OVERALL PERFORMANCE ASSESSMENT OF AN INTEGRATED SOLAR POWER PLANT - ENERGY, EXERGY AND EXERGO-ECONOMIC ANALYSIS

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Contents

Summary

Hybridization of Concentrated PhotoVoltaic and ThermoElectric Generator (CPV-TEG) offers an effective means of utilizing and reducing the cost of solar energy. In this chapter, energy, exergy and exergo-economic analysis of a CPV-TEG system is presented. The performance of CPV-TEG system is analyzed based on the first and the second laws of thermodynamics. SPecific Exergy COsting (SPECO) is employed to study the cost effectiveness. The performance of the CPV-TEG systems in terms of overall energy and exergy efficiency is better than that of the CPV system operating alone. From an exergo-economic standpoint, the CPV-TEG is more cost effective based on overall system cost as compared to an isolated CPV system. This chapter aims at

estimating the optimum water-cooled CPV-TEG design parameters that yield the maximum overall performance. The influence of key parameters (such as Direct Normal Irradiance (DNI), geometric concentration, thermo-electric figure of merit, temperature ratio of thermoelectric junction and heat sink thermal resistance) and their significance on the performance and cost of the system is examined. A performance measure known as the Overall Performance Index (OPI) is used to evaluate the optimum design of a CPV-TEG system operating within the limits of allowable cell temperatures. The variation of the OPI provides an indication of the performance of the hybrid system under different design parameters. The selection of the optimum system design corresponds to the case where the OPI is a maximum.

1. Introduction

Renewable energy sources such as solar energy can provide an attainable and lasting solution to the problem of high energy demand and overall energy crisis, because they are inexhaustible and clean. Harvesting of solar energy is typically done in two forms, namely, thermal, and electrical energy. Direct conversion of solar energy to electricity can be achieved using a PhotoVoltaic (PV) system, while thermoelectric generators can be used for thermal to electrical energy conversion. Combining thermoelectric generator with photovoltaic cells allows broader utilization of solar spectrum whereby part of the solar spectrum in the visible and ultraviolet region is used by the PV and the remaining which is in the infrared region can be used by the thermoelectric generator. PV technology has the potential to increase the contribution of renewable energy supply in the overall electricity demand by 5% in 2030. Among the various types of PV technology, Concentrator PhotoVoltaic (CPV) has the highest conversion efficiency in terms of solar to electrical energy conversion. A record efficiency of 46% has been achieved at cell level while the average efficiency is still around 30% for commercial applications. A CPV system uses an optical concentrator to direct sunlight unto a small highly efficient multijunction solar cell to convert it to electrical energy. Although the high conversion efficiency of CPV systems has encouraged worldwide commercialization with cumulative installation size of 370MWp, the levelized cost of electricity of CPV system is still high compared to non-concentrating flat plate PV systems. For CPV technology to be competitive with the conventional PV systems, an efficiency of 40% at the system level should be reached for commercial application. One way of enhancing the efficiency of CPV system is to couple it with a ThermoElectric power Generator (TEG).

A thermoelectric device is a two-way energy transformer which can either be used as cooler/heater or micro-power generating device based on the mode of operation. It is regarded as a thermoelectric power generator (TEG) when it converts heat to electricity through Seebeck effect due to imposed temperature gradient. TEG holds several unique advantages (such as high durability and reliability, easy scalability, small size, no gaseous emission and noise during operation) over other technologies. However, its low efficiency and high cost of material have limited its wide use. Hence some research on TEG has been directed at improving the conversion efficiency and minimizing the cost of material. The performance of a TEG is usually determined by the thermoelectric figure of merit ($\overline{zT}$) of the material and the temperature gap between the junctions. The figure of merit is a dimensionless quantity that lumps together the thermo-physical properties of TEG material in the expression $\overline{zT} = \left(s^2/\gamma k\right)T$, where s represents the Seebeck coefficient, γ is the electrical resistivity, k is the thermal conductivity and T denotes the absolute temperature. One way of improving the performance of a TEG is to use thermoelectric material with high $\overline{zT}$, which involves a low electrical resistivity, low thermal conductivity and a high Seebeck coefficient. The low value of $\overline{zT}$ which is the consequence of low conversion efficiency of commercial TEG, limits their competitiveness with photovoltaic and mechanical cycles. Therefore, effective coupling of a TEG with a CPV could serve as a power boost which mitigates the drawback in the performance of both components.

