Performance Characteristics of A Simulated Hybrid Solar-Photovoltaic-Thermoelectric System for Renewable and Direct Power Generation Applications

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Abstract: Advanced nonconventional renewable and alternative green energy technologies which are used for generation of electrical power have shown real promise and received renewed interest in recent years due to an increasing concern of environmental issues of greenhouse gas emissions, air pollution, and the limitations and conservation of natural energy resources. Solar-photovoltaic (PV) systems directly convert renewable solar energy into green electrical energy. However, their power production and efficiencies tend to decrease when operating at relatively higher temperatures. Therefore, reducing the temperature of PV modules using efficient cooling methods would improve their performances. Thermoelectric power generation (TEG) technology could be used to convert a portion of the waste-heat energy dissipated from PV systems, thus cooling them, and at the same time generates extra power. Hence, hybrid photovoltaic-thermoelectric power generation (HPV-TEG) systems integrate TEG modules with a PV module to form a more efficient power generation system. The main objective of this paper is to investigate the viability and performance characteristics of a hybrid HPV-TEG through detailed lab-simulated tests. Experimental results and in thermal images showed that the HPV-TEG system was able to generate more DC power than the solo PV system while operating at higher irradiance intensities and lower TEG's inlet coolant temperature. At the irradiance of 615W/m^2, the power generation from the hybrid HPV-TEG system increased by 4.1% compared to the solo PV system. The results also indicated that when the irradiance was increased to 750W/m^2, the power generated from the hybrid system increased to approximately 8.6% higher than the power generated from the solo PV system at the same irradiance. The integration of the concentrators in the hybrid PV system increased the maximum power point by 23.3% compared to the hybrid PV system without concentrators.

Keywords: Renewable energy, power generation, solar-PV systems, thermoelectric power generation, hybrid power technology, solar energy, lab-scale solar simulator, Thunder Bay, Canada.

1. INTRODUCTION

Increasing electricity demand especially in remote locations, fossil-based fuel prices, and stringent regulations for environmental issues of greenhouse gas emissions and air pollution have increased interest and research of novel renewable energy technologies for electrical power generation. Renewable solar-photovoltaic (PV) systems are known for their ability to directly convert solar energy (i.e. sun light) into electrical energy. In addition, PV systems emit zero pollution when operating, are reliable, have a long operating life, have no mechanical moving parts, and require little to no maintenance once properly installed. They are also an extremely adjustable power source, generating microwatts to megawatts, depending on the size of the PV system and the required application [1]. However, it is also known that conventional PV system's performance degrades when operating at elevated temperatures [1]. Thus, decreasing the operating temperature of PV modules using efficient cooling methods tend to improve their overall efficiency and as a result increase their power production. Thermoelectric technology (TEG) also has the ability to directly convert thermal energy directly into electrical power. TEG devices (modules) are a solid-state, reliable technology with no moving parts, and thus are silent in operation. They are also position independent, environmentally friendly, and very safe to use [2, 3]. Once coupled with PV modules, TEG modules have the innovative capability to convert a portion of the waste heat thermal energy dissipated from PV modules (due to their relatively high temperature), thus cooling them, and simultaneously generate additional power. Hence, hybrid photovoltaic-thermoelectric power generation (HPV-TEG) systems integrate TEG modules with PV modules to form a more efficient combined power generation system. In general, HPV-TEG systems have the potential to become a viable hybrid energy technology in locations where PV modules operate at high temperatures.

There have been few published investigations that have explored the hybrid concept of HPV-TEG systems and characterized in detail the performance of these systems. For example, Daud *et al*. [4] developed a hybrid photovoltaic-thermoelectric module and investigated its performance in an outdoor setting. In their

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work [4], the HPV-TEG system produced a higher energy conversion efficiency by approximately 1.84% at an irradiance intensity of 601.12W/m^2 compared to an individual PV system. They [4] also reported that as the HPV-TEG system tends to yield a higher efficiency than the solo PV system as the irradiance intensity increases. In a recent research, Najafi and Woodbury [5] have numerically modeled and analyzed the potential of cooling a PV system by inputting power to multiple TEG modules. The Matlab simulation in their [5] research showed that as the ambient air temperature and irradiance intensity increased, the power required by the TEG modules to maintain the temperature of the PV module increased exponentially. The results of their numerical study concluded that it was not feasible to operate the TEG modules at the optimal performance because the amount of power generated by cooling the PV modules was far less than the power consumed by the TEG modules. They [5] reported that the alternative method of operating the TEG modules at the optimal current suggested extra power could be produced from the proposed hybrid system if the TEG modules have a high figure-of-merit value ($Z > 0.005K^{-1}$). Another numerical study by Najafi and Woodbury [6] simulated the performance of an HPV-TEG system by developing a thermal circuit model and implementing energy balance analysis. Their model had TEG modules installed on the backside of a PV module, where the cold side of the TEG modules were maintained using an air-cooling system. Their [6] numerical results suggested that the power output from the combined PV and TEG modules increased asymptotically and exponentially as the irradiance intensity increased. Liao *et al*. [7] recently developed a theoretical model of a hybrid photovoltaic-thermoelectric power generation system. This HPV-TEG system was made from a 75-Watt PV module and 11 TEG modules operating with a constant cold-side temperature of 300K. The material properties of the TEG modules are considered to be temperature-dependent in their numerical model. Several factors, such as the thermal conductance between the PV module and TEG module, concentration ratio, and figure-of-merit were analyzed with respect to the power output from the PV module and TEG module. Their theoretical model suggested that the optimal electrical load for the PV module decreased asymptotically, while the optimal load resistance for the thermoelectric generator increased as the irradiance intensity increased. The numerical work of Liao *et al*. [7] has provided meaningful insights into the design criteria required to optimize the performance of an actual HPV-TEG system. The feasibility of an HPV-TEG system operating in Malaga, Spain was theoretically analyzed by Van Sark [8]. In his study [8], a model under ideal conditions was developed in order to determine the performance of an HPV-TEG system operating in Malaga, Spain. The simulation results showed that the TEG module was able to establish approximately 24.7% of the total power from the HPV-TEG system, assuming a constant figure-of-merit of 0.004K^{-1}.

