Decentralized Photovoltaics
Working Paper for the Office of Technology Assessment

David Morris
John Furber

July 1980

a publication of

New Rules Project
1313 5th St. SE, Suite 303
Minneapolis, MN 55414

612-379-3815
www.newrules.org

Other publications from the New Rules Project of the Institute for Local Self-Reliance:

Rural Power: Community-Scaled Renewable Energy and Rural Economic Development, by John Farrell and David Morris, August 2008

Balancing Budgets by Raising Depletion Taxes, by Justin Dahlheimer, June 2008

Concentrating Solar and Decentralized Power: Government Incentives Hinder Local Ownership, by John Farrell, May 2008

Broadening Wind Energy Ownership by Changing Federal Incentives, by John Farrell, April 2008

Driving Our Way to Energy Independence, by David Morris, April 2008

Ethanol and Land Use Changes, by David Morris, February 2008

Carbon Caps With Universal Dividends: Equitable, Ethical & Politically Effective Climate Policy, by John Bailey, January 2008

Minnesota Feed-In Tariff Could Lower Cost, Boost Renewables and Expand Local Ownership, by John Farrell, January 2008

Municipal Broadband: Demystifying Wireless and Fiber-Optic Options, by Christopher Mitchell, January 2008

The Policy Gap: Minnesota Energy Policy vs. Minnesota Climate Policy, by John Farrell, John Bailey and David Morris, November 2007

Big-Box Swindle: The True Cost of Mega-Retailers and the Fight for America's Independent Businesses, by Stacy Mitchell, November 2007, Beacon Press

Burlington Telecom Case Study, by Christopher Mitchell, August 2007

Wind and Ethanol: Economies and Diseconomies of Scale, by John Farrell, July 2007

Since 1974, the Institute for Local Self-Reliance (ILSR) has worked with citizen groups, governments and private businesses to extract the maximum value from local resources.

A program of ILSR, the New Rules Project helps policy makers to design rules as if community matters.

Table of Contents

Summary

Residential applications of photovoltaics will become competitive with continental central power station electricity by the mid 1980's. There may be as many as 10 million homes generating their own electricity by the time the first solar power satellite is scheduled to be launched.

The Public Utilities Regulatory Policies Act of 1978 requires utilities to purchase electricity from renewable-based power plants at their avoided cost of power. State regulatory commissions to date have established prices that are approximately equal to, or higher than, the retail price of electricity. If this practice should continue into the mid 1980's, on-site photovoltaic systems will not only provide energy for internal use, but will become income generators for their owners. It can be expected that there will be a rapid increase in demand for such household systems.

In fact, it appears that there will be a shortage of polysilicon supplies to meet this demand in the mid 1980's. Even with an unprecedented increase in manufacturing capability, the SPS may be competing directly with decentralized photovoltaics for scarce raw materials in the early part of the next century. In fact, the polysilicon shortage appears to be the major constraint on the potential supply of photovoltaics in the next twenty years. The quantity of electricity generated by photovoltaics is independent of the demand projections for electricity, but highly dependent on the ability of the manufacturing sector to increase production, and to have access to raw materials.

If decentralized applications achieve the same array efficiency as those projected for SPS arrays, and if buildings are designed to maximize photovoltaic potential, the residential sector can meet all its energy demands from rooftop arrays, and have enough electricity left over to operate family vehicles, or to export into the grid system. High rise buildings will need additional array area installed on surrounding parking lots, although vertical arrays in northern latitudes can collect 50-75 percent of the energy that an optimally tilted array could.

The potential for self-reliance from photovoltaics in the commercial sector depends on the load density of the specific business. Load density currently varies by an order of magnitude, or more, in that sector. On average, a major portion of the commercial sector's energy requirements can be met by on-site photovoltaic applications.

Decentralized energy systems can provide a significant portion of industrial energy consumption except in those industries that operate on three shifts, and are highly energy intensive. These industries would probably shift to cogeneration, so that their relationship to the grid would also be that of a small power producer. Industrial energy generation and demand profiles can be integrated with those of surrounding residential or commercial enterprises.

Although stand-alone systems are viable, there are economies to grid-connected systems. Excess energy from one part of the community can be used by others. Grid-connected systems permit a smoothing of demand curves, and higher efficiency by power conditioning components, and certain savings in storage systems.

As solar array prices decline, subsystem component cost becomes extremely important. By the mid 1980's for example, off-roof photovoltaic arrays will cost twice that of roof-mounted arrays because of the cost of structural supports.

NASA estimates that the cost of electricity from the first SPS will be about 40 cents per kilowatt hour. The current electricity costs of decentralized photovoltaics in the southwest is in that approximate range. If the SPS is integrated into utility planning horizons, the SPS would become the basis for their avoided cost of new power supplies. Therefore, it will be the basis upon which the price of decentralized energy is established. Decentralized and SPS systems will thus compete directly.

On-site applications of photovoltaics can be integrated into metropolitan and regional energy systems that use wind energy and hydroelectric generators, as well as pumped storage, and biomass. There appears to be a good "fit" between wind and insolation, the former having stronger intensity during the night and winter months.

It appears that SPS costs can only become competitive with decentralized applications if 12-15 are launched. A decision to reduce the number of satellites would be a costly one once the initial R & D has been invested. Decentralized photovoltaics are modular in nature, and flexible in the light of different policies.

Assuming decentralized photovoltaics have the same array efficiency and cost as the SPS, electricity would cost 1.5 cents to 10.36. cents per kilowatt hour depending on location, and whether storage is used.

Decentralized Photovoltaic Systems: Rationale

The advent of photovoltaics provides the United States with an unparalleled opportunity to combine the American philosophy of self-reliance with good economics. Photovoltaics are modular with applications down to very small sizes, allowing flexibility in their location. There are few, if any, economies of scale in the *generation* of electricity by photovoltaics. (although there are manufacturing economies of scale.) All projected cost reductions indicate that photovoltaics will first become economically attractive for remote applications and only later for central power stations.[1]

There will be a five to fifteen year period during which the *only* option for a mass market for photovoltaics will be in a decentralized mode. *At issue is whether the federal government should encourage household and community-scale applications during and after that initial period, and to what extent these dispersed operations can meet future energy needs, and at what cost.*

When given the opportunity, Americans can be quite outspoken in their support for solar energy precisely because of its democratic potential. In 1978, under orders from the White House, the Department of Energy held ten regional hearings to elicit public comment on the federal role in encouraging solar energy. To date those hearings remain the only substantial sampling of public opinion on this issue. More than 1,300 people presented oral or written testimony. More than 7,000 people came to listen and ask questions. DOE's final report, The Great Adventure, commented:

> The most surprising aspect of the hearings was the lack of discussion of the energy crisis. The support for solar energy was far less a response to the energy crisis, or the need for a switch fron non-renewable to renewable energy resources than it was a reaction to the scale of institutions in America. To most people, the benefit of solar was in its social and political implications.

The report concluded, "the dominant theme of every hearing was strong support for the decentralizing and self-reliant characteristics of solar energy."[2]

Decentralized applications permit us to plan more flexibly and to allocate resources more effectively. On-site photovoltaics can be erected rapidly, and incrementally, thus allowing us to match the supply to the demand. An investment in such plants would earn a profit quickly. Very large-scale systems, such as orbiting satellite systems, take many years before adding massive amounts of energy. It can take 10 to 20 years before investments in such plants begin to generate revenue. In order to plan such investments efficiently, we must be able to accurately predict the shape and functions of society almost a generation into the future. We learned in the 1970's how difficult this is. For example, the 1979 peak electric demand increased by 0.7 percent, one tenth of that predicted by the Edison Electric Institute and the National Electric Reliability Council. As A.J. Prister, general manager of the huge Salt River Project concedes, "We still do not fully understand the interaction of these very complex factors, and even with the help of the most sophisticated models, one should only make future predictions with a great deal of trepidation."[4]

Indeed the interaction between demand and supply may be a great deal more dynamic than we imagine. Decentralized supply systems seem to encourage conservation.

When people own a limited supply, they tend to alter consumption patterns to maximize their independence. (In the San Luis Valley, Colorado, and Berkshire County, Massachusetts, planners and engineers found this to be the case with respect to passive solar energy systems.) [5] Although investments in conservation are clearly more economical than investment in renewable energy technologies, those same solar technologies can actually accelerate conservation. Thus it may be that the very speed with which we bring decentralized photovoltaic systems on-line will change future energy demand patterns.

Decentralized solar electric systems are attractive not only because they permit greater flexibility and margins of error in planning, but because they allow us the possibility of developing more stable systems. A few dozen power plants which generate almost all of our electric supply leaves us vulnerable to forced outages due to natural accidents, or military or paramilitary actions. National security can best be served through local self-reliance.

On-site systems permit us to design energy efficient systems. A solar cogeneration system captures waste heat as well as electricity. Centralized systems have no means of transporting the waste heat to end consumers. Decentralized systems can be integrated in solar house designs, industrial hot water supplies, or into waste utilization systems.

Factors Affecting the Penetration of Decentralized Photovoltaic Applications

The photovoltaic industry has emerged for terrestrial applications precisely because of the maintenance-free characteristics of the technology, and its ability to function- reliably in a wide variety of environmental conditions. The Electric Power Research Institute evaluated the possibility that extended periods of frost, freezing rain, or snows, followed by subfreezing temperatures, might cause forced outages. It concluded:

> Very little hard data exists for this type of problem. Personnel directly associated with the General Electric Valley Forge Office Building and Boston School Project solar thermal panel installations indicated that prolonged snow cover and frost have not been significant problems. Even with freezing weather following a snow storm, the arrays have always cleared themselves within a day or two. Array inspections have shown that if any portion of the array is exposed to sunlight, such as a panel edge or corner, the heat generated in the small portion quickly spreads across the array. The usual smooth array surface then permits the snow cover to slide off tilted arrays, provided there is room at the bottom of the tilted surface for the snowfall. Therefore this is more a PV design problem than a location problem.. [6]

EPRI analyzed the impact of wind velocity on the arrays, and concluded that there might be some problem with

> concentrating collectors... be (ing) strong enough to maintain their structural alignments and their highly accurate surface contours over many years in the presence of heavy winds and adverse weather conditions ...PV installations near coastal areas where historical data shows hurricanes have penetrated several hundred miles inland will have array designs that will withstand wind up to 60 m/s (135 mi/h). Such a constraint may preclude the use of sophisticated high-concentration-tracking designs for these areas. Similarly, it may not be possible to use concentrators possessing highly reflective surfaces in those regions where wind-borne dust and sand particles are a problem. Dust and sandstorms are, of course, notably indigenous to the southwest.[7]

Thus decentralized photovoltaic flat plate arrays appear to have few limitations, although there might be some restrictions on the use of tracking concentrator systems in hurricane areas or areas with high winds and dust storms.

Variation in regional insolation is, of course, a factor in evaluating the potential impact of decentralized photovoltaic applications, but it does not appear to be highly significant. Sandia Laboratory reports, "The average daily total insulation on a tilted flat collector varies by less than a factor of two over the United States. Insolation variation, therefore, exerts a relatively small influence on photovoltaic potential compared to variation in energy consumption and utilization factor."[8]

Annual variations in insolation appear relatively unimportant as well. MIT's Energy Laboratory, after analyzing worst and best years of insolation data, concluded, "the economics of the residential photovoltaic system (particularly for homes that are air-conditioned) is not sizeably dependent on the choice of years for simulations purposes. This would also seem to obviate the need to worry about the effect of long-term changes in weather and solar radiation on the economics of residential photovoltaics."[9]

The important factors determining the significance of decentralized applications are the overall system efficiency, and the demand profiles of individual units. Conservation, and seasonal and diurnal load profiles play a critical role in evaluating the future of decentralized photovoltaic applications.

Demand Assumptions

The analysis of the role of decentralized photovoltaics in this paper is based in part on two demand scenarios supplied by the Office of Technology Assessment.

<u>Scenario A</u> of the National Academy of Sciences CONAES report is the basis Type to enter text for the low demand projections. The <u>Series C</u> projections of the Energy Information Administration form the basis for the high growth model. Both were extrapolated to 2030.[10]

Under the low growth projections primary energy consumption increases from 70.8 quads in 1975 to 73.6

quads in 2030, a modest 4 percent rise. Under the high demand model, primary energy demand increases from 75.6 quads in 1977 to 182 quads in 2030, a dramatic 140 percent increase.

Under both projections the transportation sector's demand remains relatively stable, The high demand model predicts a slight 4 percent rise. The low demands models predicts an 18 percent decrease.

Both the high and low demand scenarios expect strong conservation efforts in the residential sector. Under the low demand scenario this results in a two thirds reduction in primary energy. The high demand model foresees demand reductions of 13 percent in residential end use consumption. However, this energy will be generated outside the house by increasingly inefficient means. There will be a 146 percent increase in electrical consumption. Overall primary energy demand therefore will rise by 40 percent.

The low demand scenario predicts a minor 10 percent increase in commercial demand; under the high growth model primary energy demand increases by 184 percent in this sector, fueled in large part by the 367 percent increase in electrical energy consumption.

It is difficult to compare industrial demand projections because the categories used by the two studies are not comparable. Yet both models point in similar directions--an overall increase in industrial demand and an increase in its relative importance in the overall national energy picture.

Overall the major difference between the low and high demand projections is the difference in electrical consumption. Under the low demand projections electrical demand consumes 25.4 quads of primary energy in 2030, or about 35 percent of total energy demand, while under the high demand projections it consumes 94 quads of primary energy or 52 percent of total primary energy demand. Since both projections presume very little solar electric contribution, the difference between the two scenarios rests in large degree on the difference in fuel wasted in the electrical conversion process. Of the 110 quads difference in total primary energy demand between the two scenarios, 62 percent is accounted for in this manner.

