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Meteorologic/Atmospheric Effects on the Performance of Solar Photovoltaic Energy Conversion Devices

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METEOROLOGIC/ATMOSPHERIC EFFECTS ON THE PERFORMANCE OF SOLAR PHOTOVOLTAIC ENERGY CONVERSION DEVICES

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1. INTRODUCTION

Photovoltaic energy conversion devices and power systems constitute one option for renewable energy supplies. Such devices/systems convert available solar radiation (insolation) directly to electricity by means of the photovoltaic effect. A wide variety of materials, devices, and systems are under consideration and development by the Department of Energy (DOE), universities, industry, and others, Prince (1983). The ultimate goal of such research and development is to eventually produce and install photovoltaic products that will have a significant impact on our nation's energy supply, Annan (1983). In order to accomplish this, the cost of electricity produced by such systems must become comparable to the cost of electricity from other new generation options, Taylor (1983). In addition to the cost requirement on photovoltaic power systems, such systems and devices will have to produce electricity reliably and predictably so that they produce electricity in harmony with other systems/power plants (conventional).

The purpose of this paper is to highlight and summarize those meteorologic/atmospheric effects on the performance of solar photovoltaic energy conversion devices (and systems). Areas of performance considered will include the production of electricity, cost, reliability, and predictably. All of these areas, as discussed above, impact the ability of photovoltaic devices, systems, and power plants to eventually become a significant source of electricity for the United States. In addition, this paper will identify the pertinent meteorologic, atmospheric, and solar radiation data required to ensure the proper research, development, design, application, and operation of photovoltaic devices, systems, and power plants.

2. PHOTOVOLTAIC/SOLAR ISSUES

Taylor (1983) has identified and discussed several "solar issues" which must ultimately be considered and resolved if photovoltaic systems are to become a viable energy-significant option. Those issues are catagorized as follows.

Planning
- Load forecasts
- Energy displacement
- Capacity factor
- Mix reoptimization
- T&D design

Institutional
- Rate structures

- Financing
- Incentives
- Environment
- Ownership
- Safety
- Siting

Operations
- System reliability
- Reserve margin
- Maintenance
- Dispatch
- Weather forecasting

Hardware
- Plant construction
- T&D construction
- Performance characteristics
  - Solar power device
  - Interface components
  - Existing system
- Cost

The following is a selected list of elements, from the above list, that are impacted/determined (in part) by meteorological/atmospheric conditions.

- Energy displacement
- Siting
- System reliability (design)
- Weather forecasting
- Performance characteristics
- Cost

Accurate meteorologic, atmospheric, and solar radiation (insolation) data and scientific understanding are required to help resolve and address the above elements. The remaining section of this paper will discuss the specific meteorological/atmospheric/solar radiation data and parameters that effect research, development, design, and application of photovoltaic energy conversions systems.

3. PHOTOVOLTAIC SYSTEM ELECTRICITY PRODUCTION

The amount of electricity produced by a given photovoltaic system can be given as

$$E = H \cdot \eta_s \qquad (1)$$

where E is the electrical energy produced (per unit time and area of photovoltaic collector/array), H is the incident solar radiation (insolation) per unit area and time (hour, day, month, annual), and η_s is the effective system efficiency over the time period and conditions (as related to H) that E was produced. Equation (1) obviously shows that the output of a photovoltaic system is directly proportional to and strongly driven by the amount of solar radiation incident on the collector (array).

If one were to utilize Equation (1) to design a photovoltaic system and/or predict electrical energy production at a specific geographical site then one would require insolation data (H) for that site. The insolation data required depends on the particular collection approach used. Currently, the following collection approaches are in general use.

- Concentrators (focusing) - direct beam insolation
- Fixed Flat Plate - total insolation on a fixed tilted surface
- Tracking Flat Plate - total insolation on a tracking flat plate.

Also shown above is the specific insolation component required according to the collection mode (direct beam, total on fixed tilted surface, and total on a tracking flat plate). For a specific geographical location, the relative amounts of insolation available to each of the collection modes will depend on the relative mix of direct beam and diffuse (sky and ground reflected) insolation. This mix is largely determined by the meteorological (cloud cover) and atmospheric conditions (water vapor, aerosols, etc.) at the site (along with site latitude). Therefore, meteorological/atmospheric conditions effect the selection of the collection mode of a photovoltaic system.

4. PHOTOVOLTAIC SYSTEM EFFICIENCY

The system efficiency term, η_s, shown in Equation (1) is a fairly complex function made up of several other components which are associated with the various components of a photovoltaic power system. In general these components consist of the following,

- Photovoltaic array/collector,
- Power conditioning, and
- Storage.

The photovoltaic array is made up of individual photovoltaic devices/cells which make up individual photovoltaic modules which make up the array. The overall system efficiency, η_s, is a function of the specific efficiencies of the array, modules, devices/cells, power conditioning, and storge ocmponents.

The efficiency of a specific photovoltaic device/cell is a function of the broadband (insolation) and spectral characteristics of the incident solar radiation. This is due to the fact that photovoltaic devices/cells are spectrally sensitive (spectral response). The specific spectral response and efficiency of a photovoltaic cell depends on the particular material(s) used, temperature, method of construction, etc. A wide range of methods and materials are being addressed in order to achieve high efficiency devices and low cost, Prince (1983).

