Trifold PV-T-TEG (photovoltaic-thermal-thermoelectric generators) panel characterization overview

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Abstract. The anticipated depletion of conventional fuels (crude oil, coal) reserves as energy sources triggered extended researches for renewable energy sources. In the last few decades, technologies for energy conversion from solar to electric and thermal energy evolved rapidly. Some recent photovoltaic (PV) panel cooling methods involve thermoelectric (TE) elements. The authors proposed a trifold panel that employs both thermal (T) and TE cooling to lower the temperature of PV panel operation and extract energy from waste heat. Recently, an important number of publications tackled various aspects of PV-TE and PV-T-TE hybrid systems, especially for building integration applications. This paper attempts to cover important topics, with emphasis on aspects related to design and characterization of mobile applications.

1. Introduction
Energy crisis from the 1970s and the increase of pollution awareness in the 1990s triggered an intensive search for energy from sustainable and renewable sources. Many important technological development steps performed lately toward energy conversion from solar, wind, biomass, geothermal and hydropower sources increased the efficiency of such processes. Yet, the most available and, at the same time, the most underused resource remains the solar energy. The share of solar energy in global electricity production is about 2%, [1, 2].

Solar energy harvesting technologies involve conversion to thermal or electrical energy. Solar thermal technologies for small-to-medium applications use various types of collectors to heat up the fluid agent to prepare domestic hot water (DHW) or for space heating purposes: flat panel (FPC), evacuated tube (ETC), or heat pipes (HP-ETC). Industrial-size systems operate at much higher temperatures and use the thermal agent either in heating applications or in conversion to electrical energy. The concentrated solar power (CSP) plants include either Linear Fresnel Reflectors (LFR), parabolic trough collectors (PTC) or dish reflector (PDR), or heliostat field concentrator (HFC).

Solar electric technologies rely largely on photovoltaic cells for direct conversion to electricity. Although based on a physical phenomenon discovered almost two centuries ago (Becquerel, 1839), the research in this area increased in the last few decades, when the production costs decreased based on new technologies and materials. Yet, in recent years, a new conversion method emerged, i.e. use of thermoelectric (TE) elements in solar applications. Thermoelectric effect discovered around beginning of the 19th century, encompasses physical phenomena discovered by Volta (1794), Seebeck (1821), Peltier (1834) and Thomson (Lord Kelvin, 1851) and include the Joule heating effect, as well. Dealing
in the past with very small voltages, in the order of hundreds of millivolts, the effect of converting a certain temperature gradient into electricity became more interesting recently, due to new materials.

The large number of publications in photovoltaics area, on new materials, production methods and technologies, conversion efficiency, demonstrate the increased scientific research interest to enhance the conversion efficiency of solar energy into electricity. Annually, NREL compiles available data on PV cell efficiency and publishes the most recent findings [3]. Figure 1 demonstrates that, for the last four decades, there was a clear trend in research to increase cell efficiency, which peaked in 2015 [4] with a conversion efficiency of 46% for a special four-junction configuration with optical concentrator and in laboratory conditions. The commercially available units range from 10% to about 25%, with a trend towards lowering costs for both materials and production.

From the first theoretical studies on PV cells and arrays published in the early 1980s [5, 6], it was obvious that a PV system should operate at the lowest possible temperature. The simplest PV model configuration is a single diode non-linear system, with the characteristic \( (I-V) \) curve mathematically described as [7]:

\[
I = I_a - I_o \left[ \exp \left( \frac{V + IR}{a} \right) - 1 \right] - \frac{V + IR}{R_{sh}}
\]

where \( a \), the diode quality factor, is expressed as:

\[
a = \frac{n k T}{q}
\]

where \( n \) is the ideality factor, \( k \) is the Boltzmann constant, \( T \) is the absolute temperature, and \( q \) is the elementary charge, [8]. Therefore, the operational temperature is an important factor that influences the PV cell performance.

Numerous published studies, both analytical and experimental, reviewed in [1], revealed that the open circuit voltage of a PV cell decreases with increasing cell temperature. Even if current increases slightly, the decrease in voltage is more significant and the power decreases accordingly, figure 2.

The research intensified in the area of controlling the operational temperature and optimizing the PV panel performance, as an estimated 80-85% of the incident solar energy represents waste heat, i.e.
thermal energy that had to be removed. By tapping into this waste energy, the overall efficiency of the solar panel (electrical and thermal) improves greatly.

