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Performance Characteristics of a Combination Solar Photovoltaic Heat Engine Energy Converter

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PERFORMANCE CHARACTERISTICS OF A COMBINATION SOLAR PHOTOVOLTAIC HEAT ENGINE ENERGY CONVERTER

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Abstract

A combination solar photovoltaic heat engine energy converter is proposed. Such a system is suitable for either terrestial 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. A mass and area comparison between the proposed Space Station organic Rankine power system and a combination PV-heat engine system is made. 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, m²

A_h effective heat transfer area of PV array, m²

A_{PV} active photovoltaic area, m²

A_{RAD} radiator area, m²

A_{REC} aperture area of receiver, m²

A_s structural area in PV array, m²

A_T total area of PV array, $A_{PV} + A_s$, m²

a ratio of A_h to A_T

B electrical storage specific mass, KG/kw

C concentrator specific area, m²/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/m²K

K heat transfer parameter for PV array (Eq. (20)), K

M mass, kg

m specific mass, kg/kW

P power, W

P_{SUN} solar flux (1.35 kW/m² at earth orbit), kW/m²

R receiver specific mass, kg/kW

r radiator specific mass, kg/kW

T temperature, K

ΔT temperature rise between working fluid and PV array, $T_{PV} - T_B$

t_{SH} time system is in shade

t_{SUN} time system is in sunlight

u heat transfer parameter for PV array (Eq. (C-7)), 1/K

α absorptivity of PV array

α_{BAT} specific energy density of electrical energy storage system, kWh/kg

β_{REC} specific mass of receiver, kg/kW

Γ_{BAT} parameter that compares electrical energy storage efficiency to thermal energy storage efficiency (Eq. (5))

γ_{BAT} parameter that determines effectiveness of electrical energy storage (Eq. (15))

ϵ emissivity

η efficiency

μ time parameter (Eq. (6))

ρ reflectivity of PV array

σ Stefan-Boltzmann constant, 5.67×10^{-8} W/m²K⁴

τ transmittance of PV array

Subscripts

B   working fluid location at entrance to PV array

BAT   electrical energy storage system

c   concentrator

EL   electrical power output

HE   heat engine

in   input power

PV   PV array

REC   receiver

REJ   heat leaving PV array to working fluid of system

st   stored energy or power

T   PVHE system

O   heat-engine-only system

Introduction

The proposed energy converter combines a PV array and a heat engine to produce a higher combined power system efficiency than either a PV array or heat engine alone can attain. Improved efficiency is achieved by splitting the solar spectrum. Part is converted by the PV array and the remaining part converted to heat for use in a heat engine. 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 approach attempts to construct a multiple-bandgap cell as a single structure. The other approach 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 the optical losses wereconsidered. However, the latter study using highly efficient beam splitters[2] predicts an efficiency greater than 30 percent for a three cell system.

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 which 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.

Description of Solar PV Heat Engine (PVHE) Systems

There are two possible configurations for the PVHE converter. Both of these configurations are shown in Fig. 1. In the transmitting system (Fig. 1(b)), 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. 1a) 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 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. For electrical energy storage a portion, P'_{st}/n'_{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}/n_{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.

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. Thus radiation emission losses of the receiver would 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 backside 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 for the PV array to 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. First of all, a system without energy storage, second a system with all thermal energy storage, and finally a system with both electrical and thermal energy storage. As shown in Ref. 5, the all thermal energy storage system has higher efficiency 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 that uses 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. In this study only the combination electrical and thermal energy storage PVHE system will be considered.

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 of the purposes 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, τ absorptivity, α, and reflectivity, ρ). 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. Also, the electrical power output, P_{EL}', of the PV array is given in terms of the power from the concentrator reaching the PV array, P_c, the PV efficiency, n_{PV}, and the fraction of active PV area, f_{PV}.

$$P_{EL}' = f_{PV} n_{PV} P_c \qquad (1)$$

Also, for conservation of energy, the following relation holds for the PV array.

$$\alpha + \rho + \tau + f_{PV} n_{PV} = 1 \qquad (2)$$

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, n_T. This efficiency is defined as follows.

$$n_T \equiv \frac{(t_{SH} + t_{SUN})(P_{EL} + P_{EL}'')}{t_{SUN} P_{in}} \qquad (3)$$

The numerator of Eq. (3) is the total electrical energy produced and the denominator is the total input energy. Where 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 earth orbit $t_{SH} + t_{sun}$ is the orbit period. In Ref. 5 the derivation of n_T for the various PVHE systems is presented. The form of the expression for n_T is the same for both the transmitting and reflecting systems. For a transmitting system that uses both electrical and thermal energy storage the overall efficiency is the following

$$n_T = \mu n_c \left\{ f_{PV} n_{PV} (\Gamma_{BAT} - n_{HE}) + n_{HE} \right. $$
$$\left. \times \left[1 - \tau (1 - n_{REC}) - \rho \right] \right\} \qquad (4)$$

Appearing in the expression are the concentrator efficiency, n_c, the PV efficiency, n_{PV}, the heat engine efficiency, n_{HE}, the receiver efficiency, n_{REC}, the fraction of active PV area, f_{PV}, the PV array transmittance, τ, and reflectivity, ρ, and the parameters, Γ_{BAT} and μ.

$$\Gamma_{BAT} \equiv \frac{1 + \dfrac{t_{SH}}{t_{SUN} n_{st}}}{1 + \dfrac{t_{SH}}{t_{SUN} n_{BAT} n_{st}}} \qquad (5)$$

$$\mu \equiv \frac{t_{SUN} + t_{SH}}{t_{SUN} + \dfrac{t_{SH}}{n_{st}}} \qquad (6)$$

The important approximations made in obtaining n_T are the following.

