PHOTOVOLTAIC DESIGN OPTIMIZATION FOR TERRESTRIAL APPLICATIONS*

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ABSTRACT

As part of the Jet Propulsion Laboratory's Low-Cost Solar Array Project, a comprehensive program of module cost-optimization has been carried out. The objective of these studies has been to define means of reducing the cost and improving the utility and reliability of photovoltaic modules for the broad spectrum of terrestrial applications.

This paper describes one of the methods being used for module optimization, including the derivation of specific equations which allow the optimization of various module design features. The method is based on minimizing the life-cycle cost of energy for the complete system. Comparison of the life-cycle energy cost with the marginal cost of energy each year allows the logical plant lifetime to be determined. The equations derived allow the explicit inclusion of design parameters such as tracking, site variability, and module degradation with time. An example problem involving the selection of an optimum module glass substrate is presented.

INTRODUCTION

Within the national photovoltaics program sponsored by the U.S. Department of Energy there are a number of activities addressing the optimization of photovoltaic systems and components for a variety of future applications. A significant fraction are involved with design tradeoffs at the system level and associated with determining the true worth of solar energy in comparison with alternative fuels and systems. The most comprehensive of these analyses model the dynamics of solar energy within a utility grid including hourly weather and load modeling. This in-depth level of modeling is providing needed insight into the true characteristics of solar systems and the true value of the generated energy.

A second level of analysis being conducted is focused at photovoltaic system configurations, with the objective of selecting the optimum subsystem characteristics. These analyses often use hour-by-hour system simulation programs to model the dynamic operation of the photovoltaic subsystems such as the array, power conditioning, and storage.

At a level below the system configuration tradeoffs is the class of optimization problems addressed by this paper. This set of problems is associated with subsystem and subassembly optimizations which are often associated with design details such as selection of optimum materials and dimensions.

This class of optimization is often carried out within the constraints of interface requirements to produce the lowest cost of highest performing element possible. Such an approach has the advantage of minimizing design interaction across the interface, but may lead to significant system penalties if the cost and performance interaction across the interface is ignored. The challenge is to develop a simple framework for addressing the optimization of subassembly features which still allows the important system interactions to be included. The development of such a method is the subject of this paper.

A FRAMEWORK FOR OPTIMIZATION

The development of an approach or framework for subassembly optimization requires consideration of three important objectives. These include ease of application to detailed design features, flexibility to adapt to a variety of problem types, and incorporation of important system interface interactions. A key first step in meeting the last objective is the proper choice of the objective function to be minimized.

Objective Function Selection

To properly include important system interactions it is necessary that the objective function to be used reflect the true system design objectives. There are a number of alternate system objective functions in common use today:

- Minimum system life-cycle cost per initial kilowatt of system power output.

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- Minimum system life-cycle cost per life-cycle kilowatt-hr of system energy output.
- Minimum system initial cost per initial kilowatt of system power output.
- Maximum utility profit based on hourly marginal cost of energy, etc.

The advantages and disadvantages of the alternative objectives depend critically on the details of the particular problem being worked. If none of the tradeoffs in the optimization affect the time-dependent behavior of the system, then minimum system initial cost is an appropriate objective function. However, if time-dependent behaviors such as maintenance, replacement, or performance degradation are important, then an objective function which reflects the importance of event timing must be used.

The time-dependent value of money is generally incorporated by using the life-cycle cost of the total photovoltaic power system. The life-cycle cost for a photovoltaic system is basically the initial cost of the entire plant, including interest during construction, and the "present value" or recurrent costs, such as operation and maintenance, which are distributed throughout the life of the plant. A standardized DOE/EPRI methodology exists with a specific method for calculating system life-cycle cost[1].

An equally important consideration, but one having received little emphasis to date, is the time-dependent worth of the power or energy generated. When considering tradeoffs which involve different performance variations with time, such as different degradation rates, one must use an objective function which also reflects the time-dependent worth of the plant output. A companion paper treats this subject in some detail[2].

One candidate function which accommodates the variation of plant output with time is the ratio of the life-cycle plant cost to the life-cycle revenue received from the sale of the energy. Mathematically this function can be represented as

$$\text{Objective Function} = \frac{\sum_{n=0}^{L} C_n (1+k)^{-n}}{\sum_{n=0}^{L} E_n R_n (1+k)^{-n}} \qquad (1)$$

where

C_n = cost outlay in year n (startup-year \$)

E_n = energy generated in year n (kW-hr)

R_n = sale price of energy (startup-year \$/kW-hr)

L = number of years plant will be operated.

k = present value discount rate

Intuitively this concept can be interpreted as minimizing the life-cycle investment per unit of life-cycle revenue.

