HIGH PERFORMANCE HYBRID SOLAR PHOTOVOLTAIC-THERMOELECTRIC PANEL

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EXECUTIVE SUMMARY

The proposed high-performance hybrid solar electric panel can achieve a high solar electric efficiency of up to 40% with a power output of 100 W. It integrates state-of-the-art technological advances in concentrating solar photovoltaic (CPV) cells, solar thermoelectric generator (TEG), oscillating heat pipe (OHP), and radiative sky cooling (RSC) panel. The innovations are

- Extra high thermal conductivity of flat-plate OHPs makes it possible to integrate both CPV and TEG and efficiently utilize solar energy.
- Passive RSC embedded with flat-plat OHPs can further increase the temperature difference resulting in higher efficiency of power generation.
- The innovative linear Fresnel lens can significantly increase the thermal efficiency of the CPV cells.
- TEGs are operated at high temperatures generated by concentrated sunlight on CPV cells and the surrounding absorption area. Therefore, the electric efficiency of TEG can be significantly enhanced.

Due to these innovations, the proposed hybrid solar electric system will have the following features:

- A solar-electricity efficiency of 40% can be achieved for a 100 W power output.
- A compact design can be achieved.
- The proposed solar panel can be used as a single power source, or as a basic unit of moderate or large scale systems.
- High-performance passive cooling without additional electric power consumption.
- No dependence on mechanical moving parts results in high reliability.

- The simplicity of the proposed system supports cost-effective manufacturing and implementation.
- The proposed system has effectively integrated the state-of-the-art technologies, which makes the proposed system to achieve Tier 1 at TRL 6 - 8.
- It is expected that the system efficiency and cost will benefit the rapid global expansion of the solar panel market.

Specific Areas of Interest: Solar-electric technologies to power Army MDO in the 2035 environment

Category: Tier-1

Title: High-Performance Hybrid Solar Photovoltaic-Thermoelectric Panel

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1. BACKGROUND

The 2019 Army Modernization Strategy (AMS) highlights priority research in RF electronic materials that directly use optical and thermal energy to obtain electrical energy. Solar energy, with a typical energy density of 1 kW/m^2, is expected to meet the energy demand for a variety of equipment associated with multi-domain operations (MDO). In addition to reducing fossil fuel consumption, solar energy is attractive in terms of military security. Larger-scale solar power plants allow the military to maintain an independent source of power in case of a natural disaster or a cyber-attack that disables the public grid. Medium-scale solar stations reduce the need for easily attacked convoys to deliver diesel flues to generators at military sites without access to conventional electricity. Small-scale mobile solar power units silently keep critical functions like radar, GPS, and satellite communication in hostile territory. Solar energy has proven to be a viable form of renewable energy in the civilian sector and is poised for continued growth in the military. The U.S. Department of Defense has embraced clean energy sources in recent years, doubling its renewable power generation between 2011 and 2015. The U.S. Army has set a goal to derive 25% of its total energy consumption from renewable sources by 2025 as well as a commitment to deploy one gigawatt of renewable energy on Army installations by 2025. For example, SunPower Corp. is developing a 12.5-megawatt photovoltaic solar power plant at the U.S. Army's Redstone Arsenal in Alabama.

At present, two primary devices of capturing solar energy for electrical generation are **solar photovoltaic (PV) cells** and **solar thermoelectric generators (TEG)**. Solar PV cells directly convert the energy of sunlight into electricity by the PV effect. A typical solar cell is composed of an N-type and a P-type semiconductor, which are combined to form a P-N junction. Photons in sunlight excite the electrons in the N-type semiconductor to stream towards the positive charge in the P-type semiconductor, thereby creating an electric current in the solar cell. Solar cell performance is evaluated by the solar-electric efficiency, which refers to the portion of sunlight energy that can be converted via PV effect into electricity. The solar cell efficiency for commercial solar panels in 2019 was 20.5%–22.8%. This efficiency is significantly affected by **semiconductor materials**. Conventional crystalline silicon (c-Si) cells, with a cost of $1/watt, have an efficiency below 27.6%, while emerging gallium/arsenide (GaAs) multi-junction (M-J) cells, with a cost of $300/watt in 2018, had reached an efficiency of 44.7% in 2013 [1]. Concentrating PV (CPV) cells use a Fresnel lens to concentrate sunlight from a larger area into a smaller area; thus, CPV cells enable higher efficiency. Moreover, expensive multi-junction PV cells are now considered economically available due to their lower space requirements. **The cell temperature** is another critical factor for solar cell efficiency. The temperature coefficients of conventional c-Si solar cells and emerging GaAs M-J cells are −0.5 % / °C and −0.05 % / °C, respectively [2]. In addition to the development of new materials with high PV efficiency, improving PV efficiency with effective thermal management of solar panels is more feasible and cost-effective. The thermal management system of solar panels includes passive cooling, active cooling, and phase change material (PCMs) based on thermal energy storage [3].