1. Radiation loss from PV array negligible compared to radiation loss from receiver.

2. Radiation from receiver impinging on PV array is neglected.

Equation (4) is for a transmitting system. By interchanging τ and ρ the results for a reflecting system are obtained. The parameter, Γ_{BAT}, compares the electrical storage efficiency to thermal storage efficiency. If electrical energy storage efficiency ($n_{BAT} n_{st}$ where n_{BAT} is the efficiency the stored energy is delivered to the load and n_{st} is the efficiency the energy from the PV array is stored) is greater than the thermal energy storage efficiency, n_{st}, then $\Gamma_{BAT} > 1$. The more likely situation is that $n_{BAT} n_{st} < n_{st}$. As a result $\Gamma_{BAT} < 1$.

Now consider a comparison between the PVHE system and a heat engine only system. To obtain the efficiency, n_o, of the heat engine only system let $f_{PV} n_{PV} \to 0$, $\tau \to 1$ and $\rho \to 0$ in Eq. (4).

$$n_o = \mu n_c n_{REC} n_{HE} \qquad (7)$$

Therefore, from Eqs. (4) and (7) for the case where μ, n_{REC}, n_c and n_{HE} are the same for both the PVHE and heat engine only systems the following is obtained.

$$\frac{n_T}{n_o} = \frac{f_{PV} n_{PV}}{n_{REC}} \left[\frac{\Gamma_{BAT}}{n_{HE}} - 1 \right] + \frac{1}{n_{HE}} \left[1 - \tau - \rho \right] + \tau \qquad (8)$$

This result applies for a transmitting system, but by interchanging τ and ρ results for a reflecting system are obtained.

For an efficient reflecting system it is required that $\tau \to 0$, whereas for an efficient transmitting system $\rho \to 0$ is desired. For these conditions since $0 \le \rho \le 1$ and $0 \le \tau \le 1$ the terms $1/n_{REC} (1 - \tau - \rho) + \rho$ for a reflecting system and $1/n_{REC} (1 - \tau - \rho) + \tau$ for a transmitting system will always be greater than 1. Also, if $\Gamma_{BAT}/n_{HE} > 1$, then as Eq. (8) shows, $n_T/n_o > 1$. In Fig. 2, n_T/n_o is plotted as a function of n_{HE} for the case $\Gamma_{BAT} = 1$. This result applies to both the transmitting and reflecting systems for $1/n_{REC} (1 - \tau - \rho) + \tau = 1$ in the transmitting case and $1/n_{REC} (1 - \tau - \rho) + \rho = 1$ in the reflecting case. Since these terms are greater than 1, as discussed above, and for most cases $\Gamma_{BAT} \ge 0.9$ the results in Fig. 2 should be representative of

PVHE systems. 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 $\eta_{HE} \approx 0.2$ the PVHE system shows an improvement in efficiency $1.4 \leq \eta_T/\eta_0 \leq 2$ over the heat engine only system. For $\eta_{HE} \approx 0.3$, $1.2 \leq \eta_T/\eta_0 \leq 1.6$ and for $\eta_{HE} \approx 0.4$, $1.1 \leq \eta_T/\eta_0 \leq 1.4$. Therefore, the PVHE system offers significant improvement in efficiency over a heat engine only system. In the next section an estimate of area and mass savings for the PVHE system will be made.

Concentrator area savings. The concentrator area savings for the PVHE system compared to a heat engine only system are given by the following result[5].

$$\frac{C_T}{C_0} = \frac{\eta_0}{\eta_T} \qquad (9)$$

Where $C_T = A_C/(P_{EL} + P_{EL}^*)$ is the concentrator specific area in the PVHE system and C_0 is concentrator specific area in the heat engine only system. 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 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. In Ref. 5 the following expression for the ratio of the radiator specific area, $r_T = A_{RAD}/(P_{EL} + P_{EL}^*)$, for for the PVHE system to radiator specific area r_0, for the heat engine only system is developed.

$$\frac{r_T}{r_0} = \frac{\eta_0}{\eta_T} \left[\frac{\alpha}{\eta_{REC}} + \tau \right] \qquad (10)$$

This result is for a transmitting system; replace τ by ρ to obtain the result for a reflecting system. In obtaining Eq. (10) it is assumed that both systems operate with the same radiator temperature, emissivity and heat engine efficiency. 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 brackets in Eq. (10) will be less than one. In that case the reduction in r_T/r_0 will be greater then the concentrator area reduction, C_T/C_0.

Only the heat engine radiator has been considered above. 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.

