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A DISCUSSION ON THE DIVERSITY IN THE APPLICATIONS OF PHOTOVOLTAIC SYSTEMS

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ABSTRACT

This paper is an attempt to classify the diverse nature of application of photovoltaic (PV) systems around the world. The five classes presented in this paper are - (i) stand alone, (ii) grid-connected, (iii) PV-thermal, (iv) PV-wind and (v) dedicated applications. 73 papers are cited and classified into these five categories including a brief summary of each paper. Out of these, 42 papers relate to grid-connected applications in many industrialized countries of the world. These papers reflect the importance given to such applications. Due to the fast changing nature of PV and the related industries only the papers published during the last 10 years have been considered.

1.0 INTRODUCTION

Photovoltaic (PV) power has found applications in all corners of the earth - from the Polynesian Islands to Ethiopian villages, and to the large utility scale projects in California. PV is used in water pumping, lighting, consumer electronics, refrigeration in third world village pharmacies, utility scale projects and space applications. Even though PV found its first applications in space, the magnitude of its terrestrial applications at this time overshadows the extra-terrestrial uses. Because of this reason, the discussion in this paper is limited to terrestrial applications, consumer electronics excluded.

Recently Sugimura and Wood [1] presented a survey of recent literature on the utility application of photovoltaic power generation. In the 79 papers they reviewed several issues related to central station and residential/intermediate systems were addressed. This paper has filled a long standing need for such a comprehensive reference. We, however, feel that the world-wide readership of the IEEE Transaction of Energy Conversion would benefit from a discussion on the diverse applications of PV systems (beyond the two listed above) that are found all over the world. Such a review would also trace how PV based systems have progressed in size and diversity over the years. For this reason our paper may be considered as a supplement of the Sugimura and Wood paper.

The objective of this paper is to present the categories into which PV power applications can be grouped, to discuss the advantages and disadvantages of using PV for such applications, and to suggest ways to improve the performance of PV systems. The categories are:

1. **Stand-alone application**
2. **Grid-connected application**
3. **PV-thermal application**
4. **PV-wind application**
5. **Dedicated application**

An extensive literature search has revealed several papers in each of these five categories. In order to keep the search comprehensive, yet manageable we have primarily consulted the following sources.

1. Proc. of the IEEE PV Specialists Conference
2. Proc. of E.C. PV Solar Energy Conference
3. Proc. of the International PV Science and Engineering Conference
4. Proc. of the Intersociety Energy Conversion Engineering Conference
5. IEEE Transactions on Power Apparatus & Systems
6. IEEE Transactions on Energy Conversion
7. ASME Transactions on Solar Energy
8. Solar Energy

It must be noted, however that the bibliography in this paper is representative, not exhaustive. We have therefore, not reviewed any of the PV related reports that have been published over the last several years. We take the position that authors of these reports would have published their significant findings in one or more of the publications listed above. Moreover, for the sake of conciseness not all PV related papers in these journals are cited. We have tried to include papers which are typical of the concepts discussed in this paper. We may have missed some important papers in this process and would hope that readers would understand the constraints we are faced with.

This paper is divided into five sections according to the five categories listed above. For each category the state-of-the-art technology and application are discussed and its unique features are pointed out. It is expected that such categorization will be beneficial both to the users and manufacturers in identifying the appropriate application of PV power.

2.0 STAND-ALONE APPLICATION

Stand-alone application is one of the original applications of PV power. Significant among these are the rooftop modules used for serving the lighting needs of village households. These are generally DC systems providing upto 100 watts of electric power, and have battery back-up. These systems have been found to be price competitive with diesel electricity or kerosene or benzene lighting in Fiji, French Polynesia, Western Samoa and the Cook Islands [2]. These small PV systems are privately owned and are now competing against commercial fuel for production of electricity. Additional uses of stand-alone PV power include radio, TV, refrigeration, hospitals, communications, street lighting and water supply. There are of course numerous examples of remote, stand-alone PV demonstration projects all over the world. A great majority of them, however, have been designed to test the technical rather than the economic feasibility. These include the remote home power system project on the Navajo reservation in U.S.A. [3], the PV power system project for the Indonesian village in Picon in West Java [4], the multipurpose Chinese-German stand-alone solar energy project near Beijing, China [5], the rural electrification program in French overseas territories [6], the electrification of six remote localities in Girona, Spain to demonstrate the feasibility of decentralized PV application [7], the electrification of a village in an isolated island in Japan [8], the construction and testing of the 300 kW Delphos PV plant in Italy for the

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dual operation in stand-alone and grid-connected modes [9], the 350 kW concentrating PV power system supplying power to three remote villages in Saudi Arabia [10], the 10 kW PV powered agricultural experimental school in Egypt [11], the 100 kW PV power system for the Natural Bridges National Monument in a remote part of Utah (U.S.A.) [12] and the stand-alone village PV electrification program in Salojpalli in Andhra Pradesh (India) [13]. Almost all of these projects use some form of storage and/or diesel backup.