In any case, in evaluating the potential for decentralized photovoltaics the growth figures are only modestly useful. They can help us determine what manufacturing capability would be necessary to meet the potential market. But this would be the same for decentralized or centralized photovoltaic systems, (except for the production volumes of inverters, other types of power conditioning devices, and storage batteries).

The viability of decentralized applications depends on the total energy consumption , and load profile, of individual units. If there is sufficient area to generate enough energy to operate a single family home, it doesn't matter if there will be ten or one hundred such homes in the future, unless the load density (that is, the amount of energy, or power, used per unit area). increases.

Series C--EIA

Sectoral Consumption

	1979		**2030**	
	End Use	**Primary**	**End Use**	**Primary**
Residential	11.3 Q	16.4 Q	9.83 Q	23.07 Q
Commercial	6.0 Q	9.8 Q	9.98 Q	27.77 Q
Transportation	20.2 Q	20.2 Q	21.01 Q	21.01 Q
Industrial	23.3 Q	29.12 Q	72.79 Q	106.95 Q
Total	**60.6 Q**	**75.6 Q**	**114 Q**	**182 Q**

Percentage of Total Consumption by Sector

	End Use		**Primary**	
	1977	**2030**	**1977**	**2030**
Residential	19%	9%	22%	13%
Commercial	10%	9%	13%	15%
Transportation	33%	18%	27%	12%
Industrial	38%	64%	39%	59%

Electric Consumption by Sector

	1977		**2030**	
	%	**Quads**	**%**	**Quads**
Residential	36%	2.4	20%	5.9
Commercial	25%	1.7	27%	7.9
Transportation	0%		0%	
Industrial	39%	2.6	53%	15.3

Neither the high or low demand scenario predicts that individual units (i.e. cars, trucks, manufacturing units, homes or office buildings), will operate more inefficiently in the future. (With respect to end use energy consumption. It has already been noted that the shift to electrical energy consumption, if done by conventional processes, will increase the amount of primary energy used per unit.)

Thus the critical element in evaluating the potential of decentralized PV is the load density of the individual industry, commercial enterprise, or residential unit, that is, the amount of energy consumed per square foot, as well as the seasonal and daily load profiles.

Fortunately, for the residential sector, Scenario A, the low demand projection, provides us with the number of individual units in 2030.[13] There will be 76.5 million single family units, 48.6 multi-family units, and 11.8 mobile homes in that year. Assuring that single family homes, because of their size and income level consume four times the energy per unit as mobile homes, and assuming moreover that multi-family units consume 50 percent more energy than mobile homes, single family dwellings will consume 2.46 quads per year in 2030, with a house hold consumption of 32 million BTU's. This is equivalent to 9.4 MWh end use consumption annually.

In order to check the validity of this projection, we solicited information from utilities around the country concerning total energy consumption for single family all-electric homes. The average was about 24 MWh.[14] In an Office of Technology Assessment study on decentralized solar applications, single family homes were assessed to use 24-27 MWh per year.[15] This would appear to be the average for homes built in the early 1970's. Yet the Virginia Electric Power Company reports that in its service area all-electric homes used 24 MWh/yr in the mid-1970's but only 19 MWh in 1979 as a result of rising electric prices.[16]

Westinghouse and General Electric estimated that an-energy conserving home will use 15-19 MWh per year.[17] This is for a circa 1968 house, with little appliance or domestic hot water conservation.

It appears reasonable that by the next century homes will he designed with energy conserving appliances, and other design features, and that the average all-electric home will consume 50 percent of what GE and Westinghouse predict for the short term, and what the current suburban single family home in Virginia now consumes.

Under the low demand scenario a multi-family unit will consume 5.6 MWh per year. This is in comparison

Scenario A-CONAES

Electrical Consumption by Sector

	1975		2030	
	Quads	**%**	**Quads**	**%**
Buildings (Residential and Commercial	3.7 Q	18%	5.4 Q	21%
Energy Producing Industries	13.2 Q	66%	15.49 Q	61%
Energy Consuming Industries	2.3 Q	11%	2.59 Q	10%
Transportation	0	0%	0	0%
Total	19.2 (20.1)[12]		23.48 (25.4)[12]	

Percent of Total Consumption by Sector

	1975	2030
Residential	16%	5%
Commercial	7%	7%
Energy Consuming Industries	28%	38%
Energy Producing Industries	24%	29%
Transportation	24%	19%

Sectoral Consumption

	1975	2030
	Primary	**Primary[1]**
Residential	11.3 Q	4.0 Q
Commercial	5.0 Q	5.5 Q
Buildings (Residential and Commercial	11.6 Quads[11]	9.5 Quads
Energy Consuming Industries	20.0 Q	28.2 Q
Energy Producing Industries	16.7 Q	21.7 Q
Industrial (consuming and producing)	36.7 Q	49.9 Q
Transportation	17.3 Q	14.2 Q
Total	70.8 Q	73.6 Q

to OTA's 16-17 Mirth per unit for high rise apartment complexes. It represents a similar reduction compared to contemporary demands as that of the single family homes.

In conclusion, it seems as if a total energy load of 9.5 MWh for an all electric single family dwelling is a reasonable projection for a serious energy conservation scenario, while energy consumption would be 19 MWh for a similar dwelling under a business-as-usual scenario. In the multi-family dwellings, 5.6 - MWh for the low demand scenario and 13 MWh for business-as-usual appears reasonable.

The commercial and industrial sector presets a more complicated problem. Yet since both demand projections predict that the industrial and commercial sectors' relative importance will increase in the next fifty years, these sectors should be of primary interest in evaluating the potential for decentralized photovoltaic applications.

As one analysis of a fast food restaurant, high school, dental clinic, small shopping center, and a machinery fabricator concluded, "the load density (i.e. peak electrical demand per square foot of floor area) varies by a factor of ten for the five establishments."[18]

The top ten services,commercial, industrial, and institutional sectors 50 percent of their total electrical energy in 1974.[19]

Order	SIC Code	SIC Code Description	% of Total
1	33	Primary Metal Industries	13.68%
2	28	Chemicals, Allied Products	10.40%
3	54	Food Stores	4.41%
4	82	Public and Parochial Schools	3.59%
5	26	Paper and Allied Products	3.42%
6	46	Pipe Lines, Excluding Natural Gas	3.22%
7	20	Food and Kindred Products	3.09%
8	80	Health Services	2.99%
9	65	Real Estate	2.48%
10	58	Eating and Drinking Places	2.46%

Research Triangle Institute has broken out contemporary energy consumption by establishment in New Hampshire. These are actual consumption patterns. The chart indicates that the majority of firms tend to use relatively little energy, but the few very large ones bring the mean up. Thus it would appear, at least on the surface, that the majority of installations would have relatively low load densities. The few very high load densities would be met by cogeneration, possibly. In this respect we might note that the paper and allied products industrial sector already produces about 50 percent of its electricity internally through cogeneration techniques. Dow Chemical in a 1975 report, estimated that by 1985 industry could economically justify producing one third of its electrical power and half of its process steam through cogeneration.

Three shift industries may represent the worst case for decentralized photovoltaics. We have segregated out those that appear to have three shift,seven day a week operations, based on seasonal average daily load profiles supplied by Research Triangle Institute. These represent a significant portion of the industrial energy consumption. Some portion of their energy needs could be met with on-site PV, but probably not a substantial percentage. Again, cogeneration is a possibility or the use of a wind/hydroelectric grid.

As noted above, this study did not assume conservation efforts. A recent publication from Japan indicates that Japanese iron and steel, production use 26 percent less energy per unit of output than that in the United States. It uses 48 percent less energy in its chemical industry, and 44 percent less energy in its cement industry.[20] It would appear that the long term potential for industrial conservation would be greater than these contemporary comparisons.

Available Area for Arrays

How much array area is available for generation capacity,especially in our urban areas? More than two-thirds of the country live in urban areas, but the majority live in sparsely populated sections of these areas.

As one expert notes:

> The twentieth century has been a period of strong population deconcentration within American metropolitan areas. Population deconcentration has been consistent across metropolitan areas and systematic over time. Changes from the "hoof and foot" cities of the nineteenth century to the automobile city of 1970 have been remarkable. At the turn of the century a city of 100,000 was likely to be concentrated in an area of ten to twenty square miles. Population density at the core of the city would have been relatively high ... As a contrast, contemporary Los Angeles and San Diego have rather even population densities of three to five thousand people per square mile spread over hundreds of square miles. As demonstrated by this research, variations in population concentration per area are not chaotic.[21]

The highest population densities occur in the larger cities. Yet of all cities with more than 100,000 population, the average density is only 4.480 people per square mile.[22] Densities range from New York's 26,343 residents per square mile to Oklahoma City's 577 people per square mile. While Manhattan holds 67,808 people per square mile, Staten Island, with only 5,138 people per square mile is closer to the average density of all large cities. Single family homes comprise two thirds of all housing structures in urban areas.[23]

The most dense cities are in the North Central states. The least dense are in the South and West. Of the 18 cities which have population densities higher than 10,000 people per square mile, 10 are in the Boston-Washington corridor.

SIC Code	SIC Code Designation
22	Textile Mill Products
26	Paper and Allied Products
27	Printing and Publishing
28	Chemicals and Allied Products
29	Petroleum and Coal Products
33	Primary Metal Industries
34	Fabricated Metal Products
36	Electrical and Electronic Equipment
37	Transportation Equipment

Decentralist applications of photovoltaics, however, depend not only on the total community density, but the range of densities within populated areas. The city as a whole may have a low density, but its commercial and residential areas may be quite dense. Two 1950 studies of Dayton and Cincinnati done just before the suburban exodus began can shed some light on this issue. These older industrial cities would be expected to have higher densities. Thus these should represent the worst cases. Within one mile of the central city both Dayton and Cincinnati had populations of 20,000 to 80,000 people per square mile, depending on the neighborhood, or 20 to 120 people per acre. Between one mile and three miles from city center densities sharply dropped off to 5-30,000 people per square mile, in Dayton; in Cincinnati, the drop was even more abrupt. Between 6-8,000 people per square mile, or 9 to 12 people per acre, lived in the ring between on mile and three miles from the city's center. Outside of the three-mile ring densities began to equal those of the overall large city average, 4,460 per square mile, or about 8 people per acre.[25]

Thus it would appear that the only places that might be extremely difficult to make energy self-reliant (assuming sufficient insolation) are the inner circles of the older, industrial cities of the North Central, and possibly the Midwestern states (although as a consequence of Urban Renewal many of the cities' downtowns have been dispersed).

How much of the south side of a structure can be exposed to solar energy in our compact cities? Using a concept called a solar envelope, which is the largest volume in which a building will not shade adjacent parcels, Professors Knowles and Berry at the University of Southern California demonstrated that quality moderate-density development is achievable

