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A Hybrid Photovoltaic-Thermoelectric Energy Harvester for Day and Night Automobile Applications

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Abstract: Automobiles and other industries waste substantial energy as heat. Conventional photovoltaic power generation in daylight is unavailable at night. In this study a portable hybrid photovoltaic–thermoelectric energy-harvesting prototype is developed to generate electrical power from solar energy during the day and thermal energy at night. The daytime subsystem used a monocrystalline-silicon photovoltaic panel positioned between adjustable aluminum reflectors. Reflector angles, voltage, and electrical power were measured with a protractor, multi-meter and power meter, while an Arduino-based photoresistor circuit monitored light intensity. The nighttime subsystem used four bismuth-telluride thermoelectric generators connected with an aluminum plate and heat sink; voltage was measured under clear and cloudy nighttime conditions. Dual reflectors increased photovoltaic power efficiency by up to 34%, with an optimum reflector angle near 43°, and the measured prototype results in power generation of 130 W m^{-2}, extrapolated to a potential 156 W for a typical windshield area. The thermoelectric subsystem produced a mean 62.97 mV under clear sky and 45.1 mV under cloudy sky, corresponding to reported power densities of 35.9 and 18.4 mW m^{-2}, respectively. The prototype demonstrates complementary day/night energy harvesting, although full-scale automobile validation and higher-output thermoelectric materials are needed.

Keywords: Energy and Sustainability, Energy Harvesting, Photovoltaics, Thermoelectric Generator.

I. INTRODUCTION

Energy harvesting converts otherwise unused ambient energy into electrical power and can supplement conventional energy sources. Waste heat is a major opportunity: this study identified large energy losses as waste heat in industrial systems and automobiles.[1]

Photovoltaic (PV) cells convert incident photons into electron–hole pairs in a semiconductor p–n junction, producing current through an external circuit.[2] Thermoelectric generators (TEGs) provide a complementary pathway by converting a temperature gradient directly into voltage through the Seebeck effect.[3]

Prior work has investigated energy harvesting for low-power devices and nighttime electricity generation, including radiative-cooling approaches.[4,6] Reflectors can also increase the irradiance received by a solar panel, and reflector/tilt geometry influences output power.[7]

The goal of this research was to engineer and experimentally evaluate feasibility of a portable automobile-oriented device that combines these two mechanisms: (1) an adjustable-reflector solar concentrator for daytime photovoltaic generation and (2) a thermoelectric unit for nighttime thermal-energy harvesting. The design also incorporated continuous light-intensity monitoring and was developed through multiple prototypes. The distinguishing engineering concept is the complementary integration of photovoltaic and thermoelectric harvesting in one automobile-focused system rather than reliance on a single source.

II. METHODS

A. *Prototype Design and Materials*

Five prototypes were iteratively developed. The final concept combined a foldable trifold solar concentrator, electronics, and a photovoltaic–thermoelectric generator (PVTEG). The solar-concentrator assembly used a thin-film monocrystalline-silicon solar panel (215 mm × 155 mm), two aluminum reflector panels, a wooden hinged support, a power meter, and a power bank. Electronics included an Arduino Uno R4 Wi-Fi microcontroller, a light-dependent resistor (LDR) photoresistor, breadboard, jumper wires, and resistors. The thermoelectric assembly used four bismuth telluride (Bi_2Te_3) TEG modules, thermal paste, a black-painted aluminum plate, an aluminum finned heat sink, a breadboard circuit, and an Amprobe multimeter.

