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Technical Report

An Overview of Photovoltaic and Battery Applications

by

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I. Introduction

Solar energy is pollution-free, and politically and economically stable. Its source does not, on whim, change its availability or its price. Its reserves are essentially inexhaustible and its users can collect it at no direct cost. Its disadvantages are its diffuse nature and the fact that it is sometimes unavailable in two ways: a predictable one (at night) and an unpredictable one (due to cloud cover).

For these reasons, solar energy is attractive as an energy source, and especially so from an environmental standpoint as a potential replacement for the consumption of coal and petroleum. Coal and petroleum generate significant quantities of particulate and SO_2 emissions when burned in stationary uses, and petroleum used in transportation vehicles generates large amounts of VOC and CO emissions, even at today's levels of automotive emission control.

II. Energy Uses and Fuel Sources

Two-thirds of all energy consumed in the U.S. goes to heat-- for stationary uses, or propulsion-- for transportation; the remaining third is consumed by power utilities to generate electricity. The distribution of this energy use among major user sectors is shown in Table 1, with liberal rounding for clarity.

Table 1

Distribution of U.S. Fuel Energy by User (percent)

User	Consumed by User As Fuel	Consumed by Utilities to Generate User Electricity
Industrial	25	10
Residential	10	15
Commercial	5	10
Transportation	25	
TOTAL	65	35

Accounting for the fuel mix consumed directly by the users, and the mix of fuels used for utility power generation, and apportioning that among the using sectors, the distribution of energy fuels is as shown in Table 2, again with liberal rounding.

Table 2

Distribution of Source Fuel Energy
Among Using Sectors (percent)

User	Coal	Oil	Gas	Other
Industrial	10	11	11	4
Residential	7	3	7	4
Commercial	6	2	5	3
Transportation		27		
TOTAL	24	42	23	11

The intersection of Tables 1 and 2 for coal and oil is given in Table 3. It shows that a new energy technology such as solar would have the most impact on coal use if applied to electrical power generation, and on oil use if applied to transportation.

Table 3

Coal and Oil Use, by
Purpose and User (percent)

	Percent of Coal Use	Percent of Oil Use
Electricity:		
Industrial	30	low
Residential	30	low
Commercial	25	low
Fuel:		
Industrial	15	25
Residential	low	5
Commercial	low	5
Transportation	low	65
TOTAL	100	100

Although the industrial use of coal and oil as fuels is not insignificant, most of it is for process heat, only half of which is amenable to solar heating. The other half of process heat energy needs could use solar thermal energy: about half of that involves low temperature processes which could use simple flat panel solar collectors; the balance goes into high temperature processes which would require solar concentrators. Thus the industrial sector's fuel use is not really very fertile ground for simple (non-concentrating) solar thermal technology.

The use of oil for residential and commercial heating is not very significant at the national level (10 percent of all oil use). Energy for heating is significant to individual homes and businesses, however, with space heating accounting for some 40 percent of their total energy consumption. Home and business space heating energy comes nearly half from natural gas, about one-third from oil, and most of the remainder from electricity. Hence solar thermal space heating could provide consumer benefits, but not much environmental benefit. It would reduce the consumption of natural gas, making more of it available for other purposes.

III. Solar Electric Power

Table 4 illustrates that large-scale electrical energy needs could be met using modest fractions of land area, if solar energy could be collected and converted to electricity at an overall efficiency of 10 percent.

Table 4

Solar Power Area Requirements vs.
Electricity Needs, Large-Scale Areas

	Total Annual Solar Energy, Gigawatt-hrs*	Annual Electrical Use, Gigawatt-hrs	Solar Array Area: % of Total	Acres
U.S.	15 billion	2.5 million	0.17%	3.8 million
Texas	1.2 billion	215,700	0.17%	280,000
California	790 million	190,300	0.24%	240,000
Michigan	170 million	79,300	0.47%	170,000
Rhode Island	3.7 million	5,900	1.58%	11,000

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* horizontal flat plate

Things Smaller Than Rhode Island

For smaller areas, electrical energy use is more concentrated, of course. Table 5 is a worksheet which shows typical annual energy requirements per unit floor space for five types of buildings; note that the electrical energy consumption density at this scale is in the 5 to 25 kWh/sq ft range.

