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Compatibility assessment of TEGs arrangement coupled with DC/DC converter to harvest electricity from low-temperature heat sources

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ABSTRACT

Expanding intelligent control systems based on the Internet of Things (IoT) requires powering sensors, actuators, and wireless data transfer, which may be located off-grid or difficult to access. Energy harvesting from industrial excess heat by thermoelectric generators (TEGs) can help to overcome challenges ahead. A fully integrated TEG system, however, remains an obstacle to the effective conversion of heat into electricity for IoT applications. The purpose of this paper is to investigate experimentally the electrical arrangement of TEGs and the design of a DC-DC boost converter in order to optimize the harvesting of electrical power from low-temperature sources of heat in TEG systems. The results of this study provide a guide for selecting a suitable arrangement in a system with several TEGs as well as for the design of matched DC-DC converters with desired electrical generators and consumers. This study shows the impact of specialized arrangement of TEGs in a power generation system to optimize the output power of a DC-DC converter. Accordingly, the most suitable electrical combination of four TEG modules among series, parallel-series, and parallel connections is discussed with heat source temperatures lower than 55 °C, between 55 and 75 °C, and higher than 75 °C. Based on the results of the studied TEG system, it is determined that using inductors and capacitors lower than 0.33 μH and 0.47 μF, respectively in the converter's circuit decreases the output power dramatically, and delays the startup point to higher heat source temperatures.

1. Introduction

Increasing energy costs led to expanding research into energy efficiency and intelligent energy control for residential or industrial buildings. These intelligent control systems usually require a considerable number of sensors and controllers that may be located far from the grid. Providing power to these devices may increase the manufacturing or maintenance costs of the system. Since there are various sorts of heat sources in different locations of residential and industrial buildings, energy harvesting is a safe, durable, and environmentally friendly way to overcome the above challenges. Energy harvesting using thermoelectric generators (TEGs) is an ideal choice due to their long lifespan, no moving parts, noiseless operation, no orientation limitations, and wide operating temperature ranges [1]. A TEG is made of semiconductor materials providing electrical potential when a temperature difference is applied across the module. Power generation in a TEG is based on the Seebeck effect. It is well known that TEGs can be used widely in energy harvesting applications [2,3] such as wearables [4,5], infrastructures [6], wireless sensor networks [7], and hybrid energy harvesting [8,9]. The low conversion efficiency, however, prevents TEGs from being widely used, particularly in low-temperature applications.

Lee et al. [10] developed inorganic and efficient thermoelectric materials with chalcogenide-nanostructured carbon nanotubes to increase power density at human body temperature. They fabricated a flexible module with 150 thermoelectric pairs and a maximum power density of 24 mW/m^2 at a 5 K temperature difference across the module. In parallel with material development, Rezania et al. [11] applied the Taguchi method for optimization of TEG structure, where the length to height ratio of the thermoelectric elements had a significant impact on achieving maximum efficiency. Toan et al. [12] developed high-performance electrochemical-based thermoelectric materials. The power factor of their proposed material was enhanced approximately-three times and its thermal conductivity was reduced to half compared to pure bismuth telluride films under the same operating conditions. One of their fabricated devices, with 66 thermoelectric pairs and dimensions of 30 mm × 30 mm × 2.8 mm, successfully provided maximum output power and power density up to 601 μW and 66.8 μW/cm^2, respectively, at an applied temperature difference of 11 K. Their

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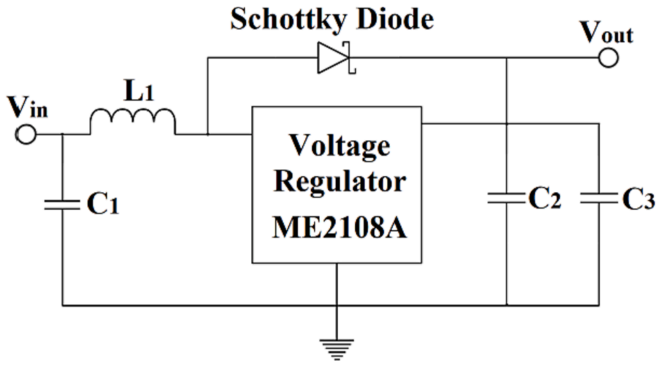

Fig. 1. Schematic of circuit of the DC-DC boost converter.

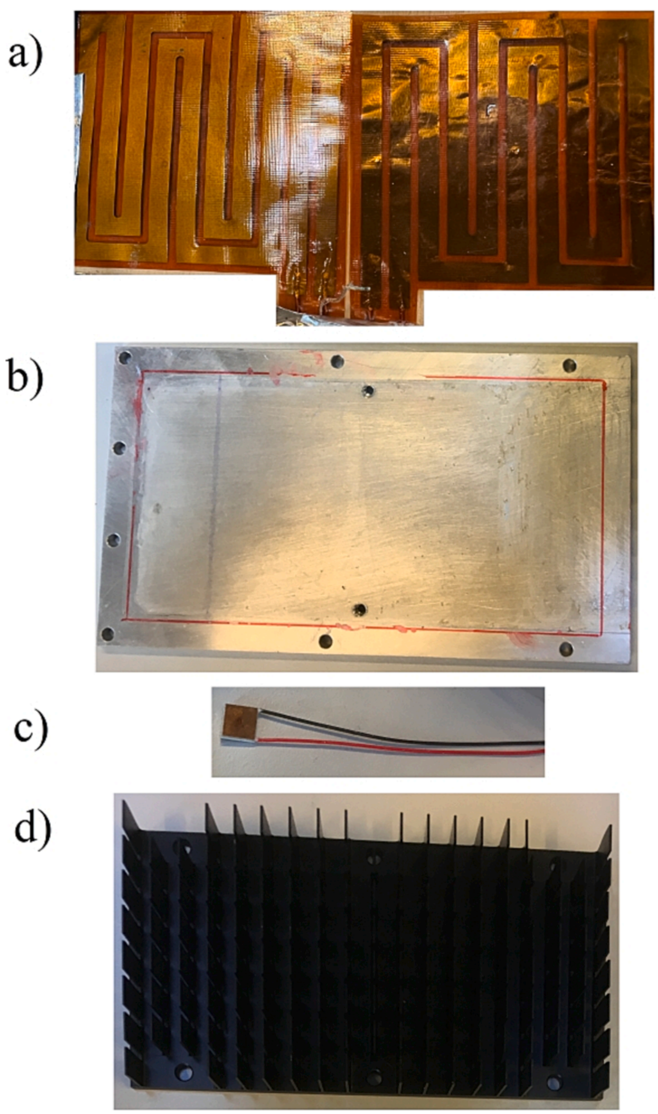

Fig. 2. Employed a) heaters, b) heater plate, c) TEG, and d) heat sink.

team also tested other wearable TEGs connected to a DC-DC converter to harvest thermal energy from the human wrist to power a wristwatch [13]. The output voltage of the DC-DC converter in their suggested application reached 2.8 V and 4 V at 2℃ and 8℃ temperature differences, respectively. Karimi Rad et al. [14] evaluated the impact of thermoelectric material properties such as thermal conductivity, the Seebeck coefficient, and electrical resistivity on the performance of

