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Efficiency of solar collectors – a review

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Abstract. The progress of solar energy conversion technologies during the last few decades triggered the development of various types of collectors, thermal, photovoltaic (PV), or hybrid. In this paper, authors present the basic elements of thermal (energy and exergy) analysis solar collectors and their efficiency. The review of thermal analyses covers basic types of collectors and is extended to some constructive variations, e.g. with supplemental thermal elements (TEG). Thermal radiation proves to be the most important energy loss factor, due to the large temperature difference between the collector surface and the sky. To determine the total efficiency of solar collector operation, as a more complex analysis method of solar collector systems is proposed, to include economic, environmental and life-cycle analysis elements.

1. Introduction

Search for clean and cheap energy sources generated, especially in recent decades, an expansion of the scientific research on solar energy conversion technologies.

Solar thermal panels were continuously developed to improve the conversion efficiency, domestic applications using flat panel collectors (FPC) to evacuated tube (ETC), or with heat pipes (HP-ETC). For industrial systems, the concentrated solar power (CSP) plants were designed to follow the Sun's passage on sky, the tracking devices being classified by the number of axes. The linear focus (one-axis movement) devices include Linear Fresnel Reflectors (LFR) and parabolic trough collectors (PTC), while the focal point (two-axes movement) devices include Heliostat Field Concentrator (HFC) as well as Parabolic Dish Reflector (PDR), figure 1.

Solar photovoltaic panels include multiple photovoltaic (PV) cells to directly convert solar energy into electricity. Initially, PV cells were too expensive to use on industrial scale, but recent materials and manufacturing technologies made possible to mass produce PV cells at lower costs and improved conversion efficiency.

Once the necessity for cleaner energy resources amplified, scientists intensified their research to enhance the conversion of solar energy into electricity. Studies published in the literature during the last 3-4 decades demonstrate the strong dependence of PV cell performances to maintaining lower cell operation temperature, [1-15], figure 2.

The recent years witnessed huge advances in developing hybrid solar panels, photovoltaic thermal ones, i.e. PVT panels/collectors. First concepts published in the late '70s, early '80s on PVT systems, analysed solar FPC in combination with PV cells. Later, when PV cells manufacturing price became realistic, the research concentrated on combining PVs with thermal management solutions, to improve efficiency of energy conversion from solar to electricity: air and/or water cooling, micro-scale heat exchangers, thermo-electric generators (TEG), or other renewable energy systems, [16-25].

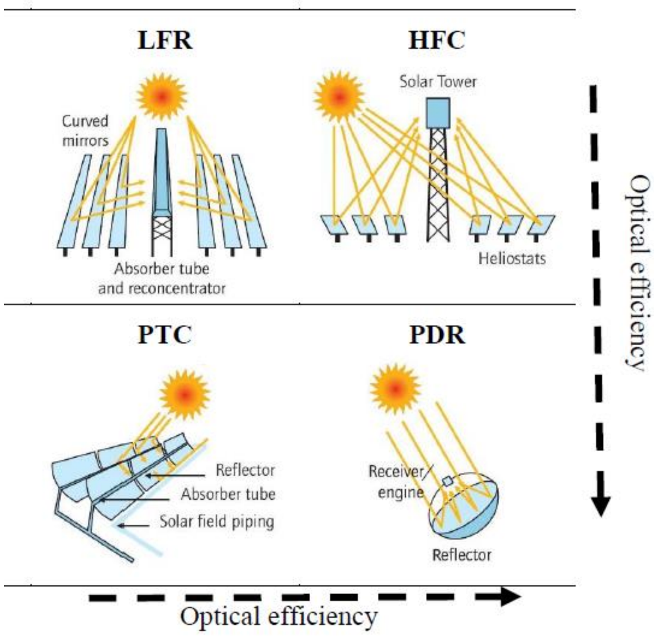

Figure 1. CSP devices, classified per number of tracking axes (column) and mobility (line).