There are other papers which address various operational issues dealing with stand-alone PV systems. For example, Kanematsu et al [14] present the dynamic characteristic analysis for the inverter/battery combined power conditioning of a stand-alone PV project in Okinawa, Japan. Furthermore, for stand-alone applications, the load management becomes an important issue. As designers attempt to minimize both the array size and storage requirements for optimizing the system design, it often becomes necessary to serve a diverse nature of loads using limited resources. Groumpos and Papageorgiu [15] discuss the optimum load management strategies for stand-alone photovoltaic energy power systems. They take the approach of minimizing the life-cycle cost of the system and improving the battery life while maintaining the load priorities. Cull and Eltimsahy [16] also discuss the need for energy management for PV systems and present an analytic tool that can be used to determine the proper control algorithms and control variables for a range of applications with or without applying energy management.

3.0 GRID-CONNECTED APPLICATION

It is the informed judgement of the experts that PV systems will make their mark in developed countries through large scale grid-connected applications. This is substantiated by various completed or ongoing projects in U.S.A., Europe and Japan. Sugimura and Wood [1] present a bibliography of 79 papers that surveys the recent literature on utility application of photovoltaic power generation.

One of the purposes of the current paper, however, is to give the reader an overview of the types of grid-connected PV projects in existence all over the world, control systems used, types of cells, power conditioning systems, and a performance comparison of some selected systems. This overview is expected to be useful for utilities in deciding which alternatives would be best for their application, and for manufacturers to evaluate the market trend and the relative success of some designs vis-a-vis others.

A considerable amount of work has been done on the integration of photovoltaic (PV) systems with the electric utility. Such PV systems studied vary from simple residential systems to large MW-sized central stations. The existing literature may be divided into three general categories according to the nature of the study. These are:

- Systems Study
- Operations Study
- Planning and reliability study

Systems study belongs to a group where only the photovoltaic system is examined in the light of the solar resource. Operational study comprises of the investigation into the specific nature of the impact of the PV systems into the utility's existing network. Such effects may be harmonics and power factor effects, generation scheduling effects, frequency control effects, etc., all of which relate to the short term impacts. Planning and reliability study on the other hand refers to the long-term impact on the utility. Factors that are of interest in this study are long term expansion planning , capacity credit, reliability study, etc. The relationship among these three avenues of research are illustrated in Figure 1.

The following discussion exemplifies the research literature available in each of these areas.

3.1 Systems Research

The survey is initiated with a number of reports from large central station power projects which are already operating in interconnected mode with electric utilities. Other aspects of the systems research are then explored.

Patapoff [17] discusses the design and construction process for three large photovoltaic facilities in Lugo, Carissa Plains and Sacramento, California. These plants are operating as central station power plants providing their host utilities with additional resources in their energy mix. The Lugo facility is rated at 1 MW, built by ARCO Solar and is interfaced with a 12 KV distribution system of the Southern California Edison Company at Hesperia, CA. The monthly average of the 24-hour capacity factor of this plant has varied between 21% and 37% during its operation. The author points out an important feature of the system -- that of the coincidence of peak load matching between the Edison company's summer loads and the PV output. The plant at Carissa Plains is reported by the author to be a 6 MW rated system, also constructed by ARCO Solar. The design is similar to the plant at Lugo, except that the system uses reflector enhancements on its two-axis tracking arrays. Use of reflection mirrors enhances the solar radiation incident on the modules by 80%. The net effect is reduction in the number of modules needed. The plant is connected to the Pacific Gas & Electric Company's 115 KV grid. The PV system shows a good match with summer-time peak demands at this site as well. The plant at Sacramento is rated at 1 MW and is supplying power to the Sacramento Municipal Utility District (SMUD). The plant consists of one-axis tracking arrays and was constructed by Acurex Corp. The author concludes that although some issues remain to be resolved, none of them represent impediments to widespread use of PV. Low annual capacity factors are not detrimental if availability is high when demand is the highest.

Arnett et al. [18] describe the conceptual design, prototype testing, production, assembly and installation of these two MW-sized plants constructed by ARCO Solar. Estimates of increased annual energy production of upto 45% for the two-axis tracking over the fixed tilt arrays were projected. Cheatham et al., [19] in elaborating on the Lugo plant and the Carissa Plains plant, emphasize on advantages of a large MW-sized central station power plant. These are: (a) Modularity, (b) environmentally benign, (c) low operating and maintenance costs, (d) predictable reliability, (e) speed of installation and (f) system life expectancy.

Spencer [20] describes the SMUD project as being only a beginning of the bigger 100 MW project which was to be completed over a 12 year period. At present, two of the phases are operating and feeding power into the 12.47 KV SMUD distribution grid. Further development has essentially been discontinued. The entire project was expected to cost $3.2 million per MW. Each MW of PV power corresponds to roughly 9 acres of land area.