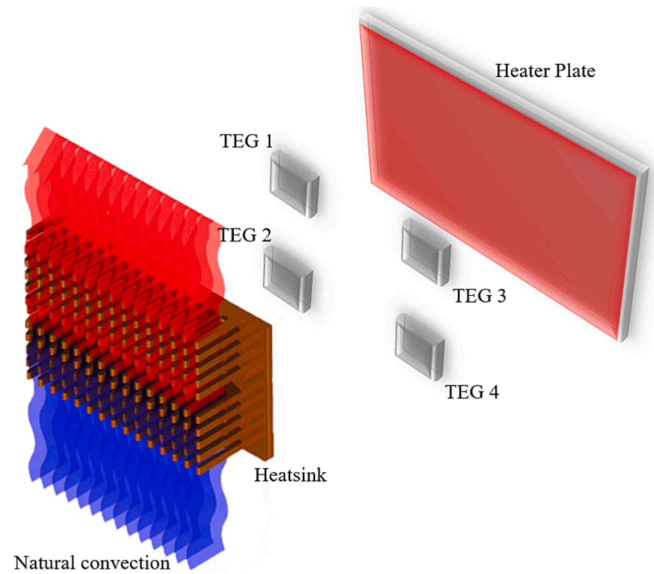

Fig. 3. A schematic diagram from the orientation of the thermoelectric energy harvesters.

TEGs. They developed a mathematical model resulting in that increasing the power factor by a factor of 15, which corresponds to a 13.33 enhancement in thermal conductivity, can increase the output power by 45 %. Shwetha and Lakshmi [15] designed an implantable self-powered TEG with a DC-DC converter device for a pacemaker. Their investigations show the high potential of thermal energy harvesting devices for biomedical applications. Implementing self-powered devices improves the reliability of these devices and can eliminate surgeries for replacing the batteries.

TEGs have been used in industries to control and measure several parameters at various places. Wu et al. [16] used TEG energy harvesting to sense and monitor a gas turbine. Their prototype provided output voltage and power of 2.4 V and 0.92 W, respectively, with a heat source temperature of 325℃. Nevertheless, a high-temperature heat source is not available in most industries for high efficiency energy harvesting. Therefore, energy harvesting from a low-temperature heat source, suitable for sensory and wireless communication applications, is a substantial challenge. Many researchers utilize two-phase heat pipes to enhance heat transfer at a small temperature difference since the heat transfer coefficient dramatically increases during evaporation and condensation [17]. For example, Casi et al. [18] investigated optimization of industrial waste heat recovery by TEG and used a two-phase heat exchanger to improve the temperature difference on the cold side of TEGs while the thermal resistance of the system was calculated under 0.25 K/W. They developed a numerical model using their setup to find the optimal configuration of the TEGs for maximizing the performance of the whole TEG system. Their TEG system generated 4.6 W of average electrical power for a 30-day testing period with an efficiency of 2.38 %.

The output voltage of a TEG is a function of the temperature difference across the module. Since temperature variations can affect the output voltage and the supplied voltage is usually low, most TEG-fed sensor applications use DC-DC converters to provide a suitable electrical potential for sensors. Vostrikov et al. [19] developed comprehensive modeling for a low-temperature gradient TEG. Their model contained a DC-DC converter for the TEG system with an accuracy of 9 % mean error for estimation of output power. They evaluated the output power at different thermal resistances between the TEG and the heat sink with consideration of the TEG's design parameters, the numerical model of the DC-DC converter, and ambient conditions. Cai et al. [20] developed an analytical model to study the response of TEGs to a transient and complex heat source. They employed a maximum power point

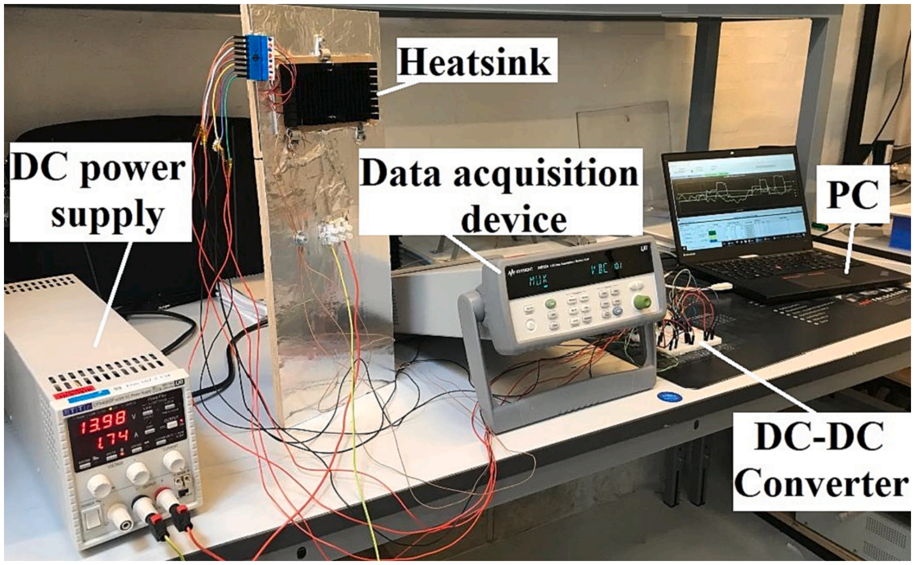

Fig. 4. Experimental setup.

Table 1
Defined reference values.

Parameter	Values	Unit
L_1	22	μH
C_1	0	μF
C_2	14	μF
C_3	14	μF
Output voltage	5	V
Ambient temperature	23.5 ± 0.5	°C

algorithm to apply optimal variable load on the TEG circuit to maximize power generation of the system. Moreover, the levelized cost of energy was improved by 13.2 % under random boundary conditions compared to steady-state heat input.

Singh and Kundu [21] proposed a digitally controlled DC-DC boost converter for TEG energy harvesting applications based on a discontinuous mode of operation. Their proposed converter provides output voltage and power of 1 V and 500 W, respectively, with a maximum efficiency of 72.59 % by using an adaptive pulse generator. Lin et al. [22] presented a self-startup and ultra-low-voltage boost DC-DC converter for TEG energy harvesting applications. They have used a two-stage auxiliary boost startup circuit with a large duty cycle circuit and a multi-stage voltage multiplier as well as a maximum power point tracking (MPPT) system to enhance tracking accuracy with low output voltage ripples. The converter could achieve peak end-to-end efficiency of 71 % at output voltage and power of 1.25 V and 540 μW, respectively. Miranda et al. [23] implemented a novel and complex topology for a high step-up DC-DC converter with a 4.5 V input and 218.2 V output voltage. They modeled the proposed converter in MATLAB/Simulink. Sahu et al. [24] designed and developed a DC-DC boost converter integrated with TEGs. They used 4 thermoelectric couples in their energy harvester that generated 325 mV open circuit voltage at a 410 °C temperature difference, while the DC-DC converter amplified this electric potential to 10 V. However, in most studies from the electrical point of view, DC-DC converters were designed without considering variations of thermal boundary conditions and TEG properties for investigation of the converter operating conditions. In contrast, load variations of the TEG affect its thermal and electrical behavior. On the other hand, cost or geometry limitations do not allow using a complicated converter circuit in many industrial applications.

