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Design and Performance Characteristics of a Hybrid Photovoltaic-Thermal Regeneration System under Indoor and Outdoor Solar Radiation Conditions of Thunder Bay, Ontario

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ABSTRACT

Numerous energy sources continuously emit large amounts of waste energy into the earth's atmosphere. Significant losses, nearly 85% of the incident light on a PV panel, are either reflected from the PV surface, accounting for up to 20%, or dissipated as heat. In this work, a novel lab-scale hybrid photovoltaic-thermal regeneration (HPVT-R) system is designed, constructed, and tested to restore some of the reflection losses in the PV system. The new HPVT-R system design permits the PV and thermal co-systems to perform autonomously while revitalizing some of the reflection losses by hybridization. Thorough testing of the HPVT-R system was performed under lab-scale indoor simulated light and outdoor solar radiation conditions in Thunder Bay, Ontario. The HPVT-R system regenerated approximately 14 % of the reflected light in these tests, transforming it into electrical power and heat. Under the solar-simulated lights, the indoor test setup regenerated around 17 mW of electric power from the reflected light accounting for slightly less than 1% of more electric power per unit PV surface area. However, the outdoor solar radiation tests rejuvenated nearly 137 mW of electric power, accounting for approximately 3% more electric power per unit PV surface area, with a conversion efficiency of nearly 7%. Regarding heat energy, the HPVT-R system regenerated approximately 34% more in indoor and outdoor performances entirely from the reflected light. This research investigates the performance aspects of the HPVT-R system operated under different working conditions.

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1. Introduction

Recent environmental concerns about greenhouse gas (GHG) emissions that cause global warming, climate change, and the depletion of energy resources have sparked substantial research into new methods of producing electricity. For instance, from 2007 to 2035, carbon dioxide emissions are expected to rise by 43%, according to the International Energy Outlook (IEO) [1]. The predicted emission would increase from 29.7 billion metric tonnes in 2007 to 33.8 billion metric tonnes in 2020 and 42.4 billion metric tonnes in 2035. A 49% rise in global energy usage was predicted between 2007 and 2035. IEO2010 anticipated that from 2007 to 2035, the global consumption of renewable energy for electricity generation will increase by an average of 3.0% per year, reaching 4.5 trillion kWh [1]. Canada ranks seventh in energy consumption and fifth in energy production. Approximately 17% of Canada's primary energy supply comprises renewable energy sources. Nearly 60% of Canada's electricity is produced from the most plentiful renewable energy source, hydroelectricity. Solar, wind, tidal, and biomass resources contribute 3% to the production of power [2].

Significant amounts of waste-heat energy are constantly being released into the Earth's atmosphere from various energy sources. For instance, 30–40% of the elemental gasoline fuel energy is lost as waste heat energy in the exhaust gases produced by a gasoline spark-ignition-driven engine. The waste heat discharged in the exhaust gases from a typical passenger automobile moving at a regular speed is 20–30 kW [3-5].

Ismail and Hazrat [6] used a novel Stirling engine (SE) setup to directly convert waste heat energy from exhaust gases into green electrical power. To explore the SE's capability of converting the exhaust waste heat generated by a real four-stroke SI engine into electrical power, in their study, a novel experimental test setup featuring a prototype gamma-configuration SE system was designed, built, and tested [6].

A hybrid solar PV-T system can generate both heat and electricity at the same time by combining photovoltaic (PV) and thermal (T) components. Compared to thermal collectors and PV modules installed side by side and operating independently, HPVT systems produce more energy per unit surface area [7]. Even though PV modules convert sunlight directly into electrical DC power, most of the solar radiation they absorb is wasted and transferred to them as waste heat. The PV modules' temperature rises due to solar energy that cannot be converted into electricity, lowering their electrical conversion efficiency. In order to partially satisfy the heating demand, the heat generated can be transferred to a heat exchanger in surface thermal contact with PV modules [8]. Different designs have been proposed to increase the overall energy effectiveness of HPVT systems. For instance, a hybrid PV solar and thermoelectric (HPV-TEG) system for direct power generation from solar and waste heat energy was the subject of an experimental investigation by Ismail and Bujold [9]. In their HPV-TEG system's design, they used a flat PV panel and reported an improvement in the system's efficiency and power generation output. A hybrid PV solar and thermoelectric (HPV-TEG) system for direct power generation was also experimentally characterized by Ismail and Bujold [10] under indoor and outdoor Thunder Bay's solar radiation and climate conditions. Their [10] investigation shows that the HPV-TEG system provided more DC power than the traditional PV system while operating at higher irradiance intensities and lower TEG's inlet coolant temperatures. The findings from the indoor testing and IR thermal images demonstrated this. According to their indoor experiments, the HPV-TEG system's design optimization is essential to be a competitive alternative to traditional PV systems. However, their [10] outdoor experiments contrasted the HPV-TEG system's performance traits with those of a typical PV module in a range of weather-operating conditions. According to their findings, the HPV-TEG system produced about 5% more electrical power during outdoor tests than the traditional PV module. Furthermore, it was found in their research that the HPV-TEG system's ability to produce more electrical power was primarily due to its ability to lower the temperature of the PV modules. The integration of the TEG was found to have contributed up to 23% of the hybrid system's overall additional electrical power output [10].

One of the most critical losses in a PV panel is reflection loss. Even with antireflection coatings, up to 20% of the incident light is reflected [11]. Studies of this reflected light's numerical quantification exist. However, there are few good experiments or applications to use them. Buildings that need both electric power and heat simultaneously are a great fit for HPVT systems. An HPVT system typically consists of thermal and photovoltaic subsystems that work together to maximize the use of incident solar radiation. A silicon-based PV module is limited in responding to the solar spectrum, dissipating high-intensity IR radiations as heat, and converting light in the visible and near IR ranges into energy with an electrical efficiency of up to 20%. According to Kalogirou's work [12], the efficiency of the PV cells fell by roughly 1% for every degree that the temperature increased due to the dissipated heat. Thus, a thermal collector and PV panel can be combined to cool the PV panel and recover the lost heat. Building rooftops and façades can benefit from hybridizing PV flat panels with a thermal collector since it lowers manufacturing and installation costs. According to [13, 14], flat plate PV-T systems produce low-temperature heat due to cooling the sun cells since solar cells are ineffective thermal absorbers. The experimental performance of glazed and unglazed liquid-type PV-T collectors in outdoor settings was investigated by Kim *et al*. [15]. According to their findings, the glazed PV-T collector had a thermal efficiency that was 14% greater than the unglazed PV-T collector. However, the unglazed collector had an electrical efficiency of nearly 1.4% higher than the glazed collector. Compared to the unglazed collector, the glazed collector performed about 12.6% better on average. A 10 m^2 Trough Concentrating PVT (TCPVT) system featuring a parabolic trough concentrator, receiver, electrical energy output system, and thermal energy storage system was investigated by Li M. *et al*. in their study [16]. The thermally conductive tape was used to attach Supercell arrays, GaAs cell arrays, and Si cell arrays to the lighting plate of the receiver. Their research [16] pumped pressurized water through the receiver's interior chamber, cooling the solar cells while producing heat. According to their experimental findings, each cell type had average electrical efficiency of roughly 3.6%, 8.9%, and 3.7%, respectively. The electrical conversion efficiency increased for each cell type by 0.9%, 2.62%, and 5.47%, respectively, when mirror reflectivity was raised from 0.69 to 0.92 [16]. The performance analysis of a TCPVT system was investigated by Manokar *et al*. [17] since the standard PV system either reflects or absorbs as heat 85% of the solar radiation incident on the system. Their research [17] used a channel PV/T collector as the receiver and a parabolic trough as the light concentrator. They incorporated a "V"-shaped receiver to capture the most reflection from the trough. The PV system's temperature was raised by 20^oC by the concentrator, which was subsequently transferred to cooling water.

