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**COST OF PHOTOVOLTAIC ENERGY SYSTEMS AS
DETERMINED BY BALANCE-OF-SYSTEM COSTS**

**Louis Rosenblum
Lewis Research Center
Cleveland, Ohio 44135
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COST OF PHOTOVOLTAIC ENERGY SYSTEMS AS
DETERMINED BY BALANCE-OF-SYSTEM COSTS

by Louis Rosenblum

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

ABSTRACT

The effect of the balance-of-system (BOS), i.e., the total system less the modules, on photovoltaic energy system costs is discussed for multikilowatt, flat-plate systems. Present BOS costs are in the range of 10 to 16 dollars per peak watt (1978 dollars). BOS costs represent approximately 50% of total system cost. The possibility of future BOS cost reduction is examined. It is concluded that, given the nature of BOS costs and the lack of a comprehensive national effort focussed on cost reduction, it is unlikely that BOS costs will decline greatly in the next several years. This prognosis is contrasted with the expectations of the Department of Energy National Photovoltaic Program goals and pending legislation in the Congress which require a BOS cost reduction of an order of magnitude or more by the mid-1980s.

INTRODUCTION

In the commercialization of any of the solar energy technologies, cost is an important consideration. In the early days of technology development - before a large body

of experience has been accumulated - cost numbers are difficult to ascertain. Often the numbers are alloyed with a measure of unsubstantiated speculation and partisan desire. Yet realistic cost estimates are vital to the deliberation of public policy, the formulation of implementation strategy, and the assessment of cost-benefits. In this light, this report attempts to clarify a major issue concerning the cost of solar photovoltaic energy systems.

Photovoltaic system costs are commonly divided into two parts: the photovoltaic module¹ and the balance-of-system (BOS). Historically, the preponderance of effort in analyzing and defining photovoltaic costs has centered on the production of solar cells and modules; little effort has been expended in understanding BOS costs. This emphasis most likely is the result of early perceptions of priorities by the Energy Research and Development Administration (now Department of Energy - DOE) - at a time when module costs were relatively high. Pre-occupation with module cost continues to the present. This can readily be observed in publications ranging from government documents to technical journals to news articles; module cost (or more commonly what is termed array cost) is the sine qua non in discussing the economics of photovoltaic energy. By way of example, see references 1 and 2.

¹Module is the smallest, electrically interconnected, environmentally protected assembly of solar cells. The DOE National Photovoltaic Program goals are expressed in terms of module price, dollars per watt.

If in fact BOS costs are, and remain, negligible relative to module costs, then system cost will be governed by module cost and continued concentration on reducing module cost is warranted. If, however, the situation is otherwise, a new balance of effort will be required to provide the resources to define BOS costs and seek methods to reduce them.

In view of the large national photovoltaic R&D program administered by the DOE (refs. 3 and 4) and pending legislation before the Congress entailing allocation of large sums of money for the purpose of accelerating commercialization of photovoltaics (refs. 5 and 6), clarification of the BOS cost issue is timely. To this end this paper examines BOS costs for multikilowatt photovoltaic energy systems, employing flat-plate modules.

DISCUSSION

The balance-of-system (BOS) for flat-plate systems² is defined here as the total photovoltaic power system less the modules. The BOS includes the following elements:³

- o Array, Structure, and Site Preparation

- Module mounting frames
- Frame supports and foundations
- Security and safety equipment
- Site clearing, leveling, drainage

²Although P/V concentrator systems are not discussed, it can be noted that for such systems the BOS will be essentially as described herein. The major exceptions being that a portion of the array-structure category would be included in the concentrated module unit and tracking components would be included as an additional element.

³Not included are shipping, the electric power distribution lines, or the loads powered by the system.