Figure 2. Temperature dependence of (I-V) and (P-V) curves, at constant irradiance of 1000 W/m² [9].

The newly designed hybrid systems may alleviate the disadvantages of a stand-alone PV system (low electrical output, no thermal output from waste heat, high operational temperature, and low overall system stability), despite manufacturing complexity and higher costs. An extensive literature research [1] that included recent papers and conclusions from other reviews demonstrated the benefits and limitations of active cooling methods and technologies known to date, figure 3.

Figure 3. PV cooling methods and technologies known to date.
On the convective methods side, natural fluid circulation (as passive methods) is more economical, but less efficient. Similarly, the use of liquids is more effective, but incurs technological complications (and higher costs), higher pumping power, as well as corrosion, leak proofing and freezing problems. In addition, special liquids, or even water, may not be readily available in some areas. Newer methods (HP, MCHS, nFs, jet impingement, water spraying) may improve thermal output and overall system performance, but still have high production costs, material characteristics not completely controlled, and localized cooling, in some cases.

Characterized as passive cooling, the radiative methods are partially efficient, as the heat is rejected from the PV panel frontal surface. The spectrum splitting methods incurs some energy losses due to either liquids, thin film depositions or successive reflections, depending on specific technology.

The PCM methods are more successful in medium-to-large size applications, as energy is stored in the molten materials and used continuously day and night. However, the systems include supplemental equipment for conversion of solar to mechanical and then electrical energy.

During the last decade, the studies on TE-based solar systems grew exponentially, as the materials and technologies used for TE manufacturing became less expensive and with better properties. The TE modules are capable to convert the energy from the low-temperature waste heat at the backside of PV panel producing extra electricity at a minimum system cost and controlling the system temperature.

Taking the extra step towards hybridization, the authors proposed and work towards developing a complex structure of a trifold collector panel that encompass a PV panel, TE elements and a thermal recovery unit, to maximize the conversion efficiency of solar in both electrical and thermal energy.

2. Thermoelectric elements

A thermoelectric (TE) device relies on TE materials featuring the specific physical transport properties of direct conversion between thermal and electrical energy.

Independent of Alessandro Volta’s experiment in the late 1700s, Thomas Seebeck demonstrated in 1824 that a temperature gradient causes simultaneously a heat flux and an electrical current. In certain materials, mainly metals and semiconductors, the charge carriers (electrons and holes) may move freely within the lattice, carrying thermal energy (heat) as well. In the presence of a thermal gradient, energy is carried from the high-energy (hot) side towards the low-energy (cold) side. As a result, the charge-carrier-based heat transfer generates also a charge gradient (electrostatic potential). The two phenomena are directly proportional, connected by the Seebeck coefficient, \( \alpha \ [V/K] \), or thermo-power.

A decade later, in 1834, Jean Charles Peltier associates his name with the reverse phenomenon, i.e. a voltage (potential) gradient generates an electrical current and a heat flux, the proportionality constant being the Peltier coefficient, \( \pi \ [V] \).

Later, Lord Kelvin connected the two coefficients by:

\[
\pi = \alpha T
\]  

The main issue with these thermoelectric effects is that they are about two orders of magnitude smaller than the Joule effect (heating) for current flow through a conductor, \([10]\). Therefore, the use of a single element is impractical, as well as multiple elements connected in parallel. The more efficient and practical solution is the series electrical connection and parallel thermal connection of alternating n-type and p-type materials (electron or hole doped, respectively), figure 4. The substrates should be electrical insulators, but good thermal conductors.

The heat flow within a thermoelectric material is characterized by three components: the material’s thermal conductance (heat conduction), the Peltier heat absorbed at the hot side, and Joule heating of the material. The last component is equally divided among the hot and cold sides of the material. To characterize the thermoelectric capabilities of a material, the figure of merit, \( Z \ [1/K] \) is introduced as:

\[
Z = \frac{\alpha^2 \cdot \sigma}{\kappa}
\]  

being proportional to the ratio of conductivities, electrical \( \sigma \ [S/m] \) vs. thermal \( \kappa \ [W/mK] \).
Electrical conductivity depends on carrier concentration, and is the inverse of electrical resistivity, \(\rho\) [\(\Omega m\)], i.e. \(\sigma = 1/\rho\). Total thermal conductivity represents the sum of two contributions, from electrons \(\kappa_E\) and from phonons or lattice vibrations, \(\kappa_L\). The contribution from lattice vibrations is approximately constant, while electrons contribution varies proportionally with carrier concentration. Good TE materials should exhibit high \(\alpha\) and low \(\rho\) and \(\kappa\), but high \(\alpha\) implies high \(\rho\), whereas low \(\rho\) implies high \(\kappa\). Therefore, to maximize the figure of merit for TE materials the research should focus on finding the optimum carrier concentration, for high electrical and low thermal conductivities. Best compromise in this area seems to be highly doped semiconductors.