Selecting PV cell for coupling with TEG is crucial due to the complexity of the system and the additional thermal resistance. Furthermore, the effect of temperature on both systems differs. Multijunction cells are usually preferred for coupling with TEG due to their high efficiency, low sensitivity to temperature increase that reduces efficiency when operating at high concentrations and the ability of cooling with heat exchanger. The multijunction solar cell is one of the major components of a concentrated photovoltaic system and has attained highest conversion efficiency among other terrestrial PV cell applications.

A major challenge in integrating the traditional single junction cells with the thermoelectric generator is that it introduces additional thermal resistance which causes the cell temperature to rise. Since these cells have high temperature sensitivity, there is an accompanied efficiency reduction in the performance of the cells. Furthermore, the present thermoelectric material still exhibits a low performance, making their contribution in the overall system efficiency to be very small to compensate for the efficiency loss.

The case, however, is different when a CPV is employed due to having the highest efficiency of all the generation of solar cells. This high efficiency is brought about by a very low temperature coefficient which allows incorporation with a ThermoElectric Generator (TEG). Additionally, high concentration of incident solar radiation allows higher performance of the TEG due to increased temperature gradient, and a small active cell area opens opportunity for a cost-effective integration of heat sink and TEG. These advantages have been a major drive towards research and development of coupled CPV-TEG in the last few years.

Using a coupled CPV module and TEG in a concentrated system allows concentration of solar flux on the surface of the solar cell which in turn raises the temperature gradient of the TEG junctions, hence enhances the performance of the TEG. Additionally, the active area of CPV cells allows effective heat dissipation through coupling with economically affordable heat exchanger and TEG. These distinct features have driven several research interests relating to Concentrator PhotoVoltaic ThermoElectric Generator systems (CPV-TEG) over the years. Hybridization of CPV and TEG is generally done based on two concepts: one of which involves dividing the solar spectrum into two wavelength region, and directing part of the spectrum with high energy photon (low wavelength) to the CPV and the remaining part with low energy photon (high wavelength) to the TEG; the other design has the CPV thermally coupled to the TEG.

The CPV-TEG system performs better than the CPV system when the concentration factor is greater than 33. An efficiency of ~3% increase has been achieved at a concentration ratio of 50. Using the commercially available TEG module with $\overline{zT}$ of 1, the hybrid CPV-TEG system indicated a higher energy efficiency and a 71% cost reduction at 1100suns as compared to a stand-alone CPV system operating at 300suns. The hybridization of CPV and TEG is feasible and the system performance increases as the concentration factor increases.

The conflicting influence of temperature dependent characteristics on the efficiency of both components of the CPV-TEG system makes the design optimization of the integrated system very crucial. Use of a Phase Change Material (PCM) has been proposed for controlling the temperature variation in the CPV-TEG system. Although the economic value of the integrated CPV-TEG system increased when PCM is used, an appropriate value of temperature variation in the system could yield a maximum conversion efficiency. The CPV-TEG optimal nodal temperature in the system depends on the temperature coefficient of the CPV cell. The key for controlling the cell temperature within the allowable limits is to adjust the area of the TEG for a specific heat sink thermal resistance.