Additionally, they noted that the PV temperature had significantly increased, negatively affecting the electrical performance output [17]. Yamada *et al*. [11] analyzed the impact of reflection on a PV module with the optical characteristics of the materials used to construct the module. The reflection loss from a PV module was simulated using a four-layer encapsulation's optical performance by Fresnel's law. Less than 80% of the light, according to their findings [11], is transferred to the silicon cell with a 50^o incident angle. The transmittance falls dramatically when the incident angle varies from 50^o to 90^o.

A few studies investigated the PV optical losses with regenerating thermal energy using hybrid PV systems. For example, Wang *et al*. [18] designed and investigated a hybrid CPV/T unit that concentrates solar radiation by a compound parabolic concentrator (CPC) and converts solar energy into electrical and thermal energy by a PV/T module. In their work [18], the CPC was used to eliminate multiple reflections of solar radiation, which improves PV and thermal conversion efficiencies. They tested two similar CPV/T units using a two-axis and a south-north single-axis tracking device. Their experimental results showed that these two devices' average photoelectric conversion efficiencies were 13% and 12%, respectively. A more recent study by Shahsavar [19] comprehensively and experimentally examined a photovoltaic-thermal (PVT) system with a sheet-and-sinusoidal serpentine tube collector (PVT-S) from the perspective of energy, exergy, and entropy generation. The results are compared with those of the PV module deprived of cooling and the PVT unit accompanied by a sheet-and-plain serpentine pipe collector (PVT-P). [19] Combining the sinusoidal serpentine tube and the coolant nanofluid (NF) improved the PVT unit's energetic and energetic performance. Das *et al*. [20] noted in their work that even though Photovoltaic (PV) technology is mature, the effect of temperature on its efficiency is considerable, which opens up a new front of research where a combination of PV and thermal absorber is focused on harnessing thermal energy which otherwise negatively affect the PV electrical efficiency. Their study [20] emphasized using nanofluid and phase change material to harness maximum thermal energy from the PV/T system. Their study also included an insight into commercially available PV/T modules across the globe. Their paper [20] presented an enviro-economic evaluation of PV/T systems developed by various researchers and enumerated thermodynamic methods for evaluating system efficiency, including energy and exergy analysis. Their paper also provided the necessary information about the requirement of future research in PV/T. Rejeb *et al*. [21] developed a novel photovoltaic thermal collector (PVT) to improve the electrical and thermal efficiencies of the solar collector. Their goal was to maximize the electrical power and minimize the thermal losses of the solar panel. They designed and tested their

PVT system. Their PVT collector included: (1) An optical anti-reflective and low-emissivity coating to reduce the radiation losses; (2) A thermal resistance to reduce the conduction losses between the photovoltaic and absorber plate; and (3) A channel heat exchanger to decrease the thermal losses between the solar cells and the cooling fluid. In their work [21], the simulation results clearly showed the advantages of using the PVT collector compared to the conventional one. Their new PVT system produced higher electrical and thermal efficiencies (15.4%, 73%) than the conventional PVT collector (13.7%, 58%) under no loss and standard test conditions.

This research paper introduces and describes a novel design for an HPVT that permits PV and thermal systems to function independently while regenerating some of the optical losses in the PV system by hybridization. The key difference in this study compared to previous studies is the design novelty and unique compactness of the HPVT system. It uses a curved PV panel where its optical losses are reflected into a regenerative PV array attached to an airflow-type thermal collector. This research work was achieved by performing detailed tests and analysis of the new design using indoor solar simulations and outdoor solar radiation under Thunder Bay's climatic conditions to study the performance of the PV subsystem, the thermal subsystem, and the regeneration of PV optical losses. This research uses a lab-scale design of HPVT with a flexible curved PV panel of 25 W, four 0.5 W PV modules to regenerate reflected light, and an air-type thermal collector. The significant advantage of this design is that the system allows the PV panel and thermal collector to function independently while regenerating some of the reflected light by hybridization.

2. The Design Concept of the Novel HPVT-R System

In this research, an HPVT-R system was designed, fabricated, and fully instrumented to test the regeneration of electrical and thermal power. To assist in building the HPVT-R prototype, a 3-D model of the system was produced using Catia V5 (CAD) software, as shown in Fig. (**1**). A flexible PV panel of 25W, 18 V is fixed in a curved position in a wooden frame. The characteristics of the PV panel in horizontal and curved positions were identical in indoor testing. The thermal collector fixed at the focal line is made of a steel channel to allow airflow. The steel channel is wrapped tightly with a black copper sheet of high absorptivity of 0.95 with the help of thermally conductive adhesives. Four low-rating PV modules are connected in parallel and arranged at the bottom surface of the thermal collector facing the curved PV panel.

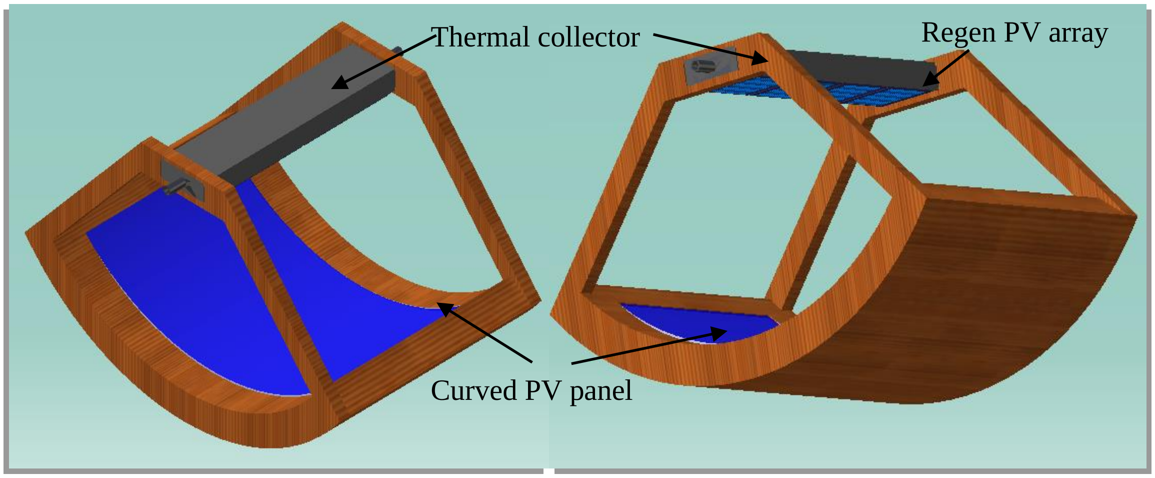


Figure 1: The 3-D model of the HPVT-R system used in this research to regenerate power from reflection loss of the curved PV panel.

The proposed HPVT-R system's energy flow diagram (Fig. **2**) shows how solar energy is transformed into heat and electricity through photovoltaic and thermal subsystems, respectively. The thermal collector in the focal line and the curved PV panel receive solar radiation. While the transmitter (unabsorbed) solar radiation is transformed into heat and some of the light incidents on the PV panel are reflected (estimated at up to 20%) from the PV surface, a portion of the incident solar radiation is converted directly into electrical DC power by the curved PV panel. With an absorptivity of 0.95, the black absorber on the thermal component absorbs solar radiation and transfers heat to the air (working fluid), flowing at a particular flow rate. The warm air can subsequently be distributed for room heating or to lighten the burden on an already-installed HVAC system. In this arrangement, the curved PV panel's light reflection is then focused on the regen-PV modules located on the thermal collector's bottom surface. The reflected light is converted into additional electrical power by the Regen-PV modules. Additionally, these Regen-PV modules dissipate the unabsorbed light into heat and then transfer it to the moving air. This additional electrical power and heat produced from the reflected light are considered the regenerated power from the HPVT-R system used in this study.

