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RESIDENTIAL SOLAR PHOTOVOLTAIC SYSTEMS

Final Report for the
Northeast Residential Experiment Station

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June 1986

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P R E F A C E

This report covers research and development work conducted by the MIT Energy Laboratory from July 1982 through June 1986. This Energy Laboratory work in the field of solar photovoltaic systems followed six years of similar work at the MIT Lincoln Laboratory under the same contract with the U.S. Department of Energy. The final report from the Lincoln Laboratory period was published by Lincoln Laboratory in 1983.

During the period of Energy Laboratory involvement, the project focused on the refinement of residential scale, roof-mounted photovoltaic systems for application in the northeastern United States. Concurrent with the conclusion of MIT's involvement, the New England Electric Company is building a major field test of residential photovoltaics in Gardner, Massachusetts to determine experimentally the effects of photovoltaics on electric power company operations. Using systems designs and technology developed at MIT, the long-term performance of these thirty residential systems in Gardner will provide a measure of our success.

Material for this report was prepared by the staff of the Northeast Residential Experiment Station: Edward Kern, Miles Russell, Daniel Bergman, Mathew Buresch, and George Hart. It was edited and compiled by Edward Kern.

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1. THE MIT RESIDENTIAL PHOTOVOLTAICS PROJECT

In 1979, Massachusetts Institute of Technology prepared a Department of Energy plan for the development of roof-mounted, grid-connected photovoltaic systems for residential applications. Ambitious in concert with the National Photovoltaic Program Plan, the "Residential Plan" assumed that the DOE goal of \$0.50 per peak watt photovoltaic modules would be met in 1986. The national commitment to develop renewable energy sources, high at outset of the plan's implementation, has since diffused. Consequently, the success of the DOE "Residential Project" in meeting its goals to develop distributed grid-connected photovoltaic systems has not been widely recognized. Current DOE program efforts are aimed at identifying and developing photovoltaic materials with lower manufacturing costs and higher power generation efficiency.

Three years ago, in July 1982, the DOE Residential Project management was restructured. The project was started by MIT Lincoln Laboratory and the project's major experimental facilities (Residential Experiment Stations) were originally directed by Lincoln Laboratory and funded through Laboratory subcontracts. Since mid-1982 the project has been directed by Sandia Laboratories, with MIT solely responsible for the Northeast Residential Experiment Station.

1.1. The DOE Residential Applications Plan

The activities of the Northeast Residential Experiment Station project have roughly followed the original Residential Plan. This plan called for three phases in the development process as illustrated in the figure below. First, "prototype" systems were to be built at research facilities to test various concepts for photovoltaic panel mounting and dc-to-ac electric power conversion, and to allow for precise system performance monitoring and assessment. Monitored houses, conventional homes without photovoltaic systems, were used to obtain data on the electric power usage patterns for correlation with photovoltaic systems generation. Second, the best designs from the prototype testing were to be built in the surrounding towns to measure performance in field conditions (Initial Systems Applications Experiments). This transfer from laboratory to field conditions was meant to identify that which we did not know about using this technology: would building codes, electrical codes, electric utilities, trees, baseballs, glare, aesthetics, inverter noise, or insurance companies present obstacles? If so, the program would address them and, hopefully, develop solutions. In the third and final phase, the systems proven best in the limited field testing would be built in a cluster (System Readiness Experiments) to demonstrate photovoltaic technology and to identify additional unforeseen problems, if any, associated with high penetrations of photovoltaic systems on electric power distribution circuits (feeders).

Fig. 1-1: The DOE Residential Systems Development Plan

We are now entering the third phase of the project at the Northeast Residential Experiment Station. Although the second phase was not conducted as planned, it has happened largely through the cooperation of the owners of privately financed photovoltaic systems. Similarly, for the third phase the Massachusetts Electric Company has provided \$1.3 million dollars for photovoltaic system purchases. A "Model Photovoltaic Community" project is being built in the City of Gardner, Massachusetts, about fifty miles west of the Northeast Residential Experiment Station. Planned with close consultation from MIT, this project has been designed to meet the needs of both the Massachusetts Electric Company's "Enterprise Plan," a major economic development and conservation program, the photovoltaic systems development effort at the Northeast Residential Experiment Station, and the photovoltaic initiatives of Massachusetts Governor Michael S. Dukakis.

Fig. 1-2: The Northeast Residential Experiment Station
(October 1985)

1.2. Completion of the MIT Photovoltaic Systems Project

The Gardner Cluster Project will become the principal legacy of the NERES project, the final experiment testing the viability of the roof-mounted, grid-connected photovoltaic system concept. Since the useful life of the Gardner photovoltaic systems will exceed the period of the experiment, they and the related instrumentation are designed to minimize any disruption at the conclusion of the experiment. Based on lifetimes of today's photovoltaic products, a 20 to 30 year lifetime for these systems is anticipated. While the Gardner Project is being built, the original NERES experimental facilities are being dismantled. The photograph below shows the neighborhood in Gardner chosen for the cluster project, and four of the 30 photovoltaic arrays. The remaining systems will be installed over the summer of 1986.

Fig. 1-3: The Gardner, Massachusetts Photovoltaic Cluster Site
(The first four systems installed)

1.3. Overview of the Final Report

The second chapter of this report provides a comparison the state-of-the-art in residential photovoltaic system design and the original goals of the DOE Residential Plan. It reviews the accomplishments of the past seven years including the current prospects for distributed photovoltaic generation on roof-tops in the United States. Chapter Three reviews research performed at MIT which addressed a broad range of issues related to electric power grid interconnection. The fourth chapter covers technology developed by the project and the fifth summarizes our experience monitoring system performance and developing a quantitative understanding of photovoltaic system performance. A principal function of the NE RES has been to be an effective advocate for distributed photovoltaic systems. The last chapter reviews MIT's record of working with the photovoltaic industry, electric utilities, solar energy associations and standards making authorities.

2. PROJECT GOALS AND ACCOMPLISHMENTS

At the May 1979 DOE Semi-Annual Review for Photovoltaic Technology and Applications, the goal and approach of the Residential Project were stated as (1):

Table 2-1: DOE Program Goals (circa 1979)

"Program Goal

- o A Private viable market for \$1.60 per peak watt (1980 \$s) PV and PV/Thermal systems by 1986

Program Approach

- o Develop and Test Residential Components and Systems:

Development Sequence	Regionally Appropriate Designs Prototype Systems (No Occupant) Initial System Eval. Experiments System Readiness Experiments
-------------------------	---
- o Develop a commercialization strategy for implementation in the post 1986 period."

Clearly, the overall goal has not been met in 1986. For the residential project, this price goal was allocated to various cost centers associated with building photovoltaic systems. As reported by Cox (2), this allocation was:

Table 2-2: System Price Goals (1980 \$s per peak watt)

Array Purchase	0.93
Array Installation	0.17
Power Conditioner Purchase	0.25
Power Conditioner Installation	0.13
System Design	0.12

TOTAL	\$1.60

The state-of-the-art in these systems is now reflected in work conducted at MIT in association with Mobil Solar Energy Corporation and Solar Design Associates. Reduction of array manufacturing, installation and operating costs was the objective of this research, which advanced prior array development work at MIT which used ARCO Solar photovoltaic panels. Cost estimates for the new arrays are based on the panel price plus the costs for labor and materials for mechanically and electrically installing the array on a rooftop. The costs associated with this new design are based on our experience with the Massachusetts Electric project and total \$837.42 for the material and labor for installation of a system, with an (already purchased) photovol-

taic array and power conditioner. For this 2200 watt peak array, the per watt price is \$0.38, comparable to a \$0.42 price in the original goals as stated above.

Table 2-3: Photovoltaic System Pricing
(Based on Massachusetts Electric Project)

		Complete System	System without Modules & PCU
BOS Manufacturer Parts		\$322.45	\$322.45
Materials Handling	20%	\$64.49	\$64.49
Direct Labor	\$29.67		
Unproductive time	\$9.89		
Labor Total		\$39.56	\$39.56
Labor Benefits	40%	\$15.82	\$15.82
Labor Indirect Cost	50%	\$27.69	\$27.69
Profit	10%	\$47.00	\$47.00
BOS Manufacturer Price		\$517.02	\$517.02
Installer: BOS Cost		\$517.02	\$517.02
PV Module Cost	\$5.75	\$12,650.00	
Inverter Cost	\$1.90	\$3,800.00	
Installer Parts Cost		\$17,484.04	\$517.02
Materials Handling	10%	\$1,748.40	\$51.70
Direct Labor	\$97.25		
Unproductive time	\$48.63		
Labor Total		\$145.88	\$145.88
Labor Benefits	20%	\$29.18	\$29.18
Labor Indirect Cost	10%	\$17.51	\$17.51
Profit	10%	\$1,942.50	\$76.13
Installer Price to Customer		\$21,367.50	\$837.42
Price per DC watt peak		\$9.71	\$0.38

From the above estimates, it can be concluded that balance-of-system cost reductions (excluding power conditioners) have met the original goals, and the cell materials and module goals have not. Further cost reductions for roof-mounted arrays are possible, but it is apparent that the greater opportunities for overall system cost reductions exist in the photovoltaic module and power conditioning costs.

The approach taken by the MIT photovoltaic systems project has followed the sequence of steps originally planned, but has not kept the schedule. Three Residential Experiment Stations were built, prototype systems were constructed at each, and each has become a regional center for investigations of systems performance issues, for discussions on photovoltaic applications issues and for dissemination of information concerning photovoltaic systems.

The Residential Experiment Stations, especially the Northeast, have also been active in the area of codes and standards development. Bringing the perspective of the photovoltaic community into committees dominated by representatives of the electric utility industry has opened a technical dialogue on the effective interconnection of dispersed photovoltaic systems with electric grids. We have contributed to the development of the National Electrical Code provisions for photovoltaic systems, to the development of standards for systems ratings, to the development of safety standards for power conditioning equipment and to the development of standards for comparison of new photovoltaic materials.

It is difficult to make an objective assessment of the contributions of the Residential Experiment Stations to the U.S. photovoltaic industry. It can, however, be asserted that virtually all of the privately financed, small grid-interconnected systems can be traced back to the DOE residential Project in some way: through the experience gained at a RES by an installer or manufacturer, through the use of a power conditioner designed by the program or through the replication of an array installation concept first proven at a RES.

The New England Electric System, through its distribution and marketing subsidiary the Massachusetts Electric Company, has provided perhaps the greatest endorsement of the Northeast Residential Experiment Station by supporting the final phase of the system development sequence. A cluster of thirty houses and six commercial buildings in the City of Gardner, Massachusetts fifty miles west of the NERES is being equipped with photovoltaic systems to assess their impacts on a power distribution feeder, to measure community response to the concept of distributed photovoltaic power generation, and to monitor system performance in a real field environment using existing houses. When the results of this experiment are known in 1988, the Residential Photovoltaic Project started at MIT a decade earlier will be complete, and the principal objective--to develop well engineered, cost effective, and field proven photovoltaic systems--will hopefully be met.

2.1. The Cost Differential for Homeowner Photovoltaics

The real price (adjusted for inflation) of electricity has been rising at a rate of 3.1% over the past six years while the real price of photovoltaics has dropped considerably, suggesting future economic viability should current trends continue. Calculation of a single nationwide breakeven point, however, is a misleading exercise as it ignores the effects of two independent variables which have first order effects on the result. These are the level of insolation (solar resources) and the price of conventional electric utility supplied power. Insolation ranges from over 2600 kwh per square meter annually in the high desert Southwest to 1200 kwh per square meter in cloudy areas of the Northwest, with the rest of the country in between. Prices of electricity range from about two cents per kilowatt-hour in the

Pacific Northwest to over 16 cents in the New York City area. Certain cities, most notably San Diego and Honolulu, have both high insolation and electricity prices and can be identified as early cost effective markets. Others, such as Seattle register low on both counts and might never develop a photovoltaic market.

Table 2-4: Financial assumptions used for economic analysis

Mortgage	14.7%(1980-84)	Marg Tax 1	34%
Down Paymt	20.0%	Marg Tax 2	39%
Mort Per(yr)	30	Marg Tax 3	49%
Gen Infla	6.9%(1980-85)	Sys Life(yr)	30
Elec Infla	8.5%(1980-85)	Buy Margin	1
Payment (yr)	\$2,587	Cnst\$ Disc	7.8%
Maintenance	\$25	ElcPrcl984	4%

A state-by-state model has been developed to quantify these factors. Using the tabulated financial assumptions and system costs, the economic viability of photovoltaic systems for each state can be calculated. These results are derived using a model reported by Kern (4), and give the cost of photovoltaic supplied electricity as a percentage of electric utility supplied electricity for the three income tax rate assumptions.

Table 2-5: Assumed System Performance Characteristics

Photovoltaic Array		Power Conditioner	
Rating (Wdc)	2200	Rating (Wac)	2000
Temp Loss	91%	Efficiency	88%

Table 2-6: Photovoltaics-to-Electric Grid Kilowatt-hour Price Ratios by State

(Based on Massachusetts Electric Project)

State	500 kwh average	PV Gen (kwh)	Ratio 1 (Average 500 kwh price)	Ratio 2	Ratio 3
Hawaii	\$57.99	3413	226%	205%	166%
Arizona	\$42.99	4130	252%	228%	185%
California	\$40.09	3433	325%	294%	239%
New Mexico	\$41.60	4104	262%	237%	193%
Florida	\$42.55	3194	329%	298%	242%
Nevada	\$34.94	4142	309%	280%	227%
Kansas	\$37.76	3387	349%	317%	257%
New York	\$64.14	2194	318%	288%	234%
Louisiana	\$32.03	3084	452%	410%	333%
Oklahoma	\$34.28	3039	429%	389%	316%
Utah	\$40.90	3665	298%	270%	219%
Texas	\$40.47	3194	346%	313%	254%
Colorado	\$34.44	3665	354%	321%	261%

Rhode Island	\$48.44	2504	369%	334%	271%
Massachusetts	\$48.80	2504	366%	332%	269%
Arkansas	\$35.23	3091	410%	372%	302%
Wyoming	\$27.79	3697	435%	394%	320%
South Dakota	\$35.67	3007	417%	378%	307%
Missouri	\$33.30	3020	444%	403%	327%
New Jersey	\$53.29	2407	348%	316%	256%
Indiana	\$39.79	2574	436%	395%	321%
Delaware	\$50.24	2613	340%	308%	250%
Connecticut	\$55.08	2194	370%	335%	272%
Iowa	\$40.69	3007	365%	331%	269%
Vermont	\$42.96	2613	398%	361%	293%
Nebraska	\$32.94	3317	409%	371%	301%
North Carolina	\$37.02	2710	445%	404%	328%
Maryland	\$39.48	2613	433%	393%	319%
Pennsylvania	\$46.36	2407	401%	363%	295%
Michigan	\$35.24	2523	503%	456%	370%
Illinois	\$42.12	2574	412%	373%	303%
South Carolina	\$37.65	3026	392%	355%	289%
Mississippi	\$33.54	2962	450%	408%	331%
Ohio	\$41.68	2394	448%	406%	330%
North Dakota	\$33.23	2833	475%	430%	349%
New Hampshire	\$47.54	2387	394%	357%	290%
Alabama	\$35.98	2962	419%	380%	309%
Virginia	\$37.44	2768	431%	391%	317%
Alaska	\$36.36	2187	562%	509%	414%
Georgia	\$31.97	2710	516%	467%	380%
Minnesota	\$32.42	2471	558%	506%	410%
Montana	\$23.22	2684	717%	650%	528%
Kentucky	\$30.76	2781	522%	473%	384%
Maine	\$38.74	2387	483%	438%	356%
Wisconsin	\$33.98	2658	495%	448%	364%
West Virginia	\$32.73	2465	554%	502%	408%
Idaho	\$19.78	3446	656%	594%	483%
Tennessee	\$24.98	2987	599%	543%	441%
Dist. of Columbia	\$27.26	2942	557%	505%	410%
Oregon	\$22.81	2536	773%	700%	569%
Washington	\$19.19	2329	1000%	906%	736%

The effects of changing the prices of modules in the current system design is shown on the following table. In it the cost of the power conditioning equipment is held at the current level, \$1.90 per peak watt. Numbers shown are estimates of the number of residences, nationwide, for which photovoltaics would be cost effective, this number as a percent of all residences, and the resulting cumulative market size in megawatts of peak capacity assuming two kilowatt systems. The calculations are made using the average and the highest kilowatthour costs from conventional utilities in each state.

