Combination Solar Photovoltaic Heat Engine Energy Converter

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A combination solar photovoltaic heat engine energy converter is proposed. Such a system is suitable for either terrestrial or space power applications. The combination system has a higher efficiency than either the photovoltaic array or the heat engine alone can attain. Advantages in concentrator and radiator area and receiver mass of the photovoltaic heat engine system over a heat-engine-only system are estimated. The critical problem for the proposed converter is the necessity for high-temperature photovoltaic array operation. Estimates of the required photovoltaic temperature are presented.

Nomenclature

A_c = concentrator collection area, m^2
A_h = effective heat-transfer area of PV array, m^2
A_{PV} = active photovoltaic area, m^2
A_{RAD} = radiator area, m^2
A_{REC} = aperture area of receiver, m^2
A_s = structural area in PV array, m^2
A_T = total area of PV array, $A_{PV}+A_s$, m^2
a = ratio of A_h to A_T
C = concentrator specific area, m^2/kW
C_p = specific heat of working fluid at PV array, J/kg K
f_{PV} = fraction of active area in PV array, A_{PV}/A_T
h = heat-transfer coefficient between PV array and working fluid, $W/m^2 \cdot K$
K = heat-transfer parameter for PV array [Eqs. (C6) and (C9)], K
M = mass, kg
m = specific mass, kg/kW
P = power, W
p_{SUN} = solar flux (1.35 kW/m^2 at Earth orbit), kW/m^2
r = specific area of radiator, m^2/kW
T = temperature, K
ΔT = temperature rise between working fluid and PV array, $T_{PV}-T_B$
t_{SH} = time system in shade
t_{SUN} = time system in sunlight
u = heat-transfer parameter for PV array [Eq. (C7)], $1/K$
α = absorptivity of PV array
α_{BAT} = specific energy density of electrical energy storage system, kW·h/kg
β_{REC} = specific mass of receiver, kg/kW
Γ_{BAT} = parameter that compares electrical energy storage efficiency to thermal energy storage efficiency [Eq. (B18)]
γ_{BAT} = parameter that determines effectiveness of electrical energy storage [Eq. (17)]
ϵ = emissivity
η = efficiency
μ = time parameter [Eq. (B19)]
ρ = reflectivity of PV array
σ = Stefan-Boltzmann constant, 5.67×10^{-8} $W/m^2 \cdot K^4$
τ = transmittance of PV array

Subscripts

B = working fluid location at entrance to PV array
BB = input to heat engine
BAT = electrical energy storage system
C = concentrator
EL = electrical power output
HE = heat engine
in = input power
PV = photovoltaic array
REC = receiver
REJ = heat leaving PV array to working fluid of system
st = stored energy or power
0 = heat-engine-only system

Superscripts

$(\ )'$ = PV portion or PVHE system
$(\ )''$ = electrical energy or power supplied to load from PV portion of PVHE system

Introduction

INPUT energy to an energy conversion system is usually in the form of heat. The performance of the conversion system is then determined by classical thermodynamics, Carnot efficiency being the limit of performance. However, in a solar-driven system, the input energy is in the form of light. By using a receiver that takes advantage of the quantum nature of light, it is possible to attain a higher overall efficiency than would be possible with a system that uses a receiver to convert light to heat for use in a heat engine. The obvious candidate for a wavelength-dependent receiver is a photovoltaic (PV) cell, which is a receiver and converter combined. However, the PV cell converts only part of the solar spectrum to electrical energy. As a result, its efficiency based on the entire solar spectrum is low. If only solar energy greater than the bandgap energy is incident on the PV cell, the efficiency can be much higher. A system that splits the spectrum so that part can be used efficiently by a PV cell and the remaining portion converted to heat for use in a heat engine will theoretically result in a higher overall system efficiency than a system that uses the entire spectrum in only a heat engine or a PV array.

Photovoltaic systems that split the solar spectrum in order to obtain better performance have been considered.[1-4] Multiple cells with different energy bandgaps are used in these systems. Each cell is designed to have maximum response to a different portion of the solar spectrum. Two approaches have been considered. The first attempts to construct a

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multiple-bandgap cell as a single structure. The other uses separate PV cells and splits the solar spectrum with beam splitters,[2] prisms,[3] or diffraction gratings.[4] Early studies[3,4] using prisms or diffraction gratings showed no improvements in performance when all of the optical losses were considered. However, the latter study, using highly efficient beam splitters,[2] predicts an efficiency greater than 30% for a three-cell system.

The proposed energy converter combines a PV array and a heat engine to produce a higher combined power system efficiency than either can attain alone. For the proposed PV/heat engine (PVHE) converter to be successful, the PV array must absorb photons in the energy range that can be efficiently converted to electrical energy. Photons outside this energy range must be either transmitted or reflected to a receiver that converts the photon energy to thermal energy. The thermal energy is then converted to electrical energy by a heat engine.

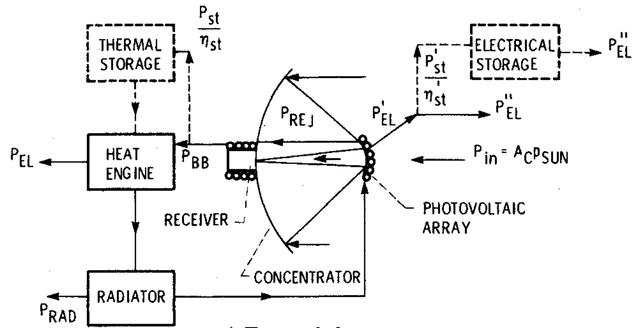
Improved efficiency means that a smaller, less massive energy converter can be constructed. As a result, the PVHE converter is applicable to both terrestrial and space applications. Besides the efficiency, size, and mass improvements, the PVHE converter offers another important advantage. Since the PVHE converter consists of two independent energy converters, there is system redundancy. Should one of these energy converters fail, the other converter is available to produce a portion of the electrical power requirement. This system redundancy is inherent in the PVHE system. In order to provide system redundancy with a single-energy-converter system, an additional energy converter is necessary.

The proposed PVHE converters are described in the next section, followed by an analysis of the performance of the PVHE systems. Analytical expressions for the system performance are derived. The increase in efficiency of the PVHE systems over a heat-engine-only system is calculated. Also, a comparison is made between the solar collector area, radiator areas, and receiver masses for the PVHE systems and the heat-engine-only system. After that, the power split between the PV array and the heat engine is discussed, followed by an estimate of the operating temperature of the PV array. The major problem of the PVHE systems is that the PV portion of the system must operate at higher temperatures than conventional PV arrays.

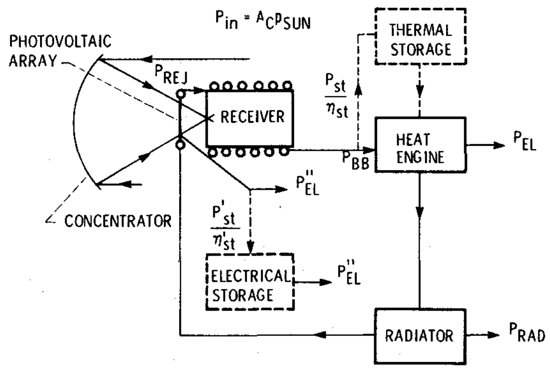
Description of Solar PV/Heat Engine (PVHE) Systems

There are two possible configurations for the PVHE converter, both of which are shown in Fig. 1. In the transmitting system (Fig. 1a), the PV array absorbs the portion of the spectrum that can be efficiently converted to electrical energy p'_{EL} and transmits the remaining spectrum to the receiver. In the reflecting system (Fig. 1b), the PV array reflects the unused portion of the spectrum to the receiver. The photon flux incident on the receiver is converted to thermal energy. This energy, together with the thermal waste energy of the PV array P_{REJ} is then used by the heat engine to produce electrical energy P_{EL}. The waste heat P_{RAD} must then be rejected. For a space system, the waste heat must be rejected as thermal radiation.

For a space system in Earth orbit, the storage of energy is necessary during the portion of the orbit that is in sunlight. This energy is then used during the shade portion of the orbit. In Fig. 1, both electrical and thermal energy storage are indicated. In the next section, it will be shown that using all thermal energy storage leads to the highest performance. For electrical energy storage, a portion P'_{st}/η'_{st} of the total PV array power output P'_{EL} is stored and the remaining portion P''_{EL} is supplied to the load. A portion P_{st}/η_{st} of the thermal power output of the receiver during the sun portion of the orbit is stored for use by the heat engine during the shade portion of the orbit.



a) Transmitting system.



b) Reflecting system.