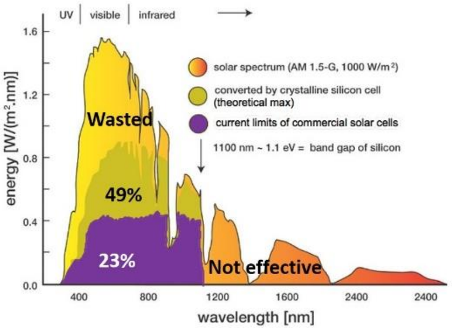

Figure 1. The spectrum of sunlight used by a c-Si solar cell [4].

Figure 1 shows the spectrum of sunlight used by a c-Si solar cell. A c-Si solar panel can absorb about 80% of total solar energy as effective energy. Theoretically, 49% of total solar energy can be converted into electrical energy, but only 23% is practical. The remaining energy, about 57%, is converted into thermal energy. Therefore, by effectively using this thermal energy to generate electricity in a **thermoelectric generator (TEG)**, the total solar-electric efficiency should be significantly improved. TEG works are based on the Seekbeck effect wherein an electric potential builds up when dissimilar metals are exposed to a variance in temperature. For a given pair of thermoelectric material, the high efficiency of TEG requires a large temperature difference between the hot and cold ends of TEGs. The solar-electric efficiency of solar TEG is only 0.63% with a temperature difference of 70 °C. A CPV cell can achieve a much higher temperature with concentrated sunlight. Its solar-electric efficiency might reach 5–6% theoretically and 4.6 –5.25% experimentally, with a temperature difference of 180 °C [4]. Currently, the commercial CPV cell needs active cooling for controlling the cell's maximum temperature below 110°C. The solar-electric efficiency can be improved by effectively using this thermal energy by TEGs.

Radiative sky cooling (RSC) cools an objective on earth by emitting thermal infrared radiation to the cold universe through the atmospheric window. The concept of RSC is based on the energy density mismatch between solar irradiance (wavelength 0.3–2.5μm at 5,778 K) and the low infrared radiation flux from a near ambient temperature surface (wavelength 8–13μm at 300 K). RSC under direct sunlight can be achieved with an ideal material that strongly emits thermal energy and barely absorbs sunlight, as shown in Figure 2. Very recently, owing to the progress in nanoparticles and metamaterials, RSC was experimentally demonstrated to achieve a surface temperature of up to 10 °C below ambient temperatures and a cooling power larger than 100 w/m^2 under direct sunlight [5]. RSC surfaces are prepared with micrometer-sized SiO_2 beads in the polymer matrix and a silver reflector. RSC surfaces are commercially available as cooling plastics films and self-cooling paints.

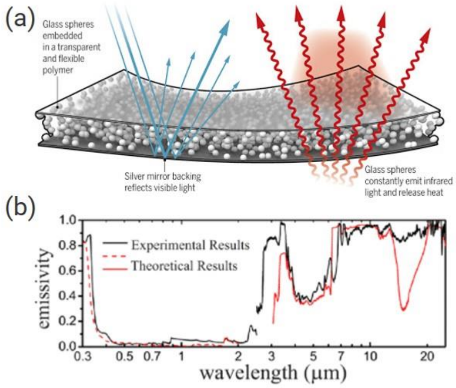

Figure 2. Radiative sky cooling. (a) Working principle, (b) emissivity at various wavelength [5].