Table 2-7: Effect of Module Price Reductions
in Current System Design

(Average and highest kwh costs for each state)

Module Price (FOB)	System Cost (\$/W)	Levelized Economics (Average kwh cost)		Module Sales (MW)	Levelized Economics (Highest kwh cost)		Module Sales (MW)
		Market Size (1000s)	Penetra- tion		Market Size (1000s)	Penetra- tion	
\$5.75	\$9.71	0	0.0%	0	0	0.0%	0
\$5.00	\$8.81	0	0.0%	0	0	0.0%	0
\$4.50	\$8.20	0	0.0%	0	0	0.0%	0
\$4.00	\$7.60	0	0.0%	0	12	0.1%	25
\$3.50	\$6.99	0	0.0%	0	12	0.1%	25
\$3.00	\$6.39	0	0.0%	0	198	1.0%	436
\$2.50	\$5.78	0	0.0%	0	223	1.1%	490
\$2.00	\$5.18	12	0.1%	25	657	3.2%	1,444
\$1.50	\$4.57	49	0.2%	107	1,413	6.8%	3,109
\$1.00	\$3.97	185	0.9%	408	1,958	9.4%	4,307
\$0.50	\$3.36	768	3.7%	1,691	3,639	17.5%	8,006

If one used the least expensive photovoltaic modules and power conditioning currently on the market ratios of photovoltaics to utility costs and market sizes are significantly improved. The following tables assume this "Best 1986 Scenario," pricing a photovoltaic system using 1986 technology but assuming pricing based on producing 1000 systems (\$4 per peak watt modules, \$.40 per peak watt PCUs) and taking the highest electric power prices in each state.

2.2. Remaining Obstacles to Residential Photovoltaics

The principal impediment to photovoltaic technology reaching the residential grid-connected market is photovoltaic module price. Grid-connected photovoltaics must compete in the electric power commodity market, and one would not expect that consumers or utilities would, in general, select one form of electric power supply over another based on criteria other than the bottom line price. Without the promise of prices sufficiently low to compete with conventional sources of electricity, much of the enthusiasm for photovoltaic technology would vanish and the principle rationale for federal research and development efforts would be eliminated.

In addition to price, however, there are two other sources of uncertainty relating to the grid-connected photovoltaic market. First, there are technical uncertainties concerning the lifetime of photovoltaic panels in field usage and concerning the operation of distributed photovoltaic generation on conventional electric distribution systems. Second, there are institutional impediments involved in reaching this market. They include considerations such as the openness of electric utilities

to the technology, the endorsement of the buildings trades and building codes groups, the premiums charged by insurance companies, the treatment by state and local taxing authorities, the tax policy of the Internal Revenue Service and the continued support by the Departments of Energy and the Justice for the policies enacted through the PURPA legislation.

**Table 2-8: Photovoltaic System Pricing
(Best 1986 Scenario)**

			Complete System
BOS Manufacturer Parts			\$322.45
Materials Handling	20%		\$64.49
Direct Labor		\$29.67	
Unproductive time		\$9.89	
Labor Total			\$39.56
Labor Benefits	40%		\$15.82
Labor Indirect Cost	50%		\$27.69
Profit	10%		\$47.00
BOS Manufacturer Price			\$517.02
Installer: BOS Cost			\$517.02
PV Module Cost	\$4.00		\$8,800.00
Inverter Cost	\$0.40		\$800.00
Installer Parts Cost			\$10,634.04
Materials Handling	10%		\$1,063.40
Direct Labor		\$97.25	
Unproductive time		\$48.63	
Labor Total			\$145.88
Labor Benefits	20%		\$29.18
Labor Indirect Cost	10%		\$17.51
Profit	10%		\$1,189.00
Installer Price to Customer		\$13,079.00	
Price per DC watt peak		\$5.95	

**Table 2-9: Photovoltaics-to-Electric Grid Kilowatt-hour
Price Ratios by State**

(Based on Best 1986 Scenario)

State	500 kwh PV Gen highest	Ratio 1	Ratio 2	Ratio 3
			(Highest 500 kwh price)	
Hawaii	\$76.99	3413	106%	96% 78%
Arizona	\$57.50	4130	117%	106% 86%
California	\$65.00	3433	124%	113% 92%
New Mexico	\$52.01	4104	130%	118% 96%
Florida	\$60.40	3194	144%	130% 106%
Nevada	\$46.39	4142	144%	131% 107%
Kansas	\$55.65	3387	147%	134% 109%

New York	\$77.88	2194	162%	147%	120%
Louisiana	\$55.00	3084	164%	148%	121%
Oklahoma	\$55.70	3039	164%	149%	121%
Utah	\$46.17	3665	164%	149%	121%
Texas	\$52.69	3194	165%	150%	122%
Colorado	\$44.25	3665	171%	155%	126%
Rhode Island	\$60.42	2504	183%	166%	136%
Massachusetts	\$59.81	2504	185%	168%	137%
Arkansas	\$47.53	3091	189%	171%	140%
Wyoming	\$39.50	3697	190%	172%	140%
South Dakota	\$48.54	3007	190%	172%	140%
Missouri	\$47.84	3020	192%	174%	142%
New Jersey	\$59.29	2407	194%	176%	144%
Indiana	\$54.33	2574	198%	180%	147%
Delaware	\$52.57	2613	202%	183%	149%
Connecticut	\$62.41	2194	203%	184%	150%
Iowa	\$45.27	3007	204%	185%	151%
Vermont	\$51.18	2613	207%	188%	153%
Nebraska	\$40.18	3317	208%	189%	154%
North Carolina	\$49.17	2710	208%	189%	154%
Maryland	\$50.45	2613	210%	191%	156%
Pennsylvania	\$53.89	2407	214%	194%	158%
Michigan	\$50.55	2523	217%	197%	161%
Illinois	\$49.23	2574	219%	199%	162%
South Carolina	\$41.58	3026	220%	200%	163%
Mississippi	\$42.04	2962	223%	202%	165%
Ohio	\$49.57	2394	234%	212%	173%
North Dakota	\$41.62	2833	235%	213%	174%
New Hampshire	\$48.82	2387	238%	216%	176%
Alabama	\$39.30	2962	238%	216%	176%
Virginia	\$41.82	2768	240%	217%	177%
Alaska	\$52.65	2187	241%	219%	178%
Georgia	\$40.95	2710	250%	227%	185%
Minnesota	\$43.96	2471	255%	232%	189%
Montana	\$39.66	2684	261%	236%	193%
Kentucky	\$37.44	2781	266%	242%	197%
Maine	\$43.18	2387	269%	244%	199%
Wisconsin	\$38.40	2658	272%	247%	201%
West Virginia	\$39.03	2465	288%	262%	213%
Idaho	\$26.86	3446	300%	272%	222%
Tennessee	\$28.08	2987	331%	300%	244%
Dist. of Columbia	\$27.26	2942	346%	314%	256%
Oregon	\$29.00	2536	377%	342%	279%
Washington	\$31.46	2329	378%	343%	280%

Table 2-10: Effect of Module Price Reductions
(Best 1986 Scenario as base)

(Average and highest kwh costs for each state)							
Levelized Economics				Levelized Economics			
Module Price (FOB)	System Cost (\$/W)	(Average kwh cost)		Module Sales (MW)	(Highest kwh cost)		Module Sales (MW)
		Market Size (1000s)	Penetration		Market Size (1000s)	Penetration	
\$5.00	\$7.16	0	0.0%	0	12	0.1%	25
\$4.50	\$6.55	0	0.0%	0	24	0.1%	53
\$4.00	\$5.95	0	0.0%	0	223	1.1%	490
\$3.50	\$5.34	12	0.1%	25	361	1.7%	794
\$3.00	\$4.74	29	0.1%	64	1,395	6.7%	3,069
\$2.50	\$4.13	79	0.4%	174	1,617	7.8%	3,558
\$2.00	\$3.53	704	3.4%	1,549	3,138	15.1%	6,903
\$1.50	\$2.92	1,735	8.4%	3,817	4,584	22.1%	10,084
\$1.00	\$2.32	4,262	20.5%	9,375	6,660	32.1%	14,652
\$0.50	\$1.71	6,821	32.8%	15,007	7,275	35.0%	16,006

Demonstrated price superiority of photovoltaics over other forms of electric power generation would, of course, do much to force the resolution of these remaining technical and institutional impediments. Such price superiority, however, is unlikely. Therefore, as photovoltaic technology approaches price parity with conventional forms of generation in the electricity commodity market, it is essential that the remaining technical and institutional issues be resolved to counter disincentives that favor the status quo and work against substitutions of new technologies.

The Residential Experiment Stations in the Northeast, Southeast, and Southwest United States were designed to address these technical and institutional issues and to communicate the results of this work to institutions which will have some effect on the adoption of photovoltaic technology. Resolution of such issues in the minds of scientists and engineers working within the National Photovoltaic Program or within the photovoltaic industry is by no means sufficient. Each electric utility, building code group, safety standards group, insurance company, building inspector, etc., must accept these results individually. For the more technically inclined institutions, such as electric utilities, this may mean repeating experiments that have already been conducted by the federal program so that utility engineering and scientific personnel are personally convinced of the performance of the technology. A role of the Residential Experiment Stations has been to assist such groups in their own testing of photovoltaics, so that lessons learned in the RES experiences are not lost, and prior mistakes are not repeated.

2.3. Recommendations for Continued Research and Development

The staff of the Northeast Residential Experiment Station has been involved with the National Photovoltaic Program residential efforts since early 1977 and had hoped to see this project through the conclusion of the Gardner, Massachusetts, photovoltaic cluster experiment. Without continued DOE support, and with involvement of the Electric Power Research Institute in the Gardner installation aspects of the NERES work delayed, MIT elected to terminate the project.

We have identified four broad areas of where continued work would be most helpful to the acceptance of residential photovoltaics: (1) designing, testing and evaluating new designs for low-cost arrays, (2) supporting the Gardner cluster experiment, (3) developing photovoltaic system and array rating procedures and associated instrumentation, and (4) studying the effect of the spectral distribution of irradiance on the performance of new systems using photovoltaic materials.

In 1984 the Northeast Residential Experiment Station built three systems as part of a "Retrofit Systems" activity. These arrays have lead to further work involving Mobil Solar Energy Corporation and Solar Design Associates with whom we built a stand-off array prototype which is being replicated many times in the Gardner Cluster experiment. Significant advances have been made in simplifying array design for mounting on shingled residential roofs: our first recommendation is to explore ways in which these designs could be extended to other types of arrays, for example to flat roof mounting and ground mounting. As an important part of this work, a revision of our 1984 "Residential Photovoltaic Systems Handbook" incorporating progress in the design of roof-mounted systems achieved during the past two years should be written.

The cluster experiment in Gardner is our second area of interest. We expect that the introduction of photovoltaic systems in a neighborhood will result in virtually no adverse effects on the electric power distribution system. Accordingly, the experiment is expected to produce a null result. Nevertheless, it is essential that as this experiment is conducted to prove to the electric power industry that no adverse conditions result. We feel that it is necessary to place sufficient instrumentation in this project to sense performance abnormalities even though we do not expect them. The New England Electric system timeline on this project calls for the systems to be completely installed by the fall of 1986. Starting at that time, they will begin a two-year experimental period. A research proposal for this activity, in which the NERES staff would have had a major role, has been submitted by New England Electric to the Electric Power Research Institute.

The area of systems rating and array diagnostic instrumentation is of interest because there is presently no precise means for establishing the characteristics of an array. Our ability to

characterize an array is limited by the accuracy of I-V curve tracing equipment, the spectral sensitivity mismatch between pyranometers and a photovoltaic array, field procedures for measurement of an average array temperature, availability of accurate temperature coefficients, and the analytic procedure for I-V data translation. Present methods leave uncertainties larger than five percent in establishing the rated array power and other array characteristics. This number is too large for scientific purposes such as measuring array degradation and validating performance models. Five percent is also too large for establishing whether a system meets a manufacturer's performance specifications.

Interest in the area of spectral distribution of irradiance derives from our interest in new materials for photovoltaic systems. In particular, we are interested in the performance of amorphous silicon, gallium arsenide, and other single and multiple-junction thin film photovoltaic devices.

2.4. References

- (1) Kern, E.C., "Residential Application Implementation Plan," DOE Semiannual Program Review, Gatlinburg, TN, May 1979.
- (2) Cox, C.H., "Residential Photovoltaic System Costs," 15th Intersociety Energy Conversion Engineering Conference, Seattle, WA, August 1980.
- (3) Russell, M.C. and Kern, E. C., "Stand-off Building Block Systems for Roof-mounted Arrays," Final Report to Sandia National Laboratories," MIT Energy Lab, March 1986
- (4) Kern, E.C., "Photovoltaics, Wind and Small Hydro Power Generation: Comparative Costs and Performance," 17th IEEE PV Specialists Conference, Kissimmee, FL, May 1984.

NOTES:

3. ELECTRIC UTILITY INTERCONNECTION ISSUES

This chapter summarizes work performed during the last four years on the photovoltaic-utility interface. Specifically, it addresses studies performed on the economic analysis of the avoided cost of electric generation for New England photovoltaic residences, the residential roof availability for photovoltaics in Massachusetts, the quantification of different metering configurations, the effects of distributed photovoltaic generation on conventional power distribution losses, and the islanding potential of distributed photovoltaic generation. In addition, this section summarizes our work on two IEEE standards coordinating committees and one ASTM standards subcommittee, to which NERES staff contributed. These subcommittees focused on distributed generation, the photovoltaic-utility connection, and cell and module measurement standards. Finally, an outline is presented on the contributions that were made to the 1984 National Electric Code (NEC) section 690 on photovoltaic systems.