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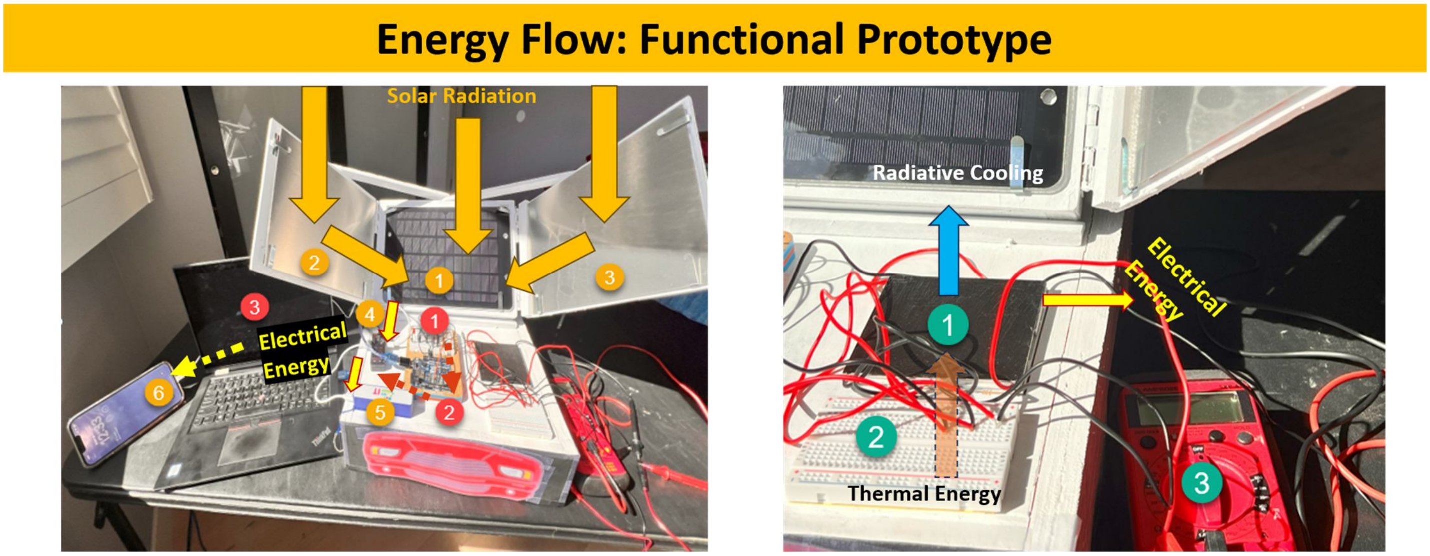

Figure 1. Energy flow diagram for combined functional experimental prototype. Photovoltaic solar concentrator (labeled in yellow): 1) Photovoltaic Solar Panel, 2) & 3) Aluminum reflectors, 4) Power meter, 5) Power bank, 6) Cell phone. Solar concentrator electronics (red): 1) Bread board with Photoresistor, 2) Arduino Microcontroller, 3) Laptop with Arduino Integrated Development Environment. Thermoelectric generator (green) 1) TEG with Aluminum plate- a. Black painted Aluminum Plate (top), b. 4x TEGs (middle), c. Aluminum Heat Sink (bottom), 2) Breadboard with circuit, 3) Multimeter

The combined functional experimental prototype for photovoltaic solar concentrator with electronics and thermoelectric generator (TEG) is shown in Figure 1. The solar energy incident on photovoltaic solar cell converts solar energy into electrical energy. The Aluminum reflectors further concentrate solar energy on the photovoltaic solar cell. The electrical power generated is measured using Dork power meter. The generated power can be stored in a power bank as well. The photoresistor on breadboard measures in records the readings continuously on the serial monitor of the Arduino IDE.

Four thermoelectric generators (TEGs) are connected in series. A heat sink with fins is attached at the bottom of the TEGs to enhance heat transfer. An Aluminum plate is put on the cold side of the TEGs. The top of Aluminum plate is painted black to enhance radiation into the sky. The thermal energy from inside the hot hood of the car passes through the finned heat sink to the hot side of TEGs. The thermal energy from the cold junction of the TEGs (top) is conducted through the Aluminum plate and radiated into the sky. The temperature difference between the bottom and top of the TEGs lead to generation of electrical energy due to thermoelectric effect. The voltage generated by TEGs in series is measured using AMPROBE multimeter and recorded.