Fig. 1 Schematic diagrams of photovoltaic heat engine (PVHE) systems.

As will be shown, the efficiency relations for the two systems in Fig. 1 have similar forms. Therefore, efficiency, mass, and area improvements compared to a heat-engine-only converter will be similar for each system. Different design advantages and disadvantages exist between the systems, however. For the transmitting system, there are no difficult optical design problems for the PV array; whereas the reflecting system requires an accurate optical surface on the PV array in order to direct the input light flux to the receiver. It may also be possible to design the PV array in the transmitting system as a lens to focus the input light on the receiver aperture. The radiation emission losses of the receiver would thus be reduced.

The principal design difficulty for the PV array of the transmitting system is providing for the removal of the waste heat. If cooling coils are used within the array, then the light intercepted by the coils cannot be utilized by the PV array. It would be desirable to locate the cooling coils on the outer edge of the PV array to eliminate the light-blockage problem. The reflecting system does not have this problem. The back side of the PV array can be covered with cooling coils without causing any performance loss.

Since the reflecting system is a Cassegrainian design, it has structural advantages over the transmitting system. With the concentrator and receiver located next to each other, pointing of the system is simpler than for the transmitting system.

Although there are design advantages and disadvantages for both systems, the major problem for either system is the necessity that the PV array operate at high temperature. In order to make the PVHE concept feasible, a high-temperature PV cell must be developed. In a later section, the temperature requirements for the PV array will be discussed.

Three different configurations of the PVHE converter are of interest: 1) a system without energy storage, 2) a system with all-thermal energy storage, and 3) a system with both electrical and thermal energy storage. As already mentioned, it will be shown that the all-thermal-energy storage system has better performance than the combination electrical and thermal energy storage system. However, it also requires that the heat engine operate at two power levels. It must produce electrical power P_{EL} during sun time and electrical power $P_{EL}+P'_{EL}$ during shade time. This is an added complication that the system using both electrical and thermal energy storage does not have. In that case, the heat engine operates at the same power level P_{EL} all the time.

Performance Analysis

In order to determine the performance of the PVHE systems, a model for the optical properties of the PV array is required. It is assumed that the PV array is made up of active PV cells separated by structural material. One purpose of the structural materials is to provide cooling of the PV cells. It is assumed that the PV cells and the structural material can be characterized by uniform total optical properties (transmittance, absorptivity, and reflectivity). Then, if the PV array is illuminated by a uniform flux, the optical properties of the array are just averages of the PV cell and structural material optical properties. In Appendix A, expressions for the PV array transmittance τ, reflectivity ρ, and absorptivity α are presented. Also in Appendix A, the electrical power output P'_{EL} is given in terms of the PV efficiency η_{PV} and the fraction of active PV area f_{PV}. [See Eq. (A8)]. Also, for conservation of energy, Eq. (A13) in Appendix A holds for the PV array. Using the described optical properties and electrical efficiency, the performance of the PV array can be calculated.

Efficiency

Of primary importance for an energy converter is the overall efficiency η_T. In Appendix B, the derivation of η_T for the various PVHE systems is presented. The form of the expression for η_T is the same for both the transmitting and reflecting systems. For a transmitting system that uses both electrical and thermal energy storage, see Eq. (B17) in Appendix B.

Appearing in the expression are the concentrator efficiency η_c, the PV efficiency η_{PV}, the heat engine efficiency η_{HE}, the receiver efficiency η_{REC}, the fraction of active PV area f_{PV} [Eq. (A9)], the PV array transmittance τ, reflectivity ρ, and the parameters Γ_{BAT} [Eq. (B18)] and μ[Eq. (B19)]. The important approximations made in obtaining η_T are that: 1) the radiation loss from the PV array is negligible compared to the radiator loss from the receiver and 2) the radiation from the receiver impinging on the PV array is neglected.

Equation (B17) is for a transmitting system. By interchanging τ and ρ, the results for a reflecting system are obtained [Eq. (B20)]. The parameter Γ_{BAT} [Eq. (B18)] compares the electrical storage efficiency to the thermal storage efficiency. If the electrical energy storage efficiency $\eta_{BAT}\eta_{st}$ (where η_{BAT} is the efficiency, the stored energy is delivered to the load, and η'_{st} is the efficiency where the energy from the PV is stored) is greater than the thermal energy storage efficiency η_{st}, then $\Gamma_{BAT}>1$. The more likely situation is that $\eta_{BAT}\eta'_{st}<\eta_{st}$. As a result, $\Gamma_{BAT}<1$. If all of the thermal energy storage is used, then $\Gamma_{BAT}\rightarrow 1$ and the efficiency for the reflecting system is given by Eq. (B26) in Appendix B. For the heat engine of the all-thermal-energy storage system to operate with a positive output P_{EL} during sun time, the condition given by Eq. (B24) must be satisfied.

Since $\eta_{BAT}\eta'_{st}<\eta_{st}$ is expected, the all-thermal-energy storage system will be more efficient than the combination electrical and thermal energy storage system. However, as mentioned earlier, the all-thermal-energy storage system requires that the heat engine be capable of operating at two power levels. During sun time, the heat engine operates with electrical output P_{EL}. However, during shade time, the heat engine must deliver the full electrical load $P_{EL}+P'_{EL}$. Also, as will be discussed later, there will be no radiator area savings for the PVHE all-thermal-energy storage system compared to a heat engine system.

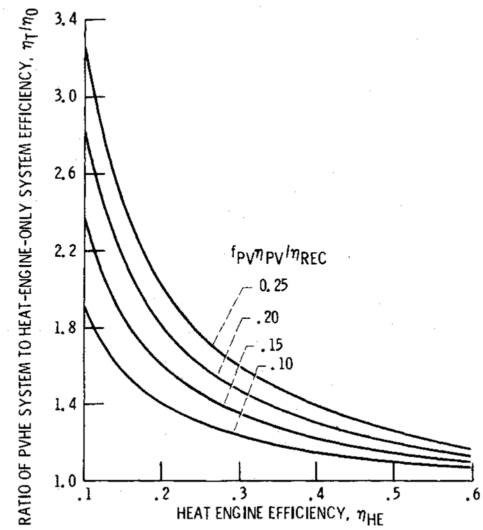


Fig. 2 Efficiency improvement for PVHE system over heat engine with both systems operating with same concentrator efficiency η_C and receiver efficiency η_{REC}. Also, for reflecting PVHE system $1/\eta_{REC}(1-\tau-\rho)+\rho=1$, and for transmitting PVHE system $1/\eta_{REC}(1-\tau-\rho)+\tau=1$. For combination electrical and thermal energy storage $\Gamma_{BAT}=1$.

Equations (B17) and (B26) are efficiency results for systems that include energy storage. To obtain results for the case of no energy storage, merely set $t_{sh}=0$ (t_{sh} is the shade time). In that case, Eq. (B26) becomes

$$\eta_T=\eta_c\{f_{PV}\eta_{PV}(1-\eta_{HE})+\eta_{HE}[1-\rho(1-\eta_{REC})-\tau]\}\quad \text{reflecting system with no energy storage} \tag{1}$$

To obtain results for a transmitting system, merely interchange ρ and τ in Eq. (1).

Now, consider a comparison between the PVHE system and a heat-engine-only system. To obtain the efficiency η_0 of the heat-engine-only system, let $f_{PV}\eta_{PV}\rightarrow 10$, $\rho\rightarrow 1$, and $\tau\rightarrow 0$ in Eq. (B26); thus,

$$\eta_0=\mu\eta_c\eta_{REC}\eta_{HE}\quad \text{heat-engine-only system with thermal energy storage} \tag{2}$$

Therefore, from Eqs. (B26) and (2), for the case where μ, η_{REC}, η_c, and η_{HE} are the same for both the PVHE and heat-engine-only systems, the following is obtained:

$$\frac{\eta_T}{\eta_0}=\frac{f_{PV}\eta_{PV}}{\eta_{REC}}\left(\frac{1}{\eta_{HE}}-1\right)+\frac{1}{\eta_{REC}}(1-\tau-\rho)+\rho \tag{3}$$

This result applies for a reflecting system; however, by interchanging τ and ρ, results for a transmitting system are obtained. Also, it applies for either the case of all-thermal-energy storage or no-energy storage. The result for the case when both electrical and thermal energy storage are used is [from Eq. (B17) and (2)]:

$$\frac{\eta_T}{\eta_0}=\frac{f_{PV}\eta_{PV}}{\eta_{REC}}\left(\frac{\Gamma_{BAT}}{\eta_{HE}}-1\right)+\frac{1}{\eta_{REC}}(1-\tau-\rho)+\tau \tag{4}$$

This result is for a transmitting system, but results for a reflecting system are obtained if τ and ρ are interchanged.