Receiver mass savings. The receiver (including thermal storage material) is one of the most massive components in a heat engine system. To estimate the receiver mass assume the mass, M_{REC}, is porportional to the input power.

$$M_{REC} = \beta_{REC}P_{REC} \qquad (11)$$

where β_{REC} (kg/kW) is a constant and P_{REC} is the total receiver power input. Using results from Ref. 5, the following is obtained for the ratio of PVHE receiver specific mass, $(R_T = M_{REC}/(P_{EL} + P_{EL}^*)$, to heat engine only receive specific mass, R_0.

$$\frac{R_T}{R_0} = \left[1 - f_{PV}\eta_{PV} - \rho \right] \frac{\eta_0}{\eta_T} \qquad (12)$$

Equation (12) applies for a transmitting PVHE system; replace ρ by τ to obtain the result for a reflecting system. In obtaining Eq. (12) it was assumed that both systems have the same η_c, t_{SUN}, t_{SH} and β_{REC}.

In the PVHE system part of the energy storage is done electrically. Therefore, to make a valid comparison of receiver mass savings between the PVHE and heat engine only systems the electrical energy storage mass must be included. Assume the electrical energy storage system mass, M_{BAT}, is proportional to the amount of stored energy, E_{st}'.

$$M_{BAT} = \frac{E_{st}'}{\alpha_{BAT}} = \frac{t_{SUN}P_{st}'}{\alpha_{BAT}} \qquad (13)$$

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

Based on the results of Ref. 5, the following is obtained.

$$\frac{B_T}{R_0} = \gamma_{BAT}f_{PV}\eta_{PV} \frac{\eta_0}{\eta_T} \qquad (14)$$

Where B_T is the electrical storage specific mass, $(M_{BAT}/(P_{EL} + P_{EL}^*))$, and the parameter, γ_{BAT}, is a measure of electrical energy storage effectiveness. The smaller γ_{BAT} is, the more effective electrical energy storage will be.

$$\gamma_{BAT} = \frac{t_{SUN}t_{SH}\eta_{st}'}{\beta_{REC}\alpha_{BAT} \left(t_{SUN}\eta_{st}\eta_{BAT} + t_{SH} \right)} \qquad (15)$$

In deriving Eq. (14) it was assumed that η_c, t_{SUN}, and t_{SH} are the same for both the PVHE and heat engine only system.

If Eqs. (12) and (14) are added the following results.

$$\frac{R_T + B_T}{R_0} = \left[1 + f_{PV}\eta_{PV} \left(\gamma_{BAT} - 1 \right) - \rho \right] \frac{\eta_0}{\eta_T} \qquad (16)$$

This result applies to a transmitting PVHE system. If ρ is replaced by τ then results for a reflecting PVHE system are obtained. As Eq. (16) shows, the receiver mass savings for the PVHE system are sensitive to the parameters γ_{BAT} and Γ_{BAT} (determines η_0/η_T, Eq. (8)). Evaluating Γ_{BAT} and γ_{BAT} requires choosing a specific electrical energy storage system. Consider three battery storage systems as being representative of the state of development of electrical storage systems. First, assume for the the presently available nickel-cadmium battery[6] that $\alpha_{BAT} \approx 0.004$ kWH/kg, $\eta_{st} \approx 0.8$, $\eta_{BAT} \approx 0.9$. Second, assume for the soon to be available nickel-hydrogen battery[6] that $\alpha_{BAT} \approx 0.0139$ kWH/kg, $\eta_{st} \approx 0.8$, $\eta_{BAT} \approx 0.9$. Finally, for a future system consider

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the sodium-sulfur battery[7] with $\alpha_{BAT} \approx 0.077$ kWH/kg, $n_{st}' \approx 0.8$, $n_{BAT} \approx 1$. For the receiver assume $\beta_{REC} \approx 6.4$ kg/kW and $n_{st} \approx 0.9$, which is representative of the receiver being considered for the Space Station Rankine cycle power system.[8] Therefore, for a system in low earth orbit with $t_{SUN} \approx 1$ hr, $t_{SH} \approx 38$ min, Eqs. (5) and (15) yield the following results. For Ni-Cd; $\Gamma_{BAT} \approx 0.91$, $\gamma_{BAT} \approx 14.6$, for Ni-H2; $\Gamma_{BAT} \approx 0.91$, $\gamma_{BAT} \approx 4.2$ and finally for Na-S; $\Gamma_{BAT} \approx 0.95$, $\gamma_{BAT} \approx 0.72$. Since $\Gamma_{BAT} > 0.9$ for all three systems, the efficiency ratio, n_o/n_T, will be nearly the same for each system. However, the wide variation in γ_{BAT} means there will also be a wide variation in $(R_T + B_T)/R_o$. In Fig. 4 $(R_T + B_T)/R_o$ is shown as a function of heat engine efficiency for the same conditions as Fig. 2 with $f_{pv}n_{pv}/n_{REC} \approx 0.15$ and for three values of the quantity $1 + f_{pv}(\gamma_{BAT} - 1) - \rho$ for the transmitting PVHE system or $1 + f_{pv}n_{pv}(\gamma_{BAT} - 1) - \tau$ for the reflecting PVHE system. A value of 3 is representative of Ni-Cd, a value of 1.5 is representative of Ni-H2 and a value of 1.0 is representative of Na-S. As Fig. 4 indicates no receiver mass savings will occur if Ni-Cd batteries are used. In the case of Ni-H2 batteries savings will occur for $n_{HE} < 0.25$ and for Na-S batteries savings occur for all n_{HE}. A large mass addition will result if a PVHE system must use Ni-Cd batteries. This large mass penalty makes a PVHE system using Ni-Cd batteries unattractive for a low earth orbit power system.