The main objective of this paper is to experimentally investigate in detail the viability and performance characteristics of an HPV-TEG system using a fully instrumented laboratory-scale HPV-TEG test setup under solar-simulated operating conditions. The intention of this research is to provide further insights and understanding of the performance characteristics of PV systems when integrated with TEG modules that could be used to optimize the design and performance of these systems for better power generation and efficiency.

2. THE CONCEPT OF THE HPV-TEG SYSTEM

A schematic showing the concept of a hybrid HPV-TEG system used in this research work is shown in Figure **1**.In this concept, the solar photovoltaic (PV) module is placed on the top of the hybrid system, whereas the thermoelectric generator (TEG) is directly attached to the bottom of the PV module as shown in Figure **1**. When solar energy from the Sun, also known as irradiance, falls on the PV module, a small portion of the energy is converted into electrical energy and transferred to the electrical load R_{PV}. The remaining portion of the incident solar energy is converted into low-grade thermal energy (i.e. waste heat) that is dissipated in form of heat transfer rates from the top, $\dot{Q}_{PV,top}$ and from the bottom, $\dot{Q}_{PV,bot}$ of the photovoltaic module. The transfer of heat into the bottom surface of the PV module, $\dot{Q}_{PV,bot}$ tend to heat up this surface and acts as a heat source (input) for the attached TEG module. In this case, the top surface of the TEG module is maintained at a relatively high temperature (T_H). A temperature gradient ΔT (equals T_H-T_C, where T_C is the bottom surface temperature of the TEG module) is established across the thickness of the TEG module by providing a heat sink (e.g. cooling) on the bottom surface of the TEG module. The waste heat dissipates from the bottom surface of the TEG module at a rate of, $\dot{Q}_c$ as shown in Figure **1**. During this process, two major benefits from using the HPV-TEG concept occur, namely: (1) the PV operating module temperature is decreased as a result of removing the thermal energy (waste heat) from the bottom surface of the PV module and as a result decreasing the operating PV temperature which tends to increase the power delivered by the PV system and improve its overall performance, and (2) the dissipated waste heat from the PV module across the TEG module is converted into additional electric power (using Seebeck effect [3]) once connected to another electrical load R_{TEG} as shown in Figure **1**. Thus, integrating a TEG module into the PV system simultaneously decreases the operating temperature of the PV module and increases the overall electrical power delivered by the hybrid system. In general, HPV-TEG systems have the potential to become a viable hybrid energy system in locations where the PV modules are subject to relatively high operating temperatures.

3. THE LAB-SCALE HPV-TEG TEST SETUP AND EXPERIMENTAL METHODOLOGY

As discussed previously, there is a lack of published research that experimentally characterized in detail the performance of HPV-TEG systems. In this research, a lab-scale test setup was designed, constructed and fully instrumented using real-time computerized loggers in order to characterize in detail and gain more understanding of the performance of an HPV-TEG system under various operating conditions of modules temperature and irradiance intensity. A schematic diagram showing the test setup used in this work is shown in Figure **2**. The lab-scale test setup mainly

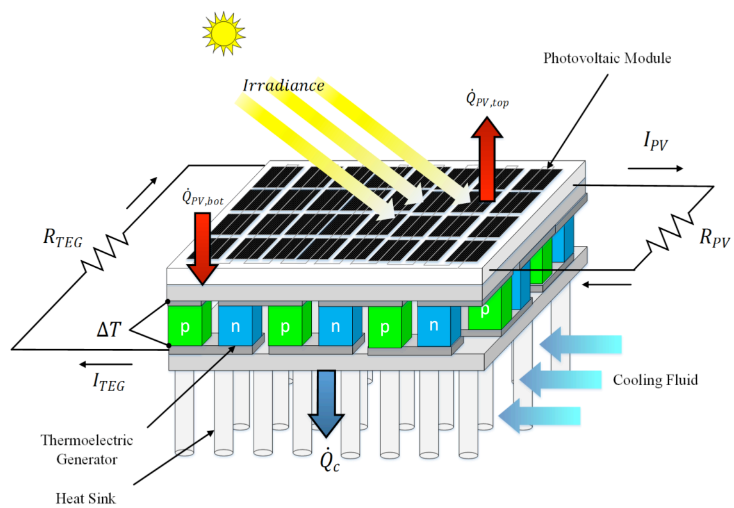

Figure 1: A schematic diagram showing the concept and main components of a hybrid solar-photovoltaic thermoelectric power generation (HPV-TEG) system used in this investigation.

