDs heatsink pitch affects its fin efficiency [2] as asserted with a 2-in-1 thermoelectric multi-utility water heater (that heated water from 25°C to 50°C) and a simultaneous air conditioner. The temperature on the used TEDs cold and hot-sides varied from 22.6°C to 41.1°C. A heating coefficient of performance (CoP_h) of 2 and a cooling coefficient of performance (CoP_c) of 1 were attained and operating it for 16 to 17 h/day saved 97% of electricity demand, relative to using electric residential water heaters. A carbon dioxide (CO_2) emission reduction of ∼54% was also achieved. Using TEDs as opposed to traditional air-conditioners subdued the problems of noise, size, and vibration [3]. They also reported that the comparison of CoP between TEC and conventional air conditioners respectively gave a CoP between 2.6–3.0 and 0.38–0.45. Furthermore, an electrical heater is less efficient than a thermoelectric (TE) heat pump, because its heating coefficient is 1.6 more under desirable operating environments [4]. They developed two unique instant water heaters and the model with a circulating water pump can conserve power usage greater than 40%, relative to traditional electric water heaters; whereas the model with integrated thermosiphon can conserve power greater than 38%. Notwithstanding, the latter is more advanced and environmentally friendly. Drinkable water can be produced using an efficient thermoelectric distillation system [5]. Their research rationale was to simultaneously use the thermoelectric module hot-side heat to evaporate water and then use the cold-side to condense the water vapor. This novelty significantly decreased the energy usage and enhanced the system performance. Their experiments found that the water production average was 0.0285 L/h with a 1.14 Wh/mL specific energy usage in an evaporation chamber filled with $10 \times 10 \times 30\,mm^3$ of water. According to [6], TEDs have no economic evaluation experimental-data when operated as coolers and heaters. This economic evaluation deficiency gives a wrong or a flawed decision-making information when promoting a product. Their paper focused on using thermoelectricity to produce hot and cold water and by developing and applying a specific exergy costing (SPECO) method to provide an encompassing thermal/exergetic/economic evaluation. Their findings revealed that, at the expense of time, using a lower supply voltage is more affordable. Incorporating TECs as heat pumps into a solar-air-heater (SAH) gave remarkable performance enhancements [7]. Photovoltaic (PV) module output energy was used to supply power to the TECs affixed to the SAH absorber plate and despite lower irradiance intensity, appreciable rise in the outlet air temperature was observed when compared to a reference SAH. Consequently, the TE heat pumping system enhanced heat collection by 7.14%, with an energy efficiency of 46.73%, as opposed to 28.03% energy efficiency of conventional SAH. By using TEH, the winding location temperature can be increased to > 100°C with just a power input of 30 W and this can prevent condensation and reduce thermal expansion stress, life cycle cost, material usage and increase the motor life [8]. TED was operated as a TEC or TEH in clothing, whereby water was circulated through small tubes to regulate the body temperature with respect to the ambient temperature [9]. Their system had small size, non-moving parts, no noise, and environmental friendly benefits over similar systems. As demonstrated in [10], the total CoP of a TED operated as TEC and TEH was acquired through experiments and a thermodynamics mathematical model. With one of the TED surface acting as a heat sink while the other surface rejects heat, both surfaces were utilized for cooling and heating applications. A total CoP of 4.5 was achieved, but as the temperature difference between the cold and the hot-sides was raised, the total CoP decreased. It was summed that using TED for heating and cooling can enhance its CoP which impart the electrical energy usage saving. Designing with TEDs is not straightforward, as many factors affect their performance and efficiency. Compiled in [11] are most frequently asked questions. Since a TED can be operated as a TEG, TEC, and TEH, most of the factors that affects one mode will surely affects the other. However, the Joule heating involved gives more benefit when operated in TEH mode, as this extra Ohmic heat which unfortunately decreases the cold-side temperature of the TED, fortunately increases the hot-side temperature of the TED, which eventually enhances its efficiency when operated as a TEH. The core of a TED is the type of thermoelectric (TE) material/s used. While most research has been on high temperature materials according to [12], they suggested that crystalline and polycrystalline samples with anisotropic electrical transport property have high texture degree that can be applied to enhance TED performance at low temperatures. One major drawback in thermoelectricity research has been the lack of published detailed technical data, be it from TED manufacturers and or researchers. This has led to various studies on how to determine TED parameters properties. Researched in [13] is a tailored thermal characterization system that can simultaneously measure the Seebeck coefficient and thermal diffusivity for materials in the temperature range of 73 and 373 K. In [14], the Seebeck coefficient, thermal conductivity and the electrical resistance, as well as other unknown parameters of TEDs for cooling and heating, were determined experimentally using an input–output model and when heatsinks were added, lumped parameter models were applied to measure the hot and cold sides temperatures [15]. Peculiar to TEDs when used in thermal applications is the concurrent production of heat and cold. While this uniqueness could be disadvantageous in certain applications, it is often exploited in applications that require cooling and heating, such as a TE cooling and heating water dispensing system [16, 17], a 1 kW TED heat exchanger for a vehicle cabin heating and cooling [18], by maximizing cooling/heating performance of TEMs across variable therrmal loads through optimal control using CoP curves [19], a simulated TEM heating and cooling system [20] to study the thermal performance under different working conditions, a TE water cooler and heater with an intermediate tank [21] and a TE elevator car air conditioner [22]. Theoretically, a TEC and TEH dual modes of operation should be the same when the supply voltage polarity is reversed or a TED is physically flipped around; however, this is not the case in practice when heatsinks are added to enhance its thermal conductivity. Heatsinks added on TEDs hot and cold sides also introduce contact resistance and if dissimilar, it further results to performance variations. A TEC/TEH mode cannot exist without the other, though one can be optimized at the expense of the other depending on the intended application. Articulated in [23] was a set of identical experiments conducted using 12, 10, 8, 6, and 4 V; to provide insights on TED in/efficiency when operated as a TEC. Sixteen TECs were employed in a similar test setup and all gave differing performances, with TEC9 giving the worst performance and TEC3 giving the best results. The optimal performance for all the TECs was obtained with 8 V supply voltage—8 V was just adequate to cause sufficient cooling and inadequate to cause sufficient Joule heating. While [23] focused on TEC, the same setup was modified to focus on the dual—TEH, and is engaged in details in what follows.

From the literature review, it is evident that less attention has exclusively been on TEH, perhaps because heating can be easily accomplished by other means—even though they are less efficient than TEH. However, the downside of using TEH is provision for TEC has also to be made; thus, making TEDs less appealing in applications that exclusively requires only heating. As a result, this study objectives based on the research gaps identified, are to (i) practically study TEDs in/efficiency with focus on TEH, (ii) provide extensive experimental data that TED researchers/system designers can find useful, (iii) present a copious and comprehensive information to highlight TEH operations to a broader audience and end users (iv) assert the practical TEH research highlights and insights and (v) relate the findings with [23].

This article is organized as follows: Section 1 introduces a brief background on TEHs literature, proceeded by the research methods and methodology presented in Section 2. Section 3 abridges the research results and Section 4 examines the findings. Finally, concluding remarks with future research recommendations are proffered in Section 5.

2 | Research Methods and Methodology

The different methods and methodology applied to perform the study are described in the following sections.

2.1 | Methods

This basically explains how the various items employed in the research were put together and used to perform the investigation. The rationale was to have a 3-in-1 TEDs design that can be used for TECs, TEHs, and TEGs research. However, the focus herein is on TEHs and is engaged next.

2.1.1 | TEHs-Heatsink Assembly

This presents how the TEHs were organized and integrated to the heatsinks. The assembly is the same as described in [23] with the difference being the focus is now on TEHs, whereby the power supply polarity to the TEDs is reversed and the top side is now the hot-side, enabling the TEHs research to be easily conducted from the top as illustrated in Figures 1–3.