In order to compare the material characteristics, the dimensionless figure of merit (\(Z\cdot T\)) is used:

\[
ZT = \frac{\alpha^2 \cdot \sigma \cdot T}{(\kappa_E + \kappa_L)} = \frac{\alpha^2 \cdot T}{\rho \cdot \kappa}
\]

For the same material, the dimensionless figure of merit is dependent of the charge carrier type, i.e. \(n\)-type (electrons doped) or \(p\)-type (holes doped). Scattered values for different materials are presented in literature, and Tim Hogan from Michigan State University compiled fifty years (1957 – 2007) of publishes data into two separate graphs, figure 5. Even though the research in TE materials increased in the last decade, especially in the area of nanomaterials and ceramics, the most used and lowest cost material remains Bi\(_2\)Te\(_3\). Both graphs show that at normal operational temperatures in solar application of TE devices, i.e. 300 K – 400 K, Bi\(_2\)Te\(_3\) has the highest value for the material figure of merit.

At this point, it is important to observe that some authors [11] distinguish between TE efficiencies, material figure of merit (\(zT\)) and device figure of merit (\(ZT\)). For the ideal case when the TE properties of both \(n\)-type and \(p\)-type materials are similar and temperature independent, then \(z = Z\).
Figure 5. Figure of merit for various thermoelectric materials, n-type and p-type [12].

The above observation is important, because material’s efficiency value is useless by itself, since a TE device is composed of an array of TE n-type and p-type couples. If contact resistance and radiation effects are neglected, the dimensionless figure of merit for a TE couple, $Z_{np}T_M$, is defined as, [13]:

$$Z_{np}T_M = \frac{(\alpha_p - \alpha_n)^2 \cdot T_M}{\left[(\rho_p \cdot \kappa_n)^{1/2} + (\rho_n \cdot \kappa_p)^{1/2}\right]^2}$$  \hspace{1cm} (6)$$

If the transport properties are similar for both n- and p-type materials, then the dimensionless figure of merit becomes:

$$Z_{np}T_M \approx \frac{Z_nT_n + Z_pT_p}{2}$$  \hspace{1cm} (7)$$

where $T_M$ is the average temperature if the TE couple operates between $T_H$ the hot-side temperature and $T_C$ the cold-side temperature.

Figure 6. Thermo-Electric Cooling (TEC – Peltier) vs. generation (TEG – Seebeck).
A TE couple, or module, may function two ways, figure 6. 

As a refrigerator or cooler (TEC), under the influence of a voltage gradient, an electrical current is supplied to the circuit and a heat flux occurs within the module (Peltier effect). Heat $Q_C$ is absorbed from the top side at $T_C$ producing a cooling effect, and $Q_H$ is rejected at $T_H$ producing a heating effect, figure 6 left. For refrigeration devices, the coefficient to performance, $COP$, is defined as the ratio of cooling power (useful result, $Q_C$) vs. input power (consumed energy, $P$):

$$COP = \frac{Q_C}{P_{TEC}} = \frac{Q_C}{Q_H - Q_C}.$$  

(8)

The optimization process of $COP$ yields the maximum $COP$ value as:

$$COP_{\text{max}} = \frac{T_C}{T_H - T_C} \frac{\sqrt{1 + Z_{np} T_M} - T_H/T_C}{\sqrt{1 + Z_{np} T_M} + 1} = COP_{\text{Carnot}} \frac{\sqrt{1 + Z_{np} T_M} - T_H/T_C}{\sqrt{1 + Z_{np} T_M} + 1}.$$  

(9)

As a power generator (TEG), under the influence of a temperature gradient, an electrical current is generated within the circuit (Seebeck effect). The heat $Q_H$ is supplied on the module top at $T_H$ and the bottom is cooled by extracting $Q_C$ at temperature $T_C$, figure 6 right. For power generation devices, the energy conversion efficiency, $\eta$, is defined as the ratio of power output (useful result, $P$) vs. net heat input (consumed energy, $Q_H$):

$$\eta_{\text{TEG}} = \frac{P_{\text{TEG}}}{Q_H} = \frac{Q_H - Q_C}{Q_H}.$$  

(10)