Table 1. Principal prototype components used in the experiments.

Subsystem	Component	Role
Photovoltaic	Monocrystalline-Si panel, 215 × 155 mm	Daytime electrical generation
Optical	Two aluminum reflector panels	Increase incident solar radiation
Monitoring	Arduino Uno R4 Wi-Fi + LDR	Continuous light-intensity monitoring
Thermoelectric	Four Bi_2Te_3 TEG modules	Convert temperature gradient to voltage
Thermal	Aluminum plate, thermal paste, finned heat sink	Establish and transfer temperature gradient

B. Solar-concentrator experiment
The principal components are summarized in Table 1.The photovoltaic panel was fixed at the center of a hinged trifold structure, with one aluminum reflector on each side. Side panels could be manually locked at different angles. A protractor measured the angle between each reflector and the solar panel. Voltage and electrical power were recorded with a power meter for configurations without a reflector, with a single reflector, and with dual reflectors. Measurements were made both in front of and behind an automobile windshield. The reflector-angle tests were used to determine the angle associated with the greatest power-efficiency gain. Prototype power was also scaled by area to a standard windshield area of 1.5 m × 0.8 m.

C. Light-intensity monitoring
An LDR photoresistor was connected to an Arduino Uno R4 Wi-Fi through a breadboard and jumper wires. The Arduino Integrated Development Environment was programmed to record continuous photoresistor readings on the serial monitor. The circuit provided real-time light-intensity monitoring during solar testing. The study also demonstrated wireless streaming using an HC-06 Bluetooth module.[8]

D. Thermoelectric Experiment
Four TEG modules were attached using thermal paste between a black-painted aluminum top plate and an aluminum heat sink and connected in series. The assembly was exposed outdoors at night so that a temperature difference could develop between the radiating upper surface and the heat-sink/ambient side. TEG voltage was recorded with a multimeter under clear-sky and cloudy-sky conditions. Mean and standard deviation were used in the study analysis to compare voltage distributions. Current and power were estimated from measured voltage using the manufacturer data for the SP1848-27145 module, and power was normalized by area. The manufacturer data supplied specify increasing open-circuit voltage and current with temperature difference, including 0.97 V and 225 mA at a 20 °C temperature difference for an individual module.

III. DATA ANALYSIS
Solar efficiency gain was calculated relative to the corresponding no-reflector condition, and angle-dependent trends were fitted with second-order polynomial curves. For dual reflectors, the relationships between power efficiency gain (y) and reflector angle (x) are found to be $y = -0.0117x^2 + 1.0115x - 0.0218$ and $y = -0.0187x^2 + 1.6001x - 0.0094$ for the positions behind the windshield and in front of the windshield, with the plotted optimum near 43°. Thermoelectric clear- and cloudy-sky voltage datasets were summarized by mean and standard deviation and displayed as a box plot. Power density was reported in mW m^{-2}.

IV. RESULTS AND DISCUSSION
A. Photovoltaic Performance and Reflector Geometry
The solar-concentrator tests showed that adding reflectors increased photovoltaic output and that the gain depended on reflector angle. Measurements behind the windshield were lower than measurements made in front of it, consistent with optical losses through the windshield. Table 2 summarizes the reported reflector results. With dual reflectors, the study reported a maximum efficiency gain of approximately 34.2%, compared with 28.9% for a single reflector. The fitted dual-reflector curves placed the optimum near 43°; at approximately this angle, the gain was about 34.2% in front of the windshield and 21.8% behind it. Figure 2 presents the measured/fitted angle dependence for the dual-reflector configuration.

Table 2. Summary of photovoltaic reflector results. Dual reflectors produced the largest reported efficiency gain, and performance was lower behind the windshield.