The Massachusetts Electric Model Photovoltaic Community Project in Gardner, Massachusetts has been designed to address many issues relating to the utility interface. The photograph below shows the substation serving the Gardner photovoltaic cluster in the foreground and the neighborhood of residences equipped with photovoltaics in the center of the background.

Fig. 3-1: Substation Feeding the Gardner Photovoltaic Project

3.1. Marginal Value of Photovoltaic Generation

The Public Utility Regulatory Policies Act of 1978 (PURPA) put into federal law the requirement that utilities buy electricity from cogenerators and small power producers ("qualifying facilities") at a reasonable rate. Implicit in the definition of a "reasonable buy back rate" was the intention to not only ensure a market for alternate electricity generation, but also to promote its development, even if to a small measure it was subsidized through the established "reasonable rate." Nonetheless, the interest and needs of the electric utility industry were considered to be important factors in the buyback rate setting process. After some deliberation the Federal Energy Regulatory Commission (FERC), ruled in 1979 that the reasonable buyback rate was to be the maximum allowed by PURPA, namely the utility's full avoided cost.

In determining avoided cost, utilities are permitted to take a variety of relevant issues into account. An important factor in this assessment is the marginal cost of generation. Marginal cost is defined as the cost, at any instant, of generating an additional unit of power. In addition, the utility may consider the timing and reliability of the qualifying facility's output; the utility's ability to dispatch the facility; the extent to which scheduled outages for maintenance can be coordinated with

utility plans; the fact that the addition of capacity from qualifying facilities may involve shorter construction lead times and can be used to defer the building of costly new power plants; and that the utility's transmission line losses in many cases will be reduced by the qualifying facility's generation of electricity close to the load as discussed later in this chapter.

In preparation for this work, the marginal cost data submitted in 1982 by New England Power Pool (NEPOOL), New England Electric System (NEES), Northeast Utilities (NU), and Boston Edison Company (BECo) in compliance with PURPA and the FERC ruling were obtained. As required, this material is actual data for 1981 and predicted data for 1982 to 1986, and is in the format of monthly average hourly figures for a typical weekday and weekend day. Shown below is an example of the weekday peak marginal cost figures over the six years based on the published data for the New England Electric System.

Fig. 3-2: Marginal Cost Versus Time
(New England Electric System)

Variations in marginal cost during different hours of the day show some predictable patterns. As shown below, marginal costs between 12 midnight and 5:00 a.m. are usually at their lowest because residential, commercial, and industrial loads are largely shutdown for the night. The time of day and year when a utility's marginal costs are at their peak vary according to the size and type of the loads on the system. If the major load on the utility is commercial and industrial, as is the case for most power systems, the system peak demand and peak operating and

marginal cost will be around the middle of the day when both businesses and factories are in full operation. Conversely, if the major load is residential, the peak demand and marginal cost typically occurs in the evening, when most people are home cooking and entertaining.

Fig. 3-3: Daily Price Variation Average
(New England Electric)

3.2. Value of Photovoltaic Generation and Residential Loads

The marginal cost data published by utilities can be readily correlated with data collected at the NERES on residential photovoltaic system generation and residential loads to analyze the marginal worth of photovoltaic energy generated and residential energy consumed. The objective of this study was to determine whether the timing of photovoltaic electricity generation makes it worth less or more than the electricity consumed by a residence for the particular utilities and region under examination.

A computer program was developed to perform the intended marginal worth calculations. The program multiplies the utility marginal cost data in cents per kilowatthour with the NERES photovoltaic production energy data in kilowatthours (for each monthly-average hour of the day) to yield a product that is equal to the marginal value of electricity transferred to the utility by the photovoltaic system or to the residence by the utility. At the end of each monthly average day computation, the program sums up all the energy generated or consumed and all the hourly marginal value figures and multiplies these values by the number of weekdays and weekend days in the particular month.

Knowing the monthly energy transferred and its total marginal value, the monthly average cents-per-kilowatthour marginal value can be calculated by performing a simple division. The results of these calculations are given below for the New England Electric System, the five residential loads monitored by the NERES, and on the TriSolar Corporation prototype system at the NERES.

Table 3-1: Worth of Residential Demand and PV Generation
(New England Electric)

(Cents per kilowatt-hour)

Month	Load 1	Load 2	Load 3	Load 4	Load 5	PV Gen
January	6.5	6.5	6.5	6.7	6.6	7.4
February	4.5	4.6	4.5	4.6	4.6	4.8
March	3.9	3.9	3.9	3.9	3.9	4.1
April	3.6	3.5	3.5	3.6	3.5	3.8
May	3.6	3.4	3.5	3.6	3.5	3.9
June	3.4	3.8	3.8	3.8	3.8	4.4
July	4.4	4.3	4.3	4.2	4.1	4.6
August	4.0	3.9	3.9	3.9	3.9	4.2
September	5.0	4.9	4.9	5.0	5.0	5.3
October	5.0	4.9	4.9	5.0	5.1	5.4
November	4.7	4.8	4.8	4.9	4.9	5.1
December	3.9	3.9	3.9	3.9	3.9	4.1

The marginal value of the electricity generated by the photovoltaic prototype is almost always greater than the value of the electricity consumed by the residential house. The photovoltaic generation occurs during the middle of the day and peak residential consumption occurs in the evening. Based on the marginal cost versus time of day curves we know that the peak demand on the utility and its highest marginal costs occur typically during the daytime. Since photovoltaic systems supply electricity during the daytime, their electricity will generally be worth more than the electricity consumed by residences in the evening. This is shown below where the January 1982 marginal cost for New England Electric is plotted versus time of day on the same graph with typical photovoltaic electricity generation and residential load consumption.

Fig. 3-4: January 1982 Consumption, Generation and Costs
(New England Electric)

A more important consideration to put the potential of residential photovoltaics in perspective, is the financial impact that the photovoltaic generation could have on homeowners' electric bills and utilities' revenues. Such analyses first requires making a decision about how to value photovoltaic electricity.

The valuation of photovoltaic power is contingent upon the technical consideration of how utility-interactive photovoltaic power is measured: where the kilowatthour meters are placed between the photovoltaic system and the utility. A later section of this report discusses the three standard metering configurations.) The analysis that follows was performed assuming single net metering, which involves one conventional (bidirectional) kilowatthour meter between the residence's service distribution panel and the utility grid. This metering arrangement dictates a unity buyback ratio (i.e. photovoltaic generated energy is valued at the residential rate). On bright days photovoltaic generation causes the meter to run backwards when the generation power exceeds the load and no information on the gross loads or photovoltaic generation is preserved.

The typical homeowner's bill and utility residential load revenue is determined using average residential use and residential rate data published by NEPOOL and utilities. The energy displacement of a typical residential photovoltaic system is then valued alternately at the residential rate and the marginal worth rate. The homeowner's bill and the utility's revenue is reduced by the value of the photovoltaic generation, to produce a hypo-

thetical bill or revenue assuming photovoltaic systems were installed on all suitable single-family-detached residential houses. Typical results of this calculation are tabulated below for Boston Edison and New England Electric. Notice that the typical New England Electric customer, using 6,025 kwh per year, would pay 53% of his regular bill given a two kilowatt system and single net metering. Billing using marginal cost rates would cut the bill only to 73% of the original amount. Corresponding reductions in New England Electric revenues from all single family detached residential customers are 88 and 93 percent, a lesser amount because only a fraction of such houses are believed to have adequate roof area and solar access.

Table 3-2: Revenue Impacts of Residential Photovoltaics

	New England Electric	Boston Edison
Electric Rates:		
Avg Residential	\$0.0847	\$0.0954
Avg PV marginal	\$0.0476	\$0.0606
Homeowner Bills:		
Without PV	\$510.32	\$495.13
Net metering	\$270.91	\$225.48
Marginal worth	\$375.78	\$323.84
Utility Revenues: (millions of dollars)		
Without PV	\$355 mil	\$99 mil
Net Metering	\$311 mil	\$85 mil
Marginal worth	\$330 mil	\$90 mil

Assuming that the photovoltaic energy from two kilowatt systems is valued at a rate that is close to the utility's weighted marginal cost, the typical New England photovoltaic homeowner's bill is reduced by about 25 percent and the NEPOOL single-family-detached residential load revenue is reduced by about seven percent. Marginal cost-based rates are probably more representative of the future when residential photovoltaic has reached significant levels of penetration and the utilities are valuing this small power production at "full avoided cost" rather than the residential rate.

The impact that residential photovoltaic systems would have on the individual homeowner's electric utility bill in the Northeast is significant even if the photovoltaic electricity is valued at the utility's weighted marginal cost. Despite the lower insolation in the Northeastern part of the country (as compared with southern and southwestern parts of the U.S.), modestly sized (e.g., two kilowatts) residential photovoltaic systems can supply a substantial portion of a typical homeowner's electricity demand .

On the other hand, the impact of residential photovoltaics on the utility's electricity demand or revenues is less percept-

ible. This conclusion is qualified, as discussed earlier, by the fact that only single-family-detached residence photovoltaic systems are being considered among a variety of other photovoltaic system options. From the utility perspective, residential photovoltaics may not be considered a major source of electricity. Nonetheless, the availability of decentralized generation of this type of photovoltaic power provides the utility with certain advantages. photovoltaic electricity is generated at a time when the utilities in the Northeast are often experiencing high levels of demand and high costs of generation. photovoltaic electricity is also generated close to the load and can thus reduce line losses associated with transmission and distribution as discussed later in this chapter.

The photovoltaic-weighted marginal cost analyses presented in this study provide utilities and rate-setting boards examples for consideration when they determine avoided cost and buyback rates for photovoltaic generation. For the most part, utilities in the Northeast experience their highest marginal cost of generation during the day and at a time when photovoltaic generation is available. (Additional winter peaks also occur, but the trend appears to be toward more rapid growth of summer peaks.) As a result, the marginal value of the photovoltaic generation almost always exceeded the marginal value of electricity consumed by the typical residential load (based on the 1982 marginal cost data published by the utilities and NEPOOL). This difference in marginal value is due entirely to the difference in timing of generation and demand.

In summary it is evident that residential photovoltaic systems could significantly reduce the electricity bill of a typical New England homeowner. The loss in revenues that the electric utilities would experience due to reduced daytime demand would be small, and mostly offset by the financial benefits of reduced line losses and reduced fuel expenditures. Although not considered in NERES studies because of its relatively small contribution to photovoltaics worth, residential photovoltaic systems will provide some capacity benefit to electric power companies, a benefit whose value is increasing in the Northeast owing to a resurgence in the rate of increase of electric power demand and continued uncertainty about the completion and continued operation of major nuclear power stations in New England. (See Reference 1 for further elaboration on the material presented above.)

3.3. Residential Roof Availability in Massachusetts

Under the auspices of Mass Save, Inc., the Residential Conservation Service in Massachusetts, residential energy audits in Massachusetts have included consideration of active solar heating and solar domestic hot water systems. A computer program was written at the NE RES to extract information about a residence, from the Mass Save data base, if certain criteria were met. These criteria were that the azimuth orientation of the audited dwelling be less than or equal to 45 degrees from true south and the roof tilt angle was within the range of latitude

plus or minus 10 degrees. (In retrospect, the requirement for roof tilt was too stringent. Many New England homes have roof pitches in the 20 to 30 degree range and NERES studies have indicated that there is a minimal insolation penalty for such roof pitches [see Chapter Five].) If these two requirements were met then the dwelling was categorized as having solar access and the available roof area and other characteristics of the dwelling were noted.

Application of this program to the Mass Save data base indicated that out of a total of 15,795 audited dwellings, 27 percent had solar access. This number is clearly conservative given the stringent roof pitch requirements cited above. This result does agree with a study performed by Total Environmental Action, Inc. which indicated that 26 percent of all residential buildings [with four units or less] in the Northeast are suitable for photovoltaic systems [2]. The corresponding available roof area of the audited houses was approximately one million square feet. Assuming 117 peak watts of photovoltaic power per square meter of roof area, these surveyed homes represent a potential market for approximately 11 peak megawatts of photovoltaic power.

Extrapolation of these figures to the complete Massachusetts housing stock was made using the 1980 Massachusetts census of population and housing (3). The census reports that there are 1.075 million single family detached homes in Massachusetts. Making the assumptions that the statewide relative roof area and solar access is comparable to the audited homes, an estimate of 750 peak megawatts of potential photovoltaic generation was deduced. At a 15 percent generation capacity factor typical for the Northeast, this capacity would produce 985,500 megawatt-hours per year.

3.4. Metering Configurations

An important consideration for residential photovoltaics and one that was addressed in a number of ways by NERES staff, is the quantification of the utility-interactive photovoltaic energy. The value of photovoltaic-produced energy perceived by utilities and homeowners is dependent upon the placement of kilowatt-hour (kWh) meters. There are three practical metering configurations for a utility-interactive photovoltaic residence shown in the figure below: (1) net metering, (2) dual metering, and (3) simultaneous buy/sell metering.

(a) SINGLE NET METERING

(b) DUAL METERING

(c) SIMULTANEOUS BUY/SELL
METERING

Fig. 3-5: Three fundamental metering configurations

The net-metering configuration utilizes a single conventional (bi-directional) kWh meter between the photovoltaic residence's service distribution panel and the utility. A unity buyback ratio is implicit in this configuration because the meter can run both backward and forward, depending on whether there is net photovoltaic generation or net load. In both the dual-metering and simultaneous buy/sell configurations, the utility distinguishes between the load and the photovoltaic generation. In both cases this distinction is made to permit a non-unity buyback ratio (usually less than 1).

The dual-metering configuration permits the residence's photovoltaic energy to be used directly without being detected, thus valuing it at the residential rate. Special ratchets must be added to make these meters unidirectional. Excess photovoltaic power, however, is integrated by the meter and can be valued at another rate. The dual-metering scheme encourages the photo-

voltaic homeowner to maximize its direct utilization fraction (DF) because excess photovoltaic energy sold back to the utility will typically be valued at less than the selling price.

In the simultaneous buy/sell configuration, all photovoltaic-generated energy is recorded and effectively "sold" to the utility before the residence can buy it back at the residential rate.

An understanding of the three different metering configurations is facilitated by introducing a method for determining the utility bill under any of the schemes. $B(t)$ (buy) will represent the power provided by the utility and consumed by the load at time t , and $S(t)$ (sell) the net (excess) power sold to the utility at time t . The integration of these quantities over time results in energy bought from the utility (B) and sold to the utility (S). R will represent the rate in \$/kWh that the utility charges for energy, and r will stand for the buyback ratio which is dimensionless. DF will represent the direct fraction over the specified time period where direct fraction is taken to be the fraction of photovoltaic generation which is directly supplied to the onsite load. L and I will stand, respectively, for the total residential load and system output over the specified time period.