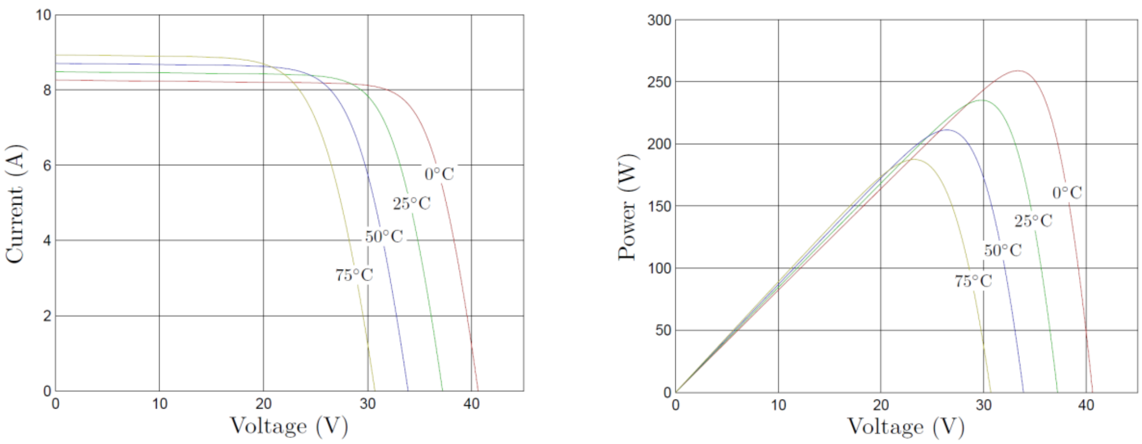

Figure 2. The (I-V) and (P-V) curves for various operational temperature, [11].

Commercially available solar panels may reach a conversion efficiency of 40-60% to thermal and 15-20% to electrical energy. The PVT collectors embed cooling systems for PV panels with various designs for the fluid flow passages: tubes, channels (rectangular, square box, corrugated), spiral, flat plate or encapsulated heat pipes. The cooling agents are fluids with regular or cooling characteristics (air, water, glycol or fluids with nanoparticles), flowing in one-, two- or multiple passes, in glazed or unglazed collector configurations. Thus, the total conversion efficiencies (thermal and electrical) may increase to 43 – 87%, [26-44].

Besides concept presentations and experimental performance analyses, many studies [45-58] on PVT collectors included mathematical models, numerical simulations or analysis on electrical, thermal and overall system efficiency. When PVT performances where compared with separate thermal and PV systems, the energy and exergy analyses observed higher values for energy conversion efficiency.

2. Thermodynamic 2-E analysis

From thermodynamic point of view, the 2-E (i.e. Energy – Exergy) analysis is based on first law and second law. For a closed systems that undergoes a steady-state process between two states 1 and 2, the laws are mathematically expressed as, [59-64]:

$$\int_1^2 \delta Q - \int_1^2 \delta W = E_2 - E_1 \quad \Rightarrow \quad Q_{1,2} - W_{1,2} = E_2 - E_1 \tag{1}$$

$$\int_1^2 \frac{\delta Q}{T} \le S_2 - S_1 \quad \Rightarrow \quad S_{gen} = S_2 - S_1 - \int_1^2 \frac{\delta Q}{T} \ge 0\,. \tag{2}$$

The exergy concept represents a combination of the first and second law of thermodynamics and is used to improve the analysis, design and performance of thermal systems. It is defined as maximum amount of useful work that can be obtained during a process where a flow of mass or energy comes to equilibrium with the reference environment. In general, the exergy balance is defined as:

$$\sum \dot{E}x_{in,net} - \sum \dot{E}x_{out,net} = \sum \dot{E}x_{loss} \tag{3}$$

For a thermal machine that produces work, the losses due to internal irreversibilities are

$$\dot{W}_{lost} = T_0 \dot{S}_{gen} \tag{4}$$

where T_0 is the reference temperature at which exergy (available energy) content is zero (dead state). The efficiency of a process is defined as a measure of the real process deviation from a reversible, ideal one. It is also known as *exergy efficiency* or second law efficiency:

$$\eta_{II} = \frac{\dot{W}}{\dot{W}_{max}} = 1 - \frac{\dot{W}_{lost}}{\dot{W}_{max}} \tag{5}$$

whereas the first law efficiency, merely a metric criterion, is defined based on efficiency of the ideal Carnot cycle

$$\eta_I = \frac{\dot{W}}{\dot{Q}_H} = \eta_{II}\left(1 - \frac{T_L}{T_H}\right) = \eta_{II}\eta_{Carnot}\,. \tag{6}$$

An exergy efficiency analysis takes into account the exergetic input, output and losses and exergy efficiency becomes

$$\eta_{ex} = \frac{\sum \dot{E}x_{out,net}}{\sum \dot{E}x_{in,net}} = 1 - \frac{\sum \dot{E}x_{loss}}{\sum \dot{E}x_{in,net}}\,. \tag{7}$$

3. The 2-E analysis of solar collectors

The following review attempts a logical presentation of these 2-E analysis concepts, applied to solar thermal collectors, PV panels, hybrid PV/T collectors and PVT-TEG hybrid systems.