Photovoltaic arrays sized to meet these buildings' electricity needs would have areas of the same order of magnitude as the floor space. Solar thermal collector areas sized to meet heating needs are smaller.

In sunnier areas at lower latitudes, air conditioning requirements will increase electrical demands, but energy available from photovoltaic arrays will increase also; the reverse is true for less-sunny locales at higher latitudes.

Table 5

Annual Energy Required Per Sq Ft Floor Space: Buildings

Type of Building	Electricity, kWh/ft^2	Heat, Btu/ft^2
Residence	6.3	80,000
Warehouse	6.1	50,000
School	12.2	100,000
Wholesale/Retail	21.7	150,000
Hospital	23.9	200,000

Photovoltaic array size* needed to furnish electricity needs (assuming 10 percent overall conversion and power conditioning efficiency):

Residence	42% as large as floor space
Warehouse	41% as large as floor space
School	81% as large as floor space
Wholesale/Retail	145% as large as floor space
Hospital	159% as large as floor space

Solar thermal collector array size* needed to furnish heat needs (assuming 80 percent collection/distribution efficiency):

Residence	20% as large as floor space
Warehouse	12% as large as floor space
School	24% as large as floor space
Wholesale/Retail	37% as large as floor space
Hospital	49% as large as floor space

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* Based on a nominal U.S. solar insolation of 150 kWh/ft^2, or 512,000 Btu/ft^2, on a horizontal flat surface.

Table 6 illustrates this kind of regional variance for a more or less typical residential photovoltaic system (one without energy storage); it also illustrates how the purchase of night-time energy from the power grid can be offset by energy generated in excess of the house's daytime needs. It is worth noting that a PV-powered house or business thus has a double benefit: it does not contribute to daytime peak load demands on the grid, and in fact, can furnish power into the grid at that time.

Table 6

Solar PV Residential Energy Balance, kWh/Year
(same Solar Array all sites, approx. 700 sq ft)

	Fresno CA	Madison WI	Washington DC
Electricity requirements:	8,500	9,420	8,140
Electricity generated	12,710	9,420	9,440
Consumed by house	4,590	3,600	3,520
Sold to Utility, day	8,120	5,820	5,920
Bought from Utility, nite	3,910	5,820	4,620
Net bought/sold	4,210 sold	even	1,300 sold

Things Smaller Than a House

Photovoltaic powering of a realistic car extends into the range wherein power demand is too concentrated for the area that can be used for solar panels, as shown in Table 7. Even using solar power just for vehicle air conditioning is not practical.

Table 7

Vehicle Energy Requirements vs. Photovoltaic
Panel Capacity, Small Sedan (watt-hours/mile)

Electrical energy required for vehicle propulsion:	300
Electrical energy required for air conditioning-- full capacity:	65
-- summer avg:	30
Electrical energy available* from photovoltaic panel on roof:	8

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* 100 watts/sq ft solar insolation, 10 percent conversion efficiency, 20 sq ft available on roof.

Although running cars solely by means of solar cells *on* the cars shows no early potential for practicality, solar power *for* cars can be quite feasible, by using battery-powered cars and recharging them from stationary solar arrays at the home or workplace. Table 8 shows that a solar array of reasonable size can handle the energy requirements of a reasonable car operating at a reasonable usage intensity. Note that the photovoltaic array to run the car is about half the size of the one (Table 6) to run the house.

Another way to power vehicles from a photovoltaic base station would be to use the electric power to generate hydrogen via the electrolysis of water, and use the hydrogen as a clean fuel for combustion engines or fuel cells in the vehicles.

Table 8

Battery Electric Car and Solar Recharger

Vehicle Energy Requirement:	0.300 kWh/mile from battery; 0.460 kWh/mile into charger
	5,040 kWh/year at 30 miles/day
Solar Array:	at 150 kWh/ft^2 insolation, 10 percent efficiency,
	340 sq ft

Utility Compatibility and Cost

It would appear that the best niche for solar photovoltaic power generation is electric utility use, and the best utility niche is peaking power generation rather than base load power. Peak power demand for utilities occurs in the summer in the afternoon, just at the same time that the solar insolation, and therefore solar array output, is also at a maximum. Some parts of the country receive nearly 60% of their annual solar energy during the five peak power demand months. Such an application, without the cost burden of night-time energy storage, is a natural match between solar photovoltaic power and utility power needs.

