AMERICAN SECTION OF INTERNATIONAL SOLAR ENERGY SOCIETY, INC.

PHOTOVOLTAIC SYSTEMS AND APPLICATIONS PERSPECTIVE*

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ABSTRACT

The National Photovoltaic Program is currently in the process of increasing emphasis on full-scale system experiments in the potential user environment, a natural occurrence in the evolution of system design and development. At this point large amounts of design information are available and need to be brought together in usable form to support this effort. This paper reviews the state of understanding in the system definition area for the major applications, and indicates the remaining issues, especially as they impact the field test activities.

1. INTRODUCTION

The U. S. National Photovoltaic Program was initiated in January 1975. The intervening five years have been marked by technical and engineering advances which have brought photovoltaics systems ever closer to commercial competitiveness. In addition to the reductions in module costs and the increase in conversion efficiency, there has been a great increase in the understanding of system operation and the requirements of the potential applications. Studies have analyzed the various markets to determine their specific characteristics and requirements as well as the properties of the overall environment in which they exist. For each of the promising applications, the possible system and subsystem options have been treated in detail to identify the most appropriate candidate systems. While questions remain, especially with regard to institutional issues and utility interface questions, further progress in the system definition area depends on experience which can be obtained only by operating systems in real environments. Some small amount of field testing has been done in the past at such sites as the MIT Lincoln Laboratory Agricultural Test Bed at Mead, Nebraska or the NASA/Lewis Research Center village power system at Schuchuli, Arizona. While valuable information has been gained from these sites, more detailed application specific testing is now required. The National Program has responded to these needs through the intermediate sector application experiments now entering the construction phase, and the residential experimental program now beginning.

With the start of these large scale test and application projects, it is important to review the available information in the system design area to ensure the most effective experimentation effort. The purpose of this paper is to review the status of design definition and development in each of the major application sectors and summarize the principal results. The impact of these findings and of the unresolved issues on the test program planning will be discussed and future plans addressed.

2. RESIDENTIAL PHOTOVOLTAIC SYSTEMS

The single family residence has long been recognized as a promising photovoltaic application for a variety of technical and economic reasons. The homeowner buys electrical energy at relatively high rates, is allowed

*This work was supported by the U. S. Department of Energy, Division of Distributed Solar Technology.

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to deduct interest payments from taxable income, and has available a relatively low real-discount rate. All of these factors contribute to providing the most favorable economic environment for the photovoltaic system. Equally important, the typical residence can be designed to provide the primary support structure to the photovoltaic array, offsetting at least the part of the balance of system cost due to structures. Obviously revisions of tax laws could unfavorably affect the overall residential system attractiveness, but tax credits could just as easily increase its attractiveness, and are much more likely.

2.1 Status

Because of its apparent potential, several studies have addressed new construction in the residential sector (1-7). The country has been divided into regions and the most cost effective systems determined in each. Currently efforts are underway to treat these systems in detail and develop a series of design documents. The first of these, for an all-electric residence in the Southwest, is now available (8) and others will be issued shortly. In addition studies have addressed specific system design issues such as the module definition work sponsored by Jet Propulsion Laboratory (9).

There is general agreement in the results to date that the regions with the best cost to benefit ratio are the Southwest, Northeast and Southeast in that order. The Southwest is typified by Phoenix, and has high solar insolation levels and a large daytime load in the form of air conditioning. Utility rates do not play a major role in this case since they are near the national average. The Northeast is usually represented with Boston, and its position as second best site is due solely to its high utility rates. Solar insolation in this area is about 60% of that in Phoenix. The third priority region, the Southeast, is typified by Miami and Charleston. The high air conditioning load combines with good insolation and medium utility rates to make this a good potential area. In addition, the rapid growth of this region and its dependence on oil makes it very interesting as a potential market-place.