Leonard [21] attempts to answer some of the questions that need to be addressed before PV can become economically and technically attractive. The author begins with an overview of six existing utility interconnected projects and leads to the design study of a 100-200 MW utility interconnected plant. It is pointed out that although the projected cost of completion of the 1 MW SMUD plant at Sacramento was $12 million, actual costs incurred were less. This data provides strong evidence that projections of the cost of a PV plant are likely to be quite reliable in the future mainly because the cost of PV modules are on a downward trend. The large-scale system design studies confirm that array fields in PV plants will almost certainly be divided into a number of subfields, each with its own power conditioning subsystem (PCS). With only a few exceptions, failure of a component will lead to the shutdown of no more than one subfield and the loss of only 5-10% of the total plant output. Another conclusion of the author is that no generally preferred array field design can be defined, because different array concepts will be optimal in different utility systems (with different diurnal or seasonal demand profiles).

A study conducted by Shushnar et al. [22] reveals that PV and area-related Balance-of-System (BOS) costs make up 75% to 85% of the total costs in all cases considered in the study. The study results indicate the high sensitivity of BOS costs to PV efficiency, system configuration design and identify efficiency and configuration (fixed, tracking, etc.) as the most effective avenues for system cost reduction.

Smith [23] examines the economics of large-scale photovoltaic power generation and a projected break-even cost for photovoltaic cell systems in the light of an electric utility's hourly energy profile. The author concludes by saying that the PV system may prove to be economical for utility systems where a substantial reduction in conventional power generation is realized and the total PV system costs approach $0.75 per peak watt. The analysis is based on a 19% cell efficiency.

A number of papers have been devoted to improvements in power conditioning subsystems (PCS). Chu et al. [24] have studied several options for central station utility interactive power conditioning. They have compared the development potential for two PCS designs, 50-500 KW and 1-10 MW. The 1-10 MW sized PCS employs new switching devices which are faster and can be switched at higher rates than those existing. Through the use of Pulse Width Modulation (PWM) and chopper waveshaping techniques, the need for magnetic filtering is significantly reduced. Total harmonic currents are limited to 5% and the power factor is maintained between 0.95 leading and 0.95 lagging during normal operation. Projected PCS efficiencies are reportedly greater than 96% from one quarter to full load. PCS cost projections are made at $0.07 to $0.12 per watt for the most probable combination of volume, voltages and ratings.

In a similar study, Key et al. [25] study and compare the designs of PCS units ranging from ratings of 2 KW to 5 MW. Both line and self-commutated inverter designs for single and three-phase applications are described. Both types of inverter designs have been used successfully. The 1 MW line-commutated unit at SMUD achieved 97% efficiency and power quality has been reported to be good.

Krauthamer et al. [26] predict that the technical viability and to some extent, the economic viability of central station PV generation will depend on the availability of large power conditioners that are efficient, safe, reliable, and economical. The authors go on to present the technical cost requirements that must be met to develop economically viable PCS.

Pickrell et al. [27] discuss the optimization of an inverter/controller design as part of an overall photovoltaic power system (PPS) designed for maximum energy extraction from the solar array. The special design requirements for the inverter/controller include: (a) a power system controller (PSC) to control continuously the solar array operating point at the maximum power level based on variable solar irradiance and cell temperatures, and (b) an inverter designed for high efficiency at rated load and low losses, at light loadings to conserve energy. The authors found that although good overall immunity to transients is achieved in utility line voltages, oscillations in the injected utility line power and solar array voltage are encountered at low irradiance levels.

Wood [28] proposes a new scheme for power conditioning in a central station PV plant. Instead of each array subfield being served by an inverter, the author proposes that the subfields be served by a dc-to-dc converter, a boost converter. The dc voltage is increased by a factor of 4-6 through the converter, and the transformed dc is collected by an underground distribution. A single transformation is then used to tie into the utility sub-transmission or transmission system.

Several authors have discussed detailed design considerations for a multimegawatt-sized central station photovoltaic system. Stranix et al. [29] present a conceptual design of a 50 MW PV power plant based on the technology of thin film amorphous silicon (A-si) panels. The design is for a location in New Jersey; the performance evaluation based on actual irradiance. The design criterion minimizes the installed plant cost per annual kilowatt-hour of energy generated. Based on a design and performance evaluation, the input dc voltage is 2000 Vdc while the ac output is 34 KV, 3 phase; the PCS delivers power at unity power factor over the operating range; the annual energy production is 85.5 GWh at a capacity factor of 19.4%; the costs are projected at 0.93-1.55 $/Wp (1982 dollars) intermediate and near term goals.

Simburger et al. [30] present a similar design study for a 200 MW rated central station PV plant. The plant located at Barstow, CA (southwestern U.S.), uses fixed-tilt flat plate panels consisting of 8X20 feet arrays, with single crystal silicon cells. According to the authors, the basic plant size for a commercial scale central station power plant is in the range of 200 to 300 MW. The reason for this size selection is that the output of the PV plant is expected to be similar to an intermediate load conventional fossil-fuel generating station.