Table 9 summarizes the magnitude of installed capacity of U.S. utilities. The typical capacity of peaking power units is that of new plants fueled with natural gas or petroleum; all of the new gas- or oil-fired plants in 1987 were combustion turbine or internal combustion units.

Table 9

U.S. Electric Utility Plant Capacity, Summer megawatts, 1987

	Total Capacity:		Avg. Plant Capacity:		
Fuel	All Plants	New Plants	All Plants	New Plants	Capacity Range, New Plants
Coal	292,600	2,100	230	354	1.0 to 800
Gas	118,200	200	59	43	2.4 to 65
Nuclear	93,600	8,300	875	1,034	833 to 1,259
Hydro	89,700	270	26	15	0.3 to 207
Oil	76,100	50	23	2	0.1 to 7
Other	4,000	--	35	--	--

In order to compare the costs of a potential solar photovoltaic powerplant to those of current powerplants, the typical capital costs and operating costs for current peaking power units were determined; these are given in table 10, with costs for base load plants also shown.

Table 10

Utility Powerplant Costs

	Peaking	Baseload
Fuel	Natural gas	Coal
Size	50 mW (gas turbine)	1000 mW (two 500 mW boilers)
Capital cost	\$300-\$340/kW	\$1100-\$1360/kW
Operating and Maintenance cost	1.355 ¢/kWh	0.429 ¢/kWh
Fuel	2.52 ¢/kWh	1.52 ¢/kWh
Total Operating	3.88 ¢/kWh	1.95 ¢/kWh

These are nominal values. Electricity costs vary significantly across utilities. Some operating costs run much higher, such as 27-53 ¢/kWh at PG&E and 37 ¢/kWh at Southern California Edison on hot days, and 18 ¢/kWh as the summer daytime average for large residential customers of Long Island Lighting.

In evaluating the capital cost of a solar photovoltaic powerplant, a common methodology has been to separate the solar cell module cost from the balance of system (BOS) cost. The BOS cost is everything needed for the powerplant, other than the solar cell modules: the land, the frames to hold the solar cell modules, the power conditioning, etc. It is important to know what the BOS cost is so that the effect of solar cell module price can be put into perspective. BOS costs are usually expressed as dollars per unit area of solar array, so the cost per kW of power capacity is dependent on conversion efficiency of the array. BOS costs were the subject of a number of in-depth studies in 1984; these reports show BOS capital costs ranging from $700 to $1,200 per kW (in today's dollars) for non-tracking flat plate arrays and 10% conversion efficiency..

Current estimates of solar module capital costs are in the range of $700 to $1,100 per kW, for thin film amorphous silicon cells, the most mass-producible, low cost cells in production in quantity today. Hence, the total capital cost of a complete photovoltaic system appears to be in the $1,400 to $2,300 per kW range. The operating and maintenance costs of solar photovoltaic power systems were estimated in 1984 at 0.54¢/kWh to 1.7¢/kWh (today's dollars).

IV. Energy Storage For Solar Photovoltaic Systems

What about when the sun goes down? The storage of solar-derived electricity for use when it is dark or cloudy can be done with thermal storage, hydrogen generation, pumped water, pneumatic or hydraulic storage, superconducting magnetic energy storage, flywheels, or batteries. For this report, we have selected batteries as the example storage media. For stationary power generation, either for utility power or for home use, cost effectiveness is the major concern, with less emphasis on power or energy per unit weight.

Batteries for a utility application were discussed in the July/August 1989 issue of the EPRI Journal. Costs cited for a 10 mW, 3-hour plant are $425/kW for sodium-sulfur batteries, $425-600/kW for a similar plant using zinc-bromine batteries, and $635/kW for lead-acid batteries.