Twaha et al. investigated the performance of a TEG system connected to a DC-DC converter for MPPT of the system's output [25,26]. They have considered the thermal and electrical properties of TEG in their model. They have controlled the output voltage by the duty cycle of the converter and variation of the switching time of the converter circuit. This modification resulted in an increase in output voltage depending on the duty cycle, however with relatively lower efficiency than the conventional perturb and observe method. Zhang et al. [27] developed an arithmetic optimization algorithm for MPPT of a centralized TEG energy harvester to identify a unique global maximum power point under different temperature gradients. They achieved 34.44 %, 8.17 %, and 6.03 % higher conversion efficiencies than perturb and observe, grey wolf optimization, and particle swarm optimization methods, respectively, with their developed algorithm.

In most thermoelectric energy harvesting applications, the voltage supply must be in a specific range to achieve a particular output voltage by the converter utilizing a certain duty cycle. MMPT control methods impose an additional load on energy harvester circuits. This study, however, aims to demonstrate that in a TEG system consisting of multiple modules and with limited range of output voltage and current, optimal TEGs arrangement and a DC-DC converter complemented with that arrangement can offer a simple and efficient method to improve the conversion efficiency and to reduce the cost of the energy harvesting system. This study, therefore, addresses the lack of research in investigation of critical power converter components such as inductors and capacitors as well as the effectiveness of these components on the performance of the DC-DC converter connected to TEGs in energy harvesting systems.

Moreover, in TEG systems with multiple energy harvesters, different electrical connections among the TEGs provide various levels of current–voltage inputs to the converter, which makes non-identical electrical output properties, especially in low-temperature energy harvesting applications. Most measuring devices and sensors are designed for a constant input voltage supply. Since the output voltage of TEGs mainly depends on the temperature difference created across the TEG, a converter with a constant duty cycle must be utilized to provide this supply voltage. A series connection of TEGs boosts the supplied voltage, while parallel connection of TEGs increases the supplied current. Thus, this study evaluates critical components of the converter for optimal startup condition and high-power generation in low-temperature energy harvesting applications. In this regard, the performance of TEGs connected to a DC-DC converter is investigated experimentally under low-temperature heat sources.

To the best knowledge of the authors of this work, the specialized design of DC-DC boost converters for constant output voltage in

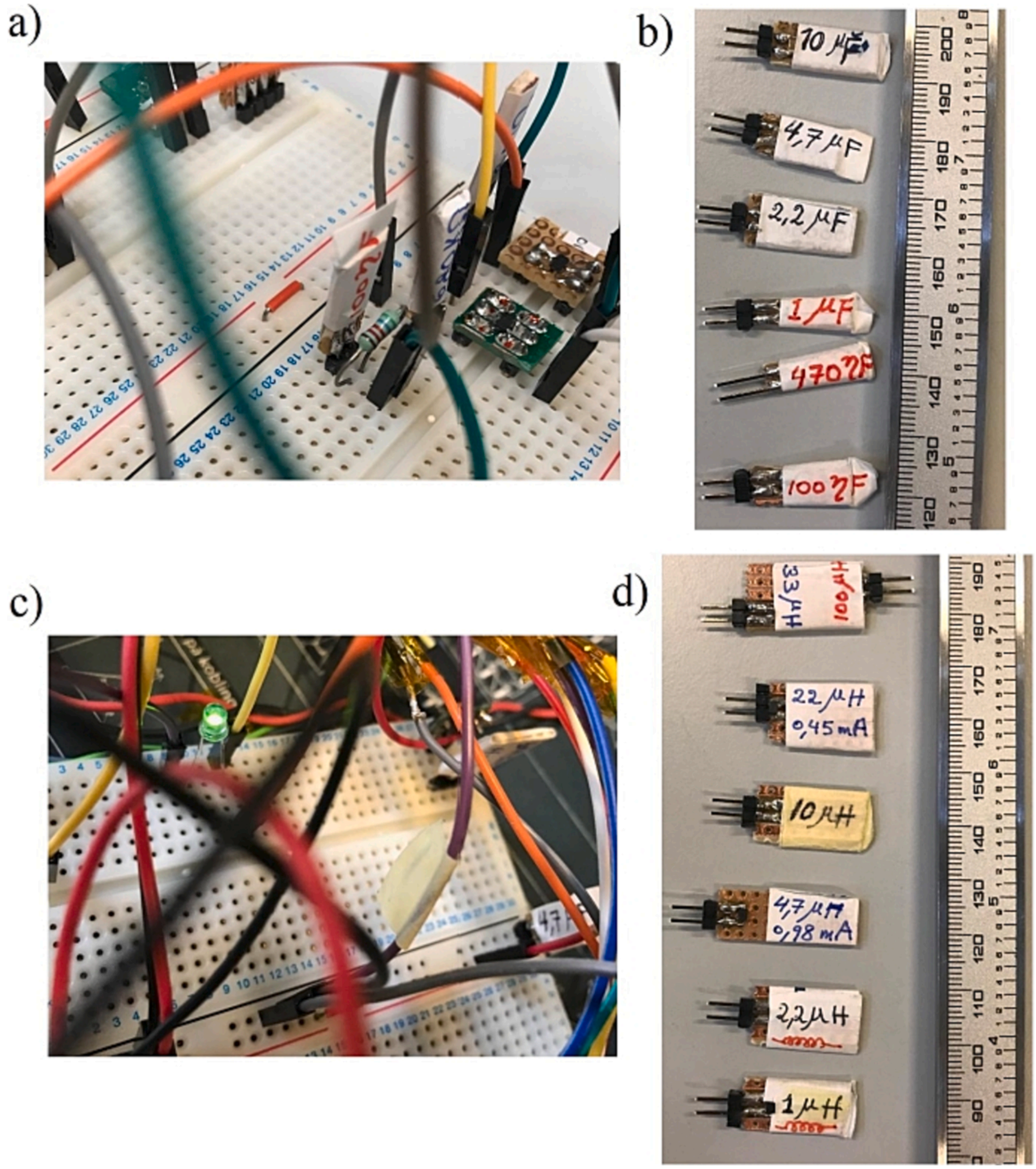

Fig. 5. Converter components a) voltage regulator of the DC-DC converter, b) utilized capacitors, c) external LED load, and d) utilized inductors.

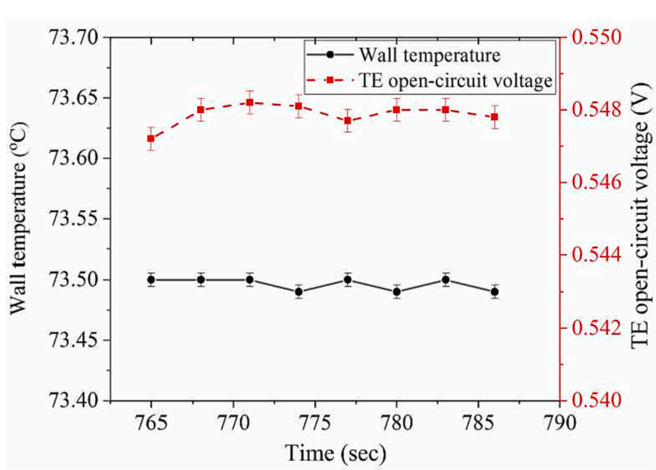

Fig. 6. Sample measurement of the wall temperature and open-circuit voltage of the TEGs.

thermoelectric energy harvesters has not been investigated yet. Moreover, for the first time, the effect of combinations of TEG electrical connections on the performance of the DC-DC converter is analyzed in this paper. This study will provide a guideline for an arrangement of low-temperature thermoelectric energy harvesters coupled with optimized DC-DC converters. It demonstrates effective links between electrical arrangement of the TEGs in series, parallel-series, and parallel connections, and electrical properties of the DC-DC converter for maximum power delivery.