Average Energy Per Establishment for New Hampshire Energies in Megawatt-Hours

SIC	Industry	Total Energy	No. of Estab.	Energy/ Employee	Average Energy/ Estab.	Modal Group	Modal Energy/ Estab.	Median Group No.	Median Energy/ Estab.
20	Food and kindred products	86,799.9	75	33.3	1,157.3	1	89.7	3	482.6
22	Textile mill product	109,899.9	55	21.5	1,998.2	4	784.6	4	784.6
23	Apparel and other finished products	7,000.0	44	3.39	159.1	1	3.4	4	123.3
24	Lumber and wood products, except furniture	67,699.9	247	18.1	274.1	1	34.3	2	129.4
25	Furniture and fixtures	18,000.0	50	11.3	360.0	1	13.1	3	216.8
26	Paper and allied products	379,899.9	41	64.2	9,265.8	4	2,286.9	4	2,286.9
27	Printing, publishing, and allied industries	45,800.0	176	9.01	260.2	1	22.5	2	65.3
28	Chemicals and allied products	33,100.0	23	44.0	1,439.1	2	245.2	2	245.2
30	Rubber and miscellaneous plastics products	113,399.9	54	17.0	2,100.0	6	2,732.8	4	587.4
31	Leather and leather products	0.0	70	0.0	0.0	6	0.0	5	0.0
32	Stone, clay, glass, and concrete products	85,599.9	77	35.8	1,111.1	1	89.6	2	256.3
34	Fabricated metal products	37,500.0	99	8.83	378.8	4	258.5	3	122.3
35	Machinery, except electrical	118,000.0	159	10.7	742.1	1	21.2	3	166.9
36	Electrical and electronic machinery, equpt. and supp.	137,399.9	74	11.2	1,856.8	1	25.5	4	350.9
37	Transportation equipment	33,300.0	19	25.0	1,752.6	1	25.0	2	200.0
38	Instruments, optical goods and clocks	47,600.0	43	8.72	1,107.0	1	9.7	2	49.4
39	Miscellaneous manufacturing industries	0.0	49	0.0	0.0	1	0.0	1	0.0
41	Local and suburban transit and hwy. pass. trans.	15,000.0	86	1.37	114.0	1	3.4	2	9.8
42	Motor freight transportation and warehousing	73,399.9	283	31.4	259.4	1	52.9	1	52.9
44	Water Transportation	500.0	19	5.49	26.3	1	13.7	1	13.7
45	Transportation by air	12,900.0	17	0.0	758.8	1	0.0	1	0.0
46	Pipe lines, except natural gas	157,099.9	2	0.0	78,549.9	1	0.0	1	0.0
47	Transportation services	2,900.0	37	20.1	78.4	1	44.6	1	44.6
48	Communication	51,400.0	99	12.0	519.2	4	363.1	3	172.9
49	Electric, gas, and sanitary services	118,399.9	69	65.4	1,715.9	1	150.0	3	895.2
50	Wholesale trade--durable goods	76,099.9	645	12.6	118.0	1	31.6	1	31.6
51	Wholesale Trade--nondurable goods	300.0	398	0.0	0.8	1	0.2	2	0.5
52	Building materials, hardware, garden supply, and mobile homes	13,700.0	364	5.67	31.6	1	13.5	1	13.5
53	General merchandise stores	114,899.9	239	17.5	480.8	1	34.6	2	122.2
54	Food stores	215,000.0	781	22.9	275.3	1	50.3	1	50.3
55	Automotive dealers and gasoline service stations	651,000.0	1042	9.65	62.5	1	21.8	1	21.8
56	Apparel and accessory stores	24,900.0	414	8.31	60.1	1	21.4	1	21.4
57	Furniture, home furnishings, and equipment stores	17,200.0	334	10.1	51.5	1	20.4	1	20.4
58	Eating and drinking places	119,899.9	990	10.1	121.1	1	16.8	2	74.4
59	Miscellaneous retail	44,800.0	1143	6.33	39.2	1	12.9	1	12.9
60	Banking	35,200 0	167	8.67	210.8	4	260.0	3	131.5
61	Credit agencies other than banks	119,000.0	139	13.4	85.6	1	36.0	1	36.0
62	Security and commodity brokers, dealers	1,100.0	18	0.0	61.1	1	0.0	1	0.0
63	Insurance	13,600.0	78	3.00	174.4	1	4.7	2	21.0
64	Insurance agents, brokers and service	6,900.0	303	4.41	22.8	1	9.1	1	9.1
65	Real estate	120,699.9	520	69.8	232.1	1	1,055.0	1	105.5
66	Combinations of real estate, insurance, loans, law offices	19,000.0	41	10.7	46.3	1	27.2	1	27.2
67	Holding and other investment offices	400.0	29	1.79	13.8	1	2.6	1	2.6
70	Hotels, rooming houses, camps, and other lodging places	69,899.9	440	16.7	158.9	1	21.3	1	21.3
72	Personal services	36,000.0	546	12.6	65.9	1	24.7	1	24.7
73	Business services	71,899.9	388	22.9	185.3	1	43.8	1	43.8
75	Automotive repair, services, and garages	22,200.0	332	13.6	66.9	1	27.6	1	27.6
76	Miscellaneous repair services	7,700.0	148	15.3	52 0	1	21 1	1	27.1
18	Motion Pictures	5,300.0	49	19.3	108 2	1	28 0	1	28.0
79	Amusement and recreation services, except motion pictures	42,100.0	256	13.0	164.5	1	20.1	1	20.1
80	Health Services	145,899.9	1021	9.27	142.9	1	18.4	1	18.4
81	Legal services	4,100.0	294	3.24	13.9	1	6.0	1	6.0
82	Educational services	192.699.9	216	29.9	892 1	1	53.3	1	53.3
83	Social Services	60,800.0	252	15.8	241.3	1	30.0	1	30.0
84	Museums, art galleries, botanical and zoological gardens	1,300.0	6	28.9	216.1	1	72.2	1	72.2
86	Membership organizations	63,400.0	624	172	101.6	1	35 7	1	35.7
A9	Miscellaneous services	61,000 0	259	52.6	235 5	1	93.7	1	93.7

while protecting solar access. Averaging results from six different sites, a density of 52 dwelling units per acre was achievable.[26] Assuming two people per unit, the density of 66,000 people per square mile is considerably higher than that of our larger American cities.

The Jet Propulsion Laboratory evaluated the potential for rooftops in the San Fernando Valley in California to supply household energy from photovoltaics. Nevin Bryant, the author of the 'report, concluded:

"For the sixty-five square mile study area the results showed that with half the available flat and south facing roofs used and assuming the availability of energy storage, 52.7 percent of actual energy demand could have been met in 1978 using photovoltaic collectors."[27]

The Urban Innovations Group at the University of California at. Los Angeles compared three solar urban futures for a city of 100,000.[28] It concluded that the residential sector could be totally self-sufficient if 80.7 percent of available residential roof area is used. The commercial sector could collect 67 percent of its energy demand by using about 50 percent of available parking area, and 100 percent of available rooftops The industrial sector could collect 18 percent of its energy needs on-site. We have not obtained a copy of this report, and therefore do not know what the efficiencies of the systems were assumed to be, and how much storage was integrated into the systems. The study concludes, "however, if land area in the hypothetical city is increased 34.5 percent (from 10,000 to 13,450 acres, or from a gross density of 10 persons per acre to approximately 7.4 persons per acre) all three sectors could be energy self-sufficient."

Individual Unit Evaluations

There appears to be enough available space on residential rooftops to provide all the annual energy requirements from decentralized photovoltaic systems, assuming -the building is designed to permit maximum installation of solar arrays, and energy conservation is emphasized during design and construction.

In the analyses of decentralized photovoltaics to-date, little or no conservation was assumed. The OTA Solar Study assumed that single family dwellings use 24-27 MWh per year, while General Electric and Westinghouse assumed modest conservation which would reduce this to 14-29 MWh per year. This compares to our estimate of 9.5 MWh annual consumption assuming maximum conservation, and 19 MWh assuming a - business as usual scenario. OTA assumed 17 MWh per year for a multi-family unit compared to our assumption of 5.6 MWh under a maximum conservation, and 12' MWh under a business as usual scenario. The OTA evaluation also assumed an array efficiency of .12 percent, 22 percent less than the array efficiency assumed for the purposes of comparing SPS and decentralized photovoltaics.

Population Density of Selected Cities with Populations Greater per Square Mile (1970) than 100,000 [24]

CITY, STATE	POPULATION DENSITY (per Square Mile)
New York City, New York	26, 343
Akron, Ohio	5,082
Albuquerque, New Mexico	5,542
Austin, Texas	3,492
Hartford, Connecticut	9,081
Houston, Texas	2,841
Los Angeles, California	6,073
Memphis, Tennessee	2,868
Miami, Florida	9,763
Montgomery, Alabama	2,875
Oklahoma City, Oklahoma	577
Salt Lake City, Utah	2,966
Spokane, Washington	3,357
Toledo, Ohio	4,727
Washington, D.C.	12,321
Worcester, Massachusetts	4,721

Only Westinghouse has examined stand-alone systems. It evaluated single family dwellings with annual energy consumption levels of 15-19 MJh, with 80-100 square meters of solar arrays, and a 1.5 kW on-site fossil fueled generator which operated fewer than 1000 hours a year. Each house had 20 kWh of electrical storage in lead acid batteries. Westinghouse concluded, "Hourly computer simulations indicate that, for an average site, only 10 percent of the electrical and 20 percent of the thermal residential requirements would require the use of backup fuel and that the 1-2 kWh electrical backup would always suffice." Stand-alone systems, which do not require utility connections, were found to be viable "virtually everywhere that utility backup systems are viable."[29]

OTA evaluated the potential of single family dwellings with peaked roofs to provide energy for the household. Peaked roofs permitted only 590 square feet (56.4 square meters) of array space. Assuming no electrical storage, a Boston household could generate 12.15 MWh per year, and sell 3.9 MWh to the grid.[30] In Albuquerque a similarly sized array would provide 17.1 MWh to the building and sell 6.7 MWh to the grid.[31]

OTA modelled a 196 unit, 10 story high rise, in Boston using one axis concentrator arrays with multi-tank low temperature thermal storage.[32] It had 4,262 square meters of array, covering the roof plus the parking lot. It supplied 1,675 MWh per year for the building, and 44 MWh to the grid. If flat plate arrays are substituted, and electrical storage added, less energy is produced. Approximately the same amount of array area provides 837 MWh annually to the building, and 135 MWh to the grid.[33]

A high rise in Albuquerque with 1,725 square meters of array area of two axes 4 concentrators, generates 1,873 MWh of electricity and sells 24.9 to the grid.[34] This system takes up slightly more space than the rooftop, and has 6,000 KWh of low temperature hot water storage. One axis concentrators supplying the same building would require more than twice the array area to supply similar amounts of energy.[35]

Our own analysis evaluated photovoltaic potential in Boston and Albuquerque. Assuming an array efficiency of 17.10 percent (18 percent less 5 percent degradation during the first year), and inverter efficiency of 90 percent, and a round trip battery efficiency of 75 percent, 100 square meters in Boston and Albuquerque supply the total annual energy requirements of the building, although it will not provide the worst winter months' requirements for total energy in Boston.

Our conclusions on the basis of existing studies, and our own, is that at projected array efficiencies similar to those of the SPS, the residential sector can become self-sufficient in energy from rooftop photovoltiac arrays. This is true whether there is maximum conservation, or business-as-usual, although the excess generated under the maximum conservation scenario can be used in other sectors. If all single family houses had 100 square meters of arrays in 2010 the total amount generated if they were in a Boston-like climate would be 5.6 Quads. In a Phoenix-like climate 9.5 Quads of energy would be generated. This agrees with the assessment of DOE:

> For grid connected PV applications, sufficient roof area will exist in the residential sector to satisfy residential electrical energy requirements when the sun is shining. And, on the average, sufficient roof area will exist to supply a large percentage of the total electrical energy requirements. In fact, if 10 kWp capacity per dwelling is installed on a large fraction of existing homes, the residential sector can become a net exporter of electricity.[36]

There is a complicated relationship between on-site generating capacity, storage, and electricity distributed to the grid. MIT Energy Lab's analysis indicated that as arrays become larger the fraction of energy that they generate which can be used by the household decreases. Both the MIT and the General Electric studies show that larger arrays become viable with storage. (See Following pages)

General Electric modelled various array sizes and storage capacities in different climatic regions. It found that without storage, there is a significant mismatch between energy generation, and demand within the house. For example, a house in Boston with solar arrays generates 7.3 MWh per year, but only 4.3 MWh goes directly to load. The rest goes to the utility, and the household buys 10.79 MWh from the utility. A Phoenix household would show this effect even more dramatically. An array of 71 square meters generates 15.2 MWh, more than the annual household energy demand of 14.7 MWh. However, because of the insolation/demand mismatch, Phoenix exports 8.3 MWh to the utility, and imports 7.7 MWh from the utility. In Seattle the mismatch is almost the same. A household with a 94 square meter array would sell almost 7 MWh to the utility, and buy 8.5 MWh from it.

In the commercial sector, as noted above, load densities vary enormously. OTA evaluated the potential of decentralized photovoltaics on a shopping center in Omaha. With 61,176 square meters of flat plate, air cooled silicon arrays, it could generate 47 percent of its annual needs,and provide 1,,558 MWh to the grid [42] OTA also evaluated an Albuquerque community of 30,000 residents, with a shopping mall. Using a two-axis concentrator, seasonal Iron-REDOX electrical storage, multi-tank low temperature thermal storage,

Potential Solar Array Area

Name of Study	Type of Building	Height (in Stories)	Floor Space (Sq. Ft.)	Potential Solar Array Area (Sq. Ft.)	
				Northern	Southern
General Electric	Single Family Dwelling	2 (Northern)	1,520	1,100	1,300
		1 (Southern)			
OTA	Single Family Dwelling	1	1,695	1,212 [1,3]	1,095 [2,3]
	Single Family Dwelling	1	1,695	490 [4]	490 [4]
	Townhouse-- 8 units	11	104,000	9,037 [1]	8,162 [2]
	Low Rise--36 units	3	41,040		
		Slanted Racks on Horizontal Roof		5,800 [1]	7,273 [2]
		Roof Plus parking Lot		12,378 [1]	15,514 [2]
	High Rise--196 Units	10	170,600		
		Slanted Racks on Horizontal Roof		8,596 [1]	10,778 [2]
		Roof Plus parking Lot		44,377 [1]	55,642 [2]
	Shopping Mall	1	311,040		
		Slanted Racks on Horizontal Roof		131,444 [1]	164,819 [2]
		Roof Plus parking Lot		542,214 [1]	679,881 [2]

1. Boston
2. Albuquerque
3. Roof Sloped at Latitude
4. Peaked Roof

and absorption chillers, it could supply 100 percent of the needs of the community. This would require 95 acres of collectors, and 1.5 million kWh of electrical storage. Assuming a population density of 20 people per acre, the community would cover 1,500 acres. Thus only 6 percent of the land would be required to meet 100 percent of the needs. (A 114,000 kWh reserve boiler is included in the system, but in an average year it doesn't appear to be needed.) [43]

The Research Triangle Institute analyzed the potential of decentralized photovoltaics for a variety of commercial, institutional and industrial applications in various climatic regions. Assuming a 10 percent array efficiency, it found that roof-mounted arrays could meet 27 percent of the needs of a dental clinic, ground mounted arrays could provide a machinery fabricator with 54 percent of its needs, and ground-mounted arrays could provide 40 percent of the energy requirements of a fast-food restaurant.[44] Research Triangle Institute concludes from a sensitivity analysis, "Increasing array efficiency from 10 percent to 15 percent makes a critical difference."

In evaluating the potential for industrial use of decentralized photovoltaics, we used the figures on New Hampshire industrial enterprises developed by Research Triangle Institute. We identified the seven industries that are three-shift enterprises. Except for two, these tended to be among the top energy users per establishment. We assumed that 75 percent of the energy generated would go through the battery system, giving this analysis the lowest system efficiency of any used in this study. Thus this could represent the worst case evaluation, given that the industrial energy consumption estimates are based on contemporary consumption figures (which, as has been noted above, are already improved by 25-50 percent by Japan and Germany), the industries in New Hampshire can be expected to be older, and therefore more energy inefficient than in other parts of the country, and these are three shift operations.