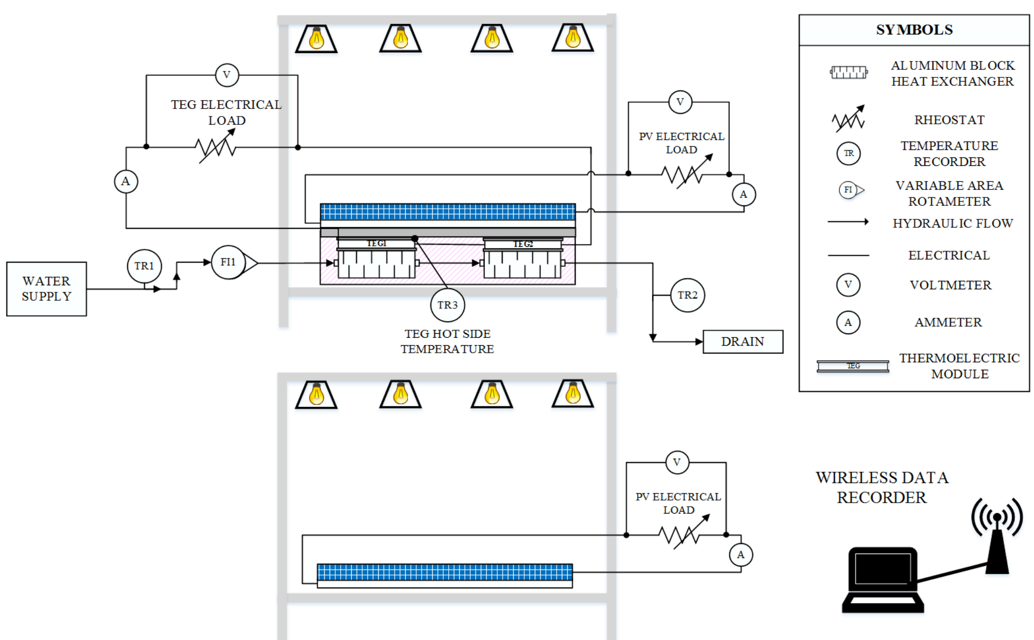

Figure 2: A schematic diagram showing the lab-scale test setup used in this investigation for (**a**) the hybrid HPV-TEG system, and (**b**) the solo PV system.

consists of a solar simulator, two types of hybrid HPV-TEG systems, a conventional solo PV system, electrical loads, data acquisition loggers and computer, and a TEG cooling unit. The three identical PV modules used in the setup are Coleman 40-Watt monocrystalline modules (model # 51840) each with a face area A_{PV} of 0.2625 m^2. There are 10 identical TEG modules (TEC, model # TEG1-12611-6.0) attached on the bottom surface of the PV module, thus making up the hybrid HPV-TEG system. The 10 TEG modules were connected electrically in series. The TEG modules are comprised of bismuth telluride compounds, and each has a cross-sectional area of 56 mm x 56mm. A T-type thermocouple used for temperature measurements is directly mounted to the hot side surface of the TEG module. An aluminium layer is placed between the bottom surface of the PV module and top surface (hot side) of the TEG module in order to create a uniform heat distribution between the two modules. The heat sink on the bottom of the HPV-TEG system is obtained using 10 identical cooling aluminium made blocks, which use coolant (liquid water) flow at a fixed temperature and flow rate. Each side of the TEG module is covered with a high thermal conductivity paste in order to create an excellent thermal contacts between the aluminium layer and the cooling blocks. The inlet and outlet temperatures of the coolant are measured using T-type thermocouple probes TR1 and TR2. It should be noted that the error associated with measuring the temperature difference between inlet and exit of the coolant is within ± 3%, as specified by the thermocouples manufacturer. Real-time water inlet and outlet temperatures measurements are recorded every 10 seconds during each experimental simulation in order to ensure that the water inlet temperature does not vary by more than 5%. Real-time measurements of the hot side temperature thermocouple TR3 are also recorded every 10 seconds for consistency. A variable area rotameter FL1 is used to control the volumetric flow rate of the coolant. A variable resistance load, also known as a rheostat, is connected across the PV and TEG modules. The electric currents and voltages across the electric loads connected to the PV and TEG modules were measured using real-time wireless loggers and the DC power delivered by the PV and TEG modules to the electric loads were determined by multiplying the current times the voltage. Thermal profiles of the PV modules are obtained using a FLIR E4 infrared (IR) camera set at an emissivity of 0.88. Steady-state operation occurs when the hybrid system's PV module power at a constant electrical load resistance and TEG open-circuit voltage do not deviate by more than 0.1% after 5 minutes of operation. The entire PV system is insulated using rigid foam insulation in order to ensure that all the heat is transferred through the TEG system, as shown in Figure **2**. The solar simulator consists of eight 500-Watt tungsten halogen lamps arranged in a 4 x 2 matrix, which are used to simulate the sun and provide solar irradiance. The simulated solar irradiance intensity was measured using a Pyranometer positioned parallel to the PV module plane. The irradiance intensity is controlled and varied by illuminating particular lamps and by changing the height of the solar simulator platform as shown in Figure **2**. For the sake of comparisons and experimental consistency, the hybrid HPV-TEG and solo PV systems were simultaneously characterized and evaluated under the same operating conditions. In addition, another hybrid system named HCPV-TEG which utilizes concentrators (ordinary mirrors) is used in order to study the effect of concentrating the simulated irradiance on the performance of the hybrid system. For distinction purpose between the two hybrid systems under investigation in this study, the first hybrid system is termed 40W-HPV-10TEG whereas the second one (with the concentrators) is termed 40W-CHPV-10TEG. The conventional solo PV (with no TEG system) is simply termed 40W-PV. Photographs of the HPV-TEG test setup and its components used in this investigation are shown in Figures **3** and **4**.