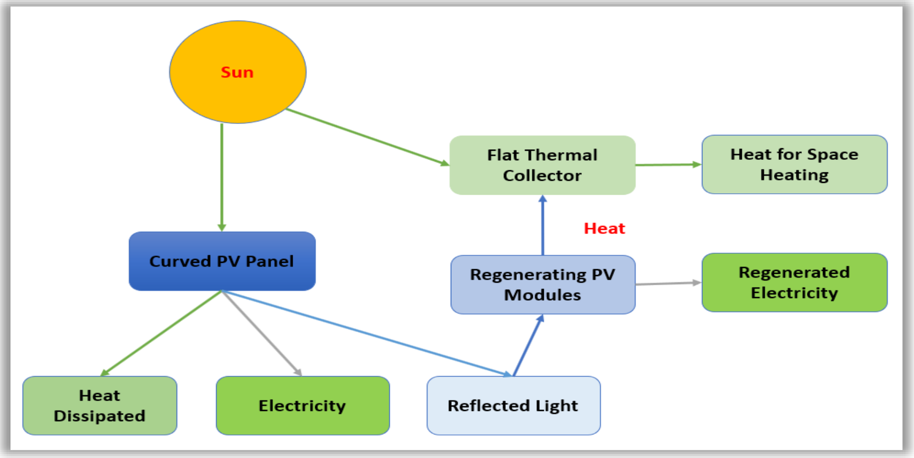


Figure 2: The energy flow diagram of the HPVT-R system used in this study.

3. Experimental Test Setup and Analysis of the hpvt-r System

The experimental test setup was designed and constructed to study the performance characteristics of the curved PV panel, thermal collector, and Regen-PV array in detail. This requires careful and real-time measurements of irradiation, voltage, current, temperature, air flow rate, and emittance, as shown in Fig. (**3**). As shown in Fig. (**3**), the HPVT-R test setup was fully instrumented with real-time data acquisition sensors for temperature measurements at various locations across the thermal collector. In addition, the system is equipped with voltage and electric current measurement sensors for the DC power output from the curved and regen PVs, irradiance, and emittance sensors to measure input global solar radiation impinging on the photovoltaic and

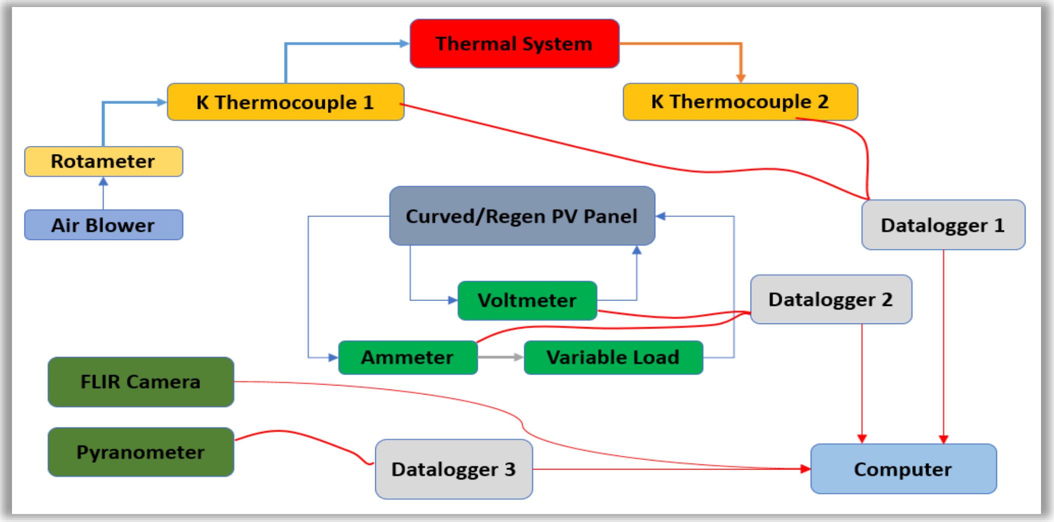


Figure 3: The experimental test setup of the HPVT-R system used in this study.

thermal subsystems, respectively. A photograph showing the experimental test setup of the HPVT-Regen used in this research is shown in Fig. (**4**). The curved PV panel and regen PV array were tested under an indoor solar simulator and outdoor solar radiation of Thunder Bay city, using a 4-wire Kelvin circuit consisting of a voltmeter, ammeter, and variable load. Since the indoor simulated radiation is almost constant throughout, a variable load is used to characterize the PVs. The real-time characterization under the outdoor solar radiation was performed using Solmetric PVA-600V PV Analyser. A pyranometer measured the input solar radiation impinging on the HPVT-Regen system. The maximum power output from the photovoltaic subsystem is calculated using the,

$$P_{\text{max}} = V_{\text{mp}} I_{\text{mp}} \tag{1}$$

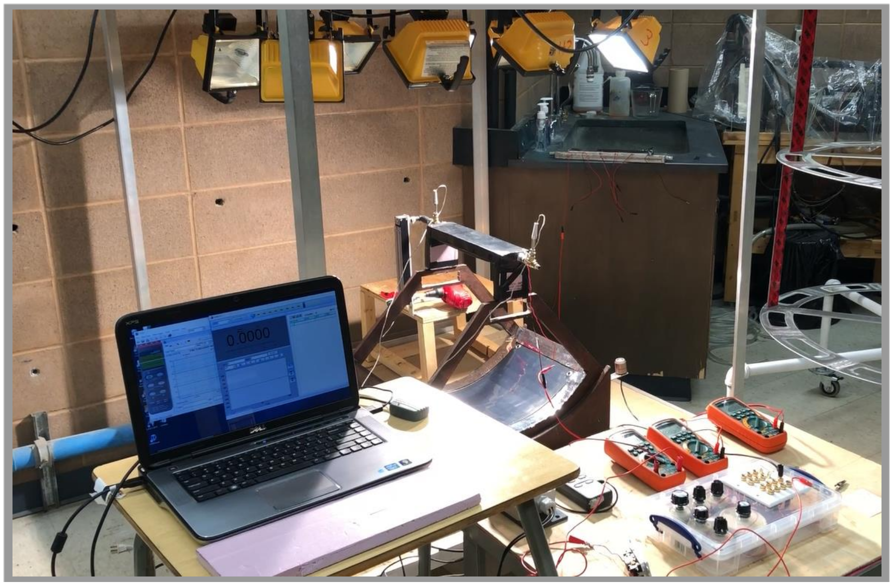


Figure 4: A photograph showing the experimental test setup of the HPVT-R system used in this work.

Vmp and I_{mp} are the output DC voltage and current, respectively, at the maximum power point. The electrical conversion efficiency of the PV subsystem is given by,

$$\eta_{\text{pv}} = \frac{P_{\text{max}}}{P_{\text{in,pv}}} \tag{2}$$

Where $P_{\text{in,pv}}$ is the incident solar radiation measured by the pyranometer.