2. Experimental setup

In this section, the experimental setup for investigation of the specialized design of the DC-DC boost converter made for thermoelectric energy harvesters is described. Fig. 1 shows the electrical circuit of the DC-DC boost converter in this study (L and C refer to inductor and capacitor, respectively). The DC-DC boost converter stores the electrical energy of the TEGs in an inductor and releases it at a higher voltage. Inductor circuits are connected to ground via a voltage regulator, also known as a switching transistor. When the voltage regulator switches

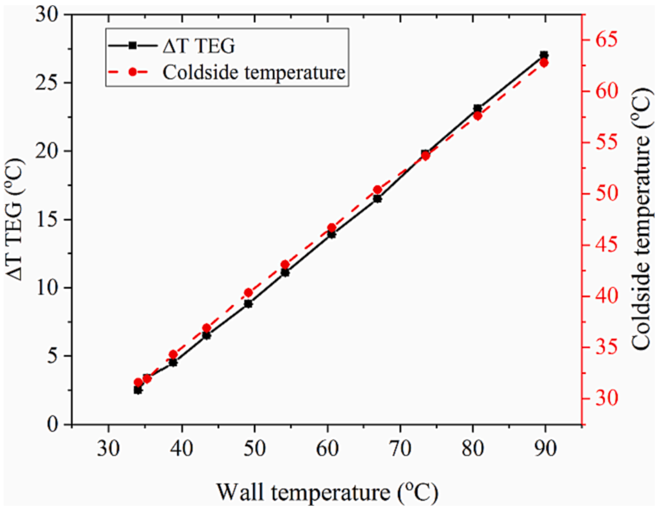

Fig. 7. Cold side temperature of the tegs and variation of the δt_{TEG} with the hot side temperature.

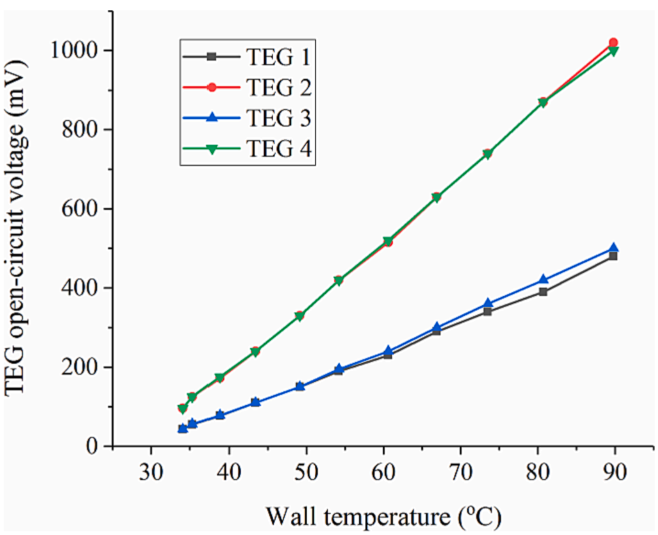

Fig. 8. Individual variation of open-circuit voltage of the TEGs with hot side temperature.

on, the inductor circuit connects to ground and stores input electrical power. Upon switching off, the stored energy is released to the output circuit by the Schottky diode circuit. The switching frequency of the boost converter determines the boosted output voltage. The relation between input and output voltages is determined as follows [28]:

$$V_{out} = \frac{V_{in}}{(1 - D)} \tag{1}$$

where, D is the duty cycle of the voltage regulator. Therefore, the inductance and capacitance in the converter do not affect its boosting ratio but influence the current and voltage ripples and the startup level. In this study, the input port of the converter is fed by four 8.7 mm × 8.7 mm × 1.7 mm TEGs, which are arranged in three different electrical combinations, including four TEGs in series (4S), two parallel branches of two TEGs in series (2P2S), and four TEGs in parallel (4P). Each TEG comprises 97 uni-couples with element dimensions of 0.6 mm × 0.4 mm × 0.4 mm. The resistance and figure-of-merit of the TEG modules were measured 13.70 Ω and 0.00162 K^{-1}, respectively, with a Z-meter device (DX4095 Peltier Z-Meter, TEC 308 Microsystems GmbH) at an ambient temperature of 24.7 °C. Two electrical heaters with a maximum power of 36 W are employed to impose thermal energy on the TEGs at different power levels. This creates various temperatures on the hot side of the TEGs. A heat sink (HS-DC-1/1-LFC-18) with dimensions of 116.8 mm × 61 mm × 18.2 mm (length × width × height) is used to reject heat from the cold side of the TEGs by natural air convection. Fig. 2 demonstrates the employed heaters, heater plate, TEGs, and heat sink. A green GaP light-emitting diode (LED) with diameter, resistance, and power dissipation of 5 mm, 173.9 Ω, and 85 mW, respectively, is used as an external load in the output circuit of the converter. Fig. 3 demonstrates a schematic diagram of the orientation of the TEGs in the experimental setup. As shown in this figure, four TEGs are used to provide electric power. In order to identify the TEGs, they are named TEG #1, TEG #2, TEG #3, and TEG #4.

In order to determine the average temperatures of the TEGs on the hot and cold sides, K-type thermocouples were connected in the center of the heater and heat sink. The temperatures, voltages, and currents were measured using a data acquisition device (KEYSIGHT 34972A). Fig. 4 shows the instruments included in the experimental setup. A DC power supply was used to apply voltage ranges between 4 and 14 V to the heater to create different wall temperatures. In the following, it is investigated how variations in inductance (L_1) and capacitance (C_1) (see Fig. 1) affect the performance of the energy harvester system. C_2 and C_3 are fixed at recommended values by the manufacturer since their capacitance values do not affect the input circuit. The inductance of L_1 and capacitance of C_1 vary in the ranges of 1–100 μH and 1–10 μF, respectively. Other parameters are kept fixed at their reference values during evaluation of the system response versus variation of design parameters. Table 1 shows the reference values determined in the experiments. The utilized voltage regulator, inductors, capacitors, and LED load applied to the converter's output are demonstrated in Fig. 5.

The experiments were repeated several times to check the output voltages of the TEGs individually, the electrical behavior of the system in the three different TEG combinations, and comparison of these parameters under the external load and open-circuit condition.

3. System characterization and error analysis

In this study, the performance of the system is evaluated by variation of parameters such as the wall temperature (the hot side temperature induced by the heater), electrical organization of the TEGs in combinations of parallel, series, and parallel-series, as well as the inductor, L_1, and capacitor, C_1, in the DC-DC converter. Temperatures of the wall, heat sink and ambient, as well as output voltages and currents of the TEGs and converter are measured and recorded by the data acquisition device. Therefore, the uncertainty of the experiments is measured based on the accuracy of the thermal and electrical parameters. Fig. 6 shows real-time measurements of the wall temperature and open-circuit voltage of the converter during a steady-state period in a sample test. Standard deviations of these data obtained by equations (2) and (3) [29] are ±5.477 × 10^{-3} °C and ±3.151 × 10^{-4}V for the wall temperature and open-circuit voltage of the TEGs, respectively, which shows high accuracy of the measurements.

$$Sx = \left[\frac{1}{N-1}\sum_{i=1}^{N}(X_i - \overline{X})^2\right]^{\frac{1}{2}} \tag{2}$$

$$\overline{X} = \frac{1}{N}\sum_{i=1}^{N} X_i \tag{3}$$

where, N is the number of sample data and X_i is the value of the measurements at each point.

