

Chapter 1. INTRODUCTION

As overall world energy use increases and conventional fossil-based resources contribute a diminishing fraction of the total demand, developing new resources and energy conversion technologies becomes increasingly important. Preferred replacement resources and conversion technologies are those which are expected to be sustainable, available in sufficient quantities when and where needed, and have minimal environmental impact. Electricity generation via photovoltaic energy conversion is one option which demonstrates these desirable characteristics. This thesis introduces a new computer-based method for estimating the performance of a subset of photovoltaic power generation systems which operate in a manner referred to as direct-coupled operation.

1.1 Thesis Organization

The first part of this chapter is background: basic principles, history, and applications of photovoltaic (PV) power are outlined in order to better define specific aspects of direct-coupled PV performance modeling addressed in this thesis. The second part of this chapter provides an overview of available models. The final part outlines key components of a new performance analysis method. Chapters 2 - 4 explain the various steps which make up the new method. Chapter 5 describes a long-term performance model based on the new method and simulations which were run to assess the validity of the new model. Chapter 6 discusses the results of the simulations, and offers recommendations for improvements to this work. Program flowcharts, FORTRAN codes,

and auxiliary calculations are contained within the Appendices.

1.2 Background

Photovoltaic energy conversion is the direct conversion of light energy to electric energy. PV power is generated when the following conditions are satisfied. Radiation of appropriate wavelengths must be absorbed by an upper layer of dissimilar semiconducting materials so that some electrons jump to a higher conducting band energy level, thereby creating mobile electron/hole pairs. The electron/hole pairs must then migrate to opposite sides of a built-in voltage barrier between the dissimilar materials, where the charges are collected at low resistance metallic contacts. Direct-current (DC) power can be extracted if the two oppositely charged contacts are then connected through an external load circuit. Desired currents and voltages are obtained by connecting cells in series and parallel to form modules, and by aggregating modules in series and parallel groupings to form arrays. Though the magnitudes of currents and voltages differ, the electrical characteristics are similar for cells, modules, or arrays.

This study is concerned with macroscopic PV effects in terms of the current, I , and voltage, V , that can be produced when the conditions listed above are satisfied. The complex microscopic phenomena of how charges are created, separated, and collected are not considered. Typically, the semiconductors used are silicon and silicon alloy, although several other compounds are also used. Gallium arsenide based cells have demonstrated higher efficiencies than silicon and their commercial importance is increasing [1]. The modeling techniques developed in this thesis are applicable for any PV material, as long

as the material's characteristic bandgap energy is known. It is also beyond the scope of this study to examine how factors such as doping, layer thickness, structural imperfections, and others affect the conversion efficiency of the PV cell. Rather, the intent here is to examine how the current-voltage-power characteristics of commercially available PV modules vary with radiation intensity (measured in Watts/m²) and temperature. There are a number of texts available which detail PV device theory; among them, Sze [2] and Kreider [3] are recommended.

The photovoltaic effect was first reported in 1839 by Becquerel, yet commercial development for power production did not begin until the mid 1950's [3]. Until the mid-1970s, PV power was used almost exclusively for spacecraft applications. Production costs, although dropping steadily from about \$100/W (peak rated output) in 1962 [4] to as low as \$2.50/W in 1988 [5], have, until recently, been too high for PV generation to be competitive with conventional power sources for most terrestrial applications. Although today's cumulative PV electric capacity of about 160 MW (based on data from Kreider [3] and the International Solar Energy Intelligence Report [6]) is a negligible portion of the world's electric generating capacity, the industry is growing rapidly; the cumulative capacity as of 1980 was only about 5 MW.

PV is already the economic choice for many remote corrosion protection and communications applications. At \$2/W, it is anticipated that PV use would significantly penetrate markets currently supplied by the utility grid, and that at \$1/W, PV could be integrated on a large scale by utilities [7]. With such reductions in cost, and with

improvements in conversion efficiency and product lifetime, PV power is projected to increase to 5,000 - 20,000 MW by the year 2000 based on estimates from Duedney and Flavin [8], using data from the U.S. Congress' Solar Photovoltaic Energy Research, Development, and Demonstration Act of 1978. A more conservative lower bound estimate published in 1982 by the Commission of European Communities put annual world sales at 100 MW by 1990 and at least 200 MW/yr. by the year 2000 [9].