If one assumes a constant sale price of energy R then Eq. (1) reduces to

$$R_L = \frac{\sum_{n=0}^{L} C_n (1+k)^{-n}}{\sum_{n=0}^{L} E_n (1+k)^{-n}} \qquad (2)$$

In this equation R_L is the energy selling price required to obtain a return on investment consistant with the chosen discount rate, if the plant is operated for L years. An appropriate objective for a module optimization is to minimize this price.

To further explore Eq. (2), consider the hypothetical plant depicted in Fig. 1. In this figure the plant is arbitrarily represented as having a linearly decreasing output together with a gradually increasing O&M cost as the plant ages. Two questions can be asked: What is the minimum selling price of the energy, and what is the plant lifetime?

The questions are addressed in Fig. 2, where the marginal cost per kilowatt-hour C_n/E_n is plotted together with the life-cycle energy cost R_L for an example discount rate of 8%. Note that all dollars are constant dollars based on the year of the plant startup, so that the 8% is in excess of the rate of inflation. The marginal cost per kilowatt-hour is the actual operating expense in year n, in startup-year dollars, per kilowatt-hour produced in year n.

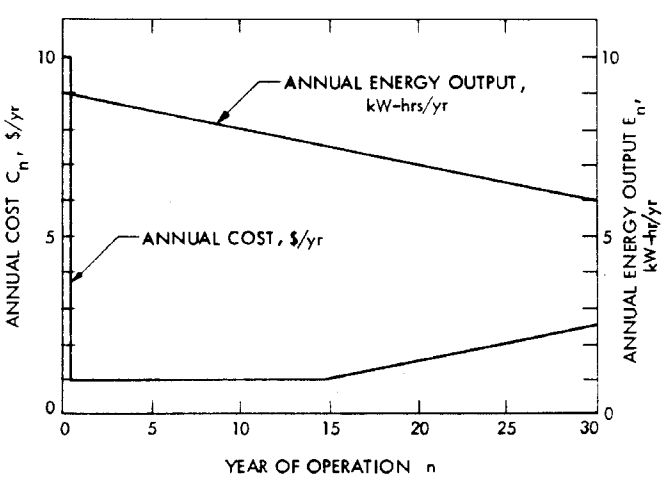

Fig. 1. Annual cost and annual energy output for hypothetical plant versus year of operation

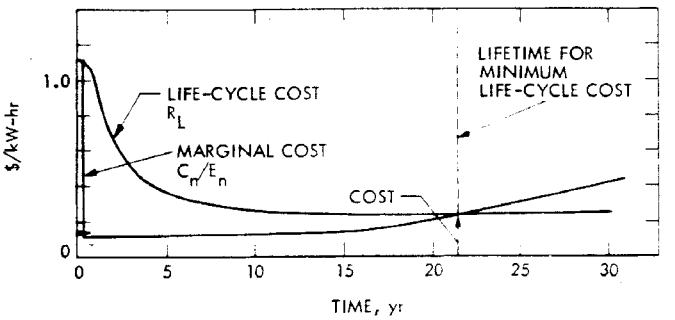

Fig. 2. Life-cycle cost per kilowatt-hour versus plant life L and marginal cost versus year of operation n for a hypothetical plant

An important observation from Fig. 2 is that the life-cycle energy cost R_L goes through a minimum, and the minimum occurs at the point where the marginal cost curve crosses the life-cycle cost/kW-hr curve. This point defines the practical end-of-life of the plant. It can be shown mathematically that if the same discount rate is used for both the cost and energy (revenue) streams, the minimum life-cycle cost/kW-hr will always coincide with the crossing of the marginal cost/kW-hr curve. In other words, operation to the right of the minimum results in annual operating expenses in excess of the annual revenue associated with the minimum.

An additional observation from Fig. 2 is that this plant could be abandoned after 10 years with only a minor increase in the required selling price of the energy over that associated with the optimum lifetime of around 21 years. The reason is the large present-value discount associated with costs and revenues in later years. The drastic reduction associated with the present-value of future costs is illustrated in Fig. 3 for discount rates of 6, 8 and 10%. These curves also represent the plant depreciation with time associated with the chosen discount rate.