2.1.2 | Temperature Instruments/Sensors Used

Discussed herein are the different temperature apparati employed in the research. The Toptronic T235H multimeter with the K-type thermocouple was utilized to record the lab ambient temperature during the 60 different TEHs experiments. The Fluke Ti20 infrared camera was utilized to take heat maps of the TEHs hot-side. Placement of the temperature sensors on the TEHs sides was very critical. As a result of the design drawbacks, the thermocouples probes were not exactly placed on the TEHs sides but rather inserted inside the middle grove of the heatsinks on the TEHs hot and cold sides. Four MAX6675 temperature sensors were utilized to record the TEHs cold-side temperature. This was done by placing in turns from Row0-3 (a row has four TEHs), each MAX6675 K-type thermocouple probe (labeled TA to TD) inside the middle grove of the heatsink on each TEH cold-side as pictured in Figure 3. The MAX6675 temperature sensor cannot record less than 0°C and is also based on the SPI interface, hence it becomes infeasible to interface 16 MAX6675 to the ESP32 to measure at once all the 16 TEHs cold-side temperature. Therefore, four MAX6675 were used and were applied in turns from Row0 to Row3, such that TA, TB, TC, and TD respectively measure in turns only Column0, Column1,

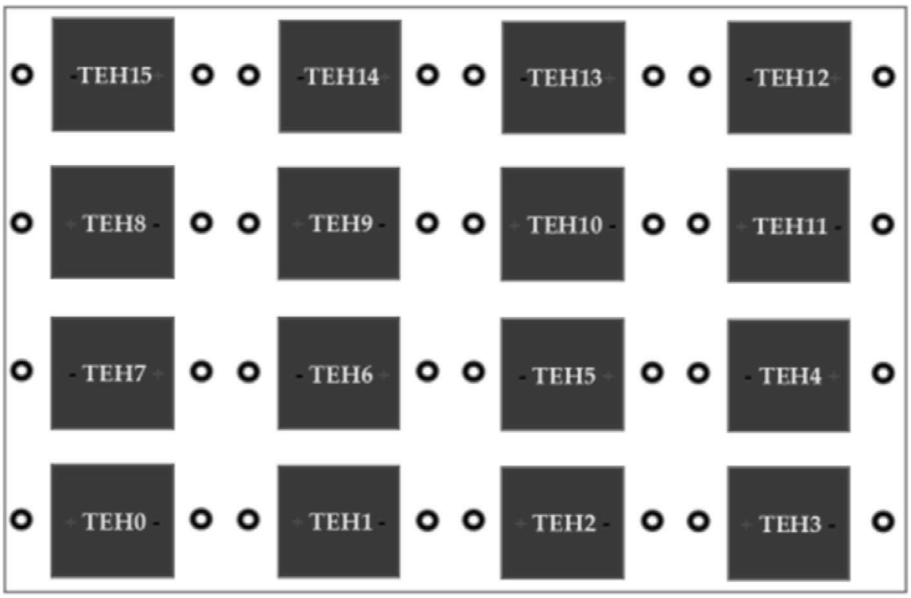

FIGURE 1 | Arrangement of the 16 TEHs in the metal tray (top view showing the TEHs hot-side).

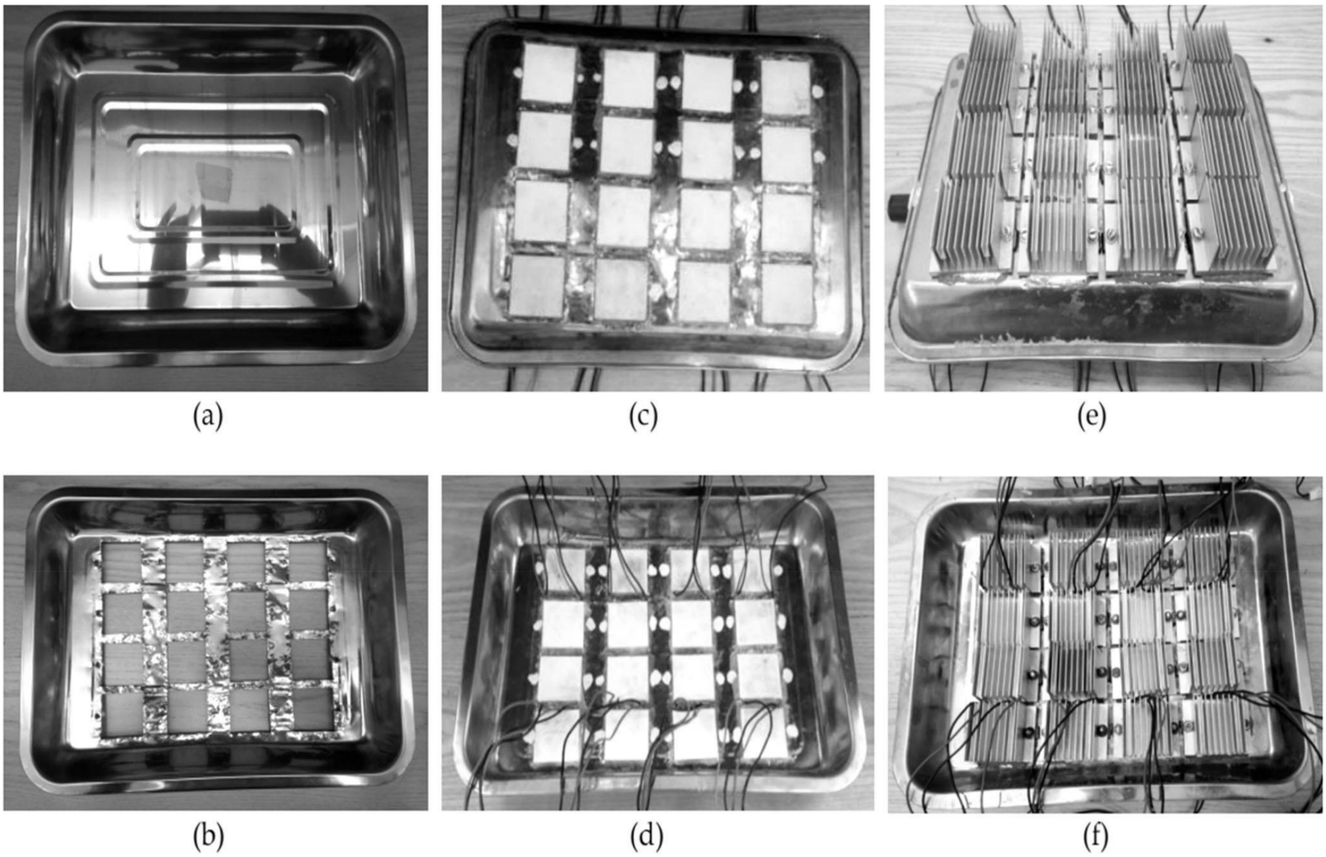

FIGURE 2 | Construction of the 16 TEHs in the metal tray (a) the metal tray, (b) the metal tray cut into 16 square holes, (c) bottom view of the 16 TEHs inserted and glued in their respective square holes, (d) top view of the 16 TEHs inserted and glued in their respective square holes, (e) bottom view of the 16 TEHs with heatsinks and (f) top view of the 16 TEHs with heatsinks (adapted from [23] with Elsevier CCC permission).

FIGURE 3 | Depiction of MAX6675 thermocouples TA, TB, TC, and TD, respectively inserted briefly inside the middle grove of the heatsink on Row0 TEHs (TEHs0–3) cold-side. During measurement at a particular voltage (12, 10, 8, 6, and 4 V) in succession; TA, TB, TC, and TD will be in turns moved to Row1, then Row2, and finally Row3 to measure all 16 TEHs heatsink cold-side temperature, before moving to the next voltage and the procedure repeated. By so doing, TA will only measure Column0 TEHs, TB will only measure Column1 TEHs, TC will only measure Column2 TEHs and TD will only measure Column3 TEHs. The x16 DS18B20 thermocouples are each permanently inserted inside the grove of the heatsink on the TEHs hot-side.

Column2, and Column3 TEHs cold-side temperature as Figure 3 depicts. The average cold-side temperature of the TEHs was calculated and used further where required. Unlike the TEHs cold-side temperature measurement accuracy being less significant, measuring the TEHs hot-side temperature accurately was of paramount significance; as a result, the DS18B20 temperature sensors (x16) were used. The DS18B20 was considered, because; (i) it can record as high as 125°C (appropriate for the research), (ii) it is rooted in the One-wire interface needing only one GPIO pin of a microcontroller, power supply lines, as well as one pull up resistor to interface all 16 of them and (iii) very affordable (about $1/pc). Each DS18B20 sensor probe was inserted inside each of the TEHs hot-side heatsink middle grove to make sure the probes were nearest to the heatsink surface in contact with the TEHs hot-side. Figures 4 and 5 exemplify the temperature devices used.

2.1.3 | Electronic Modules Used

Three types of electronic modules were employed to link different sections of the setup to one another. The modules include MAX6675 modules (x4), an ESP32 Wroom-32 development board, and a DS18B20 breakout module which interfaced all the sixteen DS18B20 temperature sensors connections to the ESP32. The ESP32 development module with the Wroom-32 chipset is

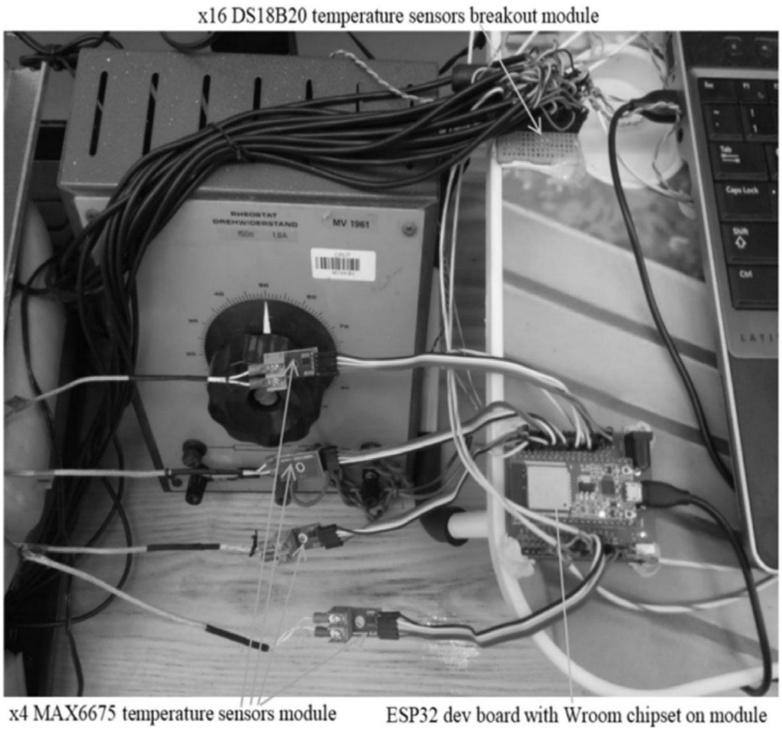

FIGURE 4 | Depiction of the different electronic modules employed.