There has been a growing interest on the effective utilization of available energy sources. This interest has led researchers to adopt a method known as the exergo-economic analysis for evaluating the performance and cost effectiveness of energy systems. Exergo-economic analysis makes use of energy, exergy and economic principles to provide performance assessment vital to the design and optimization of energy systems that are cost effective. The electrical output of the coupled system can only be promoted if the contribution of the TEG in terms of efficiency surpasses the efficiency reduction in the PV cell. The irreversibilities increase as concentration increases and the Thomson effect has a negative effect on the performance of the coupled system. Therefore, the optimization of coupled CPV-TEG system is crucial from cost viewpoint. Since exergy represents the true value of energy stream entering or exiting an energy system, it is thus meaningful to apply exergy costing to such system. In this chapter, an exergo-economic assessment of a CPV-TEG system is presented using SPecific Exergy COsting (SPECO) and exergo-economic factor. Additionally, a CPV-TEG design that maximizes performance using optimum thermal resistance of the TEG is determined. The effects of concentration ratio, TEG thermal resistance, heat sink thermal resistance and cell temperature of the CPV-TEG system on exergy destroyed and cost of electrical energy are examined.

There is a trade-off between improving the CPV-TEG system efficiency and reducing the cost. To address this issue, a single performance measure is introduced whereby the optimum values of the system parameters such the TEG thermal resistance and convective heat transfer of the heat sink could be calculated. The performance of the coupled CPV-TEG is examined based on the overall performance index (OPI). The overall performance index is an optimized performance measure that accounts for several performance indicators that are crucial to the performance assessment of a thermal system. The concept of OPI is to select a suitable number of performance indicators of a thermal system based on application, design priority, user demand and real operating conditions. Then weight coefficients are assigned to the performance indicators in accordance to their importance and user priority. The effects of various parameters of the CPV-TEG on the performance and the economics of the system are considered under different operating conditions. The optimum configuration corresponds to the point of maximum overall performance index (OPI).

2. Description of the Power Plant

The configuration of the coupled CPV-TEG consists of a multijunction solar cell thermally integrated to a TEG and a cooling system as illustrated in Figure 1a. The triple junction solar cell (GaInP/GaInAs/Ge) is considered due to its high efficiency and low efficiency temperature coefficient that decreases the efficiency loss at high operating temperatures. The CPV cell converts a fraction of the incoming solar radiation into electricity while the remaining energy is directed to the hot side of the TEG module through different material layers in the form of heat. The CPV cell is attached to a copper plate using a solder paste. The copper plate acts as a heat spreader to maintain a uniform temperature distribution at the hot junction of the TEG module. The TEG module converts fraction of the heat into electrical power while most of the remaining heat is removed from the cold side by the heat sink. The heat sink helps to maintain the cell temperature of the CPV within the effective performance range and at the same time increases the temperature difference across the TEG module. The thermal resistance diagram of the CPV-TEG is illustrated in Figure 1b. Each component of the system is represented by an internal thermal resistance starting with the thermal resistance to the radiative heat loss at the top surface of the cell followed by the thermal resistances of the CPV cell, the thermal interface material (TIM) (solder paste, copper plate and ceramic), the TEG and the thermal resistance to convective heat loss from the heat sink. The parameters and properties of the various layers of the CPV-TEG system are given in Table 1.

Layer	Material	Thickness (mm)	Thermal conductivity (W/mK)
Concentrator	Polycarbonate	2.5	0.2
CPV	Ge	0.19	60
Solder paste	Sn-Ag-Cu	0.125	78
Copper plate	Cu	0.3	400
Ceramics	Alumina	0.2	25
Interconnect	Ag	0.1	429
TEG material	Bi_2Te_3	-	1.5
Interconnect	Ag	0.1	429
Ceramics	Alumina	0.2	25
Heat sink	Al	-	200