- o Electrical
 - Wiring, interconnects
 - Control circuits/instruments
 - Load management circuits
 - Voltage regulation, power conditioning
 - Enclosure or building
- o Storage
 - Batteries
 - Racks and venting equipment
 - Enclosure or building
- o Installation and Checkout
- o Other
 - Module test and inspection
 - System sizing and design
 - Packaging and freight preparation
 - Maintenance equipment

Current BOS cost can be ascertained by examining the costs of recently installed photovoltaic (P/V) systems. The following information is derived from a detailed cost analysis of 14 P/V systems ranging in power from 25 to 3600 watts peak (ref. 7). These systems were designed by the NASA-Lewis Research Center for use in near-term, life-cycle cost effective applications. The applications were selected and sited in the 1976-78 period.⁴

⁴This activity, with one exception, is part of the DOE Photovoltaic Tests and Applications Program, managed by NASA-Lewis Research Center for the DOE. Applications and users include: forest lookout towers (2)/Forest Service; insect survey traps (2)/Department of Agriculture; water cooler/Owens Valley Inter-agency Committee, California; remote weather stations (6)/National Weather Service; refrigerator/Public Health Service; highway dust storm warning sign/DOT, Arizona; village power system for Schuchuli, Arizona/Papago Tribe and Public Health Service. A system, sponsored by U.S. Agency for International Development, for water pumping and grain grinding for the village of Tangaye, Upper Volta, Africa, was included.

Figure 1 provides a graphical summary of BOS costs in 1975 dollars. As a check on the cost analyses, three commercial manufacturers of photovoltaic systems were surveyed to obtain current BOS costs for a nominal 2 kilowatt peak system.⁵ The BOS costs obtained were in agreement with those of the above-described cost analysis. Thus, BOS costs for present multikilowatt photovoltaic systems are found to be in the range of 10 to 15 dollars per watt (1975 dollars) or 11 to 17 dollars per watt (1978 dollars).

Using the results of the analysis, the BOS costs over the range of P/V system power from about 0.4 to 4 kilowatts peak, are found to be 57% to 46% of the total installed system cost.⁶ In absolute numbers, for the 1.8 kilowatt peak system, for example, the BOS cost is \$15.60/Wp and module costs range from \$14.70 to \$18.30/Wp in 1978 dollars.⁵ These reflect actual procurement costs for BOS components, materials, and labor, and module costs on the May 1978 GSA schedule.

It is clear that BOS cost constitutes a substantial fraction of system cost. This means that as module cost continues to decline, as projected in the DOE goals, and without a commensurate decline in BOS cost, system cost will be dominated by the BOS.

⁵Module peak power based on 60°C cell temperature, 100 mW/cm² solar insolation, AM 1, measured at 15.8 volts.

⁶It is of interest to mention that all of the above systems were designed to power d.c. loads; as such no d.c.-a.c. inverters were used. (If an inverter were needed, the BOS costs would increase accordingly.) The operating voltages, depending on application, ranged from 12 to 120V.

What is the prognosis for reducing BOS cost? That question can best be answered by undertaking a detailed economic and technical analysis of each element of the BOS. In the absence of such an analysis, it is possible to appraise the difficulty involved in reducing BOS costs and examine some of the more likely options for cost reduction. Therefore, in the interest of gauging this important matter, the following is offered.

Starting with the distribution of cost among the several BOS elements, it was found that for the 14 P/V systems examined in reference 7, the spread was as follows:

<u>BOS Element</u>	<u>% of BOS Cost (Average for 14 Systems)</u>
Array, structure, site preparation	18
Electrical	33
Storage	20
Installation and checkout	20
Other	9

As can be seen there are no dominant elements overshadowing the others in cost. With a spread of this sort, the pursuit of possible cost reduction needs to be undertaken across the board.

Next, we observe that the items of material of the BOS, e.g., structural steel or aluminum, concrete, electrical wire, batteries, are all products of relatively mature technologies and production. Some moderate reduction in unit cost for

energy storage may be anticipated,⁷ but for the other BOS items, components and materials, there is little reason to expect reduction in unit cost. Likewise the unit cost of labor associated with each BOS element cannot be expected to decrease.

Nevertheless, there appear to be approaches that may help bring about overall BOS cost reduction. These lie partly in the realm of the module, partly in the system assembly and installation, and partly in standardization.

