DESIGN CONSIDERATIONS OF SOLAR ARRAYS FOR TERRESTRIAL APPLICATIONS*

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Abstract

The use of photovoltaic solar arrays for terrestrial applications poses a number of unique requirements which must be addressed by the array designer and user. The requirements result from the physical characteristics of photovoltaic devices, the nature of typical terrestrial photovoltaic applications, the demands of the terrestrial environment, and the competitive forces associated with the terrestrial power supply market. Various terrestrial array requirements and design considerations are discussed both in terms of the current state-of-the-art and in terms of the goals of the U.S. National Photovoltaics Program. Included are discussions of the relative performance of various array module designs currently on the market together with thoughts for further design improvements.

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Introduction

Though solar photovoltaic arrays have been used for many years as a primary source of power for space vehicles, the terrestrial use of photovoltaics has come into prominence only within the last couple of years. In support of decreased dependence on our limited fossil and nuclear fuel supplies, the U.S. Energy Research and Development Administration (ERDA) has an active program which addresses the greatly expanded development and utilization of terrestrial photovoltaic systems[1]. A major part of the National Photovoltaic Program is centered at the Jet Propulsion Laboratory and is referred to as the Low-cost Silicon Solar Array (LSSA) Project.[2] The primary objective of the LSSA project is the timely development of low-cost commercial-quality photovoltaic arrays through an active program of industrial and academic involvement. Analysis of the current state of terrestrial photovoltaics technology and the definition of future array requirements is an important and necessary step toward meeting this objective.

II. Array Requirement Definition

The examination and development of array requirements is a cooperative effort involving all elements of the National Photovoltaics Program together with the array manufacturers, power system designers, and potential users.

Understanding the user and power system needs is critical to the success of the array development effort. To this end, the ERDA program contains three major system-oriented activities, a mission analysis activity to identify and evaluate potential user groups and their system needs, a system analysis activity to examine the development of system designs to meet the user needs, and a demonstration program activity to evaluate and demonstrate final system performance. An active attempt is also being made to work with present and potential users in the development of requirements to meet their specific needs.

A second important ingredient in the definition of terrestrial array requirements involves understanding the solar array design factors and sensitivities which result from the physical characteristics of the photovoltaic devices themselves and the manufacturing factors affecting their production. To achieve this understanding the LSSA project has a broad program directed toward the design, manufacturing, and marketing factors affecting array price and performance. These activities include cost studies of various manufacturing approaches, experimental programs aimed at both device

and manufacturing process improvement, and the procurement and testing of present state-of-the-art solar arrays.

A third major ingredient of the requirement definition process involves characterizing the natural terrestrial environment and developing appropriate environmental test requirements. These requirements must be consistent with both the operational lifetime needs of the potential user groups and the economical and technical constraints associated with available manufacturing methods.

The remainder of this paper presents an overview of array requirement trends beginning to evolve from the various ERDA activities and contrasts these trends with the current state of the terrestrial photovoltaics technology.

III. Array Design Considerations

For present terrestrial arrays the primary requirement is to generate power for small, often remote electric-power applications. Typical examples include radio relays, navigational lights and horns, and remote climatological and environmental instrumentation. As shown in Table I, the nature of these applications, their size, their diversity and their technical needs strongly influences the characteristics of current arrays. Likewise, the applications are limited to those which can profitably utilize current array characteristics at their present high price.

To meet an objective of increased energy independence requires that photovoltaics become economically viable for large energy consumption of the future. The obvious applications with significant energy usage include central electric utilities, industrial and commercial applications, and residential applications. As indicated in Table II, these applications place significantly different requirements on future solar arrays.

The largest requirement change is in the area of cost. Whereas small remote applications can achieve cost effectiveness with array prices of $30/watt and higher, large scale applications require array prices of 50¢/watt and less to compete with conventional means of electrical energy production. A major thrust of the ERDA program is directed at achieving this cost reduction through a combination of technological advances and mass production methods. Approximately three fourths of the current cost of solar arrays is involved in the solar cells themselves. This is spread more or less equally between the cost of the silicon, the cost of making a single crystal wafer, and the cost of implanting the diode junction and metalization.

Table I. Present Array Characteristics Versus Present Photovoltaic Power Application Characteristics

Present Application Characteristics	Present Array Characteristics
Small diverse markets, often requiring custom treatment, but individually incapable of supporting a significantly different array design or mass production methods.	Widely varying designs between manufacturers. Each manufactuer's line easily adaptable to widely varying applications and geared to hand assembly operations. Little or no interchangeability between manufacturers.
Consume less than 1000 watts of low voltage (<40 volt) DC power generally to charge storage batteries.	Modular design for various low power and low voltage levels consistent with typical lead-acid batteries. Electrical safety at low voltages not of concern.
Capable of paying a high price ($30/watt) for power and of buying a complete system just for evaluation purposes.	Moderately high priced, with primary emphasis on real time performance demonstration. Support structure and installation costs of secondary importance.
Subjected to widely varying environmental extremes, generally in remote areas.	Designed for low maintenance under widely varying environmental extremes.

