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SOLAR PHOTOVOLTAIC SYSTEMS FOR RESIDENCES IN THE NORTHEAST* +

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ABSTRACT

Under sponsorship of the U. S. Department of Energy, MIT Lincoln Laboratory is conducting a program to develop residential solar photovoltaic (PV) systems. The first phase of this activity involves the design, construction and testing of four prototype systems at the Northeast Residential Experiment Station. The systems employ roof-mounted photovoltaic arrays of 500-800 square feet which provide solar-generated electricity sufficient to cut in half the electrical demand of an energy-efficient, passive-solar residence. Construction of these systems will be complete by December 1980, and will be followed by a one-year test period.

1. INTRODUCTION

The dominant energy demand of a residence in the Northeast is space heating, which typically is needed almost nine months of the year. A state-of-the-art solar residence, however, through the use of extra insulation, the judicious placement of windows, and the inclusion of passive thermal storage and a solar domestic hot water system, can cut the thermal loads of a cold-climate residence by over 50 percent, leaving the demand for electrical energy as the dominant load. The addition of a photovoltaic power system to this solar residence can reduce the demand for expensive auxiliary electrical energy and result in a nearly self-sufficient solar residence. Integrated photovoltaic power systems represent the ultimate energy-saving solar technology for energy-efficient residences; consequently, the development of photovoltaic power systems is currently being emphasized by the U. S. Department of Energy.

Under sponsorship of the U. S. Department of Energy, MIT Lincoln Laboratory (MIT LL) is conducting a multi-year program to develop solar photovoltaic (PV) power systems for residential applications. This effort is part of the Department of Energy's Photovoltaic Program aimed at reducing photovoltaic system costs to levels competitive with traditional energy sources by the mid-1980s. The MIT LL Solar Photovoltaic Residential Project focuses on a three-phase sequence of testing and development activity involving three regions of the country (Northeast, Southwest, Southeast). The first phase of the project involves the design and construction of several Prototype Systems for photovoltaic residences. This activity is currently under way at the Northeast Residential Experiment Station (NE RES) in Concord, Massachusetts, and at the Southwest Residential Experiment Station (SW RES) located in Las Cruces, New Mexico. A third experiment station, to be located in the Southeast, is planned for the future. The Prototype Systems, described more fully in the following sections, will undergo engineering evaluations at these experiment stations. The second phase of activity in the project is to duplicate refined versions of some of the Prototype Systems in occupied residences near the experiment stations. The focus of testing during this phase will be on system engineering performance as well as occupant acceptance and perception of the PV system. The third phase of the project will focus on marketing and institutional issues. The approach to this activity will be to construct large clusters of PV residences all served by the same utility substation.

The goal of this project is to develop PV systems which are technically and economically sound when integrated into an energy-efficient residence.

2. PROTOTYPE PHOTOVOLTAIC SYSTEMS

An artist's rendering of Prototype Systems installed at the Northeast Residential Experiment Station is shown in Fig. 1. The Prototype Systems are unoccupied shells, based upon a full-size PV residential design incorporating energy conservation and passive solar features to minimize the thermal demands. The

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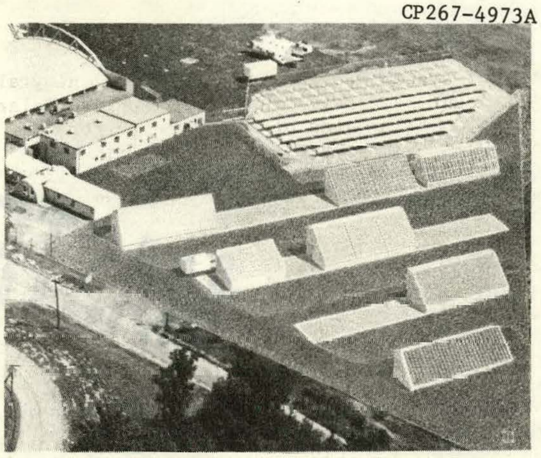

Fig. 1. Artist's rendering of Prototype Photovoltaic Systems at the Northeast Residential Experiment Station.

