THE NEW ENGLAND ELECTRIC PHOTOVOLTAIC SYSTEMS RESEARCH AND DEMONSTRATION PROJECT

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ABSTRACT

Photovoltaic systems have been designed, installed and operated at 30 residences and 8 commercial or institutional sites. All residential systems are rated at 2.2 kW of dc power under standard test conditions (STC) and produce ac power at 240 volts. The commercial/institutional (C/I) systems range from 1.8 to 7.3 kW of dc power at STC; three-phase power is produced at 120/208 volts. The photovoltaic (PV) modules in all systems are crystalline silicon with an efficiency of 11%. Residential inverters are forced-commutated; C/I inverters are line commutated. The residential arrays and 3 of the 8 C/I arrays are attached to brackets mounted directly on roof surfaces. Frameworks of structural steel or aluminum are used to mount the remaining systems, and the tilt angle is 45 degrees for these systems.

The prime purpose of the residential project was to examine the interaction of a high concentration (53% of the residences served) of independent PV systems with a single distribution feeder. Other purposes included collecting data on PV system performance in New England and showcasing the PV system components, all of which were manufactured by companies in the New England Electric service area.

Energy production for the residential systems has averaged 2,195 kWh per year over two years. Maximum production occurs in July (270 kWh); minimum production occurs in January. The reliability of all components is now excellent. No adverse effects have been observed on the distribution system in terms of operations or safety as a result of installing the PV systems.

The commercial/institutional systems were completed in February of 1989. Installation was more complex for these systems, and the operating environment is generally more severe. Nevertheless, data collected to date indicate reliable performance of all components.

KEYWORDS

Photovoltaic systems, PV systems, residential PV systems, commercial PV systems, line-connected PV, interactive PV

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INTRODUCTION

The New England Electric System is conducting a unique photovoltaic (PV) systems research and demonstration project in two of its subsidiaries: the Massachusetts Electric Company (MECo), and the Narragansett Electric Company (NECo), located in Rhode Island. This is a four-year project with multiple objectives, namely: (1) gather information about the performance, reliability and cost effectiveness of residential and commercial state-of-the-art photovoltaic systems installed at 38 customer locations; (2) record the variation in production of electricity during the year, particularly during peak load periods; (3) showcase PV system components made in Massachusetts, and (4),for the residential project, study the effects that a cluster of PV generating systems has on a single distribution feeder.

The Electric Power Research Institute (EPRI) has provided funding to another New England Electric subsidiary, New England Power Service Company (NEPSCo), to fund objective 4 above. NEPSCo in turn awarded subcontracts in three areas. Electric Research and Management, Inc. studied the effects of brief power outages and voltage transients due to lightning and other causes on the PV systems and their subsequent interaction with the distribution system. Worcester Polytechnic Institute examined the harmonic performance of inverters and their effect on household appliances, other inverters, and the distribution system. Ascension Technology, Inc. had the task of studying the effects of fast and slow changes in sunlight, such as those caused by cloud movements, on the system.

The Demand Planning Department of NEPSCo has overall responsibility for day-to-day operations and monitoring of energy production at all PV sites. The NEPSCo Electrical Engineering Department was responsible for the overall coordination of the feeder monitoring experiment in Gardner and for evaluating the impact of such an installation on the planning of power distribution systems in the future.

All of the PV system components were manufactured in Massachusetts. Mobil Solar Energy Corporation (MSEC), of Billerica, was chosen to supply the PV modules and to serve as general contractor. The construction coordinator was Solar Design Associates, located in Harvard. Residential inverters were made by the American Power Conversion Corporation of Burlington. Acheval Wind Electronics Corporation of Dracut made the inverters for the commercial and institutional buildings.

GENERAL COMMENTS ON RESIDENTIAL SYSTEMS

A PV array covering a total of 240 square feet of roof has been installed on each of 30 houses with southern exposures on two neighboring streets in Gardner, Massachusetts. This city is located about 50 miles west of Boston. All 30 residences receive electricity from the same substation, and 28 of 30 are located on one phase of a distribution feeder.