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 $(\alpha n_c P_{in})$ to the heat engine working fluid.

To estimate, T_{pv}, a simple heat transfer analysis presented in Ref. 5 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

4. radiation from PV array neglected

Using these assumptions the following result was obtained for Ku >> 1.

$$\Delta T = T_{pv} - T_B = \alpha K \qquad (17)$$

Therefore, in order to minimize ΔT the absorptivity must be low.

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).

$$u = a \left(\frac{A_T}{A_c}\right) \frac{h}{n_c P_{SUN}} \qquad (18)$$

$$a = \frac{A_T}{A_h} \qquad (19)$$

$$K = \frac{1 + \dfrac{t_{SH}}{t_{SUN}n_{st}}}{\alpha + \tau n_{REC}} \frac{\Delta H}{C_p} \qquad (20)$$

The ratio of PV array area, A_T, to the heat transfer area, A_h, is given by the parameter, a. Since, the heat transfer area will be equal on less than total array area, $a \leq 1$. The expression for K given by Eq. (20) is for a transmitting PVHE system. For a reflecting system merely replace τ by ρ in Eq. (20).

Consider values for K that are representative of heat engines being studied for the Space Station. Two of these are the toluene Rankine[8] heat engine ($\Delta H/C_p \approx 280$ K) and the HE - Xe Brayton[8] heat engine ($\Delta H/C_p \approx 180$ K). Also, assume a low earth orbit ($t_{SH}/t_{SUN}n_{st} = 2/3$) and $\alpha + \tau n_{REC} = 0.7$ for a transmitting system or $\alpha + \rho n_{REC} = 0.7$ for a reflecting system. For the Brayton cycle under these conditions $K \approx 430$ K and for the Rankine cycle $K \approx 670$ K. If $\alpha < 0.3$ then, according to Eq. (17), 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[8] the bottom temperature of the cycle is $T_B \approx 340$ K. The HE - Xe Brayton heat engine system[8] 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[8] is $T_B \approx 380$ K. Therefore, for $\Delta T \approx 200$ K the PV array temperature would be $T_{pv} \approx 540$ to 580 K. Operation of gallium arsenide (GaAs) PV cells at temperatures >600 K are discussed in Ref. 1. The efficiency, n_{pv}, decreases with increasing temperature.[1,9] However, the decrease in efficiency can be partially balanced by operating at high intensity, as in the proposed PVHE systems. Efficiency increases with intensity[1,9] up to about 1000 P_{SUN}. Two possible candidates for a high temperature, high intensity PV cell are the vertical multijunction (VMJ) cell[10-12] and the interdigitated back contact PV cell considered for thermophotovoltaic conversion.[13,14]

Besides low absorptivity, a reduced value of the parameter, K, will also result in lower array temperature, T_{pv}. A possible method for reducing K is to reduce ΔH. This can be done by increasing the mass flow rate in the heat engine cycle. However, such a change will also alter the heat engine

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cycle performance. In the design of a PVHE system it will be necessary to vary the heat engine operating conditions in order to find the optimum.

COMPARISON OF SPACE STATION ORGANIC RANKINE CYCLE AND PVHE

Earlier it was shown how the PVHE system can result in significant reductions in mass and area compared to a heat engine only system. Now consider a mass and area comparison between the toluene Rankine cycle (ORC) being considered for the Space Station[8] and a PVHE system that uses the same Rankine cycle. The Space Station system consists of two modules that each produce 25 kWe. Table I lists the ORC performance parameters for a 25 kWe module taken from Ref. 8, as well as, the assumed values used for the PVHE system. The assumed PVHE system is either reflecting ($\rho = 0.5$, $\tau = 0.05$, $\alpha = 0.3$) or transmitting ($\rho = 0.05$, $\tau = 0.05$, $\alpha = 0.3$). Using Eq. (8) and the parameters in Table I, the efficiency ratio is the following.

$$\frac{n_T}{n_0} = 1.39$$

The overall efficiency of the ORC system is 0.17, which includes the power conditioning efficiency and the electrical power for the concentrator controls. Assuming these losses are the same for the PVHE system then the efficiency of the PVHE system is the following.

$$n_T = 0.17(1.39) = 0.23$$

Table II presents the results of the mass and area comparison. The concentrator and radiator areas for the PVHE system were calculated using Eqs. (9) and (10). The PVHE concentrator and radiator masses were obtained by assuming they are proportional to their respective areas. Receiver and battery mass for the PVHE system were calculated using Eqs. (12) and (14). Two battery masses are shown in Table II; one based on bipolar nickel-hydrogen batteries[6] ($\alpha_{BAT} \approx 0.139$ kWH/kg) and the other on sodium sulfur batteries [7] ($\alpha_{BAT} \approx 0.077$ kWH/kg). The mass of the Rankine power conversion unit for the PVHE system was obtained by assuming the mass is a linear function of power output. Interface structure mass, (including the gimbel joint for the concentrator,) for the PVHE system was obtained using the same fraction of the total mass as for the Rankine only system (structure mass/total mass = 0.15). Mass of the PV array in the PVHE system was calculated assuming the same specific mass as that of the concentrator (6.6 kg/m^2) and a concentrator to a PV array area ratio of $A_c/A_{PV} = 50$. A radiator is necessary to reject the waste heat of the electrical storage. An estimate of the mass and area of this radiator was obtained by assuming the waste heat was rejected at a temperature of 30 °C and emissivity of 0.9 with the same mass/area as the heat engine radiator. Not included in Table II is the mass of the power conditioning equipment.