The incident solar radiation, G, has three components [65]: beam, diffuse, and ground-reflected. Although each component should be treated separately, the incident solar radiation may be considered affected by an effective transmittance-absorptance product, $(\tau\alpha)_{eff}$, (or optical efficiency, η_o, [66]).

3.1. Solar thermal collectors

Out of the vast diversity of types of thermal collectors, this paper presents the analysis of simple FPC, with the intent to clarify the method and its use. This may be extended on other types of panels, with pipes or serpentines, ETC, HP-ETC, etc.

For uniform collector plate temperature, the useful heat rate absorbed by the fluid is, [64-68]:

$$\dot{Q}_u = \dot{m}C_p\left(T_{fl,out} - T_{fl,in}\right). \tag{8}$$

In most practical applications, the collector plate temperature is not uniform, and the heat removal factor is often used instead.

$$\dot{Q}_u = F_R A_c\left[(\alpha\tau)_{eff}\, G - U_L\left(T_{fl,in} - T_a\right)\right] \tag{9}$$

where the overall heat loss coefficient, U_L , is used to account for heat transfer losses from collector to atmosphere, both by convection and radiation:

$$\dot{Q}_{loss} = U_L A_c\left(T_c - T_a\right) \tag{10}$$

and heat removal factor is defined as:

$$F_R = \frac{\dot{m}C_p}{U_L A_c}\left[1 - \exp\left(\frac{-F' U_L A_c}{\dot{m}C_p}\right)\right] \tag{11}$$

where F' is the collector efficiency factor.

Energy efficiency of solar thermal collector is:

$$\eta_{en} = \frac{\dot{Q}_u}{GA_c}. \tag{12}$$

The exergy balance on a FPC may be expressed as:

$$\dot{E}x_{in} + \dot{E}x_{st} + \dot{E}x_{out} + \dot{E}x_{loss} + \dot{E}x_{des} = 0. \tag{13}$$

The inlet exergy rate, $\dot{E}x_{in}$, accounts for two components: the inlet exergy with fluid flow, [59, 69]

$$\dot{E}x_{in,fl} = \dot{m}C_p\left(T_{fl,in} - T_a - T_a \ln\frac{T_{fl,in}}{T_a}\right) + \frac{\dot{m}\Delta P_{in}}{\rho} \tag{14}$$

and the inlet exergy absorbed from solar radiation, [69]

$$\dot{E}x_{in,S} = \eta_o G A_c\left[1 - \frac{4}{3}\left(\frac{T_a}{T_S}\right) + \frac{1}{3}\left(\frac{T_a}{T_S}\right)^4\right]. \tag{15}$$

To define the exergy rate of incident solar radiation, several factors have to be taken into account, [70, 71]. First, black-body radiation and diluted black body radiation, more precisely the difference between the two, i.e. the entropy transported by the two kinds of radiation. Second, the apparent Sun temperature is considered as ¾ of the blackbody temperature of the Sun, 5770 K.

The stored exergy rate is zero at steady-state:

$$\dot{E}x_{st} = 0. \tag{16}$$

The outlet exergy rate accounts for the outlet exergy with fluid flow:

$$\dot{E}x_{out,fl} = -\dot{m}C_p\left(T_{fl,out} - T_a - T_a \ln\frac{T_{fl,out}}{T_a}\right) - \frac{\dot{m}\Delta P_{out}}{\rho} \tag{17}$$

similar to equation (14), where ΔP_{in} and ΔP_{out} are pressure difference between fluid and environment at the collector inlet and outlet, respectively.