If the energy provided by the PV system is greater than site energy needs at any given time, the excess energy flows back through the meter to the distribution system. The meter rotates backward as a result of this reverse power flow. Consequently, the customer gets full credit for all of this excess energy.

Most of the homes are of the ranch type, with basements. The average roof pitch is 23 degrees. Average area is approximately 1,100 square feet and the mode regarding number of rooms is 5. No homes have central air conditioning but 6 of the 30 have window-mounted A/C units. Baseboard electric heat is used in 11 of these residences.

At the conclusion of the research phase of this project, ownership of the PV systems will be transferred to the participating home owners.

RESIDENTIAL PV SYSTEM COMPONENTS

Photovoltaic Arrays

The cells used in New England Electric's photovoltaic research project are composed of thin crystalline silicon sheets, 2 inches by 4 inches. Approximately 11% of the radiant energy reaching cells under peak conditions is converted into dc power. The cells are encapsulated under glass on large aluminum modules, 4 feet by 6 feet (1.22 m by 1.83 m), that can be mounted on special brackets attached directly to roofs with lag bolts. These modules produce 50 Vdc and 4.4 amps dc under standard test conditions, or 220 watts per module. Standard test conditions are defined as insolation of 1,000 watts per square meter, cell temperature of 25 degrees C and air mass = 1.5.

Every home has 10 modules located in two rows of five modules each. The modules in each row are connected in series, thereby making up what is called a "string", to produce power at approximately 250 Vdc. Positive, negative and ground conductors for both strings are led into a roof-mounted feedthrough assembly and then down to the basement or garage into a "string combiner".

String Combiners

These devices contain surge protection components (metal oxide varistors, also called movistors), string isolation switches, blocking diodes and a grounding resistor network. The movistors will absorb voltage surges if lightning strikes nearby, but can not provide any protection from a direct lightning strike on the PV system. The string isolation switches provide a convenient way to remove dc power from the inverter for test or service purposes.

The resistor network ties one side of each string to ground through a high resistance (100,000 ohms), which limits the current flow to a small value if part of the string should become shorted to ground. This network also provides connections to test jacks on the front of the string combiner. Using these test points, it is possible to quickly determine whether any part of the array is grounded.

If one PV cell or module in a string should develop a short circuit, this would create a problem for the other string in the array. Blocking diodes in the string combiner prevent current flow from a normally operating string to a string with a shorted PV cell or module, thereby eliminating this problem. The strings are tied together in parallel (hence the name combiner) after the blocking diodes, to present single positive and negative conductors to the inverter.

Inverters

The residential inverters use forced commutation to provide 240 Vac output power, and are completely automatic in that the owner does nothing after turning it on. The units disconnect from the house service panel wiring immediately upon loss of utility power, start automatically as soon as sufficient light hits the array, and shut down when insolation falls to an impractical level. Further, this model has a maximum power tracking feature that always optimizes the product of array voltage and current, thereby maximizing output power. There are panel lights indicating standby status, startup mode, normal operating mode, and array ready mode. These provide the owner with very helpful information on the status of the PV system. Perhaps the best feature from the owner's perspective is the power output indicator. This consists of 10 LEDs stacked vertically in a "bar graph" configuration, such that an LED is lit (starting at the bottom LED) for each 10% increment of maximum power. Home owners have indicated they like to watch this indicator on sunny days when all 10 LEDs are lit, which confirms they are getting full power from their system. Inverter efficiency is approximately 92% over the range of 38% to 100% of full power.

ANALYSIS OF RESIDENTIAL ENERGY PRODUCTION

Within this paper, the analysis of data collected from the NEES Photovoltaic Project focuses on four specific topics: the correlation between hourly PV production and System daily load profile; the potential impact of PV production on residential customer load, the relationship between PV energy production and cloud cover, and the monthly variation in energy output.