Improvements in solar cell efficiency and increases in module packing efficiency (projected cell area/module area) will result in increased power generated per unit area of module. A factor of three improvement in module power may be conjectured.⁸ The effect of increased power per unit

⁷For lead-acid batteries (traction or float service batteries) now used in P/V systems, the best that may reasonably be expected in cost reduction would be to approach the level of cost for starting/lighting/ignition (SLI) batteries. SLIs, now made by semi-automatic production methods, cost \$50/kWh. Traction and float service batteries manufactured using non-automatic production methods cost approximately \$75/kWh. It should also be noted that for the SLI battery contributions to the selling price are as follows: 55% materials; 5-7% labor, 38-40% plant overhead, taxes, profits, etc. Redox energy storage, now emerging from technology development, may provide storage at \$40/kWh (in 1978 dollars) by the mid-1980s.

⁸The most recent Jet Propulsion Laboratory procurement of modules for DOE, Block III, have packing factors ranging from 54% to 71%. The maximum practical packing efficiency (assuming square or rectangular cells) is about 90%. Encapsulated cell efficiency for Block III modules ranged from 9.6% to 11.7%. Based on the practical limits of efficiency believed to be achievable for space-type silicon cells (but not yet realized), ultimate cell efficiency under terrestrial conditions might approach 20%.

area of module will cascade through the system, resulting in smaller array size, less support and foundation, less labor for installation, etc. It should be recognized, though, that increases in cell efficiency will frequently be gained at increased cost. At this point in time it is impossible to know where the crossover lies between system cost credit for increased cell efficiency and increased system cost for more efficient cells.⁹

Another area where BOS cost reduction may be possible involves system assembly and installation. This too is a trade-off situation. If more of the subsystem and system assembly tasks are performed in a factory setting, the work can generally be accomplished at a lower cost than in the field. This approach will reduce field installation time and associated costs.

Standardization of parts as well as reducing the number of system designs to some small number will help reduce system cost. It can be observed that up to now almost all systems deployed of a few hundred watts or more have had individual designs. The introduction of an "all purpose" power system unit would allow economies to be achieved by using standard

⁹ It is possible that as module price decreases BOS costs, particularly those which are area sensitive, may set a floor to system cost. Therefore, careful consideration is needed of the effect on system cost of "low cost, low efficiency modules". A case in point might be thin film cadmium sulfide and thin film polycrystalline silicon modules. These may eventually be produced at a very low cost, i.e., DOE goal, 10¢ to 30¢ per peak watt, but because of inherent limitations, it may not be possible to realize better than 10% efficiency.

parts, standard assembly lines, and standard installation procedures. Additionally such a system should be modular so that a power system once installed could be enlarged in power level and function by the addition of the required number of "all purpose" P/V system units.

CONCLUDING REMARKS

Significant reduction of BOS costs will not be easy, inasmuch as costs are spread among several major and disparate elements; thus, cost reduction of items in any one BOS element will not markedly reduce the total BOS cost. Also, the BOS is composed of materials and parts which are products of relatively mature technology and production. Further, the possible cost reduction approaches mentioned herein do not unequivocally assure large BOS cost reduction, since trade-offs are involved in most instances. In any event, the probability of achieving potential BOS cost reduction is not great in the absence of a comprehensive well focussed program (comparable to the DOE Low-Cost Solar Array Project) to address the BOS cost problem in a system context.

In view of the above, the author believes it unlikely to expect BOS costs to decline greatly in the next several years - certainly not by an order of magnitude or more as has been projected by others. Thus, the BOS cost prognosis given here is in disagreement with the BOS cost inferred from the 1982 and 1986 energy cost goals found in the DOE National