Several interesting results are pointed out by Table II. First of all the total PVHE system mass for $\alpha_{BAT} = 0.0139$ kWH/kg is nearly 25 percent less than the ORC system. The PVHE concentrator area is 30 percent less than the ORC system concentration area. Also, the PVHE radiator area is

40 percent less than the ORC system radiator area. The major mass and area savings for the PVHE system occur for the radiator. Finally, since batteries are not a major portion of the total mass, using the optimistic sodium-sulfur batteries rather than nickel-hydrogen batteries does not result in a major reduction in the total mass of a PVHE system. For an all PV array power system the batteries are the major mass component. Therefore, in that case a large energy density electrical storage component is critical for obtaining a low mass sytem. Whereas, the PVHE system mass is much less sensitive to the electrical storage mass.

The large radiator mass and area savings of the PVHE system result because the waste heat of the PV array (P_{REJ} in Fig. 1) is used by the heat engine rather than rejected to space. Only by operating the PV array at high temperature is it possible to utilize the PV array waste heat in the heat engine cycle. If the PV array can not operate at high temperature then P_{REJ} would have to be rejeted to space. This low temperature heat rejection would require a large radiator area.

Consider an estimate of the PV array temperature, T_{PV}, required in the above example. Assuming Ku >> 1, then Eq. (17) can be used to estimate T_{PV}. From the data in Table I, K = 646 K. Therefore, using Eq. (17) and a bottom temperature[8], $T_B = 60$ C, the following is obtained, $T_{PV} = 527$ K. Reaching PV array temperatures this high is the critical issue for the space PVHE system. Without high temperature PV array operation the large area and mass savings are not possible.

Conclusion

Both transmitting and reflecting PVHE systems result in significant efficiency improvements, over a heat engine only system ($1.1 \leq n_T/n_0 \leq 2$). Choosing between the reflecting and transmitting systems depends on several things. One important consideration is the PV array absorptivity, α. In order to maintain a high 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 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.

As a result of improved efficiency over a heat engine ($n_T/n_0 > 1$) the PVHE systems will have corresponding savings in concentrator area ($C_T/C_0 = n_0/n_T$). Also, the PVHE system will result in heat engine radiator savings greater than concentrator area savings. Receiver and energy storage mass savings will occur for the PVHE system if high energy density electrical storage ($\gamma_{BAT} < 1$) is available. A mass penalty will occur if low energy density electrical storage, such as nickel-cadmium batteries are used.

A mass and area comparison was made between the Space Station organic Rankine cycle power system and a hypothetical PVHE system using the same Rankine system. Nearly a 25 percent reduction in

overall mass was calculated, as well as a concentrator area reduction of 30 percent and a radiator area savings of 40 percent for the PVHE system.

Besides efficiency, area and mass savings the PVHE systems have a degree of inherent system redundacy. 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.

References

1. Stirn, R.J., "An Overview of Novel Photovoltaic Conversion Techniques at High Intensity Levels," Radiation Energy Conversion in Space, K.W. Billman, ed., AIAA, New York, 1978, pp. 136-151.

2. Jurisson, J., "Multicolor Solar Cell Power System for Space," Radiation Energy Conversion in Space, K.W. Billman, ed., AIAA, New York, 1978, pp. 152-158.

3. Ratajczak, A.R., "Theoretical Performance of Solar-Cell Space Power Systems Using Spectral Dispersion. I - Dispersion by Prism Reflector," NASA TN D-4156, 1967.

4. Klucher, T.M., "Theoretical Performance of Solar-Cell Space Power Systems Using Spectral Dispersion. II - Dispersion by Diffraction Grating," NASA TN D-4157, 1967.

5. Chubb, D.L., "Combination Solar Photovoltaic Heat Engine Energy Converter," Journal of Propulsion and Power, Vol. 3, No. 4, July-Aug.1987, to be published.

6. Manzo, M.A. and Hoberecht, M.A., "A 37.5kw Point Design Comparison of the Nickel-Cadmium Battery, Bipolar Nickel-Hydrogen Battery, and Regenerative Hydrogen-Oxygen Fuel Cell Energy Storage Subsystems for Low Earth Orbit," Advanced Energy Systems - Their Role in Our Future (19th IECEC), Vol. 1, American Nuclear Society, La Grange Park, IL, 1984, pp. 287-294.

7. Wise, J.F., "Comparison of High Power Solar Power System Concepts to Other Options," Eighteenth IEEE Photovoltaic Specialists Conference, IEEE New York, 1985, pp. 418-423.

8. "Space Station WP-04 Power System, Preliminary Analysis and Design Document DR-02," Vol. 1, RI/RD85-320-2, Rocketdyne Division, Rockwell International, Canoga Park, CA, Dec. 1986.