It is more difficult to generalize about the commercial and industrial sectors potential for decentralized photovoltaic applications. DOE is less sanguine about the possibilities in these sectors than for residential applications:

> Although exceptions will exist, in general the intermediate load centers (commercial and industrial sectors) will-not-be able to meet their electrical demands by on-site PV because of lack of available adjacent land. This will be particularly true in most urban areas. Not only will PV systems not be able to provide a large percentage of intermediate load requirements on-site, they will also be constrained in the amount of instantaneous load they can supply. In these situations the grid could be used to supply a greater percentage of the total electrical load than in the residential or remote sectors.[45]

Our own investigations support the contention that at the elevated array efficiencies predicted for the SPS systems, and adequate storage, a majority of the commercial and industrial needs can be met with on-site energy systems. These systems will require more land than exists on rooftops plus surrounding parking lot space. This assumes conservation efforts in these sectors.

The demand scenarios discussed above predict no use of electricity in the transportation sector by the year 2030. This appears unrealistic, especially in the light of recent breakthroughs in electric vehicle storage systems. Gulf and Western recently unveiled a zinc-chlorine battery that is capable of more than 1,400 charging cycles (equivalent to 200,000 miles of driving).[46] It can propel a modified Volkswagen Rabbit 150 miles at 55 miles per hour, and should go 200 miles in a car especially designed as an electric. General Motors also announced a nickel-zinc battery that would propel a car 100-130 miles at 45 miles per hour, and would run for more than 30,000 miles before the batteries went out. GM predicts a total annual J S. electric car sales or 200,000 units by 1990. Gulf and Western foresees 1.3 million.

Assuming a car uses -1.5 kWh for each mile driven, an average car driven 10,000 miles per year would use 41 kWh per day or 15 MWh per year. A single family home in Phoenix will generate sufficient energy on an annual basis to meet the total needs of the house, even with the business-as-usual demand level, plus have enough for the family electric car. In Boston there would not be enough energy generated by a 100 square meter array, even if the house were designed for very. Energy efficient operation.

It is not within the scope of this study to do an in-depth analysis of electric requirements for transportation. It does appear, however, that electric vehicles can meet the vast majority of automobile passenger mile requirements, and those of taxicabs, and mass transit systems. This represents over 50 percent of transportation energy consumption at the present time.

PV-Only Systems (Shingle-Concept) Performance[37]
All Electric, Without Storage

	Region	PV area (m2)	Energy Output (kWh)	Energy to House (kWh)	Electricity Sales to Utility (kWh)	Electricity Purchases from Utility (kWh)	Household Energy (kWh)
1	Boston	51.4	7,322	4,329	3,003	10,792	15,111
		71.2	10,137	4,775	5,362	10,336	15,111
		94.9	13,137	5,107	8,410	10,004	15,111
2	Washington, D.C.	94.9	12,750	5,274	7,476	9,364	14,638
3	Charleston	94.9	14,704	4,533	9,171	8,003	13,566
4	Miami	94.9	15,662	7,241	8,421	8,403	15,643
5	Bismarck	51.4	8,496	4,856	3,640	12,923	17,779
		71.2	11,763	5,403	6,360	12,376	17,779
		94.9	15,684	5,830	9,854	11,948	17,779
6	Madison	94.9	13,800	5,581	8,319	11,265	16,746
7	Omaha	94.9	15,139	5,869	9,270	10,268	16,137
8	Ft. Worth	51.4	8,774	5,233	3,541	8,866	14,099
		71.2	12,148	5,752	6,396	8,346	14,099
		94.9	16,198	6,127	10,071	7,972	13,749
9	Nashville	94.9	14,222	5,093	9,129	8,657	14,701
10	Phoenix	51.4	10,998	6,445	4,553	8,255	14,701
		71.2	15,229	6,987	8,242	7,715	14,701
		94.9	20,305	7,361	12,944	7,340	12,745
11	Albuquerque	51.4	11,433	5,054	6,379	7,691	12,745
		71.2	15,830	5,385	10,445	7,359	12,745
		94.9	21,107	5,545	15,462	7,100	12,745
12	Seattle	94.9	11,341	1,353	6,988	8,527	12,882
13	Santa Maria	94.9	18,439	5,243	13,196	6,433	11,676

PV-Only Systems (Shingle-Concept) Performance[38]
All Electric, With Storage

Region	PV area (m^2)	Battery Storage (kWh)	Energy Output (kWh)	Annual Excess (kWh)	Household Energy (kWh)
Boston	71.2	20	7,332	939	15,111
		30	7,838	399	
		40	7,979	253	
		60	8,082	122	
	94.9	20	8266,	3,075	
		40	9,567	1,495	
		60	9,901	1,070	
	118.6	20	8,784	5,844	
		40	10,521	3,567	
		60	11,035	2,844	
Ft. Worth	71.2	20	9,301	1,138	14,099
		40	10,082	399	
		60	10,178	255	
	94.9	20	10,082	3,997	
		40	11,963	1,940	
		60	12,240	1,574	
	118.6	20	10,464	7,529	
		40	12,509	4,966	
		60	12,978	4,210	
Phoenix	51.4	20	9,540	249	14,701
		40	9,792	66	
		60	9,824	42	
	71.2	20	11,423	1,714	
		30	12,367	1,057	
		40	12,484	926	
		60	12,559	754	
	94.9	20	12,166	4,835	
		40	14189	3229	
		60	14392	2822	

Energy Transfers From Solar Array to Load and Grid by Time-of-Day Period and by Array Size: Boston[39]

Array Size in m^2	**5**	**15**	**25**	**35**	**45**	**85**
KwH Transfers						
PSTL	383.3	1,019.5	1,482.4	1,744.4	1,931.0	2,393.1
BSTL	121.6	418.1	688.9	887.4	1,043.6	1,520.9
Total STL	504.9	1,437.6	2,171.3	2,631.8	2,974.6	3,914.0
PSELL	30.5	148.5	464.2	980.9	1,572.9	4,641.1
BSELL	51.9	74.5	132.0	261.9	434.1	1,427.6
Total SELL	82.4	223.0	596.2	1,242.8	2,007.0	6,068.7
Total Transfers	587.3	1,660.6	2,767.5	3,874.6	4,981.6	9,982.7
Percent Solar Going to Load	86.0	86.6	78.5	67.9	59.7	39.2

Key:
PSTL: Peak-period solar-to-load transfers
SSTL: Shoulder;period solar-to-load
BSTL: Base-period solar-to-load
PSELL: Peak-period sellback to grid
SSELL: Shoulder-period sellback
BSELL: Base-period sellback

Energy Transfers from Solar Array to Load and Grid by Time-of-Day Period and by Array Size: Phoenix[40]

Array Size. in m^2:	**5**	**15**	**25**	**35**	**45**	**85**
KWH Transfers						
PSTL	117.7	317.7	491.8	646.4	783.3	1,258.0
BSTL	662.1	2,296.4	3,493.5	4,256.5	4,873.2	7,287.6
Total STL	779.8	2,614.1	3,985.3	4,902.9	5,656.5	8,545.6
PSELL	0.0	35.4	96.8	177.6	276.2	743.3
BSELL	187.8	253.3	756.0	1,692.8	2,775.9	7,160.6
Total SELL	187.8	288.7	852.8	1,870.4	3,052.1	7,903.9
Total Transfers	967.6	2,902.8	4,838.1	6,773.3	8,708.6	16,449.5
Percent Solar Going to Load	80.6	90.1	82.4	72.4	65.0	52.0

Description of Generic Technologies

There are three basic silicon-based photovoltaic technologies applicable to decentralized applications. They are the flat plate, air cooled silicon array, the tracking concentrator photovoltaic cogeneration system, and the Texas Instruments photovoltaic fuel cell. The first generates electricity only. The second generates electricity and thermal energy. The third generates hot water, as well as hydrogen and bromine, which are then recombined in a fuel cell to generate electricity.

Single crystal flat plate air cooled silicon modules are commercially available today. While it is possible to design nonconcentrating solar arrays which provide both electricity and heat, several studies indicate that such an array would be less efficient and more expensive than separate solar heat and solar electric arrays.

The system is simple to understand and use. There are no moving parts. Wires must be insulated and hardware must be secure to be able to withstand high winds. There should be no environmental concern, at least in operation. There is potential for pollution during manufacture, but since the manufacturing process would be quite similar to the production of photovoltaic arrays for the solar power satellite, the pollution if any per unit area of terrestrial array would be similar to that for the SPS.

These systems are modular. A system for a house can be installed in one day. Material needs are similar to those of the solar modules placed on the SPS, except that the terrestrial modules would probably use tempered glass covers, while the SPS modules would use plastic or very thin glass covers. At noon, one peak KW of electrical output would require 5.9 square meters (64 square feet) array area. This is based on an assumed terrestrial (AM 1.5) efficiency of 18%, which is equivalent to the 16.6 efficiency in space (AMO) assumed for the reference SPS.[47] We further assumed that terrestrial array output declines 5% the first year due to dirt and degradation, leaving a net efficiency of 17%.[48]

The power output of a nontracking PV module is directly proportional to the light striking it. The issue of supply vs. demand vs. storage vs. interconnection and backup systems is very complex, and is addressed elsewhere in this paper.

Contribution of Solar Electricity to Residential Electricity Needs (Percent)[41]

Array Size (m2)	Boston	Omaha	Phoenix
5	4.6%	6.0%	4.3%
15	12.9%	16.4%	14.5%
25	19.5%	23.0%	22.0%
35	23.6%	27.0%	27.0%
45	26.7%	30.0%	31.2%
85	35.0%	38.1%	47.0%

Industry	Annual Energy Requirements	City	Array Area
Textile Mill Products	1,998 MWh	Boston	11,200 m^2
		Phoenix	6,600 m^2
Paper and Allied Products	9,265 MWh	Boston	52,200 m^2
		Phoenix	30,600 m^2
Printing and Publishing	260 M.Wh	Boston	1,400 m^2
		Phoenix	861 m^2
Chemicals and Allied Products	1,439 MWh	Boston	8,100 m^2
		Phoenix	4,766 m^2
Fabricated Metal Products	378 MWh	Boston	2,131 m^2
		Phoenix	1,252 m^2
Electric and Electronic Equipment	1,856 MWh	Boston	10,465 m^2
		Phoenix	6,147 m^2
Transportation Equipment	1,752 MWh	Boston	9,876 m^2
		Phoenix	5,802 m^2

The 1980 production level is about 3 MW per year. Costs have been dropping steadily for several years and are expected to continue to do so. For this paper we assume that DOE's 1986 cost goal of \$0.80Wp is met, but the argument is independent of specific dates. The SPS reference system cost is \$35/m^2 (\$3.24/ft.^{2}) which translates to \$0.21/Wp for the terrestrial system.

If the flat plate collector is installed in a residential shingle array, as part of the roof, the savings due to reduced roofing material and labor costs exceed the cost of installing the photovoltaic parts. If the DOE goal of $0.80/Wp is met for 1986 and certainly if the $0.21/Wp goal for the SPS is met, the balance of system cost will be the dominant factor in estimating the economics of decentralized applications.

Tracking concentrator photovoltaic cogeneration systems provide both electricity and heated liquid when the sun shines. They can track the sun around one or two axes. At an outlet temperature of 175 degrees Fahrenheit, we assume 15 percent of the insolation striking the collector aperture will be converted into electricity, and 45 percent into heat.

An active tracking system moves the system every few seconds to keep it pointed at the sun. The heat storage system requires two storage tanks, pipes, pumps and a simple control system to move the hot water from the collectors to storage. The tracking system is not very complex, due to its slow speed, but it might require periodic oiling and brushing the dead leaves or snow away. There should be no safety problems.
The concentrator replaces most of the solar cell area with a glass or plastic optical element. Both the glass and plastic industries are well established and regulated. Some additional steel would be required to produce the tracking frames. We foresee no unusual pollution arising from this system.

The thermal output of the collectors is easily stored in hot water tanks. The three to one ratio of thermal to electric output is fairly well matched to winter home and commercial building needs. In the summer excess heat will be generated.

Dozens of prototypes have been built by researchers around the country. At least one company in the United States is selling commercial systems. Several other companies appear likely to put systems on the market by 1983.

The major costs are likely to be those associated with the moveable frame, and installation of the system. The assumed costs of the system are described in the table below:

Texas Instruments' photovoltaic fuel cell operating characteristics are similar to those of the single crystal flat plate air cooled silicon modules. The system provides both heated liquid and stored electricity. Both the thermal and electrical outputs can be stored economically in on-site tanks for use when needed. No other batteries or grid interconnection is necessary.

This system is illustrated schematically in Figures 1 and 2. It has separate storage tanks for hydrogen, in the form of metal hydride, hydrogen bromide solution, and hot water. Pipes, pumps and a simple control system are required to transfer the fluids between the collectors and storage tanks. The system might consist of a number of modular units, with each module completely independent. The system is completely automated and requires no attention from the user, other than a periodic maintenance check by the service man.

Hydrogen is flammable and can be explosive if mixed with air. Sulfuric and Hydro-bromic acids are corrosive. Great care must be taken in system design if this system is ever to be acceptable for household use.

The power output is a perfect match with the load profile because of the built-in storage feature of the system. Texas Instruments speculates that the system may reach the market in the late 1980's.

The major cost determinants appear to be the production and installation of a sealed system which will not release hydrogen and bromine. Mounting racks, and an invertor will be required as well. Texas Instruments at this time believes it is too early to make reliable estimates of system cost. Their initial estimate indicates a total installed cost of \$10,000 for a residential system capable of 8 kilowatt peak output, with between 25 and 100 kWh of storage. This assumes 100/m^2 of collectors, or about 100/m^2 for the entire system including installation, storage, and power conditioning.