FIGURE 5 | Temperature sensors/instruments used.

the controller used to interface, process, and control all aspects of the experiments. Arduino IDE was used to program, periodically read, log, timestamp, and process the temperature measurements sent by the sixteen DS18B20 and the four MAX6675 temperature sensors. Figure 4 illustrates the electronic modules employed.

2.1.4 | Power Supplies Used

The same power supplies setup used in [23] (check for details) was used here. Summarily, three different kinds of power supplies were used to supply different sections of the setup. The 16 TEHs were organized in 4 rows and 4 columns as portrayed in Figure 3. Each row of TEH was tested in turns. To supply each TEH in a row, four Sinilink XYS3580 (0.6–36 V/5 A) DC-DC buck-boost converters were used, such that, a Sinilink power converter powers a TEH in a row. Once a row experiment is done, they are similarly connected to the next row. Starting with 12 V, then 10, 8, 6, and finally 4 V, all the four rows were tested amounting to the 20 A-C number of experiments that were performed. The current limit of each Sinilink power converter was set to 5 A to safeguard the TEHs. Two Power Man 12 V/18 A AC—DC power adapters were utilized to supply the 16 TEHs through the four Sinilink DC–DC converters. More about this next. The 9–24 V/5 A AC–DC power adapter (model #: HuazhenYuan-009) was set to 12 V and was used to supply the breakout module. Figure 6 portrays the power supplies used.

2.2 | Methodology

The workflow about how the different experiments were performed based on the setup in Section 2.1 is discussed. The 16 TEHs were divided into 4 rows and 4 columns as depicted in Figure 7. NB: Just four Sinilink DC-DC power converters were used as illustrated in Figure 8; as a result, each TEH one row at a time was tested, beginning from Row0 to Row3 and re/iterated when a new supply voltage is set. For instance, to test TEHs in Row0; Sinilink DC-DC power converters labeled D0, D1, D2, and D3 as shown in Figure 8, were set to 12 V/5 A current limit and respectively connected to TEH0, TEH1, TEH2, and TEH3. After Row0 testing, Row1 was next tested by respectively connecting D0, D1, D2, and D3 to TEH7, TEH6, TEH5, and TEH4. To test Row2; D0, D1, D2, and D3 were also correspondingly connected to TEH8, TEH9, TEH10, and TEH11 and lastly Row3 was tested by respectively connecting again D0, D1, D2, and D3 to TEH15, TEH14, TEH13, and TEH12. On this premise, whenever a row of TEHs was tested, the Sinilink DC–DC power converter; (a) D0; supplied power just to Column0 TEHs (TEH0, TEH7, TEH8, and TEH15), (b) D1; supplied power just to Column1 TEHs (TEH1, TEH6, TEH9, and TEH14), (c) D2; supplied power just to Column2 TEHs (TEH2, TEH5, TEH10, and TEH13) and (d) D3; supplied power just to Column3 TEHs (TEH3, TEH4, TEH11, and TEH12). A total of 20 A to C (60 in total) experiments were conducted. Beginning with Row0 to Row3; each row of TEHs was in turns supplied first with 12 V (note, in reverse polarity) and the TEHs temperatures were recorded after 0, ~5, and ˜10 min. The experiment was also repeated at 10 V from Row3 to Row0 TEHs and back again at 8, 6, and lastly 4 V. The following parameters were measured; (i) the ambient temperature of the lab using the T235H multimeter with the K-type thermocouple, (ii) the TEHs hot-side heatsink temperature using the permanently inserted ×16 DS18B20 temperature sensors labeled T0 to T15 corresponding to TEH0 to TEH15, (iii) the TEHs cold-side heatsink temperature with the removable ×4 MAX6675 temperature sensors

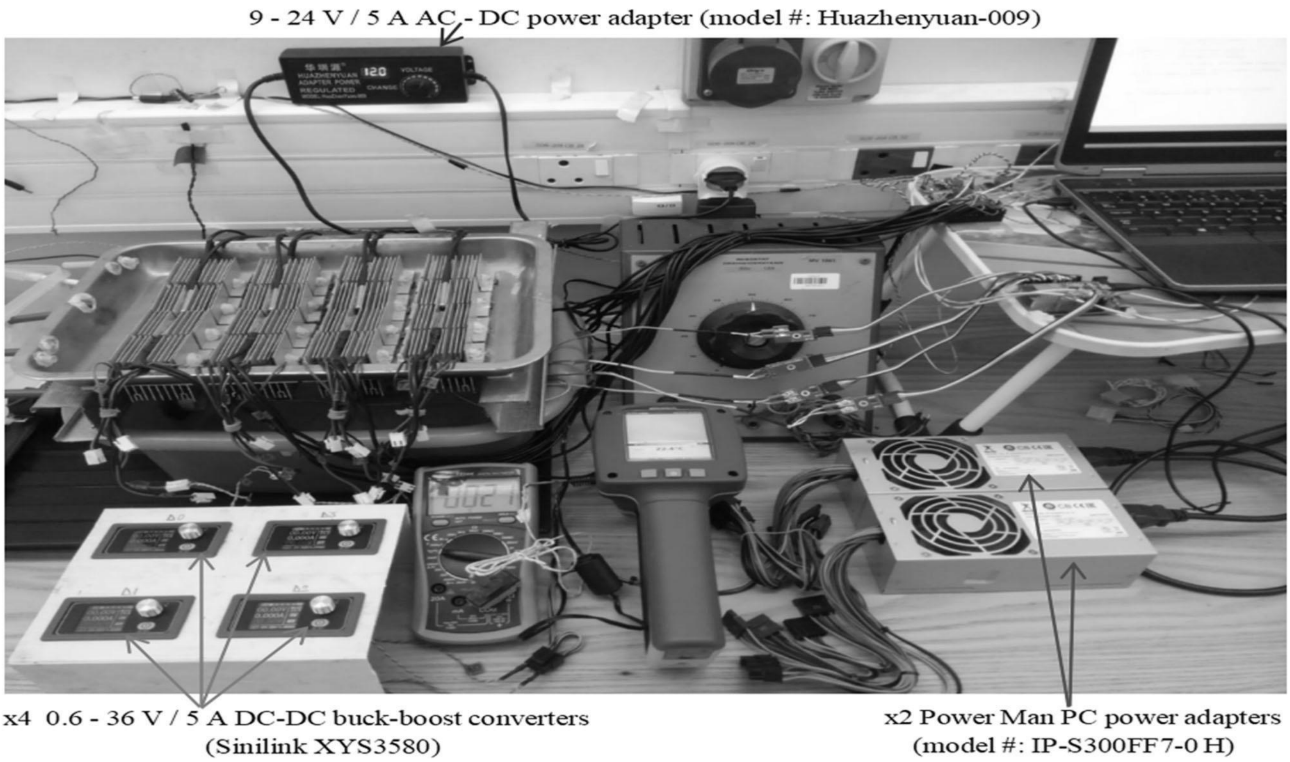

FIGURE 6 | Illustration of the power supplies used.