Hourly PV Output versus NEE System Load Profile

From the electric utility perspective, a major attribute of PV systems is their ability to contribute capacity during summer peak periods. Figure 1 compares the NEES hourly load profile to the average hourly PV production profile on a day with clear skies in August of 1987. The residential PV systems reach their peak output shortly after the System reaches its peak load. Approximately 60% of the total daily PV system output is supplied during the peak period, if this period is defined as the time when load is equal to or greater than 95% of the maximum load reached in the day. On an hourly basis, the PV systems provide an average of 1.2 kW of demand reduction during the peak period.

NEES LOAD & PV OUTPUT vs. TIME

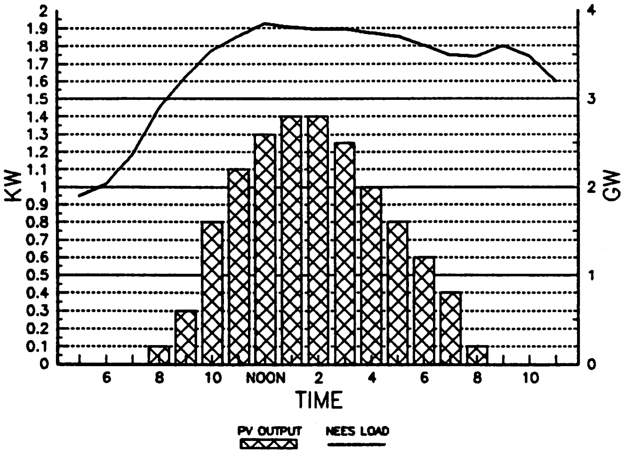

Figure 1

Hourly PV Output versus Residential Load Profile

A question frequently asked concerning these residential systems is "How much of the home's energy needs can be supplied by the PV system?". The answer is zero to more than enough, depending on the time of day and the season. Summer is the optimal season for these roof-mounted arrays because their average tilt angle is 23 degrees from horizontal. Figure 2 shows the residential load profile on a typical clear day and the corresponding average PV system profile. During the hours from 11:00 a.m. through 3:00 p.m. the PV system supplies all of the house energy needs on a diversified basis. The word diversified is important, because each PV system is incapable of meeting any house demand in excess of 2 kW. It is only because the distribution system acts like a battery, in the energy storage sense, that one phase of the feeder can be considered to be powered by the PV systems on it.

AVERAGE RES. LOAD & PV OUTPUT vs TIME

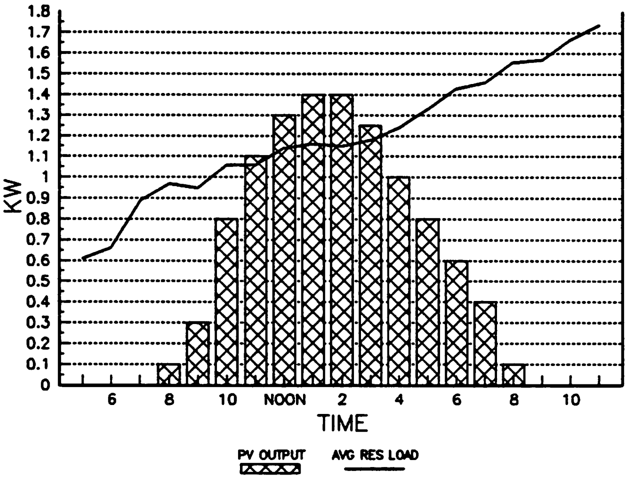

Figure 2

The 28 homes on phase B of the feeder can in fact supply enough energy for 25 other homes without PV systems in the hours from noon to 2:00 p.m. on clear days in summer. Since each home uses about 500 kWh per month, and the PV system produces about 270 kWh per month under good conditions, customers have seen reductions on the order of 50% in their summer monthly electricity bills.