The result of this rapid reduction in the present-value of future dollars is a general insensitivity to events such as output degradation, which occur late in the plants life. This fact lends additional credibility to the use of optimizations which are limited to initial costs for certain problems. For problems where time-dependent behavior is important, use of a methodology such as the life-cycle cost of energy is recommended.

Reducing the Problem to a Workable Form

The chief difficulty in working with the objective functions described in the preceding section is that they are written directly in terms of annual costs and energies. On the other hand, most engineering data is in terms of module initial costs and performance variations.

For purposes of developing an optimization strategy consider the problem of selecting between two module design options on the basis of minimizing

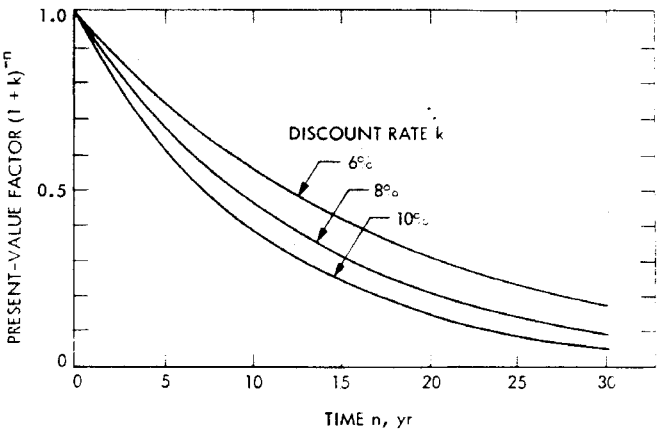

Fig. 3. Present-value of future costs or revenues for discount rates of 6, 8 and 10%

the life-cycle energy cost (Eq. 2). Even more specific, consider the problem of selecting between two alternative glass sheets for use as a module superstrate. In this application the flat glass sheet is mounted above the solar cells and protects them from wind and hail loads. Therefore the optical transmission of the glass plus surface soiling attenuates the cell power output. Consider two glasses: one untempered with a very high transmission, and one tempered, and thus stronger, but with a lower transmission per unit thickness. Also assume that they reach different equilibrium soiling levels. Which is best?

There are two strategies: one is to develop the effects of the module options on the system costs and energy output; the other is to decompose the life-cycle energy cost equation into module-related terms. The second has the advantage of leading to a permanently useful tool for module optimization.

As a first step consider describing the plant energy output in year n as a fraction of the initial energy output at plant startup. Equation (2) thus reduces to:

$$R_L = \frac{\sum_{n=0}^{L} C_n (1+k)^{-n}}{E_o \sum_{n=0}^{L} \varepsilon_n (1+k)^{-n}} \equiv \frac{C_{LC}}{E_o \, \varepsilon_{LC}} \qquad (3)$$

where

R_L = life-cycle cost of energy

C_n = cost outlay in year n

C_{LC} = life-cycle cost

E_o = initial annual energy production

ε_n = fraction of initial annual energy in year n

ε_{LC} = life-cycle summation of ε_n

k,L = discount rate and plant life

Next, it is desirable to expand the initial annual energy production E_o in terms of insolation level S, total module area in the plant A_M, module efficiency η_M, balance-of-plant efficiency η_B, and peak-insolation-hours per year H. Thus,

$$R_L = \frac{C_{LC}}{SA_M\eta_M\eta_B H\varepsilon_{LC}} \tag{4}$$

To obtain R_L more explicitly in terms of module parameters we next expand the life-cycle cost into its module-dependent and module-independent parts and articulate the costs in terms of module area and array power. Thus

$$\boxed{R_L = \frac{C_M + C_{MD} + C_{MLC}}{\eta_M\eta_B SH\varepsilon_{LC}} + \frac{C_{BLC}}{H\varepsilon_{LC}}} \tag{5}$$

where

R_L = total system life-cycle energy cost, \$/kW-hr

C_M = initial module cost per unit area of module, $\$/m^2$ of module

C_{MD} = balance of module-dependent system initial cost per unit area of module, $\$/m^2$ of module

C_{MLC} = module-dependent life cycle cost exclusive of initial costs, per unit area of module, $\$/m^2$ of module

C_{BLC} = total module-independent balance-of-plant life-cycle cost per kilowatt of total plant output power at insolation S and NOCT, \$/Pk kW of plant output

η_M = module efficiency (power output per unit of total module area at insolation S and NOCT, divided by S)

η_B = balance-of-plant efficiency (average plant power output divided by array power input)

S = reference insolation level, kW/m^2

H = peak-insolation-hours per year captured by the array (Langleys/day divided by S, mW/cm^2, times 423.4), hr/yr

ε_{LC} = life-cycle summation of annual fraction of initial energy output

NOCT = nominal operating cell temperature with module field installed, °C

Equation (5) is a particularly useful form for many optimization problems.