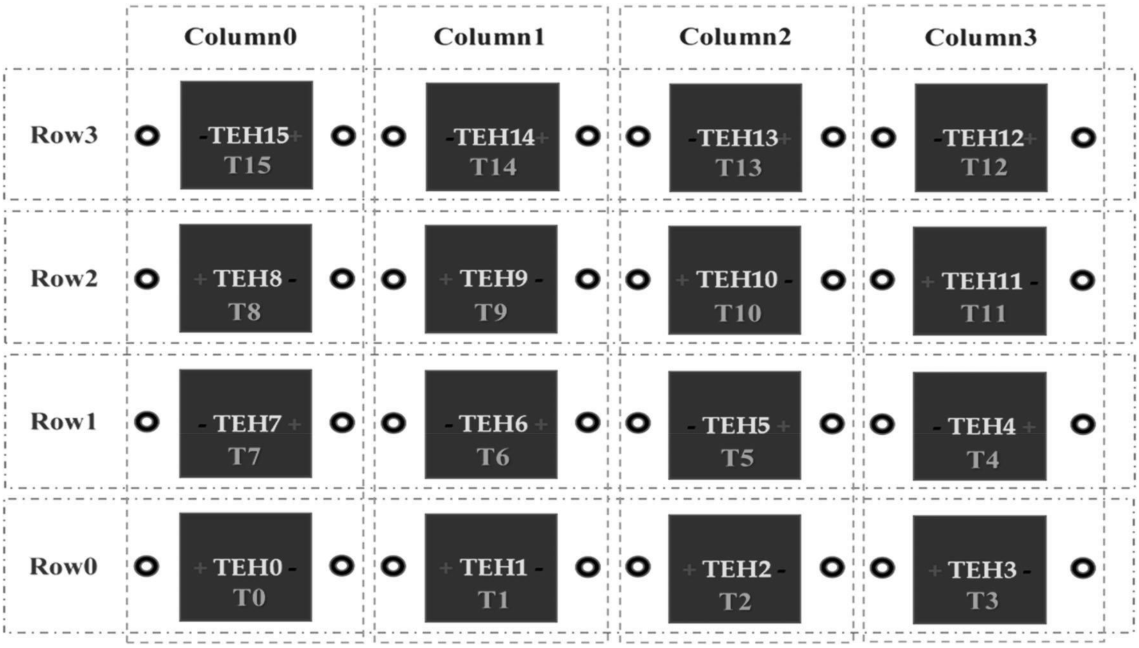

FIGURE 7 | TEHs test matrix top view from the hot-side.

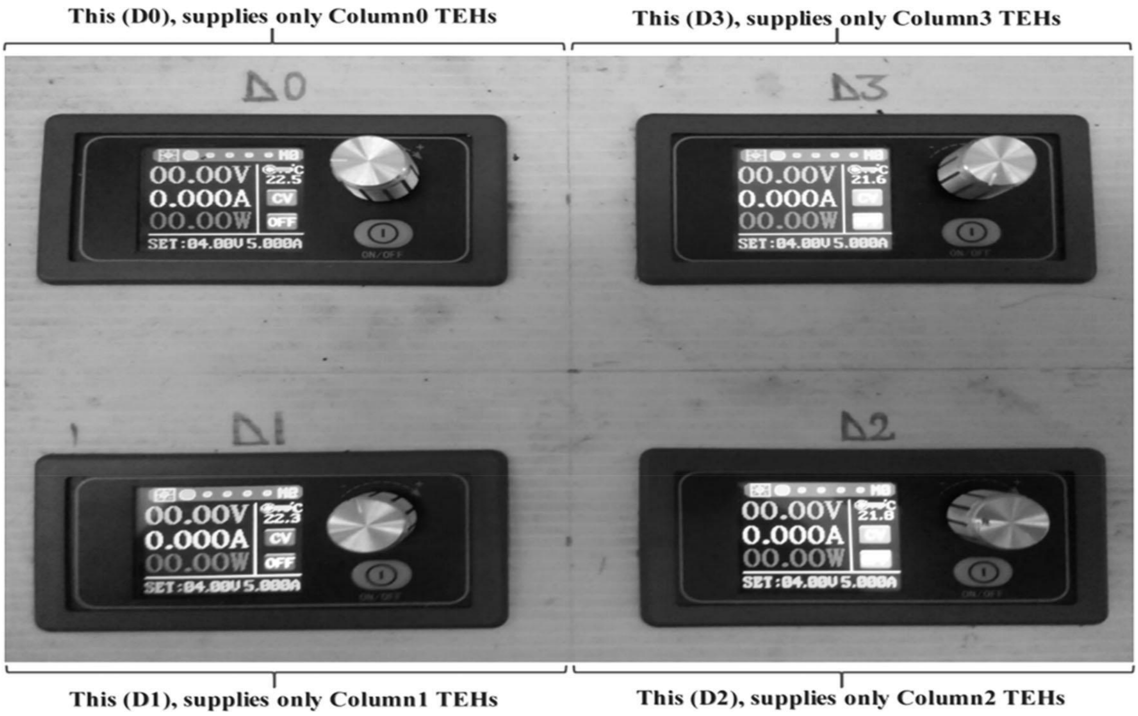

FIGURE 8 | Sinilink DC-DC power converters display.

denoted TA, TB, TC, and TD, (iv) the TEHs hot-side heat maps using the Fluke Ti20 infrared camera, and (v) the TEHs input voltage, current and power. NB: prior to first powering-on the TEHs and starting the measurements row by row, the TEHs hot-side is first filled with 500 mL of cold water to; (a) serves as the thermal load and (b) protect the TEHs hot-side from overheating and imminent damage. As a result, the TEHs hot-side heatsink water temperature must always first be checked to be ~11°C before powering-on the TEHs under test. If the TEHs hot-side heatsink water temperature was > 14°C or < 8°C, it was adjusted accordingly to be ~11°C with a +/− 3°C tolerance. This was just to make sure that all the tested TEHs were powered-on under similar starting temperatures and to ensure that the measurements were also performed in similar test, performance, environmental, and operational conditions. The 60 experiments results summary are presented next.

3 | Results

Herein, the TEHs results of the 60 experiments that were conducted after ~0, ~5, and 10 min of powering-on and in succession at 12, 10, 8, 6, and 4 V, are abridged and presented. This data includes the TEHs power usage, voltage supplied, and current drawn, the test lab ambient temperature, the TEHs cold-side heatsink temperature, the TEHs hot-side heatsink water temperature, the TEHs cold and hot-sides temperature differences, and the TEHs hot-side heat map that were recorded. Supporting Information S1 to S3 has all the detailed results.

3.1 | Experiments 1–4 (TEHs Row0–3 @ 12 V) Results

Experiments 1–4 results that were performed at 12 V/5 A current limit is abridged as follows: Experiment 1C findings of Row0 TEHs (TEH0–3 with T0–3), Experiment 2C findings of Row1 TEHs (TEH4–7 with T4–7), Experiment 3C findings of Row2 TEHs (TEH8–11 with T8–11) and Experiment 4C findings of Row3 TEHs (TEH12–15 with T12–15). The detailed raw measurements of Experiments 1–4 results are respectively captured in Figure S1 to Figure S4 as structured in Supporting Information S1. They are also respectively tabulated in Supporting Information S2 in Tables S1–S4 and summarized in Table S21. Experiments 1C–4C input power versus hot-side temperature findings are plotted in Figure 9.

3.2 | Experiments 5–8 (TEHs Row0–3 @ 10 V) Results

Experiments 5–8 results that were performed at 10 V/5 A current limit is abridged as follows: Experiment 5C findings of Row3 TEHs (TEH12–15 with T12–15), Experiment 6C findings of Row2 TEHs (TEH8–11 with T8–11), Experiment 7C findings of Row1 TEHs (TEH4–7 with T4–7) and Experiment 8C findings of Row0 TEHs (TEH0–3 with T0–3). The detailed raw measurements of Experiments 5–8 results are respectively captured in Figure S5 to Figure S8 as structured in Supporting Information S1. They are also respectively tabulated in Supporting Information S2 in Tables S5–S8 and summarized in Table S22. Experiments 5C–8C input power versus hot-side temperature findings are plotted in Figure 10.

3.3 | Experiments 9–12 (TEHs Row0–3 @ 8 V) Results

Experiments 9–12 results that were performed at 8 V/ 5 A current limit is abridged as follows: Experiment 9C findings of Row0 TEHs (TEH0–3 with T0–3), Experiment 10C findings of Row1 TEHs (TEH4–7 with T4–7), Experiment 11C findings of Row2 TEHs (TEH8–11 with T8–11) and Experiment 12C findings of Row3 TEHs (TEH12–15 with T12–15). The detailed raw measurements of Experiments 9–12 results are respectively captured in Figures S9–S12 as structured in Supporting Information S1. They are also respectively tabulated in Supporting Information S2 in Tables S9–S12 and summarized in Table S23. Experiments 9C–12C input power versus hot-side temperature findings are plotted in Figure 11.

3.4 | Experiments 13–16 (TEHs Row0–3 @6 V) Results

Experiments 13–16 results that were performed at 6 V/5 A current limit is abridged as follows: Experiment 13C findings of Row3 TEHs (TEH12–15 with T12–15), Experiment 14C findings of Row2 TEHs (TEH8–11 with T8–11), Experiment 15C findings of Row1 TEHs (TEH4–7 with T4–7) and Experiment 16C findings of Row0 TEHs (TEH0–3 with T0–3). The detailed raw measurements of Experiments 13–16 results are respectively captured in Figure S13 to S16 as structured in Supporting Information S1. They are also respectively tabulated in Supporting Information S2 in Tables S13–S16 and summarized in Table S24.