Table 1. Properties and thicknesses of the layers used in the model

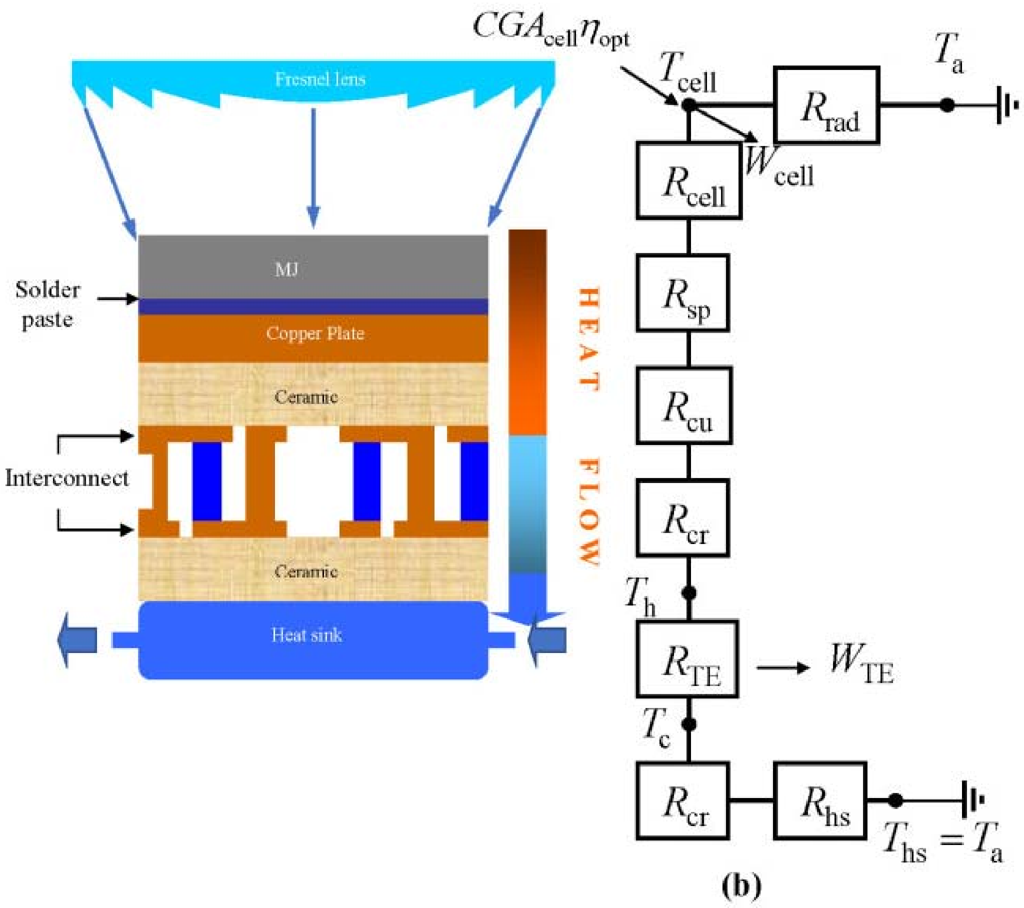

Figure 1. (a) Schematic diagram of the CPV-TEG system layers (b) Thermal resistance diagram of CPV-TEG system

3. Thermodynamic Analysis

3.1. Assumptions

The efficiency and power generated by each component (CPV & TEG) depends on the temperature variation across the system. The formulation of the mathematical model for the system is carried out using the following assumptions:

- The system is thermally insulated from all sides hence heat loss to the environment occurs only from the top of the CPV system and from the cold side of the TEG.
- The thermo-physical properties of the n and p type thermo-elements and their dimensions are considered to be identical
- Heat loss in the form of convection from the top surface of the CPV cell is ignored
- An ideal thermal contact is assumed for all the layers of the system
- MJ cells are modeled as a single Ge block hence uniform temperature is assumed across the layers of the cell.