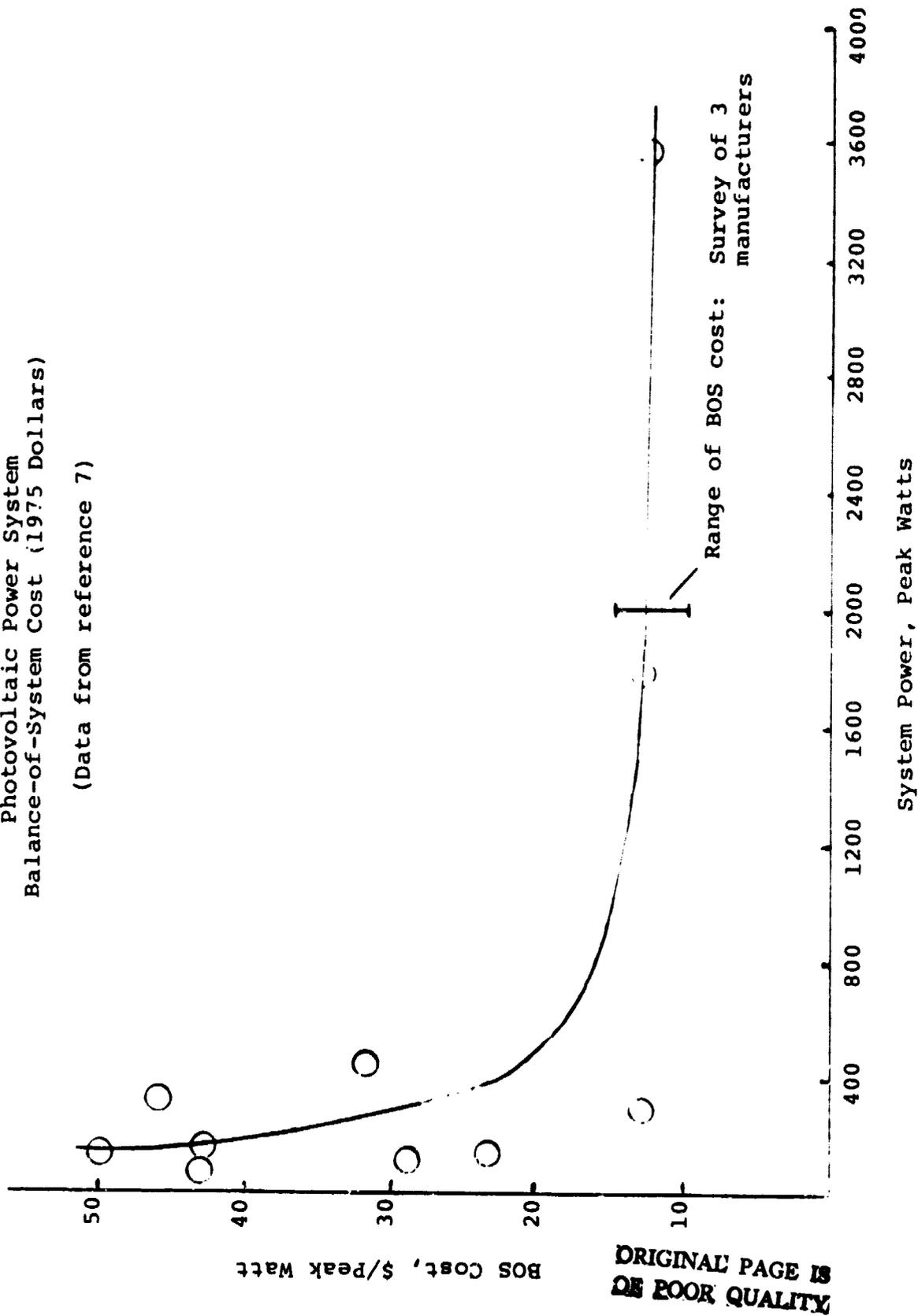
Photovoltaic Program Plan (ref. 3). To meet the stated DOE energy cost goals, BOS costs of about \$1.00/watt peak and \$0.50/watt peak would be required in 1982 and 1986, respectively. Also, the same disagreement exists with HR 10830, the Solar Photovoltaic Energy Research, Development, and Demonstration Act of 1978 (ref. 6), now in Congress. A stated objective of this bill is "to reduce the average cost of installed solar photovoltaic energy systems to \$1 per peak watt by December 31, 1988". The \$1 per peak watt system cost implies \$.50 per peak watt BOS cost (assuming \$.50 per peak watt module cost).

Accurate estimates of future BOS cost for photovoltaic systems can only be made by a careful and thorough analysis of technology options, system trade-offs, and production costs. Such an analysis can also provide guidance for technology development and system design approaches that are most likely to produce BOS cost reduction. In the absence of such an analysis and in the absence of a national focus on mastering the BOS cost problem, the credibility of the stated national photovoltaic goals and objectives is uncertain.

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Figure 1
Photovoltaic Power System
Balance-of-System Cost (1975 Dollars)
(Data from reference 7)



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