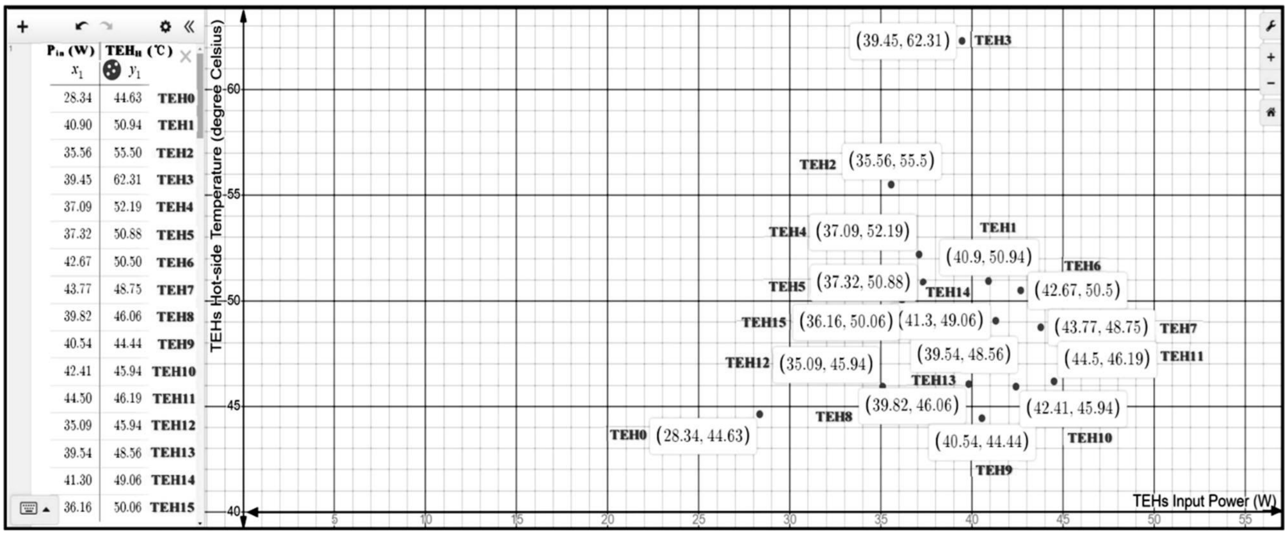

FIGURE 9 | Experiments 1C–4C (TEH0–3, TEH4–7, TEH8–11, and TEH12–15) power input (W) versus TEHs hot-side heatsink temperature (°C) at 12 V.

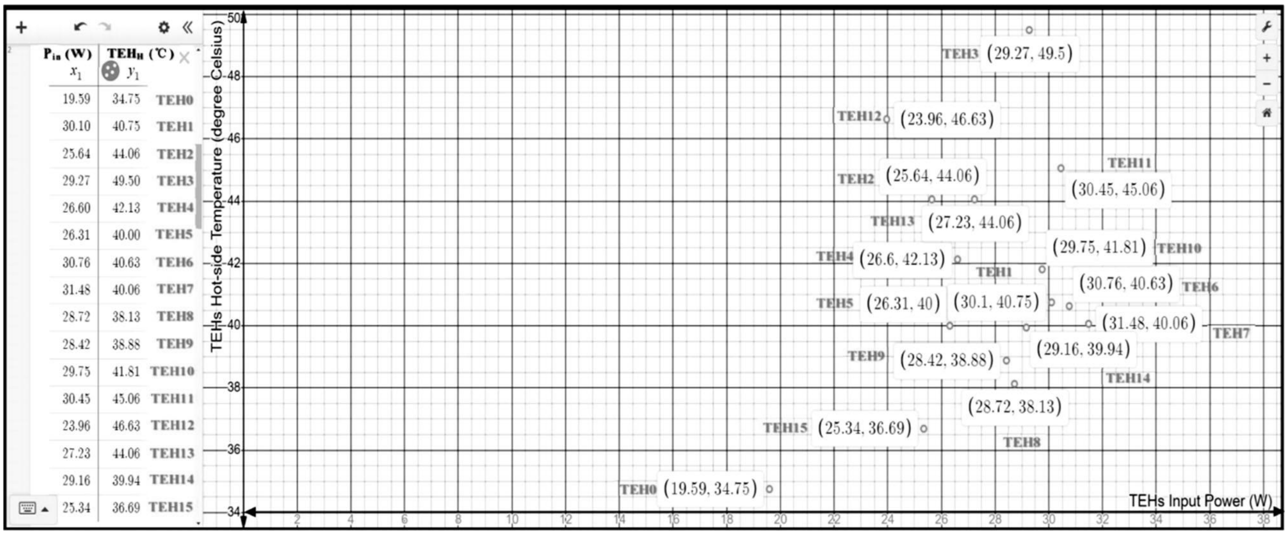

FIGURE 10 | Experiments 5C–8C (TEH12-15, TEH8-11, TEH4-7, and TEH0-3) power input (W) versus TEHs hot-side heatsink temperature (°C) at 10 V.

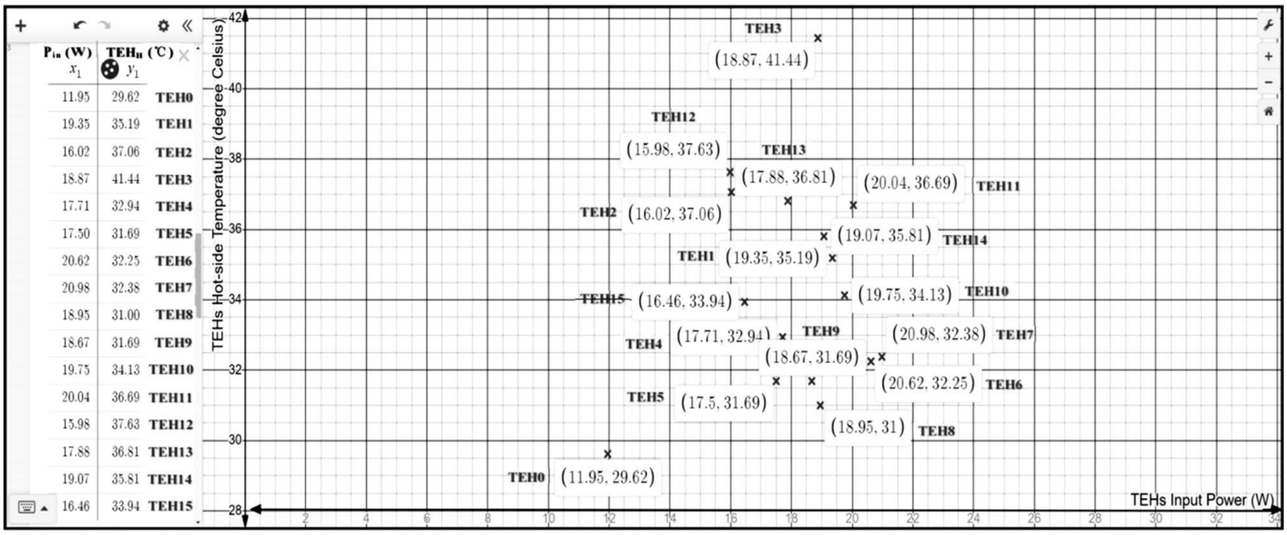

FIGURE 11 | Experiments 9C–12C (TEH0-3, TEH4-7, TEH8-11, and TEH12-15) power input (W) versus TEHs hot-side heatsink temperature (°C) at 8 V.

Experiments 13C–16C input power versus hot-side temperature findings are plotted in Figure 12.

3.5 | Experiments 17–20 (TEHs Row0–3 @4 V) Results

Experiments 17–20 results that were performed at 4 V/5 A current limit is abridged as follows: Experiment 17C findings of Row3 TEHs (TEH12–15 with T12–15), Experiment 18C findings of Row2 TEHs (TEH8–11 with T8–11), Experiment 19C findings of Row1 TEHs (TEH4–7 with T4–7) and Experiment 20C findings of Row0 TEHs (TEH0–3 with T0–T). The detailed raw measurements of Experiments 17–20 results are respectively captured in Figure S17 to Figure S20 as structured in Supporting Information S1. They are also respectively tabulated in Supporting Information S2 in Tables S17–S20 and summarized in Table S25. Experiments 17C–20C input power versus hot-side temperature findings are plotted in Figure 13.

The research results highlights are summarized in Tables 1–4 and in Figure 14. The findings are interpreted in Section 4.