3.2. Energy Analysis of CPV System

The temperature and efficiency of the stand-alone CPV system are calculated by applying energy balance equation between the top surface of the CPV cell and the heat sink:

$$CGA_{\text{cell}}\eta_{\text{opt}}\left(1-\eta_{\text{cell}}\right)-\dot{Q}_{\text{rad}}-\frac{T_{\text{cell}}-T_{\text{hs}}}{R_{\text{tot}}+R_{\text{hs}}}=0, \tag{1}$$

where C is the geometric concentration ratio, G is the direct normal irradiance taken as 900W/m^2, A_{cell} is the cross-sectional area of the CPV cell, η_{opt} is the optical efficiency of the concentrator, T_{cell} and T_{hs} are the operating temperature of the CPV cell and the temperature of the coolant in the heat sink, respectively. The conversion efficiency of the CPV cell is expressed as:

$$\eta_{\text{cell}}=\eta_{T_{\text{ref}}}\left[1-\beta_{\text{ref}}\left(T_{\text{cell}}-T_{\text{ref}}\right)\right], \tag{2}$$

where $\eta_{T_{\text{ref}}}$ is the peak efficiency of the cell (GaInP/GaInAs/Ge) taken as 40.8% at reference condition of temperature ($T_{\text{ref}}=25°\text{C}$) and $C=250$. The efficiency temperature coefficient is considered to be. $\beta=4.7\times10^{-4}\,\text{K}^{-1}$

The radiative heat loss is considered for environmental conditions since both the CPV system and the CPV-TEG system are operated in outdoor conditions. The radiative rate of heat loss is expressed as:

$$\dot{Q}_{\text{rad}}=\frac{T_{\text{cell}}-T_{\text{a}}}{R_{\text{rad}}}, \tag{3}$$

where the radiation thermal resistance R_{rad} given as:

$$R_{\text{rad}}=\frac{1}{h_{\text{rad}}A_{\text{cell}}}. \tag{4}$$

h_{rad} is the radiative heat transfer coefficient and it is expressed as;

$$h_{\text{rad}}=\varepsilon\sigma\left(T_{\text{cell}}^2+T_{\text{a}}^2\right)\left(T_{\text{cell}}+T_{\text{a}}\right). \tag{5}$$

ε is the emissivity of the CPV cell and is taken as 0.9, σ is the Stefan Boltzmann's constant given as $5.67\times10^{-8}\,\text{Wm}^{-2}\text{K}^{-4}$.

The total thermal resistance of the interface materials including the CPV cell R_{tot} is given as:

$$R_{\text{tot}} = R_{\text{cell}} + R_{\text{sp}} + R_{\text{cl}} + R_{\text{cr}}\,, \tag{6}$$

where R_{cell}, R_{sp}, R_{cl} and R_{cr} are the thermal resistances of the cell, the solder paste, the copper plate and the ceramic layer respectively in K/W in the CPV system. The absolute thermal resistance of the heat sink is defined as:

$$R_{\text{hs}} = \frac{1}{hA_{\text{hs}}}\,, \tag{7}$$

where h is the convective heat transfer coefficient. The area of the cooling system A_{hs} is taken to be the same as that of the cell (i.e., $A_{\text{hs}} = A_{\text{cell}}$).

3.3. Energy Analysis of CPV-TEG System

Integrating a TEG module with the CPV module increases the resistance to heat transfer between the CPV cell and the heat sink. Thus, the performance of the CPV-TEG system is analyzed by solving additional energy balance equations. For the CPV-TEG system, the energy balance equation between the top surface of the CPV cell and the hot side of the Thermo-Elements (TE) is given as:

$$CGA_{\text{cell}}\eta_{\text{opt}}\left(1-\eta_{\text{cell}}\right) - \dot{Q}_{\text{rad}} - \frac{T_{\text{cell}} - T_{\text{h}}}{R_{\text{tot}}} = 0\,. \tag{8}$$