Single Crystal Flat Plate Air Cooled Silicon Module Costs

Single Crystal flat plate air cooled modules*	\$35/m^2 [49]	\$0.21/Wp
Install lying on roof	\$13/m^2 [50]	\$0.08
Install in place of roof	\$-0.78/m^2	\$0
Install on frames on roof	\$42-76/m^2	\$0.25-0.45
Install on frames on field	\$53-87/m^2	\$0.31-0.51
Install on columns above ground	\$63-97/m^2	\$0.37-0.57
Power Conditioning	\$60/kW	
Battery initial costs	\$36/kW	
Battery O&M costs in ¢/ kWh discharged	0.028	
Battery housing costs	\$0.4.70/kW/of capacity	
Lightning protection	\$500	
Efficiency:		
Flat Plate air cooled silicon array	17.1% [49]	

*All costs are in 1980 dollars

Technology Chosen

In our analysis of SPS and decentralized photovoltaic systems the flat plate, air cooled silicon array has been chosen as the basis of the comparison. There were several reasons for this.

1. The operating characteristics of flat plate air cooled solar cell arrays are well understood, and the projected short term price reductions have been relatively accurate in the period 1973-1980.

2. It makes it easier to compare to SPS directly, since the array cost and array efficiencies can be translated directly into terrestrial applications.

3. Flat plate arrays can be integrated directly into the roof structure. General Electric has already designed a residential shingle that would eliminate additional costs for support structures.

There is some disagreement among analysts as to the value of thermal/electric hybrid systems compared to electric only arrays. General Electric concludes that "PV only solar energy systems for residential use should be emphasized since their potential economic viability was as good as or better than other solar energy options evaluated in *all* regions..." The report adds, "Combined PV/thermal collector systems must show improved performance and reduced costs over those assumed in this study to show economic viability."[53]

On the other hand, OTA concludes with respect to concentrator PV systems, "It can be shown in most cases that if a use for low temperature thermal energy exists, it is preferable to accept these losses of efficiency (due to reduced efficiency of solar cell because of raised temperature) and use the thermal output from cells directly rather than to maximize cell performance and attempt to use a photovoltaic powered heat pump to produce thermal energy."[54] Westinghouse agrees with GE, that thermal/electric systems need more research and development, but recommends that such a Research and Development effort be done especially because of the advantage of these systems in the cooler regions and for stand-alone systems."[55]

Material Requirements:

A comparison of materials requirements between decentralized PV systems and SPS depends upon the ratios of peak decentralized PV power to peak SPS power. If energy demands were constant, around-the-clock, the peak decentralized PV power would have to be about four or five times the peak SPS power in order to carry the same loads, due to the effects of night and weather. However, in the United States, more power is used during the daylight hours than at night, so a smaller decentralized PV capacity will suffice. For the following rough estimate of materials requirements, we will assume a ratio of 3.5:1. This implies an installed decentralized PV capacity in 2030 of 1050 kWp. We will assume that it is installed over 40 years for the purposes of determining annual materials requirements. This implies the installation of 154 million square meters per year of flat plate PV.

Tracking Concentrator Photovoltaic Cogeneration System Costs

Tracking hybrid collector	\$128/m^2 [51]	\$0.85/Wp
Install on roof	\$34-68/m^2	\$0.23-0.45
Install in field	\$44-78/m^2	\$0.29-0.52
Install on columns above ground (same subsystem costs as flat plate	\$53-87/m^2	\$0.35-0.58
Efficiency:		
Hybrid (PV cogeneration)	15% electrical	
	45% with thermal output at 175° F	

We will use the following estimates of materials requirements per square meter of PV collector:

	Quantity/m^2	Source
Glass in collector	6 kg	a
Steel in collector	0-3 kg	a
Silicon cells	0.24-0.71 kg	a
Lumber in racks	16 board ft.	b
Concrete in piers and footings	0.0363 yds	b
Steel in piers and footings	1.53 kg	b

If one-third of the collectors are mounted on roofs so they don't need racks, and one-third are mounted on concrete footings and piers, then the total annual requirements are listed in the table below.

It should be bourne in mind that there is a high degree of substitutability in the materials requirements for the decentralized systems. In outer space, there may be only one material which meets the criteria of light weight and tolerance to the space environment, but on Earth, almost any common building material can be used to support arrays. If one material becomes expensive or in short supply, another will most certainly be used. While the variety of alternatives is not quite as great, there is still quite a latitude for material substitutions even among such things as pipes, tanks, storage batteries, wires, and PV module encapsulants.

There are several different batteries which are expected to fall within the price range projected here. If materials for one type of battery becomes in short supply, another type will be used. Among the candidate batteries are: Improved lead-acid, nickel-iron, nickel-zinc, zinc-chloride, zinc-bromine, sodium-sulfur, lithium-sulfer, iron-redox, and the Texas Instruments photovoltaic hydrogen-bromide fuel cell. [c/] If we assume enough storage to provide 300 GW of electricity for 24 hours is installed over 40 years, the resulting requirements is 1.4 to 4 million MT of batteries per year at 20-60 Wh/lb. [d/]

The electronic controls and power conditioning systems do not require very much materials, and are not expected to have any more impact than, for example, everyone buying a new stereo every 40 years.

a/ OTA. Solar. Volume 1, p. 221
b/ Burt Hill Kosar Rittleman Associates. Residential Photovoltaic Module and Array REquirement Study. (DOE/JPL-955149-79/1) June 1979, Appenidx 14, p. 34.
c. Bechtel National, Inc. Handbook for Battery Energy Storage in Photovoltaic Power Systems. (SAN-2192-T1_ Nov. 1979, pp. 1-9 to 1-10.
d. Ibid.

Economic Analysis of Decentralized Photovoltaic Applications

Using the methodology outlined by the Planning Research Company in Solar Photovoltaics: Applications Seminar, daily, monthly, and annual insolation data on optimally tilted solar arrays was compiled. The results are indicated below

Assuming a 100 square meter array in Boston and Phoenix, the total insolation striking the array on an annual basis is 142,970 kWh in Boston, and 241,463 kWh in Phoenix.

Texas Instruments Photovoltaic Fuel Cell Costs

Flat Plate Hybrid Collector - Texas Instruments	$72/m^2 [52]	$0.80/Wp
Install lying on roof	$28 [52]	$0.31
Install in place on roof	$13 [49]	$0.14
Install on frames on roof	$60-94	$0.67-1.04
Install on frames in field	$70-104	$0.078-1.16
Install on columns above ground	$80-114	$0.89-$1.27
Efficiency:	8-10% [52]	

In evaluating the on-site systems with and without storage, we assumed that all electricity generated without storage was used either within the house or delivered to the grid system. With an inverter efficiency of 90 per cent the system efficiency is 15.4 percent. Thus a house in Boston will generate 22,017 kWh per year and 440,347 kWh over the 20 year estimated life of the array. A house in Phoenix will generate 37,185 kWh per year, or 743,700 kWh over the 20 year life of the array.

To analyze the total energy generated by houses with storage, we assume that 50 percent of the energy generated by the array went directly to load at 15.4 percent efficiency, and 50 percent went to storage, and then to end applications, at 11.54 percent efficiency. In Boston this system would generate 19,105 kWh per year, or 382,102 kWh over the estimated 20 year life of the system. In Phoenix the house would generate 32,524 kWh per year, or 650,480 over the estimated 20 year life of the system.

Using the financial assumptions listed above we estimated the cost per kilowatt hour with and without storage, for systems operating in Boston and Phoenix, under three cost estimates: roof replacement, flat on roof, or on elevated structures on surrounding grounds. The results are given on the next page.[95]

Some conclusions can be drawn from the chart. Costs are substantially lower in Phoenix than Boston, and between systems with storage and without storage. As solar array costs drop in price, the balance of system costs becomes a very important portion of the total system costs. This is indicated by the 163 per cent increase in costs per kilowatt hour for households in Boston and Phoenix if the solar arrays are not integrated into the roof structure, but are placed on expensive elevated racks on the ground.

The same process was done in evaluating industrial applications, except that since industrial structures will not be designed with sloping roofs, we assumed that arrays would be located on racks on the roof, or on elevated racks on surrounding grounds. We also assumed a three shift operation, so that 75 percent of the energy generated would go through the battery storage at 11.54 percent efficiency.

In order to compare these costs with those of the solar power satellite systems, charts on pages 44 and 45 were developed. The first graph makes clear a very important point. Ten to twelve satellites must be launched in order for any of them to be economical. We cannot stop after one or two satellites and reconsider unless we are prepared to absorb large investment write offs, as can be seen on the second graph. If the entire system is to be finished, $769 billion will be committed, according to NASA estimates. On the other hand, decentralized PV systems are produced and installed in modular arrays, and stopping or changing course at any time, as circumstances dictate, should be neither costly nor difficult.

The second graph calculates decentralized PV investment by assuming an average installed total system cost of about $1000/Wp. Some systems will be more expensive, some less, of course, as some will have storage, etc. and others will not. The capacity of the PV industry is assumed to double each year for 10 years from a base of 3 MW in 1980, and to double every other year from 1990 to 1996 when it reaches a plateau of 25 GW. It should be noted that this is roughly the same level of PV manufacturing growth necessary to supply two SPS per year if the first one were launched in 2000. This is because each reference 5 GW SPS requires 10.79 GWp of arrays according to NASA; two each year would require slightly more than 21.5 GWp.

Total Annual Material Requirements

Glass	924,000 MT
Steel	80,000-540,000 MT
Silicon Cells	37,000-110,000 MT
Lumber	1,640,000,000 board ft.
Concrete	1,860,000 cubic yds.

We arbitrarily stopped buying decentralized PV systems in 2023, when 1050 GWp had been installed. The SPS program stops in 2030 with 300 GWp.

One final note. The NASA SPS costs presented here are busbar costs going into the utility transmission line, whereas the decentralized PC costs are delivered costs to the customer and don't require the addition of transmission, distribution, and administrative overhead. Because the reference SPS cannot beam power to earth north of 40˚ latitude, the transmission costs to northern cities could be significant. On the other hand, if decentralized PV systems are backed-up by remote wind and hydroelectric plants, there will be additional transmission costs as well.

Economies of Community Wide Systems

Although Westinghouse' study indicates that stand-alone systems, with a household generator as backup, are viable in all parts of the country, there are reasons to move beyond the household level. A larger number of buildings will match different load profiles. Since people tend to use energy at different times, as we add

Boston: Latitude 42.2

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
kWh/m^2/day	3.36	3.73	4.08	3.98	4.35	4.29	4.58	4.41	4.36	4.08	3.01	2.75
kWh/m^2/month	104.2	104.4	126.5	119.4,	134.9	128.7	142.0	136.7	130.8	126.5	90.3	85.25

Phoenix: Latitude 33.3

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
kWh/m^2/day	5.95	6.97	7.36	7.50	6.57	6.20	5.74	6.18	7.03	7.31	6.68	5.96
kWh/m^2/month	184.5	195.2	228.2	225.0	203.7	186.0	177.9	185.4	217.9	226.6	200.4	184.8

Household and Industrial Photovoltaics: Costs and Efficiencies

System Assumptions

- Array Efficiency--18 percent
- Degradation--5 percent first year, stable thereafter
- Systems Life--20 years
- Inverter Efficiency--90 percent
- Battery Efficiency--75 percent round trip Array, .Cost--$35 per square meter
- Additional Installation costs assuming roof replacement--$0.0
- Additional installation costs assuming array flat on roof--$13 per square meter
- Additional installation costs assuming array on ground--$80 per square meter
- Operation and maintenance--5 percent: of initial costs per year
- Lightning Protection-
  - Household: $500
  - Industry: $0
- Inversion and power conditioning--$82/kW
- Battery Lifetime (deep cycles)--2,000
- Battery initial costs ($/kWh capacity) -- $49/kWh
- Battery 0 & M cost (ft/kWh discharged)--.038/kWh
- Battery total cost(¢/kWh discharged)
- Household--4.161/kWh
- Industrial--3.19¢/kWh
- Battery housing and related costs($/kWh capacity)--6.4
- Backup generator, residential--$306/kw
- Industrial cogenerator steam turbine--$1446/kw

Financial Assumptions:

- Household:
  - Twenty year loan, 10 percent interest for system excluding storage loan Six year loan, 10 percent interest for storage
  - Thirty percent tax bracket
  - No additional property taxes

- Industry:
  - Twenty year loan, 12 percent interest for system excluding storage Six year loan, 12 percent interest for storage
  - Fifty percent tax bracket
  - Straight line depreciation--10 year system life basis for array; six year system life for storage
  - Twenty percent investment tax credit
  - No additional property taxes

households, we need not add a proportional amount of array area, or storage capacity. In a community which contains commercial and industrial sectors as well as residential applications, load profiles will be quite distinct, and in interacting with one another, can reduce the unit cost of the system per customer.

Moreover, a stand-alone system would require a back-up generator to operate during down times. Such an investment on the household level would be costly.

Although battery storage is possible on the household level, the dangers involved in having large quantities of heavy- duty batteries in each household can be reduced by placing them in a central place. The costs of battery shelters is not directly proportional to their size. Larger shelters cost less per kWh than smaller ones. As the EPRI study concluded, it is best to have storage that can be charged by system wide generation capacity, and not dedicated to a single photovoltaic array.[56]

Some of the subsystems components can be more efficient and less costly if larger. EPRI notes some disadvantages of small systems:

> "losses in an inverter sized for this type array (approximately 10 kw) will be larger per kw than the more efficient 5) inverters, that can be

Costs of On-Site Photovoltaics (1980¢/kWh

	Household				Industry			
	Without Storage		With Storage		Without Storage		Without Storage	
	Boston	Phoenix	Boston	Phoenix	Boston	Phoenix	Boston	Phoenix
Roof Replacement	2.6¢	1.5¢	6.76¢	5.66¢				
Flat on roof	3.3¢	1.9¢	7.46¢	6.09¢				
Columns on roof or ground	6.2¢	3.6¢	10.36¢	7.76¢	5.47¢	3.22¢	8.66¢	6.41¢

> designed in the tens-of-megawatts range."