The continuing vigorous growth of PV power merits a closer look at 1) the types of applications for which PV s are being used and 2) how the performance of such systems may be estimated without relying on data from monitored prototype systems. PV systems are commonly configured in several ways to serve a variety of electrical loads. Figure 1 is a schematic illustration of some typical configuration options. Solid lines indicate the type of configurations for which this new modeling method applies, and dashed lines indicate other possibilities.

The basic distinction among system configurations is whether the end use load requires DC or AC (alternating current) power. Systems are also categorized as either stand-alone or grid-interactive. Grid-interactive systems can either deliver to, or receive power from, a utility source. Direct-coupled systems can only serve DC loads, and are limited to stand-alone applications.

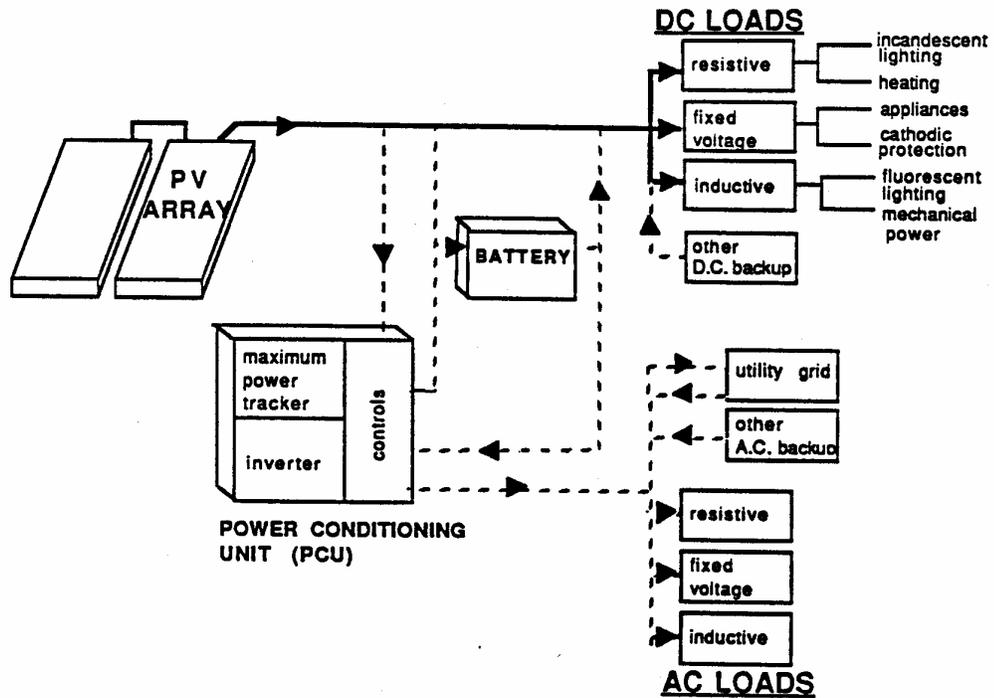


Figure 1. Typical PV System Component Configurations

Another important aspect is battery storage. Although direct-coupled systems can be (and often are) used with batteries, the method developed in this study does not apply to systems with storage. This is a likely area for future work. For all AC loads, an inverter is required. An inverter is also required if DC loads are served from an AC source. The inverter and several other components are included in a power conditioning unit (PCU). The PCU also includes system protection hardware, dispatch controls, instrumentation, and often, a maximum power tracking device.

The purpose of the maximum power tracker (MPT) is to force the array to operate at a voltage which produces the greatest power output at any moment, regardless of the voltage required to serve the electrical load. The MPT provides the most important distinction between direct-coupled and de-coupled, or maximum power-tracked, systems.

Direct-coupled systems do not use a MPT device. With the MPT, the PV system and load can operate at separate voltages.

The benefit of a MPT is due to a fundamental difference between a conventional utility power source and a PV source. A utility supply remains at a (nearly) constant AC voltage, independent of the amount of current drawn. The PV supply voltage is dependent on the amount of current being drawn and the current in turn is limited by the amount of radiation being absorbed. For a PV system at a given irradiance and cell (or module, or array) temperature, the relationship between current and voltage is fixed. This characteristic of PV power is shown below in Figure 2 for a typical module. Current values are referenced by the left side Y -axis scale, and the corresponding power values are referenced to the right side scale. The module can produce power over a range of voltages between zero volts (also called the short circuit current condition) and the open circuit voltage (current is zero at this point). There is a single I-V pair on this curve whose product represents the maximum possible power output under the given conditions. Under different conditions, the maximum power voltage will vary, and the MPT must continuously hunt to find the maximum power voltage.