The TEG module has pairs of semiconductor thermo-elements electrically and thermally connected in series and parallel, respectively. The module operates at steady state condition and heat losses from all sides due to convection and radiation are considered negligible. Additionally, thermal and electrical contact resistances are neglected. The heat absorbed at the hot side of the thermo-elements accounts for three heating effects namely: Seebeck effect which causes electricity generation due to temperature difference, the Joule heat resulting from flow of current through thermo-element and the Fourier heat transfer due to temperature difference across the thermo-element. Hence, the one-dimensional energy transport through the TE with temperature dependent thermo-physical properties is given as

$$\dot{Q}_{\text{h}} = sI_{\text{TE}}T_{\text{h}} - \frac{I_{\text{E}}^{2}\gamma_{\text{TE}}}{2} + \frac{\left(T_{\text{h}} - T_{\text{c}}\right)}{R_{\text{TE}}}\,, \tag{9}$$

$$\dot{Q}_{\text{c}} = sI_{\text{TE}}T_{\text{c}} + \frac{I_{\text{E}}^{2}\gamma_{\text{TE}}}{2} + \frac{\left(T_{\text{h}} - T_{\text{c}}\right)}{R_{\text{TE}}}\,, \tag{10}$$

where the electrical current through the thermo-element I_{TE} is given as:

$$I_{\text{TE}} = \left(\frac{s\left(T_{\text{h}} - T_{\text{c}}\right)}{\gamma_{\text{TE}} + \gamma_{\text{L}}}\right), \tag{11}$$

and s represents the Seebeck coefficient ($s = (s_{\mathrm{P}} - (-s_{\mathrm{N}}))$) of the thermoelectric material. The temperature dependent expressions for the properties of a Bi_2Te_3 thermoelectric material are given as:

$$s = 2\left(22224 + 930.6T_{\mathrm{m}} - 0.9905T_{\mathrm{m}}^{2}\right)\times 10^{-9}, \tag{12}$$

$$\rho_{\mathrm{p}} = \rho_{\mathrm{n}} = \left(5112 + 163.4T_{\mathrm{m}} + 0.6279T_{\mathrm{m}}^{2}\right)\times 10^{-10}, \tag{13}$$

$$k_{\mathrm{p}} = k_{\mathrm{n}} = \left(62605 - 277.7T_{\mathrm{m}} + 0.4131T_{\mathrm{m}}^{2}\right)\times 10^{-4}, \tag{14}$$

where T_{m} is the average temperature of the hot and the cold junctions of the thermo-element. The electrical resistivity and the thermal conductivity of the p and n-type thermo-elements are denoted by ($\rho_{\mathrm{p}} = \rho_{\mathrm{n}}$) and ($k_{\mathrm{p}} = k_{\mathrm{n}}$), respectively.

The electrical load resistance and the electrical series resistance are denoted by γ_{L} and γ_{TE} respectively. Assuming an ideal thermal contact, the electrical resistance γ_{TE} and thermal resistance R_{TE} of the TEG module are expressed as:

$$\gamma_{\mathrm{TE}} = \left(\frac{\rho_{\mathrm{n}} l_{\mathrm{n}}}{A_{\mathrm{n}}} + \frac{\rho_{\mathrm{p}} l_{\mathrm{p}}}{A_{\mathrm{p}}}\right) + \gamma_{\mathrm{ic}}, \tag{15}$$

$$R_{\mathrm{TE}} = \left(\frac{l_{\mathrm{n}}}{k_{\mathrm{n}} A_{\mathrm{n}}} + \frac{l_{\mathrm{p}}}{k_{\mathrm{p}} A_{\mathrm{p}}}\right) + R_{\mathrm{ic}}, \tag{16}$$