For home application, the battery and power conditioning issues are different since the end-use voltage, 120 or 240 volts AC, is different. A house unit might be able to power its own air conditioner during the day, but excess energy would have to be stored to run the air conditioner at night if the unit were to be totally solar powered. A storage approach might be to use the same power conditioning system that is used for the home and run the battery charger from that system. The cost of such a system would then depend on the cost of the charger, the batteries, and the power conditioning needed to make the battery output usable.

Any excess power that couldn't be utilized by the then current load or the battery could be sold back to the utility, used for hot water heating, or other uses.

Using data from the EPRI Journal article and assuming that the system needed to power an air conditioner overnight requires about 30 kWh, then a storage system cost of roughly $3,000 would be projected.

V. Batteries for Electric Cars

Two parameters of critical interest for batteries for electric cars are: specific power and specific energy. Specific power (watts/lb) can be related to the acceleration capability of the electric car, and the range of an electric car is a strong function of a battery's specific energy (watt-hours/lb).

One way to look at the capabilities of batteries is to use a Ragone plot in which specific power is plotted against specific energy. Figure 1 is based on the one in the JPL report entitled "Should We Have A New Engine?", but we have modified it to show where the gasoline-fueled conventional engine would be.

On the plot, higher and farther to the right is better. The figure shows that there is a substantial difference between batteries of different types and that none of the batteries shown match the energy density of the conventional engine using gasoline as the fuel. The log-log nature of the plot tends to visually reduce the differences. For example, gasoline is hundreds of times better than the lead-acid battery shown. It is no wonder that battery cars accelerate slowly and have limited range capability.

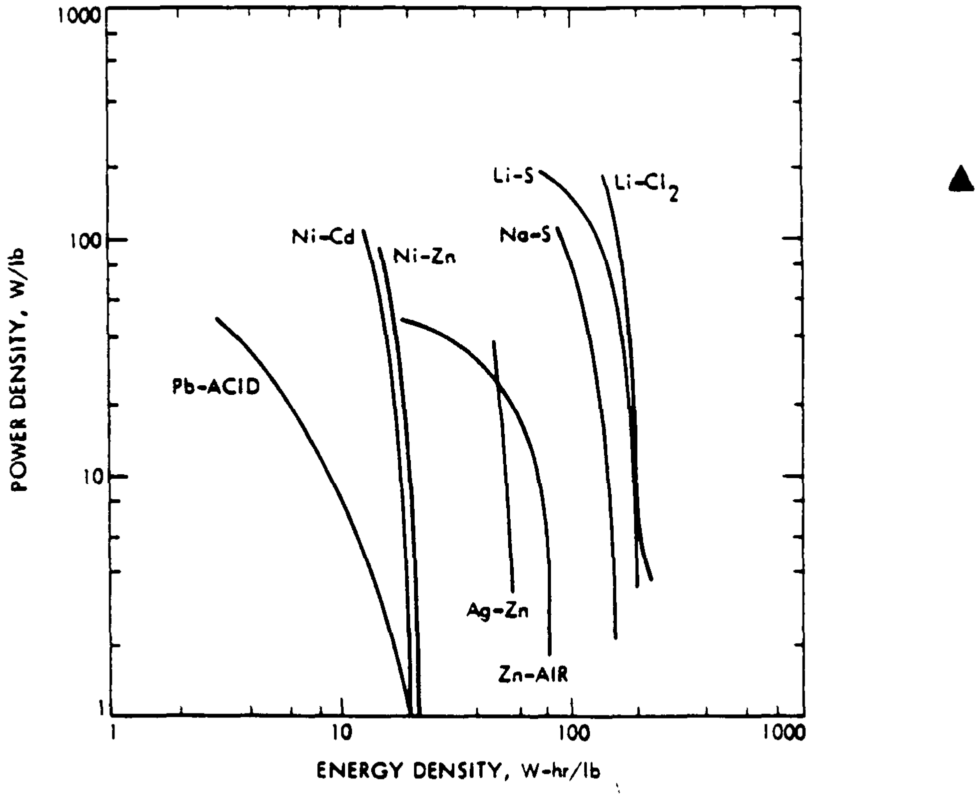
The batteries for electric cars can represent a substantial portion of the car's cost, between 25 and 50 percent depending on the battery type, according to Hamilton's report and the Claremont report. A summary of some characteristics of batteries considered potentially applicable is shown in Table 11. Most of these values were excerpted from the Claremont report.

