tion or character of the natural surfactants in the seawater from Aquatron inlet, a result of increasingly stormy weather and the seasonal decline of biological activity in Labrador Current water over this period. These circumstances strongly suggest a parallel between stable microbubble formation and the seasonal occurrence of natural organic particles (*10*).

In an experiment designed to test microbubble stability as a function of time, a population generated on 7 November was maintained at 22°C in the cell and examined periodically for changes in size and number. After 4 hours there were no apparent changes; after 22 hours, while there was little reduction in number, the microbubbles generally were smaller (Fig. 2B), and bubbles that previously were aspherical had become less so. Thirty hours after formation, few visible microbubbles remained.

Because a significant proportion of the bubbles produced by a breaking wave at sea are smaller than 200 μm in diameter (*11*), and because small bubbles dissolve in saturated seawater as a result of surface tension alone, the number of stable microbubbles that can be produced by breaking waves may be very large and show strong periodicity.

The presence of stabilized microbubbles in various numbers in the marine environment requires investigators of oceanic bubble populations to consider not only the sea state, but the season, the recent history of the sea state, the atmospheric pressure, and other possible bubble sources such as local surf. In particular, bubble populations determined acoustically must be interpreted with regard for the effect of stabilizing surfaces on bubble resonance frequencies. This effect, as Medwin (*12*) points out, can result in an overestimation of bubble size from acoustic data.

While we demonstrated that stable microbubbles do form in seawater, we examined only a relatively small number of such bubbles during a short period. Hence, our data should be considered only as a starting point for continuing study.

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Solar Photovoltaic Power Systems: Will They Reduce Utility Peaking Requirements?

Abstract. *From an analysis of the long-run electric generating requirements of several representative utilities, it is concluded that the energy supplied by solar photovoltaic power devices will displace primarily base-load, and to a lesser extent intermediate, generating plants, even at relatively modest penetrations corresponding to several percent of the utility peak load. Attaching photovoltaic devices to the utility grid will not yield significant fuel oil savings over the long run, in which utilities approach the economic optimum generating mix, and will increase peak plant requirements. Utility capacity and fuel savings of photovoltaic devices are reported both for the case without storage and for the case in which the utility has access to load-leveling storage.*

Solar photovoltaic (PV) power systems, capable of converting incident sunlight directly to electricity, have become the subject of an intensive national research and development effort. Although costs of PV arrays are currently high, there is considerable optimism among researchers that system costs will be reduced significantly over the coming decade. If development efforts are successful, PV devices may one day be capable of generating electricity at costs competitive with conventional utility power.

Given the intermittent nature of solar radiation and the high cost of electric storage, most applications will require addition of an auxiliary power supply to supplement the PV system output and ensure that load is reliably met (*1–3*). Having the electric utility provide this backup power is a major rationale for attaching PV devices to the electric grid. For grid-connected PV systems, available solar power will be either delivered to a local load or exported back to the utility system, in both cases displacing power that would otherwise be supplied by the utility's conventional generating units. Should PV system penetration levels become significant, the aggregate output from the PV devices will cause major changes in the shape and magnitude of the utility load curve and, in the long run, directly affect utility capacity, fuel, and operating requirements.