For the net-metering scheme the bill can be expressed by Equation 3-1:

$$BILL = R (B - S). \quad (3-1)$$

For the dual-metering arrangement we have:

$$BILL = R (B - rS). \quad (3-2)$$

And for the simultaneous buy/sell configuration we have:

$$BILL = R (L - rI). \quad (3-3)$$

We also have the following identities which are expressions of the conservation of energy:

$$S = I (1 - DF). \quad (3-4)$$

$$B = S - I + L = L - I DF. \quad (3-5)$$

Using both Equations 3-4 and 3-5, the bill for all three metering schemes can be summarized as:

$$BILL = R (L - rI - T DF I (1 - r)). \quad (3-6)$$

Equation 3-6 reduces to the net-metering configuration when r is equal to one, it corresponds to the dual-metering scheme when T is equal to one, and it reduces to the simultaneous buy/sell configuration when T is equal to zero. Because the last term in

Equation 3-6 is only present in the dual-metering scheme, T can be thought of as the "dual-metering factor." This factor allows for a reduction term in the utility bill calculation which is based on DF . It is worth noting that the BILL under the dual-metering scheme reduces to the BILL under the simultaneous buy/sell configuration when DF is equal to zero.

From inspection of Equation 3-6, it is apparent that the utility bill is minimized under the net-metering configuration (assuming $r \leq 1$). For a fixed R and DF ($r < 1$ and $DF < 0$), the bill is maximized under the simultaneous buy/sell configuration. The table below summarizes the annual (1983) utility bill for the four NERES monitored houses with the hypothetical photovoltaic-generation profile of the TriSolarCorp prototype scaled to 4 kWp.

Table 3-3: Billing under Differing Metering Configurations
($r = 0.5$, $R = \$0.10/\text{kWh}$)

	House 1	House 2	House 3	House 4
Net	\$1080.	\$191.	\$1073.	\$385.
Dual	1188.	351.	1171.	526.
Simultaneous Buy/Sell	1322.	433.	1316.	628.

Massachusetts law permits the net-metering configuration described above. This configuration was used at the NERES and at two photovoltaic residences for a five-year monitoring period. In addition, the New England Electric System photovoltaic project in Gardner Massachusetts, which consists of 30 photovoltaic retrofit residential and 5 non-residential sites, employ the net-metering configuration.

3.5. Distribution Loss Reduction with Photovoltaics

This section presents results of load flow and voltage regulation case studies using the NERES system performance data base. Earlier results identified that photovoltaic systems operating on the grid reduced utility distribution losses (4). Work performed at the NERES (5) extends the previous effort by shifting focus from the reduction in distribution losses at a point in time to an averaged reduction in distribution losses over a year. The following discussion examines the effects of both a concentrated photovoltaic source located at the end of a feeder and nonconcentrated photovoltaic sources dispersed along the feeder.

3.5.1. Concentrated Photovoltaic Source

To understand the effect of dispersed photovoltaic generation on utility power distribution, load-flow studies, including the injection of photovoltaic power at a dispersed location, must be performed. Electrically, the residential photovoltaic system

can be represented as a current source operating in parallel with the utility, with line impedances and connected loads networked in between. The photovoltaic system behaves as a current source and operates at the line voltage approximately equal to that established by the utility at the point of interconnection. The method used to solve this network was to treat the utility substation as an ideal voltage source, the photovoltaic system as a current source, and to use the principle of mathematical superposition to determine the resultant currents and voltages throughout the circuit. (In reality, the photovoltaic system model had a prescribed power from which a current based on iterative estimates of the voltage at the point of photovoltaic interconnection is calculated.)

Four relevant algebraic quantities in this discussion are PV PWR, δ SUB PWR, δ CUST LOAD, and δ DIST LOSS. At any point in time, conservation of energy dictates that:

$$\text{PV PWR}(t) + \delta \text{SUB PWR}(t) = \delta \text{CUST LOAD}(t) + \delta \text{DIST LOSS}(t).$$

(3-7)

In Equation 3-7 the δ SUB PWR and δ DIST LOSS correspond to reductions in power and the δ CUST LOAD corresponds to an increase in power. Taking this into account, the power put into the feeder by the photovoltaic source can be viewed as the sum of the photovoltaic power and the reduction in distribution losses. This total power put into the feeder system is distributed between a reduction in substation operating power and an increase in customer load:

$$\text{PV PWR}(t) - \delta \text{DIST LOSS}(t) = \delta \text{CUST LOAD}(t) - \delta \text{SUB PWR}(t).$$

(3-8)

The figure below illustrates the power flow for a dispersed photovoltaic source, with the numbers shown based on an example using the Concord Municipal Light Plant (CMLP) feeder that serves the NERES. For the example depicted, the photovoltaic source power factor has been set to unity as it is throughout this study (state-of-the-art power-conditioning units for residential-scale photovoltaic systems operate at near unity power factor), and the substation operating power is 1 MW. (Reference 5 shows that δ DIST LOSS, δ CUST LOAD, and δ SUB PWR are all sensitive to the substation operating power.)

Fig. 3-6: Disposition of Reduced Distribution Losses

The increase in customer load is a result of the relationship between power consumption and voltage in electric equipment. Increases in voltage cause increased currents in real-power-consuming devices and hence increase the loads. The instantaneous effect of voltage on load power, however, mitigates over time as the residential load is primarily composed of fixed-energy-consuming appliances. These are thermostatically controlled (refrigerators, water heaters, air conditioners, heat pumps, resistance heaters and stoves) and operate for shorter periods due to the increase in voltage and hence power. (A related assumption is that the efficiency of the appliances in question is constant over the voltage range experienced.) For the purposes of this study, these factors were taken as sufficient justification for dropping this contribution of increased customer load to substation power demand when quasi steady state feeder operation is considered, and would result, in the case under consideration, in the power reduction of 1117 watts at the substation owing to a 1000 watt photovoltaic generation source at the end of the feeder circuit.

3.5.2. Feeder Circuit Model

The model that is used to generate the output parameters, $\Delta\text{DIST LOSS}$, $\Delta\text{CUST LOAD}$, and $\Delta\text{SUB PWR}$, is a computer program which simulates the feeder network. The input to this model is NERES monitored data: $\text{PV PWR}(t)$, $\text{MHx LOAD}(t)$ (MHx stands for monitored house x, where x can range from 1 to 4 corresponding to four instrumented houses for which appropriate data are available), and $\Delta\text{SUB PWR}(t)$. The output characterizes the effect of the dispersed source on the utility. The model's algorithm uses the principle of superposition treating the substation as an ideal voltage source and the dispersed photovoltaic source as a current source based on the prescribed power.

Both feeders used in this case study are 2400/4160V three-phase circuits with maximum operating power levels of 2 MW. Both feeders are treated as balanced three-phase systems (each phase assumed to have 1/3 of the total load). The network is then taken to be the equivalent single-phase circuit carrying the entire load. The load at each point was estimated by apportioning the total feeder load in direct proportion to the connected distribution transformer kVA. (Reference 4 gives a detailed description of the feeder characteristics.)

The output of the model can be consolidated into one parameter which is termed the power gain. The power gain [PG(t)] is defined as the ratio of the power reduction at the substation end of a radial-feeder circuit to the power generated by the dispersed photovoltaic source at a particular instant in time:

$$PG(t) = \frac{\delta CUST\ LOAD(t) - \delta SUB\ PWR(t)}{PV\ PWR(t)} \quad (3-9)$$

The power gain serves as an instantaneous expression of the total reduction in substation power. (The amount by which the power gain exceeds unity reflects reduced distribution losses and represents a utility power savings. The product of [PG(t) - 1] and PV PWR(t) represents the instantaneous power savings to the utility beyond that of the photovoltaic generation.)

Before discussing the results of the analysis, it is important to specify exactly what the photovoltaic power represents. There are two ways of viewing this parameter: (1) as the net photovoltaic power injected into the feeder, which is taken to be the positive difference between the photovoltaic generation and load if the photovoltaic generation is greater than the load and zero otherwise [NET PV PWR(t)], as would be detected in the dual-metering approach, and (2) as the total output power of the photovoltaic system [PV PWR(t)], as would be detected in the simultaneous metering approach. The distinction between these two methods of representing the photovoltaic power is important and will be made clear throughout the discussion that follows.

3.5.3. Model Output

The computer model output is an instantaneous value of the power gain. The magnitude of the power gain and its relationship to various input parameters is illustrated below. (Reference 4 presents a method for averaging the power gain over a specified period of time.) Note that the power gain shows a weak dependence on NET PV PWR and a strong dependence on substation operating power. The small negative slopes of these lines are a result of the line characteristics of the feeder and the location of the photovoltaic source and are not an indication of a general relationship.

Fig. 3-7: Power Gain Predictions for the NERES location

3.5.4. Nonconcentrated Photovoltaic Sources

Although the concentrated photovoltaic-source configuration discussion above provides one framework for studying the effect of dispersed generation on a utility feeder, a feeder would probably be modified if a large concentrated photovoltaic source were added. Another scenario is that of the gradual introduction of dispersed photovoltaic sources to an existing feeder. In such an arrangement, each photovoltaic house by itself can be viewed as having a negligible effect, but the collective effect for all the houses on the feeder can be as dramatic as the case of the concentrated photovoltaic source.

In order to analyze the nonconcentrated photovoltaic-source scenario, each dispersed photovoltaic system was taken to be a current source in parallel with the load of the house on which it is mounted. (This is equivalent to the total photovoltaic power approach as opposed to the net photovoltaic power approach presented earlier). This circuit was solved using the principle of superposition, with the substation again considered as an ideal voltage source and each photovoltaic source as a current source operating at a level consistent with the given hourly insolation.

The nonconcentrated photovoltaic system was analyzed for two feeders whose electrical performance characteristics were monitored at the NERES: (1) Concord Municipal Light Plant (CMLP) which is the feeder that serves the NE RES and (2) Boston Edison's (BECO) Lexington feeder which represents primarily a residential load.

For a mix of dispersed systems, it is reasonable to expect that the location of the photovoltaic source would affect the degree to which distribution losses are reduced. Accordingly, the placement should affect the power gain as defined by Equation 2-10. Using the conservation expression of Equation 2-7, this can be expressed:

$$PG(t) = \frac{PV \text{ PWR}(t) - \delta \text{ DIST LOSS}(t)}{PV \text{ PWR}(t)} \quad (3-10)$$

The power gain as a function of distance for a 10-kWp photovoltaic source for substation operating powers of 500, 1000, 1500, and 2000 kW is shown below for Boston Edison feeder. The characteristics of these curves are largely dependent on the attributes of the circuit, but the trend toward larger power gains at greater distances from the substation can be generalized to any radial feeder and photovoltaic source.

Fig. 3-8: Power Gain versus Radial Distance
(10 kW of Photovoltaic Capacity)

The results of this study indicate that feeder distribution losses can be reduced substantially by grid-connected photovoltaics. For the two feeders studied, annual values for the power gain ranged between 4.5 and 9.5 percent, depending on configuration. The power gain effect cited is of the same order of magni-

tude as off-azimuth and thermal effects and an order of magnitude greater than module mismatch effects (both of which are important concerns in photovoltaic system design). Determining who should receive the economic benefit of this energy savings remains an open question. However, given the potential magnitude of the effect, it is apparent that the concept of power gain should be given careful consideration in evaluations of dispersed photovoltaic generation.

3.6. Islanding (run on) Results

Islanding experiments were performed at the Northeast Residential Experiment Station during the week of 22 July 1985. The experiments were formulated through the joint efforts the NERES staff and the Research and Development Department of Public Service Electric and Gas Co. (PSE&G) of New Jersey. Similar tests were conducted earlier in 1985 at the Southeast Regional Experiment Station (SE RES) in Cape Canaveral, FL, and the Southwest Regional Experiment Station (SWRES) in Las Cruces, NM.

3.6.1. Test Configuration

The NERES is serviced by a 2400/4160-Volt three-phase feeder. The eight prototype photovoltaic systems are distributed between the three phases; systems on two of the phases were used for these tests. The nominal configuration under study was the parallel operation of a line-commutated and a force-commutated inverter.

The two combinations of inverters studied were: (1) a Acheval Silci (10 kW) inverter operating in parallel with an American Power Conversion Corporation (APCC) Sunsine 4000 inverter and (2) a Windworks Gemini (8 kW) inverter operating in parallel with a Helionetics DECC (5 kW) inverter. Under configuration (1) there was the capability of substituting a Gemini inverter for the Acheval inverter and some tests were performed with this modification. In addition, under configuration (2) it was possible to have a third inverter, the APCC Sunsine 2000 operating in parallel with the other two.

The tests that were performed were similar to those performed at both the SWRES and SERES. This redundancy was intended for the purposes of comparison and to give another set of data points from an independent test configuration. The main distinction in the tests at the three facilities were the number of inverters operating in parallel, the point of disconnection from the utility (primary vs. secondary voltage side of the distribution transformer), the capability to match the load to the real and reactive components of the inverter output and the placement of the capacitance (primary or secondary side of the distribution transformer).

3.6.2. Test Definition

The following tests were performed on both of the configurations described above under various load scenarios: (1) open the primary side of the distribution transformer (2) open the secondary side of the distribution transformer, and (3) open the primary side of the transformer leaving a 100 kVA capacitor in the islanded circuit.

3.6.3. Measurements

A Honeywell Visicorder (Model 1858) was utilized to record current and voltage transients. Current transformers and shunt resistors were used to achieve the appropriate voltage input for current channels and voltage dividers were used to get the correct voltage for voltage inputs. The channels recorded were: primary voltage and current, secondary current on both 120 V legs, and current and voltage on each leg of both inverters under test. The strip chart recordings were made for a very short period of time (approximately six seconds) and had to be carefully coordinated with the utility disconnection to capture the relevant data.

3.6.4. Results

The results are tabulated below. The numbers under the last three headings refer to the number of 16.67 ms intervals (60 Hz cycles) of run-on. (Because each of the inverters exhibit run-on with irregular frequencies, the actual number of cycles is not a useful reference.)