For an efficient reflecting system, it is required that $\tau\rightarrow 0$; whereas, for an efficient transmitting system, $\rho\rightarrow 0$ is desired. For these conditions, since $0\leq\rho\leq 1$ and $0\leq\tau\leq 1$, the terms $1/\eta_{REC}(1-\tau-\rho)+\rho$ and $1/\eta_{REC}(1-\tau-\rho)+\tau$ in Eqs. (3) and (4) will always be greater than 1. As a result, $\eta_T/\eta_0>1$ for the thermal storage system [Eq. (3)]. Also, if $\Gamma_{BAT}/\eta_{HE}>1$,

$\eta_T/\eta_0 > 1$ for the combination thermal and electrical energy storage system. In Fig. 2, η_T/η_0 is plotted as a function of η_{HE} for the all-thermal-energy storage system. This result applies to both the transmitting and reflecting systems, for $1/\eta_{REC}(1-\tau-\rho)+\tau=1$ in the transmitting case and $1/\eta_{REC}(1-\tau-\rho)+\rho=1$ in the reflecting case. Since these terms are greater than 1, as discussed above, the results in Fig. 2 are conservative. For an actual case, the curves in Fig. 2 will be shifted upward. It is expected that $0.1 \leq f_{PV}\eta_{PV}/\eta_{REC} \leq 0.25$. As a result, η_T/η_0 is plotted as a function of η_{HE} for $f_{PV}\eta_{PV}/\eta_{REC}=0.1$, 0.15, 0.2, and 0.25.

From Fig. 2, it can be seen that, for a heat engine with $\eta_{HE}\approx 0.2$ (organic Rankine cycle), the PVHE system using all-thermal-energy storage shows an improvement in efficiency $1.4 \leq \eta_T/\eta_0 \leq 2$ over the heat-engine-only system. For $\eta_{HE}\approx 0.3$ (Brayton cycle), $1.2 \leq \eta_T/\eta_0 \leq 1.6$ and, for $\eta_{HE}\approx 0.4$ (Stirling cycle), $1.1 \leq \eta_T/\eta_0 \leq 1.4$. Therefore, the PVHE system offers significant improvement in efficiency over a heat-engine-only system. An estimate of area and mass savings for the PVHE system will be made in the next section.

Concentrator Area Savings

Consider the concentrator area savings for the PVHE system compared to a heat-engine-only system. If A_c is the concentrator area and p_{SUN} is the solar flux (kW/m^2), then the input power to the system is that indicated by Eq. (B2). The concentrator specific area of the PVHE system C_T is then defined as

$$C_T = A_c/P_T \tag{5}$$

where P_T is total power output ($=P_{EL}+P'_{EL}$ or $P_{EL}+P''_{EL}$). Therefore, using the definition of overall efficiency η_T [see Eqs. (B1) and (B2)] in Eq. (5) results in

$$C_T = \frac{t_{SH}+t_{SUN}}{t_{SUN}}\,\frac{1}{\eta_T p_{SUN}} \tag{6}$$

This same result applies for a heat-engine-only system.

$$C_0 = \frac{t_{SH}+t_{SUN}}{t_{SUN}}\,\frac{1}{\eta_0 p_{SUN}} \tag{7}$$

Therefore, dividing Eq. (6) by Eq. (7) yields

$$C_T/C_0 = \eta_0/\eta_T \tag{8}$$

Thus, the reduction in concentrator specific area is inversely proportional to the efficiency improvement. Figure 3 shows C_T/C_0 as a function of the heat engine efficiency η_{HE} for the case of thermal energy storage with the same conditions as Fig. 2. As can be seen, significant reductions in concentrator specific area are possible with the PVHE system.

Heat Engine Radiator Area Savings

For a PVHE system that uses only thermal energy storage, there will be no radiator area savings compared to a heat-engine-only system. The heat engine in the thermal energy storage PVHE system must produce full-load power during the shade time. Therefore, it requires the same radiator area as the heat-engine-only system when both systems have the same power output.

If both electrical and thermal energy storage are used, then the PVHE system will require less radiator area than a heat-engine-only system. The radiator area is determined by the amount of power that must be radiated P_{RAD}, as

$$P_{RAD} = P_{BB} - P_{EL} = \sigma\epsilon_{RAD}A_{RAD}(T_{RAD}^4 - T_\infty^4) \tag{9}$$

where P_{BB} is the power input to the heat engine, σ the Stefan-Boltzmann constant, ϵ_{RAD} the radiator emissivity, A_{RAD} the radiator area, T_{RAD} the radiator temperature, and T_∞ the sink temperature. Using the definitions of η_{HE} [Eq. (B15)] and P_{BB} [Eq. (B16)] in Eq. (9) yields the following result for the radiator specific area r_T:

$$r_T = \frac{A_{RAD}}{P_{EL}+P''_{EL}} = \frac{\mu n_c(1-\eta_{HE})}{\sigma\epsilon_{RAD}(T_{RAD}^4 - T_\infty^4)\eta_T}(\alpha+\tau\eta_{REC}) \tag{10}$$

This expression applies to a transmitting system. However, if τ is replaced by ρ, the result applies to a reflecting system.

Now consider a heat-engine-only system. In this case, the radiator specific area r_0 can be obtained from Eq. (10) by setting $\eta_T=\eta_0$, $\alpha=0$, and $\tau=1$, as

$$r_0 = \frac{\mu\eta_c(1-\eta_{HE})}{\sigma\epsilon_{RAD}(T_{RAD}^4 - T_\infty^4)\eta_{HE}} \tag{11}$$

With the PVHE system and the heat engine system both operating with the same T_{RAD}, T_∞, ϵ_{RAD}, and η_{HE}, the following is obtained from Eqs. (10) and (11):

$$\frac{r_T}{r_0} = \frac{C_T}{C_0}\left(\frac{\alpha}{\eta_{REC}}+\tau\right) \tag{12}$$

In obtaining this result for the transmitting system, Eqs. (2) and (8) have been used. For a reflecting system, replace τ by ρ in Eq. (12).

As will be discussed later, in order to have T_{PV} (PV array temperature) as low as possible, the absorptivity α must be small. Therefore, the term in parentheses in Eq. (12) will be less than one. In that case, the reduction in r_T/r_0 will be greater than the concentrator area reduction C_T/C_0. It should be remembered, however, that for a combination electrical and thermal energy storage system, the concentrator area reduction C_T/C_0 will not be as small as for the all-thermal-energy storage system. The larger η_T/η_0 [Eq. (3)] possible for the all-thermal-energy storage system means that C_T/C_0 [Eq. (8)] for the all-thermal-energy storage system will be less than C_T/C_0 for the combination energy storage system.

Thus far, only the heat engine radiator has been considered. If the electrical energy storage efficiencies η'_{st} and η_{BAT} are not large, then the radiator area necessary to reject the waste heat from the electrical energy storage system may be significant. Therefore, in a more complete study of the PVHE system than this investigation, the radiator area necessary for the electrical storage system will have to be considered.

Receiver Mass Savings

The receiver (including thermal storage material) is generally the most massive component in a heat engine system. To

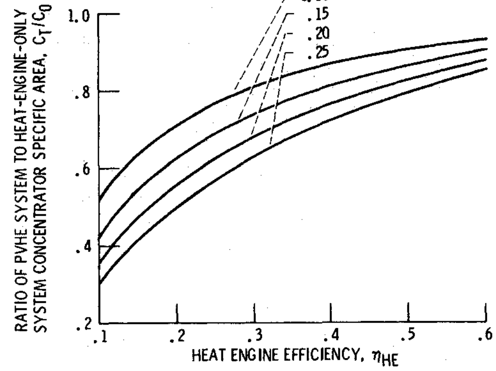


Fig. 3 Concentrator area savings for PVHE system over heat engine with same conditions as Fig. 2.

estimate the receiver mass, assume the mass M_{REC} is proportional to the input power,

$$M_{REC} = \beta_{REC} P_{REC} \tag{13}$$

where β_{REC} (kg/kW) is a constant and P_{REC} the total receiver power input. If a combination electrical and thermal energy storage system is used, then the electrical energy storage system mass must be included if receiver mass savings over a heat-engine-only system are being calculated. Assume the electrical energy storage system mass M_{BAT} is proportional to the amount of stored energy E'_{st},

$$M_{BAT} = \frac{E'_{st}}{\alpha_{BAT}} = \frac{t_{SUN} P'_{st}}{\alpha_{BAT}} \tag{14}$$

where α_{BAT} (kW·h/kg) is the specific energy density of the electrical energy storage system.