This report summarizes findings of a recent study that evaluated the long-run

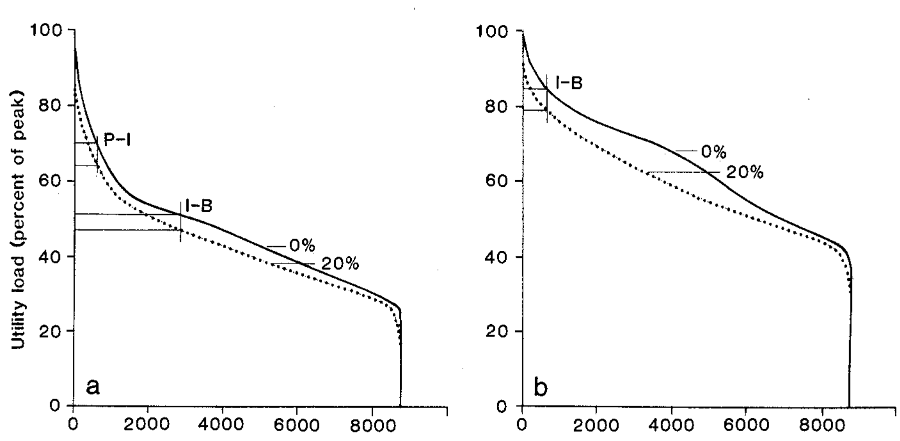

Fig. 1. Annual load duration curves, or cumulative frequency distributions, for 1975 for service areas in the (a) Mid-Atlantic and (b) Southwest regions. Loads are normalized to the maximum no-solar yearly load. Load duration curves are shown for 0 percent solar and for an aggregate (rated) PV capacity equal to 20 percent of the peak utility load. Vertical lines *P-I* and *I-B* refer to the breakpoints between most efficient operation of peak, intermediate, and base-load plants. For the Southwest utility only the breakpoint between coal and oil generation (*I-B*) is shown.

impacts of PV devices on conventional electric supply in several representative utility service areas. In particular, it examined the impact of PV devices on long-run utility fuel consumption. Extending earlier studies, we evaluated PV devices both for the case of no storage and for the case in which the PV devices compete with load-leveling utility storage (*4, 5*). A utility cost-allocation method was applied to derive the economic optimum generating and transmission plant capacity and mix as a function of the PV system penetration level, and to determine the long-run capital, fuel, and operating savings of the PV devices. Since the estimates are long-run, they pertain to planning horizons beyond the construction time of projects to which utilities are already firmly committed.

Four utility service areas that span a range of climatic and load conditions were evaluated. In this report we present detailed results for two service areas, located in the Mid-Atlantic and Southwest regions. [Results for all four sites are given in (*6*).] The Mid-Atlantic service area is sharply summer-peaking; the Southwest service area has roughly equal summer and winter peak loads and has an average annual insolation about 50 percent higher than the Mid-Atlantic area. The "design year" of synoptic weather and load data used in the analysis was 1975. Hourly temperature and insolation data were the SOLMET data (*7*). Hourly system load data were obtained directly from the individual utility companies.

We simulated the performance of a residential, flat-panel, passively cooled silicon array with 12 percent efficiency. Accounting for transmission and distribution line losses, reductions in the utility's system load were determined over the full annual (8760 hours) cycle for aggregate (rated) PV device capacities up to 30 percent of the generation peak load. At the 30 percent penetration level, the PV devices displaced 12 and 15 percent of the total electricity generated by the Mid-Atlantic and Southwest utilities, respectively.

The degree of overlap of the PV output with peak utility loads varied significantly among utilities studied. However, in general, the utility loads, driven by air-conditioning, peaked in late afternoon, well after the time of maximum PV system power output. Qualitatively, the PV systems tended to narrow the width rather than flatten the utility peak loads. As a consequence, they had only limited peak

Table 1. Breakdown of utility savings of PV systems without storage.

Installed PV system capacity		System load reduction (MWe)	Generation peak capacity reduction† (MWe)	Annual utility load factor‡	Average utility savings (1980 $/kW_r$)						Electricity displacement by plant type (kWh/kW_r-year)‖				Utility oil displacement (bbl/kW_r-year)
					Capital		Variable								
MW_r*	Percent of peak load				Generation	Transmission	Fuel	O&M§	Cycle	Total	Peak	Intermediate	Base	Total	
Mid-Atlantic area															
120	3.3	83	96	0.472	345	155	380	70	10	960	46	869	771	1686	0.11
375	10.3	213	250	0.475	325	130	345	60	5	865	24	503	1159	1686	0.06
750	20.7	273	323	0.463	255	85	330	55	0	725	11	330	1345	1686	0.03
1125	31.1	284	342	0.445	215	60	310	50	−15	620	11	−58	1733	1686	0.03
Southwest area															
18	3.1	17	0.2	0.655	145	10	210	50	−10	405	−22	−36	2712	2654	−0.10
60	10.2	40	5.8	0.658	155	30	190	50	−30	395	−7	−103	2764	2654	−0.16
120	20.5	41	20.4	0.630	160	35	190	50	−40	395	−6	−109	2769	2654	−0.17
180	30.7	41	22.7	0.600	115	30	210	50	−45	360	−3	−67	2724	2654	−0.10