The one system identified by all studies as being of interest over most of the U.S. employed the photovoltaic system to meet the normal electric loads as well as the space conditioning loads by means of a high efficiency heat pump. This would be much like incorporating a photovoltaic array into a well-built, all-electric residence. For such systems, the most appropriate flat plate modules are those which mount either directly on the roof sheathing, replacing the shingle layer, or actually replace the sheathing, mounting integrally with the roof (9). Promising photovoltaic concentrator arrays are currently under development and may prove to be the appropriate choice for flat-roofed residences. In the present designs several options exist for meeting the domestic hot water (DHW) loads including a solar thermal DHW system (5), use of waste energy from the photovoltaic system (6), and use of waste heat from the air conditioning cycle of the heat pump (8). The last option appears to be the most cost effective, especially in areas with high air conditioning requirements.

The other general class of systems which appeared to have potential employed a photovoltaic array to meet the diversified electrical load and some form of solar thermal system to meet the space conditioning and domestic hot water requirements (6). These systems appear at their best in regions with high heating loads and little or no air conditioning. In such regions heat pumps may not be cost effective leading to the selection of fossil fuel heating systems which are easily supplemented with solar thermal systems. The major question in these designs is the type of thermal collector to be used. From the standpoint of area utilization it would be good if the photovoltaic and thermal collector could be combined into a single unit. While this is easily and effectively accomplished in actively cooled concentrators, results for flat plate combined collectors have been less than promising to date (10-12). Initial analysis indicates that great cost reduction and performance improvement are required before combined collectors break even economically with separate photovoltaic and thermal side-by-side configurations (6).

Most of the effort within the residential program is directed at systems which interact with the utility, receiving credit for energy pumped into the grid. For credits as low as 0.40 times the price of electricity to the user, such systems are favored over those with on-site energy storage, such as batteries (13). There has been a great deal of discussion of the appropriate magnitude of such a sellback credit, but recent rulings by the Federal Energy Regulatory Commission have addressed this issue and appear to have assured at least this 0.40 minimum level (14). The question of on-site storage in response to time-of-day rates is considered to be a separate question in which storage economics are independent of the photovoltaic system to first order (13). The sellback credit issue extends far beyond the question of on-site storage. The projected ratio also is the principal factor in determining system size (8,15). For sellback ratios greater than 0.45, analysis indicates that arrays of over 10 kW_p are the most cost effective and array size will usually be limited by available south-facing roof area. In addition the cost-to-benefit ratio of such systems is almost completely insensitive to significant shifts in load magnitude. This last feature has obvious implications in the design and marketability of such systems. The second major factor in determining system size is the ratio of fixed-to-variable costs for the system. Detailed assessment of these costs shows that smaller systems will be more expensive than larger ones on a $/kW_p$ as well as energy cost basis.

2.2 Future Efforts

Up to this point, most of the work in the residential area has been done by computer simulation and modeling. While this allows the definition of promising designs and tradeoffs in system sizing and configuration, there is no way to take into account all the subsystem options such as various manufacturers' collectors or power conditioning units. This evaluation must be done on actual test systems. Obviously this is one of the main thrusts of any field test program. In the residential area however, other important questions must also be addressed.

Almost all modeling work done to date has used time-averaged hourly load data which removes the transients from the modeling process. This has led to some questions concerning the effect of load spikes on electrical signal quality, system reliability, and the utility interface. System economics may even be affected by very noisy load profiles. Therefore the residential test program at MIT/Lincoln Laboratory will be using real-time load data to study these effects. Another major issue in the residential sector is the question of institutional acceptance from such groups as lending institutions, insurance companies, and building code officials (16). One of the primary means of overcoming potential barriers is the development of a data base indicating reliable safe operation. This can only be developed by a strong test program involving information transfer to these groups. This is one of the main purposes of the Residential Experimental Stations (RES) currently being developed.

Several questions also remain to be addressed in the system definition area. The above discussion of design was restricted to new construction because of ease of incorporation of the system at that time as well as the inclusion of passive solar features to reduce the space conditioning load. The retrofit market at this time remains somewhat of a mystery. This year it is planned to make an assessment of the building stock by region to determine the characteristics and number of suitable residences (south-facing roof, unobstructed insolation, sufficient roof area and tilt, etc.). The economics of retrofit remains the largest uncertainty especially in the area of module installation. Except in the rare instances in which direct mount modules make sense, it appears that standoff mounting will be required, doubling the projected installation costs (9). Obviously this area requires a detailed design effort.