Batteries that are substantially better in one or more of the performance indices in Table 11 would be considered attractive candidates for electric car use. It should be noted that some of the best current battery technologies, from the standpoint of high watt-hour/lb capability, can release hazardous and/or toxic materials into the environment. We are not sure these problems are receiving sufficient attention by electric vehicle designers and proponents.

Figure 1

Ragone Plot: Battery Power Density vs. Energy Density

(Triangle Indicates Today's Gasoline-fueled Auto Engine)



Source: JPL, "Should We Have a New Engine?

Table 11

Battery Characteristics

Battery Type	Specific Energy (w-hr/lb)	Specific Power (w/lb)	kW-hr per cu ft	$/kWh	Safety/ Toxicity Concern?
Na-S	41-75	45-80	3.1-9.9	120-130	Yes
Li-Metal Sulfide	36-64	45-64	3.1	90-130	Yes
Ni-Metal Hydride	33	84	--	60	No
Zn-Cl	27-32	--	2.1	95	No
Zn-Br	25-30	36-41	2.4-2.8	75-80	No
Ni-Fe	20-25	36-50	2.4	125-400	No
Pb-Acid	20-23	27-47	2.5-3.0	70-95	Yes
Ni-Cd	11-26	36-91	--	300 plus	Yes

VI. Other Vehicle Applications

Solar Photovoltaics

Given that photovoltaic power tends to be low in watts generated per square foot it is of interest to investigate how photovoltaic power could be used for mobile applications.

One attractive application is for ventilation. When a car is parked in the sun on a hot day, interior temperatures can exceed ambient temperatures by a substantial amount. On a 100°F day, interior temperatures can reach 120°F or more. Such hot interior air sets the maximum design capacity point for automotive air conditioning systems, since performance targets are usually based on "pulldown," i.e., reducing the vehicle interior temperature to a comfortable level in a short period of time. If a way could be found to reduce interior heatup while parked, then the air conditioner could potentially be downsized, yielding cost and/or weight and/or fuel consumption benefits.

Solar photovoltaic ventilation units that can be retrofitted to cars are available for sale today at a retail price of $30-35. If they were to be integrated into the design of the air-handling system of the car and produced in car-type production volumes the cost would probably fall to somewhere in the $10 to $15 range.

Another possible application is for powering the vehicle air conditioner itself. As shown earlier, solar photovoltaics cannot provide enough power for current technology automotive air conditioners; however, current belt-driven compressor air conditioners were not designed to utilize solar photovoltaics, and some air conditioner R&D could possibly yield more promising results. The match between the problem (hot cars caused by sun loading) and the possible solution (solar photovoltaics working best under the same conditions) is too close a match to ignore.

It is likely that solar photovoltaics could be used to assist in battery charging. This could reduce the charging power from the engine substantially, but not much has been reported in that area.

Advanced Batteries

Advanced batteries have applicabilities in addition to the obvious potential for electric car or hybrid car propulsion. An advanced battery with greater power density could replace the current starting, lighting, and ignition (SLI) battery and achieve a weight savings. To the extent that the package could be smaller, that would also be an advantage. Alternatively, the same weight or volume could be used to provide more electrical power or energy, and given the trends in increasing electrical power demand for cars, this is the route that we expect will be taken.

VII. Conclusions

1. As concerns increase over greenhouse gas emissions due to the consumption of fossil fuels to generate electricity, solar photovoltaic power will become more and more attractive.

2. Solar photovoltaic power has a natural match with peak load electrical power demands caused by air conditioning usage.

3. The environmental benefits of solar photovoltaic power should be assessed by comparing its negligible emissions to the emissions of particulate, SOx, NOx, VOC, CO, and toxics from utility peak load power plants, not base load plants.

4. Why aren't solar peaking power units in widespread use now? Because no one has invested in high volume solar cell panel production capacity to make economy-of-scale reductions in panel costs needed for cost-competitiveness.

5. When considering advanced technology batteries for power or transportation needs, the safety and environmental impact aspects of the battery materials and designs may need closer scrutiny than it appears is being given.

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