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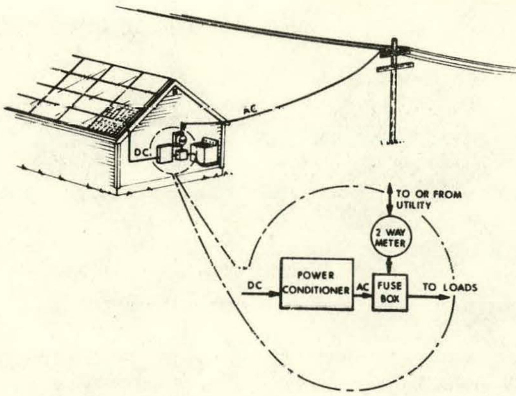

Fig. 2. Utility interactive residential photovoltaic system.

Prototypes consist of a full-size, roof-mounted photovoltaic array, and structure sufficient to hold the roof at the proper tilt angle and house the instrumentation and PV system-related equipment.

Four contracts have been awarded for the construction of Prototype Systems for the Northeast. Each contract began by designing a full-size residence (1400-2000 square feet) incorporating energy conservation and passive solar features and a roof-mounted photovoltaic array. The energy demands of each residence were estimated for the Boston climate. Each PV system was required to satisfy at least 50 percent of the total annual estimated residential electric load, including the diversified base electrical load and any heating- or cooling-related electrical loads. The Prototype System was then designed to replicate as closely as possible the part of the conceptual residence containing the photovoltaic array.

The PV power systems utilized in the four residential photovoltaic Prototype Systems now under construction must convert the variable DC photovoltaic array output to a normal 110/220-V, 60-Hz, single-phase AC residential service, in parallel with the electric utility. During periods when the photovoltaic array power exceeds the electrical demand of the residence, the excess power is sent to the utility grid. Systems of this type are termed "utility interactive." No on-site storage is used in these systems. The photovoltaic system may be broken down into three functional subsystems: the PV array, which produces solar-generated DC power; the power-conditioning unit (PCU), which converts the DC power to normal AC power as described above; and the system control and protection subsystem, which must include elements to guarantee automatic, efficient and safe operation of the PV system. A simplified diagram of an installed PV system of this design is illustrated in Fig. 2.

The four Prototype Systems may be categorized by the method used to mount the photovoltaic modules on the roof. Each of the Prototype Systems and its associated conceptual residence are discussed under the appropriate mounting category below.

2.1 Integral Mount

An integral-mount photovoltaic array is depicted in Fig. 3. In this scheme, the photovoltaic modules replace the standard roofing and substructure material and provide the residence's weatherseal. This method of array mounting is most applicable to a new-construction residence and has several potential advantages over other methods. By replacing the plywood, felt and shingles of a conventional roof, the integral-mount scheme receives "credit" for materials not purchased. A recent study of residential photovoltaic-array requirements[2] concludes that not only is the integral-mount method potentially the most economical but it is also aesthetically desirable to keep the PV array a continuation of the roof plane. However, this mounting scheme also involves the greatest risk since it provides the residence's roof weatherseal.

The two Prototype Systems utilizing an integral-mount PV array are discussed below.

2.1.1 Westinghouse Prototype System

The conceptual residence designed for this Prototype utilizes a 16-foot-high by 40-foot-wide array of ARCO Solar PV modules flush mounted in the roof rafters. Eight 1 by 4-foot

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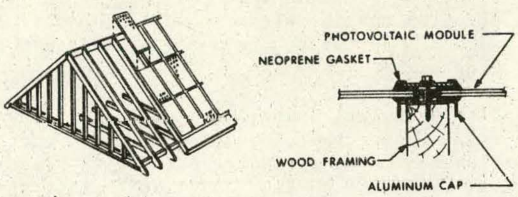

Fig. 3. Integral-mount photovoltaic array.

PV modules are mounted in a 2 by 16-foot extruded-aluminum frame. Twenty of these frames are then mounted from eave to ridge between rafters 24 inches on center to make the 640-square-foot array. The aluminum frames are sealed to the rafters utilizing elongated slots to account for the differential thermal expansion of aluminum and wood. This mounting scheme has been used for active solar thermal applications in the past.