It should be noted that, in some of the presented results, the measurements were captured in reverse—this is not a mistake but to align it with the order in which some of the experiments were conducted. Normally, the experiments first started with 12 V applied to TEHs 0–3, then TEHs 4–7, followed by TEHs 8–11, and finally TEHs 12–15. Once 12 V is done, 10, 8, 6, and 4 V were supplied to each group of TEHs and tested in turns again. Now, being a time-consuming exercise, to save time and avoid mistakes changing over the TEHs power supplies order and the cold-side temperature sensors on TEHs 12–15 to TEHs 0–3 and vice versa once a particular voltage testing was done, it was prudent when

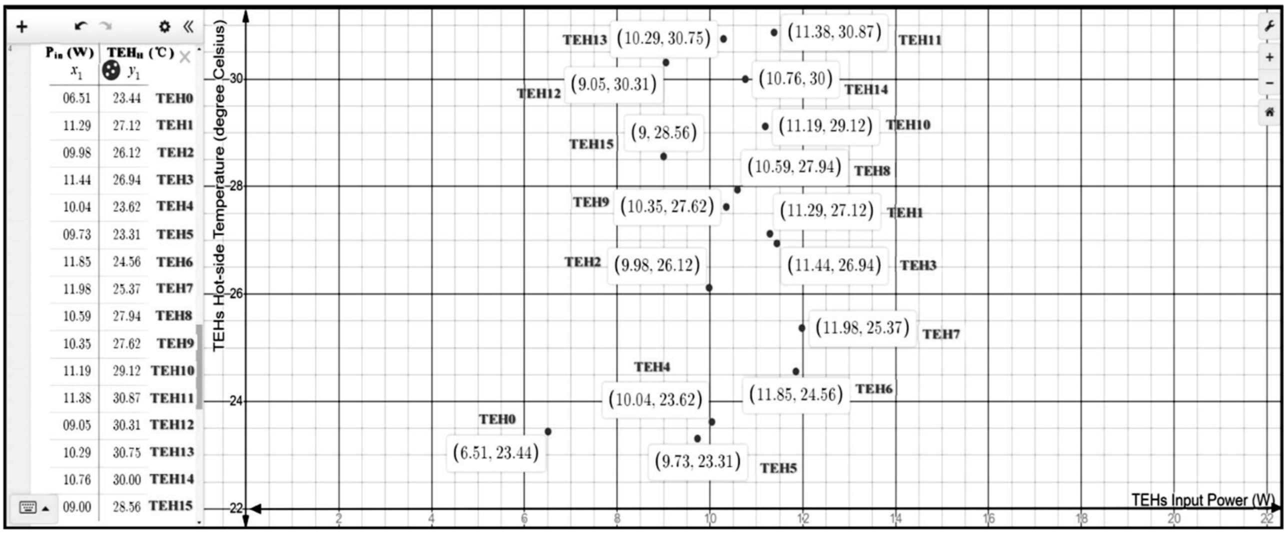

FIGURE 12 | Experiments 13C–16C (TEH12-15, TEH8-11, TEH4-7, and TEH0-3) power input (W) versus TEHs hot-side heatsink temperature (°C) at 6 V.

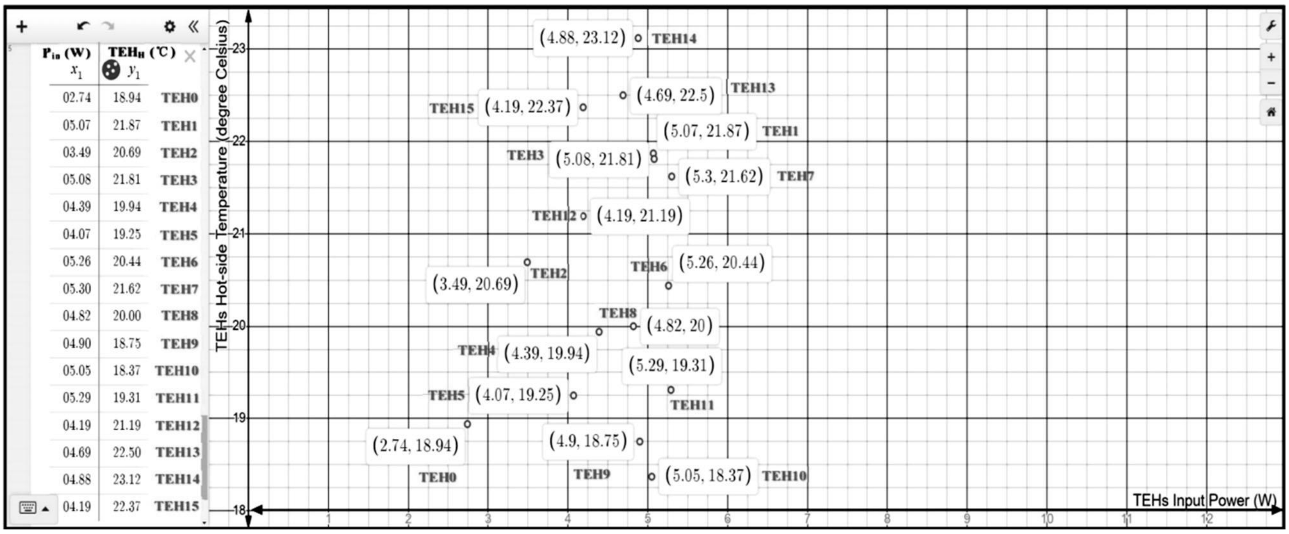

FIGURE 13 | Experiments 17C–20C (TEH12-15, TEH8-11, TEH4-7, and TEH0-3) power input (W) versus TEHs hot-side heatsink temperature (°C) at 4 V.

changing from one voltage to the other, to just leave everything in place and perform the experiments in descending order and then back again in ascending order. So, shown in Supporting Information S1 was how the experiments were conducted/recorded. For further details, refer to Supporting Information S2 and S3 for more explanations. The presented findings including those in Supporting Information S1 to S3 are succinctly analyzed and summarized in what follows.

4 | Results Analysis

This section interprets the findings that were summarily presented variously in Section 3. Supporting Information S1 contains the raw results, which are further tabulated in Supporting Information S2 and analyzed extensively in Supporting Information S3 and herein as briefly as possible. It should be noted that Figures S1 to S20 and Tables S1–S20 each has three sets of measured experimental data labeled A–C. Measurements A were done after ~0 min of powering-on the TEHs, Measurements B were done after ~5 min of powering-on the TEHs, and Measurements C were done after ~10 min of powering-on the TEHs. This was to investigate the effect of TEHs operational duration on its performance/efficiency. Measurements C (recorded after 10 min of powering-on the TEHs), gave the best results across—it was observed that all the TEHs efficiency increased with time. That is, for the duration all the TEHs were powered-on, regardless of the supply voltage used, and with everything being constant, all the TEHs hot-side temperature increased with time while their input power decreased with time (see the color coding in Tables S1–S20)—this was simply due to Ohmic heating, which over time consequently increased, hence increasing all the TEHs hot-side temperature, as well as their resistance—and the higher the supply voltage (or input power), the higher the Joule

TABLE 1 | Summary of TEH0–TEH15 hot-side temperature measurements at 12, 10, 8, 6, and 4 V, $T_{hot\ mean}$, and H_{rank}.

TEH0–TEH15 hot-side heatsink water temperature measurements at 12, 10, 8, 6, and 4 V, as well as $T_{hot\ mean}$ (°C)								
TEHs	**DS18B20**	**12 V**	**10 V**	**8 V**	**6 V**	**4 V**	$\mathbf{T_{hot\ mean}}$	$\mathbf{H_{rank}}$
TEH0	T0 (°C)	44.63	34.75	29.62	23.44	18.94	30.276	16
TEH1	T1 (°C)	50.94	40.75	35.19	27.12	21.87	35.174	7
TEH2	T2 (°C)	55.50	44.06	37.06	26.12	20.69	36.686	2
TEH3	T3 (°C)	62.31	49.50	41.44	26.94	21.81	40.400	1
TEH4	T4 (°C)	52.19	42.13	32.94	23.62	19.94	34.164	9
TEH5	T5 (°C)	50.88	40.00	31.69	23.31	19.25	33.026	13
TEH6	T6 (°C)	50.50	40.63	32.25	24.56	20.44	33.676	11
TEH7	T7 (°C)	48.75	40.06	32.38	25.37	21.62	33.636	12
TEH8	T8 (°C)	46.06	38.13	31.00	27.94	20.00	32.626	14
TEH9	T9 (°C)	44.44	38.88	31.69	27.62	18.75	32.276	15
TEH10	T10 (°C)	45.94	41.81	34.13	29.12	18.37	33.874	10
TEH11	T11 (°C)	46.19	45.06	36.69	30.87	19.31	35.624	5
TEH12	T12 (°C)	45.94	46.63	37.63	30.31	21.19	36.340	4
TEH13	T13 (°C)	48.56	44.06	36.81	30.75	22.50	36.536	3
TEH14	T14 (°C)	49.06	39.94	35.81	30.00	23.12	35.586	6
TEH15	T15 (°C)	50.06	36.69	33.94	28.56	22.37	34.324	8
$TEH_{hot\ mean}$		49.49	41.44	34.39	27.23	20.64	34.638	

Note: * = anomaly, H_{rank} = TEH hot-side temperature rank, $T_{hot\ mean}$ = A TEH mean temperature from 4 to 12 V, $TEH_{hot\ mean}$ = TEH0-15 hot-side mean temperature per a supply voltage.