Referring to Fig. 1a for a transmitting PVHE system, the total receiver power input P_{REC} is the sum of the solar flux $\tau\eta_c P_{in}$ and the waste heat of the PV array $\alpha\eta_c P_{in}$,

$$P_{REC} = \eta_c P_{in}(\tau + \alpha) \tag{15}$$

For a reflecting system, replace τ by ρ. Now, use Eqs. (B12) and (B13) to obtain P'_{st} and Eq. (15) for P_{REC}. As a result, the specific mass m_T can be determined,

$$m_T \equiv \frac{M_{REC} + M_{BAT}}{P_{EL} + P''_{EL}} = \frac{t_{SH} + t_{SUN}}{t_{SUN}} \frac{\eta_C}{\eta_T} \beta_{REC} [1 + f_{PV}\eta_{PV}(\gamma_{BAT} - 1) - \rho] \quad \text{electrical and thermal energy storage} \tag{16}$$

In obtaining Eq. (16), Eqs. (B1) and (A13) were used. Equation (16) is for a transmitting system. For a reflecting system, replace ρ by τ. The parameter γ_{BAT} is defined as follows:

$$\gamma_{BAT} = \frac{t_{SUN} t_{SH} \eta'_{st}}{\beta_{REC} \alpha_{BAT} (t_{SUN} \eta'_{st} \eta_{BAT} + t_{SH})} \tag{17}$$

This parameter determines the effectiveness of electrical energy storage. The smaller γ_{BAT} is, the more effective electrical energy storage becomes. Small γ_{BAT} results from large energy density β_{BAT} and small shade time t_{SH}.

For all thermal energy storage, the result for m_T is obtained from Eq. (16) by letting $\gamma_{BAT} = 0$

$$m_T = \frac{t_{SH} + t_{SUN}}{t_{SUN}} \frac{\eta_c}{\eta_T} \beta_{REC}(1 - f_{PV}\eta_{PV} - \rho) \quad \text{all thermal energy storage} \tag{18}$$

This result is for a transmitting system. For a reflecting system, replace ρ by τ. Comparing Eqs. (16) and (18), it can be seen that the all-thermal-energy storage system yields the smallest m_T.

In order to compare the PVHE system with a heat engine system, an expression for the heat engine receiver specific mass m_0 is required. This can be obtained by setting $f_{PV}\eta_{PV} = 0$, $\rho = 0$, and $\eta_T = \eta_0$ in Eq. (18).

$$m_0 = \frac{t_{SH} + t_{SUN}}{t_{SUN}} \frac{\eta_c}{\eta_0} \beta_{REC} \quad \text{heat engine system} \tag{19}$$

Now, assume β_{REC} is the same for both the PVHE system and the heat engine system. Therefore, dividing Eq. (18) by Eq. (19) yields

$$\frac{m_T}{m_0} = \frac{C_T}{C_0}(1 - f_{PV}\eta_{PV} - \rho) \tag{20}$$

In obtaining Eq. (20), $\eta_0/\eta_T = C_T/C_0$ was used. To obtain the result for a reflecting system, replace ρ by τ. Since the term in parentheses is less than one, the receiver mass ratio m_T/m_0 will be smaller than the concentrator area ratio C_T/C_0. Figure 4 shows m_T/m_0 for $f_{PV}\eta_{PV}/\eta_{REC} = 0.15$ as a function of η_{HE} for $1 - f_{PV}\eta_{PV} - \rho = 0.7$ and 0.8 and $1/\eta_{REC}$ $(1 - \tau - \rho) + \tau = 1$ for a transmitting system. Figure 4 also applies to a reflecting system for the indicated valves of $1 - f_{PV}\eta_{PV} - \tau$ and $1/\eta_{REC}$ $(1 - \tau - \rho) + \rho = 1$. As already discussed, using $1/\eta_{REC}$ $(1 - \tau - \rho) + \tau = 1$ or $1/\eta_{REC}$ $(1 - \tau - \rho) + \rho = 1$ yields conservative results for C_T/C_0 $(= \eta_0/\eta_T)$. Therefore, the results in Fig. 4 should be conservative.

The receiver mass savings for the all-thermal-energy storage PVHE system shown in Fig. 4 are large. For a combination electrical and thermal energy storage system, the savings will not be as great. In that case, results for m_T/m_0 are sensitive to the parameters Γ_{BAT} [determines η_T/η_0, Eq. (4)] and γ_{BAT}. Evaluating Γ_{BAT} and γ_{BAT} requires choosing a specific electrical energy storage system. As optimistic estimates for Γ_{BAT} and γ_{BAT}, consider the sodium/sulfur battery system used in Ref. 5. In that case, $\alpha_{BAT} = 0.077$ kW·h/kg, $\eta'_{st} = 0.8$, and $\eta_{BAT} \approx 1$. Also, from Ref. 5 for Rankine heat engine system, $\eta_{st} = 0.95$ and $\beta_{REC} \approx 5$ kg/kW. Therefore, for a system in low Earth orbit with $t_{SUN} = 1$ h and $t_{SH} = 38$ min, Eqs. (17) and (B18) yield $\Gamma_{BAT} = 0.92$ and $\Gamma_{BAT} = 0.93$. Since the energy density α_{BAT} used for the sodium/sulfur battery is more than a factor of 10 larger than α_{BAT} for a presently available nickel/cadmium system, the $\Gamma_{BAT} = 0.92$ should be considered an optimistic result. If an electrical energy storage system with $\Gamma_{BAT} \leq 1$ and $\Gamma_{BAT} \approx 1$ is available, then m_T/m_0 for the electrical and thermal energy storage system will be nearly the same as m_T/m_0 for the all-thermal-energy storage system.

Performance Comparison of All Thermal Storage and Combination Electrical and Thermal Storage PVHE Systems

The preceding analysis has shown that significant efficiency (η_T/η_0) gains result for PVHE systems compared to heat-engine-only systems. All-thermal-energy storage yields the largest gain. However, for an efficient $(\Gamma_{BAT} \geq 0.9)$ electrical energy storage system, the combination electrical and thermal storage system will have nearly the same η_T/η_0. The same conclusion applies for concentrator area savings $(C_T/C_0 = \eta_0/\eta_T)$. Only the combination energy storage system produces a heat engine radiator area reduction (r_T/r_0). As Eq. (12) indicates, the radiator area savings will be even greater than the concentration area savings for the combination storage system. As Eq. (20) shows, the receiver mass reduction m_T/m_0 for the thermal energy storage system will be greater than the concentrator area savings. For the combination energy storage system [Eq. (16)], the mass savings depends on the parameters Γ_{BAT} and γ_{BAT}, as just discussed.

It is beyond the scope of this study to determine if all-thermal-energy storage or combination thermal and electrical energy storage is the better system. However, if an efficient $(\gamma_{BAT} \geq 0.9)$ high-energy density $(\gamma_{BAT} \leq 1)$ electrical energy storage system is available, then the combination storage system will have performance (η_T/η_0), concentrator area savings (C_T/C_0), and receiver mass savings (m_T/m_0) nearly equal to the all thermal storage system. Therefore, the added heat engine radiator area savings makes the combination energy storage system more attractive. The combination system also offers two other benefits. First, the heat engine is required to operate at only a single power level. As already mentioned for the all thermal storage system, the heat engine must operate at two power levels. Second, the use of electrical energy storage gives redundancy to the system. Both thermal and electrical energy are available.

Power Split

The PVHE systems consist of two power sources: the PV array and the heat engine. In the design of a PVHE system, it is necessary to know what fraction of the output power is produced by each of these sources. First, consider the PVHE system that uses a combination of electrical and thermal energy storage. The ratio of the heat engine output P_{EL} to the total PV array output P'_{EL} $(=P''_{EL}+P'_{st}/\eta_{st})$ is obtained by using Eqs. (B4) and (B16), as

$$\frac{P_{EL}}{P'_{EL}}=\frac{t_{SUN}}{t_{SUN}+t_{SH}/\eta_{ST}}(\alpha+\tau\eta_{REC})\frac{\eta_{HE}}{f_{PV}\eta_{PV}} \tag{21}$$

This result is for a transmitting system. Replacing τ by ρ yields the result for a reflecting system.