Table 3-4: Number of Run-on Cycles Under Various Conditions

TEST	CONFIGURATION	LOSS OF UTILITY	100 kVa CAP	NO LOAD	MATCHED REAL LOAD	
					W/O MOTOR	W/ MOTOR
1,4	DECC + Gemini w/ APCC 2kW in parallel	Scndry	NO	3	2	--
2,3,7	DECC + Gemini	Scndry	NO	3	2	20*
5,8	Gemini	Scndry	NO	--	0.25	28
6,6'	DECC	Scndry	NO	--	18.5,18.5	26
28,29,	Acheval +	Scndry	NO	4.5	0.5	6
30	APCC 4kW	Scndry	NO	--	1.5	--
31	Acheval	Scndry	NO	--	2	--
33,34, 36	APCC 4kw + Gemini#	Scndry	NO	0.5	2	5

35	Gemini#	Scndry	0	--	0.25	--
P13,P16 P19	Acheval + APCC 4kW	Prmry	NO	3	0.5	2.5
P14,P17	APCC 4kW	Prmry	NO	0.25	0.5	--
P15,P18	Acheval	Prmry	NO	1	0.25	--
P20,P23 P26	Acheval+ APCC 4kW	Prmry	YES	12	3	3
P21,P24	APCC 4kW	Prmry	YES	20	8	--
P22,P25	Acheval	Prmry	YES	12	6	--
P27,P27'	Gemini#	Prmry	ES	18,81	--	--
P1,P5	DECC + Gemini	Prmry	NO	--	2	7
P2	DECC + Gemini w/ APCC 2kW in parallel	Prmry	NO	--	2	--
P3,P12	Gemini	Prmry	NO	0.5	1,1	--
P4,P4'	DECC	Prmry	NO	--	31,32	--
P6,P6' P10	DECC + Gemini	Prmry	YES	45	18	15
P6'',P7	DECC +Gemini w/ APCC 2kw in parallel	Prmry	YES	84	9	--
P6''' P8	Gemini	Prmry	YES	66	14	--
P6'''' P6''''' P9,P11	DECC + Gemini	Prmry	YES	21,21+	12,15	--

* only the DECC experienced run-on
different Gemini on this phase
+ half of the real load was matched

The pair of two inverters, of the four under study, that demonstrated "prolonged" run-on were the DECC and Gemini. Both did, however, disconnect within 84 equivalent 60 Hz cycles or

approximately 1.4 seconds. These are the same two inverters that individually demonstrated continuous run-on (they were manually shut down) at the SWRES under similar conditions. For the DECC, these conditions were a matched real load with no additional capacitance and for the Gemini, they were no load and the presence of capacitance. These same configurations were tested at the NERES (Test P4 and P6'') and run-on of 31 and 66 equivalent 60 Hz cycles were found. The SE RES was similarly able to demonstrate continuous run-on for these two inverters under specific conditions. The differences in our results are attributable to different island characteristics, ability to match load, and the magnitude of the capacitance.

Conclusions that can be drawn from our study are: (1) the primary capacitance in most cases increased the run-on; the state-of-charge of the capacitor, which is a function of the point in the cycle when the disconnection is made, appears to be an important variable in the length of the run-on and (2) the transformer appears to be transparent to the inverters; that is, results for loss of utility on the primary and secondary side of the transformer without capacitance were virtually the same. (See Reference 6 for further elaboration of the material presented above.)

3.7. Contributions to the IEEE SCC23 (DSG)

In 1983, the IEEE established a Standards Coordinating Committee to oversee the development of standards relating to the interconnection of all forms of distributed storage and generation (DSG) with electric power grids. A member of the NERES staff has served on this committee since its inception. The principal effort of the group is the development of what will be titled the "IEEE Guide for Interfacing Dispersed Storage and Generation with Utility Systems." The purpose of this guide is formally stated to be:

"The purpose of this guide is to alert electric utilities, manufacturers of DSG equipment, consultants, contractors, potential DSG users, and public regulatory commissions to the engineering problems inherent in operating small customer-owned generators in parallel with utility systems; to describe proper interface construction techniques and operating procedures for these generators; to emphasize the safety aspects involved; and to call attention to possible DSG impact on other customers."

This group has met three times per year and is currently finishing a first draft of the guide. The NERES role in this effort has been to draft and coordinate the materials for two of the ten sections of the guide. The first is "Dispersed Storage and Generation Technologies," which is "...intended to provide brief descriptions of the various types of dispersed generating systems in general use today. Various types of generators and prime movers are discussed. Emphasis is on renewable energy

sources."

The second NERES section is entitled "DSG User Requirements and Technical Considerations." This provides an introduction and references to various standards and codes governing interconnection of distributed generation and governing typical generation equipment. "The purpose of this section is to advise the DSG user, or potential user, of the technical requirements of dispersed generators, and to provide guidance so that the user may receive maximum benefit from his DSG installations."

The completion of this Guide is not expected until sometime in 1987. Fortunately, the NERES material is in close to final form. NE RES participation in this effort was terminated after the Committee's May 1986 meeting.

3.8. Contributions to IEEE SCC 21

The Institute of Electrical and Electronic Engineers (IEEE) established their Standards Coordinating Committee 21 (SCC 21) to develop consensus standards addressing terrestrial photovoltaic systems and components. IEEE SCC 21 was initiated in 1980, following the completion of the DOE funded pre-standards effort to identify, develop and promulgate performance criteria and test methods for solar photovoltaic systems (7). This DOE work was sponsored by the Solar Energy Research Institute, but represents a cooperative effort by individuals from national and private laboratories, industry, government and public interest groups. Portions of the DOE-funded performance criteria work were adopted by the IEEE committee and formed the basis of their consensus standard efforts. Four subcommittees were established under SCC 21: (1) Photovoltaic Cells and Arrays, (2) Power Conditioner, (3) Storage Systems, and (4) Photovoltaic Systems.

The four subcommittees are composed of volunteer members from industry, government and university laboratories and electric utilities. The individual subcommittees determine what standards are needed within their specific area. A NERES staff member of the MIT Energy Laboratory has served on the Photovoltaic Systems Subcommittee of SCC 21 since its inception. This subcommittee is responsible for generating standards applicable to a certain class of photovoltaic systems which are small-to-intermediate in size, contain no storage means and may be utility interconnected. The Systems Subcommittee was initially approved for four standards; two of these were merged into a single standard after several years. The three documents currently being prepared by this subcommittee are:

P926	Terrestrial Photovoltaic System Power Rating Procedure (near completion)
P928	Performance Criteria for Terrestrial Photovoltaic Power Systems (completed)

The MIT representative had principal responsibility for preparing P926, "Terrestrial Photovoltaic System Power Rating Procedure." This document provides standard procedures for determining the following quantities for the photovoltaic array and system:

- (1) **Predicted Ratings**--Predicted ratings for array and system maximum power, array current and voltage at maximum power, array open-circuit voltage and short-circuit current are calculated from manufacturer's component specification data which is available to a system planner/designer. The calculations would typically be done prior to system installation. Predicted ratings may be used to satisfy the marking/labelling requirements of local installation safety codes (for example, the National Electrical Code).
- (2) **Measurement-based Ratings**--The procedure for determining measurement-based ratings for the array and system maximum power (and in some cases, also for array open-circuit voltage and short-circuit current) requires measuring the electrical performance characteristics of an installed photovoltaic system at ambient test conditions. Using this data, the ratings are calculated at peak rating conditions. (1000 W/m² irradiance, 25 C average cell temperature). The measurements required are divided into two sections: photovoltaic array measurement and power conditioning subsystem measurement. Measurement results are used to determine both the photovoltaic array and system power output at peak rating conditions. The ratings determined by this measurement-based procedure at the time of system installation may be used to: (a) establish array and system ratings, or (b) verify Predicted Ratings for the array and system. This procedure may also be used periodically over the system lifetime to aid in assessing changes in system characteristics.
- (3) **Predicted Annual Energy Production**--Utilizing the ratings from (1) or (2) above, and site-specific meteorological data, procedures are given to predict the annual energy production of the array and system. The photovoltaic Array and System Predicted Annual Energy Production are not system energy ratings because the method accounts for neither the variability of long-term average insolation differences for locations without insolation records nor the year-to-year variances from long-term averages at a specific location.

The procedures in P926 apply only to flat-plate, non-concentrating systems, using single-crystal or poly-crystalline silicon

solar cell technologies. It is also assumed that systems are designed to operate continuously at or near the array maximum power point. Systems employing electrical storage subsystems are not addressed in the document.

NERES representation on the Systems Subcommittee was terminated in March 1986. Completion of two of this subcommittee's documents remains.

3.9. Contributions to ASTM Photovoltaic Subcommittee

The American Society for Testing and Materials has 14 subcommittees involved in the generation of renewable energy standards under committee E44. The subcommittee on photovoltaics, E44.09, was established in 1978 and has been responsible for photovoltaic cell and module standards.

The ASTM standard document development procedure represents a typical consensus standards approach. The need for a standard is identified by the sub-committee, whose members represent a broad cross-section of industry, government laboratories, and users. A title is generated for approval by the Executive Subcommittee of E44. After approval, the document is drafted by one or several subcommittee members. The draft is reviewed at the subcommittee meeting where extensive modifications and discussion may occur. After the necessary revisions are incorporated, the document is distributed to the entire membership of E44.09 for formal balloting. (See Reference 8 for further discussion of the ASTM photovoltaic subcommittee.) E44.09 has produced eight society documents and is currently working on another eight, which are in various stages of completion. The society documents are used throughout the industry as accepted manufacturing standards and measurement procedures.

A NERES staff member has served on this subcommittee for one and one half years, principally as an advisor making contributions to several subsections of documents. MIT representation on the ASTM photovoltaic subcommittee was terminated in March 1986.

3.10. Contributions to National Electric Code (Art. 690)

The National Fire Protection Association (NFPA) established the Ad Hoc Subcommittee on Solar Photovoltaic Systems in 1980 to address the special requirements of photovoltaic systems which were not effectively addressed in the National Electrical Code (NEC). The NEC is an installation safety guide which has been widely adopted in communities and states across the country. The Code is updated every three years to keep pace with developments in technology and safety practice. Proposed Code changes must pass a lengthy, multilevel formal review process before implementation. The Subcommittee was tasked with preparing a new section to cover specifically the safety issues of a photovoltaic system for the 1984 edition of the NEC.

Members of the MIT Lincoln Laboratory Solar Photovoltaic

Project and the MIT Safety Office prepared a working document in early 1981 summarizing the major photovoltaic system safety issues, from which the Ad Hoc Subcommittee could begin. By September 1981 proposed Article 690, "Solar Photovoltaic Systems" was ready for initial balloting.

Article 690 was officially adopted and became part of the 1984 National Electrical Code. MIT maintained membership on the Ad Hoc Subcommittee through 1985. A brief description of the sections of this article is given below:

A) General

This section contains a statement of the scope of the document, definitions of the many terms used therein, and overall system-level installation requirements.

B) Circuit Requirements

Covered in this section are requirements for computation and limitation of maximum voltage, circuit sizing and current rating, and overcurrent protection.

C) Disconnecting Means

This section presents the requirements for disconnection of all conductors and photovoltaic equipment, and discusses fuses, switches and circuit breakers and array disablement.

D) Wiring Methods

Permitted wiring methods, component interconnection means, connector requirements and wiring access requirements are contained in this section.

E) Grounding

This section presents the requirements for system grounding and equipment grounding.

F) Marking

This section explains the required labelling of photovoltaic modules and the photovoltaic power source.

G) Connection To Other Sources

This section describes the requirements for interfacing a photovoltaic system with another power source, such as a utility.

In preparation for the 1987 edition of the NEC a new committee has been established and is addressing in more detail the issues of interconnection with another power source. A proposed Article 701, which was dismissed from consideration for the 1984 edition has been revised and will be brought forward for consideration in the 1987 edition.

3.11. References

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4. TECHNOLOGY DEVELOPMENT

Technology advances have been made at the NERES in several areas of note: circuit monitoring equipment, array mounting hardware, and array string combiner/safety circuits. These areas are addressed in the sections below.

4.1. Circuit Monitor

During the conduct of the Residential Photovoltaic Project at MIT Lincoln Laboratory and the continuation of the work through the MIT Energy Laboratory, considerable expense was incurred in the design and procurement of data acquisition equipment. Each monitored experimental photovoltaic system or house required up to three sets of sensors and transducers to monitor rms real power, reactive power, voltage and current. In addition, provision had to be made for digital to analog conversion, and interfacing the digitized results to information storage media.

The advent of personal computing occurred during the same period as the project. To reduce the considerable expense of instrumenting photovoltaic houses, a general purpose digital ac circuit monitor was designed, prototyped and tested at the NERES. The monitor has the following features:

1. Rapid sequential (nearly simultaneous) measurement of up to eight AC circuits.
2. Calculation of RMS voltage, RMS current, real power, reactive power, frequency, harmonic distortion, load impedance and admittance, dc voltage, dc current. Separation of the real and reactive power flows into and out of a circuit, analogous to ratcheted kilowatt-hour and kilovar-hour meters.
3. Full programmability. Any combination of measurements can be taken on any sets of input circuits independently.
4. Programming and output is in ASCII characters over a standard RS-232c line at speeds up to 19,200 baud. Baud rate, parity, stop bits, and character echo are switch selectable
5. Output is directly readable in engineering units (eg., volts, amperes, watts, hertz)
6. The AC Monitor can be used as a data logger or test instrument by connecting it to a computer terminal, or it can be used as a sensor peripheral to any computer equipped with a serial RS-232c port.
7. It can output digitized current and voltage waveforms showing 64 samples per cycle from which "oscilloscope

tracings" of current and voltage waveforms can be constructed on a host graphics computer.

8. It can be programmed to output either automatically at intervals or when polled by the user.
9. It can be programmed either to output sampled values of the inputs or averaged values, over periods of up to 18 hours.

The AC Monitor is designed to be a flexible instrument which is cost effective in a wide range of applications where 60 Hz ac circuits are to be instrumented and the results interfaced to a computer for data acquisition and/or control purposes. It is designed to function as a data acquisition system, replacing analog transducers and a data logger. Although the monitor was designed with photovoltaic power systems in mind, it is an excellent instrument for other applications.

4.2. Stand-off Array Mounting System

One of the areas of interest at the NERES when the project separated from the Lincoln Laboratory was the design of photovoltaic arrays for mounting on existing houses. The first set of systems at the NERES were designed with the understanding that they would be built as part of the construction of a new home, thus making feasible the integral mounted and, to some degree, the direct mounted array types. In 1984 a new stand-off roof-array mounting system was developed using what are called roof-jacks. These are used in conjunction with photovoltaic panels, an assembly of modules mechanically configured roughly four by five or six feet in size, to build roof-mounted arrays. The stand-off array project led to the fabrication of three new prototype structures with varying roof pitches at the NERES, each equipped with a two kilowatt array consisting of 45 ARCO M53 modules. These ARCO-based arrays represented a significant advancement in roof-mounted array design as they significantly lowered both the parts and the installation labor costs.

In 1985 a follow-on project was undertaken, under contract to Sandia Laboratory, to design and develop a low-cost building-block photovoltaic array for roof-mounted, grid-connected photovoltaic installations. MIT was assisted in this work by Mobil Solar Energy Corporation (Waltham, MA) and Solar Design Associates (Lincoln, MA). The effort was divided into two phases: a four-task design phase, followed by a hardware prototyping phase. It aimed at standardizing the array mounting hardware and installation methods to achieve a dramatic reduction in the installed system cost. The target price for all non-module-and-power-conditioner hardware and labor was \$50 per square meter of installed photovoltaic array.

The building-block design resulting from this effort was prototype tested during the early fall of 1985. The design was costed assuming a typical markup chain and all necessary labor

trades, rates, overheads and profits and using time and materials actually incurred with the prototype. The result: a total installed consumer price for all balance-of-system hardware and labor of \$0.41 per peak watt, or \$40.78 per square meter of installed photovoltaic array. (Under a slightly different distribution and mark-up scenario, these costs work out to \$0.38 per peak watt as reported in Chapter One)

The array mounting system includes two main elements: specially prepared photovoltaic panels and the panel supports, or roof jacks, which support the panels above and parallel to the roof surface.