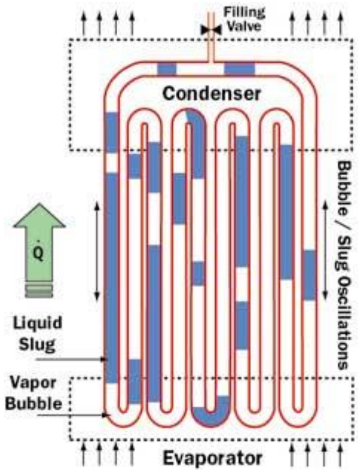

Figure 3. Schematic of an oscillating heat pipe [6].

The oscillating heat pipe (OHP) has effectively integrated high heat transfer coefficients of phase change heat transfer and the oscillating flow of liquid slugs in microchannels resulting in an ultra-high effective thermal conductivity [6]. Unlike heat pipes traditionally used to cool CPV solar cells, OHPs do not contain a wick structure. This difference makes OHPs cheaper to manufacture and, more importantly, allows OHPs to handle more than 200 times more heat. OHPs increase capability and reduce the cost for a wide range of high-performance military applications, such as naval GBIT devices, aerospace lightweight heat spreaders, and satellite cooling systems. Besides, OHP heat transfer performance does not depend on gravity and can be fabricated into any shape. ThermAvant Technologies LLC, co-founded by the PI in 2007, has worked with several leading defense contractors and military agencies to integrate the OHP technology into military and commercial systems.

2. APPROACH

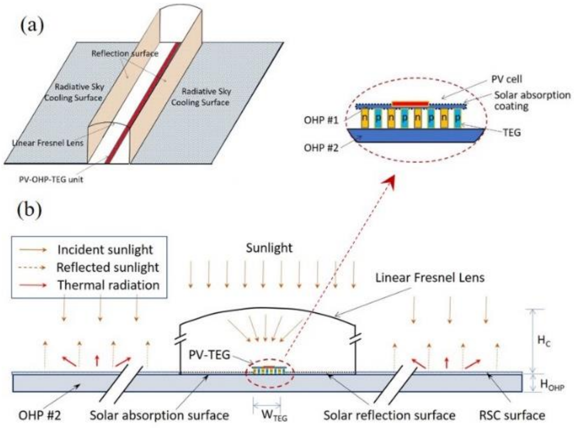

Figure 4. The proposed hybrid PV-OHP-TEG. (1) Layout, and (2) frond view.

The proposed high-performance solar-electric panel integrates state-of-the-art technological advances in the CPV cell, TEG, OHP, and RSC. The proposed solar-electric panel consists of a linear Fresnel lens, PV cells, TEGs, and OHPs. Figure 4 shows the layout and the front view of the proposed hybrid PV-TEG panel. Linear Fresnel lens concentrates the sunlight by 20 times and optimizes solar radiation incidents on the PV-OHP-TEG units. In a unit of PV-OHP-TEG, a PV cell and a TEG are mounted on two sides of a flat-plate OHP #1 section. Besides the PV cells, the other sunlight exposed surface of this OHP #1 is coated with carbon solar absorption material to absorb the solar thermal energy from misaligned sunlight. The thermal energy is collected by the OHP #1 and transported to the TEG hot end. Part of the thermal energy generates electricity in the TEGs, while the residual heat is conducted into the OHP #2, where the TEG cold ends are attached. The residual heat is transferred from the center to the ends of a flat-plate OHP #2, and dissipated to the environment from the SRC surface.

The hybrid PV-TEG system is proposed for a 100 W panel output at an efficiency of 40%. The proposed system consists of linear Fresnel lens (64 pieces), 4-junction PV cells (64 pieces), TEGs

(64 pieces), flat-plate OHP #1 (2 pieces), and flat-plate OHP #2 (32 pieces). The overall dimensions of the panel (without support frame) are 75 cm wide, 160 cm long, and 14 cm high. The sunlight collection area (i.e., the area of linear Fresnel lens) is 0.25 m^2, and the radiative sky cooling area is 0.95 m^2. The overall weight of the proposed system is about 7.0 kg. The detail information for the components is as follows:

(1) SolarVolt^{TM} low-cost 20X silicon linear Fresnel lens

SolarVolt^{TM} thin high-efficiency linear Fresnel lens, produced by Entech Solar, Inc., has a low concentrating factor of 20X. It is made in ready-to-use form (no lamination required) by continuous roll-to-roll manufacturing methods, resulting in a meager cost. SolarVolt^{TM} lens has been used in the NASA deep-space program since 1986 [7]. The unit size is 15.5 cm (W) × 2.5 cm (L) × 13.7 cm (H), and a total of 64 units are used. The total weight of the lens is about 0.8 kg.