Jones et al. [31] discuss a number of guidelines to be followed in the design of large photovoltaic systems. The guidelines include considerations related to the selection of collector type, array field configuration, hardware specifications, system installation and checkout.

Leonard [32] uses the basic computer simulation approach for the design of a central station PV plant. The central element of the design process is a computer simulation of the operation of the photovoltaic system at the assumed location. Hour-by-hour computation of system performance are carried out with the aid of a mathematical model of the system and an hourly representation of the irradiance to be expected at the site. The simulations are carried out for a full year of simulated operations and yield as a figure of merit, the capacity factor.

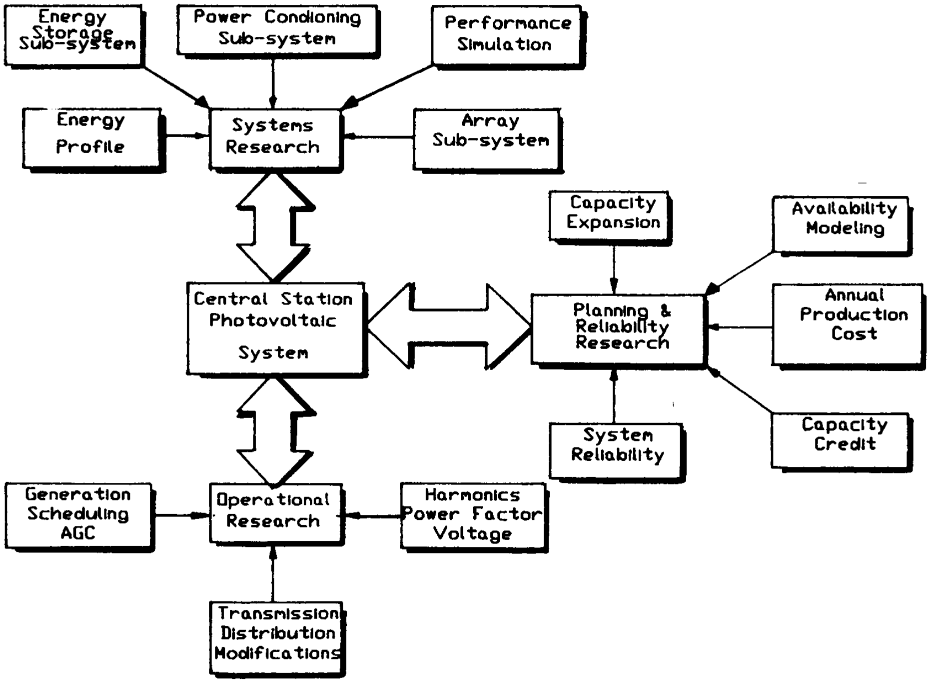

Figure 1. Relationships Among Three Avenues of PV Related Research

Post et al. [33] provide detailed cost comparisons of five competing photovoltaic system options for large sized PV power plants. The options include fixed tilt, one-axis tracking and two-axis tracking flat-plate collectors as well as concentrators, utilizing linear and point-focus fresnel optics. For a high insolation location, such as the southwest U.S., concentrator systems offer a slight cost advantage for current PV technology. For the same location, however none of the competing system options is a clear winner over the others for tomorrow's technologies (mid 1990s). The system options depend on the site being considered for the installation.

Rosen [34] calls for attention toward the balance-of-system costs as the next most important cost element after the array cost. The author discusses development requirements with regard to array design, dc voltage level, array field grounding, power conditioning, operating and maintenance requirements and system prediction. Thomas and Jones [35] reassert the fact that utility owned central station PV plant will constitute a major potential application in the foreseeable future. The authors also point that solar availability dictates the allowable cost of the PV system.

In an EPRI report [36] it has been stated that after reaching compatibility between allowable costs and achievable performance and price, the ultimate limits to penetration are likely to be set by operational issues, like system reliability, dispatch, etc. The author lists a number of implications of PV research and development. Among these, an important issue is the establishment of a better solar data base, which can be used to determine requirements for regulating capacity. These requirements can also be used to more accurately establish generation expansion scenarios.

In another EPRI report [37] the authors discuss a new microcomputer based evaluation model to determine the value of a PV plant to the electric utility. The model consists of a simplified utility production cost code and a simplified PV system performance code. The model accepts data on the existing generation mix (unit rating, fuel type, heat rate, forced outage rate and monthly dispatch order), the electrical demand (hourly demand profile for a typical week in each month) and the contribution from an alternative generation source (hourly for a typical day in each month). For any given hour, the model dispatches units in a pre-specified order to meet the hourly electrical demand (dispatch order in the analysis is based on the principle of least cost generation). Upon meeting the load, the model checks the amount of available contribution from the PV plant and displaces an equal amount of the last unit dispatched (the marginal generation). The procedure is reiterated hour-by-hour for each typical week. The simulation gives an estimate of the type and quantity of fuels displaced. Using the value determined from the simplified production cost model, the authors obtain the allowable cost of PV generation in cents per KWh.