Forced air circulation in the thermal collector was provided using an air blower. The airflow rate is measured and regulated by an OMEGA-FL-3840ST rotameter. K-type thermocouples measure the inlet and outlet air temperatures. The temperature measurements are acquired every 20 minutes at an interval of one minute. The thermal collector was calibrated to eliminate the effect of heat added by the air blower and heating of thermocouples by irradiation. A calibrated FLIR-IR camera measures incident thermal radiation received by the thermal collector. The thermal power output from the solar collector is given by,

$$P_{\text{th}} = \dot{m}\, C_{\text{p,air}} [T_{\text{out}} - T_{\text{in}}] \tag{3}$$

Where $\dot{m}$ is the air mass flow rate measured by the rotameter, $C_{\text{p,the air}}$ is the specific heat of air, and T_{out} and T_{in} are the outlet and inlet air temperatures, respectively. The collector receives thermal radiation from the top surface by direct irradiation and from the bottom surface by reflected radiation from the curved PV panel. Total thermal radiation received by the top and bottom surfaces is given by,

$$P_{\text{in,th}} = \sigma A[\varepsilon_1 (T_{\text{SA}})^4 + \varepsilon_2 (T_{\text{SB}})^4] \tag{4}$$

Where σ is the Boltzmann constant, A is the area of the radiated surface, ε_1 and ε_2 are the emissivities of the top black Cu absorber and bottom Regen PV silicon, respectively, T_{SA} and T_{SB} are the temperatures (in K) of the top and bottom surfaces, respectively, after being calibrated.

4. Experimental Results and Discussion

As previously stated, thorough experimental tests and measurements were carried out to characterize the HPVT-R system's performance completely. The *I-V* characteristics of the curved PV panel tested in an indoor simulator are shown in Fig. (**5**). Under the irradiation of approximately 173.0 W/m^2 from the solar lab simulator, the curved-PV panel generated electric power of 2.6 W with an electrical conversion efficiency of almost 13%, as shown in Fig. (**5**). According to the pyranometer data, the Regen-PV array got 14.7% of the incident simulated light as reflected light. The Regen-PV system regenerated around 17.05 mW of electric power from this reflected light with an efficiency of approximately 4.3%, accounting for slightly less than 1% more electric power per unit PV surface area.

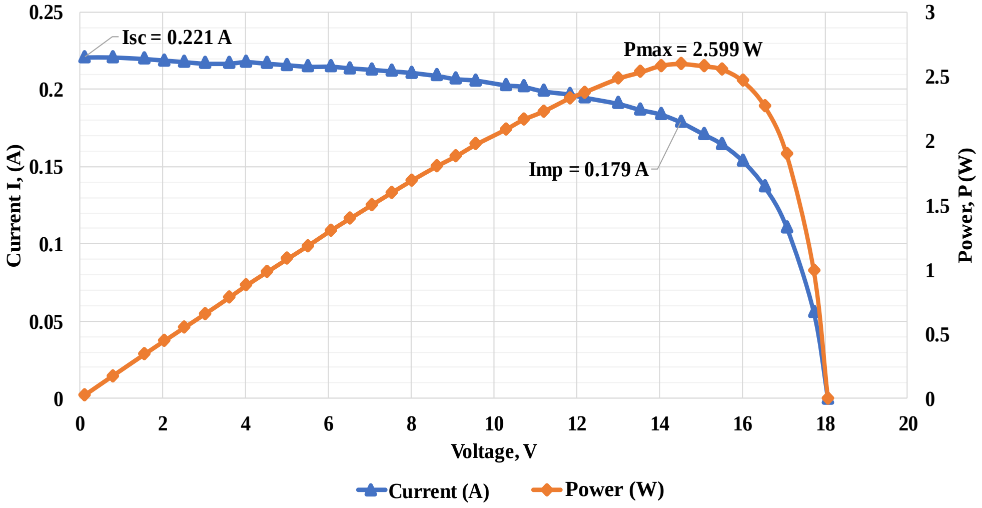


Figure 5: *I-V* characteristics of the curved PV panel under indoor solar simulated light.

The *I-V* characteristics of the Regen-PV system operating under reflected radiation are displayed in Fig. (**6**). The test was unstable because the Regen-PV modules were operating with variable reduced illumination. The electrical

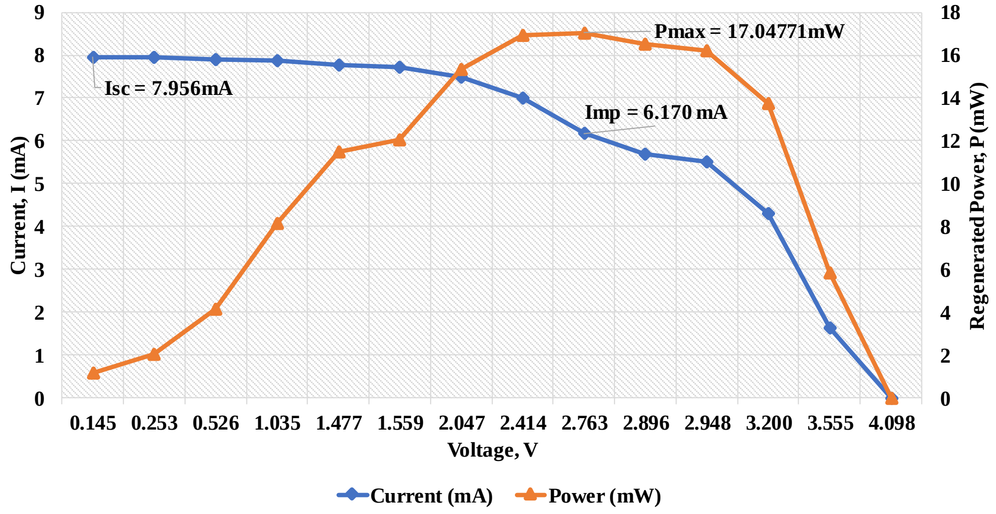


Figure 6: *I-V* characteristics of the PV-R array under indoor solar simulations.

load was carefully adjusted to accommodate changes in DC voltage (V) and current (mA). The test results demonstrate that, as compared to indoor simulations, the curved PV panel produced nearly twice as much electrical power. However, because the PV panel's capacity to absorb the intense solar radiation was substantially lower, the electrical efficiency of the curved PV panel drastically decreased. In this instance, the PV panel generated approximately 4.35 W of electric power at a nearly 3.6% electrical efficiency. Fig. (**7**) illustrates the fluctuation in maximum power output concerning solar radiation and the outdoor performance parameters of the curved-PV panel. The intermittent sky clouds during the testing day were revealed to cause the decrease in irradiation and power in Fig. (**7**). The Regen-PV array demonstrated auspicious outdoor performance. The results of the outdoor testing revealed that the curved-PV panel reflected approximately 14.3% of the incident radiation, comparable to the 14.7% seen during the indoor testing. This was discovered to conform with the findings of Yamada *et al*. analysis of the PV panel's optical characteristics [11].

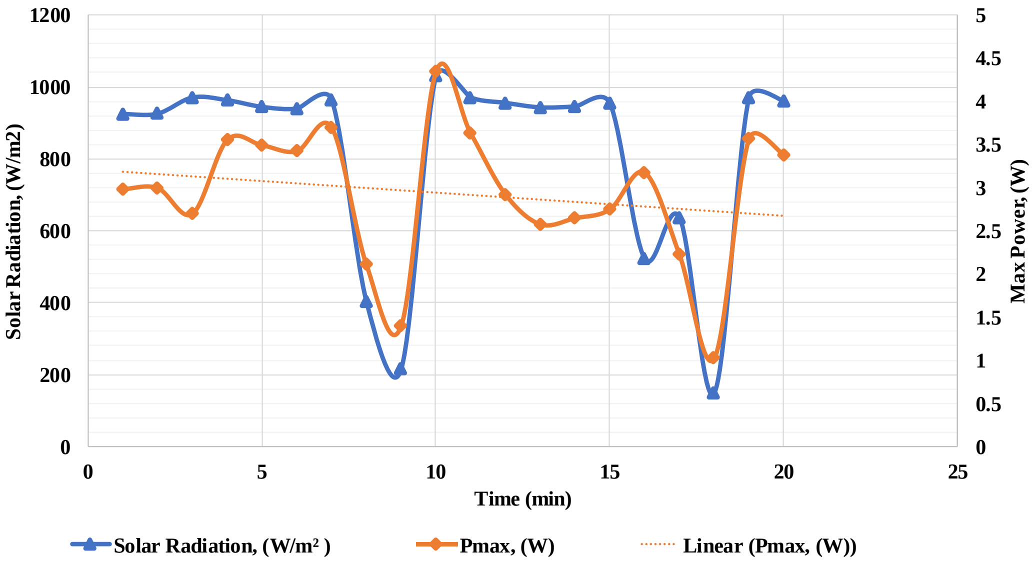


Figure 7: Variation in maximum power of the curved PV panel with respect to solar radiation for a duration of 20 minutes.