The optimization of conversion efficiency yields the maximum $COP$ value as:

$$\eta_{\text{max}} = \frac{T_H - T_C}{T_H} \frac{\sqrt{1 + Z_{np} T_M} - 1}{\sqrt{1 + Z_{np} T_M} + T_C/T_H} = \eta_{\text{Carnot}} \cdot \frac{\sqrt{1 + Z_{np} T_M} - 1}{\sqrt{1 + Z_{np} T_M} + T_C/T_H}.$$  

(11)

The output from a single TE module is not practically useful. For real-life applications, multiple TE modules connected electrically in series and thermally in parallel, electrically isolated on top and bottom by two ceramic substrates, form a TE device (figure 4). The equivalent electrical circuit is very simple [14] and is modeled in similar manner for both cases, TEC and TEG.

For solar PV cooling applications, multiple TE devices connected on the backside of the panel absorb the waste heat and thus control the operational temperature of the PV, figure 7.

Figure 7. Equivalent electrical circuit for a PV – TE device.
3. PV-TE or PVT-TE?
Reviews of advancements on TE devices published in recent years [15 - 17] are mainly concerned with materials properties and manufacturing technologies, but mention future trends and applications, such as waste heat energy recovery, cooling, power generation, thermal energy sensors or aerospace.

Although solar applications with TE were considered since late 1990s, the coupling of TE elements with PV cells represents a relatively new research area.

The early PV-TE applications were concerned with PV cooling solutions rather than increasing the conversion efficiency from solar to electric energy. The goal was to control the PV panel operational temperature, and thus, increase the conversion efficiency.

Lowering the PV temperature, the PV-TE efficiency increased to 11-14% in outdoor applications and up to 23% in laboratory tests [18]. However, measurements demonstrated that only 10% of these values (i.e. 1-1.5%) represent the TE modules contribution. Other research [19] published similar conclusions, as PV-TE and PVT-TE cooling solutions revealed that overall PV efficiency improved, but the TE contribution to electrical production was a mere 1%. Also, [20, 21] accounted only for PV efficiency improvement (1-18%) due to TE cooling, with a 6-26% panel temperature drop.

During the second part of the current decade, the advancements in materials and technologies allowed a new perspective over TE module usage in solar PV applications.

Materials for PV cells and TE modules have better conversion efficiency and lower manufacturing costs. The research in the PV cells area conducted to newer materials, which, even if exhibit lower conversion efficiencies than Si-based materials, are much cheaper to obtain and to embed in PV modules. Also, for TE materials, reviews [15, 17] identified the parameters that improve the thermal to electrical conversion: Seebeck coefficient, electrical and thermal conductivities, and thus figure of merit of material and device, energy gap and band structure, charge carrier concentration and mobility, material composition (metal based, semiconductors, ceramics, polymers), diffusion, thermal expansion coefficient, brittleness, compressibility.

The analysis and characterization of a PV-TE system performance [22, 23] quantify the power output of PV and TEG systems combined and separated. The most important parameters identified were open circuit voltage \(V_{OC}\), short circuit current \(I_{SC}\), PV power output, TE power output, operational PV module temperature, environmental temperature, etc.

The idea of solar cogeneration devices, i.e. simultaneous production of both thermal and electrical energy from a single source (solar energy), implied the partial recovery of energy contained in the waste heat from the backside of the PV panel. The photovoltaic-thermal (PVT) devices developed witnessed a sharp increase in total conversion efficiency, since solar-to-thermal conversion has an efficiency of minimum 30%. Several well-known reviews [24-30] identified PV cooling methods with emphasis on the thermal conversion as well.

Early ideas of using PVT and TE for cooling [31] simply compared the methods and concluded that fluid cooling are far superior as process efficiency, in direct parallel comparison. However, at the same time, authors note that PVT behavior is not optimum and consider the idea that both cooling methods are useful for specific applications.
Experiments proved that PV water-cooling is very effective in increasing conversion efficiency, [32], and it increases even more by adding TE devices, but only at lower irradiation values. As solar irradiation increases, the TE output cannot compensate the decrease in PV electrical output, the main benefit being the recovery of thermal energy from the PV panel waste heat. Similar research indicated that a higher concentration ratio results in higher power production from TEG module due to increased absorbed heat flux, [33]. Additionally, the PV cells temperature is maintained at optimum operational value by decreasing thermal resistance between the PV cells and TEG module. Simulations indicate an increased efficiency of TEG modules, the total power production of integrated PV-TE system being augmented.