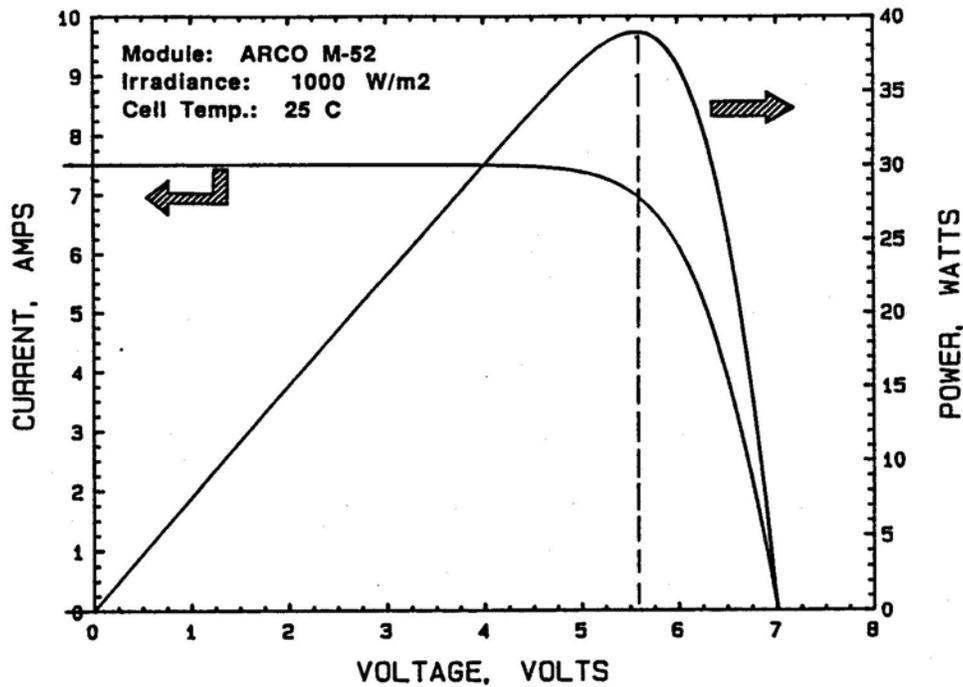


Figure 2. Sample I-V and POWER- V Curve

With maximum power-tracking electronics, the load voltage is not affected by changes in the maximum power voltage. For direct-coupled systems, however, the PV system voltage must match that required by the load. When coupled together the useful power output may be much less than the maximum possible if the load voltage is not close to the maximum power voltage. Therefore, direct-coupled systems must be designed to provide a good match between the ordinary load voltage and the average PV maximum power voltage. Photovoltaic I-V and Power-V curves are examined in detail in Chapter 2, and load I-V curves are detailed in Chapter 3. Methods for finding the intersection of the load and array I-V curves are described in Appendix B.

Despite the prospect of more efficient performance from the maximum power-tracked system, there are tradeoffs which make the direct-coupled system a better choice

for some applications. MPT devices are not 100 percent efficient; 95 percent is typical. The MPT device increases the cost and decreases the reliability of the overall system. Many stand-alone applications are left unattended for long periods and system reliability may be critical. In addition, for many load types (e.g., batteries, fixed voltage devices, and some motors), the load and array design can be matched well enough so that up to 98 - 99 percent of the maximum possible output can be extracted without the MPT [10].

From Figure 1, it is apparent that the types of loads and system configurations for which the modeling method developed in this study applies are only a subset of the possible configurations for all PV systems. However, a 1988 report issued by Battelle Pacific Northwest Laboratories referenced in the International Solar Energy Intelligence Report [6] provides some perspective on the potential utility of such a method. The Battelle report includes a historical breakdown of PV capacity produced for various market sectors. Each year, the stand-alone market has accounted for about 50 percent of all PV sales. Battelle's report indicates they expect "the potential for stand-alone applications to be extremely large," and that "the stand-alone market will likely expand at a modest rate in the future with or without government support."

PV power will be the economic choice for remote stand-alone applications such as water pumping before it becomes competitive with utility grid power because the alternatives at remote sites (batteries, small diesel generators, or human or animal power) are more expensive than electricity at locations where grid power is available. Ruedisili and Firebaugh [7] agree that water pumping (a good direct-coupled application) has one

of the highest potentials of all PV applications, with sales in the 50 - 500 MW/year range at a price of between \$5/W - \$15/W. about where the industry price is today. It is for such applications that simplified direct-coupled performance analysis methods can provide low cost system design assistance.