4.2.1. Photovoltaic Panels

Panel is a term which has been defined as a module or mechanical assembly of modules which is approximately 24 to 32 square feet in size and is the field-installed elemental unit of the photovoltaic array. A panel will be prewired in a shop environment (as opposed to on-site or on the roof) such that all modules in the panel are connected, leaving the panel with a single positive and negative termination for field wiring. To expedite field wiring, these wiring terminations are provided with AMP Solarlok j-box receptacles, which mate with a plug-in type connector. Prewiring is simplified if the panel is a single large module rather than an assembly of many small modules. Panels are further prepared with mounting pins in four positions which will mate with the mounting supports, roof jacks, on the roof. The pins consist of bolts anchored to the panel frame with approximately 0.5 inches of the threaded member extending outward from the frame edge. A durable sleeve is slipped over the exposed threads and a cap nut is secured at the end of the bolt holding this sleeve against the panel frame as shown in the figure below.

Fig. 4-1: Panel-to-Roof Jack Attachment

4.2.2. Roof Jacks

The roof jacks support the photovoltaic panels and are designed for simple and quick array installation. Several roof jacks are shown below.

Fig. 4-2: Interior and End Roof Jacks

There are two styles of roof jacks, one for finishing off the ends of a row of panels, and the other for the spaces between adjacent panels. The jacks are made of steel, finished with a durable zinc chromate and baked enamel coating. A panel is installed on four jacks such that the panel's pins align with the openings in the jacks and slide snugly into the bottom of the slots as illustrated. The double-wing interior type jacks are shared by adjacent panels, while the simpler end jacks are used only by one panel. The gap height underneath an installed array will depend upon frame depth and pin placement as well as jack dimensions. The opening is designed to be roughly 3.5 inches for a two-inch frame depth, to promote ambient air circulation and photovoltaic panel cooling. Further benefits are derived by the point-support nature of the roof jack system, which result in all sides of the photovoltaic panels open to air movement.

Fig. 4-3: Detail of Roof Jack to Photovoltaic Panel Attachment

Jacks are installed with a tape-type sealant on the underside which provides an effective weatherseal for roof penetrations. Lag screws with a neoprene sealing washer are used to secure the jacks directly to the roof sheathing. This is a key feature of the installation which eliminates the need to gain access to the underside of the roof or to require precise dimensioning of the photovoltaic array supports coincident with rafter spacing. The mount is designed such that the load transferred to the roof is spread over a large roof jack footprint, to prevent exceeding the punch loading or deflection limits of the roof, while maintaining an open stand-off array which promotes rear-surface air circulation cooling.

A comprehensive final report was prepared on the building-block design and prototyping experience (Reference 1). The commercial use of this mounting technique is illustrated below by one of the initial systems installed as part of the Massachusetts Electric Gardner Photovoltaic Model Community Project.

Fig. 4-4: A Two Kilowatt System in Gardner, Massachusetts

4.3. Photovoltaic Source Circuit Equipment

The requirements for system electrical safety were incorporated in the design of the building-block photovoltaic system (above). Electrical design of the system is based upon meeting the requirements of the National Electrical Code (NEC) and incorporating features which improve system safety, reliability, performance or installation ease. Two pieces of interface equipment were developed to meet these standards while maintaining low cost: a roof penetration connector box and a novel string combiner and protection box was developed in the context of overall system electrical safety design as described below.

4.3.1. Roof Penetration Junction Box

In the prototype building-block system, the dc circuit conductors from each building-block (or series string) and the frame ground terminate in a junction box which is attached to the roof. This nonmetallic box is equipped with AMP Solarlok receptacles to expedite field wiring connections. At this junction box the cable used to interconnect panels terminates. The conductor used from this point down to the dc combiner and protection box is standard Romex used in regular interior house wiring. Type NM cable (nonmetallic) is used outdoor array wiring runs. No bus-

sing of conductors is done in this roof junction box. The roof junction box allows a transition to be made from one conductor type to less expensive Romex conductor, at a point where the dc wiring leaves the roof array area. Additionally, this simplifies system installation by creating an interface which separates roof work from interior work, allowing for contributions by separate subcontractors.

4.3.2. String Combiner and Protection Equipment

The dc array wiring is brought into the dc string combiner box which provides the following: (a) disconnecting switches to isolate all current-carrying conductors, (b) surge protection for all congs Combiner and Protection Equipment

The dc array wiring is brought into the dc string combiner box which provides the following: (a) disconnecting switches to isolate all current-carrying conductors, (b) surge protection for all conides the following: (a) disconnecting switches to isolate all current-carrying conductors, (b) surge protection for all conductors, (c) blocking diodes and (d) bussing of inputs to yield a single output circuit. In addition an isolated ground circuit, discussed below, is included to enhance system safety. The string combiner box is intended to be wall-mounted near the power conditioner. The commercially-available version of this string combiner and an typical installation with a Sunsine 2000 power conditioner are shown below.

Fig. 4-5: DC String Combiner and Circuit Protection Device

Fig. 4-6: Typical Power Conditioner and String Combiner Layout
(Massachusetts Electric Gardner Photovoltaic Project)

4.3.2.1. Residential Photovoltaic System Grounding

Three segments of the photovoltaic system must be grounded: (1) one conductor of a two-conductor dc circuit or the neutral conductor of a three-conductor (bi-polar) dc circuit, (2) metallic frames or supports which are ordinarily nonconducting, and (3) the neutral conductor of the utility service to the residence. These grounds must all be common (that is, not separately grounded.)

There are distinct advantages to reconsidering the so-called "hard" grounding requirement for the dc circuit. Specifically, in the case of a maintenance person who might come in contact with both the grounded frames and the grounded dc circuit, there is the potential for lethal current flow. One solution to this hazard is the isolated ground as illustrated below. In this case the current flow is limited by the high resistance in the path to ground, thereby protecting the individual in contact with the frames and dc circuit. This isolated ground feature meets the spirit of the NEC, which allows for an exception to the hard ground requirement if the function can be performed in another way. This isolated ground will also preclude the initiation of an arc developing between the cell circuit and ground (frames,

for example), which could present a fire hazard in a non-isolated ground system.

Fig. 4-7: Personnel Safety Attributes of an Isolated Ground

The isolated ground circuit has the further advantages of providing test points for a voltmeter to indicate whether there is any leakage current from the cell circuit to the frames. This can be checked with the circuit switches opened, prior to performing any system maintenance. The meter will indicate magnitude of any current flowing in this path, which will indicate the presence of a ground fault and help to locate it.

4.4. References

- (1) Russell, M.C., and Kern, E.C., "Stand-Off Building-Block Systems for Roof-Mounted Photovoltaic Arrays," final report, MIT Energy Laboratory under Sandia National Laboratories contract SAND 58-8796, February 1986.

NOTES:

5. PHOTOVOLTAIC SYSTEM PERFORMANCE

One of the principal objectives of the Northeast Residential Experiment Station's work over the past six years has been to evaluate the performance of residential photovoltaic systems. This activity has involved extensive monitoring and analysis of system performance data, computer modelling of system components and directed experiments aimed at furthering the understanding of specific performance issues. These aspects of system performance and analysis are summarized in the following sections.

5.1. Software Tools

Significant software capabilities were developed as part of the NERES project. Two distinct, general purpose software packages are described below.

5.1.1. The PCUSIM Simulation Program

Utility-interactive residential photovoltaic systems consist of two main components: the photovoltaic array and a dc-to-ac power conditioner. The most effective power conditioners for such systems are sophisticated devices with maximum-power-tracking circuitry which continuously controls the photovoltaic array voltage within fixed limits, to maximize energy production. One of the fundamental design tasks which a system designer must undertake is to determine the appropriate number of modules to be connected in series (establishing photovoltaic array voltage) and in parallel (establishing photovoltaic array current and power) in order to best match the photovoltaic array and power conditioner. At stake are energy production opportunities which can be lost when, for example, the photovoltaic array's maximum-power voltage lies outside the power conditioner's voltage-tracking limits. Similarly, array maximum power may exceed the limit of the power conditioner, which will then operate the photovoltaic array at a power level off its maximum power point. Realistically, the occurrence of these "lost opportunity" events is minimized, but not eliminated even for the optimum system configuration.

For small photovoltaic systems, typical of residential installations, the array sizing task is often performed almost literally on the back of an envelope, despite the fact that the optimum configuration will depend not only upon the module and PCS characteristics, but also on the array tilt angle, azimuth angle, thermal operating environment and site meteorological conditions. Consequently, there is a real likelihood that a non-optimal match will result.

In order to investigate the matching of specific modules and specific power conditioners, a photovoltaic system simulation program called PCUSIM was developed. It was initially used for a case study of array--power conditioner matching involving a total of nine system configurations of Arco M53 photovoltaic modules with a Sunsine 4000 power conditioner. For each configuration,

a one-year simulation was conducted using 1984 meteorological data from the NERES with a simulation timestep of six minutes. The high resolution of this data was essential to obtain an accurate estimation of the energy production rate differences among the various system configurations. The models and features of the program are described below.

5.1.1.1. Simulation Description

The driving input to the simulation is the insolation data. In the case study, six-minute average values of direct-normal (measured by a pyrheliometer) and total horizontal insolation (measured by a pyranometer) were input to analytic models for computing the insolation on the plane-of-array (POA). Standard formulations are used for computing the direct component of the tilt insolation from the measured direct-normal and the reflected component of the tilt insolation from the measured horizontal value (1); the Perez model (2) is used for computing the diffuse insolation component on the tilted array surface. For each six-minute interval a value for POA insolation is calculated by these models using direct-normal and total-horizontal insolation.

The Arco M53 was chosen as a representative high-voltage module which could be utilized with the Sunsine 4000 power conditioner. The module's characteristics--open-circuit voltage, short-circuit current, max-power voltage, max-power current and maximum power--are used to establish three points on the I-V curve of each array configuration. Using these characteristics at the specified irradiance and cell temperature conditions, a baseline I-V curve is modelled using the TRW equations (3). This model fits an exponential curve to these three points and interpolates between them to provide a complete I-V curve at the specified irradiance and cell temperature conditions, a baseline I-V curve is modelled using the TRW equations (3). This model fits an exponential curve to these three points and interpolates between them to provide a complete I-V curve in analytic form. Since it is necessary to model the entire photovoltaic array I-V curve at each timestep in the simulation, the array temperature is calculated using a thermal model adapted from PVFORM (4).

Inputs to the array thermal model are POA irradiance, ambient temperature and wind speed. The baseline I-V curve is translated from the initial irradiance/temperature conditions to the new conditions at each timestep using the Sandstrom equations (5). At each timestep, a complete array I-V curve is generated and the power conditioner model determines the precise photovoltaic array operating voltage, current and power.

The operating state definition for the Sunsine 4000 (6) includes the power conditioner's operating characteristics--standby ac power consumption, dc turn-on threshold power, voltage tracking lower limit, voltage tracking upper limit, maximum operating dc power, and nighttime ac power consumption. A detailed model was developed in which seven distinct modes of operation are defined. In addition the efficiency of the Sunsine was

modelled. The peak efficiency does not occur at the highest operating power level and further, the efficiency is dependent upon the dc input voltage. These two factors are critical in the determination of the optimum array configuration and demonstrate the marked deviation of the real PCS from an assumed constant efficiency often used in simulations.

5.1.1.2. Applications for the PCUSIM program

The precision with which the operating characteristics and control strategy of the Sunsine power conditioner have been modelled, coupled with the six-minute resolution meteorological data base at the NERES, have allowed detailed computer simulation investigations into the energy production of photovoltaic systems. The operating state diagram of the Sunsine is characteristic of other power conditioners as well, which will facilitate adapting the PCUSIM simulation models to these other components. The true capability of PCUSIM has not yet been fully utilized. This computer program could be used to lead to a better understanding of the losses for sizing "mistakes", and the determination of the optimum array configuration for matching specific components and site parameters.

5.1.2. The ARRAY Simulation Program

Solar photovoltaic module and array designers need to be able to predict the effects that different types of array shadowing and cell failures have upon the performance of a photovoltaic module or array. These effects can then be minimized by varying the array composition, physical layout, series/parallel groupings and strategy for diode placement. One of the principal methods for assessing an array's performance is to plot the array's current versus voltage curve.

In fulfillment of this need, a computer simulation program was developed to model the dc current-voltage (I-V) characteristics of a photovoltaic array or module. The model operates as a function of the internal components of the array, and their interconnection topology. The program, called ARRAY, has been written in BASIC and runs on an HP 9845B computer. The user defines any series/parallel arrangement of cells, diodes and resistances to be the electrical structures of interest (eg. arrays, modules, strings). These arrangements can then be combined to form more complex structures. Circuit description is facilitated by the ability to assign names to array components, and then refer to them later by their defined names. The program can prepare plots of I-V curves, determine maximum-power voltages and currents, as well as identify subsections of a structure that dissipate energy, i.e. "hot spots."

The program has been found to be well suited for a number of applications: (1) photovoltaic array design where a prediction of the effects of different types of shadowing and failures upon the performance of an array are needed, (2) the determination of optimal diode placement in a module or array, and (3) the evalua-

tion of both cell and module mismatch losses in module and array design.

Input to ARRAY consists of a file specifying the primitive electrical elements that are found in the array to be modeled. The specifications are given in an easily used command language. The allowable electrical primitives are photovoltaic cells or modules, diodes, and resistances, although an array need not contain all of these types. The user provides statements which symbolically name elements, state which of these three types they are, and give values to particular parameters which determine their electrical characteristics. The required parameters depend on what type of primitive element is being specified. A diode specification requires its characteristic voltage (the temperature-dependent voltage associated with the p-n junction of the diode) and reverse saturation current (the leakage current through the diode when the voltage across it is reversed); a resistor requires only its resistance; a photovoltaic cell requires open-circuit voltage, short-circuit current, maximum-power-point voltage and current, breakdown voltage and shunt resistance (for specific values of irradiance and cell temperature).

The first and fourth quadrant characteristics of a photovoltaic cell's I-V curve is based on the TRW model (1). These models requires data defining three characteristic points of the cell: open-circuit voltage, the short-circuit current, and the voltage and current at the maximum-power point. The models fits an exponential curve to these points and interpolates between them to provide a complete I-V curve. (The portion of the curve in the second quadrant is established by extending a line, with slope equal to the cell's shunt resistance from the current-axis intercept to the breakdown voltage, where the curve turns sharply toward infinite currents.)

The I-V curves for resistances and diodes are generated based on Ohm's Law and the standard ideal current-voltage equation for a p-n junction (the Shockley equation).

The second type of information in the input file consists of definitions of the complex electrical structures of interest (perhaps blocks, strings, and modules). The electrical elements discussed in the previous paragraph (cells, diodes and resistors) are termed "primitive elements" as they have no components, in contrast with the "complex structures" defined here. The user provides a definition stating what types of elements are part of the structure, how many of each appear, and whether the "substructures" are connected in series or parallel. (The building process permits a complex structure to contain other previously defined complex structures.)