Each photovoltaic module contains 35 series-connected cells and has a rated power output of 34 watts at an insolation level of 100 mW cm^{-2} and a nominal operating cell temperature (NOCT) of 45°C. The array utilizes 160 of these modules, and therefore, has a rated power output of 5.4 kilowatts. The roof containing the PV array is pitched at approximately 45°. Using tabulated insolation data for the Boston climate[3] on a south-facing 45° slope, the estimated annual PV energy output is 7400 kWh DC. Assuming an average DC-to-AC power-inverter efficiency of 80 percent, the annual net usable solar-generated energy is approximately 5900 kWh AC, which is equal to 80 percent of the total estimated annual residential electric demand for diversified loads.

Among the unique features of this PV power system is the provision for venting the back surface of the photovoltaic array. The rafter-mounted modules are backed by plywood to form a channel behind the PV array. This channel is vented at the roof ridge and soffit to enhance heat transfer from the PV cells, thereby reducing the operating temperature and improving the solar-to-electric conversion efficiency.

The power-conditioning unit of the system consists of an Abacus Controls 6-kVA inverter which converts the DC power into regulated 60-Hz sinewave power and which also contains the system control and protection circuitry. This unit weighs just over five-hundred pounds and would be floor mounted.

The Prototype System is currently under construction at the NE RES.

2.1.2 TriSolarCorp. Prototype System

This PV system design also employs an integral roof-mount PV array. Thirty-six Applied Solar Energy Corp. modules of a new design form a 48 by 11-foot array. The modules will be sealed in the roof with waterproof glaze and rubber gaskets in a standard 2-inch extruded-aluminum batten.

Access to the modules is provided from the attic space immediately behind the array roof section. This space can be force-ventilated to assist in maintaining low-PV cell-operating temperatures.

The PV modules consist of a 32 by 64-inch sheet of 1/8-inch-thick Sunadex glass with 253 square PV cells attached to the underside, to achieve a very high packing density. The electrical connections within a module provide 23 cells in series and 11 cells in parallel. The estimated power output of a module is 122 watts at 100 mW cm^{-2} insolation and a cell temperature of 45°C, resulting in an array power rating of 4.4 kW. The estimated annual energy output of this array, mounted at 45°, is 6000 kWh DC, and the net useable AC output is 4800 kWh.

The power-conditioning unit for this Prototype System is a Windworks Corp. Gemini model.

The residence design from which this Prototype System was derived is shown in Fig. 4. Included in this residence are several energy-saving features, including a south-facing clerestory window to provide solar gain, natural daylighting and summertime ventilation. A solar greenhouse/sunspace has also been integrated into the house plan to provide thermal gain and seasonal living space, as well as to ease the architectural impact of the PV array by extending the "glass plane" to enclose this space. Additionally, a roof-integrated solar thermal collector array for domestic hot water heating is shown on the garage.

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Fig. 4. Conceptual photovoltaic residence design.

Insulation (R24) has been specified for walls, for floors over unheated spaces, and for ceilings (R40), resulting in an estimated heating load of 3-5 Btu/DD-ft^2-yr. For this 1850-square-foot residence then, the total annual backup energy thermal demand is approximately 9000-15000 kWh.

The Prototype System to be built at the NE RES includes the PV array-roof, but not the greenhouse or domestic hot water system.

2.2 Direct Mount

Figure 5 illustrates the concept of a direct-mount photovoltaic array. As shown, the photovoltaic modules are mounted directly on the roof surface and may or may not provide the weatherseal. In the case of a shingle-type module, the PV array would mount in an overlapping configuration, similar to conventional asphalt shingles, over the plywood sheathing and roofing felt. This method of PV array mounting is suitable for new construction or retrofit applications where roof replacement is planned.

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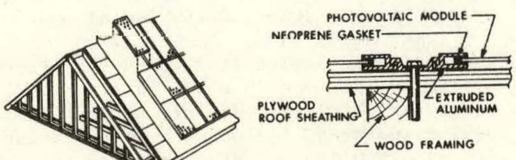

Fig. 5. Direct-mount photovoltaic array.

The direct-mounting scheme results in a somewhat smaller roofing material saving than the integral mount. However, more secure weatherseal for the roof is provided with this approach.