The other residential system that

has not been treated in detail is one employing on-site storage in a stand-alone mode. This has been primarily because the state of technology development of a suitable storage subsystem does not allow detailed subsystem specification. As currently visualized such a system would involve the incorporation of a small on-site generator in combination with the photovoltaics and storage and would have superior cost/benefit ratio over grid-connected systems with dedicated storage (6).

Other residential activities currently underway involve a dynamic model of the utility/power conditioning interface, development of exemplary designs, and the publication of a simplified design methodology.

3. INTERMEDIATE-SIZED SYSTEMS

The other major areas of photovoltaic grid-connected applications have been combined together under the nondescriptive title of intermediate-sized systems in the current program structure. This includes all applications which are not remote, residential, or utility central station. Obviously, this covers a wide range of possible users extending from farms, schools, and offices through shopping centers and factories. It is difficult to make general statements about the character of potential application in this sector since there are numerous differences in economic parameters, load shapes, user requirements, and investment practices between one subsector and another.

The typical application in this intermediate area falls into a business-related tax and investment structure. Businesses may deduct operating expenses, such as electricity costs, and have a higher real discount rate. These factors discourage the replacement of an operating expense by making a capital investment. While the ability to depreciate equipment offsets this somewhat, one must then consider the typical investment lifetime. For example, the current tax laws would encourage a landlord to sell an office building after several years, to maximize depreciation benefit. Obviously this does not encourage the type of long-term capital investment philosophy needed to justify photovoltaic system purchases. Changes in the tax laws or solar investment credits could easily alter this situation. Likewise strong public interest could aid in initial corporate purchases for the purpose of public relations. At present, however, many questions remain concerning business acceptance of photovoltaic systems from the economic investment viewpoint.

3.1 Status

Those general statements that can be made about the intermediate sector follow from the previous discussion of residential systems and actually apply to all grid-connected applications. The priority of favorable regions is generally the same as for residential systems, although the relative distribution of a given application must also be considered. In general, systems that either feed back excess energy to the grid or are somewhat undersized (no excess) are favored over those with on-site storage (2,13). If an application has a thermal load, such as a process heat requirement, and can effectively utilize concentrating collectors, significant economic advantages can be obtained by using actively cooled concentrators (17). This result follows from the minimal increase in cost of an active-cooled over a passive-cooled concentrator. Likewise it does not necessarily hold for flat plate systems since the increase in cost for a combined flat-plate collector over a photovoltaic-only unit is significant.

Good load match and competing utility rates were the major factors in determining favorable applications. In the analysis done to date, the intermediate sector has been divided into three general classifications: agricultural, commercial/industrial, and residential load center. While each of these still represents a broad range of users, they do share similar issues and concerns.

Agricultural applications include irrigation, crop drying, beef and poultry feedlots, and dairy. Of these, analysis indicated that livestock-related loads offered good seasonal and daily load match, except for highly peaked loads such as dairy milking (18). Poultry feedlots appear to be a highly favorable application. Irrigation, however, does not appear to be generally attractive because of limited annual operating cycle and high peak energy demands.

This last factor makes off-season use of the photovoltaic energy very difficult because of a lack of on-farm matching loads. The exception in this area is year-round vegetable irrigation which may be quite attractive, but limited in applicability.

The commercial/industrial area is by far the most encompassing and complex. This includes schools, shoppinig centers, and factories. In general, those applications with high daytime/low night-time loads of relatively small magnitude were found to be favored. This includes small office buildings, medical clinics, schools, neighborhood shopping centers, and light industry (single shift). Larger application generally had lower utility rates and/or 24-hour load requirements. This latter factor reduces the impact of the photovoltaic system, affecting its attractiveness. For large loads, ground-mounted arrays are usually required due to lack of available roof area. There is some question of land availability in these cases, especially near urban centers. This issue reinforces the attractiveness of applications with low energy density requirements, such as low-rise offices. Several potential dc loads were also investigated ranging in size from chloralkali plants to remote desalination (20). Again the larger applications appeared unattractive because of competing rates while many of the smaller ones required regulated dc offering no major advantages over ac users. Remote water pumping and telephone switching may still be attractive loads.