The heat losses exergy rate accounts for the heat leakage rate from collector plate to environment, defined as:

$$\dot{E}x_{loss} = -U_L A_c \left(T_c - T_a\right)\left(1 - \frac{T_a}{T_c}\right). \tag{18}$$

The destroyed exergy rate includes three terms related to

- the temperature difference between the collector plate surface and the Sun

$$\dot{E}x_{des,\Delta T_s} = -\eta_o G A_c T_a \left(\frac{1}{T_c} - \frac{1}{T_S}\right) \tag{19}$$

- the pressure drop within the fluid channel

$$\dot{E}x_{des,\Delta P} = -\frac{\dot{m}\Delta P}{\rho} \frac{T_a \ln\left(\frac{T_{fl,out}}{T_a}\right)}{\left(T_{fl,out} - T_{fl,in}\right)} \tag{20}$$

- the temperature difference between collector plate surface and the fluid

$$\dot{E}x_{des,\Delta T_f} = -\dot{m} C_p T_a \left[\ln\left(\frac{T_{fl,out}}{T_{fl,in}}\right) - \frac{\left(T_{fl,out} - T_{fl,in}\right)}{T_c}\right] \tag{21}$$

Defining the exergy efficiency of the solar collector as:

$$\eta_{ex} = \frac{\dot{E}x_{out,fl} - \dot{E}x_{in,fl}}{\dot{E}x_{in,S}} \tag{22}$$

yields:

$$\eta_{ex} = \frac{\dot{m}\left\{C_p\left[T_{fl,out} - T_{fl,in} - T_a \ln\left(\frac{T_{fl,out}}{T_{fl,in}}\right)\right] - \frac{\Delta P}{\rho}\right\}}{G A_c \left(1 - \frac{T_a}{T_S}\right)}. \tag{23}$$

3.2. Solar photovoltaic panels

The photovoltaic cell represents a non-linear system characterized by the (I-V) current–voltage, and (P-V) power–voltage curves, [19, 50, 72, 73], with equivalent electrical circuit described in figure 3.

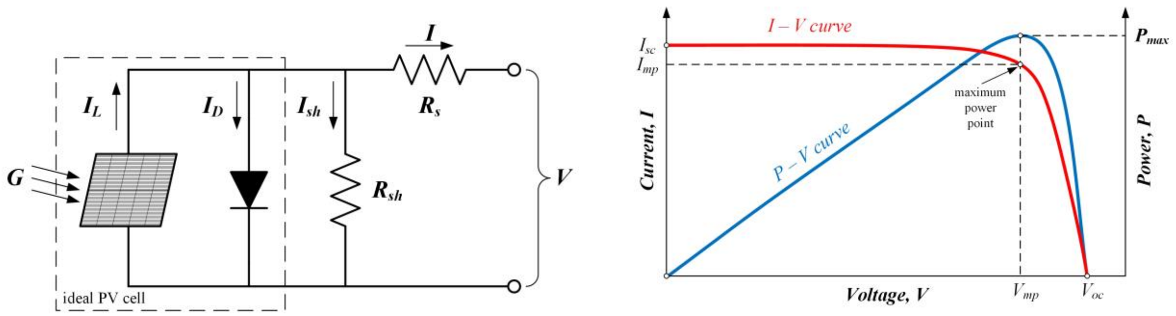

Figure 3. Equivalent electrical circuit and characteristic curves for a PV cell.

Depending on the ideality factor, *a*, the (I-V) curve is mathematically described as:

$$I = I_L - I_D - I_{sh} \quad \Rightarrow \quad I = I_L - I_o\left[\exp\left(\frac{V + IR_s}{a}\right) - 1\right] - \frac{V + IR_s}{R_{sh}} . \tag{24}$$

The characteristic points of the electrical circuit, as presented in figure 3, are:

- the short circuit current values: $I = I_{sc,ref}$ $V = 0$
- the open circuit voltage values: $I = 0$ $V = V_{oc,ref}$
- the maximum power point values: $I = I_{mp,ref}$ $V = V_{mp,ref}$.

The reference conditions (standard rated conditions, SRC) are temperature of 25°C and radiation intensity of 1000 W/m^2.

The overall heat loss coefficient from a PV panel includes both losses by convection and radiation:

$$U_L = h_{cv} + h_{rad} . \tag{25}$$

The convective heat transfer coefficient is estimated using empirical correlation, as suggested in [50, 52], depending of the wind speed, V_w:

$$h_{cv} = 2.8 + 3V_w . \tag{26}$$

In order to obtain a radiation heat transfer coefficient of a similar form to the convective one, it may be derived from the net radiative heat exchange between the PV cell and environment:

$$h_{rad} = \varepsilon_{cell}\sigma\left(T_{sky} + T_{cell}\right)\left(T_{sky}^2 + T_{cell}^2\right) \tag{27}$$

where the effective sky temperature is approximated by empirical correlations, suggested in [50, 52]:

$$T_{sky} = T_a - 6 \tag{28}$$

or in [64]:

$$T_{sky} = 0.0552 T_a^{1.5} . \tag{29}$$

Maximum value for the energy efficiency of a PV cell is defined as:

$$\eta_{en,max} = \frac{V_{oc} I_{sc}}{GA_{cell}} . \tag{30}$$

The fill factor, *FF*, represents measure of the “square area” under the (I-V) curve, of how “square” or “rounded” is the curve. Mathematically, it is defined as:

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} . \tag{31}$$

The maximum theoretical value for the *FF* is determined by differentiating the power from a solar cell with respect to voltage and finding where this is equal to zero. The empirical formula is:

$$FF = \frac{V_{oc} - \ln\left(V_{oc} + 0.72\right)}{V_{oc} + 1} . \tag{32}$$

Therefore, the energy efficiency of a PV cell is actually identical to electrical efficiency, which may be expressed in terms of maximum power point values or in terms of circuit characteristics, as:

$$\eta_{en} = \eta_{el} = \frac{V_{mp} I_{mp}}{GA_{cell}} = \frac{FF \times V_{oc} I_{sc}}{GA_{cell}} . \tag{33}$$

The exergy analysis for the PV panel involves similar terms as the exergy balance in equation (13). The inlet exergy rate absorbed from solar radiation, equation (15), and heat loss exergy rate, equation (18) are identical, observing that A_c is now the area of the PV cell, instead of the collector area.

The exergy destruction terms are caused by

- the optical losses:

$$\dot{E}x_{des,opt} = GA_{cell}\left(1-\frac{T_a}{T_s}\right)\left[1-(\alpha\tau)_{eff}\right] \tag{34}$$

- temperature difference between the PV cell and the Sun, similar to equation (19):

$$\dot{E}x_{des,\Delta T_s} = \eta_o GA_{cell}T_a\left(\frac{1}{T_{cell}}-\frac{1}{T_S}\right) \tag{35}$$

- the PV cell temperature variation with respect to environmental state, [50, 52]:

$$\dot{E}x_{des,\Delta T_{cell}} = \frac{m_{cell}C_pT_a}{\Delta t}\left[\ln\left(\frac{T_{cell}}{T_a}\right)-\frac{(T_{cell}-T_a)}{T_{cell}}\right] \tag{36}$$

- electrical exergy destruction:

$$\dot{E}x_{des,el} = \left(I_{sc}V_{oc}-I_{mp}V_{mp}\right). \tag{37}$$

Exergy efficiency of the PV cell is:

$$\eta_{ex} = \frac{\dot{E}x_{in,S}-\left(\dot{E}x_{loss}+\sum\dot{E}x_{des}\right)}{\dot{E}x_{in,S}}. \tag{38}$$

3.3. Solar photovoltaic-thermal (PVT) panels

There are various combinations of constructive solutions and working fluid for a PVT panel. This review covers the case of PV panel physically bonded to the FPC, using water as a working fluid. The 2-E analysis represents a combination of previous equations, considering A_{PVT} as area of the absorber.

Combining equations (8) and (9), the rate of useful thermal energy for the PVT panel is:

$$\dot{Q}_u = \dot{m}C_p\left(T_{fl,out}-T_{fl,in}\right) = F_RA_{PVT}\left[(\alpha\tau)_{eff}G-U_L\left(T_{fl,in}-T_a\right)\right] \tag{39}$$

with the removal factor defined as

$$F_R = \frac{\dot{m}C_p}{U_LA_{PVT}}\left[1-\exp\left(\frac{-F'U_LA_{PVT}}{\dot{m}C_p}\right)\right]. \tag{40}$$

The thermal efficiency of the PVT panel may be re-written as:

$$\eta_{th} = \frac{\dot{Q}_u}{GA_{PVT}} = F_R\left[(\alpha\tau)_{eff}-\frac{U_L\left(T_{fl,in}-T_a\right)}{G}\right]. \tag{41}$$

For the PVT panel, the thermal efficiency is coupled with electrical efficiency. Here, the electrical power consumed by the water circulation pump has to be considered in the analysis.

$$\dot{E}_p = \frac{\dot{m}\Delta P}{\rho\eta_p}. \tag{42}$$

The electrical efficiency of a PVT panel becomes:

$$\eta_{el} = \frac{V_{mp} I_{mp} - \dot{E}_p}{G A_{PVT}} . \tag{43}$$

Exergy efficiency of a PVT panel in calculated in terms of net output exergy rate that accounts for both thermal and electrical energy rates.