3.2 *Operational Research*

This aspect of central station PV plants refers to the situation which is brought about when the utility has already decided to install the PV plant and the problem is to find out the optimal way to operate and control the output in real time. The problems associated are complex. The more important ones are: generation dispatch, load frequency control, power factor control and system protection.

Simburger et al. [38] present a new model which was synthesized in order to simulate the operation of an entire electric power system. This model simulates the operation of the generation system and the automatic generation control in response to changes in net demand. When a large, widely varying power generation source like the PV system is added to an existing system, the impact on this system would be the same as reducing the total energy required from the remainder of the system while increasing the short term swings in net system demand. A 24-hour simulation shows that with a 500 MW wind system, some changes in base operating system need to be made. For example, a peaking unit of 500 MW capacity would have to operate under AGC for the entire 24-hour period to accommodate the wind power system. Also, some unscheduled interconnected power will have to be interchanged, which might create area control error problems.

Thomas et al. [39] investigate the potential impact of photovoltaic systems on the utility operations. The results show that a small (1-4%) penetration of photovoltaic systems will not adversely affect the utility operations even under the "worst case", which is a rapidly moving cloud front. As individual plant size approaches $\cong 5\%$ of the control area capacity, difficulties might arise. Some of the authors' recommendation for alleviating the problems are:

- Reduced energy density of the array field i.e., install 50 MW/*mi*^{2} as opposed to 100 MW/*mi*^{2}.
- Disperse the array field. Install four 25 MW fields instead of one 100 MW field.
- Forecast approaching cloud fronts via National Weather Service type data or from sensors located in close proximity of the array field.
- Alter the generating types used for regulation to give an improved ramp rate during times of problematic cloud movement.

Patapoff et al. [40] present the utility experience in the operation of a MW-sized plant. The plant is the 1 MW PV station at Lugo, CA. The facility is interfaced with the Southern California Edison utility company through a 12 KV/480 V delta-wye 1 MVA transformer. Protection equipment include over and under voltage, over and under frequency and overcurrent relays. During normal operation, either the two 500 KVA self-commutated inverters are operated in parallel, or the 1000 KVA line-commutated inverter unit is operated. The total harmonic distortion values of the self-commutated inverters are lower than those of the line-commutated inverter at all power levels, for both current and voltage, but the level is not much of a concern to the utility.

Lee et al. [41] present a method for estimating the load following and spinning reserve requirements for a power system containing intermittent generation. The authors incorporate the generations in an optimal generation expansion planning model which evaluates the effect of such requirements on the generation mix and the production costs. The authors use the "negative load" concept in which intermittent generation is deducted from the load demand at each hour. Load following and spinning reserve requirements are evaluated for the two cases of with and without intermittent generations. The requirements increase linearly with penetration of intermittent generations. According to the authors, the overall effect of integrating the intermittent generations were: it increased the annual production costs, decreased the annual fixed costs, and substantially reduced the energy and capacity credits otherwise attributable to intermittent generations.

A paper by Chowaniec et. al. [42] summarizes the results of a study which investigated the operation of combined PV/battery system in a total utility system context. The analysis made sure of the conventional economic dispatching philosophy used in planning the day-to-day operation of utility systems. They concluded that the optimum operation of utility scale PV/battery plants can only be determined within the context of the total utility system.

A number of studies have been devoted solely to the harmonics and utility interconnection issues of PV systems. Campen [43] and Takigawa, Kobayashi and Takeda [44] discuss the utility interface problems and solutions for dispersed small scale PV systems. Cokkinides et al. [45] conducted experiments and simulation studies to investigate problems of interface, such as harmonic generation and propagation, and safety assessment during faults. The authors conclude that present technology of power conditioning units generate lower level harmonics than those existing in the system from other sources. Guess et al. [46] present the result of a conceptual design study for a central station PV power conditioning system. The authors propose promising methods for the power converters to minimize subsystem costs, harmonic currents, and size, while maximizing efficiency.

Firstman and Vachtsevanos [47] review the work conducted in the United States on the impacts of dispersed PV sources upon utility operations. The PV arrays are roof-mounted and connected to the utility grid by appropriate power conditioning equipment. They addressed some technical concerns as protection of equipment and personnel safety, power quality and utility operational stability.

3.3 *Planning and Reliability Research*

This aspect of the research on central station PV applications is concerned with incorporation of this new system into the various utility planning and reliability models. These models are required prior to making decisions regarding the planning of electric power components, constructing components, continuing or delaying construction, etc. Two basic objectives have to be satisfied in any such planning models.

- To serve the load most reliably; and
- To accomplish the above with the least cost generation.

The following is a discussion of the advances made in the field of incorporation of PV systems in the planning and reliability models.