9. Hovel, H.J., Semiconductors and Semimetals, Vol. 11 - Solar Cells, Academic Press, New York, 1975, p. 173.

10. Sater, B.L., Brandhorst, H.W. Jr., Riley, T.J., and Hart, R.E. Jr., "The Multiple Junction Edge Illuminated Solar Cell," 10th IEEE Photovoltaic Specialists Conference, IEEE, New York, 1973, pp. 188-193.

11. Sater, B.L. and Goradia, C., "The High Intensity Solar Cell - Key to Low Cost Photovoltaic Power," 11th IEEE Photovoltaic Specialists Conference, IEEE, New York, 1975, pp. 356-363.

12. Goradia, C. and Sater, B.L., "A First Theory of the P^+-n-n^+ Edge-Illuminated Silicon Solar Cell at Very High Injection Levels," IEEE Transactions on Electron Devices, Vol. 24, No. 4, Apr. 1977, pp. 342-351.

13. Swanson, R.M., "Recent Developments in Thermophotovoltaic Conversion," IEEE International Electron Devices Meeting, IEEE, New York, 1980, pp. 186-189.

14. Swanson, R.M. and Bracewell, R.N., "Silicon Photovoltaic Cells in TPV Conversion," EPRI-ER-633, Electric Power Research Institute, Palo Alto, CA, Feb. 1978.

TABLE I. - PERFORMANCE PARAMETERS OF SPACE STATION
25 kWe ORGANIC (TOLUENE) RANKINE CYCLE (ORC)
POWER SYSTEM AND HYPOTHETICAL PVHE SYSTEM
USING THE SAME ORC

	ORC	PVHE
Concentrator efficiency, η_C	0.90	0.90
Receiver efficiency efficiency, η_{Rec}	.90	.90
Storage Efficiency	$\eta_{st} = .91$	$\eta'_{st} = .80$ $\eta_{BAT} = .90$
Heat engine Efficiency, η_{HE}	.27	.27
PV array efficiency, $f_{PV}\eta_{PV}$		.15
SUN time τ_{SUN}, min	54.7	54.7
Shade time, τ_{SH}, min	36.3	36.3
Receiver specific mass, P_{REC}, kg/kW	6.35	6.35
PV array absorptivity, α		.30
PV array reflectivity, ρ		0.50 reflection system .05 transmitting system
PV array transmittance, τ		0.50 reflection system .05 transmitting system

TABLE II. - COMPARISON OF SPACE STATION ORC POWER SYSTEM AND

HYPOTHETICAL PVHE SYSTEM USING THE SAME ORC

[Electrical Power Output = 25 kWe]

| Component	Mass for ORC, kg	Mass for PVHE, kg	Area for ORC, m^2	Area for PVHE, m^2
Concentrator	1414	1018	213	153
Receiver and thermal storage	1426	821		
Electrical storage		610(α_{BAT} = 0.0139 kWH/kg) 110(α_{BAT} = 0.077 kWH/kg)		
Heat engine	567	340		
PV array		20		
Heat engine radiator	2182	1309	160	96
Electrical storage radiator		199		15
Interface structure and Beta Gimbel joint	982	756(α_{BAT} = 0.0139 kWH/kg) 668(α_{BAT} = 0.077 kWH/kg)		
Total	6571	5073(α_{BAT} = 0.0139 kWH/kg) 4485(α_{BAT} = 0.077 kWH/kg)	373	261

ORC efficiency, n_o = 0.17   PVHE efficiency, n_T = 0.23;
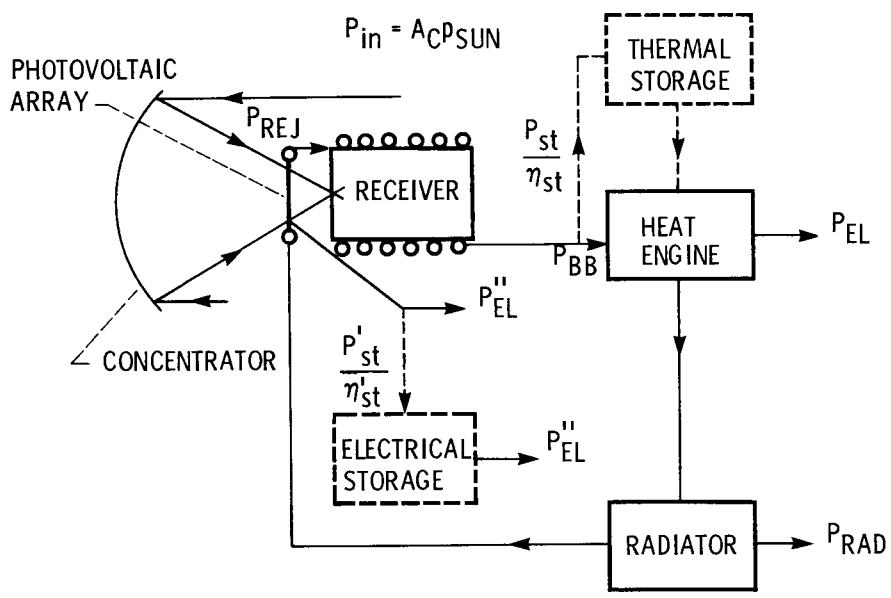ORC specific mass = 263 kg/kWe   PVHE specific mass = 203 kg/kWe (α_{BAT} =0.0139 kWH/kg)
                                                          PVHE specific mass = 179 kg/kWe (α_{BAT} =0.077 kWH/kg)