The last classification in the intermediate sector is residential load center which includes housing clusters, condominium complexes, apartment buildings, mobile home parks and nursing homes (21). Such applications offer economies of scale, better energy utilization, and minimization of the retrofit barrier when compared to single-unit, dedicated systems. Unfortunately, these advantages are not without their attendant problems. The major barrier in this area is the economics mentioned in the introduction. The closer a residential load center can approximate homeowner economics, the more attractive it becomes. This favors cooperative ownership of a photovoltaic system as might be available in a condominium situation. Commercial ownership such as in an apartment application is least favorable, especially in light of laws forbidding master metering. Under these conditions a landlord would essentially be selling back all energy to the utility rather than serving the apartment load. As in the residential case, roof-mounted arrays were found to be favorable over ground-mounted whenever practical.

3.2 Future Efforts

As with the residential sector, most of the work on intermediate systems has been in the form of computer modeling. Therefore, questions remain regarding actual system operation under real-time loads, and overall system reliability and operation and maintenance requirements. This last item is extremely important in achieving commercial acceptance of the photovoltaic system. While much discussion has been directed at these areas no data has been developed under actual field conditions. However, this will change shortly, as the application experiments resulting from two recent DOE Program Research and Development Announcements (PRDAs) begin operations. Following a competitive design phase involving 29 different application designs, nine projects have been selected by DOE for construction and operation (22). These include most of the major applications in the commercial/industrial area with the exception of a small medical clinic and light industry. It is currently planned that simultaneous load monitoring near experiment sites will help expand the load/system interaction data base. In addition, future application experiments for selected application/region pairs are planned. As for residential systems, the major thrust of this testing will be to determine the operational characteristics of the systems under the actual environmental conditions, verify the appropriateness of system design, and establish system reliability. The transfer of these data to the potential users has been assured by involving contractor/user teams in the entire experimentation process.

Major systems questions remain in the areas of utility interfacing requirements and dynamic energy flow characteristics. In addition, more information is needed on small commercial, low-energy density applications as well as off-farm energy use. Activities directed at these areas are planned to begin this year. A series of exemplary designs will be begun soon, paralleling the residential design effort already underway (8), and a design handbook will be issued.

4.0 CENTRAL STATION APPLICATIONS

Since photovoltaics is a modular energy technology by nature, it has always been associated with distributed energy applications. Requirements for lower array costs and advanced installation concepts have had the effect of reducing the emphasis on utility central stations as a potential application. However, with sufficiently low system prices there is no reason why photovoltaics cannot eventually become a part of the utility generation mix. Additionally, for photovoltaics to make major impact on nonrenewable fuel consumption, such systems may be necessary.

Several studies (3,23,24) have analyzed photovoltaic systems in utility applications and more work will probably take place. Results indicate that at grid capacity penetration levels up to 5%, the photovoltaic system can get capacity credits as high as 40% of their peak rating. The presence of more system storage on the utility grid can extend this value to higher penetration levels. To be cost effective in private utilities, it appears that system prices in the \$1.10-\$1.30/W_p (1980\$) range are needed, probably requiring advanced collector technology. However, because of economic factors as well as high fuel costs, it appears that for a large number of public utilities, breakeven costs lie in the \$1.50-\$2.00/W_p range (25). This requires the same baseline collector technology as a typical intermediate load center and has increased photovoltaic program interest in this sector.

While no testing applicable to central station has been started, two studies did address the requirements and design of a hypothetical test facility (26,27). During both efforts several utilities were contacted to determine their interest as well as help define the requirements of such a facility. Of these utilities, most wanted several years of experimental data to establish reliability on systems in the 5-10 MW_p range. They felt that this size would be large enough to show whatever technical problems might be present, such as subfield interference. While a central station implementation plan is being drafted, there is no present commitment to test facility construction.

5. SUMMARY

For the most part, the conceptual design activities within the photovoltaic program are drawing to a close. The current emphasis is on the development of exemplary system designs incorporating all of the available information and of sufficient detail to allow system costing. As test activities begin to produce actual performance and reliability data, these will be factored into the designs, eventually resulting in design guidelines for the potential consumer. The entire focus of all of this activity is the definition of appropriate designs and design tools for the user.

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