Configuration / condition	Reported result
Single reflector	Maximum power-efficiency increase: 28.9%
Dual reflectors	Maximum power-efficiency increase: 34%
Optimum dual-reflector angle	≈43°
At ≈43°, in front of windshield	≈34.2% efficiency gain
At ≈43°, behind windshield	≈21.8% efficiency gain
Scaled standard windshield (1.5 m × 0.8 m)	Potential power generation: 156 W

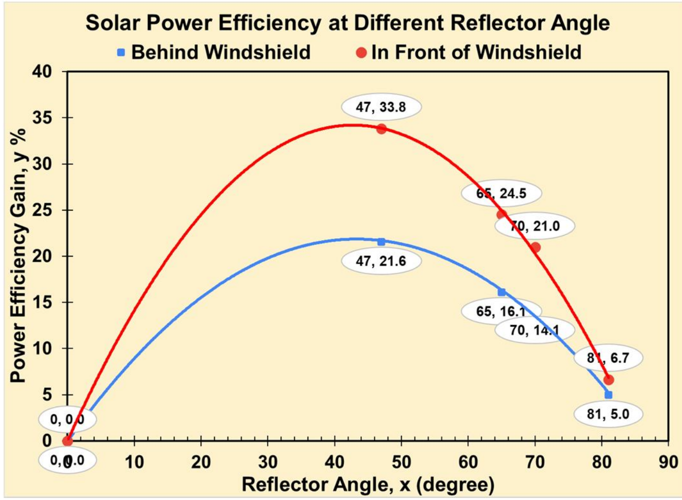

Figure 2. Dual-reflector photovoltaic efficiency gain versus reflector angle. The in-front-of-windshield measurements reached approximately 34% near 43–47°, while the behind-windshield measurements peaked near 21.7%

The estimated possible power generation of 156 W for a standard 1.5 m × 0.8 m windshield by extrapolating the measured photovoltaic output by area. This value is a scale-up estimate rather than a full-size vehicle measurement; therefore, it should be interpreted as an engineering projection. A full-scale test would need to account for nonuniform illumination, reflector geometry, windshield transmission, temperature effects, wiring losses, and available mounting area.

B. Thermoelectric Nighttime Performance

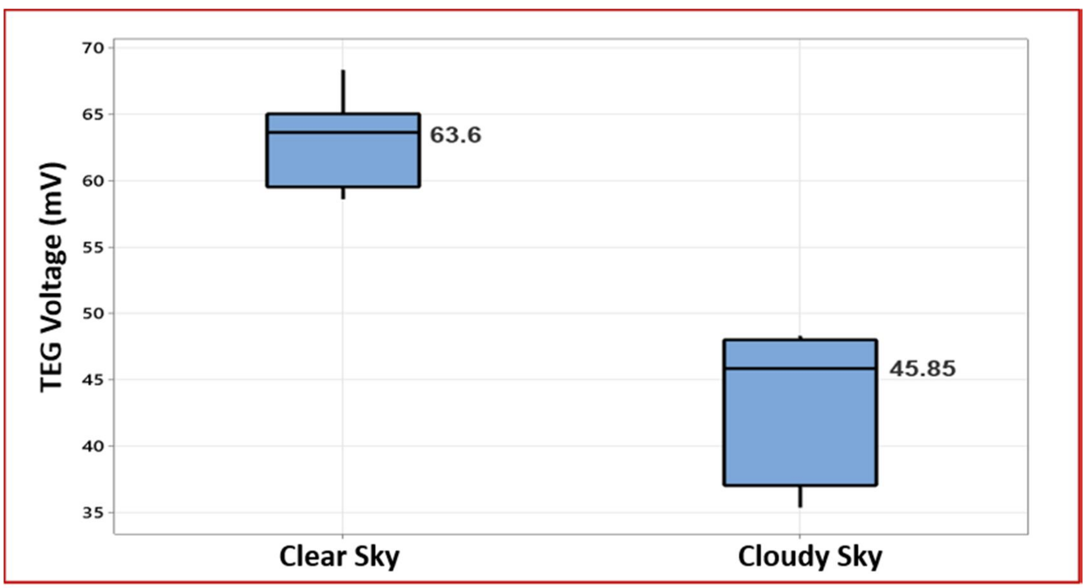

Figure 3. Box plot of nighttime thermoelectric performance under clear and cloudy skies. Median TEG voltage is higher under clear-sky conditions