Fig. (**8**) shows how the Regen-PV array performs when exposed to reflected light. With an electrical efficiency of nearly 7%, the Regen-PV panel generated approximately 0.137 W of electrical power under the solar radiation impinging on the surface, adding around 3.2% more electrical power per unit PV surface area. The Regen-PV panel's characterization test conducted outside in the sun was comparatively more stable than the inside testing.

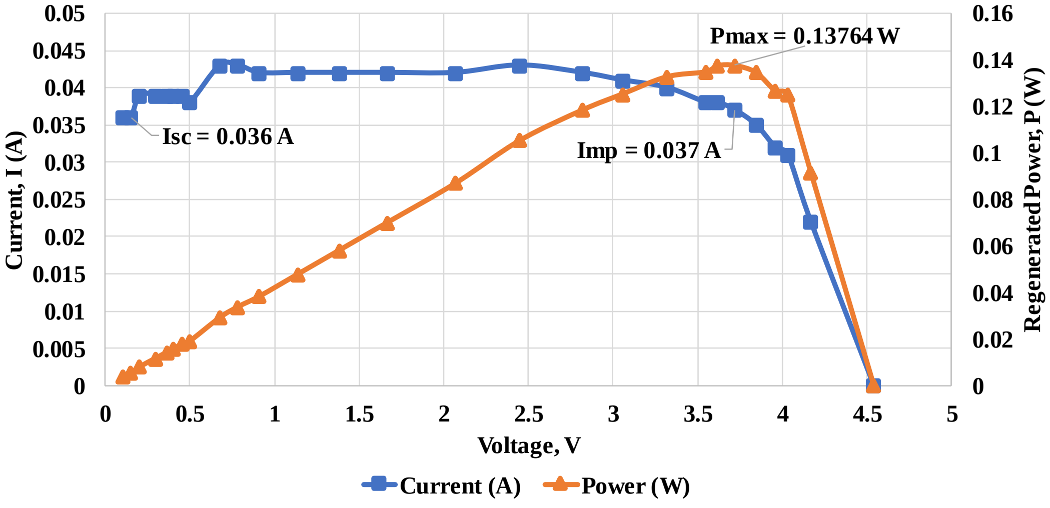


Figure 8: *I-V* characteristics of the PV-R array obtained while testing under outdoor solar radiation.

The electrical subsystem of the HPVT's important performance characteristics and values for indoor and outdoor testing are compared in Table **1**. Under the lab simulated lights and solar radiation, the thermal collector's performance was examined for an air volumetric flow rate of 0.000295 m^3/s. Since there is unaccounted-for heating from the air blower and thermocouple heating from radiation exposure, the temperature gain caused by the air could not be determined directly. Thus, the actual increase in air temperature was ascertained by calibrating the temperature data. For calibration, the temperature data from the actual operation of the thermal subsystem was subtracted from the heat addition caused by the air blower and thermocouple heating, which were measured separately on various days. By insulating the top surface of the PV panel, the experiment additionally included separate measurements of the temperature rise caused by reflected light for indoor and outdoor testing. Fig. (**9**) depicts the temperature gain caused by the circulated air for a 20-minute test period during indoor solar simulations. Fig. (**9a-b**) shows the total temperature gain and the gain caused by reflected light, respectively. The experimental findings from Fig. (**9**) demonstrate that, in indoor solar simulations, air passing through the thermal collector at a rate of 0.000295 m^3/s had a total temperature rise of 11^{o}C 3^{o}C was entirely attributable to the reflected light (i.e., the optical losses).

Table 1: Comparison of performance parameters of the electrical subsystem of the HPVT-Regen system for indoor and outdoor testing.

Parameters	Indoor Testing	Outdoor Testing
Irradiation, $P_{in,pv}$	173.039 W/m^2	892.54 W/m^2
Reflected solar radiation, $P_{in,regn}$	25.5 W/m^2	127.75 W/m^2
Percentage reflection	14.73 %	14.31 %
Max power-curved PV, $P_{max,pv}$	2.599 W	4.345 W
Electrical efficiency- curved PV	12.95%	3.63 %
Max power-Regen PV, $P_{max,regen}$	17.04 mW	137.64 mW
Electrical efficiency- Regen PV	4.28 %	6.90 %
Regeneration of electric power	< 1%	3.16 %

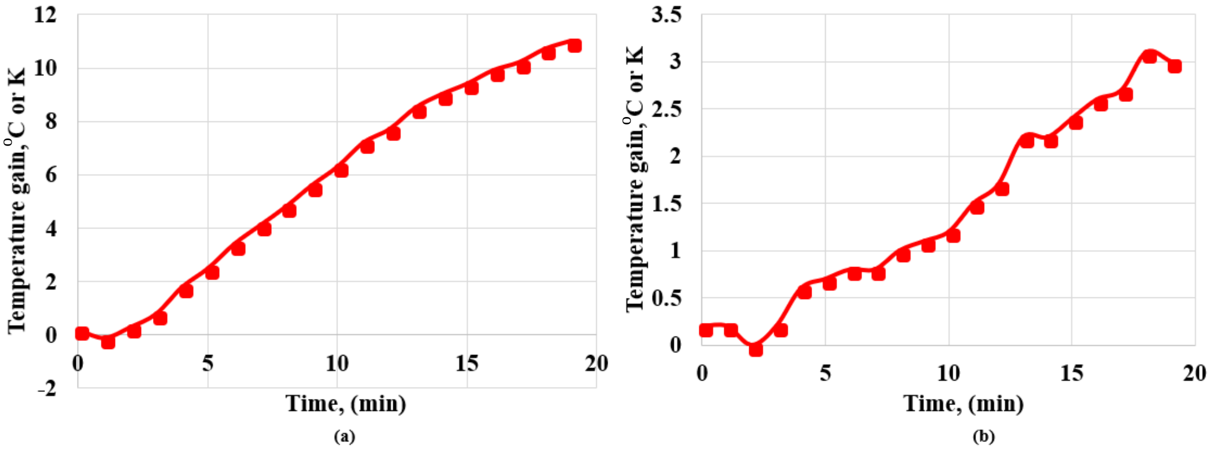


Figure 9: Temperature gain by the air in thermal collector when tested for 20 minutes under indoor simulator, (**a**) total gain in temperature, (**b**) temperature gain solely due to reflected light.

