Photovoltaic-thermoelectric hybrid systems: A general optimization methodology

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The present work outlines a general optimization methodology for hybrid systems consisting of photovoltaic (PV) and thermoelectric (TE) modules. Exemplarily, hybrid systems with hydrogenated microcrystalline silicon, hydrogenated amorphous silicon, and bulk heterojunction polymer thin-film solar cell for different solar TE generator efficiencies are evaluated. The proposed methodology optimizes the partitioning of the solar spectrum in order to yield the maximum conversion efficiency of a PV-TE hybrid system with a solar cell operating at ambient temperature. © 2008 American Institute of Physics. [DOI: 10.1063/1.2947591]

Solar cells are one of the promising technologies to convert the incident solar radiation into electric power. Without subsidies, however, this technology is still far from being able to compete with fossil fuel based energy conversion technologies. The single junction wafer technology is limited by its relatively low efficiency and increasing wafer costs.1 In addition to continuously driving down the manufacturing cost, there are two directions to make the solar cell technology more cost effective. One employs highly efficient, yet expensive, multijunction solar cells2 that can be combined with a solar concentrator to increase the solar radiation incident on a reduced solar cell size. The other is based on thin-film technologies, either semiconductor or polymers, which leads to reduced costs, often at the expense of efficiency.3–5 On the other hand, solar energy converters using a high temperature stage such as thermophotovoltaic6 or thermophotonic7 and the concept of a coupled thermal and photovoltaic (PV) converter8 have promise for high efficiencies.

Furthermore, thermoelectric (TE) material as alternative solid state power generation material has drawn increasing interest. The use of nanostructures to control the TE transport properties for improving the electron energy carrying capability and reducing the thermal conductivity emerged over the last ten years as a very promising approach for realizing highly efficient TE devices.9–12 Due to this recent and rapid progress in the field of thermoelectrics, the concept of a coupled thermal and PV converter was taken up by Vorobiev et al.13 Two stacked PV-TE hybrid system designs are discussed in more detail. In one design the solar cell is mounted on top of a concentrator which concentrates the solar radiation transmitted by the solar cell on the TE module. In the other design, the solar cell is placed directly on the TE module below the concentrator and runs at elevated temperatures. In both cases, the ideal solar cell and TE generator efficiencies are used to estimate the hybrid system conversion efficiency the spectral response of the solar cell is not included in the modeling.

Here we propose a general optimization scheme that can be applied to hybrid systems using different solar cells operating at ambient temperature and different solar TE generator (TEG) designs in order to realize the full potential embedded in such PV-TE hybrid systems. In our approach, the spectral conversion efficiency of the solar cell is determined from experimental data. Both modules of the hybrid system have to be optimized for the incident radiation power obtained from this simulation. Alternatively, the incident radiation can be adjusted by means of concentration. Using this general principle, we have analyzed the performance of several example PV-TE hybrid systems.

The general strategy of such hybrid systems is to partition the broad solar spectrum into three segments, as illustrated in Fig. 1, for an optimized hybrid system with a hydrogenated microcrystalline silicon thin-film solar cell (mc-Si:H) (Ref. 14) and solar TEG with a given efficiency. One radiation segment, in which the solar cell spectral efficiency (to be discussed in detail later), is larger than that of the solar TEG efficiency, is directed to the solar cell, as shown in Fig. 2. The photons in the other two segments are directed toward the TEG which features constant photon absorption and conversion ability in the whole solar spectrum. The correspond-

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FIG. 1. Segmentation of AM1.5G spectrum in three regions for a mc-Si:H solar cell and solar TEG with 4% efficiency. Normalized accumulated radiation power. Pie chart: converted power fraction of each module.