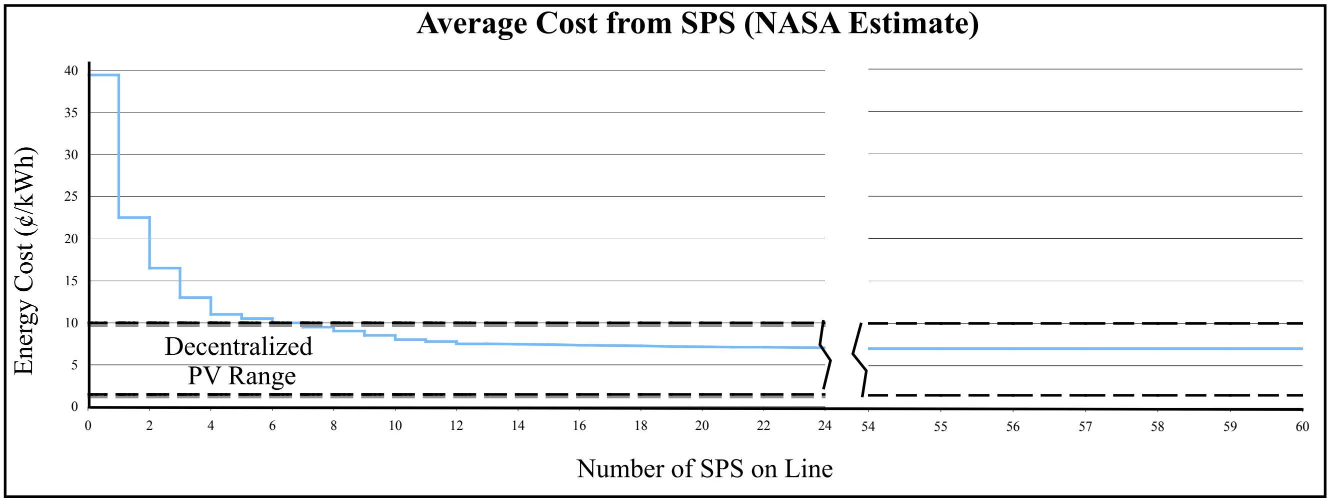
EPRI concludes that household inverters will have an efficiency of 90 percent compared to a 97.8 percent efficiency for inverters sized in the tens of megawatts. Thus, a community which has a dedicated solar energy park could realize the benefits of more efficient inverters at the expenses of less efficient load utilization.

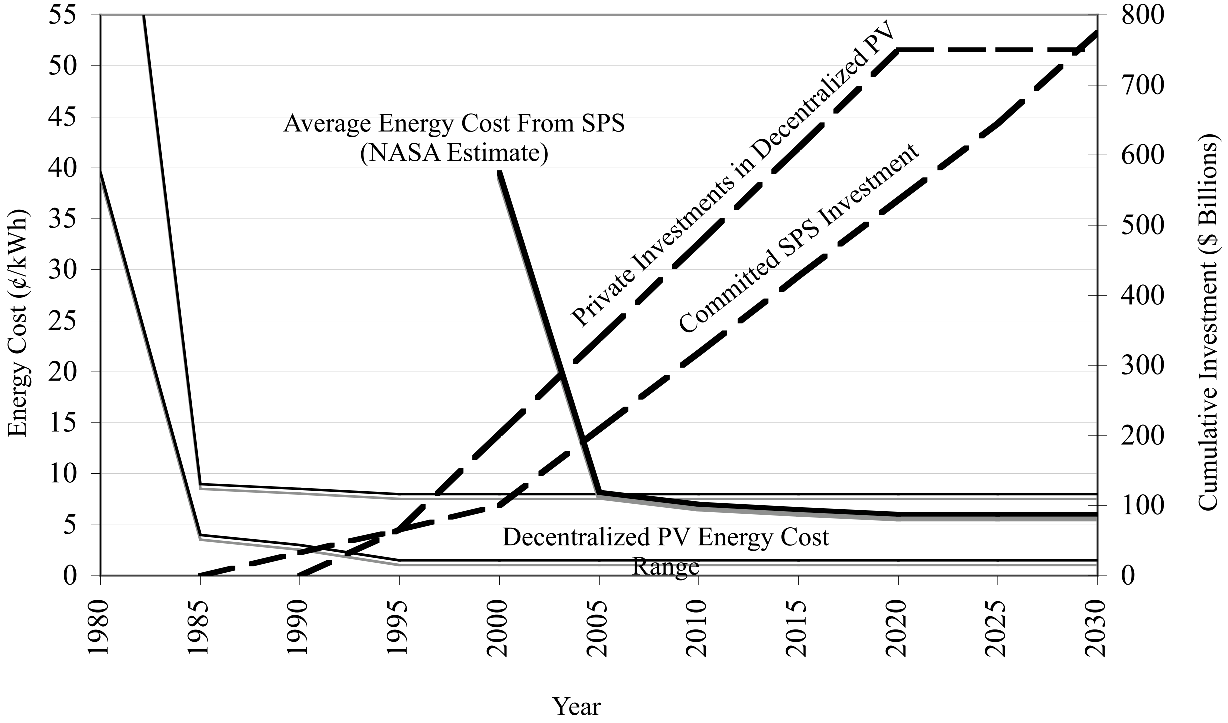
It is also clear that although on-site stand alone systems are possible, in many parts of the country poorly oriented buildings, and tree covered structures will not have sufficient space available for solar cells. These structures would pay the penalty of having to purchase all their energy and having no revenue from their own export of energy. At least one study concluded that while there are such structures in all communities, there is also a great deal of open space available in communities for establishing solar cell arrays.

Finally, as has been noted in previous sections, a building might generate sufficient energy on an annual basis to meet all its energy needs, but because of the mismatch of insolation and internal demand, half the energy would be best sent through the grid system, and half imported from the grid. Stand alone systems would have to rely on costly storage systems to use all the energy generated on an annual basis.

Utility Interconnections and Economics

The most difficult issue confronting decentralized electric systems is institutional. The OTA Solar Study states, "large amounts of power from photovoltaic devices would require a fundamental change in the ways in which the Nation now supplies and consumes electric energy."[58] The year in which that comment was written the federal government enacted the Public Utilities Regulatory Policies Act. It made it national policy to encourage small scale, dispersed electric generating capacity. In March of 1980 the Federal Energy Regulatory Commission established the final rules under which state regulatory commissions will


Average Cost from SPS (NASA Estimate)



have to formulate prices that utilities will pay qualifying power facilities. The Act requires utilities to pay on the basis of their avoided cost of power. Several state regulatory commissions have established a price equal to or greater than the retail price of electricity.

Congress appears to make the institutional relationship of photovoltaics and utilities a central concern of DOE's planning. Public Law 95-590, the Solar Photovoltaic Energy Research, Development and Demonstration Act, says:

> subsection 10(c):
>
> the Secretary is authorized and directed within one year of the date of the enactment of this Act, to make recommendations to the President and to the Congress for Federal policies relating to barriers to the early and widespread utilization of photovoltaic systems in order to realize the goals set forth in section 2. These recommendations shall include but not be limited to...
>
> (1) the potential for integration of electricity derived from photovoltaic energy systems into the existing national grid system, including the potential of photovoltaic generated electricity to meet the peakload energy needs of electric utilities, load management, and reliability implications of the utilization of photovoltaic electricity by utilities, the implications of utility ownership of photovoltaic components leased to others primarily for decentralized applications, the impacts of utility use of electricity derived from photovolvaic energy systems on utility rate structures, and the potential for reducing or obviating the need for energy storage components for photovoltaic energy systems through utility interface."

Under such directives the Electric Power Research Institute undertook an analysis of decentralized photovoltaic applications. Some of its key conclusions were.[59]

> 1. Established utility generation planning methods are applicable to studying photovoltaic generation, with minor modification. The proper criterion for comparison is total utility system costs.
>
> 2. Energy storage dedicated to the photovoltaic plant offers little. if any,

> advantage. Energy storage has its greatest value as system storage, designed and operated for the benefit of the total utility system.
>
> 3. The disadvantage of small, dispersed individual load photovoltaic plants, whether utility-owned or user-owned, probably outweigh any potential advantages.

The MIT Energy Laboratory criticized many analyses of decentralized photovoltaic systems because "their analysis required *utility ownership* of the systems, and thus the framework in which their financial analysis was performed failed to capture many of the potential advantages of residential, user-owned systems"[60]

As an example of the diversity of interests, studies indicate that the penetration of PV systems into the utility network increases system reliability. However, as DOE notes, "P/V power systems may add considerably to the reliability of the consumer's supply of power, though they may or may not be adding to the overall reliability of the system."

> A case in point is the experience gained in the Meade, Nebraska, agricultural p/v experiment... during the first 15 months of operation of the Meade system, power from the utility has been unavailable 47 times. For the most part, these interruptions have been caused by failures in the distribution system, in which the Meade station lies at the end. During the same period of time, the photovoltaic power system was unavailable for power production only 15 times. Thus, with sufficient electrical storage, a p/v system can be considerably more reliable at the customer end that with the utility alone.[61]

The user may value reliability differently than the utility. Utilities currently try to maintain enough capacity to ensure that failure of the generating plant will curtail power no more than 2.4 hours per year. Southern California Edison uses a standard of 1 hour in 10 years. "It has been argued, however, that this standard for generating reliability is too high, and that the last few hundredths of a percent of reliability are enormously expensive, particularly since the transmission and distribution system is usually less reliable than the generating plant."[62]

OTA comments:

> "Standards for reliability cannot be measured in any systematic way. Requirements will differ from customer to customer. Some industries, for example, would face catastrophic losses if they lost power for an extended period (say several hours), while residential customers might not be willing to pay a premium for extremely high reliability. One of the disadvantages of providing power from a centralized utility grid is that all customers must pay for high system reliability whether they need it or not On-site generation would permit much greater flexibility in this regard."[63]

DOE adds:

> "Within the utility industry, reliability is frequently measured in terms of loss of load probability. Reliability as seen by the customer is a function of the probability of loss of load by the generators, by failures in transmission and most significantly, by failures in distribution systems. Of these three, from the viewpoint of the customer, failures in distribution have the highest probability. However, the probability of distribution failure differs widely among customers. Rural areas, customers at the end of distribution lines, and customers in areas with much bad weather have higher probabilities of distribution failure. The availability of customer generated p/v power combined with energy storage will offer the option to such a consumer of choosing his own reliability level rather than accepting the level of overall system reliability."[64]

Unfortunately, as DOE admits,

> "Analysis of the requirements of different types of customers in this regard is almost nonexistent. It is difficult to anticipate how much different customers would be willing to pay for reliability if they were given a choice."[65]

For example, within the household the vast majority of total energy consumed might be considered interruptible power. Even in the dead of winter a significant minority could be placed in this category. This is an extremely important point if an attempt is made to design houses which are 100% solar powered. What is it worth to people if, five days per year, they postpone washing their clothes, or turn the thermostat lower during the night, or take shorter showers?

Interestingly, in one analysis by Westinghouse of stand-alone systems "the capability of satisfactorily supplying the hot water load is a decisive factor for some all-electric systems and for air heat-transfer thermal systems."[66]

The economic attractiveness of photovoltaics depends in large degree on 1) the rate at which the utility purchases excess electricity from the decentralized generation plant, and 2) the rate structure of the utility. General Electric observes, "It is not possible to define the break-even capital cost for a user-owned PEPS (Photovoltaic Electrical Power System) plant in the same way as has been done for utility-owned plants. This is because the economic incentive to purchase and install such a plant lies in the savings in purchased electricity costs accruing to the user."[67] The MIT report agrees:

> "The valuation is the difference in the utility bills to the user, which is determined by the utility rate structure and whatever the utility is willing to pay for surplus energy supplied by the owner to the grid. If the rate structure reflects the load demand on the utility (as under peak load pricing) then this valuation explicitly values the "quality" component of the energy supplied by the device."[68]

Yet if the utility has a rate structure which takes into account the time period of energy demand it will initially precipitate a competition between storage and photovoltaic generation. One study concludes:

> "Since storage can reduce electricity bills given a time-of-day pricing structure with or without a P/V array, the benefits to a combined system could accrue to the PV array, to the storage, or to the interaction of the two. This allocation difficulty underscores the fact that photovoltaics and storage, rather than being complementary as is commonly believed, appear in fact to be competitive or substitute devices for grid-interfaced systems... This relationship would persist so long as both are competing as peak-saving devices. Should PV ever compete as baseload generation, storage would become a complementary device."[69]

In other words, if the utility charges a higher price for electricity consumed during peak times, the household or business can either generate electricity at those times on-site or it can purchase off-peak electricity and store it for peak use.

DOE observes:

> "When a p/v system is non-utility owned, the value of storage depends largely upon the rate at which backup electrical power may be purchased by the p/v owner and the rate at which the owner may sell power back to the utility. Thus the rate structure,especially the sellback rate will ultimately determine that value of distributed storage combined with interconnected p/v systems." [70]

The interrelationship between the central utility and the decentralized producer/consumer will be a complex and dynamic one. It appears that the first decentralized photovoltaic power plant will be able to attract a good price for its product from the central utility, but as penetration levels rise above 10 percent, the value of the added capacity to the central system will decline. The MIT report observes:

> "Work to date in assessing these impacts has indicated that photovoltaic penetration at relatively low levels may improve system reliability and reduce system operating costs. The positive contribution of photovoltaics declines however, with increasing levels of penetration, and at some point the addition of pv systems would have no or even marginal impact upon the utility company. Therefore utility companies might be expected to welcome. additional PV systems until this 'saturation' point is reached and then to discourage further penetration, or at least be indifferent to further penetration. In attempting to assess the long-term market for grid-connected systems

> further study is necessary to establish the penetration levels at which utility grid systems would become saturated and market potential essentially exhausted"[71]

Unfortunately, such investigation will be extremely complicated.