The thermal collector had a thermal conversion efficiency of about 41% for indoor testing. Thermal pictures captured by a FLIR-IR camera calibrated for the top and bottom surfaces of the thermal collector, respectively, as illustrated in Fig. (**10**), were used to determine the input thermal radiation using Equations 3 and 4. Fig. (**11**) illustrates the temperature rise caused by air passing through the thermal collector at 0.000295 m^3/s for a 20-

minute test period under outdoor solar radiation. Both Fig. (**11a-b**) depicts the temperature rise overall, and the temperature gain caused only by reflected light, respectively. The experimental findings also show that the thermal collector had a 9.3°C overall temperature increase under external solar radiation, of which 2.4 °C was entirely attributable to reflected light. Based on the testing done under outdoor conditions, the thermal collector had a thermal conversion efficiency of about 50%. Table **2** compares the temperature parameters that were taken into consideration for both indoor and outdoor tests.

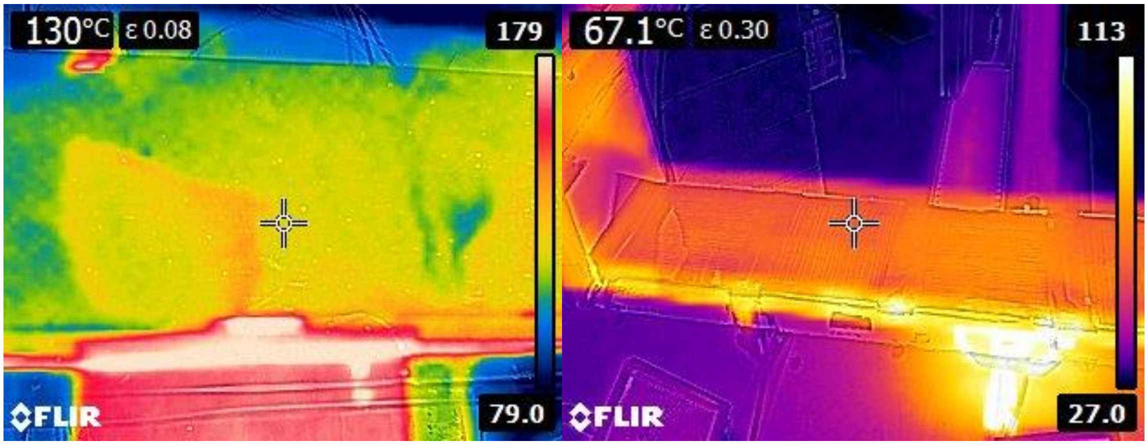
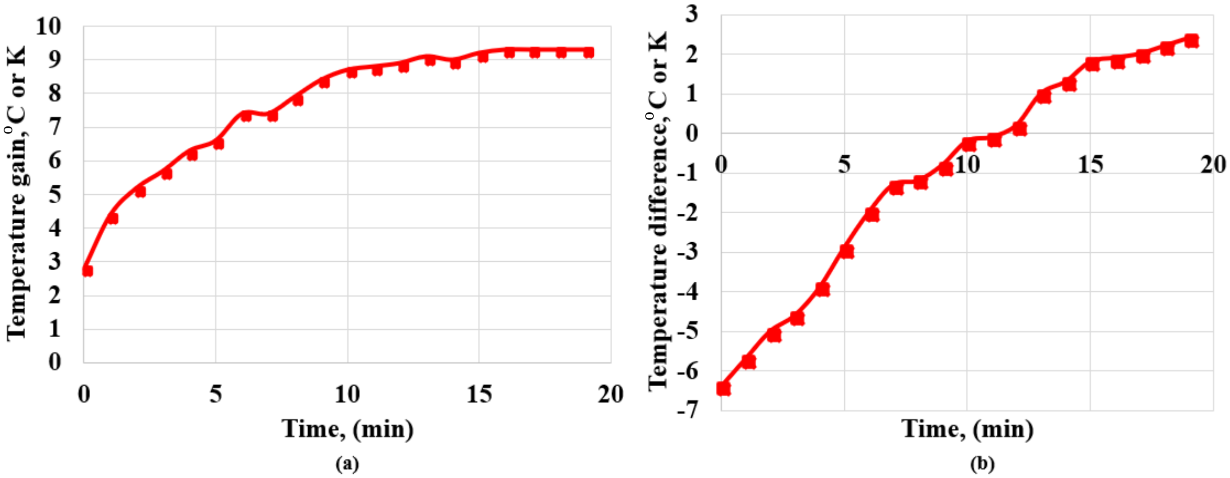


Figure 10: Thermal images of the top (left) and bottom (right) surfaces of the thermal collector taken with FLIR camera for the indoor solar simulation.



(a)

(b)

Figure 11: Temperature gain by the air in thermal collector when tested for 20 minutes under outdoor solar radiation, (a) total gain in temperature, (b) temperature gain solely due to reflected light.

Table 2: Comparison of performance parameters of the thermal subsystem of the HPVT-Regen system for indoor and outdoor testing.

Parameters	Indoor Testing	Outdoor Testing
Total air temperature gain	11 ºC	9.3 ºC
Temperature gain due to reflected light	3 ºC	2.4 ºC
Thermal Power	3.924 W	3.379 W
Thermal efficiency	40.58 %	50.23 %

Studies on outdoor experimental cases were conducted in a dynamic climate in Thunder Bay, Ontario, Canada (48.38o N, 89.25o W). On the beaches of Lake Superior, Thunder Bay is located in North-western Ontario. The weather in the city varies significantly from season to season. For instance, the coldest ambient air temperature was roughly -32.0 °C in January 2015, while the maximum was roughly 33.2 °C in July 2014. Thunder Bay city has a suitable amount of sunshine in the summer (June–August), even though there is a significant seasonal variation in temperature, which is necessary to properly investigate the functioning of the HPVT-R system used in this study. In this study, the tests were run simultaneously on two days of the same week for 20 minutes in two phases. The first phase evaluated the efficiency of the curved-PV panel, the regen-PV array, and the thermal collector for complete system operation (Fig. **12**). The impact of reflected light on the temperature of the moving air was investigated during the second phase of temperature measurements with the thermal collector's insulated top surface. On July 2, 2018, from 14:00 to 14:20, the curved PV panel was tested with the earth's North and South directions in mind. The maximum power points received from the PV panel were measured using the Solmetric PVA-600V PV-Analyzer.

Figure 12: A photograph of the fully instrumented test set up under solar radiation in Thunder Bay, Ontario.

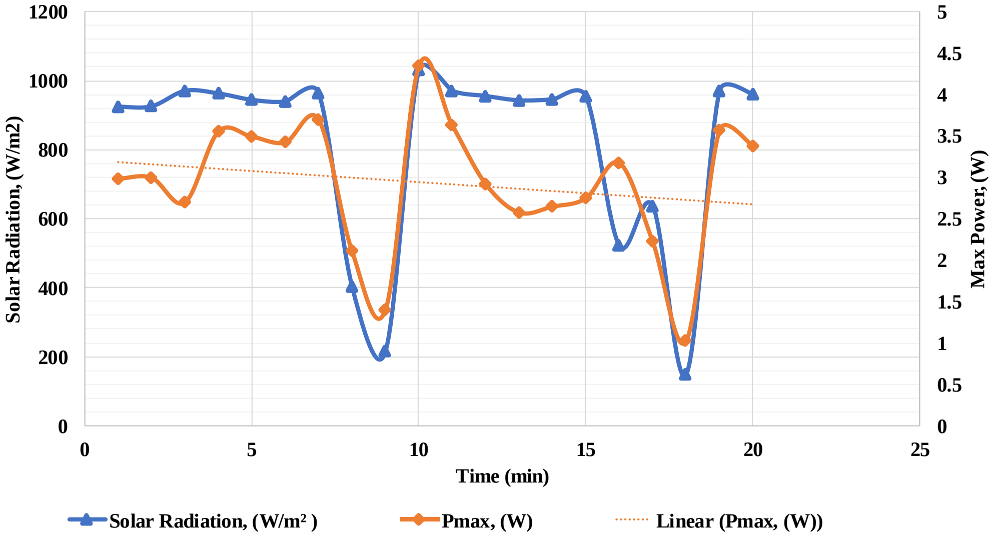


Figure 13: Variation in maximum power of the curved-PV panel with respect to solar radiation for 20 minutes.