The third type of information in the input file consists of commands producing output. Currently there are four types of outputs: maximum-power-point locations, current-voltage-power printouts at arbitrary points, plots of I-V curves, and "hot

spot" checks.

5.1.2.1. The Array Algorithm

The algorithm can be divided into three main sections: (1) parsing routines that read the input file (and commands which are entered from the keyboard), and build up a topological representation of the array's structures and arrangement, (2) I-V curve construction routines that are used to calculate an electrical representation of each array structure (special attention has been given to the problems of numerical accuracy given such extremely non-linear circuit elements), and (3) routines that perform the various output functions.

I-V curves for all primitive elements are constructed based on voltage values of equal spacing. When adding I-V curves of elements in series, voltage values sum at specific values of current, whereas with elements in parallel, current values sum at specific voltage points. This is straight forward in the first quadrant, but more complex in the second quadrant, given the discontinuity in the slope at the breakdown voltage for an I-V curve. The ARRAY program offers the user the option to save coordinates of an I-V curve at the point at which the slope changes rapidly or is not defined (including the transistion point in the diode I-V curve when it is passing current in the forward direction) in order to ensure that these features are preserved in I-V curve addition. (This feature is presented as an option because it increases execution time and in many cases this level of detail is not necessary.)

5.1.2.2. Applications of the ARRAY software

The ARRAY program is a versatile and valuable design and diagnostic tool which is capable of simulating the I-V characteristics of an array with a high degree of accuracy. Given a hypothetical array's characteristics a thorough analysis can be performed during module or array design. A full presentation of the ARRAY program, with details of the above example and other examples, can be found in Reference 3.

5.2. Insolation Models and Off-Azimuth Insolation

The NERES recorded data for a one-year period from a test stand equipped to measure which measures the insolation on tilted surfaces facing in seven azimuthal directions, and on a horizontal surface. The test stand is fitted with of eight Spectrolab Block I modules. Seven modules are oriented with a thirty degree tilt and at azimuth headings of W, SW, SSW, S, SSE, E, and one is in the horizontal plane.

The test stand was constructed in conjunction with the NERES's residential photovoltaic retrofit work in order to fulfill a need for non-south facing (off-azimuth) insolation data for the Northeast. Typical Meteorological Year (TMY) data provides insolation data for horizontal and south-facing surfaces.

There is, however, no readily available insolation data for non-south facing surfaces. The objectives of this study were to assess the accuracy of a number of insolation models for off-azimuth insolation predictions, quantify the effects of the models' predictions on photovoltaic performance assessment and to gauge microclimate effects of the NERES.

5.2.1. Data Acquisition

The off-azimuth test stand was connected to the main data acquisition system at the NERES. Sensed irradiance values from the stand were processed every five seconds, and six-minute averages were stored for postprocessing. The modules were short-circuited for use as irradiance sensors. No temperature correction was applied to the module short-circuit current data irradiance values, because it was determined that the relative effect of temperature on the sensed short-circuit current was minimal.

The NERES experiences an artificial horizon to the west. In order to account for this, data from the test stand was analyzed for the period plus and minus five hours around solar noon. In addition, all results for the west-facing sensor have been dropped. Thus, all results were reported for the azimuthal directions of SW, SSW, S, SSE, SE and E.

5.2.2. Measured Results

A summary of the annual insolation received for each of the azimuthal directions is presented below. The abscissa is the azimuthal angle in degrees where zero refers to due south, negative numbers correspond to an easterly orientation and positive numbers correspond to westerly orientations. The ordinate represents the percent difference between the total annual insolation at each azimuth angle, and the value for due south. The most striking characteristic of this plot is that a SSW heading received more annual insolation than a due south orientation by over 6%! This SSW bias existed throughout the year with the most pronounced differences occurring in the spring and summer months.

It is tempting to conclude that an important microclimate effect has been recognized for the NERES, but after examining other data from the test stand for months prior to the most recent year under study, it becomes apparent that this trend is not constant. (July, August, and September of 1984 differ significantly from July, August, and September of 1985.) Independent corroborations of the results for the test stand have been performed and reported (4). It was shown for the month of January 1985 that there existed a post-solar noon temporal bias in both the direct normal irradiance and the irradiance measured by a south-facing pyranometer. (Both of these instruments have a different field-of-view than the test stand.)

Fig. 5-1: Measured Off-Azimuth Insolation at the NERES
(October 1984 - September 1985)

5.2.3. Insolation Models

Three separate components which must be independently calculated to determine plane-of-array-insolation are: [1] the direct component, [2] the diffuse component and [3] the reflected component. For the purposes of this study, the direct and reflected formulae were held constant and the diffuse formula was varied. Five insolation models were used in this comparison: [1] Liu-Jordan, [2] Temps-Coulson, [3] Klucher, [4] Perez, and [5] Hay. Each of these models had a distinct formulation for determining diffuse insolation. (Reference 5 gives an outline of the algebraic details of each of the models).

The starting point for the evaluation of insolation models is the Liu-Jordan isotropic sky model (6). The Temps-Coulson anisotropic-sky model (7), which combines three correction factors with the isotropic diffuse radiation term of the Liu-Jordan model was the second model for evaluation. The third model for evaluation, was that of Klucher (8), who developed a modification to the Temps-Coulson model based on empirical findings. The fourth model used for comparison was that of Perez (9). This model is an empirically based anisotropic sky model which utilizes a set of measured climatic coefficients. The model accounts for the circumsolar brightening as well as horizon brightening. The final model for comparison was that of Hay (10). His model treats the diffuse radiation as the sum of an isotropic and circumsolar term. His model also utilizes a modulating factor,

which is a function of the ratio of the direct horizontal radiation to the extraterrestrial radiation.

5.2.4. Model Performance

The total annual measured and predicted insolation values for each of the azimuthal orientations are presented below. As can be seen from this figure, all the models are able to recognize the annual bias in the insolation toward the southwest. It is difficult, however, to assess the models' performance by mere inspection of this figure. One measure of the models' performance which takes into account the six data points, is the standard error of estimation.

Fig. 5-2: Total Annual Insolation: Measured and Modeled Results

The results of the application of the standard error of estimation to the models' predictions at all azimuth angles show that the Klucher and Temps-Coulson model perform the best on an annual basis followed by the Perez model, and the Hay and the Liu-Jordan models. All the models, however, are within 12 to 13% of the measured value for each of the azimuth headings and within 8% of the due south measurement.

5.2.5. Off-Azimuth Photovoltaic Energy Assessment

The ability to predict plane-of-array insolation is generally considered to be the limiting factor in photovoltaic performance predictions. The difference between the predicted annual

photovoltaic array energy production based on the measured test-stand values as compared with the predicted off-azimuth insolation (from each of the insolation models) is more complex than simply the difference in the annual insolation itself. The phasing of the insolation and ambient temperature profiles makes the photovoltaic energy production assessment particularly sensitive to the models' ability to predict plane-of-array insolation.

5.2.6. Photovoltaic Performance Simulation

In order to compare the photovoltaic energy production predictions using the different insolation models for input data, modifications were made to the PVFORM performance program (11) enabling it to utilize the five insolation models under study. The results of this simulation along with the predicted photovoltaic energy production values using the measured test-stand insolation are presented below. This figure has the same form as the prior one, which displays the measured and predicted annual insolation profiles. However, the ordinate in this case has the units of kWh/kWp. The two figures are very similar. It would appear based on the results of this annual simulation, that the ability to predict plane-of-array insolation (any tilt and azimuth) is not only the limiting factor in performance assessment, but perhaps the only significant factor. The potential effects of inaccurate module temperature assessment is clearly a second-order phenomenon. The results indicates that the ability to predict annual photovoltaic energy production decreases by approximately 1% compared with the ability to predict insolation. That is, if the insolation estimate were off by 10%, the photovoltaic generated estimate would be off by approximately 11%.

5.3. System Performance Results

Three generations of residential photovoltaic systems were designed and built at the NERES over the six year period of its operation. The first of these involved the construction of five prototype systems, four of which were supplied by industry participants (Westinghouse, General Electric, Solarex and Trisolarcorp) in the project and the fifth was an in-house MIT design. The succeeding generations of residential systems at the NERES were all MIT designed; the objective of these systems was to demonstrate reduced balance-of-system cost, improved system efficiency and improved system safety.

5.3.1. The Original Five NERES Prototypes

The first residential system built at the NERES was turned on in November, 1980, and were operated continuously for over five years. The table below identifies the startup date for each of the first five systems, along with their original rated array peak power.

Table 5-1: The Start Date and Rating of the First NERES Systems

System Name	Startup Date	Array Power (kWp)
MIT.	11/24/80	6.8
MIT	11/24/80	6.8
TrisolarCorp	12/10/80	4.8
General Electric	5/6/81	6.6
Westinghouse	2/5/81	5.1 (*4.4)
Solarex	7/9/81	5.0

(* Array was reconfigured with fewer modules in May 1982)

Data was logged from these systems from April 1981 through June 1985. A series of monthly, then quarterly performance reports were published by the NERES, summarizing in detail the performance of these systems over this period of operation.

The figure below shows the cumulative ac energy production for each of these five systems from April 1981 through June 1985. The plots are unremarkable, and for most systems show the expected result of predictable, uninterrupted system energy production patterns. The discontinuities in energy production for several of the systems in 1981-2 was due to the significant downtime owing to failures of early power conditioning equipment in the Solarex, General Electric and Westinghouse prototypes. Such events became less common as these early units were replaced in the most troubled systems. A second noteworthy aspect of this figure is the nearly horizontal line (indicating minimal energy production) of the General Electric prototype system, caused by widespread failures in the shingle module array. Over a period of several years this array suffered massive module failures, leading to the premature system decommissioning.

The next figure shows the monthly energy efficiency (sunlight to dc energy) of the five photovoltaic arrays over the entire reporting period. Beyond the intrinsic properties of the solar cells themselves, the main influences on this efficiency are the operating temperature of the photovoltaic cells and the operating voltage dictated by the power conditioner. Additionally, any failures within an array (such as for the GE shingle modules) are reflected as a decrease in array energy efficiency. Note that dramatic dips in efficiency occur in mid-winter and are due to extended periods of snow cover. Snow cover was observed to reduce photovoltaic system output for virtually all systems, but only minimally so for the Trisolarcorp prototype. The smooth sloped glass roof surface of the Trisolarcorp system promoted rapid snow shedding which significantly reduced the periods of snow coverage on this system. This system consistently maintained the highest array energy efficiency and has shown no signs of degraded performance after four years of operation.

Fig. 5-3: Energy Production Summary: NERES Prototypes

Fig. 5-4: Array Energy Efficiency: NERES Prototypes

The graph displays the power conditioner efficiency for five different systems over a five-year period. The Y-axis represents the efficiency percentage, ranging from 50 to 100. The X-axis shows the months from April 1981 to May 1985. The MIT, WEST, GE, and TRISOLAR systems show relatively high efficiency, generally staying above 80%, with some fluctuations. The SOLAREX system shows a significant drop in efficiency in early 1983, reaching a low of approximately 60%.

Month	MIT (%)	WEST (%)	GE (%)	TRISOLAR (%)	SOLAREX (%)
Apr 1981	93	93	93	93	80
May 1981	91	91	91	91	80
Jun 1981	87	90	90	90	82
Jul 1981	84	90	90	90	81
Aug 1981	85	85	85	85	80
Sep 1981	77	77	77	77	79
Oct 1981	88	88	88	88	80
Nov 1981	90	90	90	90	81
Dec 1981	90	90	90	90	80
Jan 1982	88	88	88	88	79
Feb 1982	86	86	86	86	78
Mar 1982	84	84	84	84	77
Apr 1982	86	86	86	86	76
May 1982	85	85	85	85	75
Jun 1982	83	83	83	83	74
Jul 1982	81	81	81	81	73
Aug 1982	82	82	82	82	72
Sep 1982	84	84	84	84	73
Oct 1982	86	86	86	86	74
Nov 1982	85	85	85	85	75
Dec 1982	83	83	83	83	74
Jan 1983	81	81	81	81	73
Feb 1983	82	82	82	82	72
Mar 1983	84	84	84	84	73
Apr 1983	86	86	86	86	74
May 1983	85	85	85	85	75
Jun 1983	83	83	83	83	74
Jul 1983	81	81	81	81	73
Aug 1983	78	78	78	78	72
Sep 1983	80	80	80	80	73
Oct 1983	82	82	82	82	74
Nov 1983	81	81	81	81	73
Dec 1983	79	79	79	79	72
Jan 1984	81	81	81	81	73
Feb 1984	82	82	82	82	74
Mar 1984	81	81	81	81	73
Apr 1984	82	82	82	82	74
May 1984	81	81	81	81	73
Jun 1984	82	82	82	82	74
Jul 1984	81	81	81	81	73
Aug 1984	82	82	82	82	74
Sep 1984	81	81	81	81	73
Oct 1984	82	82	82	82	74
Nov 1984	81	81	81	81	73
Dec 1984	82	82	82	82	74
Jan 1985	81	81	81	81	73
Feb 1985	82	82	82	82	74
Mar 1985	81	81	81	81	73
Apr 1985	82	82	82	82	74
May 1985	80	86	89	90	86

The two tables following show the lifetime system performance extrema and performance averages, respectively, for the five original NE RES prototype systems. System designers may find the extrema data of interest, which shows that the peak measured array power can exceed the peak rated array power (at 1000 W/m², 25C) by over 30% (the MIT and Trisolar prototypes). For this region of the country the long-term average energy

production rule-of-thumb is that a 1 kWp photovoltaic array will generate 3.3 kWh ac per day. The Trisolarcorp system demonstrated the accuracy of this rule-of-thumb for its operation over 1720 days. The MIT and Westinghouse systems fell short of this nominal energy production target, in part because of the uncertainty around their rated array powers.