(2) C3P5 triple-junction PV cells

C3P5 triple-junction GaInP/GaInAs/Ge solar cells [8], produced by Spectrolab Inc. (a Boeing company), have a typical cell efficiency of about 40%.They are fabricated at low cost backed by the high reliability of C4MJ technology. The temperature coefficient of efficiency is less than 0.06%/°C. It is estimated that the C3P5 triple-junction cells can reach an efficiency of 35.0% at a solar cell temperature of 120°C. C3P5 triple-junction solar cells have been used in NASA's space solar panels. The solar cells have a width of 1.0 cm and a total length of 160 cm.

(3) Tecteg Mfr. low temperature Bi_2Te_3-based TEGs

Low temperature Bi_2Te_3-based TEGs, produced by Tecteg. Mfr., have a ZT value of 1.4. Its theoretical thermal-electricity efficiency is about 6.0% with a temperature difference of 100 °C [9]. It assumes that solar-thermal efficiency is about 5.0% in the proposed system. The Bi_2Te_3-

based TEGs are commercially available and extensively used in harvesting the low-grade waste heat. The overall area of TEGs is 2.0 cm × 160 cm, and the P-N legs' size is 1.5 mm × 1.5 mm × 1.7 mm.

(4) ThermAvant Technologies^{TM} OHP

Flat-plate OHPs with a thickness of 3 mm, produced by ThermAvant Technologies LLC, are fabricated with aluminum and charged with water. OHP #1 has a width of 2.0 cm and a length of 80 cm. The area ratio for the PV cells and the direct solar absorption on the OHP #1 is 1:1. OHP#2 has a width of 5.0 cm and a length of 75 cm. The area of SRC surfaces on OHP #2 is four times the sunlight collection area of the Fresnel lens. The total numbers of OHP #1 and OHP #2 are 2 and 32, respectively. The total weight of OHPs in the proposed system is about 5.0 kg. Thin-plate OHPs have been commercialized and successfully used as ultrahigh heat transfer devices in the military.

(5) RSC painting

RSC paint, produced by PARC, is coated on the sunlight exposed surface of OHP #2 with a thickness of 200 µm [10]. This RSC surface can dissipate the heat of 150 W from a total area of 0.96 m^2. PARC's passive radiative cooling paint is field-tested on the aluminum surface at various temperatures, making it ready for directly painting on the aluminum OHP surfaces.

3. ADVANTAGES OF PROPOSED SYSTEM

The proposed hybrid solar-electric panel integrates two current major solar-electricity technologies with advanced thermal management processes. The advantages of the proposed system are

(1) High solar-electricity efficiency by fully extracting solar energy using both the PV effect and thermoelectric effect.

(2) High system-level thermal uniformity and effective thermal management from the high-performance OHPs.

(3) High reliability and durability owing to no mechanical moving parts.

(4) The simplicity of the proposed system supports cost-effective manufacturing and implementation.

(5) The proposed solar panel can be used as a single power source or a basic unit for middle or large-scale solar power stations.

4. TECHNICAL MATURITY AND READINESS

The technology involved in the proposed hybrid solar-panel belongs to the **Tier-1** category. Component level devices have been proven and used in military and civilian applications. The system demonstration is achievable within **2 years**.

5. TECHNICAL RISKS

The technical risk in the proposed system is the limited operating temperature of low cost solar cells. A low temperature leads to a high solar electricity efficiency for PV cells but a low thermoelectric efficiency for TEGs. Therefore, the proposed system uses the linear Fresnel lens, possessing low sunlight concentrating factor (20X), and the triple junction GaInP/GaInAs/Ge solar cells (< 110 °C), possessing a low-temperature coefficient but much higher cost. PV cells that have high solar-efficiency at a much higher operation temperature will significantly improve the efficiency of the proposed hybrid solar panel. It is expected that the system efficiency and cost will benefit the rapid global expansion of the solar panel market. For example, the price of multi-crystalline silicon was reduced by 90% from 2010 to 2020.

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