TABLE 2 | Categorical summary of TEH0–TEH15 heating performance ranking.

Remark	**TEH0 to TEH15 ranking in terms of their mean hot-side temperature ($\mathbf{T_{hot\ mean}}$) in°C**			
Best	TEH3 = H_{rank1}	TEH2 = H_{rank2}	TEH13 = H_{rank3}	TEH12 = H_{rank4}
	$T3_{hot\ mean}$ = 40.400	$T2_{hot\ mean}$ = 36.686	$T13_{hot\ mean}$ = 36.536	$T12_{hot\ mean}$ = 36.340
Better	TEH11 = H_{rank5}	TEH14 = H_{rank6}	TEH1 = H_{rank7}	TEH15 = H_{rank8}
	$T11_{hot\ mean}$ = 35.624	$T14_{hot\ mean}$ = 35.586	$T1_{hot\ mean}$ = 35.174	$T15_{hot\ mean}$ = 34.324
Good	TEH4 = H_{rank9}	TEH10 = H_{rank10}	TEH6 = H_{rank11}	TEH7 = H_{rank12}
	$T4_{hot\ mean}$ = 34.164	$T10_{hot\ mean}$ = 33.874	$T6_{hot\ mean}$ = 33.676	$T7_{hot\ mean}$ = 33.636
Bad	TEH5 = H_{rank13}	TEH8 = H_{rank14}	TEH9 = H_{rank15}	TEH0 = H_{rank16}
	$T5_{hot\ mean}$ = 33.026	$T8_{hot\ mean}$ = 32.626	$T9_{hot\ mean}$ = 32.276	$T0_{hot\ mean}$ = 30.276

heating and eventually the hotter the TEHs hot-side. Measurements C were used henceforth and hence, the results analysis discussed next, is based mostly on Measurements C. These highlights/insights, are in sum exemplified in Figure 14.

Experiments 1C–20C results analysis are abridged in Tables 1–4, whereby TEH0-15 hot-side temperature and associated input power are compared and ranked. As evident, akin to the detailed findings presented in Supporting Information S1 and S2, the TEHs performances varied across-in certain instances (e.g., TEH7s in Experiment 13–16), the TEHs hot-side heatsink water temperature is proportional to the consumed input power as expected, whereas in certain instances (e.g., TEH12 in Experiments 5–8), it is not. Generally, even though the test conditions were slightly different when the different TEHs rows at a particular voltage were tested in turns, considering the TEDs are of the same model/made, one would still expect the performances to be very close despite the tiny measurements biases. However, some TEHs, especially TEH3 akin TEC3 in [23], had the highest heating at 12, 10, and 8 V but also interestingly not at 6 and 4 V. TEH0 used the least input power regardless of the test conditions and produced the least hot-side temperatures at the respective supply voltages and this is not because TEH0 is most efficient, but because its performance range is defective.

From observing Table 1, it can be seen that the TEHs hot-side temperature was highest at 12 V and TEH3 had the highest hot-side temperature, hence ranked #1, whereas TEH0 had the lowest hot-side temperature, hence ranked #16. It can also be noticed that $TEH_{hot\ mean}$ in Table 1 has an arithmetic progression with a common difference of ~7 V between the five successive supply voltages used. The significance of this is, $TEH_{hot\ mean}$ can

TABLE 3 | Summary of TEH0–TEH15 input power measurements at 12, 10, 8, 6, and 4 V, TEH $P_{in\ mean}$, P_{rank}, and H_{rank}.

TEHs	12 V P_{in} (W)	10 V P_{in} (W)	8 V P_{in} (W)	6 V P_{in} (W)	4 V P_{in} (W)	$P_{in\ mean}$ (W)	P_{rank}	H_{rank}
TEH0	28.34	19.59	11.95	06.51	02.74	13.826	1	16
TEH1	40.90	30.10	19.35	11.29	05.07	21.342	12	7
TEH2	35.56	25.64	16.02	09.98	03.49	18.138	3	2
TEH3	39.45	29.27	18.87	11.44	05.08	20.822	10	1
TEH4	37.09	26.60	17.71	10.04	04.39	19.166	6	9
TEH5	37.32	26.31	17.50	09.73	04.07	18.986	5	13
TEH6	42.67	30.76	20.62	11.85	05.26	22.232	14	11
TEH7	43.77	31.48	20.98	11.98	05.30	22.702	16	12
TEH8	39.82	28.72	18.95	10.59	04.82	20.580	9	14
TEH9	40.54	28.42	18.67	10.35	04.90	20.576	8	15
TEH10	42.41	29.75	19.75	11.19	05.05	21.630	13	10
TEH11	44.50	30.45	20.04	11.38	05.29	22.332	15	5
TEH12	35.09	23.96	15.98	09.05	04.19	17.654	2	4
TEH13	39.54	27.23	17.88	10.29	04.69	19.926	7	3
TEH14	41.30	29.16	19.07	10.76	04.88	21.034	11	6
TEH15	36.16	25.34	16.46	09.00	04.19	18.230	4	8
$TEH_{mean\ power}$	39.03	27.67	18.11	10.34	04.59	19.948		

Note: $TEH_{mean\ power}$ = TEH0–15 mean input power per a supply voltage, $P_{in\ mean}$ (W) = A TEH mean input power from 4 to 12 V, P_{rank} = TEH input power rank.

TABLE 4 | Categorical summary of TEH0 to TEH15 mean input power consumption ranking.

Remark	TEH0 to TEH15 in terms of their mean input power ($P_{in\ mean}$) consumption in (W)			
Least	TEH0 = P_{rank1}	TEH12 = P_{rank2}	TEH2 = P_{rank3}	TEH15 = P_{rank4}
	$P_{in\ mean}$ = 13.826	$P_{in\ mean}$ = 17.654	$P_{in\ mean}$ = 18.138	$P_{in\ mean}$ = 18.230
Less	TEH5 = P_{rank5}	TEH4 = P_{rank6}	TEH13 = P_{rank7}	TEH9 = P_{rank8}
	$P_{in\ mean}$ = 18.986	$P_{in\ mean}$ = 19.166	$P_{in\ mean}$ = 19.926	$P_{in\ mean}$ = 20.576
More	TEH8 = P_{rank9}	TEH3 = P_{rank10}	TEH14 = P_{rank11}	TEH1 = P_{rank12}
	$P_{in\ mean}$ = 20.580	$P_{in\ mean}$ = 20.822	$P_{in\ mean}$ = 21.034	$P_{in\ mean}$ = 21.342
Most	TEH10 = P_{rank13}	TEH6 = P_{rank14}	TEH11 = P_{rank15}	TEH7 = P_{rank16}
	$P_{in\ mean}$ = 21.630	$P_{in\ mean}$ = 22.232	$P_{in\ mean}$ = 22.332	$P_{in\ mean}$ = 22.702

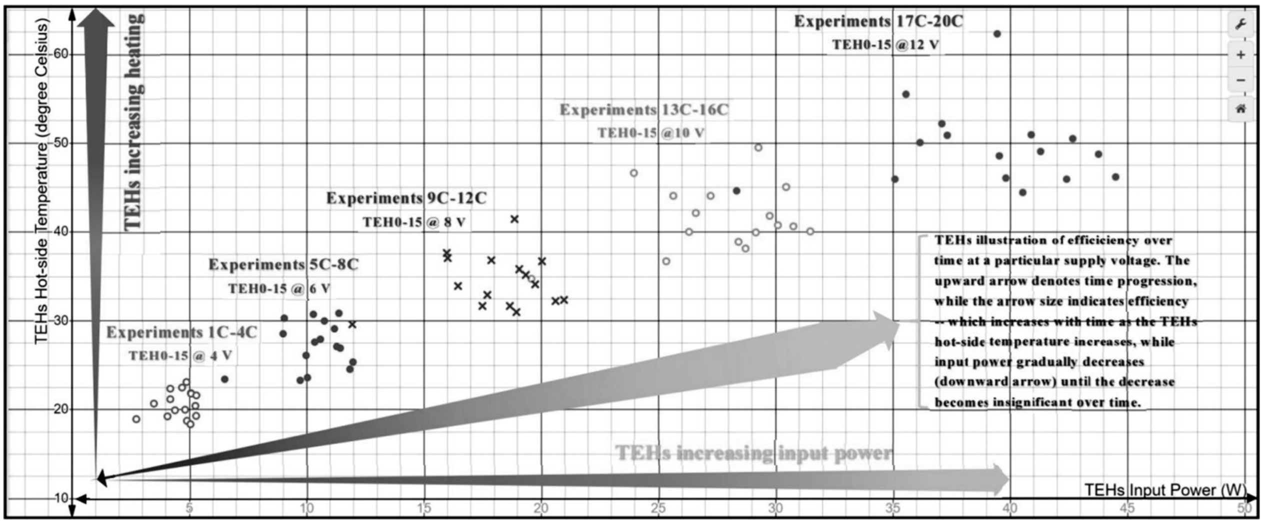

FIGURE 14 | Experiments 1C to 20C combined plots of TEH0–TEH15 showing P_{in} (W) versus $TEH_{Hotside}$ (°C) at 4, 6, 8, 10, and 12 V.

be used to easily estimate the TEHs average hot-side temperature at a particular supply voltage. For example, $TEH_{hot\ mean}$ at 14 V can be estimated to be ~56 (+/− 0.5 tolerance)°C.