1.3 Existing PV Performance Models

Several computer-based (e.g., PV i-ChaIt [11], PVFORM [12], TRNSYS [13D] and non computer-based (e.g.. Colorado Mountain College [14] and Sandia National Laboratories [15] design handbooks) methods exist for estimating the performance of PV systems for a variety of applications. The simplified computer-based method developed here introduces capabilities that do not exist in any of the available methods. Non computer-based methods, although useful for many rule-of-thumb sizing chores, are not considered because the large number of hand calculations and approximations which must be made reduces their usefulness. especially when design sensitivity cases are needed.

Smith and Reiter's 1984 review [16] of PV models compares ten models based on a uniform set of topics (e.g.. power calculation equations. tracking capabilities. type of weather inputs), and examines attributes specific to each model. Their report acknowledged that other models probably did/will exist, but most were likely proprietary manufacturer's information and not useful to the ordinary system designer. PVFORM [12], a personal computer compatible program, has since been introduced by Sandia

Laboratories. In addition, a personal computer program for stand-alone system design was published in 1988 by Sunrise Associates [17].

An important distinction among models is whether the model performs simulations over frequent, usually hourly, intervals (detailed models) or whether a reduced set of calculations is done based on average behavior over a longer, usually monthly, interval (simplified models). The detailed models require extensive weather data; either actual measurements or more often, Typical Meteorological Year (TMY) data. Simplified models typically require only long term monthly average data. Detailed data are available for far fewer locations (26 U.S. sites for TMY data [18] and 38 U.S. sites for actual hourly data [19]) than long term average data (over 300 U.S. and Canadian sites [20]).

Another major distinction is whether or not the model is limited to use on maximum power-tracked systems. None of the previous available models are able to model direct-coupled loads of arbitrary I-V shape, although several are capable of modeling direct-coupled battery loads. The method presented in this thesis is the only method which uses long-term average weather data to estimate system output for direct-coupled loads of any I-V shape. Both monthly and yearly results are calculated.

Table 1 is a brief summary of available models, updated from Smith and Reiter [16]. Some of the models included in Smith and Reiter's review are not long-term performance models and are not included in the table below. To assess the validity of the

results obtained using the new simplified method a detailed model was also written, identical to the simplified model, except that it ran hourly calculations using TMY data. This reference detailed model is not listed in Table 1. Results for several cases were also compared to maximum power results from PV f-Chart and PVFORM.

There are other attributes (e.g., economic analyses) which are commonly included among the available models. The emphasis of this work is on energy calculations and, in the case of water pumping applications, volume of water pumped. Economics calculations can easily be done once performance information is known.

Table 1. PV Performance Model Summary

MODEL	ORIGINATOR	ATTRIBUTES
Townsend M.S. Thesis	UW-Madison	Simplified; Direct-coupled or Maximum Power-Tracked systems; no storage or economics; for flat plate (f.p.) collectors.
PV f-Chart	f-Chart Software	Simplified; only for Maximum Power-Tracked (MPT) systems; includes storage and economics; for fixed, tracking f.p. or con.
PVFORM	Sandia Labs	Detailed; but can skip days to speed calcs.; MPT systems only; incl. storage and economics; fixed, tracking f.p.
PVPM (PV Performance Model)	Electric Power Research Inst.	Detailed; MPT systems only; no storage or economics; fixed, tracking f.p. or con.
E&R (Engr. & Reliability)	Jet Prop. Lab	Detailed; MPT or fixed voltage operation; no storage or econ.; fixed, tracking f.p.
LCP (Lifetime Cost & Perf.)	Jet Prop. Lab	Detailed; MPT only, no storage; includes economics; fixed, tracking f.p.
SOLCEL-II (Solar Cell Model, Version 2)	Sandia Labs	Detailed w/day skip option; MPT, fixed, or battery-coupled voltage sys.; incl. stor. And econ.; fixed, tracking f.p. or con.
SOLSYS (Solar Energy System Analysis Prog.)	Sandia Labs	Detailed; MPT, fixed voltage, battery-coupled, or load $I=f(V^2)$ operation; incl. storage; no econ.; fixed or tracking f.p. or con.
TRNSYS/ASU	UW-Mad/Arizona State/Sandia	Detailed; MPT, batt-coupled sys.; incl. storage and econ.; fixed or tracking f.p. or con.
TRNSYS/MIT	UW-Mad/Mass. Inst. of Tech	Detailed; MPT, fixed voltage operation; no storage, econ.; fixed, tracking f.p.
PV-TAP	BDM/Sandia	Transient, not appl. to long-term est.
Stand-Alone Model	Sunrise Assoc/ Cleveland St.	Simplified; fixed voltage only; includes storage and econ.; fixed f.p. only.