Day et al. [48] discuss model extensions implemented to assist in determining the potential value and reliability impact of solar plants. The principal computer programs used in the study are: A production costing model, a reliability model, and a solar plant model. This general procedure is useful in estimating the lifetime value of a solar plant to a utility system. The framework provides a vehicle for assessing the value of either a single solar plant or a number of them, independent of their cost projections. The initial step in the evaluation process is to project future loads for all years in the expansion period. An optimal generation expansion program is used to expand the conventional system without any solar plant installations. The next phase involves the optimal expansion of conventional units in the presence of a forced solar plant. Comparisons are then made between non-solar and solar expansion plan installation schedules, capital and operating costs, and present worth of plan revenue requirements.

Sissine [49] discusses the issue of capacity credit for wind and other renewable power sources. Although the paper deals mostly with wind systems, some of the suggestions made by the author are equally valid for photovoltaic systems. Capacity credit for a conventional thermal plant is determined on the basis of its capacity factor which ranges between 70% and 80%. However, the traditional capacity factor approach would be erroneous in determining the capacity credit of wind systems. The major shortcoming of this approach is reportedly, its failure to capture correlations of wind resource availability with utility loads. It is more appropriate to use a method based on the reliability of the entire generating system. Reliability analysis examines the difference in loss-of-load probability (LOLP) between two arrangements of utility equipment: the existing arrangement (base case) and an expansion arrangement that adds wind facilities to the base case. The change in LOLP due to the addition of wind facilities gauges the reliability improvements which is equated to an increase in system capacity. The ratio of this change in system capacity to the wind facilities' total rated capacity is defined as their effective load carrying capability (ELCC) and represents their capacity credit.

Peschon et al. [50] discuss the development of new mathematical models for the economic evaluation of intermittent sources of power. The purpose of these mathematical models are to answer questions related to real-time operational problems, operating savings, economic characteristics over a typical 20-25 year planning horizon and level of penetration. The computer model makes feasible the simulation of the hourly operation of the combined system for a complete snapshot year with and without the non-conventional source. With the reliability criteria satisfied by the generation mixes with and without the non-conventional source, the capacity credit is determined.

Ku et al. [51] describe a methodology used for and the results obtained from a study for assessment of the economic viability of long-range applications of PV generations in the Public Service Electric & Gas (PSE&G) Co. at New Jersey. The authors develop a mathematical and statistical process to convert actual irradiance data to hourly electric energy production patterns for average days of each season. Using the PSE&G electric system as a basis, they develop a long-range generation expansion scenario including advanced design for combustion turbines (CT). The authors then substitute various amounts of CT capacity additions with PV generating capacity which corresponds to different levels of PV penetration. The authors then determine the amount of PV kW capacity required to replace each kW of CT capacity in order to provide the same level of system reliability.

Jordan et al. [52] describe the methodology developed for evaluating capacity factor, effective capacity and total economic value of a PV system, when combined with other generating units in an electric utility. The authors adopt a total system performance model which consists of three models: the resource performance model (wind or photovoltaics), the reliability model, and the production costing model. The resource model evaluates the total PV power generations for a given system; the reliability model makes use of the long-established loss-of-load probability method with modification to represent hourly variations in both load and PV plant output, and the production cost simulation model is a standard production cost program which has been in use for years.

Dapkus et al. [53] describe a planning method which considers the uncertain and dynamic nature of the decision process. A stochastic dynamic program is used to model uncertainty in demand, the date of new technology (PV plant) commercialization, and the possible loss of service of existing technologies due to accident, regulatory action or lack of fuel. In this methodology, the state of the system at any time is completely defined by the number of units of each type of technology, the availability status of each technology and the peak level of demand.

Caramanis [54] discusses the methodology used in the software package, Electric Generation Analysis System (EGEAS) developed for EPRI, by the Massachusetts Institute of Technology. EGEAS is a comprehensive planning package which can analyze "non-dispatchable" (NDT) options in the utility. NDT refers to those generations which depend on the weather, or nature, e.g., wind, solar, hydrothermal, etc. The author addresses the issue of an additional source of uncertainty in NDT, besides equipment failure. The uncertainty is due to energy source availability fluctuations arising from the stochastic nature of wind speed, irradiance, river flow, etc., affecting the output from a particular NDT. This random variable is interdependent with system load fluctuations. This particular relationship is identified in the methodology. The rest of the methodology follows any standard optimal expansion program.

Finger [55] presents a production costing methodology which can also model solar power generations as well as other non-conventional sources of energy. The treatment of solar generations is deterministic. In other words, the hourly load demands are modified chronologically by solar generations.

Singh et al. [56] discuss a methodology which evaluates the reliability of electric power systems having PV plants. Two groups are created, one each for the conventional generation system and the other for the non-conventional generation system. A generation system is created for each group. The models of the non-conventional group are modified hourly depending on the limitations of energy. All the models are combined hourly to find the loss of load expectations and the frequency of capacity deficiency for the hour in question. This procedure is accomplished using a discrete state algorithm as well as the method of cumulants.