4. Results and discussion

Fig. 7 represents the average cold-side temperature and temperature difference across the TEGs at different wall temperatures. The

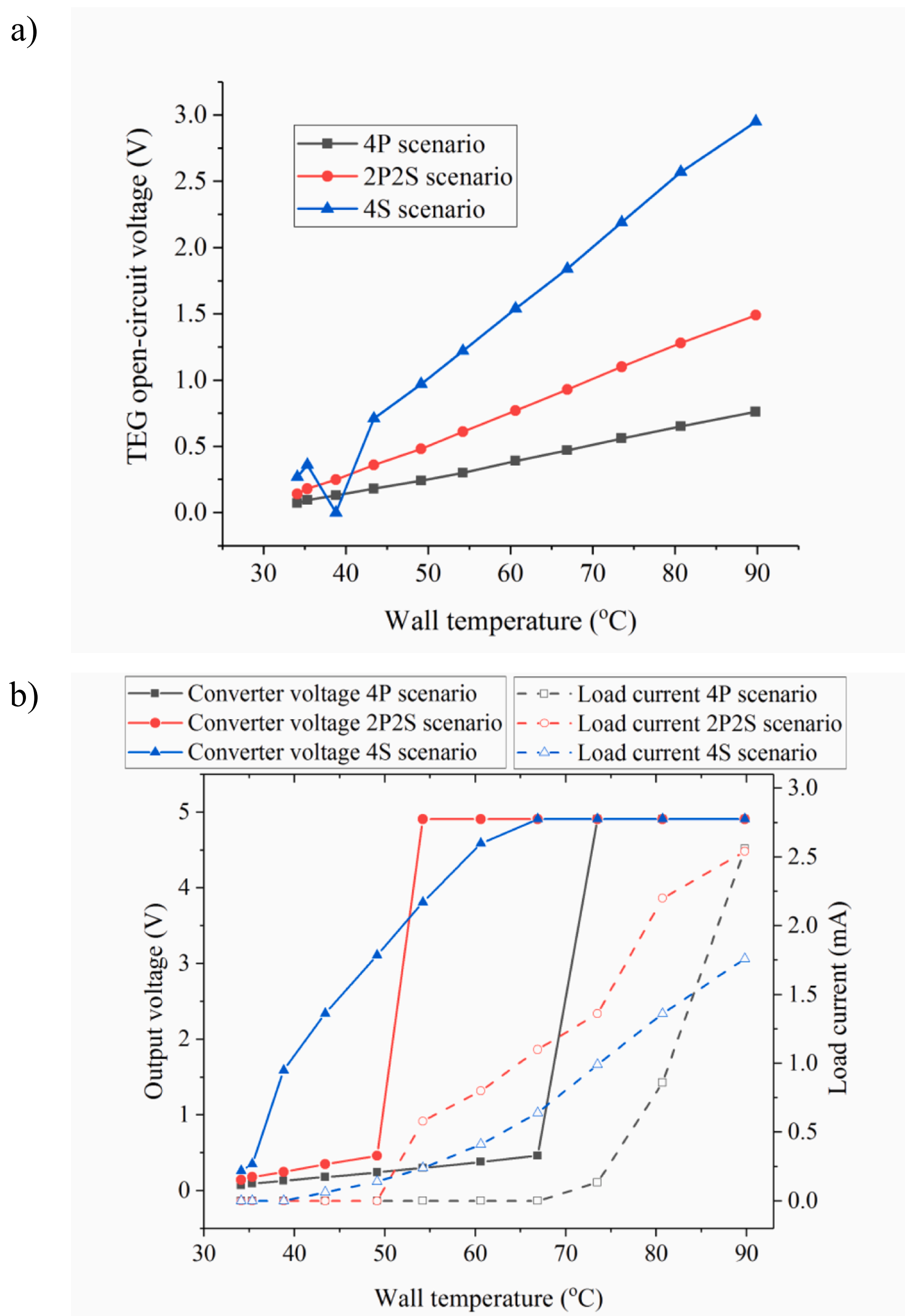

Fig. 9. Variation with hot side temperature of a) TEG voltage connected to DC-DC converter without the external load and b) converter output voltage and load current without external load at 4P, 2P2S, and 4S TEGs arrangements.

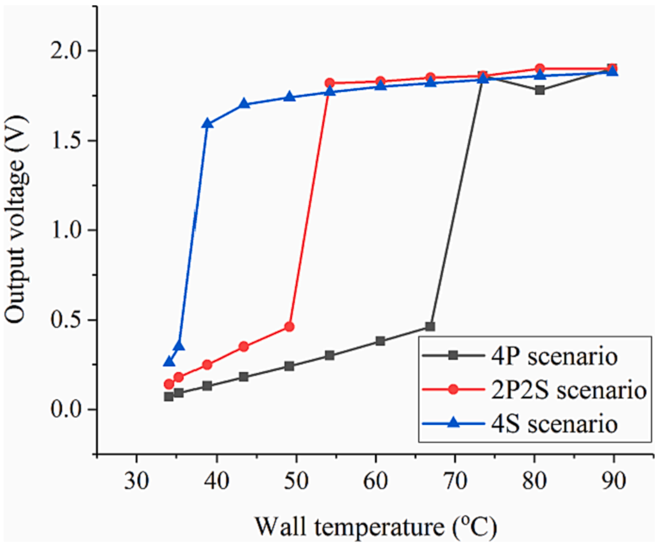

Fig. 10. Variation of output voltage of the converter with hot side temperature under external load for different TEG arrangements.

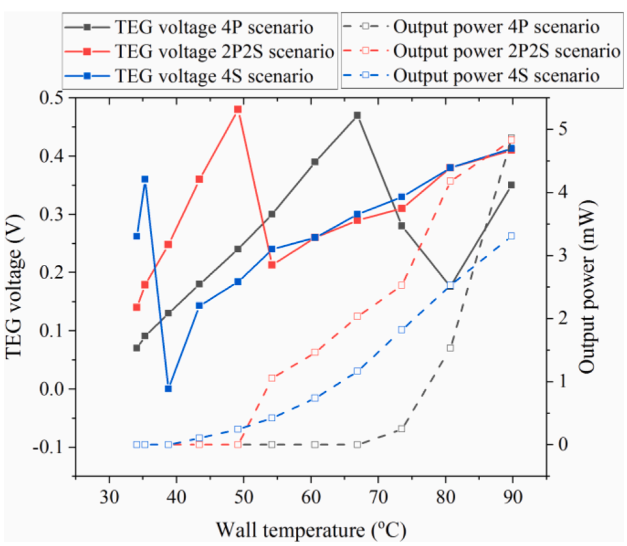

Fig. 11. Variations of TEG output voltage and output power of converter with hot side temperature under external load at different TEG agreements.

temperature difference varies up to 27 °C at the wall temperature of 89.8 °C. The heat sink is cooled by natural convection of airflow. The wall temperature and temperature of the fin base at the center of the heat sink demonstrate a linear temperature variation mainly corresponding to the variations in the coolant air temperature. There is a temperature gradient across the airflow at the base of the heat sink and wall. This is due to the variation of the airflow velocity boundary layer thickness and distribution of the thermal boundary layer in the vertical direction of the heat sink [30,31]. The velocity and thermal boundary layers' shape on the vertical heat sink causes a higher heat transfer rate at the lower part of the heat sink. Consequently, a higher temperature difference is created across the associated TEGs. This results in higher power generation by the TEGs located in the lower part of the heat sink, namely TEGs #2 and #4 in Fig. 3. Variation of the output voltage of the individual TEGs in Fig. 8 confirms this phenomenon. As shown, the open-circuit voltages of the TEGs #2 and #4, which are located in the lower part of the heat sink, are approximately two times higher than the TEGs #1 and #3. This occurs due to variation of the natural heat transfer coefficient in the vertical direction of the heat sink, which results in inhomogeneous temperature distribution on the base plate of the heat sink.