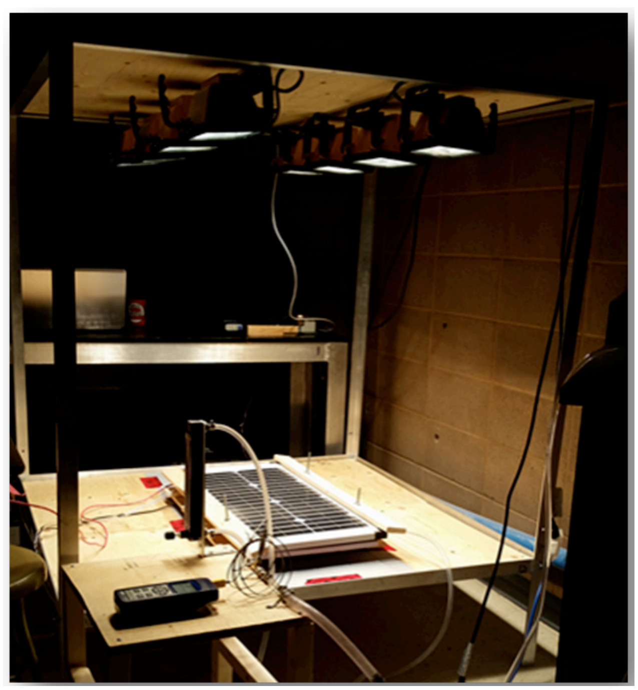

Figure 3: A photograph showing the lab-scale simulations of the HPV-TEG system placed inside the solar simulator used in this investigation.

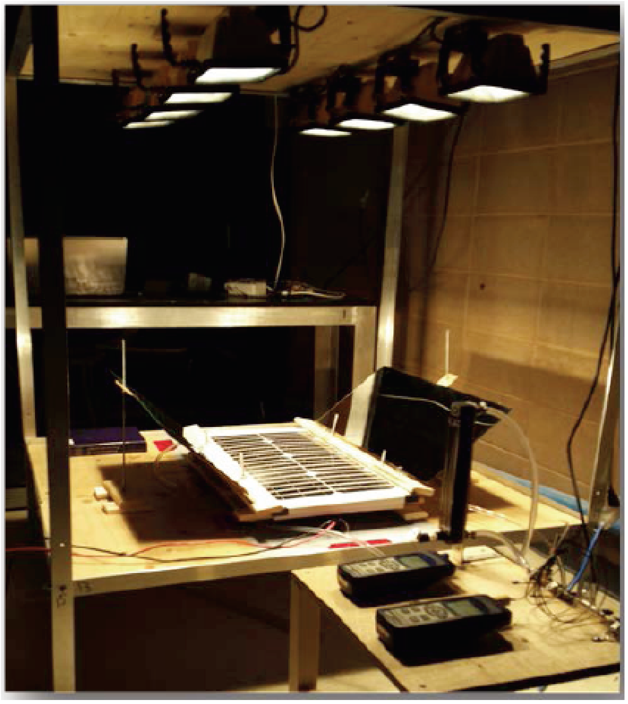

Figure 4: A photograph of the concentrated hybrid photovoltaic-thermoelectric power generation system (40W-CHPV-10TEG) being tested in the solar simulator.