For an all-thermal-energy storage system, the heat engine must be sized to produce the total load $P_{EL}+P'_{EL}$. In this case, using Eqs. (B1), (B4), and (B23) yields

$$\frac{P_{EL}+P'_{EL}}{P'_{EL}}=\frac{t_{SUN}}{t_{SUN}+t_{SH}/\eta_{st}}\left[(\alpha+\tau\eta_{REC})\frac{\eta_{HE}}{f_{PV}\eta_{PV}}+1\right] \tag{22}$$

This is for a transmitting system. If τ is replaced by ρ, results for a reflecting system are obtained.

In Fig. 5, the results from Eqs. (21) and (22) are shown as a function of the efficiency ratio $\eta_{HE}/f_{PV}\eta_{PV}$ for $\alpha+\tau\eta_{REC}$ or $\alpha+\rho\eta_{REC}=0.4$, 0.6, and 0.8. For combination thermal and electrical energy storage, the total PV array output will be larger than the heat engine output, except for large $\eta_{HE}/f_{PV}\eta_{PV}$ (>2); whereas for all-thermal-energy storage, the heat engine output will be larger than the PV array output, except for small $\eta_{HE}/f_{PV}\eta_{PV}$ (<1). It may be desirable to have nearly the same power level PV array and heat engine. Then, for small $\eta_{HE}/f_{PV}\eta_{PV}$, all thermal energy storage is applicable, while for large $\eta_{HE}/f_{PV}\eta_{PV}$, a combination of thermal and electrical storage is applicable. If the shade time t_{SH} is reduced (higher orbit), all of the curves in Fig. 5 will shift upward. The heat engine output fraction will increase.

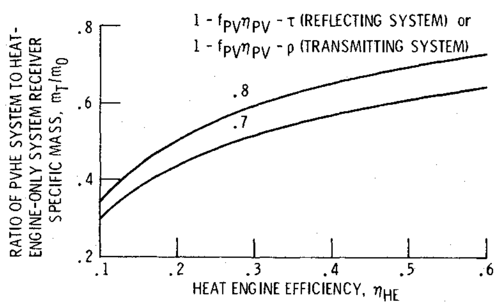


Fig. 4 Receiver mass savings for PVHE system over heat engine with same conditions as Fig. 2. In addition, $f_{PV}\eta_{PV}/\eta_{REC}=0.15$. For combination thermal and electrical energy storage $\Gamma_{BAT}=1$ and $\Gamma_{BAT}=0$.

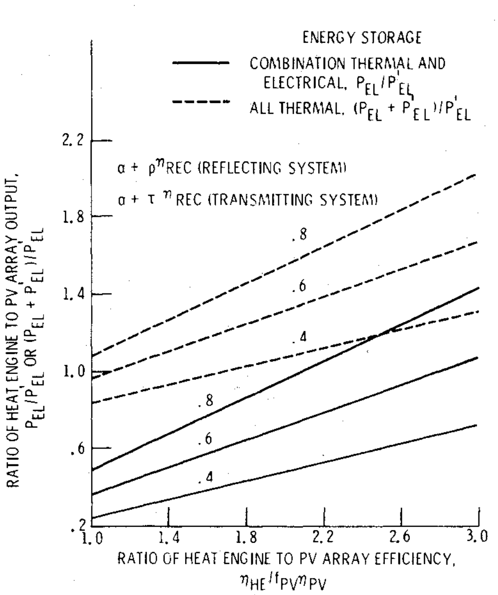


Fig. 5 Power split for PVHE systems in low Earth orbit $t_{SUN}=1$ h, $t_{SH}=38$ min.

Photovoltaic Array Temperature Requirements

As already mentioned, the major problem for the PVHE systems is the requirement for high-temperature operation of the PV array. The PV array temperature T_{PV} must be greater than the bottom temperature of the heat engine radiator T_B in order for the PV array to reject its waste heat $(\alpha\eta_c P_{in})$ to the heat engine working fluid.

To estimate T_{PV}, the simple heat-transfer analysis presented in Appendix C was carried out. The assumptions made in that analysis are the following: 1) PV array temperature T_{PV} is constant, 2) heat-transfer coefficient h is constant, 3) specific heat C_p of working fluid flowing over PV array is constant, and 4) radiation from PV array is neglected. Using these assumptions, Eq. (C5) was obtained. The parameter K has the dimension of temperature. For a transmitting, all-thermal-energy storage system, it is given by Eq. (C6), and by Eq. (C9) for a transmitting combination thermal and electrical storage system. Results for K in the case of a reflecting system are obtained by replacing τ by ρ in Eqs. (C6) and (C9). The parameter u, which has the dimension of $1/K$, is given by Eq. (C7).

The parameter K is determined by the PV array optical properties, the ratio of shade time to sun time t_{SH}/t_{SUN}, and a characteristic temperature for the heat engine. This characteristic temperature is $\Delta H/C_p$, where ΔH is the enthalpy change of the working fluid across the receiver in a heat-engine-only system and C_P is the specific heat of the working fluid at the PV array. The parameter u is determined by the ratio of total PV array area to concentrator area A_T/A_c and the heat-transfer coefficient h. Thus, u can be varied by changing the location of the PV array with respect to the concentrator (varying A_T/A_c). For the smallest ΔT, Eq. (C5) shows that $Ku \gg 1$ is desired. In that case,

$$\lim_{Ku\to\infty}\Delta T=\alpha K \tag{23}$$

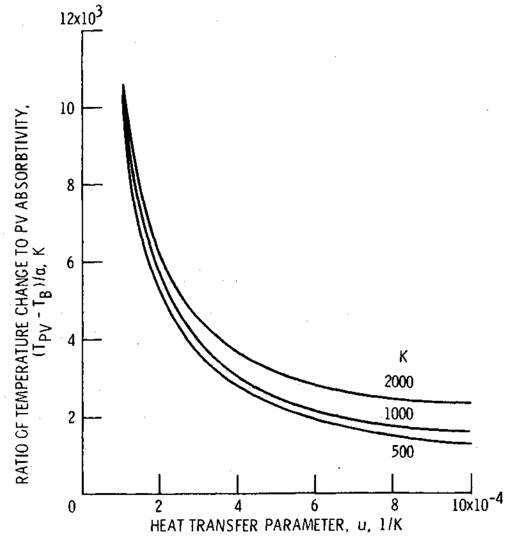


Fig. 6 Difference between PV array temperature and temperature of cycle fluid entering PV array divided by PV array absorptivity as a function of heat-transfer parameter u [Eq. (C7)]. For a transmitting PVHE system $\alpha+\tau\eta_{REC}=0.7$; for a reflecting PVHE system $\alpha+\rho\eta_{REC}=0.7$.

In Fig. 6, the quantity $\Delta T/\alpha$ [Eq. (C5)] is shown as a function of u for several values of K. The values of K were chosen to be representative of heat engines being studied for the space station. Two of these are the toluene Rankine[6] heat engine ($\Delta H/C_p \approx 280$ K, $f_{PV}\eta_{PV}/\eta_{HE} \approx 1/2$) and the He–Xe Brayton[6] heat engine ($\Delta H/C_p \approx 180$ K, $f_{PV}\eta_{PV}/\eta_{HE} \approx 1/3$). Also, a low Earth orbit ($t_{SH}/t_{SUN}\eta_{st} = 2/3$) and $\alpha + \tau\eta_{REC} = 0.7$ for a transmitting system or $\alpha + \rho\eta_{REC} = 0.7$ for a reflecting system were used in calculating K. For the Brayton cycle under these conditions, $K \approx 430$ K for a combination electrical and thermal storage system and $K \approx 630$ K for an all-thermal-energy storage system. For the Rankine cycle, $K \approx 670$ K for a combination electrical and thermal storage system and $K \approx 980$ K for an all-thermal-energy storage system.