Direct-mount modules tend to run at high operating temperatures due to the insulated back surfaces of the modules. This results in a lower solar to electric conversion efficiency than is the case for modules with air circulating on both the front and back surfaces.

One Prototype System currently under construction will utilize this mounting method; it is described below.

2.2.1 General Electric Prototype System

The residence designed by this contractor utilizes a 22 by 43-foot array of uniquely designed, hexagonal, PV shingle modules. A total of 375 modules are installed, starting at the eave and working up the roof to the ridge. The modules are nailed directly to the felt-covered plywood subroof and provide the roof's weatherseal. Electrical interconnection of the shingle modules is provided by screw terminals which align for overlapping shingles, and therefore, require no additional wiring. Access to the modules is from the top side.

Each hexagonal, shingle PV module contains 19 series-connected circular cells of 4-inch diameter. The estimated array peak power is 6.1 kW at 100 mW cm^{-2} and a NOCT of 64°C. The net annual solar-generated DC energy is estimated at 8480 kWh and the usable AC power is 6780 kWh.

The power-conditioning unit for this Prototype System is also an Abacus model that incorporates the necessary system control and protection provisions.

2.3 Standoff Mount

The standoff mount is illustrated in Fig. 6. In this method, the PV modules are mounted above and in a plane parallel to the roof and the array does not provide a weatherseal for the roof. Penetration of the roof's weatherseal is required only for the mounting brackets which hold the modules several inches above the roof. This method of PV array mounting is applicable to either new or retrofit construction. A standoff-mounting scheme has several advantages: if the edges of the array are not sealed, the space formed behind the array promotes natural convection to enhance heat transfer from the PV modules. Additionally, weatherseal effectiveness is more certain.

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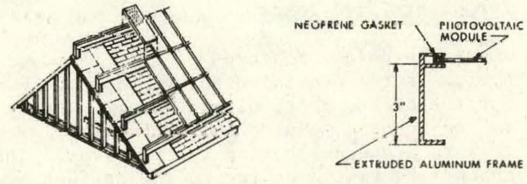

Fig. 6. Standoff-mount photovoltaic array.

The standoff-mount method does not replace roofing materials, therefore no economic credit is assumed for this mounting scheme. Among the areas of concern with the standoff mount is the effect on the modules of a buildup of snow and ice in the space beneath the array.

One Prototype System under construction is utilizing a standoff-mounting method.

2.3.1 Solarex Prototype System

The conceptual PV residence designed for this Prototype utilizes a 35 by 24-foot PV array which completely covers the south-facing roof. The PV modules are mounted on north-south-oriented wood sleepers directly over a waterproof membrane. A rubber gasket "frames" the glass modules and is fastened to the wood sleepers. This approach uses standard construction materials and provides architectural flexibility. Electrical connections between PV modules are made in the space below the modules and must withstand the outdoor environment. Modules may be removed easily for inspection or maintenance.

Each of the 72 PV modules is 32 by 48 inches and contains 96 3.7-inch-square cells. The cells are arranged electrically in two parallel strings of 48 cells. The peak module output is estimated at 86 watts, resulting in an array output of 6.3 kW at NOCT of 28°C. The estimated annual output of this array tilted at 40° is 8500 kWh DC and approximately 6800 kWh AC.

An Abacus Controls power-conditioning unit will be used with this Prototype System.

3. PROTOTYPE SYSTEM TESTING

During the construction of the Prototype Systems, all materials and labor associated with the mounting and wiring of the PV array and the power-conditioning unit will be recorded. This information will be used to evaluate the total costs of the three different mounting methods and to gain insight into ways of reducing installation time or costs.

The PV systems will be tested under simulated residential loads and fully instrumented to monitor power and energy flows and meteorological conditions. This information will be used to determine component efficiencies and to quantify the system performance. The systems will be modeled to enable performance prediction in other climate locations.

Careful attention will be given to the operation and maintenance needs and expenses of the systems in order to evaluate the various array-mounting methods.

By the end of the test period, sufficient data will have been gathered to estimate the PV system life-cycle costs.

Details of system design and performance will be made available during the test period, and a final report on each design will be available at the completion of the testing.

The second phase of the MIT LL Residential Photovoltaic Project will be to duplicate refined versions of these Prototype Systems in occupied residences.

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