The length and the effective cross-sectional area of the thermo-element are represented by l and A (where $l = l_{\mathrm{n}} = l_{\mathrm{p}}$ and $A = A_{\mathrm{n}} = A_{\mathrm{p}}$), respectively. The effective area of the thermo-element is given as

$$A_{\mathrm{p}} = A_{\mathrm{n}} = f\, A_{\mathrm{cr}}, \tag{17}$$

where A_{cr} is the cross-sectional area of the ceramic plate and it is taken to be equal to the area of the CPV cell (i.e., $A_{\mathrm{cr}} = A_{\mathrm{cell}}$). γ_{ic} and R_{ic} are the electrical and thermal resistances of the interconnecting metal strip, respectively. The area of interconnect is defined as the cross-section area of the thermo-element plus the area covered by the pitch of the thermo-element. It is related to the fill factor f as:

$$A_{\mathrm{ic}} = \frac{B\sqrt{f}}{2}\left(b\sqrt{f} + \sqrt{B}\right), \tag{18}$$

where b and B represent the width of the thermo-elements (TE) and TEG module, respectively.

The power generated by the TEG can be expressed in terms of the electrical current I_{TE} flowing through the TE and the external load resistance or, alternatively, as the difference between the absorbed heat at the hot junction and the heat loss in the cold junction as

$$\dot{W}_{\mathrm{TEG}} = I_{\mathrm{TE}}^{2}\gamma_{\mathrm{L}} = \dot{Q}_{\mathrm{h}} - \dot{Q}_{\mathrm{c}} \,. \tag{19}$$

By substituting Eq. (11) into Eq. (19), the power from the TEG is obtained as:

$$\dot{W}_{\mathrm{TEG}} = \frac{s^{2}\left(T_{\mathrm{h}} - T_{\mathrm{c}}\right)^{2}}{\left(\gamma_{\mathrm{TE}} + \gamma_{\mathrm{L}}\right)^{2}}\gamma_{\mathrm{L}} \,. \tag{20}$$

For a given TEG operating at fixed junction (hot and cold) temperatures, the maximum power is reached when the corresponding current satisfies the condition ($\gamma_{\mathrm{L}} = \gamma_{\mathrm{TE}}$). This condition is obtained by differentiating Eq. (20) with respect to the electrical current and equating it to zero. Therefore, the maximum power output becomes:

$$\dot{W}_{\mathrm{TEG,max}} = \frac{s^{2}\left(T_{\mathrm{h}} - T_{\mathrm{c}}\right)^{2}}{4\gamma_{\mathrm{TE}}} \,. \tag{21}$$

The efficiency of the thermoelectric generator can be obtained from:

$$\eta_{\mathrm{TEG}} = \frac{\dot{W}_{\mathrm{TEG}}}{\dot{Q}_{\mathrm{h}}} = \frac{s l_{\mathrm{TE}} T_{\mathrm{h}} - I_{\mathrm{TE}}^{2}\gamma_{\mathrm{TE}}}{s l_{\mathrm{TE}} T_{\mathrm{h}} - \frac{I_{\mathrm{TE}}^{2}\gamma_{\mathrm{TE}}}{2} + \frac{\left(T_{\mathrm{h}} - T_{\mathrm{c}}\right)}{R_{\mathrm{TE}}}} \,. \tag{22}$$

The energy balance equation between the cold side of the thermoelectric generator and the cooling system is expressed as:

$$\dot{Q}_{\mathrm{c}} = \frac{T_{\mathrm{c}} - T_{\mathrm{hs}}}{R_{\mathrm{cr}} + R_{\mathrm{hs}}} \,. \tag{23}$$

Finally, the efficiency of the coupled CPV-TEG system is given as:

$$\eta_{\mathrm{CPV\text{-}TEG}} = \frac{\dot{W}_{\mathrm{cell}} + \dot{W}_{\mathrm{TEG}}}{CGA_{\mathrm{cell}}\eta_{\mathrm{opt}}} \,, \tag{24}$$

where $\dot{W}_{\mathrm{cell}}$ is the output electrical power by the CPV cell and can be determined from:

$$\dot{W}_{\mathrm{cell}} = CGA_{\mathrm{cell}}\eta_{\mathrm{opt}}\eta_{\mathrm{cell}} \,. \tag{25}$$

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Biographical Sketches

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