The thermoelectric subsystem generated measurable voltage at night under both weather conditions. Mean TEG voltage was 62.97 mV under clear sky and 45.1 mV under cloudy sky. The corresponding reported power was 0.23 mW and 0.11 mW, giving power densities of 35.9 and 18.4 mW m^{-2}, respectively (Table 3). Figure 3 highlights the higher clear-sky mean voltage and reported power density. The clear-sky voltage dataset had a standard deviation of 3.44 mV, compared with 5.55 mV under cloudy sky, indicating both lower output and greater variability during cloudy conditions.

Table 3. Nighttime thermoelectric results. Clear-sky conditions produced higher mean voltage and power density than cloudy-sky conditions.

Night condition	Mean voltage (mV)	Reported power (mW)	Power density (mW m^{-2})
Clear sky	62.97	0.23	35.9
Cloudy sky	45.1	0.11	18.4

The measured clear-sky power density was compared in the this study with published nighttime electricity-generation studies based on radiative cooling.[6,10] The present device differs in geometry and thermoelectric implementation, so this comparison is best viewed as an order-of-magnitude benchmark rather than a direct performance equivalence.

C. *Complementary day/night operation*

The final prototype met the central functional objective of demonstrating two complementary harvesting modes: photovoltaic generation during daylight and thermoelectric generation at night. The photovoltaic subsystem produced substantially more power than the thermoelectric subsystem, while the TEG demonstrated that electrical generation could continue when solar illumination was unavailable. The prototype was also portable and foldable, and its Arduino/LDR electronics enabled continuous light monitoring. The combined architecture therefore emphasizes availability across different environmental conditions rather than equal power contribution from the two sources.

D. *Engineering Constraints and Limitations*

Weather was a significant experimental constraint for both subsystems, particularly cloudy conditions and rain. Reflector angles were mechanically limited to 0–90°, and the TEG requires a nonzero temperature difference; materials with a low Seebeck coefficient produce low electrical output. The prototype was constructed partly from scrap wood because of limited funding. The Arduino system primarily displayed real-time measurements. Long-term Internet-of-Things data logging can be done in future. In addition, the reported 156 W windshield value is an area-based extrapolation, not a direct full-scale measurement.

V. CONCLUSION

The present study demonstrates a hybrid automobile-oriented approach to renewable energy harvesting using adjustable-reflector photovoltaics during the day and bismuth-telluride thermoelectric generators at night. Dual reflectors increased photovoltaic power efficiency by up to 34%, with an optimum angle near 43°, and the prototype data were extrapolated to a potential 156 W over a standard windshield area. At night, the TEG assembly produced higher output under clear sky (62.97 mV; 35.9 mW m^{-2}) than cloudy sky (45.1 mV; 18.4 mW m^{-2}). The results establish proof of concept for complementary day/night harvesting, but the thermoelectric contribution remains small relative to solar generation. Future work should measure electrical energy directly with the microcontroller, automate data collection, develop a mobile monitoring application, evaluate improved TEG materials and thermal interfaces.

VI. AI ACKNOWLEDGEMENT

During the preparation of this manuscript, the author used ChatGPT (OpenAI) to organize material from the project logbook and display board and to improve language and readability. The underlying project design, experiments, measurements, data, figures, and conclusions were created by the student. The author reviewed and edited the manuscript and takes full responsibility for the content of the publication.

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Ayan Bera is a high school student interested in engineering, renewable energy, and sustainable technology. His study investigates complementary photovoltaic and thermoelectric energy harvesting for automobile applications.