> "The difficulty in determining saturation levels is that the problem is dynamic with PV penetration altering utility marginal costs, marginal costs affecting rate structures and rate structures impacting the economic viability of further investment in PV systems."[72]

In fact, at the point that further PV capacity becomes a negative value to central utilities, the homeowner has the option of expanding his or her electrical storage capacity, or bringing on small back-up systems. Westinghouse's analysis of stand-alone systems in ten cities in varying climatic regions, backed up by a 1.5 kw generator concluded:

> "stand alone systems costs are about equal to the utility backup costs ... Since stand-alone systems are viable nearly everywhere, the stand-alone system cost in effect puts a limit on an acceptable utility backup charge."[73]

Westinghouse concludes, "Electrical storage is essential if *large scale* (emphasis in the original) implementation is to be achieved. Sell-back power to the utility is not considered viable on a large scale."[74]

Most federally supported economic analyses assume a sell-back rate of 0-50 percent of the retail cost of power. Westinghouse believes a justified rate is no more than 35 percent the cost of retail power; and after 1990, when large numbers of decentralized PV systems come on-line, the ratio should drop to 25 percent. However, PURPA requires utilities to pay the "avoided cost" of power. Already the New Hampshire Public Service Commission requires more than 100 percent of the retail price for decentralized power plants using renewable resources, under the assumption that state renewable energy resources are replacing intermediate electricity, fueled by high priced oil. California and Oregon have also established sellback rates of more than 50 percent the retail price for cogeneration facilities. These high sellback rates could have a dramatic impact on both the rapidity of PV penetration in the residential market and the size of residential and business PV systems. GE, for example, found that at 50 percent sell-back ration a PV system would be viable in Boston in 1986 if a) the PV system array installed cost is $67 dollars per square meter and if b) electricity prices rose at 4 percent real inflation rate. Assuming a 100 percent sell-back ratio,, the system would be economical at a cost of over $150 per square meter, a price DOE is projecting to reach by 1983.[75]

The American electric generation system has become increasingly centralized since its inception. PURPA requires major institutional and regulatory changes in this sector. In the next twenty years we can expect significant changes as decentralized electric generation comes on-line. Most of this generation will be in cogeneration, but the institutional and regulatory changes will affect solar electric generation as well. If the electric utility system does become more diverse and decentralized in the next twenty years, it may prove difficult to integrate the SPS system, which would be composed of the largest power plants in history, into the reformed regulatory climate.

The economics of decentralized applications depends not only on the sell-back price, but on how the tax code defines the revenue generated in this manner. Under existing law, it would probably be considered as income to the owner of the p/v system. DOE believes:

> "As most owners would be able to offset most or all of the income by the costs of owning and maintaining the systems, making sell-back revenue tax exempt would result in some simplification, possibly with little or no loss in tax revenue. It may also encourage consumers to install larger systems."[76]

However, DOE notes the different impact the tax structure would have on the user-business as compared to the user-resident.

> If that taxpayer is a business, all expenses are deductible, and the depreciation need not be apportioned. If the installation is residential only half the depreciation and expenses are allowable deductions (assuming the taxpayer is consuming half the electrical generation on-site.
>
> The effect of deducting the cost of backup power and considering sellback income is important. For example, if a business in the 40 percent tax bracket buys $10,000 worth of electricity, it really costs

> $6,000. If that business sells $10,000 worth of surplus electricity, the $10,000 shrinks to $6,000 after taxes. Thus, additions to gross income from sell-back and deductions from gross income for backup power cancel each other out for businesses to the extent that the sale of surplus power equals the cost of backup power... For residential installations the story is entirely different ...revenues from the sale of residential surplus are not offset by deductible expenses from the purchase of back-up power. This reduces the value of sellback power (relative to power produced and consumed) to the homeowner and creates a bias toward smaller system sizes with a concomitant drop in total sell-back power.[77]

The economics of decentralized photovoltaic systems will also be dependent on the return the investor demands. Utility-owned centralized arrays must use a discount rate high enough to attract investment capital. User-owned systems are more flexible. The benefits of self-reliance may offset a lower return on investment for the business or homeowner. MIT Energy Laboratory makes the interesting case that since the correlation between electricity prices and market returns is negative (that is, rising electric prices may depress the economy) the value of a PV system can be seen as an "insurance policy or hedge against rising electricity prices. An investor might be expected to pay for such protection or insurance by accepting a lower return on the investment." Moreover, the authors point out that:

> "Since the returns to the photovoltaic system come in the form of savings (i.e. reductions in the utility energy bill) they are not subject to taxation and thus represent after-tax cash flows which should be discounted at an after-tax rate. Interest payments are tax-deductible to the individual investor's marginal tax rate to obtain the after-tax rate."[78]

Their overall conclusion is that the appropriate discount rate to use in evaluating the user-owned photovoltaic system is between 0 and 3 percent real rate of return.

Market Penetration

The predictions of market penetration by photovoltaics vary dramatically. Sometimes the predictions are based on price; sometimes they are based on target Years. There are fewer variations at higher priced arrays. For example, at $1 per peak watt, BDM forecasts a total market of 170 MW; Intertechnology forecasts 126 MW, and RCA 200 MW. At 50 cents per peak watt, however, the estimates vary from Texas Instruments' 100 MWp to RCA's estimate of 2 GW. Below 50 cents the variations are almost as extreme, from a DOE forecast of 5 GW to 100 GW by RCA.[79]

AS OTA observed:

> "If prices fall below about $0.50/ watt, an explosive growth in sales could occur since at this price photovoltaic equipment might provide electricity which is competitive with residential and commercial electricity rates in many parts of the United States. By the time prices fall to $0.10 to $0.30/ wp the photovoltaic electricity may be competitive with electricity sold at bulk rates to large industrial consumers. Estimating sales at these levels is extremely speculative since generating large amounts of power from photovoltaic devices would require a fundamental change 0in the ways in which the Nation now supplies and consumes electric energy."[80]

OTA points out, "when array prices reach these low levels, the overall cost and attractiveness of photovoltaic systems are likely to be dominated by factors other than the cost of the cells themselves." Westinghouse concurs. As we have observed above, at a $35/m2 price for the solar array (the projected SPS price) the balance of system costs could be twice as great as the solar array cost, except in cases where the array were part of the existing rooftop. Westinghouse shows that this is also true in the short run.[81] At a price of 50 cents per peak watt the cost of solar arrays is $90 per square meter. At that price, which will be attained in the mid 1980's, balance of system costs would comprise a significant portion of the total costs of generation. DOE agrees with these estimates, "The stock of 52,000,000 single family homes undergoes a roof replacement every 20 years. On an average, 26,000,000 roofs/year could be available for retrofit."[82]

Assuming that 25 percent of these homes would be amenable to retrofit with photovoltaic array prices of $1.60 (expected in the mid 1980's), and that 50 percent of new homes would be similarly inclined, a total market of 9.8 GWp/year is identified (this assumes 8kWp for new residential, and 4 kWp for average residential retrofit). DOE believes that intermediate load centers of average size 100 kWp would provide an additional 2.6 GW per year of sales. Thus by the late 1980's the photovoltaic market could be supplying more than 12 GWp per year. Westinghouse doesn't expect the market to open up quite that rapidly, but by the late 1990's it expects 10 million homes to have photovoltaics, and a market of approximately 2 million homes per year being retrofitted, for a total of 20 GW per year.

The other factor limiting sales in the short term, is the limited supply of polysilicon. Westinghouse identifies a potential market of almost 10 million homes by 2000. Assuming a 10 kWp system on the average house, the total required generating capacity would be 100 GW. Assuming about 100 square meters per house, this would require one billion square meters of silicon arrays. Assuming a ribbon manufacturing process with 8 mil thick silicon, this would require 500,000 metric tons. Yet in 1977 the total polysilicon production for the electronic industry was 2105 metric tons, and by 1986 it is projected to increase to only 3245 metric tons. And the photovoltaic market, according to DOE, consumes about 1 percent of that supply.[83]

> Demand for polysilicon has grown rapidly and continuously since it came into use in semiconductors in the middle '50's. Refinement capacity has kept pace. However, given the likely advent of new, cheaper technology, producers are understandably reluctant to add capital and energy intensive capacity that will probably be obsolete before or soon after it becomes operational. Thus, given continued growth in demand, it is predicted both by the DOE and by existing polysilicon producers that a shortage is likely to appear in 1982 or 1983. This shortage will heavily impact both electronic firms and photovoltaic manufactures. However, given the relatively small portion of their costs attributed to silicon material, the electronic firms will be able to outbid photovoltaic manufacturers.[84]

It takes 3-5 years to install new Siemens capacity. Currently DOE is encouraging firms to develop manufacturing capacity for lower quality silicon made especially for the photovoltaic market. It is unclear whether this will be able to meet the market demand that will open up in the late 1980's.

The penetration of the solar cell market, as explained before, will depend largely on the sell-back rate with the local utility, and with the balance of system costs. In a previous comparison with SPS we assumed a doubling of the domestic market each year between 1980 and 1990 and a doubling every other year between 1990 and 1996, with a levelling off of national manufacturing capacity at the 25 GWp per year level afterwards. Given that most estimates indicate an annual domestic market far larger than that total, we can assume major bottlenecks in supplies during the early 1990's. Since the SPS systems will be ordering 21.6 GWp each year, it would be competing in an already bottlenecked marketplace with decentralized photovoltaic applications.

We assumed 1050 GWp of decentralized photovoltaic applications in place by 2030. It is impossible to make any such estimates over such a long time period. But given this optimistic assumption, we can examine the end use consumption figures of the low and high demand scenarios for the next century to see what portion of energy demand this will represent. the low energy scenario assumes end use consumption of 56 quads in 2030, while the high energy scenario assumes 114 quads of end use demand in 2030. If total energy were to be met by electricity, at 1 quad equals 290,000 GWh there are 33 average GW's in a quad. The low demand energy scenario can thus be translated into 1,848 GW per year, and the high demand energy scenario translates into a need for 3,762 GW electrical energy per year.

If decentralized photovoltaics were to deliver 1050 GWp in 2030, it would be equivalent to about 210 GW average, or about 12 percent of total energy demand under the low demand scenario, and 6 percent of total demand under the high energy scenario. This-assumes that the United States is on a totally electric energy system. DOE and its contractors have estimated that 25 - 30 per cent of future electric requirements can be met by decentralized photovoltaics assuming that electricity continue to comprise about one third to 40 per cent of total primary energy consumption. Even if we were to move toward a total electric society photovoltaics would be reinforced by other types of energy resources. Wind power represents a form of storage, because the wind blows more strongly during the nighttime and winter, when direct solar is either unavailable, or reduced in intensity. It has been estimated that there is a potential 60 Quads of wind power in the United States.[85] If fully utilized, this would fill the entire demand of the low scenario or 53% of the high scenario.

In addition hydroelectric capacity installed or under construction in the United States in 1977 was 65.2 GW with an annual production potential of one quad.[86]

There appears to be potentially 54.6 additional GW which could produce .5 quads annually.[87] Standard hydroelectric power plants are low cost sources of renewable electric energy. In addition, they can be used to provide storage for matching wind and PV supplies to demand. If the flow of water through the dam is restricted when the wind and PV systems are able to meet the demands, additional water backs up behind the dam allowing more power to be generated during times when demand exceeds PV and wind supplies. This form of storage is not the same as "pumped hydro", which uses surplus power to pump water from a lower lake up to a higher lake, losing about two thirds of the energy in the process.

It is beyond the scope of this paper to explore the potential for a decentralized energy generation system using all the forms of solar energy. It appears that a combination of renewable and non-renewable resources, and a variety of decentralized renewable based energy systems can generate a significant portion of our energy needs by the next century.

Research and Development Needs

Research and Development needs specifically oriented toward decentralized photovoltaic applications include the following areas:

Decentralized applications of photovolaics require more accurate microclimatic data. General Electric found that there was a significant variation in energy requirements for two houses inside Los Angeles' city limits, less than 12 miles apart. A small rise in elevation and shift inland to the northwest from the airport to the Civic Center decreased by one third the energy required for space heating and doubled the cooling load as measured by degree days.

Domestic hot water consumption does not appear to vary by region. But because of the variation in the temperature of ground water, the energy needed to heat similar quantities of water can vary dramatically. The Institute of Gas Technology isolated correction factors based on these variations. There is a difference of almost 30 percent between ground water temperatures in the West South Central states, and in the Mountain Western States and the Northeastern states. (See page 61)

As solar array costs drop predictably the balance of system costs become a much more important relative cost item. Research Triangle Institute observes, "Reduction in balance of system costs below about $2 per Wp is necessary to make the SCII sectors viable." Its report observes that at array costs of $500 per square meter the inverter cost is about 2-20% of the area cost. However, as the area cost comes down to $100 per square meter the inverter cost rises to 10 to 100 percent of the area cost, and an increased sensitivity of expected profitability to inverter cost is reflected. "Expected profitability is affected more by inverter cost than by battery cost."[90]

MIT's energy lab study found that:

> "subsystem costs appear to have a significant effect on ultimate break-even costs. This should be a definite area of concern for Research and Development policy makers, since subsystem costs take on greater importance as break-even array costs fall. Of all the assumptions required to 'back out' break-even array costs, this is the most uncertain and thus critical to achieving cost goals." [91]

Westinghouse believes that volume production will reduce the cost of subsystem components, and recommends a strong precommercialization program to allow production goals to be met.[92] Because solar cells are cheaper the more matched they are to demand profiles, the market for solar arrays will become significant in the southwestern part of the United States initially. Westinghouse believes that such regional based markets will not be sufficient in and of themselves in encouraging high enough production levels to lower the costs of subsystem components.