Table 2 categorically summarizes TEH0–15 hot-side temperature in terms of best, better, good and bad performances. As noticed, TEH3, TEH2, TEH13 and TEH12 had the highest $T_{hot\ mean}$ of 40.4°C, 36.686°C, 36.536°C, and 36.34°C respectively; whereas TEH5, TEH8, TEH9 and TEH0 had the lowest $T_{hot\ mean}$ of 33.026°C, 32.626°C, 32.276°C, and 30.276°C. To put this into practical perspective, if the objective is to achieve ~36°C and power is critical (say < 18 W), then TEH12 will be the best and the most efficient TEH to use. This goes to show it is not just all about having a TEH hot-side with the highest temperature but also about the objective of the application, needing the necessary trade-offs to attain the most optimal and efficient outcome.

From observing Table 3, it can be seen that the TEHs mean input power was highest at 12 V. TEH0 had the least mean input power consumed, hence ranked #1; whereas the highest mean input power was consumed by TEH7, hence ranked #16. It should be noted that, this P_{rank} does not translate into efficiency, as TEH0 had the worst H_{rank} of 16; whereas TEH7 had a H_{rank} of 12. Since H_{rank} is indirectly proportional to P_{rank} and a TEH hot-side temperature is directly proportional to power supply voltage, a TEH is more efficient if it has a higher hot-side temperature or H_{rank} with less power consumed or P_{rank}, but not vice versa. $TEH_{mean\ power}$ in Table 3 also has a rough arithmetic progression with a common difference—that in terms of absolute value, approximates each successive power supply voltage. As examples, $TEH_{mean\ power}$ arithmetic progression common difference between 12 and 10 V power supply voltages is 11.36 W (39.03–27.67 W)—which is ~12 V; between 10 and 8 V power supply voltages is 9.56 W (27.67–18.11 W)—which is ~10 V; between 8 and 6 V power supply voltages is 7.77 W (18.11–10.34 W)—which is ~8 V and between 6 and 4 V power supply voltages is 5.75 W (10.34–4.59 W)—which is ~6 V. The signiicance of this is, $TEH_{mean\ power}$ can be used to quickly estimate the TEH average input power at a particular supply voltage. For example, $TEH_{mean\ power}$ at 14 V can be estimated to be ~52.5 (+/− 0.5 tolerance) W.

Table 4 categorically summarizes TEH0–15 average input power consumption in terms of least, less, more, and most. As noticeable, TEH0 can produce a $T_{hot\ mean}$ of 30.276°C with a $P_{in\ mean}$ of 13.826 W, as opposed to TEH7 $T_{hot\ mean}$ of 33.636°C with a $P_{in\ mean}$ of 22.702 W. In context, if the goal is to achieve ~30°C and energy resource is critical, TEH0 will be more efficient.

Some TEHs (e.g., TEH12) also individually and relatively performed better at lower supply voltages (e.g., 10 V) than at higher supply voltages (12 V). In fact, TEH1, TEH2, TEH3, TEH4, TEH12, and TEH13 at 8 V, outperformed TEH0 at 10 V in terms of both high hotside temperature produced and low power consumed. The possible reasons in addition to the low efficiency based on the TEDs semiconductor chemistry used, are substandard manufacturing/assembly, bad design, and poor workmanship. This study goes to show how tricky it is to use/design with TEDs, as the performance relatively varied across even when everything was approximately the same—therefore, how can a single or few TEDs be used in a research/application (as has been the case in some published studies/projects) and a fair conclusion on TED performance/efficiency is drawn? It is apparent that had TEH0 or TEH3, and so forth been used solely, the reported outcome would have been different and bias.

It should therefore be emphasized that a TEH consuming the least input power do not translate to the most efficient, especially if its hotside temperature is not the highest, as all the TEHs were supplied the same inputs but they all gave relatively different outputs/responses—which were used to characterize their in/efficiencies. For comparison sake, the TEHs in/efficiency were also expressed in Supporting Information S2 Tables S21–S25, in terms of the traditional TEHs heating coefficient of performance (TEH_{CoP}), the TEHs Carnot heater CoP (TEH_{Carnot_CoP}) and the combined CoP (CoP_H). However, they were not used to measure the TEHs in/effciency in this study because: (i) the TEDs used did not have a datasheet specifying the TEDs intrinsic parameters (the Seebeck coefficient, the internal resistance, and the thermal conductivity) values, (ii) as a result, the TEHs heat flux or heating power (Q_H) could not be determined, consequently (iii) could not be used to compute the TEHs actual in/efficiencies and (iv) even if the Q_H and the various CoPs were determined and used, they will not give a true measure/reflection of the TEHs in/efficiency as per the objective of the study—which is not necessarily to make a TEH efficient but to study which TEH is relatively efficient and can produce the most heat and with the least consumed power, when subjected to the same test conditions. In this case, using the conventional CoP metrics will mean TEH0 will wrongly have the best performance and TEH3 the worst performance, which will be misleading, as TEH0 high CoP is simply because it could not consumed more input power (and consequently produced the least hot-side temperature) and eventually had the least temperature difference which are the determining factors for a good CoP. Whereas, unlike TEH0 hotside maximum temperature of 44.63°C at 12 V, TEH3 produced up to 62.31°C at 12 V because it could drew more current, hence consumed more power making it to have the worst CoP. However, the correct way to use CoP in this case will be in reverse, whereby the highest CoP means the worst TEH and vice versa. As a result, it was prudent in this case to simply use the TEHs hot-side temperature and the consumed power as the apt metrics to relatively measure in/efficiency. In light of these findings, it can be concluded and recommended that, a single TED should not be used and a general performance conclusion cannot be drawn from it solely and without also stating all the technical and experimental data used/obtained.

5 | Conclusion

Energy is a very vital resource. Thermoelectricity lends itself as different forms of energy converter; however, the conversion processes are not always efficient due to intrinsic limitations in the chosen semiconductor chemistry and also in the practical physics. This paper delved on the practical physics on TEDs when operated as TEHs, as this heating aspect in most scholarly works is often overlooked and if discussed, it is mostly done in passing when discussing TECs. Like TECs, designing with TEHs is not a one shoe fits all device. In our study, by using similar tests setup and operation conditions, 20 experiments each having three measurements done immediately at power-on, after ~5 and ˜10 min later, were conducted with 16

TEHs supplied in turns with 12, 10, 8, 6, and 4 V, and various insightful observations were made and assessed. The measurements captured after ~10 min were more efficient and were used further in the study. It was noticed that, a TEH's temperature on its hot-side increases upon powering-on-which is first due to the Peltier effect and shortly after with time, the TEH hot-side temperature is enhanced by the Joule or Ohmic heating—which in turn will cause the input power to slowly keep decreasing, thereby making TEHs more efficient. Also, a TEH produces more heat on its hot-side in direct proportion to its input voltage; however, the same relative performance is not always the case across other TEHs of the same model. For example, TEH3 had a hot-side temperature of 62.31°C at 12 V which consumed a power input of 39.45 W but at 4 V, it only produced 21.81°C which consumed a power input of 5.08 W. Relative to TEH14, at 4 V, it consumed a power of 4.88 W but produced a hot-side temperature of 23.12°C, but at 12 V it produced 49.06°C with a power consumption of 41.3 W. This means TEH3 is more efficient than TEH14 at 12 V but inefficient than TEH14 at 4 V. Another observation is TEH12—which was more efficient at 10 V than at 12 V. The same observation is evident across other TEHs used. From our practical findings, it is not guaranteed a TEH will perform properly, consistently, and similarly throughout its operation. CoP could be a misleading metric to measure efficiency—which is at times research/application objective specific. The concepts of $T_{hot\ mean}$ and $TEH_{mean\ power}$ were introduced—which can be respectively used to easily estimate a TEH's average hot-side temperature and a TEH's average input power at a particular supply voltage. In conclusion, optimal TEHs design can be attained by taking different aspects into considerations; which include but not limited to good manufacturing and production standards, good design and implementation, quality devices, good workmanship, proper power supply, right application, savvy end user, operational/environmental conditions especially temperature dynamics, trade-offs, as well as monitoring and choosing good control strategies. A future recommended study will be to include other TEDs to compare and contrast their performances and taking into account all the problems faced. Also, both TEHs and TECs will be studied concurrently and in exactly the same setup with forward and reverse power supply polarities.

Author Contributions

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

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that supports the findings of this study are available in the Supporting Information S1 and S2 of this article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.