4. RESULTS AND DISCUSSION

Using the lab-scale test setup and following the experimental procedure outlined in the above section, experimental tests were performed in order to characterize the performance of the hybrid HPV-TEG under various solar simulated operating conditions. The variation of the maximum electrical power generation from the hybrid HPV-TEG (termed as 40W-HPV-10TEG) and the conventional (solo) PV system(termed as 40W-PV) as a function of simulated solar irradiance intensity are shown in Figure **5**. The results in Figure **5** show that as the irradiance intensity increased from 425 to 750W/m^2, the maximum power generated increased monotonically and linearly for both systems and that makes sense. In particular, when the irradiance increased from 425 to 615W/m^2, the maximum power output from the solo PV system increased from approximately 7.1 to 9.7 W (i.e. by 36.6%), respectively. As the irradiance further increased to 750W/m^2, the power generation increased by 63.4% from its value of 7.1W/m^2 that occurred at 425W/m^2 of irradiance. However, the increase of maximum power generation from the hybrid HPV-TEG system showed improvement with higher values compared to the solo PV system specifically at higher irradiances of 615 and 750W/m^2 as shown in Figure **5**. More particularly, at the irradiance of 615W/m^2, the power generation from the hybrid HPV-TEG system is

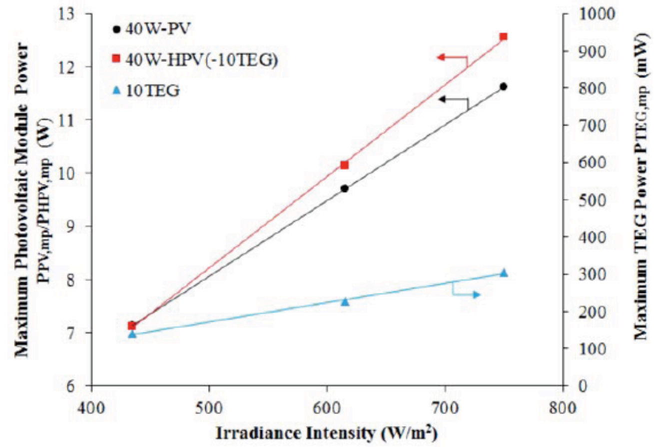

Figure 5: Comparison between the 40W-PV, 40W-HPV-10TEG, and 10TEG maximum power point vs. irradiance intensity. ($T_{w,\,in}$=2 °C, $\dot{V}=1$ L/min).

approximately 10.1 W compared to 9.7 W for the solo PV system (i.e. increased by 4.1%). Moreover, when the irradiance is increased to 750W/m^2, the power generated from the hybrid system increased to nearly 12.6 W, which is approximately 8.6% higher than the power generated from the solo PV system (i.e. 11.6 W) at the same irradiance. This means that cooling the PV system using the attached TEG modules (in the hybrid HPV-TEG system) has indeed improved its power generation compared to the solo PV system without cooling. This improvement or increase in power generation tends to increase as the irradiance increases. For all these tests, the coolant inlet temperature was maintained at 2°C with volumetric flow rate set at 1 L/min as indicated in Figure **5**. It is worth noting that the TEG modules integrated into the hybrid system also generated additional electrical power as shown in Figure **5**. In particular, at irradiance intensities of 425, 615, and 750W/m^2, the maximum power generated from the TEG modules are approximately 140, 230, and 300 mW, respectively. This is considered to be another advantage of integrating TEG modules into the hybrid system. It should be noted that cooling the PV system using the integrated TEG modules in the hybrid system has resulted in decreasing its system temperature, which in turns has improved its system performance. Thermal images were captured (using the FLIR-E4 IR camera) and recorded for both systems operating at the same conditions of irradiance and the results are shown in Figure **6**. From analyzing these images, it is clear that cooling the PV system using the integrated TEG modules in the hybrid system significantly decreased its module temperature, which resulted in improving its power generation. In this case, the average module temperature for the solo PV system was measured to be approximately 83.3°C,

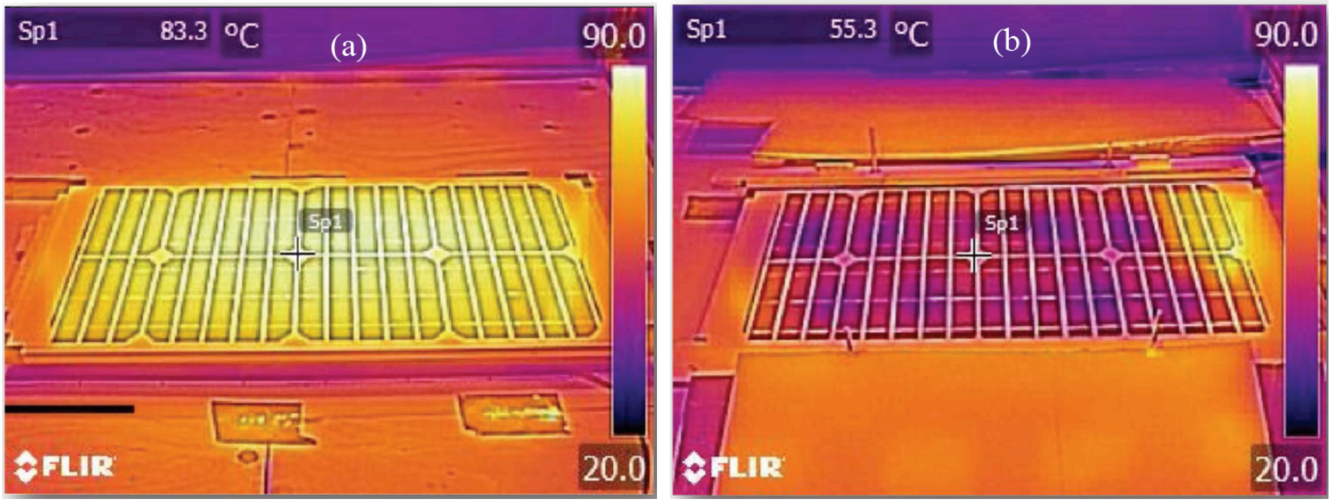

Figure 6: IR thermal images of (**a**) the solo PV system, and (**b**) the hybrid HPV-TEG system. (GT=750W/m^2, Tw, in=2 °C, $\dot{V}=1$ L/min).

whereas for the hybrid system the average module temperature dropped to approximately 55.3°C (i.e. dropped by 28°C) due to cooling effect by the attached TEG modules, as shown in Figure **6**.