Stember [57] presents two techniques for modeling the availability and maintenance costs of photovoltaic power systems. The term 'availability' refers strictly to the hardware system. The two basic availability models are: a simulation technique using the GASP-IV language, and an analytical approach using state space techniques. The simulation model developed is Solrel. It uses an event-by-event simulation to represent the 30 year life of the system with individual reliability and maintenance events modeled with statistical distributions.

Unione et al. [58] discuss the availability as a measure for estimating the expected performance for solar and wind powered generation systems and for identifying causes of performance loss. The authors discuss models ranging from simple system models to probabilistic fault-tree analysis. They develop a methodology incorporating typical availability models for estimating reliable plant capacity.

4.0 PV-THERMAL APPLICATION

Another way of using solar energy is the PV-thermal (PV/TH) application. If proper conditions exist it is beneficial to consider the combined application of PV electricity and thermal energy in a single solar energy project. These systems could be either stand-alone or grid-connected. There are several examples of such applications where electricity, hot water and steam are generated from a PV-thermal hybrid project.

Nakata and et al. [59] describe the 30 kWp concentrating PV/TH hybrid system which is being constructed in Hiroshima (Japan). That was the first concentrating PV/TH hybrid system for practical application in Japan. The 30 kWp output is composed of 5 kWp electric and 25 kWp output thermal energies and is fed into an office building for lighting, air conditioning, showering and washing. The hybrid system is controlled by a microcomputer which has some functions for sun tracking and emergency operation.

Detailed PV/TH system design studies were performed by Lambarski et al. [60] for three commercial site applications which require both electrical and thermal energy. The three site applications chosen out of eleven considered were a meat packing plant in Dixon, CA, a public school in Albuquerque, NM, and a hospital in Fresno, CA. Electrical power ratings of these PV/TH systems are 1,000 kW, 100 kW, and 125 kW respectively. Detailed designs presented here were developed as part of an effort to identify and resolve design issues, to select the most desirable commercial applications and sites, and to perform detailed designs for these site applications for PV/TH systems. They also presented life cycle cost ratios and key features of the electric and thermal designs and operating characteristics of the systems. All three systems are utility interactive.

Braunstein and Kornfeld [61] presented a theoretical analysis of the PV/TH collector using a simulation model. The PV/TH collector was designed and constructed and put through a series of experiments under varying load conditions and insolation levels. They found that there were small differences between theoretical and experimental results (up to 5%). They concluded that the total conversion efficiency of the PV/TH collector per unit area is higher than separate thermal collector and PV array efficiencies. Also, the packaging cost of a PV/TH collector per unit area seems to be lower than the conventional thermal collector and the PV array taken separately.

Wolf [62] has analyzed the performance of a combined solar photovoltaic and heating system for a single family residence using hourly U.S. Weather Bureau data for insolation and temperatures for Boston. The collector analyzed is a flat plate design with heat transfer to the load via a liquid loop. The hourly electrical load has been synthesized. The results of the analysis clearly indicate that the operation of combination solar heating and PV system is technically feasible and it may be cost-effective. There are certain operating conditions to be observed, however, which are primarily related to an upper limit on temperature to be maintained for efficient PV conversion. It will require a means of temperature control when the heat energy is more than the load.

5.0 PV-WIND APPLICATION

In order to reduce the storage requirements, and improve the reliability of PV energy systems the idea of PV-wind hybrid has been put forward. It has been observed that, for some locations, the solar and wind resources complement each other on a diurnal basis. The optimal mix of the wind and photovoltaic power and the necessary storage (for stand-alone applications) are some of the topics of research being pursued at various quarters.

Payne and Shehan [63] have done design studies for remote locations for independent and utility back-up hybrid alternate energy system applications. These applications have been for remote direct communication, ranches, and remote equipment. They concluded that hybrid alternate energy system is a cost-effective multi-energy array for remote site applications where power transmission line distance exceeds several miles. The hybrid system is expected to produce energy at a cost of 34 cents to 54 cents per kwh. This cost is expected to drop and become more and more competitive as fuel prices rise.

Castle et al. [64] has developed a methodology to design a hybrid wind/photovoltaic electric power system. A computer code has been developed to optimize subsystem sizes of a wind photovoltaic hybrid system at the minimum energy cost. They concluded that the actual matrix of a hybrid system depend upon many factors: load profile, wind speed, insolation, cost, storage, and subsystem efficiency factors. It is concluded that the present downward trend in photovoltaic array system costs will make the use of hybrid PV-wind systems an attractive alternative for many stand-alone power requirements in areas with moderate wind regimes and good insolation.