For a PVT panel, the net input exergy rate is:

$$\sum \dot{E}x_{in,net} = \dot{E}x_{in,S} = G A_{PVT} \left[1 - \frac{4}{3}\left(\frac{T_a}{T_S}\right) + \frac{1}{3}\left(\frac{T_a}{T_S}\right)^4 \right] \tag{44}$$

while the net output exergy rate is:

$$\sum \dot{E}x_{out,net} = \dot{E}x_{th} + \dot{E}x_{el} . \tag{45}$$

The thermal exergy rate accounts for the changes in exergy of the fluid flow

$$\dot{E}x_{th} = \dot{Q}_u \left(1 - \frac{T_a}{T_{fl,out}} \right) \tag{46}$$

and the electrical exergy rate represents the electrical power supplied by PV module diminished by electrical power consumed by the pump

$$\dot{E}x_{el} = \dot{E}_{el} - \dot{E}_p . \tag{47}$$

An empirical correlation is proposed [27] to compute the electrical power from a PV module:

$$\dot{E}_{el} = \eta_{el} G A_{PVT} = \eta_{el,ref} \left[1 - \beta_{ref} \left(T_c - T_{a,ref} \right) \right] G A_{PVT} . \tag{48}$$

The rate of exergy losses for a PVT panel are determined as a sum of internal and external ones.

$$\sum \dot{E}x_{loss} = \sum \dot{E}x_{loss,ext} + \sum \dot{E}x_{loss,int} = \sum \dot{E}x_{loss,ext} + \sum \dot{E}x_{des} . \tag{49}$$

The rate of exergy losses due to optical losses

$$\dot{E}x_{loss,opt} = G A_{PVT} \left[1 - \frac{4}{3}\left(\frac{T_a}{T_S}\right) + \frac{1}{3}\left(\frac{T_a}{T_S}\right)^4 \right] \times \left[1 - (\alpha\tau)_{eff} \right] . \tag{50}$$

The heat loss rate from the PVT to the ambient:

$$\dot{Q}_{loss} = U_L A_{PVT} \left(T_c - T_a \right) \tag{51}$$

and then the exergy loss rate due to this heat loss from the PVT to the ambient becomes:

$$\dot{E}x_{loss,\dot{Q}_{loss}} = \dot{Q}_{loss} \left(1 - \frac{T_a}{T_c} \right) . \tag{52}$$

The rate of exergy destruction depends on

- temperature difference between the Sun and PVT panel

$$\dot{E}x_{des,\Delta T_{S-PVT}} = (\alpha\tau)_{eff} \, G A_{PVT} \left\{ \left[1 - \frac{4}{3}\left(\frac{T_a}{T_S}\right) + \frac{1}{3}\left(\frac{T_a}{T_S}\right)^4 \right] - \left(1 - \frac{T_a}{T_c} \right) \right\} \tag{53}$$

- heat transfer at finite temperature difference between the panel and working fluid:

$$\dot{E}x_{des,\Delta T_{PVT-fl}} = (\alpha\tau)_{eff}\, GA_{PVT}\left(1-\frac{T_a}{T_c}\right) - \left[\dot{Q}_{loss}\left(1-\frac{T_a}{T_c}\right) + \dot{Q}_u\left(1-\frac{T_a}{T_{fl,out}}\right)\right] - V_{oc}I_{sc} \quad (54)$$

- pressure drop in the PVT flow channels:

$$\dot{E}x_{des,\Delta P} = \frac{\dot{m}\Delta P T_a}{\rho \bar{T}_{fl}} \quad (55)$$

- electrical exergy destruction rate that includes the energy required to pump the working fluid:

$$\dot{E}x_{des,el} = I_{sc}V_{oc} - \left(I_{mp}V_{mp} - \dot{E}_p\right). \quad (56)$$

Substituting the exergy destruction terms from equations (53)-(56) into equation (22) for exergy efficiency, yields the general formula for a PVT panel exergy efficiency:

$$\eta_{ex} = \frac{\dot{Q}_u\left(1-\frac{T_a}{T_{fl,out}}\right) - \dot{E}_p + \eta_{el,ref}\left[1-\beta_{ref}\left(T_c - T_{a,ref}\right)\right]GA_{PVT}}{GA_{PVT}\left[1-\frac{4}{3}\left(\frac{T_a}{T_S}\right)+\frac{1}{3}\left(\frac{T_a}{T_S}\right)^4\right]}. \quad (57)$$

3.4. Thermo-Electric Generators (TEG) and PVT-TEG integration

The thermo-electric (TE) modules are composed of n- and p-type materials, connected electrically in series and thermally in parallel, the whole ensemble being sandwiched between two ceramic substrates that act as external electrical insulators. The TE may operate two ways, as generators, TEG (Seebeck effect), when while being subjected to a temperature difference they generate electrical current, or as coolers, TEC (Peltier effect), when under the influence of electrical current supplied to the circuit, heat may be absorbed or rejected, figure 4 [74].