As Fig. 6 indicates, even for large $u(uK > 1)$, the temperature rises, $\Delta T/\alpha$, 500 K. This result emphasizes the importance of maintaining low absorptivity α for the PV array. If $\alpha < 0.3$, then, except for the Rankine all thermal storage system, the temperature rise $\Delta T < 200$ K should be attainable. For $\alpha > 0.3$, however, temperature rises greater than 200 K will result. In this case, the temperature of the PV array T_{PV} may be too high for PV conversion. For the toluene Rankine heat engine,[6] the bottom temperature of the cycle is $T_B \approx 340$ K. The He-Xe Brayton heat engine system[6] has a bottom temperature ≈ 290 K. However, the working fluid enters the compressor rather than the heat source at this temperature. Therefore, heat addition occurs after the compressor. At this point, the temperature[6] is $T_B \approx 380$ K. Therefore, for $\Delta T \approx 200$ K, the PV array temperature would be $T_{PV} \approx 540$–580 K. Operation of gallium arsenide (GaAs) PV cells at temperatures >600 K is discussed in Ref. 1. The efficiency η_{PV} decreases with increasing temperature.[1,7] However, the decrease in efficiency can be partially balanced by operating at high intensity, as in the proposed PVHE systems. Efficiency increases with intensity[1,7] up to about 1000 p_{SUN}. Two possible candidates for a high-temperature, high-intensity PV cell are the vertical multijunction (VMJ) cell[8-10] and the interdigitated back contact PV cell considered for thermophotovoltaic conversion.[11,12]

The condition for low $\Delta T/\alpha$ is that $Ku > 1$. Using $Ku \approx 1$, an estimate of the concentrator to PV array area ratio A_c/A_T can be obtained. From Eq. (C7), the following result for A_c/A_T is obtained:

$$\frac{A_c}{A_T} = \frac{a}{u} \frac{h}{\eta_c p_{SUN}} \tag{24}$$

Assume $h \approx 0.1$ kW/m$^2\cdot$K, $\eta_c \approx 0.9$, and $a \approx 1$. Therefore, for $p_{SUN} = 1.35$ kW/m^2, $A_c/A_T \approx 0.08/u$. Therefore, if $500 \le K \le 1000$ K and $u \approx 1/K$,

$$40 \le A_c/A_T \le 80 \tag{25}$$

Thus, it is expected that concentration ratios of 10 to 100 will be required for the PVHE system. To have as simple a system as possible with minimum mass means that A_c/A_T should be as large as possible.

The above discussion points out the necessity for small PV array absorptivity α in order to maintain the PV array temperature T_{PV} within the operating temperature range of PV cells. It would, therefore, be desirable to reduce ΔT. A reduction in the magnitude of the parameter K will result in a proportional decrease in ΔT. A possible method for reducing K is to reduce ΔH [Eq. (C6) or (C9)]. This can be done by increasing the mass flow $\dot{m}$ [Eq. (C4)]. However, such a change will also alter the heat engine cycle performance.

Conclusions

Both transmitting and reflecting PVHE systems result in significant efficiency improvements over a heat-engine-only system ($1.1 \le \eta_T/\eta_0 \le 2$). Choosing between the reflecting and transmitting systems depends on several things. One important consideration is the PV array absorptivity α. In order to maintain the PV array temperature T_{PV} as low as possible, α must be small ($\alpha < 0.3$). Also, for the transmitting system, the reflectivity ρ must be small. Whereas for the reflecting system, the transmittance τ must be small. Research on the reflecting and transmitting PV arrays is necessary to determine which can best meet these requirements. However, the critical issue for both PV array types is that operation at high temperature ($T_{PV} \approx 600$ K) is required. A suitable PV cell structure that will meet the high-temperature requirements is the essential ingredient for a successful PVHE system.

Two forms of energy storage are possible for the PVHE systems. An all-thermal-energy storage system yields a larger efficiency than the combination electrical and thermal energy storage system. However, if an efficient electrical energy storage method is possible ($\Gamma_{BAT} \ge 0.9$), then the efficiency advantage of the all thermal system is negligible.

As a result of improved efficiency over a heat engine ($\eta_T/\eta_0 > 1$), the PVHE systems will have corresponding savings in concentrator area ($C_T/C_0 = \eta_0/\eta_T$.) The heat engine of an all-thermal-energy storage PVHE system must be sized to produce the full electrical load during shade time. Therefore, no heat engine radiator savings are possible with that system. However, the combination energy storage PVHE system will result in heat engine radiator savings greater than concentrator area savings. Receiver mass savings for the all thermal storage system will be greater than the combination storage system. However, for an efficient ($\Gamma_{BAT} \ge 0.9$), high-energy density ($\gamma_{BAT} \le 1$) electrical energy storage system, the combination system will produce nearly the same mass savings. A more detailed study is necessary to determine if all thermal or combination electrical and thermal storage is more desirable.

Besides efficiency, area, and mass savings, the PVHE systems have a degree of inherent system redundancy. If the PV array should fail without blocking the input solar flux, the heat engine part of the system would still be able to provide part of the electrical load. Similarly, if the heat engine should fail without interrupting the flow of the system fluid, the PV array would be able to produce part of the electrical load.

Appendix A: Characterization of PV Array

The photovoltaic array is assumed to consist of PV cells with interspersed structural materials. See Fig. A1.

The total structural area is A_s and the total photovoltaic area A_{PV}. Assume that a uniform light flux p_c (W/m^2) is incident on the array. If the total transmittance of the structural material is τ_s and the total transmittance of the PV material is τ_{PV}, then the total transmitted power is

$$P_{TR} = (\tau_{PV}A_{PV} + \tau_s A_s)p_c = \frac{\tau_{PV}A_{PV} + \tau_s A_s}{A_{PV} + A_s} P_c \tag{A1}$$

The total input power P_c is

$$P_{in} = (A_{PV} + A_s)p_c \tag{A2}$$

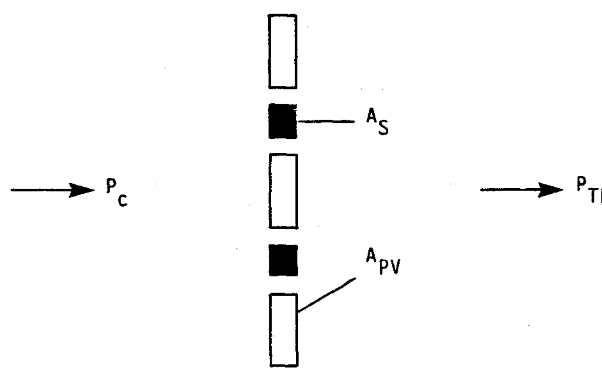


Fig. A1 Photovoltaic array.

Therefore, using Eq. (A2) in Eq. (A1) yields

$$\tau \equiv \frac{P_{\text{TR}}}{P_c} = \frac{\tau_{\text{PV}} A_{\text{PV}} + \tau_s A_s}{A_T} \tag{A3}$$

where τ is the total transmittance of the PV array and

$$A_T = A_{\text{PV}} + A_s \tag{A4}$$

Similar expressions are obtained for the total absorptivity α and reflectivity ρ,

$$\alpha \equiv \frac{\alpha_{\text{PV}} A_{\text{PV}} + \alpha_s A_s}{A_T} \tag{A5}$$

$$\rho \equiv \frac{\rho_{\text{PV}} A_{\text{PV}} + \rho_s A_s}{A_T} \tag{A6}$$

The electrical power output of the PV array P'_{EL} is the following:

$$P'_{\text{EL}} = \eta_{\text{PV}} A_{\text{PV}} p_{\text{SUN}} \tag{A7}$$

where η_{PV} is the total efficiency of the photovoltaic cell. Equation (A7) can be rewritten as follows:

$$P'_{\text{EL}} = f_{\text{PV}} \eta_{\text{PV}} P_c \tag{A8}$$

The quantity f_{PV} is the fraction of active PV area.

$$f_{PV} \equiv A_{\text{PV}} / A_T \tag{A9}$$

For conservation of energy, the following relation must be satisfied:

$$P_c = P_{\text{TR}} + P_A + P_R + P'_{\text{EL}} \tag{A10}$$

where P_A is the light power absorbed that is converted to heat,

$$P_A = \alpha P_c \tag{A11}$$

and P_R is the reflected light power,

$$P_R = \rho P_c \tag{A12}$$

Using Eqs. (A1), (A8), (A11), and (A12) in Eq. (A10) yields

$$\alpha + \rho + \tau + f_{\text{PV}} \eta_{\text{PV}} = 1 \tag{A13}$$

Appendix B: Efficiency of PVHE Systems

Define the efficiency of a PVHE system that includes energy storage as

$$\eta_T = \frac{(t_{\text{SH}} + t_{\text{SUN}})(P_{\text{EL}} + P''_{\text{EL}})}{t_{\text{SUN}} P_{\text{in}}} \tag{B1}$$

The numerator of Eq. (B1) is the total electrical energy produced and the denominator is the total input energy. Referring to Fig. 1, P_{EL} is the electrical power output of the heat engine and P''_{EL} the electrical power output of the PV array that goes to the load when electrical energy storage is used. If only thermal energy storage is used, then $P''_{\text{EL}} = P'_{\text{EL}}$, where P'_{EL} is the total power output of the PV array. The quantity t_{SUN} is the time the system is in the sun and t_{SH} is the time the system is in the shade. For a system in low Earth orbit, $t_{\text{SH}} + t_{\text{SUN}} = t_{\text{OR}}$, the orbit period. The efficiency for a system that does not include energy storage can be obtained by letting $t_{\text{SH}} = 0$.