Due to the fact that photovoltaic devices are spectrally sensitive, their performance depends on the spectral nature of incident solar radiation. The spectral characteristics of solar radiation are determined by meteorologic/atmospheric conditions. The more important meteorologic/atmospheric parameters are aerosols/turbidity, water vapor, and cloud cover, as shown by Bird and Hulstrom (1981). Researchers in the area of photovoltaic devices attempt to develop devices which have a spectral response which maximizes the capture of solar radiation energy. In order to do this they require an understanding and knowledge of the spectral characteristics of terrestrial solar radiation. Since meteorologic/atmospheric conditions determine - along with the nature of the extraterrestrial solar radiation and relative air mass - the nature of the terrestrial spectral radiation at a given site (climate), it may be beneficial to consider tayloring photovoltaic devices to various climates to maximize performance. This would require a knowledge of the spectral characteristics of solar radiation for various climates in the U.S. In order to generate such data one would have to make such measurements and/or utilize meteorologic data such as turbidity, water vapor, and cloud cover as inputs to models which would estimate the spectral data.

5. PHOTOVOLTAIC ELECTRICITY COST

The cost of electricity from a photovoltaic plant can be calculated, Taylor (1982), as follows:

$$\overline{EC} = \frac{FCR}{8760\ \ CF}\,[INDC]\,[A(\$MSQMD+\$MSQBS)+\$KWBS] + A\ \ G\ \ CRF\ \frac{\$MSQOM}{8760\ \ CF} \qquad (2)$$

where:

$\overline{EC}$ = levelized energy cost in $/kWh
FCR = annual fixed charge rate
CF = annual system capacity factor (the ratio of energy produced divided by the product of peak capacity times the number of hours in the year)
INDC = indirect cost multiplier (to account for the costs associted with marketing, distribution and installation of systems)
G = present worth factor for recurring O&M costs (a function of the inflation rate and the discount rate)
CRF = capital recovery factor (a function of the discount rate and system lifetime)
A = 1/(Average Peak Insolation) (Systems Efficiency)
A is the plant aperature area required to generate 1 kilowatt of ac power at the busbar under typical operating conditions, which are site specific
System Efficiency = balance-of-system (BOS) efficiency times the module efficiency for flat plate systems; and BOS efficiency times optical efficiency times cell efficiency for concentrator systems
$MSQMD = module cost in $\$/m^2$ for flat plate systems and $\$/m^2$ (aperature) for concentrator systems
$MSQBS = balance-of-system area-related costs in $\$/m^2$
$KWBS = balance-of-system power-related costs in $/kW
$MSQOM = annual operation and maintenance costs in $\$/m^2$-year

The module cost necessary to produce a given electricity cost is based on the preceding electricity cost equation and is calculated as follows:

$$\$MSQMD = \frac{1}{A} \quad \overline{EC} - \frac{(A \quad G \quad CRF \quad \$MSQOM)}{8760 \quad CF}$$

$$\frac{8760 \quad CF}{INDC \quad FCR} - A \quad \$MSQBS - SKWBS \qquad (3)$$

The parameter A in Equation (2) and (3) is determined by insolation characteristics and system efficiency both of which are dependent upon meteorologic/atmospheric conditions. The module cost necessary to produce a given electricity cost is inversely proportional to the product of insolation and system efficiency.

Taylor (1983) has performed analyses to determine the requirements for photovoltaic system and module efficiency to produce electricity at a competitive cost at three locations (Boston, Miami, and Albuquerque) and for various module costs. The impact/effects of the different climates (meteorologic/atmospheric conditions) on required efficiency is very clear. For example, if one selects $\$50/m^2$ as a module cost (flat plate), the required system efficiency at Boston is approximately 12% whereas Albuquerque is only 7%. Boston receives an annual average of about 8 MJ/m^2/day on a south facing tilted surface (latitude) whereas Albuquerque receives about 18 MJ/m^2/day.

6. PHOTOVOLTAIC SYSTEM DESIGN

The designing of a photovoltaic system is quite complex and is driven strongly by the intended application and the available insolation at the intended location.

One aspect of the design is that of "load matching". Electrical loads/consumption are generally defined on an hourly bases and they display significant hourly variations. As a result the photovoltaic system designer requires insolation data on an hourly basis. Meteorologic/atmospheric conditions not only determine the level of insolation but they determine the hourly profile throughout the day. This profile is mainly determined by the characteristic cloud cover pattern at a given site. Therefore, if hourly data for insolation is not available, hourly observations of opaque sky cover is extremely important. Opaque sky cover data can be utilized to predict the hourly pattern of insolation.

7. PHOTOVOLTAIC SYSTEM OPERATION

As shown in section 2, weather forecasting is pertinent to the operation of a photovoltaic power plant. In order to properly integrate and manage the photovoltaic power plant one needs to know its expected power production on a temporal basis. Since the amount of power produced by the photovoltaic power plant is determined by the available insolation one essentially needs to be able to forecast the available insolation for anywhere between one hour to probably a day or three days in advance. In order to forecast insolation one requires a weather forecast which includes cloud cover (as an absolute must), turbidity and water vapor.

8. SUMMARY

This paper has attempted to point out the effects of meteorologic/atmospheric conditions on the cost and performance of photovoltiac device/systems. Because of the importance of such effects, the photovoltaics community require certain meteorologic/atmospheric and insolation data from the meteorologic/atmospheric science community. Some of the more pertinent data needed are:

- Hourly (at least) insolation data for the direct beam, fixed flat plate surfaces, and tracking flat plates,
- Spectral (.3 to 2.5 μm) terrestrial solar radiation data representative of the various climates in the U.S.,
- Turbidity,
- Water vapor (precipitable), and
- Opaque sky cover (hourly).

Having such data as listed above, will help ensure effective photovoltaic device/system research, development, design, and operation.

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