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The EQE is an indicator of solar cells for how efficiently incident photons are converted into electrons that contribute to the cell current.\textsuperscript{16} The EQE is illustrated in Fig. 2 as well as the obtained spectral conversion efficiencies for the mc-Si:H, a hydrogenated amorphous silicon thin-film (a-Si:H),\textsuperscript{17} and a bulk heterojunction polymer thin-film solar cell (polymer).\textsuperscript{18} The total solar cell efficiency can be estimated by multiplying the spectral efficiency with the spectral incident power of the AM1.5G spectrum and integrating over all wavelengths. The obtained total cell efficiency yields 9.09\%, 9.4\%, and 3.4\% for the mc-Si:H, a-Si:H, and for the polymer solar cell, respectively. The simulated efficiencies are consistent with the reported experimental values of about 9.5\% for the silicon cells and 3.5\% for the polymer cell. However, the small discrepancies might come from the difference between the used AM1.5G spectrum and the spectrum of the artificial light source used for the solar cell experiments. Also shown in Fig. 2 are two horizontal lines corresponding to assumed solar TEG efficiencies. The ideal TEG efficiency is dependent on the hot side temperature, the cold side temperature, and on the figure of merit of the TE material according to\textsuperscript{19}

\[
\eta_{\text{TE}} = (1 - T_c/T_h) \cdot \sqrt[3]{1 + ZT/(1 + ZT + T_c/T_h)},
\]

where \( ZT \) is the average over the operational temperature range.

The maximum PV-TE hybrid system conversion efficiency \( \eta_{\text{max}} \) can be calculated with the following equation:

\[
\eta_{\text{PV,TE}} = \frac{P_{\text{PV}}}{P_{\text{ph}}} = \frac{I_{sc,\lambda} \cdot V_{oc} \cdot FF}{P_{\text{ph},\lambda}} = \frac{\text{EQE} \cdot V_{oc} \cdot FF}{h \nu_{ph}}.
\] (1)

In order to realize the full potential of the hybrid system, the optimum cutoff wavelengths \( \lambda_{c,1} \) and \( \lambda_{c,2} \), which appropriately partition the AM1.5G spectrum must be determined. The cutoff wavelengths can be obtained from the intersections of spectral efficiency characteristics of the solar cell and the solar TEG (Fig. 2). The spectral conversion efficiency \( \eta_{\text{PV,TE}} \) is defined in Eq. (1) as the ratio between the spectral output power \( P_{\lambda} \) and the incident photon power \( P_{\text{ph},\lambda} \), where \( P_{\lambda} \) is the product of the spectral short circuit current \( I_{sc,\lambda} \) with the open circuit voltage \( V_{oc} \) and the fill factor \( FF \) of the solar cell. From the relation between the external quantum efficiency (EQE) and the spectral short circuit current\textsuperscript{15} the spectral efficiency of a solar cell can be expressed in terms of the EQE, electric charge \( q \), \( V_{oc} \), FF, the photon energy \( h \nu_{ph} \).

\[
\eta_{\text{PV,TE}} = \frac{\int_{\lambda_{c,1}}^{\lambda_{c,2}} \eta_{\text{TE}} \cdot P_{s,\lambda} d\lambda + \int_{\lambda_{c,1}}^{\lambda_{c,2}} \eta_{\text{PV,TE}} \cdot P_{s,\lambda} d\lambda + \int_{\lambda_{c,1}}^{1250 \text{ nm}} \eta_{\text{TE}} \cdot P_{s,\lambda} d\lambda}{\int_{\lambda_{c,1}}^{\lambda_{c,2}} P_{s,\lambda} d\lambda}.
\] (2)

The summation of the terms in the numerator yields the output power of the hybrid system which is normalized to the total incident radiation power. \( P_{s,\lambda} \) represents the spectral AM1.5G radiation power. \( \eta_{\text{TE}} \) and \( \eta_{\text{PV,TE}} \) are the spectral efficiencies of the solar TEG, the solar cell.

In Table I the hybrid system simulation results for the mc-Si:H, a-Si:H and polymer thin-film solar cell combined with an solar TEG efficiency of 4\% and 8\% are listed, respectively. The optimum cutoff wavelengths of the long wavelength segments vary significantly for different solar cells in comparison to a weak dependence on the solar TEG efficiency. However, the maximum hybrid system efficiency shows a strong dependence on both the spectral efficiency of the solar cells and the solar TEG efficiency. The two bottom rows give the power fractions of the AM1.5G spectrum that are converted by the individual modules. The numbers in brackets indicate the short wavelength (s), respectively, long wavelength (l) portion converted by the solar TEG. The power fraction for the solar cells shrinks with increasing solar TEG efficiency and is greater for solar cells with a broad
EQE. The power fraction of the short wavelength segment directed to the solar TEG is negligibly small compared to the other two segments, suggesting in practical systems that only spectrum partitioning in two regions is needed.