Fig. 9a illustrates the voltage of the TEGs for different TEG arrangements connected to the DC-DC converter without the external load connected to the circuit. Since the power generation is affected by variations in the electrical load applied over the TEGs, the arrangement of the TEGs significantly affects the resistance of the circuit and the characterization of the output voltage and current. For instance, the parallel arrangement generates lower voltage but is more stable against variations in the external load. Nonetheless, in a series arrangement, the electrical potential is higher, but less stable since it is strongly affected by variations in the external load. As can be seen in Fig. 9a, a higher wall temperature increases the voltage generated by the TEGs. When the electrical potential of the TEGs reaches the lower threshold of the converter, the electrical load of the converter is applied to the electrical circuit of the TEGs. The electrical potential of the TEGs in the 4P and 2P2S arrangements is not affected by this electric load variation. However, in the 4S arrangement, the electrical potential of the TEGs is reduced by this load variation. When the wall temperature exceeds this critical temperature, the electrical potential increases again since the power generation of the TEGs overcomes this load, and they operate again efficiently.

Fig. 9b illustrates the output voltage of the DC-DC converter with no external load in the power circuit and the output current of TEGs. Since the generated voltages in the 4P and 2P2S arrangements are not affected by applying the converter load, the output voltages of the converter increase sharply in these cases. Additionally, in the 4S case, because the TEGs voltage drops at the threshold load of the converter, its voltage increases gradually versus the other TEG arrangements. However, the 4S arrangement has the highest voltage generation among the studied arrangements at lower wall temperatures. Based on these results, it is evident that the operating conditions and arrangement of a TEG system are essential for design of an appropriate power converter. For instance, at a wall temperature lower than 50 ℃ only the 4S arrangement can operate, but at a wall temperature between 50 ℃ and 65 ℃, the 2P2S arrangement is the most suitable choice with higher output voltages than the 4S arrangement. Additionally, for higher wall temperatures than 70 ℃, the 4P combination is preferable because of a low dependency on external load variation. The current passing through the TEGs indicates the startup load applied by the DC-DC converter on the TEG circuit. Increasing the output voltage of the converter results in a sharp increment in the load applied on TEGs.

Fig. 10 illustrates the output voltages of the converter under external load for different TEG arrangements. As can be seen, before reaching the converter threshold, the output voltages have a similar trend as the output voltages of the converter without the load connected to the circuit. However, after the startup moment of the converter, the external load holds the voltage at a value of up to 1.9 V. Accordingly, the system with the 4S arrangement starts operating at lower temperature differences, while the 2P2S arrangement produces a higher output voltage after reaching a wall temperature of 50 °C.

Electrical output of the TEGs, however, is different under external electrical load. As shown in Fig. 11, the output voltage of the TEGs increases with the wall temperature until converter startup time, but it falls after the converter starts operating. The converter startup voltage is defined at 0.45 V. After this moment, the converter applies a load on the TEGs and allows the electrical current to pass through the LED. Accordingly, the output power of the converter is created after passing the startup threshold, which occurs concurrently with the reduction of the voltage in the TEGs. In the 4S combination, the reduction of the TEG voltage is significant, and it reaches close to zero because of the load sensitivity of the series arrangement. Furthermore, the higher current available by the TEGs in the 2P2S and 4P configurations provides higher power at the startup moment. Clearly, the TEG arrangement plays a critical role in efficient thermoelectric systems that convert heat into electricity in low temperature systems. According to Fig. 11, although

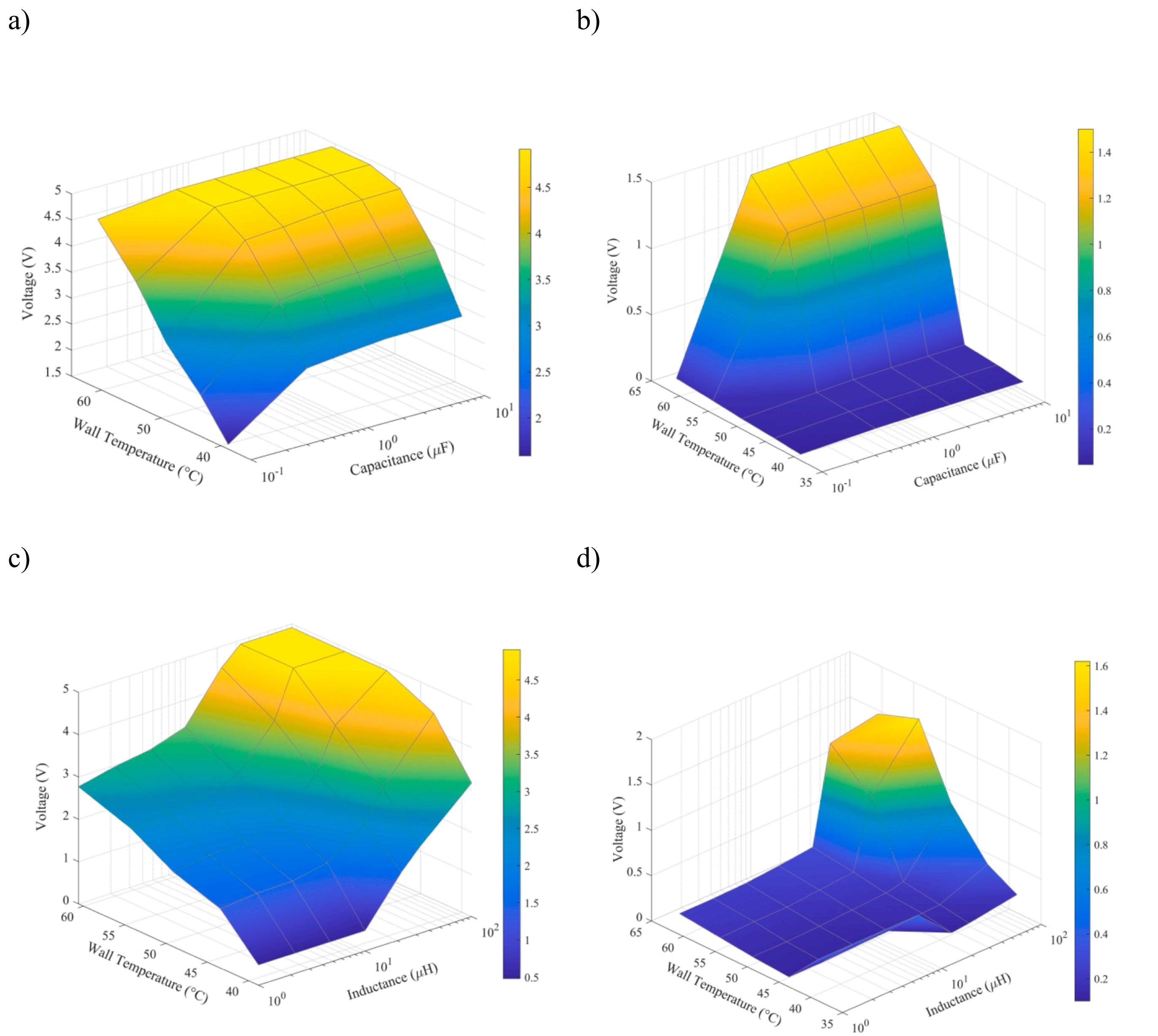

Fig. 12. Output voltage variation with the wall temperature in a) converter and b) TEG at different capacitances, and Output voltage variation with the wall temperature in of c) converter and d) TEG at different inductances.