The change of maximum power with solar radiation is depicted in Fig. (**13**). Intermittent sky clouds are to blame for the sharp decreases in irradiation and power shown in this graph. The *I-V* characteristics of the curved panel for the moment where the highest power was attained during the 20-minute test are shown in Fig. (**14**). Under an average irradiation of 814.4 W/m^2, the curved-PV panel generated an average electric output of 2.93 W with an average electrical efficiency of approximately 3.4%. The system's Regen-PV array underwent testing. Pyranometer tests show that the regeneration system receives a reflection of about 14.3% of the incident light. The four-wire Kelvin circuit was used to describe the regen-PV array irradiated by the reflected light by adjusting the electrical demand.

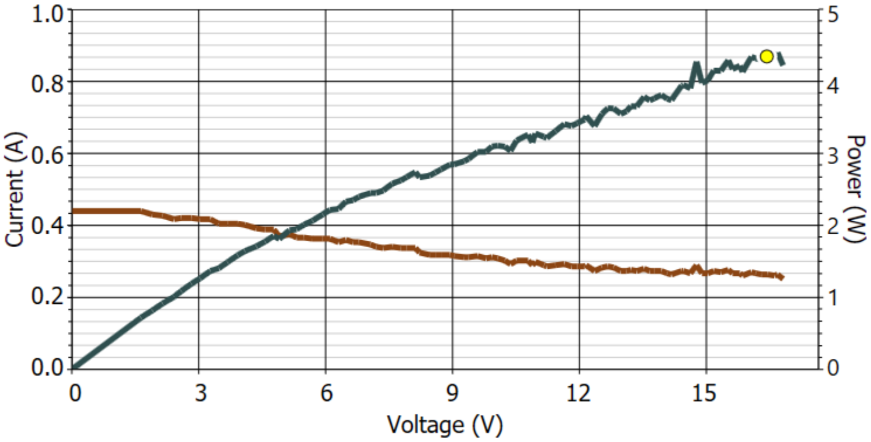


Figure 14: *I-V* characteristics of the curved-PV panel for the instant of highest maximum power obtained, measured by Solmetric PVA-600V PV-Analyzer.

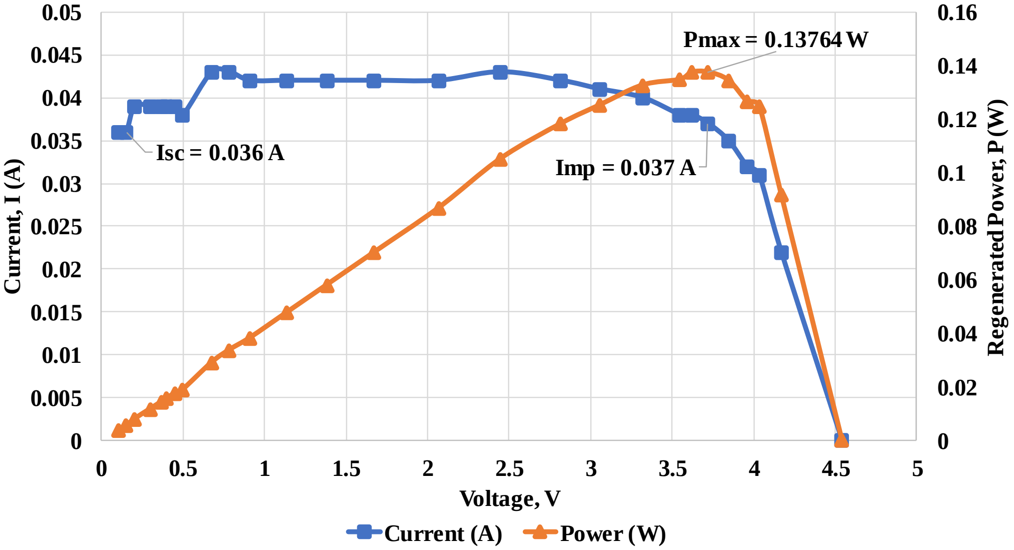


Figure 15: *I-V* characteristics of the regen-PV array obtained while testing under outdoor solar radiation.

The Regen-PVs' characterization test in direct sunlight was comparatively more stable than the testing done under indoor simulated light. Fig. (**15**) shows the *I-V* characteristics of the regen-PV array. The *I-V* characteristics are constant in measurements and have a standardized shape. The Regen-PV array generated 0.137 W of electricity with around 6.9% electrical efficiency, adding about 3.2% more per unit PV surface area. Table **3** compares the parameters of curved-PV panels and regen-PV arrays in both indoor simulation and outdoor real-time characterization. The outdoor performance outperforms the indoor simulation, according to Table **3**. Similar reflection percentages are consistent with the optical characteristics of the curved-PV panels.

The performance of the thermal system was also experimentally characterized. The air-type thermal collector was tested for temperature gain at a volumetric flow rate of 2.95× 10^{-4} m^3/s for 20 minutes. At the same time, the

Table 3: **Comparison of performance parameters of the electrical subsystem of the HPVT-Regen system for indoor and outdoor testing.**

Parameters	Indoor Testing	Outdoor Testing
Irradiation, $P_{in,pv}$	173.039 W/m^2	892.54 W/m^2
Reflected solar radiation, $P_{in,regn}$	25.5 W/m^2	127.75 W/m^2
Percentage reflection	14.73 %	14.31 %
Max power: curved-PV, $P_{max,pv}$	2.599 W	4.345 W
Electrical efficiency: curved-PV	12.95%	3.63 %
Max power: Regen-PV, $P_{max,regen}$	17.04 mW	137.64 mW
Electrical efficiency: Regen-PV	4.28 %	6.90 %
Regeneration of electric power	< 1%	3.16 %

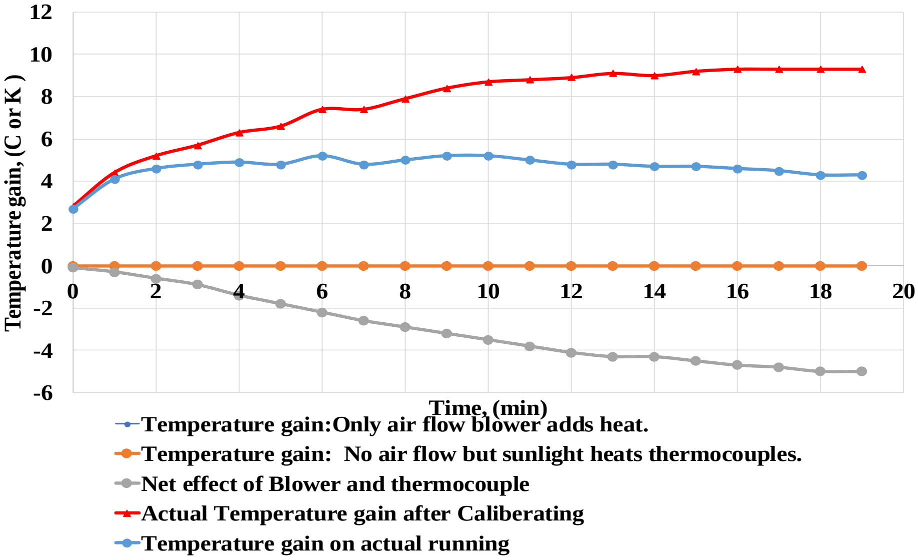


Figure 16: Compilation of the air temperature gain curves obtained in outdoor testing showing the calibration.