1.4 Summary of New Simplified Method for Direct-Coupled PV Systems

The previous two sections outlined what kinds of applications PV power is being used for, how PV systems are commonly configured, and what kinds of modeling techniques are available. This section summarizes the key steps of a new model which can estimate the output of direct-coupled PV systems without battery storage. Such systems are also both "stand-alone" and "non maximum power-tracked." A detailed explanation of each part of the new model is provided in the following chapters.

The output of direct-coupled PV systems is dependent on the applied electrical load as well as on weather and PV system mechanical/electrical characteristics. Estimating the output of direct-coupled systems is more complex than for maximum power-tracked (MPT) systems, where system output is independent of the load.

For a direct-coupled PV system, the instantaneous power output is the product of the current, I , and voltage, V , at the intersection of the load and PV array I-V curves. This intersection, or operating point, can vary widely over each day. Accurate power output estimates require frequent recalculations of the operating point. Usually updates are done on an hourly (or shorter time period) basis, with the instantaneous power assumed constant over each period. The detailed models listed in the previous section work this way. However, this type of simulation method is slow, especially on personal computers. For example, the PVFORM model, which uses TMY data to perform annual simulations on an hourly basis, takes' up to 9 hours per simulation on a standard PC (20 minutes on a

PC with a math co-processor). In addition, the TMY data required by such models are cumbersome to store and available for few cities, so the increased accuracy of a detailed simulation is lost if one has to interpolate results for a location which is not one of the TMY cities.

The method presented here generates a reduced set of hourly weather data from widely available long term monthly-average global solar insolation and ambient temperature data. Correlations are used to estimate hourly weather variations within a day and also to estimate daily variations within a month. In this manner, a reduced set of "typical days" per month is established which can reduce the number of computations required by as much as a factor of ten, yet retain the accuracy of long term estimates.

The required steps are summarized below:

1. Determine photovoltaic system I-V characteristics:

A complete description of the I-V behavior of the PV system is needed for all irradiance levels and array temperatures. This requires one I-V equation with several unknown parameters. Using data obtained from manufacturer's brochures, the parameters are solved for at a reference irradiance and reference cell temperature. Some of the parameters vary with irradiance and/or temperature, so auxiliary expressions are needed to calculate the change in these parameters at other irradiances and temperatures.

2. Determine load I-V characteristics:

Several types of electrical loads can be direct-coupled to the PV array. The shape of the PV I-V curve is similar, except for magnitude, for all cells/modules/arrays. The load I-V curve shape, however, can vary considerably among load types. The method used here is to express load voltage as an explicit function of load current ($V = f(I)$). For load types such as resistive or fixed voltage loads, the expression for load voltage as a function of current can be analytical. For loads such as motors connected to pumps, fans, or other arbitrary loads, the expression for load voltage as a function of current may be entered as a set of I-V pairs, with linear interpolation used between data pairs.

3. Determine weather characteristics:

The goal is to create hourly values of the total tilted surface irradiance and array temperature that represent long-term weather statistics. Existing correlations are used to estimate hourly irradiance and temperature based on long-term monthly averages. A key assumption is that each month can be represented by a smaller number of "typical day" segments (perhaps as few as three). Monthly output is created by scaling each "typical day" output by the ratio of actual days per month divided by the number of segments per month.

4. Determine operating point and integrate results:

The hourly irradiance and temperature data established above is used to fix the array I-V characteristics. The load expressions for voltage are substituted into an array I-V equation and then an iterative solution technique is employed to solve for the operating point. The maximum power point output is also calculated for

each hour. The ratio of the actual direct-coupled output to the maximum power output provides an indication of how effective the matching is between the array and load. Methods for calculating the operating point and the maximum power point are described in Appendix B. Hourly results are aggregated into monthly and yearly totals. The model output consists of monthly plane of array insolation, direct -coupled electric output, average ambient temperature, average clearness index, and, for water pumping applications, volume of water pumped. The output also includes yearly totals for direct-coupled electric output, maximum power-tracked electric output, and their ratio; and volume of water pumped, if applicable.