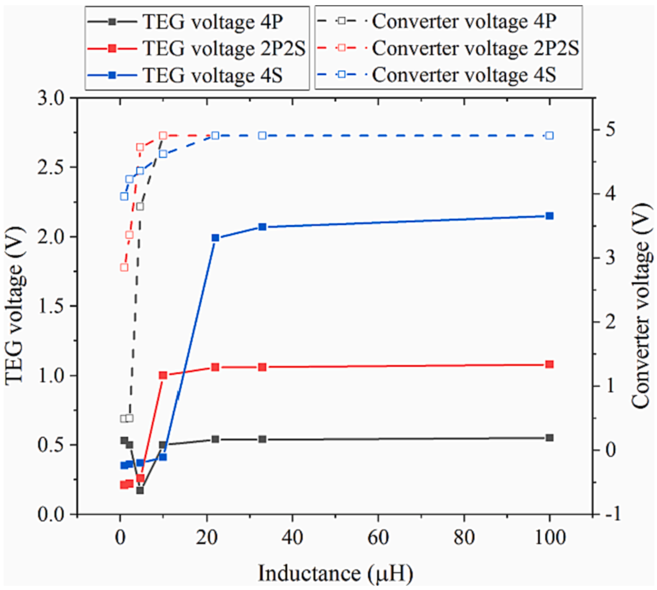

Fig. 13. Variation of output voltage of converter and TEGs with inductance at wall temperature of 73.5 °C without external load.

the series connection offers the most efficient performance at a wall temperature less than 50 °C, the series–parallel configuration supplies the greatest performance between 50 °C and 90 °C, while the parallel arrangement provides the most power at a wall temperature higher than 90 °C due to the higher current imposed on the converter from the TEGs.

Fig. 12 a) and Fig. 12 b) show output voltage variation of the converter and TEGs, respectively, in the 4S arrangement with variations of the wall temperature and capacitance without external load. The purpose of the input capacitor, C_1, is to store electrostatic energy to supply the circuit of the converter. Low capacitance diminishes voltage generation by the TEGs, so that the voltage does not rise even at high wall temperatures. This low voltage leads to a lower output voltage from the converter. Alternatively, at capacitances greater than 0.47 F, the TEG's output voltage shows a sharp increase at wall temperatures exceeding 50 °C, where the converter's output voltage reaches its optimal level at 5 V. Fig. 12 c) and d) show the impact of the inductance value on the output voltage of the converter and TEGs, respectively. As shown, higher inductance has eliminated the voltage drop of the TEGs after reaching the threshold in the converter at low wall temperatures. Moreover, higher inductance creates a higher output voltage at a lower wall temperature (lower than 50 °C in this study). A TEG-driven converter with an inductance greater than 33 μH stores the electrical current of the TEGs more efficiently during the switchover of the voltage regulator, which leads to enhancement of the electrical output of the converter. As a result, selecting an optimal input capacitor and inductor is crucial to the effectiveness of a DC-DC converter applied to TEG systems.

Fig. 13 shows the effect of inductance on the output voltage of the converter and TEGs at a wall temperature of 73.5 °C without an external load. The output voltages of TEGs are sensitive to low inductances, especially in the 4S-TEG arrangement. On the other hand, the output voltage of the DC-DC converter displays a more pronounced degree of instability when the inductances are smaller in the 2P2S and 4P arrangements. While 22 μH is the minimum inductance for maximum output voltage of the converter at the studied wall temperature, the converter in the 2P2S and 4P achieved the ideal condition with an inductor equal to 22 μH. Accordingly, due to the load-functional nature of the TEG and its variations in different combinations, higher inductance values cause higher output voltages from the TEGs and converter.

Fig. 14 shows a comparison between 4P and 4S arrangements in the electrical characterization of thermoelectric systems with different capacitances and inductances under external load at a wall temperature of 80.7 °C. Clearly, the selection of optimal inductance is crucial for the DC-DC converter to produce a suitable output voltage using TEGs as the voltage source. The system is unable to deliver efficient electrical output at small values of inductance. At this critical inductance, the output voltage in the TEGs suddenly drops, which affects the startup transmission stage in the converter. The critical value of inductance among the values considered in this study is 33 μH, where the output voltage of the TEGs shows a partial drop. This happens since the converter starts operating at a higher voltage level, and this load is applied on the TEGs circuit and makes it inefficient. In contrast, variations in the input capacitance have a negligible impact on the output voltage of the TEGs. Also, the smallest capacitor in this study, 0.1 μF, has a significant effect on the output voltage of the TEGs in the 4S combination. Nevertheless, this is an extremely critical factor for increasing the output voltage of the converter delivered to the external load. In the combination of 4S TEGs and small inductance values, higher capacitance is imperative for achieving the startup condition. Due to the forward voltage of the green LED, the output voltage of the converter does not exceed 1.9 V. This results in different electrical characteristics in both the TEG and the converter in comparison to the condition when the system is not subjected to the external load, as shown in Fig. 12. As a result, the maximum output voltage of the TEGs is 0.42 V and 0.43 V in the 4P and 4S arrangements, respectively. Inductance and capacitance less than 4.7 μH, and 0.1 μF, respectively, cause inefficient electrical output of the converter in the 4S combination. Moreover, inductance and capacitance less than 22 μH, and 0.47 μF, respectively, can be the main reason for the unsuitable output voltage of the converter under external electrical load in the 4P combination. This leads to lower output power from the converter. Therefore, it is essential to evaluate the input properties of the DC-DC converter in a thermoelectric system to provide suitable output power. Based on this evaluation, the output voltage of the converter in the 4S arrangement is less dependent upon inductance and capacitance than in the 4P arrangement. Consequently, among the capacitors and inductors assessed in this study, a capacitance higher than 0.47 μF and the highest inductance, 100 μH, are recommended to extract maximum power from the converter.

It is furthermore noteworthy that the electrical output of the TEG systems is affected not only by the electrical combination of the TEGs and the input parameters of the converter but also depends on the operating temperature of the system. Fig. 15 compares the output voltage of the TEGs and converter as well as the output power of the system under external load in the 4S and 2P2S combinations at the wall temperature of 60.6 °C. For this specific wall temperature, the 2P2S combination provides higher output voltage in the converter and output power in the system. In contrast, the voltage output of the TEG in the 4S combination is higher at most of the inductance values considered in this study. Moreover, since these differences in the output parameters are small in the output voltage, the system with the 2P2S combination delivers significantly higher power than the 4S combination at high inductances due to higher current generation in the 2P2S combination. Consequently, low-temperature energy harvesting applications require specialized design to achieve an efficient DC-DC boost converter connected to a set of TEG modules.