curved-PV panel and regen-PV array were tested. Like indoor testing, the actual air temperature gain was calculated after the blower and thermocouple heat was removed from the calibration. The thermocouple heating has no impact on calibration because the thermocouples were uniformly exposed to sun radiation. The compilation of the temperature gain curves used for calibration is shown in Fig. (**16**). In contrast, the actual temperature gain in the air during the test is shown in Fig. (**17**). From these experimental results, the thermal collector was able to raise the temperature of the air by 9.3 ⁰C by the end of 20 minutes. To study the performance of the thermal collector under reflected light, the top surface of the collector was insulated and tested on July 7, 2018, from 14:00 to 14:20 at the exact location and orientation. Since the days are on the same week, the solar radiation intensity can be approximated the same. The test results depicting the temperature gain graph are shown in Fig. (**18**). The results show that the thermal collector was able to raise the air temperature by 2.4 ⁰C by the end of 20 minutes. The IR images of the thermal collector surfaces under solar radiation used to measure input thermal radiation are shown in Fig. (**19**). The camera was calibrated for emissivity values of the black absorber and silicon, respectively, for the top and bottom surfaces. The temperature of the top and bottom surfaces determined by the thermal camera are 233.0 and 333.6 ⁰C, respectively. The thermal collector receives around 6.315 W of thermal power from the simulator lights when tested for 20 minutes. Based on the test calculations, the thermal collector obtained a thermal efficiency of approximately 53.5%. A comparison of performance parameters of the HPVT-R thermal system is shown in Table **4**.

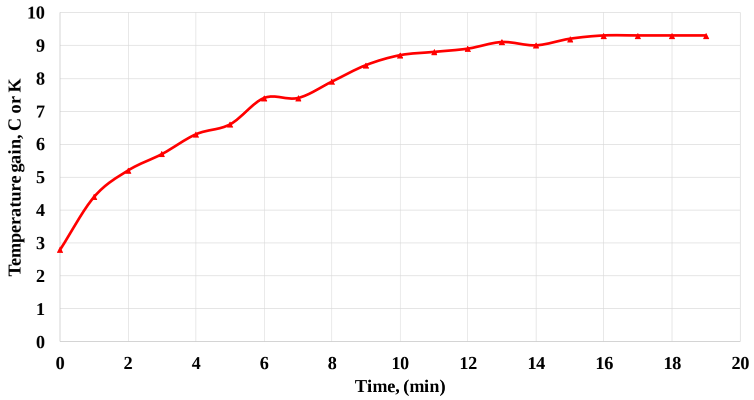


Figure 17: Actual air temperature gain after calibration obtained in outdoor testing.

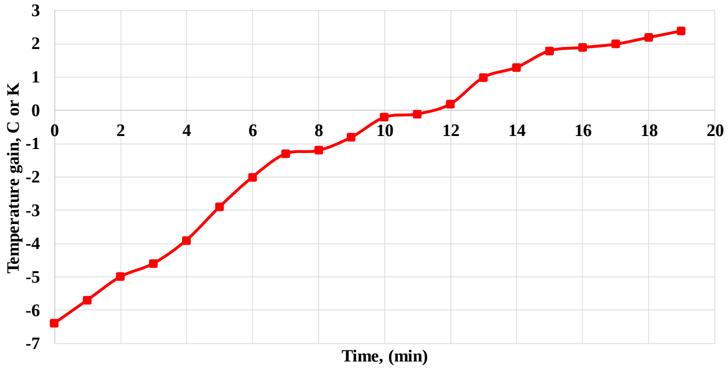


Figure 18: Air temperature gain solely due to reflected light obtained in outdoor testing.

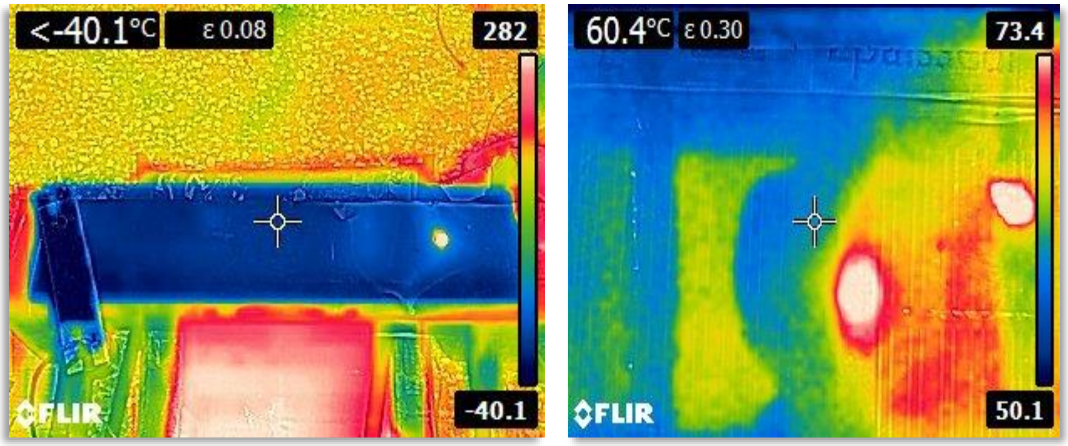


Figure 19: Thermal images of the top (left) and bottom (right) surfaces of the thermal collector taken with FLIR camera for outdoor simulation.

Table 4: Comparison of performance parameters of the thermal subsystem of the HPVT-R system for indoor and outdoor testing.

Parameters	Indoor Testing	Outdoor Testing
Total air temperature gain	11 °C	9.3 °C
Temperature gain due to reflected light	3 °C	2.4 °C
Thermal power	3.924 W	3.379 W
Thermal radiation	9.804 W	6.315 W
Thermal efficiency	40.58 %	53.50 %

5. Conclusion

The regeneration of optical losses from the curved PV surface was experimentally investigated in this study using an experimental test setup consisting of the hybrid photovoltaic-thermal system with regeneration (HPVT-R). To characterize the electrical and thermal performance of the HPVT-R system used in this research, extensive real-time testing was carried out under indoor solar light simulations and outdoor solar radiation of Thunder Bay's climatic conditions. According to the experimental findings of this study, the Regen-PV subsystem reflected roughly 14% of the incident radiation in indoor and outdoor testing. This reflected light was revitalized by the HPVT-R system and transformed into sound electrical and thermal energy. With an electrical conversion efficiency of roughly 4.3% and less than 1% more electrical power per unit PV surface area, the indoor configuration generated approximately 17 mW of electrical power. However, the outdoor setup produced approximately 3.2% more electrical power per unit PV surface area and regenerated roughly 138 mW of electricity with an electrical conversion efficiency of nearly 7%. The thermal collector generated 3 °C and 2.4 °C of air temperature from the reflected radiation in the two indoor and outdoor arrangements, respectively. While the outside testing obtained a total output power density of approximately 158.9 W/m^2 with an overall efficiency of slightly higher than 17%, the inside test simulations generated a total output power density of roughly 156.7 W/m^2 with an approximate 91% overall conversion efficiency. Although the electrical power density obtained during outdoor testing was higher, the HPVT-R system did not function effectively in outdoor solar radiation conditions. The curved-PV panel's lower power rating is thought to be the cause. The overall efficiency of the HPVT-R system would increase with the use of a high-rated PV panel of the same size, making it useful in real-world applications. To better understand this intriguing performance phenomenon, it is recommended that more thorough indoor and outdoor testing will be needed in the future. Also, it is recommended that more research be done to characterize further the performance of various geometries, shapes, and curvature of the leading PV panel in the HPVT-R concerning the regeneration of power under various solar conditions.

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