Output versus Cloud Cover

A third area of interest concerning PV systems is the sensitivity of PV production to varying levels of cloud cover. Figure 3 shows the fluctuations in PV production in relation to variations in cloud cover. In this graph a cloud cover index of 0 corresponds to clear skies, and 8 represents complete overcast. Days with total cloud cover result in PV production that is, on average, about 5% of maximum observed production capability.

CLOUD COVER & PV OUTPUT: AUGUST

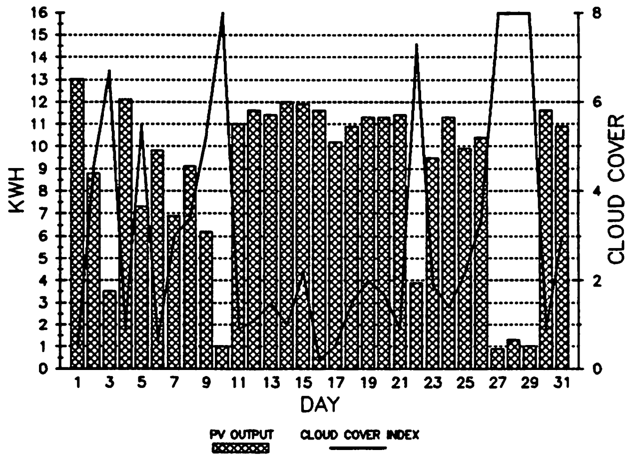

Figure 3

August of 1987 was a near-ideal month in terms of clear skies. The daily fluctuations in average PV system output in other summer months point up the inherently uncertain capacity value of PV systems in the New England climate. It would perhaps be a worthwhile measure of expected PV capacity to calculate a monthly effective capacity. This effective capacity could be the product of peak capacity under ideal field conditions times a derating factor based upon the observed average daily levels of insolation at a particular location.

Monthly and Annual PV Output

The average monthly output of residential PV systems varies from about 50 kWh in a midwinter month to approximately 270 kWh in a midsummer month. Figure 4 shows the average monthly energy production observed in Gardner from January through December, using two years of data. It is worth noting that the January, February and December values shown are more subject to change than data in other months, because of the unpredictable action of snow. Wet snow freezing to arrays will stay on them much longer than dry snow, which tends to blow off or melt more readily in sunshine.

For the two years of data analyzed, average annual energy production was 2,195 kWh.

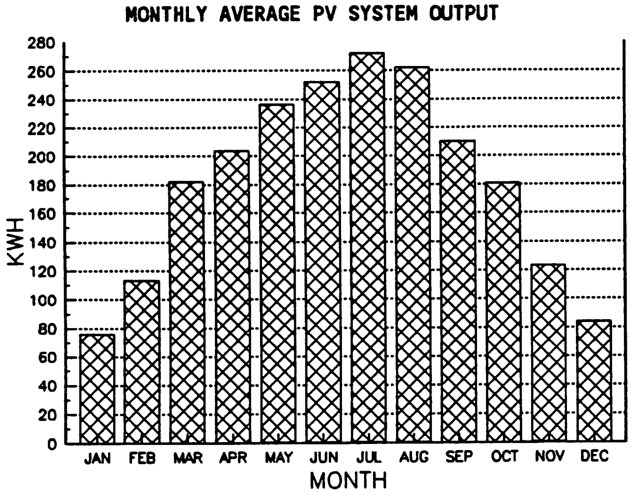

Figure 4

Output versus Orientation

The Gardner residences are oriented in a range from 39 degrees east of true south (house "SE") to 54 degrees west of true south (house "SW"). None of the homes face true south with the closest being 3 degrees west of true south (house "S"). Most of the houses, 20 to be exact, are oriented at 198 degrees + or - 6 degrees, which is approximately south-southwest (SSW); these houses comprise the Main Group, abbreviated as MG.

For present purposes, let the seasons be defined as follows: Winter - January, February, and March; Spring - April, May, and June; Summer - July, August, and September; Fall - October, November, and December. Despite the wide difference in orientation between house SE and house SW, almost 90 degrees, average energy production did not vary by more than 1% between these two houses and MG houses during summer, the most productive season. Differences are more pronounced in other seasons, as shown below.