4. Trifold panel characterization
The conclusions from solar cogeneration analyses mentioned above, triggered in-depth research, both theoretical and experimental, on solar cogeneration and even tri-generation (combined cooling, heat and power – CCHP).

Last couple of years several researchers concentrated their efforts in this hot-topic area. Theoretical concepts proposed various combinations depending on specific applications and availability of parts and technologies: compact PV-T-TE, compact PV-TE-T, and spectral beam splitting for incident solar radiation (PV-TE and T).

The PV-T-TE configuration is useful in applications that require preparation of domestic hot water along with electricity production, [34]. A fluid directly cools the backside of the PV panel, absorbing most of the energy from the waste heat rejected. On the other side of the fluid channel, the TE tap into the remaining thermal energy. This design is also useful for the high solar irradiation case [35], when PV panel may attain higher temperatures and requires an intensive temperature control.

The most common configuration is the PV-TE-T, where TE modules glued directly on the backside of the PV panel absorb the heat, cooling it down, figure 9. The working fluid may be air, water, glycol or nanofluids. The setup design using air does not raise many technical problems, but has lower efficiency. The literature reports experimental values of 4.83% and 46.16% for average electrical and thermal efficiencies, respectively, for a triangular setup with concentrator, [36]. The contribution of the TE modules represented a mere 3.3% of the total electrical power generated, i.e. 0.16% of total energy conversion. On the other hand, theoretical models [37] demonstrate maximum attainable values of up to 84% and 12% for thermal and electrical efficiencies, depending on working fluid mass flow rate and density of TE modules attached. If the goal is concentrated on controlling and optimizing the PV panel operational temperature [35], then PV-TE-T solution achieves lower conversion efficiencies of 43.06%, 27.68% and 15.38% for total, electrical and thermal efficiency, respectively. However, the system eliminates the fluctuations in operational temperature and maintains it in the 343-355 K range.

![Figure 9. Energy flow in a trifold PV-TE-T solar panel.](image-url)
Use of nanofluids, [38], further improves the total conversion efficiency, even though authors noted a decrease of about 3% in thermal conversion efficiency. The system control represents the main advantage, by easily adjusting the mass flow rate and volume fraction of the nanofluid. A comparison of all fluids demonstrated [39] the better performance of water-based system when compared to air-based ones with 2-3% and 21-22% for overall electrical and thermal efficiencies, respectively, and mentioned the benefits of using nanofluids.

The solution of spectral beam splitting for incident solar radiation relies on separating the useful 600-1100 nm bandwidth for the PV panel, while the rest of the spectrum is converted into high-grade thermal energy within solar thermal collectors, [34]. This requires a much larger surface area for both panels, electrical and thermal, as well as some technological complications, [40].

The complexity of a trifold solar system involves a large number of parameters that influence the design and operation of all system components (PV, TE, T). Some of these parameters are geometry structure and material composition, heat transfer characteristics (material properties and temperatures), environmental characteristics (location, climate, ambient temperature, and wind speed), solar concentrator system, nanofluid parameters (mass flow rate, volume fraction), exergy performance etc.

5. Conclusions
This paper performed an overview of the PV cell operations and cooling requirements, of TE module design and function and of the current solutions for solar cogeneration and tri-generation systems. The main conclusion is that trifold PV-TE-T hybrid systems exhibit a much better conversion performance when compared with stand-alone PV systems or hybrid PV-T or PV-TE systems.

Even though results of theoretical and experimental analyses demonstrate that the presence of TE modules in the proposed systems does not greatly influence the electrical conversion efficiency (power generation), it improves on controlling and maintaining the operational PV temperature within safety range. Therefore, the system will exhibit higher electrical and thermal efficiency, as well as higher system stability and security. Other ideas may further improve on system performance, such as use of nanofluids or nano-structured materials.

The manufacturing costs of entire system are higher than for individual components, but given the evolution of scientific research and the capability of simultaneous production of electrical, thermal and possibly satisfying cooling requirements, may prove to be an economical solution for specific mobile application in remote locations or for emergency disaster relief forces.

Future research should be concerned with developing materials for both PV cells and TE modules with better characteristics (conversion efficiency, figure of merit) and with lower manufacturing costs, performing theoretical analyses on energy efficiency, exergy efficiency, economic and environmental, as well as performing theoretical simulations and experimental validation of models.

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