Table II. Future Array Characteristic Versus Future Photovoltaic Power Application Characteristics

Future Application Characteristic	Future Array Characteristic
Large markets each capable of supporting a significantly different array design and mass production methods.	Distinct array designs for significantly different applications, produced by mass production methods. Standardized interfaces to allow interchangeability between manufacturers for same application.
High power, high voltage AC loads.	Modular design for high power, high voltage levels and consistent with electrical codes for insulation, grounding and safety features.
Require energy costs consistent with electric utility rates, are unable to accept significant risks and cannot afford to purchase a system for evaluation purposes	Low-cost, long-lifetime designs with proven performance histories and consistent with low system cost (e.g. low support structure cost) and low installation and maintenance costs.
Cost/benefit may be improved by photovoltaics providing additional functions such as: . Aesthetic/architectural functions . Water barrier functions as the exterior surface of dwelling or roof . Thermal-heating functions as combined photovoltaic/solar-thermal heating panels.	Will contain other functional attributes as as a means of improving cost/benefit to user.

With the achievement of 50¢/watt arrays the primary cost drivers will begin to shift toward the other elements of the photovoltaic power system. The cost of the array support structure and installation and maintenance (I&M) costs become very significant and suggest increased emphasis toward maximum power output per unit area, and the incorporation of features which reduce I&M costs. The use of larger array modules could, for example, serve to both minimize lost border area and minimize electrical and mechanical installation cost.

The effective cost of solar arrays can also be reduced indirectly by designing arrays to serve other functions in addition to power generation. By using arrays as shingles on a dwelling roof, not only is the support structure provided essentially free, but a major portion of the cost of conventional shingles could be written off against the arrays.

Another important factor influencing future array designs is the probable use of high voltage levels (250 volts and higher) and the attendant electrical safety needs associated with such voltages. Insulation integrity, module grounding, and electrical terminal protection will require substantial changes from current practices developed for low voltage applications. Special emphasis will have to be placed on personnel safety in recognition of the fact that photovoltaic arrays are difficult to turn off. The use of standardized shielded electrical connectors may serve to both improve electrical safety and minimize array installation time.

Another important factor behind the changing array requirements is the general inability of private industry to accept large financial risks or to fund demonstration efforts to lessen the risks unless the potential payoff is large. With the present small-remote applications the total financial risk is small relative to the potential payoff. This is partially due to the lower system cost, but largely due to the fact that the primary risk, per user, is with a few demonstration units, whereas the payoff is generally associated with a large number of deployed systems. With large systems, the number of systems per user is small and the relative cost of demonstration is therefore higher. In addition, the cost per demonstration is higher, and the potential payoff (mills per kW-hr) is less.

In the future these factors will place increased emphasis on proven performance history and manufacturer reputation and stability. Whereas users with small applications will continue to demonstrate (qualify) custom array designs, future large array users will require previously qualified array designs with known performance. One means of achieving this is through increased

standardization which will allow a limited number of possibly government assisted demonstrations to qualify designs for use in a variety of applications.

There are a number of elements of standardization which will require treatment in future array designs to guarantee performance and long term availability and interchangeability. Standardization of exterior dimensions including mounting hardware and tolerances is an obvious first step. Common electrical termination techniques such as shielded connectors would allow safe and efficient electrical connection and minimize installation and maintenance time.

Standardized performance is a more difficult problem that must be faced. Present solar cell and array characteristics vary considerably from manufacturer to manufacturer and make electrical interchangeability next to impossible. Power and voltage nomenclature also vary significantly. Although most electrical performance is rated at an air-mass-one solar insolation level of 100 mW/cm^2, the name plate rating may be maximum power at a standard test temperature of 28°C, short circuit or maximum power current, or some nominal power. Voltage rating is equally varied and may include maximum power voltage at 100 mW/cm^2, AM1 and 28°C, or some nominal working voltage such as 12 volts, if the array is designed to charge a 12 volt battery.

Because array electrical performance is strongly coupled to array operating temperatures, any attempt at standardization must also account for operating temperature variations between designs. Fig. 1 indicates the large difference in operating temperatures measured from a cross-section of presently available solar array modules. If each module design had the same power output at 28°C the hottest modules in Fig. 1 would have nearly 20% less power than the coolest under typical operating conditions. This amount of variation reflects not only as more or less power per "nameplate" watt, but seriously limits module interchangeability because of series/parallel mismatch losses.

Another factor which is important to future large-scale array acceptance is guaranteed or demonstrated operational lifetime. The operational lifetime of present arrays is based on limited historical field performance data together with real time field trials or demonstrations. Many of these data are compromised by the rapid obsolescence associated with the steady adoption of improved technology and manufacturing methods. The needs of future large-scale users will require increased emphasis on accelerated testing and analytical lifetime prediction techniques. The development of such techniques together with the more general problem of interface and performance standardization is an active and important part of the ERDA program.

Conclusions

The application of photovoltaic solar arrays to future large-scale terrestrial applications has been shown to require a number of changes from present terrestrial array technology. The changes result from the high cost of present photovoltaic devices, the nature of future power applications, and the financial forces associated with the future terrestrial array market. It is the purpose of the U.S. National Photovoltaics Program and in particular the JPL Low-cost Silicon Solar Array Project to achieve these changes in an orderly and timely manner with the active participation of private industry and academic institutions. Substantial progress has been made to date in all areas of array design improvement, and the prospect of future large-scale photovoltaic application appears very promising.

References

1) Magid, L. M., "The U.S. Photovoltaic Conversion Program," Presented at the International Colloquium on Solar Energy, Toulouse, France, March 1 - 5, 1976.

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