More research should be done in combination thermal/electric systems. OTA comments, "the attractiveness of photovoltaic devices can be increased significantly if effective use can be made of the thermal energy carried away by water pumped over the back surfaces of collecting cells... It can be shown in most cases that if a use for low temperature thermal energy exists, it is preferable to accept these losses of efficiency and use the thermal output from cells directly rather than to maximize cell performance and attempt to use a photovoltaic powered heat pump to produce thermal energy."[93] Westinghouse recommends, "Immediate design and development programs aimed at optimizing the performance of a combined photovoltaic thermal collector... They are particularly advantageous in the cooler regions and for stand-alone systems."

Photovoltiac programs should be closely matched to conservation programs. Westinghouse concludes, "For optimum performance and economic viability, the building should be designed as part of the system... When designing systems, the goal should be to supply the bulk of the total energy requirements of the residence from solar energy." Particularly important in this respect is lowering the space heating loads of northern latitudes buildings.[94]

Further research in the interrelationship of residential load profiles, and those of nearby commercial enterprises, and of the potential for integrating electric vehicles into the load profile/storage configuration should be encouraged.

The basic problem facing decentralized photovoltaics, as with the SPS is the shortage of polysilicon that the industry faces in the mid 1980's. Unlike the electronics industry, photovoltaics uses huge amounts of silicon per dollar of value added. As household systems prices drop to the point were the homeowner not only supplies a significant portion of his or her own energy, but also derives an income from the household power plant, the demand for photovoltaics will soar. Currently it appears that shortages of materials will hamper the industry in its first decade.

Comparison of Annual Climate Parameters for Nearby Sites - 19 km Apart [88]

Climate Parameter	Los Angeles	
	Civic Center	**Airport**
Longitude, Degrees	118.23	118.40
Latitude, Degrees	34.05	33.93
Altitude, Meters	82.00	30.00
Mean Daily Total Horiz. Insolation, KW/m^2	5.23	5.14
Mean Temperature, °C	18.20	16.50
Mean Midafternoon Relative Humid. %	53.00	65.00
Precipitation, cm	35.70	29.40
Mean Wind Speed, km/hr	10.00	11.90
Heating Degree-Days*	1,245.00	1,819.00
Cooling Degree-Days*	1,185.00	615.00
* Base 18.3°C (65°F)		

Regional Correction Factors for Domestic Hot Water Energy Usage [89]

Region	Factor
Northeast	1.08
Middle Atlantic	1.05
East North Central	1.06
West North Central	1.02
South Atlantic	0.96
East South Central	0.90
West South Central	0.83
Mountain (Western)	1.08
Pacific	0.93
Average, U.S.	1.00

Appendix

In calculating the kilowatt hour cost for decentralized photovoltaics the following formula was used:

$$C_t = C_a + \frac{C_l + C_p + C_s + O\&M}{T} - .30(C_i)$$

Where:

C_t=Total cost in cents per kilowatt hour over life of system
C_a=Cost in dollars of array over life of system
C_l=Cost in dollars of lightning protection
C_P =Cost in dollars of power conditioning
C_s =Cost in dollars of structural supports
0&M=Operating and Maintenance Costs over Life of the System
C_i =Cost of interest on loan in dollars
T=Total kilowatt hours generated by photovoltaic arrays over life of system

For example:

A 100 square meter Household Array in Boston would have the following costs (in dollars) if it were roof mounted.

C_a =\$3,500.00
C_e = 500.00
C_p = 656.00
C_s = 1,300.00
C_i = 7,724.40

$$C_T = \frac{\$13,680.40 + 1,191 - .30(7724.40)}{382,102}$$

$$\frac{12,554}{382,102} = 3.3¢/KWH$$

Footnotes

[1] See for example, Paul R. Carpenter and Gerald A. Taylor, An Economic Analysis of Grid-Connected Residential Solar Photovoltaic Power Systems M.I.T. Energy Laboratory Report, May 1978, Revised December, 1978 (hereinafter called MIT Energy Lab Report), National Photovoltaic Program, U.S. Department of Energy Multi-Year Program Plan, Washington: U.S. Department of Energy, June 6, 1979.

[2] The Great Adventure, Department of Energy, Office of Consumer Affairs, 1978

[4] Environmental Action

[5] Personal Communication

[6] Requirements Assessment of Photovoltaic Power Plants in Electric Utility Systems, Electric Power Research Institute, prepared by General Electric Company, Schenectady, New York, June 1978, (hereinafter called GE Report)

[7] Ibid.

[8] Application Analysis and Photovoltaic System Conceptual Design for Service/ Commercial/ Institutional and Industrial Sectors, hereinafter called SCII Report), Final Report, Volume I: Executive Summary, December- 1979, Research Triangle Institute, Research Triangle Park, North Carolina, p.11

[9] MIT Energy Lab Report

[10] Alternative Energy Demands Futures to 2010, Report of the Demand and Conservation Panel to the Committee on Nuclear and Alternative Energy Systems NationalResearch Council, National Research Council, National Academy of Sciences, Washington, D.C., 1979, (hereinafter called CONAES Report,)and Energy Information Administration, Annual Report to Congress, 1978.

[11] Difference in totals is due to difference in figures in CONAES Report, see pp. 25 and 80.

[12] Ibid.

[13] Ibid., p. 53 totals for 2030 are extrapolated based on 1975 to 2010 trends.

[14] Utilities in Madison, Seattle, Boston, and Phoenix provided information

[15] See, Application of Solar Technology to Today's Energy Needs, Office of Technology Assessment, Volume II, September 1978

[16] Washington Post, June 23, 1980, p. B-1

[17] See Regional Conceptual Design and Analysis Studies for Residential Photovoltaic Systems, Volume I--Executive Summary, Westinghouse R&D Center, Pittsburgh, Pennsylvania, July 1979, p. 23, (hereinafter called Westinghouse Report) and Regional Conceptual Design and Analysis Studies for Residential Photovoltaic Systems, Sandia Laboratories, Albuquerque,. New Mexico, prepared by General Electric Space Division, Philadelphia, Pennsylvania, January 1979, See Sections 4-6.

[18] SCII Report, Op. Cit., p. 27

[19] Ibid, p. 1

[20] Japan and The Oil Problem, The Committee for Energy Policy Promotion, Japan, February, 1980, p. 16.

[21] Barry Edmondston, Population Distribution in American Cities, Lexington Books: D.C. Heath and Company, Lexington, MA, 1975, p. 135-6

[22] Statistical Abstract of the United States, 100th Edition, pp. 24-26

[23] Ibid.

[24] Ibid.

[25] Barry Edmondston, Op.Cit. p. 57

[26] . R. Knowles and R. Berry, Solar Envelope Concepts: Moderate Density Applications

[27] Jet Propulsion Laboratory, Some Currently Available Photovoltaic System Computer Simulation Approaches, Technical Report 5250-2, Pasadena: U.S. Department of Energy, July 31, 1979

[28] R.L. Ritschard, Assessment of Solar Energy Within a Community: Summary of Three Community-Level Studies, Washington, D.C.: U.S. Dept. of Energy, October, 1979.

[29] Westinghouse Report, Op Cit, p.3

[30] OTA Vol. II, p. 230

[31] Ibid., p. 181

[32] Ibid., p. 405

[33] Ibid., p, 408

[34] Ibid., p. 386

[35] Ibid., p. 388

[36] Federal Policies to Promote the Widespread Utilization of Photovoltaic Systems
Vol. II Feb. 1980, DOE/CS-0114/2, p.11-5-6, (hereinafter called DOE Report)

[37] General Electric, Op. Cit., p. 10-10

[38] Ibid., p. 10-14

[39] . MIT Energy Lab Report, Op.Cit. p. 95

[40] Ibid., p. 97

[41] Ibid., p. 98

[42] OTA Vol. II, p. 569

[43] Ibid., p. 593

[44] SCII Report, Executive Summary, Vol. I, p. 38

[45] DOE Report, p. 11-6

[46] Fortune Magazine, July 14, 1980

[47] . Harold E. Benson, Cost of SPS Program, NASA, April 11, 1980

[48] Solar Photovoltaic Applications Seminar, PRC Energy Arrays Company, January 1980, pp. 2-9

[49] Benson, Op.Cit.

[50] Rest of cost figures, unless otherwise stated are from OTA Vol. II, increased 36 percent to change into 1980 dollars, pp. 689 and 696

[51] Ibid.

[52] Texas Instruments personal communication

[53] GE Report Executive Summary,,Vol I, p 8

[54] OTA Vol. I, pp. 406-407
[55] Westinghouse Report Executive Summary, p. 3

[56] EPRI Study, Requirements Assessment of Photovoltaic Power Plants in Electric Utility Systems, Electric Power Research Institute, EPRI ER-685 Project 651-1, June, 1978, Summary Report, p. 3

[57] Ibid. Full Report, pp. 6-11
[58] O7A Vol. I, p. 411

[59] EPRI Summary Report, pp. 2-3

[60] MIT Energy Lab Report, p. 21

[61] DOE Report, p. 2-13

[62] Michael L. Tolson, The Economics of Alternative Levels of Reliability for Electric Power Generation Systems, The Bell Journal of Economics, Vol. 6 No. 2, Summer 1975, p. 697

[63] OTA Vol. I., p.132

[64] DOE Report, p. 213

[65] DOE Report, p. 2-14

[66] Westinghouse Report, Executive Summary, p. 12

[67] GE Report, p. 21

[68] MIT Energy Lab Report, p. 39

[69] Ibid., pp. 51-70

[70] DOE Report, p. 2-11

[71] MIT Energy Lab Report, p. 124

[72] Ibid., p. 125

[73] Westinghouse Report, Exec. Summary, p. 24

[74] Ibid. p. 2

[75] GE Report, see pp. 8-30 to 8-34

[76] DOE Report, 4-47

[77] Ibid., p. 4-46

[78] MIT Report, p. 84

[79] OTA Vol. I, see pp. 410-411

[80] Ibid., p. 411

[81] Westinghouse Report, pp. 4041

[82] DOE Report, p. 7-23

[83] Ibid, p. 6-14 and 6-20

[84] Ibid., p. 6-21

[85] J.H. Beall, OTA, and Solar Energy Intelligence Report, July 14, 1980, quoting meteorologist Charles R. Stearns.

[86] R.J. McDonald, Estimate of National Hydroelectric Power Potential at Existing Dams, U.S. Army Corps of Engineers, July 20, 1977

Bibliography

Angelici, Gary L., and Bryant, N.A. "Solar Potential Inventory and Modellin Remote Sensing Quarterly, Forthcoming

The BDM Corporation, Design of a 100 kW Flat Panel Photovoltaic System at a Washington, D.C. Area Waste Treatment Plant, Albuquerque: U.S. Department of Energy, 1980

Battelle Columbus Laboratories, Photovoltaic Flat Panel Application Experiment: Analysis and Design of a 100-Kilowatt Solar Photoltaic Flat-Panel Power System for a Machining and Metalworking Facility in Columbus, Ohio, Albuquerque: U.S. Department of Energy, 1980

Bechtel National, Inc., Terrestrial Central Station Array Life-Cycle Analysis Support Study, San Francisco: Bechtel National, Inc., August 1980

Bryant, N.A., Urban Solar Photovoltaics Potential: An Inventory and Modelling Study Applied to the San Fernando Valley Region of Los Angeles, Pasadena: Jet Propulsion Laboratory; Abstract, 1979

Carpenter, P.R. and Taylor, G.A., An Economic Analysis of Grid-Connected Residential Solar Photovoltaic Power Systems, Report MIT-EL 78007, Cambridge: MIT Energy Laboratory

Davis, Richard B., "Alternative Power System Economic Analysis Model," JPL 10M 311. 21-105, Pasadena: Jet Propulsion Laboratory, September, 1979

General Electric Corp., Regional Conceptual Design and Analysis Studies for Residential Photovoltaic Systems, Report 7039, for Sandia, Albuquerque, 1979

General Electric Co., Requirements Assessment of Photovoltaic Power Plants in Electric Utility Systems, Report EPRI ER-685-SY, for Electric Power Institute Schenectady, 1978

General Electric Space Division, Regional Conceptional Design and Analysis Studies for Residential Photovoltaic Systems, Final Report 78SDS4239, Philadelphia: General Electric Space Division, September, 1978

Gilbert Associates, A Photovoltaic Flat Panel System for Process Power in Battery Manufacture, Albuquerque, U.S. Department of Energy, March 1980

Jet Propulsion Laboratory, Federal Policies to Promote the Widespread Utilization of Photovoltaic Systems, Volume II: Technical Document, Pasadena: U.S. Department of Energy, February 1980

Jet Propulsion Laboratory, Some Currently Available Photovoltaic System Computer Simulation Approaches, Technical Report 5250-2, Pasadena: U.S. Department of Energy, July 31, 1979

Knowles, R., Berry, R., Solar Envelope Concepts: Moderate Density Applications, Golden: Solar Energy Research Institute, 1980

Milne, M., Adelson, M., Corwin, R., Three Solar Urban Futures: Characterization of A Future Community Under Three Energy Supply Scenarios, Los Angeles: The Urban Innovations Group, April 1979

National Photovoltaic Program, U.S. Department of Energy, Multi-Year Program Plan, Washington: U.S. Department of Energy, June 6, 1979

Pacific Northwest Laboratory, "Export Potential for Photovoltaic Systems," for U.S. Department of Energy/ CS/0078, Washington, DC, April 1979

Ritschard, R.L., Assessment of Solar Energy Within a Community: Summary of Three Community-Level Studies, Washington, DC: U.S. Department of Energy, October, 1979

Tabors, Richard, Photovoltaic Power Systems, Review of Current Market Studies, Working Paper F8-006 WP, Cambridge: MIT Energy Laboratory

Tatum, Jesse, A Parametric Characterization of the Interface Between Dispersed Solar Energy Systems and the Utility Network, M.S. thesis, Cambridge: MIT September, 1978