Figure **7** shows the variation of the maximum power generation and temperature difference (the driving force for the TEG power generation) across the 10 TEG modules (in the hybrid HPV-TEG system) versus the irradiance intensity. It is evident that as the irradiance intensity increases the maximum power output and the temperature difference across the TEG modules increase as well. More particularly, as the irradiance increased from 425 to 750W/m^2, the temperature difference across the TEG system increased from approximately 22 to 35°C (i.e. by 59.1%) with power generation increase from approximately 140 to 300 mW (i.e. by 114.3%), as shown in Figures **7**. The effect of changing the coolant (i.e. liquid water) inlet temperature (in the TEG's cold-side heat sink) on the maximum power output from both the TEG system (the 10 TEG modules) and the hybrid PV system (i.e. the 40W-HPVsystem) is shown in Figure **8**. In this case, as the inlet coolant temperature increased from 2 to 20°C (i.e. increased by 10 folds), the power output from the hybrid system slightly decreased from approximately 12.55 to 12.31W (by 1.9%), whereas the maximum power output from the 10TEG system appreciably decreased from approximately 300 to 220 mW (i.e. by 26.7%). This result suggests that the effect of the TEG's inlet coolant temperature is more pronounced for the performance of the TEG system than the PV module in the hybrid system.

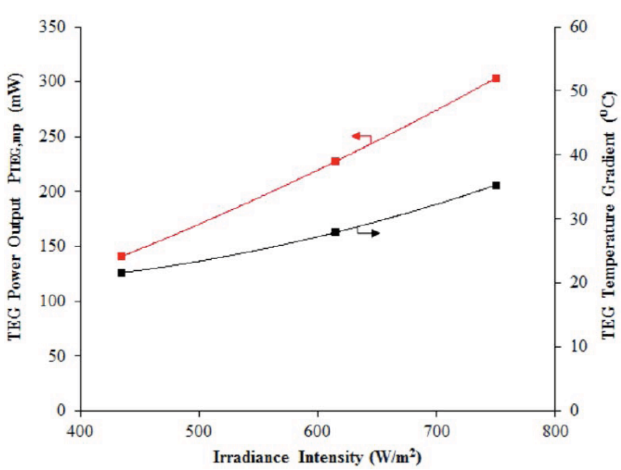

Figure 7: The maximum power output and temperature difference across the TEG system vs. irradiance intensity. (Tw, in=2°C, $\dot{V}=1$ L/min).

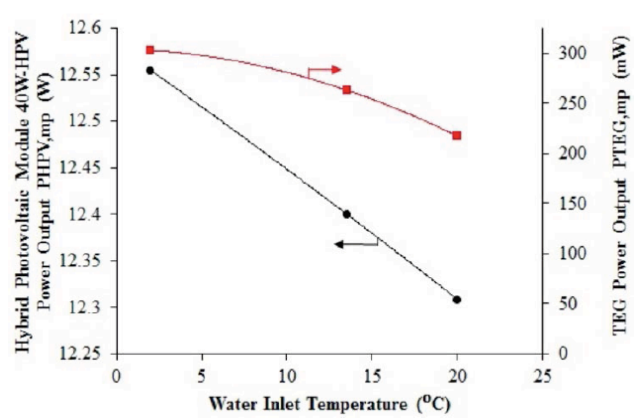

Figure 8: The power output for the TEG and HPV-TEG systems vs. coolant inlet temperature. (GT=750W/m^2, $\dot{V}=1$ L/min).

The power outputs from the PV modules in the solo PV system (40W-PV), in the hybrid HPV-TEG system (40W-HPV-10TEG), and in the hybrid system with the

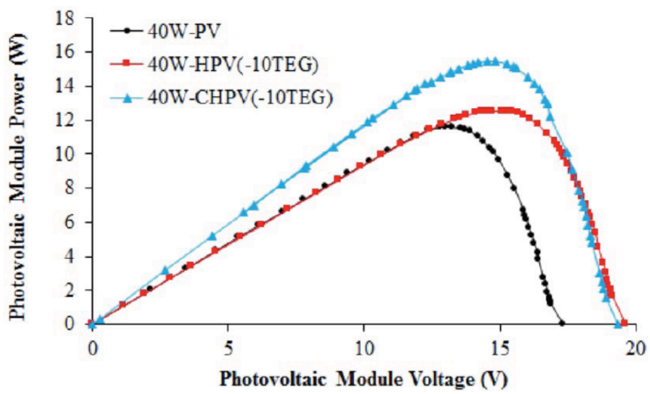

Figure 9: Comparative power output from the PV modules in the 40W-PV, 40WHPV-10TEG, and 40W-CHPV-10TEG systems vs. PV module voltage. (GT=750W/m^2, Tw, in=2 ºC, $\dot{V} = 1$ L/min).