As an additional aide for problems associated with internal module parameters it is also useful to expand the module cost C_M into three component parts: cell-related costs, encapsulant related costs, and fixed costs. Thus

$$\boxed{C_M = C_C\,\eta_P + C_E + \frac{C_F}{A}} \tag{6}$$

where

C_C = solar-cell-related cost per module, $\$/m^2$ of cell

C_E = encapsulant-related cost per module, $\$/m^2$ of module

C_F = fixed cost per module (\$/module)

η_P = module packing efficiency (total cell area per module divided by total module area)

A = total area of module, m^2

Solving the Example

To illustrate the method suggested by Eqs. (5) and (6), consider its application to the example problem of the two types of glass. The critical first step is to articulate the parameter dependencies; i.e. which of the parameters in Eqs. (5) and (6) are dependent on the choice of glass. This step can be greatly simplified by properly posing the problem.

In the example the two glass types are considered to have different strengths per thickness (tempered and untempered) and different transmission losses per unit thickness. The required glass thickness is therefore a critical parameter. To obtain comparable results, either a uniform design criteria must be applied or the lack of uniformity must be explicitly dealt with.

To simplify the problem, consider the design criteria to be that both modules will have equal resistance to damage and degradation so that maintenance costs are held constant. The thickness of the glass is therefore determined by the glass strength, the structural loading design level, and the module size.

Unfortunately an unwanted degree of freedom still exists at this point; ie., the glass thickness is dependent on the module size assumed. Several candidate strategies for eliminating this degree of freedom include:

- hold the glass thickness constant
- hold the module power constant
- hold the module size constant

Each of these constraints will lead to different dependencies between the parameters.

Holding the module size constant is chosen because it minimizes these dependencies. Changing the size would have altered the module frame, the installation cost, the module packing efficiency and many dependencies difficult to estimate.

However, with the chosen constraints — constant size and environmental durability — it is possible that the cheapest tempered glass available exceeds the durability design criteria. This may be acknowledged by reducing the maintenance cost an appropriate amount.

Increasing the module size to fully utilize the stronger glass must be approached with extreme caution because of the difficulty in estimating the effects of size on manufacturing cost, shipping cost, handling cost, etc. The natural tendency is to assume these costs are insensitive to size. This results in the option with fewer, larger modules being nearly always cheaper. Watch out!

The remaining dependencies in the example relate to optical transmission losses associated with the glass thickness, the unequal soiling assumed, and the cost difference between the glasses. Note that although the optical transmission difference is included in the module efficiency η_M, the optical loss due to soiling is, by convention, a system loss, and included in the balance-of-plant efficiency η_B. As an alternative the dust loss could be included in the life-cycle energy fraction ε_{LC}.

Table 1 summarizes the set of hypothetical dependencies for the example problem and summarizes the resulting module cost and life-cycle energy cost calculated using Eqs. (5) and (6). A life-cycle energy fraction of 10 is assumed on the basis of Fig. 4. Notice that this value is fairly insensitive to life beyond 20 years.

From the bottom line in Table 1 it can be seen that the optimum choice from a module-cost point-of-view is not the proper choice from the standpoint of lowest system energy cost.

AN ALTERNATE COST-BENEFIT APPROACH

A disadvantage of the approach used in the preceding example is that a large number of poorly known parameters exist, such as ε_{LC}, H, and C_{BLC}, which are likely to be independent of the question at hand.

An alternate strategy is to calculate the sensitivity of R_L to changes in the dependent parameters, while holding the independent parameters fixed. A beneficial design trade is then defined as one where the incremental benefit is larger than the incremental expense; i.e. the incremental change in R_L is negative. This can be expressed mathematically as

$$\frac{\partial R_L}{\partial\ (\text{design parameter})} \leq 0 \qquad (7)$$

The critical step in this approach is to correctly take the partial derivative of Eq. (5) with respect to the principal design parameter so that <u>all</u> interdependencies are properly accounted for.