The greatest efficiency gain is observed for the polymer thin-film solar cell of 1.66 (2.44). However, the efficiency of the polymer solar cell of 3.4% is relatively low due to the poor spectral efficiency, as shown in Fig. 2. The hybrid system with the a-Si:H solar cell promises a larger efficiency gain than what can be expected from the combination of the mc-Si:H solar cell with the solar TEG. With improvements in TE materials, the efficiency of TEG devices should increase. The efficiency trend as well as the resulting performance gain of the three simulated hybrid systems for increasing solar TEG efficiency is illustrated in Fig. 3. The solid lines correspond to the resulting hybrid system efficiencies (left) axis and the dashed lines represent the expected performance gain from the combination of a solar cell with the solar TEG (right) axis, relative to pure solar PV. Also plotted is a dot and dash line at 45, representing the efficiency of a pure solar TEG module. The hybrid system efficiency must lie significantly above this line in order to justify the combination of a PV with a TE module. For the hybrid system with the polymer cell, the expected performance gain diminishes with increasing solar TEG efficiency. Of course, cost analysis is necessary in the final decision on whether the hybrid system should be used or not.

In conclusion, we developed an optimization method for hybrid systems with solar cells operating at low temperature combined with a solar TEG. It gives the guideline for the combination of PV and solar TEG modules in the most efficient way to realize the full potential of such hybrid systems. Depending on the solar TEG efficiency and the considered solar cell, the short wavelength region which should be directed to the solar TEG is usually only a small portion of the total AM1.5G spectrum. This gives reason to segment the spectrum in only two regions which makes the design of the spectrum partition element simpler without significant efficiency reduction.

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### Table I. Comparison of simulation results for considered PV-TE hybrid systems.

<table>
<thead>
<tr>
<th>ηTE</th>
<th>mc-Si:H TF solar cell</th>
<th>a-Si:H TF solar cell</th>
<th>Polymer TF solar cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>ηTE</td>
<td>4%</td>
<td>8%</td>
<td>4%</td>
</tr>
<tr>
<td>λ₁ₐ</td>
<td>349 nm</td>
<td>393.5 nm</td>
<td>374 nm</td>
</tr>
<tr>
<td>λ₂ₐ</td>
<td>793 nm</td>
<td>875 nm</td>
<td>745 nm</td>
</tr>
<tr>
<td>η₁ₚ</td>
<td>10.13%</td>
<td>11.45%</td>
<td>11.24%</td>
</tr>
<tr>
<td>η₂ₚ</td>
<td>1.11</td>
<td>1.26</td>
<td>1.20</td>
</tr>
<tr>
<td>η₁ₚ/η₁ₚ</td>
<td>1.35%</td>
<td>4.13%</td>
<td>2.83%</td>
</tr>
<tr>
<td>η₂ₚ%</td>
<td>(28.55%)</td>
<td>(32.98%)</td>
<td>(46.14%)</td>
</tr>
</tbody>
</table>

\[ \text{PV fraction} = 69.32\% \quad \text{TEG fraction} = 29.90\% \]

\[ \text{PV fraction} = 62.11\% \quad \text{TEG fraction} = 37.11\% \]

\[ \text{PV fraction} = 50.25\% \quad \text{TEG fraction} = 48.97\% \]

\[ \text{PV fraction} = 47.32\% \quad \text{TEG fraction} = 59.77\% \]

\[ \text{PV fraction} = 39.45\% \quad \text{TEG fraction} = 73.98\% \]

\[ \text{PV fraction} = 25.24\% \quad \text{TEG fraction} = 73.98\% \]

\[ \text{PV fraction} = 24.00\% \quad \text{TEG fraction} = 76.00\% \]

\[ \text{PV fraction} = 11.45\% \quad \text{TEG fraction} = 88.55\% \]

\[ \text{PV fraction} = 0.00\% \quad \text{TEG fraction} = 100.00\% \]

![FIG. 3. Hybrid system efficiencies (solid lines) and relative gain in conversion efficiency (dashed lines) as a function of solar TEG efficiency for a-Si:H (▲), mc-Si:H (■), and polymer (●) thin-film solar cell. The dot and dash line represents the solar TEG efficiency only.](image-url)