TEs are attached to the back side of the PV panel to form a PV-TE or a PVT-TE hybrid module. The TE modules reduce and/or control the operating temperature of PVs, converting waste thermal energy from PV directly into electric power. Thus, the efficiency of PVT collectors increases twofold, by decreasing the operating temperature and increasing electrical output, [56, 75].

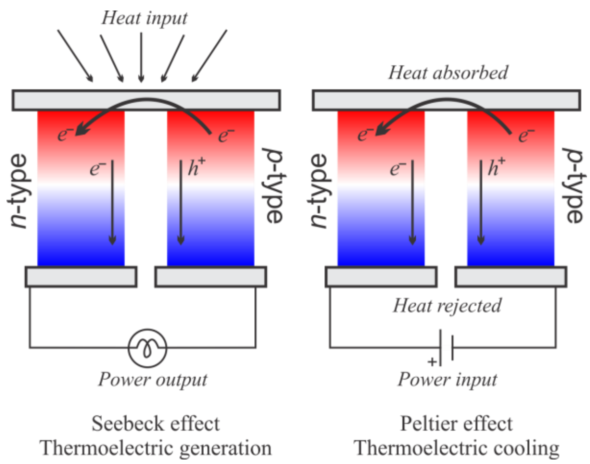

Figure 4. Thermo-Electric generation (TEG) vs. cooling (TEC), [74].

Efficiency of a TEG is defined [76-85] as:

$$\eta_{TEG} = \frac{\Delta T_{TEG}}{T_{TEG,h}} \frac{\sqrt{1+ZT}}{\sqrt{1+ZT} + \frac{T_{TEG,c}}{T_{TEG,h}}} \tag{58}$$

where the figure of merit of the TE module, Z , depends on characteristics of material, i.e. Seebeck coefficient, α , thermal conductivity, k , and thermal resistance, R:

$$Z = \frac{\alpha^2}{kR} . \tag{59}$$

Conversion efficiency of a TEG is defined as the fraction of the heat absorbed at the hot side of the device that is converted into electricity:

$$\eta_{TEG} = \frac{P_{TEG}}{Q_h} = \frac{Q_h - Q_c}{Q_h} \tag{60}$$

and it yields:

$$\eta_{TEG} = \frac{1}{4} \frac{\alpha^2}{kR} \left(T_c - T_{fl} \right) . \tag{61}$$

Total electrical power generation for solar radiation on the PV/TEG:

$$\eta_{PV-TEG} = \frac{P_{PV} + P_{TEG}}{GA_{PV}} . \tag{62}$$

Total PVT-TEG efficiency includes both electrical efficiency (from PV and TEG) and thermal efficiency of the PVT panel:

$$\eta_{PVT-TEG} = \eta_{el} + \eta_{TEG} + \eta_{th} . \tag{63}$$

4. Conclusions

The recent decades witnessed huge developments in solar energy conversion technologies that shifted from mainly solar-thermal to the solar-electrical. This was powered by the decrease of PV cells production costs, along with the increase in their efficiency.

The conversion efficiency of industrial-scale manufactured PV cells is still below 20% and their performance is greatly affected by the operational temperature. Thermal management of the PV panels induced the development of hybrid PV/T solar collectors, to address the low total energy conversion efficiency. Despite technological difficulties and supplemental electricity consumption for pumps, the hybrid PVT were further developed and improved into HP-PVT or PVT-TEG systems.

The 2-E (energy-exergy) analysis reviewed in this paper presents the basic elements for the solar thermal collectors (FPC), PV panels, hybrid PVT and PVT-TEG systems.

The extensive literature review demonstrates the keen interest for this scientific area, both energy and exergy analyses are proving to be an effective tool to study PVT systems effectiveness, showing a conversion efficiency higher than for PV systems.

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