To illustrate this approach, again consider the example problem with the two types of glass. As the first step we choose the glass cost C as the principal design parameter denoting the glass type. With this selection the problem reduces to taking the derivative of Eq. (5) with respect to C while holding all independent parameters fixed. The independent parameters are noted by an absence of a bullet in the right hand column of Table 1. Letting S=1 we get

$$\frac{\partial R_L}{\partial C}\left(\eta_M\eta_B H\varepsilon_{LC}\right)^2 = \left(\eta_M\eta_B H\varepsilon_{LC}\right)\left(\frac{\partial C_M}{\partial C}\right) - \left(C_M+C_{MD}+C_{MLC}\right)\left(H\varepsilon_{LC}\right)\left(\eta_M\frac{\partial\eta_B}{\partial C} + \eta B\frac{\partial\eta_M}{\partial C}\right)$$

Setting this expression to zero gives:

$$\frac{\partial C_M}{\partial C} = \left(C_M+C_{MD}+C_{MLC}\right)\left(\frac{\partial\eta_B}{\eta_B\partial C} + \frac{\partial\eta_M}{\eta_M\partial C}\right) \qquad (8)$$

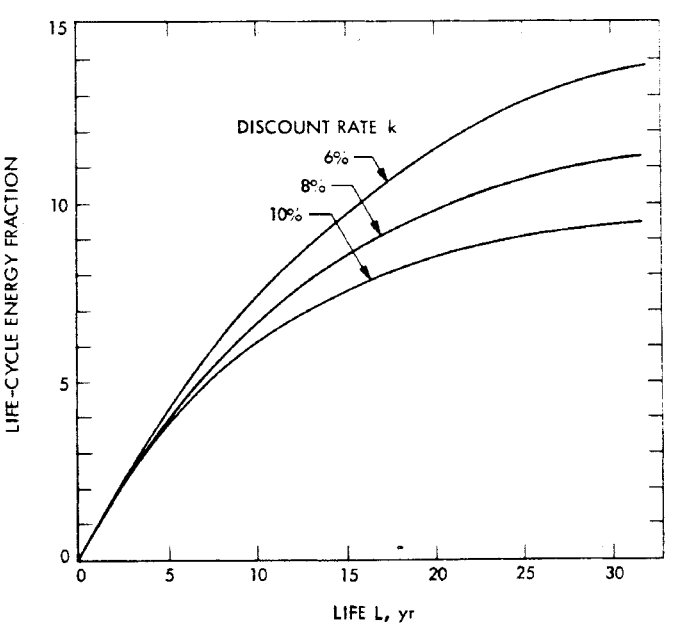

Fig. 4. Life-cycle energy fraction assuming no degradation with time (present-value of an annuity of 1) versus life

Table 1. Example parameter dependency for two types of glass superstrates

Parameter	Symbol	Numerical value: Annealed	Numerical value: Tempered	Units	Dependent parameter
Glass thickness		3.0	2.0	mm	•
Optical transmission		0.91	0.90	—	•
Dust transmission		0.89	0.93	—	•
Glass cost	C	3.00	6.00	$\$/m^2$	•
Balance-of-plant efficiency	η_B	0.801	0.837	—	•
Encapsulated cell efficiency	η_{EC}	0.133	0.138	—	•
Packing efficiency	η_P	0.90	0.90	—	
Module efficiency	η_M	0.120	0.119	—	•
Cell-related cost	C_C	60	60	$\$/m^2$	
Encapsulant cost	C_E	4.00	7.00	$\$/m^2$	•
Module fixed cost	C_F	4.80	4.80	\$	
Module area	A	3.2	3.2	m^2	
Module-dependent cost	C_{MD}	30.0	30.0	$\$/m^2$	
Module-dependent O&M cost	C_{MCL}	10.0	10.0	$\$/m^2$	
Other system life-cycle	C_{BLC}	100	100	\$/kW	
Module cost per m^2	C_M	59.5	62.5	$\$/m^2$	•
Peak hours per year	H	1825	1825	hr	
Life-cycle energy fraction	ε_{LC}	10	10	—	
Insolation level	S	1	1	kW/m^2	
Discount rate	k	0.08	0.08	—	
Plant life	L	30	30	yr	
Module cost	C_T/η_M	496	525	\$/kW	•
Life-cycle energy cost	R_L	0.0622	0.0619	\$/kW-hr	•

Solving for $\partial C_M/\partial C$ from Eq. (6) gives:

$$\frac{\partial C_M}{\partial C} = \frac{\partial C_E}{\partial C} = 1 \qquad (9)$$

If we combine Eqs. (8) and (9) and consider the differential changes as deltas we obtain:

$$\Delta C = \left(C_M + C_{MD} + C_{MLC}\right)\left(\frac{\Delta\eta_B}{\eta_B} + \frac{\Delta\eta_M}{\eta_M}\right) \qquad (10)$$

Equation (10) states that for the example problem the energy cost will decrease if the delta glass cost is less than the right-hand-side expression.