$$\text{Power ratio for PVHE system} = \frac{\text{Power output of ORC}}{\text{Power output of PV array}} = \frac{P_{EL}}{P'_{EL}} = 0.78$$
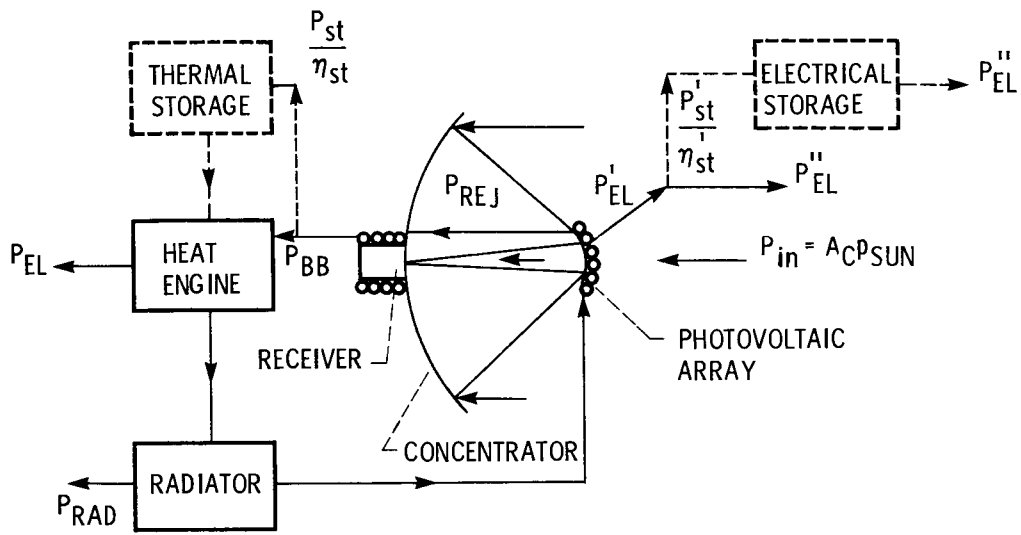
(a) Reflecting system.

(b) Transmitting system.

FIGURE 1. - SCHEMATIC DIAGRAMS OF PHOTOVOLTAIC HEAT ENGINE (PVHE) SYSTEMS.
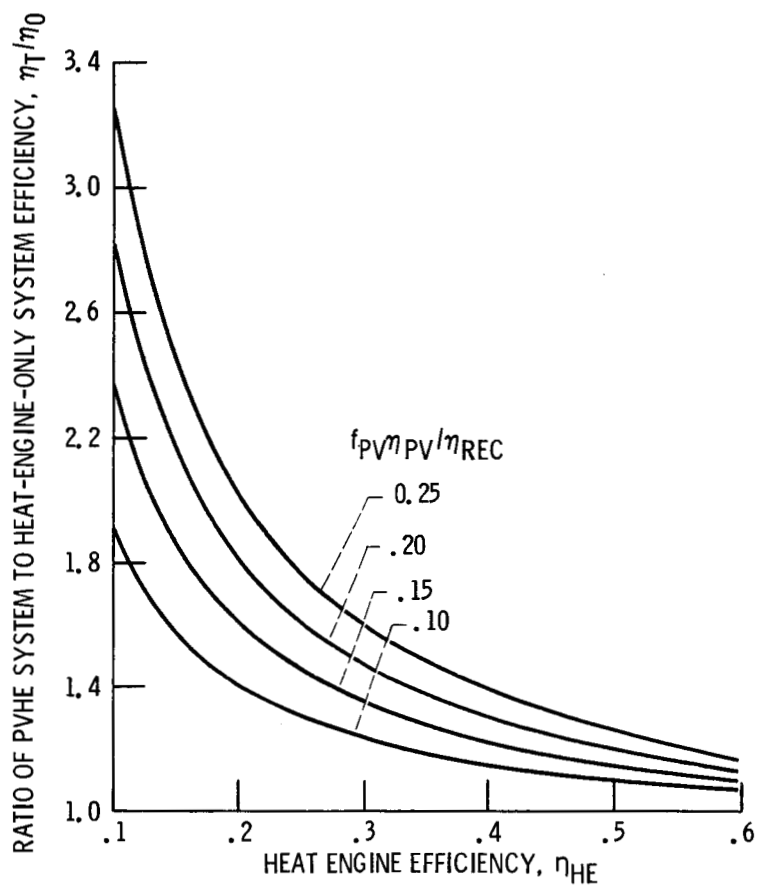
FIGURE 2. – EFFICIENCY IMPROVEMENT FOR PVHE SYSTEM
OVER HEAT ENGINE WITH BOTH SYSTEMS OPERATING WITH
SAME CONCENTRATOR EFFICIENCY η_C AND RECEIVER EF-
FICIENCY η_{REC}. ALSO, FOR REFLECTING PVHE SYSTEM
$1/\eta_{REC}$ $(1-\tau-\rho) + \rho = 1$, AND FOR TRANSMITTING PVHE
SYSTEM, $1/\eta_{REC}$ $(1-\tau-\rho) + \tau = 1$. FOR COMBINATION
ELECTRICAL AND THERMAL ENERGY STORAGE $\Gamma_{BAT} = 1$.
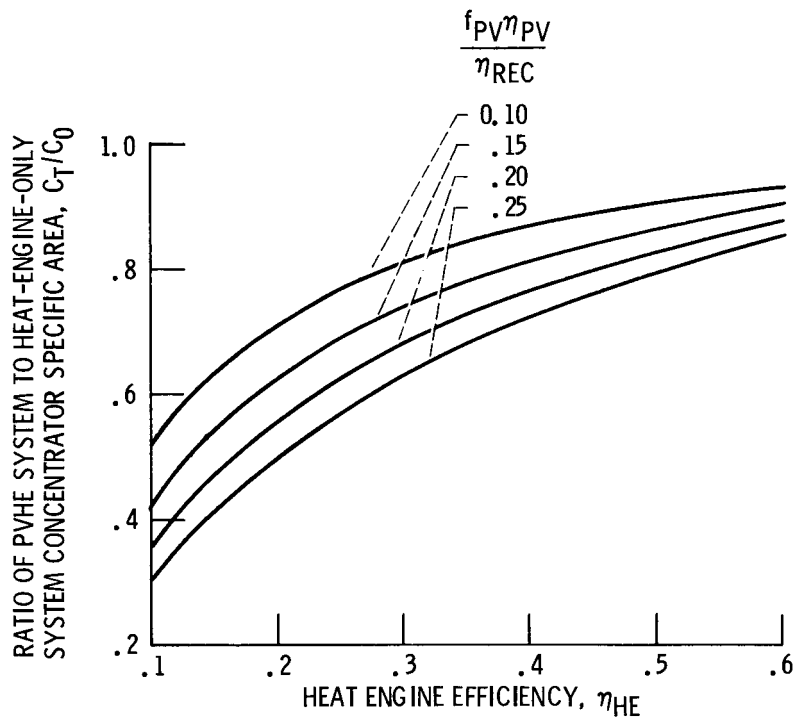
11