*MW_r, megawatts rated. †Capacity reduction over 0 percent solar case, including reserve margin requirements. ‡Annual load factors for 0 percent solar are 0.47 and 0.65 for the Mid-Atlantic and Southwest utilities, respectively. §O&M, operating and maintenance. ‖Includes electricity losses in transmission and distribution. Negative value signifies increase in electricity generated by given plant type.

Table 2. Breakdown of utility savings of PV systems with utility storage.

Installed PV system capacity		Utility storage characteristics				Generation peak capacity reduction§ (MWe)	Average utility savings (1980 $/kW_r$)						
							Capital			Variable			
MW_r	Percent of peak load	Storage system*	Discharge period (hours)†	Storage capacity (MWh)	Ratio of storage to PV capacity (kWh/kW_r)‡		Generation	Transmission	Storage	Fuel	O&M	Cycle	Total
Mid-Atlantic area‖													
375	10.3	BAT	4	740	−0.59	195	285	100	85	330	60	0	860
750	20.7	BAT	4	1140	0.24	398	285	105	−35	330	55	0	740
375	10.3	PHS	6¶	2580	−1.47	138	240	70	75	315	60	0	760
750	20.7	PHS	6	2700	−0.57	268	230	70	30	315	55	−5	695
Southwest area‖													
60	10.2	BAT	2	100	−0.16	12	215	40	−30	185	50	−15	445
120	20.5	BAT	2	100	−0.08	21	165	35	−15	215	50	−15	435
60	10.2	PHS	6¶	540	−2.00	7	−20	20	105	355	60	5	525
120	20.5	PHS	6	600	−0.51	23	70	35	25	310	55	0	495

*Battery (BAT) costs are $60 per kilowatt and $80 per kilowatt hour; PHS costs are $200 per kilowatt and $14 per kilowatt hour. †Optimum determined from among discharge periods of 2, 4, 6, 8, and 10 hours. ‡Storage capacity in excess of that for the 0 percent solar case, divided by installed PV system capacity. §Capacity reduction over 0 percent solar case, assuming an optimum storage unit before and after PV systems are added. ‖Storage capacities for 0 percent solar are: battery (960 MWh) and PHS (3130 MWh) for the Mid-Atlantic utility, and battery (90 MWh) and PHS (660 MWh) for the Southwest utility. ¶For PHS the optimum discharge period is relatively flat between 6 and 10 hours.

shaving capability, particularly at high penetration levels.

Figure 1 shows the effect of the PV system output on the utility annual load duration curve for an aggregate PV system capacity equal to 20 percent of the utility peak load. The vertical lines define the "breakpoints" between most efficient operation of base-load, intermediate, and peak plants (for example, base-load plants for hours of operation greater than *I-B*); intersection of these lines with the load duration curve specifies the long-run capacity and energy output of each plant type. Figure 1 exhibits the behavior suggested in (*8*) and (*9*), namely, PV devices displace base-load generation and shift the plant mix to a higher percentage of peak and intermediate units.

Detailed estimates of the generating plant mix were derived by using the Argonne capacity allocation model SIMSTOR (*10*). The model incorporates an hourly production costing method that observes operating constraints such as scheduled and forced outages and the cycle time of each type of generating unit.