Two energy storage methods are to be considered: either all-thermal-energy storage or a combination of both thermal and

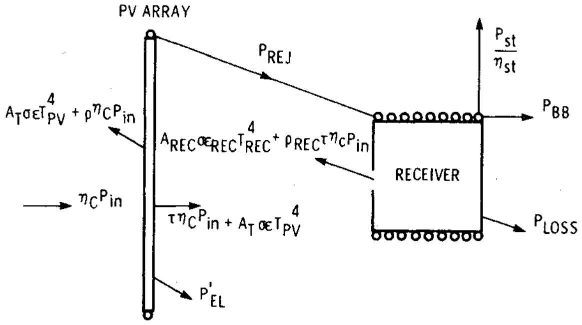


Fig. B1 Energy balance for PV array and receiver.

electrical energy storage. In order to calculate the efficiency for either of these systems, it is necessary to know the input power to the heat engine P_{BB}. In order to determine P_{BB}, energy balances for the PV array and receiver must be satisfied. Consider the transmitting PVHE system shown in Fig. B1. The power input reaching the PV array is $\eta_c P_{\text{in}}$, where η_c is the concentrator efficiency and P_{in} is total solar power collected,

$$P_{\text{in}} = A_c p_{\text{SUN}} \tag{B2}$$

For Earth orbit, $p_{\text{SUN}} = 1.35$ kW/m^2 and A_c is the concentrator area. An energy balance on the PV array yields

$$P_{\text{REJ}} + P'_{\text{EL}} = \eta_c P_{\text{in}} - \tau \eta_c P_{\text{in}} - \rho \eta_c P_{\text{in}} - 2 A_T \sigma \epsilon T_{\text{PV}}^4 \tag{B3}$$

In obtaining Eq. (B3), the fraction of radiation leaving the receiver that reaches the PV array has been neglected. This is a conservative approximation since a fraction of this energy can be absorbed and used by the heat engine. Also, it was assumed that the PV array is at a constant temperature T_{PV}, with an emissivity ϵ for both sides of the array. Since,

$$P'_{\text{EL}} = f_{\text{PV}} \eta_{\text{PV}} \eta_c P_{\text{in}} \tag{B4}$$

Equation (B3) can be rewritten as

$$P_{\text{REJ}} = \alpha \eta_c P_{\text{in}} - 2 A_T \sigma \epsilon T_{\text{PV}}^4 \tag{B5}$$

where Eq. (A13) has been used.

Now carry out an energy balance on the receiver,

$$P_{BB} = P_{\text{REJ}} + \tau \eta_c P_{\text{in}} - \tau \rho_{\text{REC}} \eta_c P_{\text{in}} - A_{\text{REC}} \sigma \epsilon_{\text{REC}} T_{\text{REC}}^4 - P_{\text{LOSS}} - \frac{P_{\text{st}}}{\eta_{\text{st}}} \tag{B6}$$

The term P_{LOSS} includes all the receiver thermal losses except the radiation loss and $P_{\text{st}}/\eta_{\text{st}}$ is the thermal power that is being stored. In obtaining Eq. (B6), it has been assumed that all the solar flux that passes through the PV array $\tau \eta_c P_{\text{in}}$ reaches the receiver. Also, any radiation from the PV array that reaches the receiver has been neglected. Now substitute Eq. (B6) in Eq. (B5),

$$P_{BB} = \eta_c P_{\text{in}} [\alpha + \tau(1 - \rho_{\text{REC}})] - A_{\text{REC}} \sigma \epsilon_{\text{REC}} T_{\text{REC}}^4 \left(1 + \frac{2 A_T \epsilon T_{\text{PV}}^4}{A_{\text{REC}} \epsilon_{\text{REC}} T_{\text{REC}}^4}\right) - P_{\text{LOSS}} - \frac{P_{\text{st}}}{\eta_{\text{st}}} \tag{B7}$$

Since the receiver emissivity ϵ_{REC} and temperature T_{REC} will be larger than the PV array emissivity ϵ and temperature T_{PV}, the PV radiation loss will be neglected compared to the receiver radiation loss. Thus, Eq. (B7) becomes

$$P_{BB}=\eta_c P_{\rm in}(\alpha+\tau\eta_{\rm REC})-\frac{P_{\rm st}}{\eta_{\rm st}}\qquad \text{transmitting system} \tag{B8}$$

In obtaining (Eq. B8), the definition of the receiver efficiency $\eta_{\rm REC}$ has been used,

$$\eta_{\rm REC}\equiv 1-\frac{\text{power losses}}{\text{power input}}$$

$$=1-\frac{A_{\rm REC}\sigma\epsilon_{\rm REC}T^4_{\rm REC}+P_{\rm LOSS}+\rho_{\rm REC}\tau\eta_c P_{\rm in}}{\tau\eta_c P_{\rm in}} \tag{B9}$$

Equation (B8) was obtained for a transmitting PVHE system. With the same approximations, the result for a reflecting system is

$$P_{BB}=\eta_c P_{\rm in}(\alpha+\rho\eta_{\rm REC})-\frac{P_{\rm st}}{\eta_{\rm st}}\qquad \text{reflecting system} \tag{B10}$$

Now that expressions for P_{BB} have been obtained, results for the efficiency can be calculated. First, consider the case where a combination of thermal $P_{\rm st}$ and electrical $P'_{\rm st}$ energy storage is used. During sun time, part of the output of the PV array $P'_{\rm EL}$ goes to the load $P''_{\rm EL}$ and part to electrical storage (batteries, fuel cells, etc.) $P'_{\rm st}/\eta'_{\rm st}$ where $\eta'_{\rm st}$ is the storage efficiency,

$$P'_{\rm EL}=P''_{\rm EL}+P'_{\rm st}/\eta'_{\rm st} \tag{B11}$$

The energy stored during sun time $t_{\rm SUN}P'_{\rm st}$ is used during shade time to supply the energy $t_{\rm SH}P''_{\rm EL}$. Therefore,

$$\eta_{\rm BAT}t_{\rm SUN}P'_{\rm st}=t_{\rm SH}P''_{\rm EL} \tag{B12}$$

where $\eta_{\rm BAT}$ is the efficiency of the electrical storage system in supplying power $P''_{\rm EL}$. Substitute for $P'_{\rm st}$ in Eq. (B11) by using Eq. (B12),

$$P''_{\rm EL}=\frac{\eta_c f_{\rm PV}\eta_{\rm PV}}{1+t_{\rm SH}/(t_{\rm SUN}\eta_{\rm BAT}\eta'_{\rm st})}P_{\rm in} \tag{B13}$$

In obtaining Eq. (B13), Eq. (B4) was used for $P'_{\rm EL}$. The thermal energy stored during sun time $t_{\rm SUN}P_{\rm st}$ is used during shade time to supply the energy $t_{\rm SH}P_{\rm EL}$. Therefore,

$$\eta_{\rm HE}t_{\rm SUN}P_{\rm st}=t_{\rm SH}P_{\rm EL} \tag{B14}$$

where $\eta_{\rm HE}$ is the efficiency of the heat engine. Since

$$P_{\rm EL}=\eta_{\rm HE}P_{\rm BB} \tag{B15}$$

Eqs. (B8) and (B14) yield

$$P_{\rm EL}=\eta_{\rm HE}P_{BB}=\frac{\eta_c\eta_{\rm HE}}{1+(t_{\rm SH}/t_{\rm SUN}\eta_{\rm st})}(\alpha+\tau\eta_{\rm REC})P_{\rm in} \tag{B16}$$