Substituting the values from Table 1 indicates that the tempered glass will be best if

$$\Delta C \le (59.5+30+10)\left(\frac{0.036}{0.801} - \frac{0.001}{0.120}\right) = 3.64\ \$/m^2$$

Since the increased cost of the tempered glass is only 3 $\$/m^2$, the tempered glass is best.

Additional Design Parameters

Using the above approach, additional cost-benefit relationships can be easily derived for use as design tools when the need arises. As an aid some of the more commonly encountered problems have

been worked and the results are presented in Table 2. All of these problems assume the system parameters η_B, H, ε_{LC} and C_{BLC} to be independent of the principal design parameter. For a detailed description of the efficiency terminology used in Table 1 the reader is referred to Ref. (3).

CONCLUSIONS

A review of system optimization objective functions indicates that minimum system life-cycle cost per life-cycle energy output is a useful function for subassembly optimization, particularly when time-dependent parameters are involved. An advantage of this function is its ability to reflect the system performance sensitivity to energy-related effects such as those associated with site variability, solar tracking, and performance degradation over time. An important design tool for module optimization has been obtained by reducing this function to a form which allows easy application to the detailed design features typically encountered with photovoltaic modules.

REFERENCES

1. Doane, J. W., et al., "The Cost of Energy from Utility-Owned Solar Electric Systems", Report Number ERDA/JPL-1012-76/3, Jet Propulsion Laboratory, Pasadena, California, June 1976.

2. Borden, C. S., "Lifetime Cost and Performance Model for Photovoltaic Central Power Station", Proceedings of the 13th IEEE Photovoltaic Specialists Conference, Washington, DC, June, 1978.

3. Grippi, R. A., "Module Efficiency Definitions, Characteristics and Examples", LSSA Report No. 5101-43, Jet Propulsion Laboratory, Pasadena, California, October 7, 1977.

Table 2. Cost-benefit relationships for photovoltaic module component tradeoff analyses

Design parameter	Benefit criteria
Cell efficiency	$\Delta C_C \le \frac{\Delta\eta_C}{\eta_C}\frac{1}{\eta_P}(C_M + C_{MD} + C_{MLC})$
Cell mismatch	$\Delta C_C \le \frac{\Delta\eta_{MIS}}{\eta_{MIS}}\frac{1}{\eta_P}(C_M + C_{MD} + C_{MLC})$
Optical transmission	$\Delta C_E \le \frac{\Delta\eta_T}{\eta_T}(C_M + C_{MD} + C_{MLC})$
Operating temperature	$\Delta C_E \le \frac{\Delta\eta_{NOCT}}{\eta_{NOCT}}(C_M + C_{MD} + C_{MLC})$
Cell shape	$\Delta C_C \le \frac{\Delta\eta_N}{\eta_N}\frac{1}{\eta_P}(\frac{C_F}{A} + C_E + C_{MD} + C_{MLC})$
Border/buss area	$\Delta C_F \le \frac{\Delta\eta_{BR}}{\eta_{BR}}(C_F + C_E A + C_{MD} + C_{MLC} A)$

where*

η_M = overall module efficiency at 100 mW/cm^2, NOCT

= $\eta_P \times \eta_{NOCT} \times \eta_{EC}$

η_P = module packing efficiency = $\eta_{BR} \times \eta_N$

η_{BR} = module border/buss/interconnect area efficiency

η_N = cell nesting efficiency

η_{NOCT} = nominal operating cell temperature efficiency

η_{EC} = encapsulated cell efficiency at 100 mW/cm^2, 28°C

= $\eta_C \times \eta_T \times \eta_{MIS}$

η_C = bare cell efficiency (100 mW/cm^2, 28°C)

η_T = optical transmission efficiency

η_{MIS} = electrical mismatch/series resistance efficiency

*For other definitions see Eqs. (5) and (6) in text.