concentrators (40W-CHPV-10TEG) versus the PV module voltage are compared in Figure **9**. The results showed that the maximum power point is shifted up (i.e. increased) in the two hybrid PV systems compared to the solo PV system. The maximum power point is higher in the hybrid system with the concentrators (i.e. the 40W-CHPV-10TEG) compared to the hybrid system without concentrators (40W-HPV-10TEG). More particularly, the maximum power point of approximately 11.61 W occurred at module voltage of 13.0 V for the solo PV system, whereas it shifted to approximately 12.55 W (increased by 8.1%) at 15.1 V for the hybrid PV without concentrators. The addition of the concentrators in the hybrid PV system increased the maximum power point to approximately 15.47 W (increased by 23.3%) at a voltage of 14.8 V compared to the hybrid system without concentrators. The reason for that increase could be due to the fact that the PV concentrators helped focus the irradiance falling on the PV module, which in turn increased the PV module temperature without damaging it. Elevating the PV module temperature tends to increase the hot-side temperature of the TEG modules and thereby increasing the temperature difference (i.e. driving force) for more power generation from the hybrid system. Comparisons of the PV module's average temperature between the three systems as captured in the thermal IR images are shown in Figure **10**. The average module temperatures are 87.0, 55.5, and 60.5°C for the solo PV module, the hybrid PV module without concentrators, and the PV module with concentrators, respectively. It should be noted that for consistency, the operating conditions were maintained the same (irradiance intensity of 750W/m^2, inlet coolant temperature of 2°C, and volumetric flow rate of 1 L/min) for the three systems.

The comparisons of the power output from the TEG system in hybrid PV system without concentrators and the hybrid PV system with concentrators versus TEG voltage are shown in Figure **11**. It is interesting to note that by adding the concentrators, the TEG power output increased (shifted up). In particular, the maximum power output of approximately 303 mW from the TEG occurred at a TEG voltage of 1.7 V for the hybrid PV system without concentrators, whereas it is approximately 418mW (an increase of 38.0%) at a voltage of 2.0 V for the hybrid system with concentrators. The results here suggest that adding the concentrators in the hybrid HPV-TEG system tend to improve its performance, however safety should be taken into account as more concentration of the irradiance using stronger concentrators in the hybrid system may result in much higher PV temperatures beyond safe limits which might damage the PV cells in the system and cause unsafe conditions to occur.

5. CONCLUSIONS

An increasing concern of environmental issues of greenhouse gas emissions and air pollution, and the limitations and conservation of natural energy resources have recently resulted in extensive research into innovative non-conventional renewable and alternative clean energy technologies of generating electrical power. Renewable solar-photovoltaic (PV) systems are known for their ability to directly convert solar energy into green electrical energy, however, their performance degrades when operating at elevated temperatures. Thus, decreasing the temperature of PV modules using efficient cooling methods tends to increase their power generation. Thermoelectric power generation (TEG) technology has the innovative capability to convert a portion of the waste-heat energy dissipated from PV systems, thus cooling them, and simultaneously generates additional power. Hence, hybrid photovoltaic-thermoelectric power generation (HPV-TEG) systems integrate TEG modules with a PV module to form a more efficient power generation system. There is a lack of published research that experimentally characterized in detail the performance of HPV-TEG systems. Therefore, in this research, a lab-scale test setup was designed, constructed and fully instrumented using real-time computerized loggers in order to characterize in detail and gain more understanding of the performance of an HPV-TEG system under various operating conditions of modules temperature and irradiance intensity. Experimental