FIGURE 3. - CONCENTRATOR AREA SAVINGS FOR PVHE
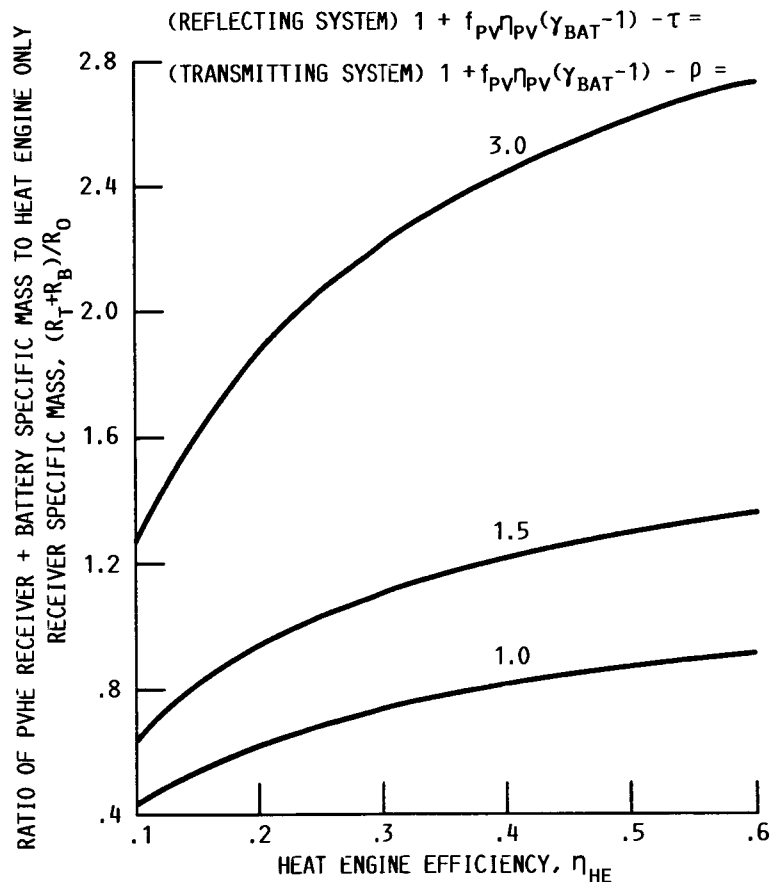 SYSTEM OVER HEAT ENGINE WITH SAME CONDITIONS
  AS FIG. 2.

FIGURE 4. - RECEIVER MASS SAVINGS FOR PVHE SYSTEM OVER HEAT ENGINE ONLY SYSTEM WITH SAME CONDITIONS AS FIG. 2. IN ADDITION, $f_{PV}\eta_{PV}/\eta_{REC} = .15$.

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15. Supplementary Notes

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16. Abstract

A combination solar photovoltaic heat engine energy converter is proposed. Such a system is suitable for either terrestial 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. A mass and area comparison between the proposed Space Station organic Rankine power system and a combination PV-heat engine system is made. The critical problem for the proposed converter is the necessity for high-temperature photovoltaic array operation. Estimates of the required photovoltaic temperature are presented.

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