CHAPTER 5

BATTERY COSTS IN SOLAR PHOTOVOL TAlC SYSTEMS

Depending upon the size and type of solar photovoltaic system, battery subsystem costs may vary from 10 percent to 50 percent of the total system cost. Precise prices can only be obtained through the competitive bidding process. Advertised list prices are not likely to be timely because material prices fluctuate with market forces. For estimating purposes this study has used published Government Services Administration prices (late 1980) including the mean delivery charge to Zone 1 locations in the United States. These prices include cell, module, electrolyte and intercell connector hardware and are representative of a number of suppliers.

Battery energy costs are expressed in dollars per battery subsystem and dollars per kilowatt-hour ($/kwh) of energy delivered at the specified rate and temperature. These costs vary depending upon the following conditions:

- Discharge energy costs normally decrease with increasing cell capacity in a line of cells of similar design
- Discharge energy cost increases with increasing chargel discharge current and decreasing charge/discharge time

Discharge energy cost rapidly increases with decreasing charge/discharge temperatures below 25^0C

- Above 25^0C, discharge energy costs decrease until energy loss from side reactions becomes significant (around 40^0C), then costs increase

- Increasing reserve energy in a battery design will increase single energy costs but may decrease total lifetime energy cost.

Stored energy costs are more difficult to assess. Some applications require relatively few cycles, but wet float lives of 15-20 years are specified, and the battery must be able to deliver its rated capacity at any time. For systems of this type the annual cost of stored energy is sometimes a battery subsystem rating factor. The lowest cost battery will be the battery with the lowest initial price and the longest service time. Other applications demand continuous cycling, and the stored energy output accumulated over all cycles. As an example, consider the relative costs of initial single cycle vs. accumulative cycle energy costs in an automotive starter-light~ignition battery, a golf cart battery and an industrial motive power battery:

Battery Type	Initial Purchase Price $/kwh	Cycle Life	Stored Energy Cost $/kwh/cycle (1981 $)
SLI Battery	80	200	.40
Golf Cart Battery	80	500	.16
Industrial	130	2000	.065

The particular application, the load, and the duty cycle will determine discharge energy costs summed over the battery life. Other associated costs can also become significant in some applications: i.e., maintenance cost, installation cost and replacement cost. Trade-offs of initial price vs. overall battery life costs can best be made by a team effort between the manufacturer's sales and application engineers and the solar PV system designer.

As an aid to the system designer, representative cell, module and battery prices are shown in tables to follow. Estimates of energy costs for a single deep discharge of rated capacity are given; and where the applicable cycle life data can be estimated, stored energy costs in dollars per kilowatt-hour per cycle are calculated.

LEAD-ACID SYSTEM ENERGY COSTS

Table 5-1 gives cell discharge rate and temperature, energy outputs, and delivered energy costs for a line of lead-calcium batteries with pasted flat plates (5-1). These batteries are for float applications and have a 20 year life expectancy. Their annual delivered energy cost at the 8-hour rate ranges from $9-20/kWh per year of life. A typical application would require no more than 1-2 rated capacity discharges per year and the remaining cycles are random depth, normally less than 20% of rated capacity.

TABLE 5-1

Energy Output and Delivered Energy Cost
50-200 Ah Pasted Flat Plate Lead-Calcium Batteries

Nominal 8-Hour Capacity to 1.75V	Discharge Temperature	Discharge Rate	Energy Output to 1.75V	Delivered Energy Cost (1981 $)
Ah	°C	h	Wh	$/kWh
50	25	500	371	202
(2-cell module)		8	189	396
		3	144	521
		1	99	758
	0	500	278	269
	-18	500	148	507
100	25	500	784	171
(3-cell module)		8	564	238
		3	431	311
		1	301	445
	0	500	88	228
	-18	500	314	427
200	25	500	1568	128
(3-cell module)		8	1128	177
		3	860	233
		1	603	332
	0	500	1176	170
	-18	500	627	319

Table 5-2 gives typical discharge rate, temperature and delivered energy costs (in 1981 $) for larger cells, (1020-3700 Ah) of the same float type, 20-year life, lead-calcium pasted plate construction (5-2). These cells are also for standby service, and cycling service is limited to 2 deep cycles per year plus standby cycles normally less than 20% depth of rated capacity. Their annual delivered energy cost ranges from $7-9/kWh per year of service .

TABLE 5-2

Energy Output and Delivered Energy Cost
1020-3700 Ah Pasted Flat Plate Lead-Calcium Batteries

Nominal 8-Hour Capacity to l.75V	Discharge Temperature	Discharge Rate	Energy Output to l.75v	Delivered Energy Cost
Ah	^{0}C	h	wh	$/kwh (1981$)
1020	25	500	5472	122
(2 cells in one jar)	25	8	3667	182
	25	3	2680	249
	25	1	1567	425
	0	500	4164	160
	-18	500	2188	304
1850	25	500	5350	92
(single cell)	25	8	3490	141
	25	3	2460	200
	25	1	1385	355
	0	500	4030	122
	-18	500	2140	229
2740	25	500	7086	106
(single cell)	25	8	4780	157
	25	3	3513	213
	25	1	2080	361
	0	500	5320	141
	-18	500	2835	265
3260	25	500	8345	114
(single cell)	25	8	5900	162
	25	3	4340	220
	25	1	2625	363
	0	500	6260	152
	-18	500	3340	286
3700	25	500	9300	123
(single cell)	25	8	6990	163
	25	3	5190	220
	25	1	3113	366
	0	500	6975	163
	-18	500	3720	306