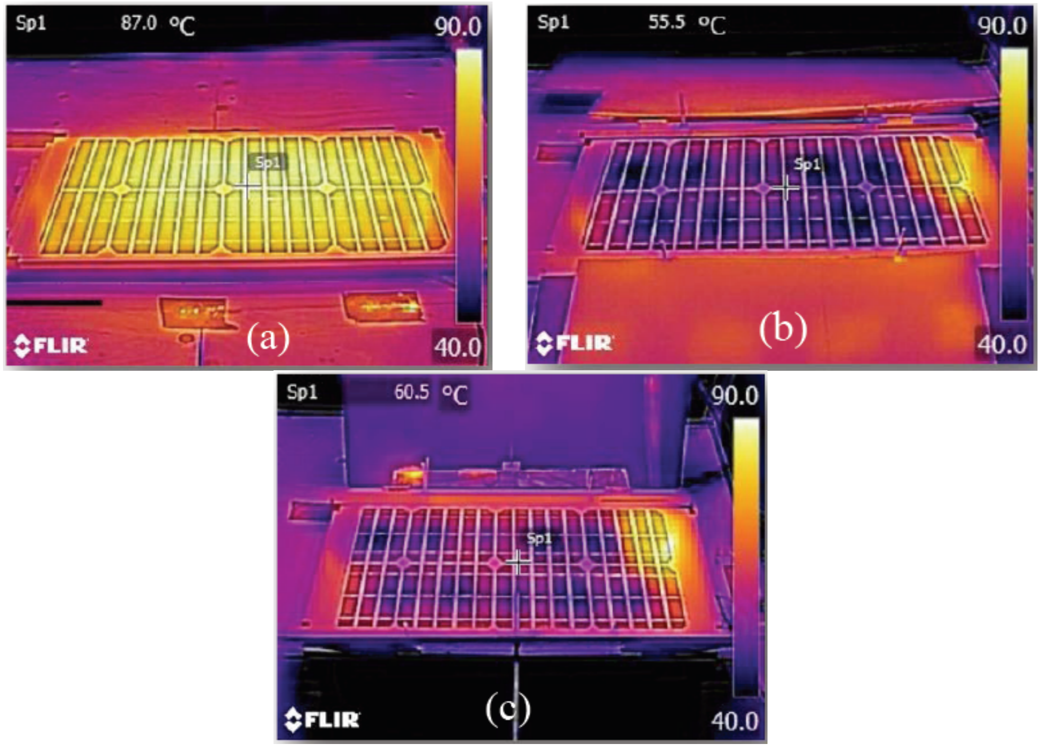

Figure 10: IR thermal I mages of the PV modules in the (**a**) 40W-PV, (**b**) 40W-HPV-10TEG, and (**c**) 40W-CHPV-10TEG systems. (GT=750W/m^2, Tw, in=2 °C, $\dot{V}=1$ L/min).

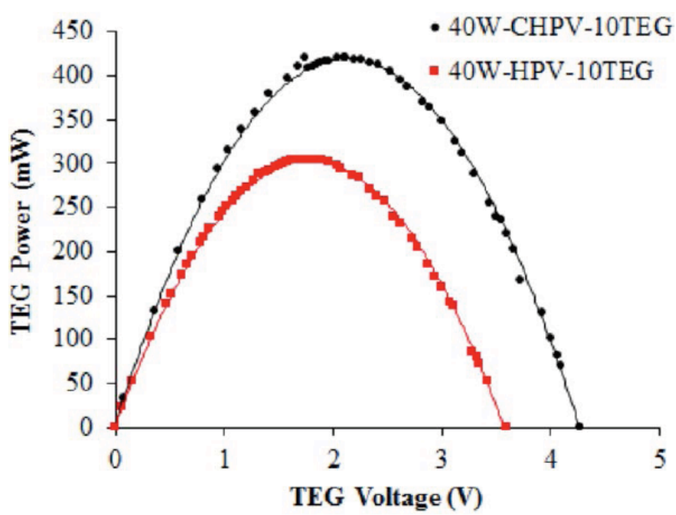

Figure 11: Comparison of the TEG power output from the 40W-HPV-10TEG and 40W-CHPV-10TEG systems vs. TEG voltage. (GT=750W/m^2, Tw, in=2 °C, $\dot{V}=1$ L/min).

results and IR thermal images showed that the hybrid HPV-TEG system was able to generate more DC power than the solo PV system while operating at higher irradiance intensities and lower TEG's inlet coolant temperature. For example, the increase of the maximum power output from the hybrid HPV-TEG system showed improvement with higher values compared to the solo PV system specifically at higher irradiances of 615 and 750W/m^2 At the irradiance of 615W/m^2, the power generation from the hybrid HPV-TEG system was approximately 10.1 W compared to 9.7 W for the solo PV system (i.e. increased by 4.1%). The results also showed that when the irradiance was increased to 750W/m^2, the power generated from the hybrid system increased by approximately 8.6% higher than the power generated from the solo PV system at the same irradiance. This suggested that cooling the PV system using the attached TEG modules (in the hybrid HPV-TEG system) has indeed improved its power generation compared to the solo PV system without cooling. This improvement or increase in power generation tends to increase as the irradiance increases. The integration of the concentrators in the hybrid PV system increased the maximum power point by 23.3% compared to the hybrid PV system without concentrators. The results also suggested that by adding the concentrators, the TEG power output increased. The maximum power output was found to be approximately 303 mW from the TEG occurred at a TEG voltage of 1.7 V for the hybrid PV system without concentrators, whereas it was approximately 418 mW (an increase of 38.0%) at a voltage of 2.0 V for the hybrid system with the concentrators. The results showed that integrating the concentrators into the hybrid HPV-TEG system tends to improve its performance, however safety should be taken into account as more concentration of the irradiance using stronger concentrators in the hybrid system may result in much higher PV temperatures beyond safe limits which might damage the PV cells in the system and cause unsafe conditions to occur.

The intention of this research was to provide further insights and understanding of the performance characteristics of PV systems when integrated with TEG modules that could be used to optimize the design and performance of these hybrid systems for optimal power generation. In the future research and based on the fundamental understanding gained from the results of this research, the authors of this work intend to modify the hybrid HPV-TEG system and fully characterize it under outdoor actual conditions of Thunder Bay, Ontario. Also, the PV system with concentrators will be studied in more details as it preliminary showed interesting results here in this study.

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