Plant cost and operating data used in the analysis refer to new plants and are representative of recent experience in each service area. Base-load plants are coal-fired in both utilities. Intermediate plants are coal-fired in the Mid-Atlantic region and oil combined-cycle units in the Southwest. Low-sulfur western coal available to the Southwest utility is priced at \$1 per 10^6 Btu's, well below the delivered coal price of \$2.30 per 10^6 Btu's for the Mid-Atlantic utility. Because of the extremely high price of fuel oil, \$36 a barrel, the percentage of energy supplied by oil-fired plants in the optimum generating plant mix is extremely small. Further real price increases in fuel oil have no significant effect on the findings.

A breakdown of utility savings with the PV devices is given in Table 1. The variable savings are expressed as capitalized values having a net present worth equal to the net present worth of the variable savings over an assumed 30-year PV system lifetime. Because savings are calculated in a utility cost-accounting framework, the approach is conceptually equivalent to assuming utility ownership of the PV devices. Unit capital cost of the PV system must be less than utility savings to achieve a net economic benefit.

For the Mid-Atlantic utility, savings decrease significantly with installed PV system capacity, primarily because the PV devices become less effective in shaving utility peak loads. The decrease in generating capacity savings is partially offset by a shift from utility base-load plant to less capital-intensive intermediate and peak plants. Fuel savings decrease because of a greater displacement of base-load energy.

Despite more favorable insolation conditions, savings for the Southwest utility are well below comparable values for the Mid-Atlantic utility. Fuel savings are lower because of the availability of low-price coal for the bulk of electricity generation. Capacity savings from peak shaving are also lower because the Southwest utility is constrained to schedule plant maintenance year-round; as a consequence, reductions in peak loads do not yield equal reductions in generating and transmission capacity. Generating capacity reductions exhibit irregular behavior because of the effect of discrete plant size (plant "lumpiness") on maintenance scheduling. Costs of plant cycling increase sharply with PV capacity.

Table 1 also presents a breakdown of the electricity displaced by the PV devices. Unlike short-run fuel savings, the predominant long-run effect is to displace energy from coal-fired base-load and intermediate generating plants. Even at penetrations of several percent of the peak load, the PV systems have an insignificant, and for the Southwest utility a negative, effect on reducing utility oil consumption. Two factors account for this behavior: (i) over the annual cycle the power output from the PV systems resembles operation of an intermediate plant slightly out of phase with the utility load, and (ii) in the optimum generating plant mix, the high price of fuel oil severely limits its use.

Table 2 gives a breakdown of utility savings of the PV devices for the case in which the utility has access to storage, either substation batteries or pumped-hydro storage (PHS). We simulated storage in a load-leveling mode, with units discharged during peak load periods and charged with off-peak electricity. Optimum storage capacities and discharge periods were determined over the range of PV device penetration levels for storage costs of \$60 per kilowatt and \$80 per kilowatt-hour for batteries and \$220 per kilowatt and \$14 per kilowatt-hour for PHS. Conceptually, the approach amounted to considering storage as one of the technologies in the utility plant mix.

The change in storage capacity following addition of the PV systems was generally small, indicating that short-duration storage and PV devices do not directly compete for utility benefits. In most cases a slight decrease in storage capacity occurred at low PV capacities, followed by an increase at higher penetrations. Narrowing of peak loads at high PV penetrations increased the need for shorter-duration storage in the Mid-Atlantic utility.

In the Mid-Atlantic utility, total PV system savings for the case in which the utility had access to batteries were comparable to those without storage. With PHS the savings were lower, because the longer-duration PHS more completely leveled peak loads, limiting capacity savings of the PV devices. Fuel savings were primarily due to displacement of base-load energy. In the Southwest utility, total PV system savings were higher with storage. By reducing peak loads in spring and fall, storage permitted additional maintenance to be scheduled during these seasons. As a consequence, reductions in summer peak loads attributable to the PV devices yielded greater capacity savings. The effect of plant lumpiness on maintenance scheduling produced the sharp swings in the tradeoff between generating fuel and capital savings for the case with PHS.

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