HOUSE ENERGY OUTPUT DIFFERENCE vs MAIN GROUP

TYPE	WINTER	SPRING	SUMMER	FALL
SE	- 24%	- 5%	0%	- 19%
S	- 15%	0%	0%	- 5%
SW	- 23%	- 2%	0%	- 12%

The final comment on orientation is that differences in winter and fall, as defined here, can vary depending on snow conditions.

Analysis of Harmonics and Transients

The EPRI-funded research in these areas has been completed and a final report is scheduled for late 1989. Interim information on current and voltage harmonics on the distribution system is presented in Reference 1. The effects of cloud movements on PV generation at the Gardner residential site, focusing on slow transients (tens of seconds) in PV system output, are described in Reference 2.

GENERAL COMMENTS ON COMMERCIAL SYSTEMS

PV arrays have been installed on eight commercial or institutional buildings. The five located in Gardner are on city hall, the town library, a restaurant, a furniture store and the local community college. Maximum generating capacity per site ranges from 1.8 to 7.3 kilowatts of direct current power. The remaining three sites are in Rhode Island, on two police stations and an office building. These locations, with electric service provided by The Narragansett Electric Company, have maximum dc power levels of 3.4, 4.8 and 5.5 kilowatts.

Each PV system is connected to the building power service panel through a 3-phase inverter, separate circuit breakers and an isolation transformer. Since the buildings all use energy at a rate considerably higher than the PV system capacity there have been no cases of reverse power flow. All energy is used on site, thereby displacing energy that would have been purchased from MECo or NECo.

Electronic load-profile recording meters are used at all sites to monitor ac power produced in 15-minute intervals. In some cases the meter is on the building side of the isolation transformer; the alternative location is directly on the output of the inverter. Meters located on the building side of the transformer measure both gross PV system output and the losses of the transformer.

Ownership of these PV systems will be transferred to individual site owners when the project is completed.

COMMERCIAL PV SYSTEM COMPONENTS

Photovoltaic Arrays

The cells comprising commercial PV arrays are also 2 inches by 4 inches in size, but two module sizes were employed: 4 feet by 6 feet (identical to the residential modules) and 16 inches X 36 inches (.41 m by .91 m). The smaller modules produce approximately 30 watts at 19 Vdc.

In contrast to the residential systems, many of the commercial/institutional PV systems consist of arrays mounted on structural steel frameworks. These roof-mounted frameworks are tied in to the building structural steel.

All framework arrays have modules inclined 45 degrees from vertical. Two sites use roof mounting brackets identical to the residential system brackets, but applied to the backs of skylights inclined 40 and 45 degrees from vertical. One site uses the brackets on a roof pitched at 14 degrees from horizontal. This site contributes most strongly to reducing NEES summer peak loads because the sun is nearly perpendicular to the array in June. The systems at approximately 45 degrees produce maximum energy in spring and fall.

String Combiners

The string combiners for each commercial/institutional (C/I) site were custom-built, reflecting the variations in number of strings per site. PV systems were designed with 3, 4, 6 and 8 strings in order to achieve the desired dc input voltage per string (186 to 240 Vdc) to the inverter.

Inverters

The 3-phase line-commutated inverters used at the C/I sites have indicator lights for normal power transfer, ac power on, and any fault in the inverter input or output circuits. In addition, a three-scale meter can be used for voltage, current and power readings. This meter provides several useful troubleshooting functions for the array and string combiner as well as the inverter. There are system monitoring circuits and LEDs inside that provide indications of unusual dc or ac conditions (undervoltage, phase fault, etc.) if they should occur.

Operation of this inverter is also totally automatic. The unit begins power production at 120/208 Vac as soon as insolation reaches a threshold level, disconnects from the array immediately if ac power is lost, and shuts down when insolation drops below the threshold.