5. Conclusion and remarks

TEGs harvest electrical energy directly from thermal resources. Since power generation in TEGs depends on the heat source temperature, a DC-DC converter has been utilized to provide a constant electric potential for sensor applications using TEGs as a reservoir of energy flow in the converter and to smooth the output voltage during temperature variations of the heat source. This study focuses on the investigation of DC-DC converter design with different combinations of four TEG modules to improve the output power of the energy harvester system and modify the startup point of the converter at low-temperature heat sources. Hence, an experimental setup is constructed consisting of a

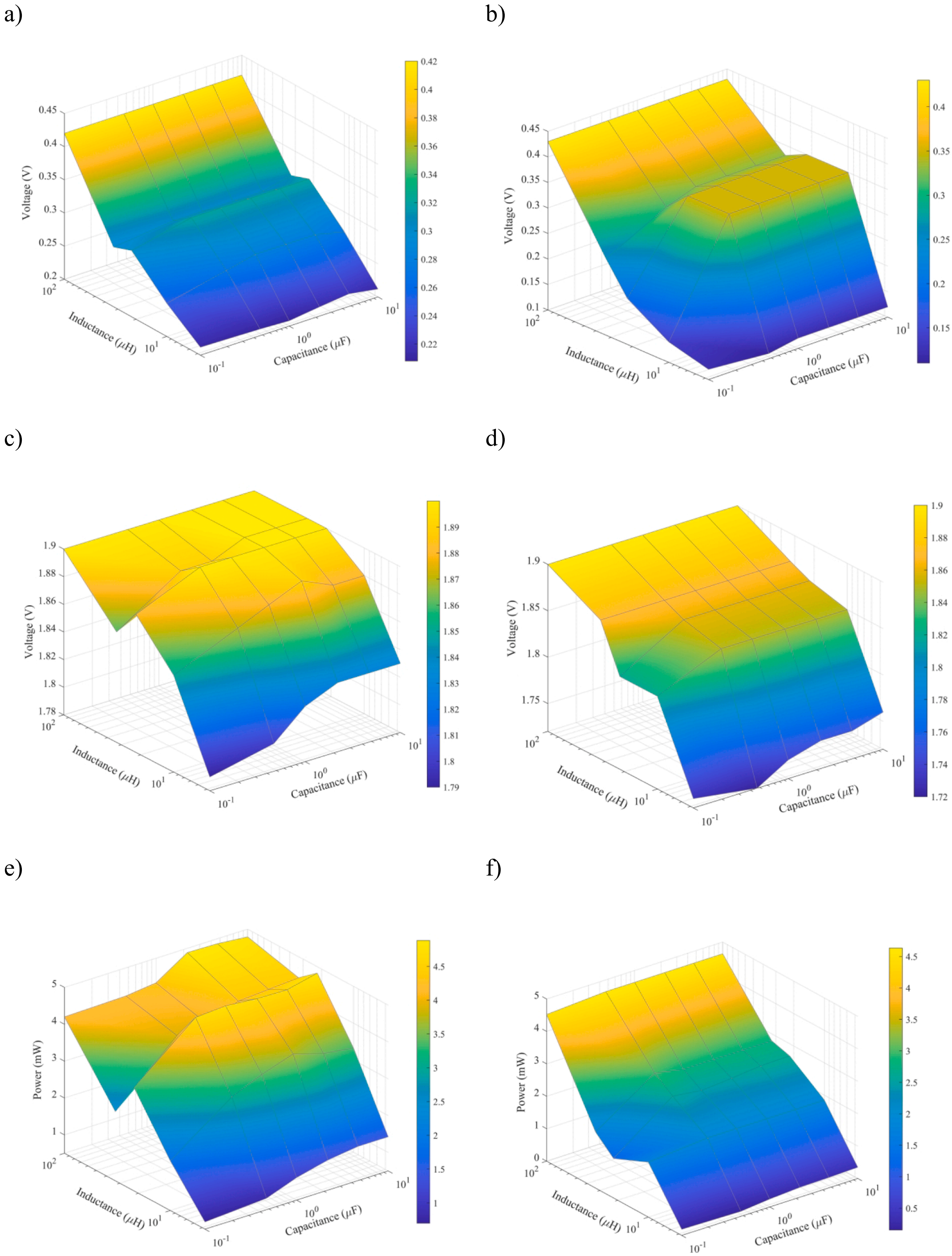

Fig. 14. Variations of a) output voltage of TEGs in 4P combination, b) output voltage of TEGs in 4S combination, c) output voltage of converter in 4P combination, d) output voltage of converter in 4S combination, e) output power of converter in 4P combination, and f) output power of converter in 4S combination at the wall temperature of 80.7 ℃.

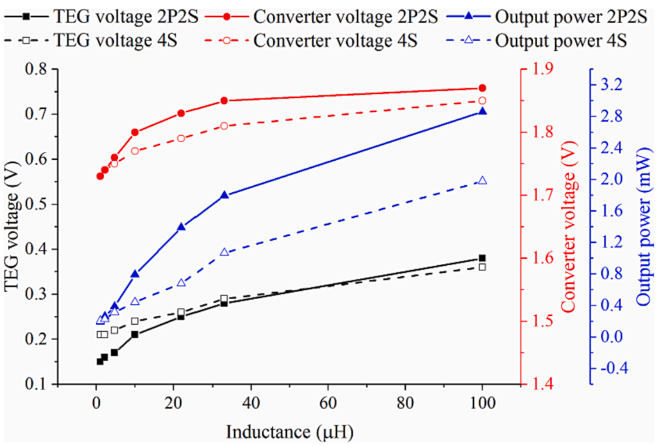

Fig. 15. Variations of TEG output voltage, converter output voltage, and output power of the system under external load at different inductances and combinations.

controlled low-temperature heat source, four TEG energy harvesters, a natural air-cooled heat sink, and a modifiable DC-DC boost converter. The results of this study show that the startup point of the DC-DC converter is affected by variations in its capacitance and inductance. Low inductances and capacitances delay the startup moment of converters to happen at a higher wall temperature. Therefore, to provide efficient operating conditions for enhancing the electrical output of the system, capacitance higher than 0.47 μF and inductance of 100 μH are recommended for TEG systems considered in this work. In this study, the series, parallel-series, and parallel combinations of the TEGs had the most effective performance at wall temperatures below 55 °C, between 55 °C and 75 °C, and higher than 75 °C. Additionally, the output voltage of the converter exhibits a lower dependence on variations in input capacitance than on variations in main inductance. This study provides a guide for selecting an electrical arrangement of TEGs in energy harvesting systems when the TEGs are coupled to DC-DC boost converters and external load resistances.

CRediT authorship contribution statement

Ali Mohammadnia: Writing – original draft, Visualization. **Alireza Rezania:** Conceptualization, Methodology, Investigation.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Alireza Rezania reports financial support was provided by CLEAN Cluster, Denmark.

Data availability

Data will be made available on request.

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