Table 5-2: System Lifetime Performance Extrema:
NERES Prototypes

		MIT	WEST	GE	TRISOLAR	SOLAREX

PV ARRAY RELATED						
Peak Rated Power	(kW)	6.8	4.4	6.6	4.8	5
Days Power Exceeded Rated Power	(days)	468	162	2	288	59
Total # Days of Operation	(days)	1640	1137	943	1720	1128
Peak Measured Power	(kW)	9	4.6	6.9	6.3	6.1
Irradiance	(kW/M ²)	1.2	1.18	1.05	1.37	1.23
Cell Temperature	(C)	23.8	37.8	17.5	38.3	21.8
Date		3/2/82	6/26/85	1/17/82	3/15/84	2/19/83
Peak Irradiance	(kW/M ²)	1.45	1.42	1.47	1.47	1.47
Date		3/15/84	3/15/84	4/9/84	3/15/84	3/15/84
Max. Measured Cell Temperature	(C)	80	67.6	84.4	66.8	79.2
Irradiance	(kW/M ²)	1.18	0.96	0.93	0.88	0.97
Ambient Temperature	(C)	32.5	29.9	33.8	27.7	30.7
Date		7/7/81	8/28/83	7/3/83	6/22/85	8/28/83
Max. Energy Output	(kWh/day)	49.7	29.3	37.2	33.8	29.7
Insolation	(kWh/m ² -day)	7.7	7.4	7.2	7.6	7.1
Average Energy Output	(kWh/day)	29.8	16	29.4	21	20.1
Date		4/17/85	3/26/84	6/13/81	4/17/85	7/4/82
POWER CONDITIONER RELATED						
Peak Measured Power	(kW)	8.3	4.1	5.7	5.8	5.5
Date		3/2/82	6/26/85	1/17/82	4/9/84	2/19/83
Max. Energy Output	(kWh/day)	45	26.4	30.2	30.3	27.1
Date		4/14/82	3/26/84	6/13/81	3/26/84	7/4/82

Table 5-3: System Lifetime Performance Averages

		MIT	WEST	GE	TRISOLAR	SOLAREX
Days Of System Operation		1551	1156	973	1551	1156
Peak Rated Array Power	(kWp)	6.8	4.4	6.6	4.8	5
Power Conditioner		Acheval	Sunsine	Abacus	Gemini	DECC
PV ARRAY RELATED						
Average DC Energy Output	(kWh/day)	24.7	14.9	11.9	17.6	13.5
Avg. Array Energy Efficiency	(%)	7.2	6.8	3.7	9.3	4.9
POWER CONDITIONER RELATED						
Average AC Energy Output	(kWh/day)	20.7	13.2	9.02	16	11.6
Avg. DC Energy Output/Rated Power	(kWh/day/kWp)	3.04	3	1.37	3.33	2.31
Avg. PCS Energy Efficiency	(%)	83.6	88.7	75.7	90.8	85.8

5.3.2. The Second-Generation Prototypes

Three new prototypes were completed at the NERES during the summer of 1984, making a total of eight photovoltaic systems at the site. These prototypes replicate conventional asphalt shingle-roof construction which is common in this region of the country. The roofs of these buildings were constructed with three different pitches (4/12, 5.5/12, and 7/12), covering the range of roof pitches that retrofit photovoltaic array designers and installers will typically encounter:

Whereas the original five NERES prototypes were all built as new-construction photovoltaic systems, these new structures formed the basis of a project to design, construct and evaluate concepts for retrofit residential photovoltaic arrays--that is, those which could be attached readily to roofs of suitable existing houses.

The requirements for a retrofit installation are significantly different from those for a new-construction situation, where physical access to the roof, attic and other areas is guaranteed and there is latitude for fundamental structural-design decisions to accommodate a photovoltaic array. For an existing house the photovoltaic installation must adapt to the given situation, with minimum disruption of the household.

There are four generic methods for roof-mounting photovoltaic modules: integral (modules replace the roof sheathing and shingles), direct (modules replace conventional shingles), stand-off (modules mount over, and parallel to, a conventional finished roof), and rack (modules are supported on a rack at a tilt different from that of the roof). The overall goal of the retrofit system design activity was to design a low-cost photovoltaic system using a stand-off type mount for use on existing roofs.

The system was also required to comply with the 1984 National Electrical Code. Design and construction of one system for each of the three new structures was completed in late summer 1984.

Several specific features were examined with these retrofit photovoltaic arrays. The first was the use of a sheathing mount (the array is not directly fastened to the roof framing). When an array is installed on an existing house, access to the attic space and the rafters is not always available and spacing of the rafters is not always uniform. Consequently, the photovoltaic array cannot always be easily attached to the rafters and might need to be mounted to the roof sheathing instead.

Second, the roof area available on an existing house is likely to be much less than that which could be made available on a custom-designed solar house. The photovoltaic array therefore should be highly efficient in order to maximize the energy produced from a smaller area. The arrays which were designed and installed on the retrofit structures are rated at approximately 2.2 kilowatts peak and cover approximately 18 square meters.

Third, the concept of minimizing field labor was addressed by a design which utilizes preassembly of off-the-shelf framed modules into multi-module panels. The panels then become the field-installed unit, resulting in a low overall array assembly and installation cost.

One of the initial questions addressed by these retrofit prototypes was in regard to the variation in insolation on the surfaces of different tilt angles. The figure below shows the average insolation for twelve months on the three surfaces. Contrary to long-term average predictions, the 18-degree tilt received the greatest cumulative insolation (1533 kWh/m²/day). However, the other surfaces, 24 and 30-degrees, received only 0.5% less insolation, demonstrating the relative insensitivity of insolation to this range of tilt angles over the monitoring period.

Fig. 5-6: Insolation Summary: NERES Retrofit Prototypes

Another of the questions addressed with these retrofit prototypes was in regard to the influence of tilt angle on the photovoltaic array's operating temperature. Identical arrays were placed on all three structures aluence of tilt angle on the photovoltaic array's operating temperature. Identical arrays were placed on all three structures and four temperature sensors were placed on the rear surface of modules in each array. These sensor readings were averaged for each array and the temperature rise coefficient calculated on a monthly basis. The array temperture rise coefficient is defined as the average array temperature rise above ambient, divided by the incident irradiance. Since there is roughly a linear relationship between array temperature rise and irradiance, this parameter is used to characterize how an array will respond thermally to its environment. Variations in this array "constant" are thought to be due to seasonal shifts in the wind speed/direction, changes in the irradiance spectrum, changes in the sky radiative temperature, inherent uncertainties in using rear-surface sensors and averaging over temperature gradients, among other causes. From the figure below it can be seen that during all but the snow-cover months steeper tilts lead to cooler array operFrom the figure below it can be seen that during all but the snow-cover months steeper tilts lead to cooler array operation. During periods of snow cover, the shallowest tilt array remains covered longer and therefore operates cooler.

Fig. 5-7: Temperature Rise Coefficient Summary:
NERES Retrofit Prototypes

The performance of two of the three systems is summarized in next two figures. (The third system is excluded because there is less than a full twelve months of system performance on this system.) The average annual array energy efficiency for these identical arrays of ARCO M53 modules was 9.1% (24 degrees) and 9.3% (30 degrees). Neither of these systems demonstrated a higher efficiency than the lifetime array energy efficiency of the Trisolarcop prototype at 9.3%. The Sunsine 2000 power conditioners' energy efficiency over twelve months were 88.3% and 86.4%. These are below the 90.8% energy efficiency of the Gemini unit which operated in the Trisolarcop prototype.

Fig. 5-8: Photovoltaic Array Efficiency:
NERES Retrofit Prototypes

Fig. 5-9: Power Conditioner Efficiency:
NERES Retrofit Prototypes

Both of these systems achieved a normalized ac energy production over the twelve-month period of 3.3 kWh/day/kWp. The next figure shows how this parameter varies monthly over the period of monitoring. Note that the lower tilt angle benefits summer output, but this effect is offset by the poorer winter performance of the shallower tilt. The result is that there was virtually no difference in system output for these two tilt angles over this period.

Fig. 5-10: Normalized Energy Production:
NERES Retrofit Prototypes

5.4. Summary

Based on the measured performance of residential photovoltaic systems at the NERES, the two best performing system designs are the integral mount system as employed in the TriSolar prototype and the stand-off system with the roof jacks as used in the Massachusetts Electric Project in Gardner. The integral mount approach is most readily used in new construction situations and has superior snow shedding performance. The stand-off mounting can be used for both new and retrofit applications, and has superior module cooling performance. Both can result in aesthetic and functional installations.

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6. TECHNOLOGY TRANSFER

In addition to the NERES role in developing and testing residential, grid-connected photovoltaic systems, transferring our knowledge of photoNERES role in developing and testing residential, grid-connected photovoltaic systems, transferring our knowledge of photovoltaic systems designs, performance and potential effects on electric utilities was an important mission of the project. This mission was carried out in a variety of ways, ranging from conducting tours of our experimental facilities, to hosting national and international conferences on photovoltaic systems and applications, and to providing staff assistance to the Massachusetts Energy Office as is defined and started its photovoltaic Center of Excellence program. On a more technical professional level, the NERES staff contributed to a number of codes and standards development activities and assisted a number of electric utilities, notably New England Electric System, with their photovoltaic projects.

6.1. Conferences

The NE RES, in association with the New England Solar Energy Association, hosted two conferences at MIT during the 1982-1986 period. The first, entitled "PHOTOVOLTAICS: Research to Reality" was held in March 1983 and had two principal themes. First, sessions on photovoltaics and electric utilities addressed the performance, interconnection issues and wider implications of photovoltaic technology to the electric power industry. The electric power industry perspective was represented by professionals from Boston Edison, New England Electric, Northeast Utilities, Consolidated Edison and the Southern Company. The second theme was off-grid photovoltaic applications in New England. Presenters from New England photovoltaic systems design companies gave reviews of their projects, discussed battery options for energy storage, and gave workshops on systems design and integration. The three day conference was attended by over five hundred participants, and was generally agreed to have achieved its goal of informing persons without prior photovoltaic experience of the status of photovoltaic technology and current practice in the design, installation and operation of state-of-the-art photovoltaic systems.

The first conference at MIT inspired a second, similar conference in San Diego in November 1984. This conference, entitled "PHOTOVOLTAICS: Research to Reality II" followed similar themes, was supported by California electric utilities and was hosted by San Diego Gas and Electric.

MIT's second major photovoltaic conference was held in June 1985 and was addressed principally to international applications and markets for photovoltaic systems, while maintaining some sessions on grid-connected applications in New England, especially the New England Electric Gardner Photovoltaic Community Project and the Boston Edison Company's IMPACT 2000 house in Brookline. The conference was designed to support efforts on the part

of both the federal government's program to aid the development of an export market for renewable energy, the Committee on Renewable Energy Commerce and Trade, and on the Commonwealth of Massachusetts' efforts to develop its photovoltaic Center of Excellence services which are being provided from their East Boston facility and, in the future, from the University of Lowell. The conference included numerous discussions of export systems designs, explanations and discussions of a host of export and trade services offered by branches of the federal government and by private financial service companies. Over two hundred attended this three day conference.

6.2. Residential Photovoltaic Systems Handbook

Among the most effective means established by the NERES to communicate systems design, installation and operation knowledge has been a handbook designed to give the solar designer a comprehensive source of information for roof-mounted, grid-connected photovoltaic systems design. This handbook, completed and printed in by the NERES in April 1984, has been reprinted commercially and is currently in use in photovoltaic systems training courses offered by the the Florida Solar Energy Center and elsewhere. The material in the handbook covers solar energy resources (insolation), photovoltaic array mechanical and electrical design, array circuit protection, dc to ac power conversion equipment characteristics and specifications, interfaces between the array and the power conditioner, interfaces between the power conditioner and the home electric service equipment, and the interface--both physical and economic--between the residential photovoltaic system and electric power companies.

Since the completion of this handbook, the NERES staff has advanced the state-of-the-art in residential photovoltaic array and balance of system design, broadened the understanding of system performance with non-optimal array orientations, and instigated a major project to explore the impacts of multiple photovoltaic systems clustered on an electric power distribution circuit. This new information might be included in a revised edition of this handbook.

6.3. Standards Development Activity

The development of codes and standards has been viewed by the NERES as an important vehicle for the transfer of technical knowledge from the DOE sponsored photovoltaic systems development activity at the NERES to the wider audience of professionals who must eventually learn to work with photovoltaics. The contributions of the NERES to Institute of Electrical and Electronic Engineers, National Fire Protection Association and American Society for Testing and Materials standards development groups is documented in Chapter Three of this report.

6.4. Joint Projects with the Photovoltaic Industry

A special relationship developed in 1985 between MIT and two

Massachusetts-based photovoltaic companies: Mobil Solar Energy Corporation and Solar Design Associates. With funding provided to the NE RES through Sandia National Laboratories, MIT headed a team which developed a new system for roof-mounting large photovoltaic panels, interconnecting these panels to form an array and combining and protecting the array strings.

This technology was, in effect, transferred instantly to industry, and has formed the basis for the residential systems in the Massachusetts Electric Gardner Project, additional Mobil Solar Energy Corporation systems using their large module design on residential and commercial buildings. Chronar/TriSolar Corporation has also used this array hardware for a system using an amorphous array in Austin, Texas. Based on early indications, this array design (see Chapter Four for details) will be widely accepted by industry.

6.5. Consultation with Electric Power Companies

The most visible impact of the NERES's efforts to transfer residential photovoltaic systems technology is manifested in the projects of several electric power companies. Among the first projects attributable to the NERES project are two systems built by Westinghouse for Georgia Power Company (the Future One House) and for Consolidated Edison Company (the Citicorp Building system). Although NE RES staff were not involved in the detailed planning for these systems, each is derived from the Westinghouse prototype system at the NERES. Recently, NERES personnel have assisted Consolidated Edison with the data reduction and system performance evaluation for the Citicorp system and in planning additional photovoltaic initiatives.

Boston Edison Company built the IMPACT 2000 house using array technology first developed by Solar Design Associates and TriSolar Corporation at the NERES and power conditioning equipment designed and built by American Power Conversion Corporation, a spin-off from the MIT photovoltaic systems project while it was run from the Lincoln Laboratory. The IMPACT 2000 house represents the state-of-the-art in integral roof-mounted photovoltaic arrays.

More recently, NERES staff have advised and discussed residential photovoltaic systems with Wisconsin Power and Light, Dayton (Ohio) Power and Light Company, Central Illinois Light Company, the Electric Council of New England, and the Eastern Electric Energy Council.

Our most significant role has been with the conceptual design and technology development for the New England Electric System project in Gardner. In guiding this project from its conceptualization through the hardware implementation, the NERES has, in effect, completed the residential program developed for DOE by MIT in 1978. The Gardner project, which is discussed in

greater detail throughout chapters one through four, is the principal legacy of MIT's work with photovoltaic systems.

6.6. Massachusetts Energy Office Programs

In November 1983, representatives of the Massachusetts Executive Office of Energy Resources first visited the NERES as part of their efforts to define a program for the Massachusetts Photovoltaic Center of Excellence. During the following six month period NERES staff assisted in the definition of the Massachusetts initiatives, in particular those in our area of expertise (grid-connected systems). The central theme of the Massachusetts program evolved toward off-grid systems for foreign applications, however, and in the fall of 1984 we hired a new staff member to work directly with the Massachusetts Energy Office staff in the area of off-grid systems.

Through this arrangement, the NERES contributed in two areas of the Massachusetts effort: the development of the Massachusetts Photovoltaic Utilization Program and the enumeration of financial services for the photovoltaic industry to be made available through the Photovoltaic Center of Excellence. Progress in each of these areas of endeavor were fully documented in NERES reports for the benefit of the Center of Excellence staff.

As the DOE supported photovoltaic systems research and development at MIT was being concluded and the NERES decommissioned in the spring of 1986, the NERES staff has made every effort to preserve useful photovoltaic modules, balance-of-systems equipment, and general purpose instrumentation for the establishment of a program of stand-alone photovoltaic systems design, development, fabrication, testing and evaluation at the University of Lowell, the university designated by the Commonwealth to assume the lead role in the Center of Excellence's photovoltaic technology initiatives.

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