COMMENTS ON COMMERCIAL ENERGY PRODUCTION

No sites have operated continuously since array installation, for several reasons. The primary reason is that key system components were either relocated or upgraded in capacity at almost every site. Second, additional equipment in the form of isolating switches and circuit breakers was installed at every site. A third source of delay was the complexity of matching array, string combiner, inverter, transformer, and unusual building voltages in some cases. As a result, data on energy production at these sites are limited. The detailed characteristics and more complete output analysis of the commercial/institutional PV systems will be the subject of a future publication.

SUMMARY

The Company has installed 30 residential PV generation systems on two streets served by one distribution feeder in Gardner, Massachusetts. These systems, rated at 2.2 peak kW under standard test conditions, have operated for approximately two years. Energy production varies from around 50 kWh in a winter month to 270 kWh in a summer month. Much of the energy production in summer occurs during NEES peak hours, so that the PV systems provide a load management benefit (reduced residential demand) in addition to the kWh conservation benefit.

Detailed studies have been done on the effects of electrical transients (described in Reference 1) and the subject of 60 Hz harmonics (described in Reference 2). A comprehensive report on the interaction of these residential PV systems and a distribution feeder will be published by EPRI in the latter part of 1989.

The reliability of all residential system elements has been excellent. The only component modifications involved upgrades of combiner diodes to improve thermal capacity and improvements in the array ground wire connectors to minimize corrosion.

All of the commercial/institutional PV sites were accepted by NEES in February of 1989, but intermittent operation of most sites has occurred since early 1988. Power levels have exceeded expectations at several sites under particular weather conditions. Energy production at these sites will be monitored until September of 1990.

CONCLUSIONS

A high concentration (53%) of residential PV generating systems has been operated on a distribution feeder for two years with no apparent adverse effects on the feeder or residences served by the feeder. Total harmonic distortion generated by the inverters is less than the background level found prior to PV system operation (Ref. 1) Customer acceptance of the systems, regarding appearance, operation and output, has been excellent. The project has shown that state-of-the-art PV electrical generating systems for residential applications can be readily assembled, installed quickly (less than half a day) by local roofers and electricians, and easily operated by home owners. As costs decline for the modules, inverters and string combiners, the economics of PV systems should become favorable to home owners within 10 to 15 years.

Regarding design and installation of PV systems on commercial or institutional buildings, the major factor is whether or not modules can be attached to a roof or skylight directly via brackets. Cost and complexity rise significantly if a separate frame must be used to mount the PV modules. The frame and array must be able to withstand the maximum probable wind at the site, which requires anchoring to the building structural framework. It is the penetrations of the roof required for this connection between array and building framework that require particular care to avoid leaks. The other additional cost factor, which is relatively minor, is that the string combiner will probably need to be custom-made for the site. Inverters providing three-phase output are readily available.

Finally, installation and operation of either type of PV system can produce important benefits to a utility. Such a project demonstrates willingness to explore an alternative source of energy well-liked by the public, with many environmental benefits. Lectures on the project can be given to local schools, public service groups, governmental agencies and technical organizations. Brochures can be developed, providing quick and positive responses to individual calls to utilities asking about their PV activities. Local newspapers and television stations are very likely to provide publicity because of strong public interest.

From a technical perspective, perhaps the most valuable benefit to a utility is the knowledge that will be gained on the performance of PV systems in its service area. Large-scale projects, such as the one described here, offer the potential of helping a utility to be ready for widespread installation of PV systems in the next century.

ACKNOWLEDGMENTS

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BIOGRAPHY

JOHN J. BZURA (M-1980, SM-1989) was born in Albany, Georgia on September 14, 1944. He received the B.S., M.E.E. and Ph.D. degrees from Cornell University, Ithaca, New York in 1966, 1967 and 1971 respectively, all in electrical engineering. In 1974, an M.B.A. degree was granted by Syracuse University, Syracuse, New York.

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