If Eqs. (B13) and (B16) are now substituted in Eq. (B1), the following result is obtained for the efficiency:

$$\eta_T=\mu\eta_c\{f_{PV}\eta_{PV}(\Gamma_{\rm BAT}-\eta_{\rm HE})+\eta_{\rm HE}[1-\tau(1-\eta_{\rm REC})-\rho]\}\qquad \text{transmitting system with thermal and electrical energy storage} \tag{B17}$$

In obtaining Eq. (B17), Eq. (A13) was used. The quantities $\Gamma_{\rm BAT}$ and μ are defined as follows:

$$\Gamma_{\rm BAT}\equiv\frac{1+(t_{\rm SH}/t_{\rm SUN}\eta_{\rm st})}{1+(t_{SH}/t_{\rm SUN}\eta_{\rm BAT}\eta'_{\rm st})} \tag{B18}$$

$$\mu\equiv\frac{t_{\rm SUN}+t_{\rm SH}}{t_{\rm SUN}+(t_{\rm SH}/\eta_{\rm st})} \tag{B19}$$

The efficiency of a reflecting system can be obtained in a similar manner. The result is

$$\eta_T=\mu\eta_c\{f_{\rm PV}\eta_{\rm PV}(\Gamma_{\rm BAT}-\eta_{\rm HE})+\eta_{\rm HE}[1-\rho(1-\eta_{\rm REC})-\tau]\}\qquad \text{reflecting system with thermal and electrical energy storage} \tag{B20}$$

Now consider a transmitting PVHE system that uses only thermal energy storage. In this case, the thermal energy stored during sun time $t_{\rm SUN}P_{\rm st}$ is used to supply the total load $P_{\rm EL}+P'_{\rm EL}$ during shade time,

$$\eta_{\rm HE}t_{\rm SUN}P_{\rm st}=t_{\rm SH}(P_{\rm EL}+P'_{\rm EL}) \tag{B21}$$

(Since no electrical power output of the PV array is being stored, $P'_{\rm EL}=P''_{\rm EL}$.) If Eq. (B4) is used in Eq. (B21), then the following results:

$$P_{\rm st}=\frac{t_{\rm SH}}{\eta_{\rm HE}t_{\rm SUN}}(P_{\rm EL}+\eta_c f_{\rm PV}\eta_{\rm PV}P_{\rm in}) \tag{B22}$$

Use Eq. (B22) in Eq. (B8) and then substitute for P_{BB} in Eq. (B15) to obtain an expression for $P_{\rm EL}$,

$$P_{\rm EL}=\eta_{\rm HE}P_{BB}=\frac{\eta_c\eta_{\rm HE}}{1+(t_{\rm SH}/t_{\rm SUN}\eta_{\rm st})}\times\left(\alpha+\tau\eta_{\rm REC}-\frac{t_{\rm SH}}{t_{\rm SUN}}\frac{f_{\rm PV}\eta_{\rm PV}}{\eta_{\rm st}\eta_{\rm HE}}\right)P_{\rm in} \tag{B23}$$

In order that $P_{\rm EL}\geq 0$, the following condition must be satisfied:

$$\alpha+\tau\eta_{\rm REC}\geq\frac{t_{\rm SH}}{t_{\rm SUN}}\frac{f_{\rm PV}\eta_{\rm PV}}{\eta_{\rm st}\eta_{\rm HE}} \tag{B24}$$

The left side of Eq. (B24) represents the fraction of power captured by the receiver and the right side the power that must be stored to make up for the PV array power not available during shade time. If Eq. (B24) is not satisfied, the all-thermal-energy storage system is not possible, since more energy is required from storage during shade time than is available. Then, using Eq. (B23) for $P_{\rm EL}$ and Eq. (B9) for $P'_{\rm EL}$, the efficiency can be obtained from Eq. (B1),

$$\eta_T=\mu\eta_c\{f_{\rm PV}\eta_{\rm PV}(1-\eta_{\rm HE})+\eta_{\rm HE}[1-\tau(1-\eta_{\rm REC})-\rho]\}\qquad \text{transmitting system with thermal energy storage only} \tag{B25}$$

A similar result is obtained for a reflecting system,

$$\eta_T = \mu\eta_c\{f_{PV}\eta_{PV}(1-\eta_{HE}) + \eta_{HE}[1-\rho(1-\eta_{REC})-\tau]\} \quad \text{reflecting system with thermal energy storage only} \tag{B26}$$

Appendix C: Photovoltaic Array Temperature

The PV array temperature T_{PV} will be determined by several parameters: the heat-transfer rate from the PV array to the heat engine working fluid h, the receiver efficiency η_{REC}, the heat engine enthalpy change ΔH, the PV array optical properties, and the concentrator to PV array area ratio A_c/A_T. To estimate T_{PV}, consider the following simplified analysis. Assume the thermal conductivity of the PV array is large enough so that the array operates at a constant temperature T_{PV}. Referring to Fig. C1, the heat absorbed by the array $\alpha\eta_c P_{in}$ must be transferred to the heat engine working fluid. Therefore, neglecting radiation from the PV array, for a steady-state condition,

$$\alpha\eta_c P_{in} = \dot{m}c_p(T_R - T_B) \tag{C1}$$

The mass flow rate $\dot{m}$ is determined by the heat engine. The temperature T_R is the temperature of the working fluid when it leaves the PV array and T_B the temperature when the fluid enters the PV array. Besides satisfying the overall energy balance given by Eq. (C1), the local energy balance determined by the heat-transfer coefficient h must be satisfied, as

$$h(T_{PV} - T)\mathrm{d}A_h = \dot{m}C_p \mathrm{d}T \tag{C2}$$

where T is the local fluid temperature, C_p the fluid specific heat, and A_h the heat transfer area. If Eq. (C2) is integrated, assuming constant h and C_p, the following is obtained:

$$\Delta T \equiv T_{PV} - T_B = \frac{\alpha\eta_c P_{in}}{\dot{m}C_p[1-\exp(-hA_h/\dot{m}C_p)]} \tag{C3}$$

In obtaining this result, Eq. (C1) was used for $T_R - T_B$. Now relate $\dot{m}$ to the power supplied by the receiver to the heat engine P_{BB},

$$\dot{m}\Delta H = P_{BB} \tag{C4}$$

where ΔH is the specific enthalpy change across the receiver and PV array. For a heat-engine-only system, ΔH is the enthalpy change across the receiver. The power P_{BB} depends on whether a combination thermal and electrical energy storage [Eq. (B16)] or an all thermal energy storage system [Eq. (B23)] is begin considered. For now, consider the all-thermal-energy storage system. Therefore, using Eq. (B23) for P_{BB} in Eq. (C4) and then substituting this result for m in Eq. (C3) yields

$$\Delta T = \alpha\left(\frac{K}{1-e^{-Ku}}\right) \tag{C5}$$

$$K = \left[\frac{1 + t_{SH}/t_{SUN}\eta_{st}}{\alpha + \tau\eta_{REC} - t_{SH}/t_{SUN}(f_{PV}/\eta_{st})(\eta_{PV}/\eta_{HE})}\right]\frac{\Delta H}{C_p} \quad K \tag{C6}$$

$$u = a\left(\frac{A_T}{A_c}\right)\frac{h}{\eta_c P_{SUN}}, \ 1/K \tag{C7}$$

In obtaining Eqs. (C5–C7), Eq. (B2) was used for P_{in} and the heat-transfer area A_h was written as a function of the total array area A_T,

$$A_h = aA_T \tag{C8}$$

where a is a constant. Since the heat-transfer area will be equal or less than the total array area, $a \leq 1$.

Equation (C6) is for an all thermal energy storage, transmitting PVHE system. For a reflecting system, replace τ by ρ. For a transmitting, combination electrical and thermal energy storage system, the following applies for K:

$$K = \frac{1 + (t_{SH}/t_{SUN}\eta_{st})}{\alpha + \tau\eta_{REC}}\frac{\Delta H}{C_p} \tag{C9}$$

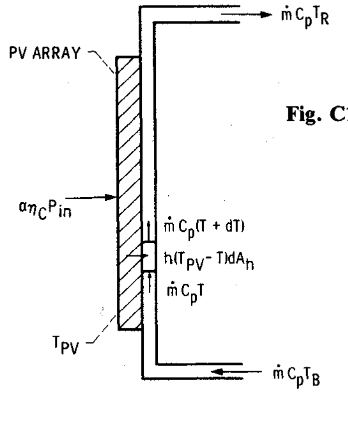


Fig. C1 Energy balance on PV array.

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