6.0 DEDICATED APPLICATION

One of the most successful and cost-effective applications of PV power in developing countries has been water pumping. The most common example is a PV array dedicated to a water pump. In this context dedicated means that PV power is solely used for one application. Due to the simplicity of its operation, inherent storage and ability to displace fossil fuel in remote locations, PV water pumping is now a success story. Optimum design of pumps and motors, and array sizing are some of the areas receiving attention from researchers and manufacturers. Flat plate collectors and DC electric pumps are the most widely used technologies. Some other dedicated applications include power for communication systems, cathodic protection, remote data acquisition systems, beacon lights and electric fence.

Pulfrey et al. [65] developed a prototype photovoltaic-powered pumping system capable of supplying 15m^3 of water per day in full sunlight at heads of around 35m. A photovoltaic-powered pumping system, using a progressive cavity pump, dc motor, dc-dc converter and a solar cell array was designed, assembled and tested. The system used a 1.5 kW progressive cavity pump coupled to a 1.1 kW permanent magnet dc motor. Power was supplied from a 800 W PV array via a dc-dc converter. They concluded that the system would appear to be an excellent candidate for supply of water to villages in many parts of the dry tropics.

Hori et al. [66] developed a prototype photovoltaic-powered small scale water pumping system. They presented operational experience and their system analysis with various insolation conditions. They analyzed individual components of a photovoltaic-powered pumping system, and developed a method to calculate system characteristics by using an equivalent circuit to couple components. They concluded that in an optimized system, pumping water flow quantity achieved 91% of the theoretical maximum flow with single crystalline solar cells, and 86% of the theoretical maximum flow with amorphous solar cells.

Cass and Hulse [67] present a design of the photovoltaic-powered pumping as irrigation system which was constructed in San Luis Valley, Colorado (US). They presented the site characteristics, design requirements and system description. Following installation, an extensive site testing and evaluation were performed. The testing was performed during extreme weather conditions. The conditions included -25°C, heavy snows, frost on the lens on most mornings, coupled with the high speed winds in excess of 30-miles per hour. They concluded that the effect of the frost was to reduce the operating time by approximately 0.75 hours per day assuming 50% of the days had no frost. The number of days analyzed were 75.

Taketani and Yoshioka [68] discuss the 6 kWp photovoltaic pumping system which is located in Petchaburi Prefecture in Thailand. They have shown that the demonstration plant operated with high reliability.

Wang et al. [69] discuss the performance of a solar powered unattended microwave relay station. This station is located in Cheng mountain, Zhejiang Province, China. Since its installation in 1984 the solar powered unattended microwave relay station has operated successfully. From the success of this project the authors concluded that using solar cell as the power supply of the microwave station is very reliable and economical.

Derrick [70] has studied the experiences of PV powered medical refrigerators and lighting systems. One hundred PV refrigerator installations and seven hundred fifty PV lighting installation have been reviewed. These installations are located in Zaire. The author concluded that the solar powered refrigerators and lighting systems are now sufficiently reliable and mature for widespread use.

Zhou and Shen [71] designed a PV power source system for military communication in China. The system consists of a 1500 W silicon solar array, a 2000 AH maintenance free lead-acid accumulator, and an automatic check and control device. It has been set up in the assigned field and operated normally for more than two years.

Wang and Huang [72] designed a solar powered cathodic protection system for the lock gates in Sheyang River, Jiangsu (China). The system is used to protect the lock gates from corrosion. Based on the economical analysis and the performance of this system the authors conclude that PV-powered current cathodic protection is the best way to solve such corrosion problems.

Cunty [73] studied the use of PV lighting system for land and water borne navigation aids. The author concludes that the French Lighthouse Service is convinced that solar generators will be best solution for buoy inspite some initial technical difficulties.

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Discussion

A. W. W. Cameron (Retired, London, ON, Canada): The dispatching problems associated with photovoltaic generation could be alleviated in some localities by the load-management technique of encouraging direct solar heating of buildings, especially by economical state-of-the-art systems using the masonry of a building as heat storage [A].

Where direct electric heating of buildings is popular, the electric load relief by a given area of solar heating panels is the range of five times the power supplied by the same area of photovoltaic cells, for the same clarity of sun. Moreover, where Solar heating is spread over a load area, the "passing-cloud" condition produces a load ripple over the area: when good heat storage is incorporated with the Solar heating panels, the fluctuation may not be noticeable.

The same applies where heat-pumps have been popularized, as has been found a useful load-management measure in some areas. However, with heat-pumps the electrical equivalent of solar heating is about halved on the average.

These remarks should not be taken as disputing the value of photovoltaic generation, but rather as facilitating its use by mitigating operating problems, and encouraging utilization of Solar energy by all means.

References

[A] U.S. Patent 4 469 087, September 4, 1984.

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S. RAHMAN, M. A. KHALLAT and B. H. CHOWDHURY. The authors would like to thank Mr. A. W. W. Cameron for his discussion of our paper. We appreciate the information about the advantages of solar heating panels over PV cells for space heating applications. This, in addition to load management applications listed in his discussion, add two more examples to our list of diverse application of solar energy.

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