TABLE 5-3

Energy Output and Delivered Energy Cost
50-200 Ah Pasted Flat Plate Lead-Antiu~ny Batteries

Nominal 8-Hour Capacity to 1.75V (1)	Discharge Temperature	Rate	Energy Output to l.75v	Delivered Energy Cost
Ah	^{0}C	h	wh	s/kwh (1981$)
50	25	500	249	301
(2-cell module)	25	8	191	393
	25	1	96	781
	0	500	187	401
	-18	500	100	750
100	25	500	788	170
(3-cell module)	25	8	573	234
	25	1	282	475
	0	500	591	227
	-18	500	315	425
200	25	500	1576	127
(3-cell module)	25	8	1146	175
	25	1	574	348
	0	500	1182	169
	-18	500	630	317

Tables 5-3 and 5-4 give the same data for pasted flat plate lead-antimony cells plus additional energy output as a function of operating temperature (5-4). Delivered energy costs are comparable for lead-calcium and lead-antimony type cells tested under similar conditions. Their wet lives are estimated to be 18-20 years. Their annual delivered energy cost at the 8-hour discharge rate for cells larger than 1000 Ah range from $7-9/kwh (1981$) per year of service.

TABLE 5-4

Energy Output and Delivered Energy Cost vs. Discharge Rate And Operating Temperature, Lead-Antimony Pasted Flat Plate Cells

(1020-3700 Ah)

Nominal 8-Hour Capacity Ah		Output Energy, Wh (2) (3)									Delivered Energy Cost $/kwh (1981 $)								
	I	1-h Rate						500-h Rate			1-h Rate			8-h Rate			500-h rate		
		-18	0	25	-18	0	25	-18	0	25	-18	0	25	-18	0	25	-18	0	25
1020	(1)	655	1228	1637	1536	2000	3840	2386	4476	5965	1017	542	406	434	333	173	279	149	
1850		560	1051	1401	1397	2620	3493	2178	4084	5445	877	467	350	351	187	141	225	120	
2740		830	1557	2076	2074	3890	5186	3103	5818	7757	904	482	361	362	193	145	242	129	
3260		1035	1941	2588	2468	4627	6169	3431	6433	8577	922	491	369	387	206	155	278	148	
3700		1249	2342	3122	.2794	5239	6985	3480	6525	8700	913	487	365	408	218	163	328	175	

Notes:
(1) 2-Cell Module; All Others Single Cells

Note: Last column of data was missing on the original document

(2) Operating Temperature, ^{0}C

(3) Output Energy at 0 and -18^{0}C Estimated

Table 5-5 gives energy output and delivered enerqy costs for cells with pure lead alloy grids and relatively thicker pasted flat plates designed for low rate service (5-5). This data is derived from tests on cells at the10A rate and the 500-hour rate over the temperature range - 40°C to 25°C.

TABLE 5-5

Energy Output and Delivered Energy Cost
Pure Lead Low Rate Charge Retaining Batteries
(110-600 Ah)

Discharge Rate		Discharge Temperature	Cell Size, Energy Output, Energy Cost (1981 $)(1) (2)					
			110 Ah		220 Ah		600 Ah	
Time	Current		Energy	Cost	Energy	Cost	Energy	Cost
h	A	°C	Wh (1)	$/kwh	Wh (2)	$/kwh	Wh (2)	$/kwh
	10	25	223	354	102	549	309	362
		0	167	473	77	727	232	493
		-18	89	888	41	1366	124	903
		-40	62	1274	29	1931	87	1287
500		25	653	121	431	130	1188	94
		0	490	161	323	173	891	126
		-18	261	303	172	326	475	236
		-40	183	432	120	467	333	336

Notes: (1) Energy output to 1.75 volts per cell; 3 cells in series

(2) Single cell

This type of cell is used in Coast Guard navigational buoys and structures and is charged daily by solar photovoltaic panels (5-6). Current requirements range from 0.30 to 3.0 A on a 10-30 percent duty cycle. The larger of these cells offers attractive low cost ($94/kWh in 1981$) and long life. Pure lead grids have an exceptionally low open circuit stand capacity loss of 15 percent per year.

The normal recharge time is 75 hours. When discharged to 100 percent depth at the 500-hour rate, only 15 cycles can be performed in a year. At other rates and discharge depths these charge retaining cells can deliver the estimated cycle life and wet life shown in Figure 5-1. In float service the annual energy cost ranges from $8 to $11/kWh (1981$) per year during a 12 year In cycle service the accumulative stored energy cost for the 600 Ah size cell, with a delivered single cycle delivered energy cost of $94/kWh (1981$), be $.25 to $.35/kWh/cycle (1981$) during a 7.5 year life and one 10% to 20% depth cycle per day. Stored energy costs rapidly increase with increasing depth of discharge and decreasing cycles per year. This cell type offers attractive opportunities for the solar PV system designer.

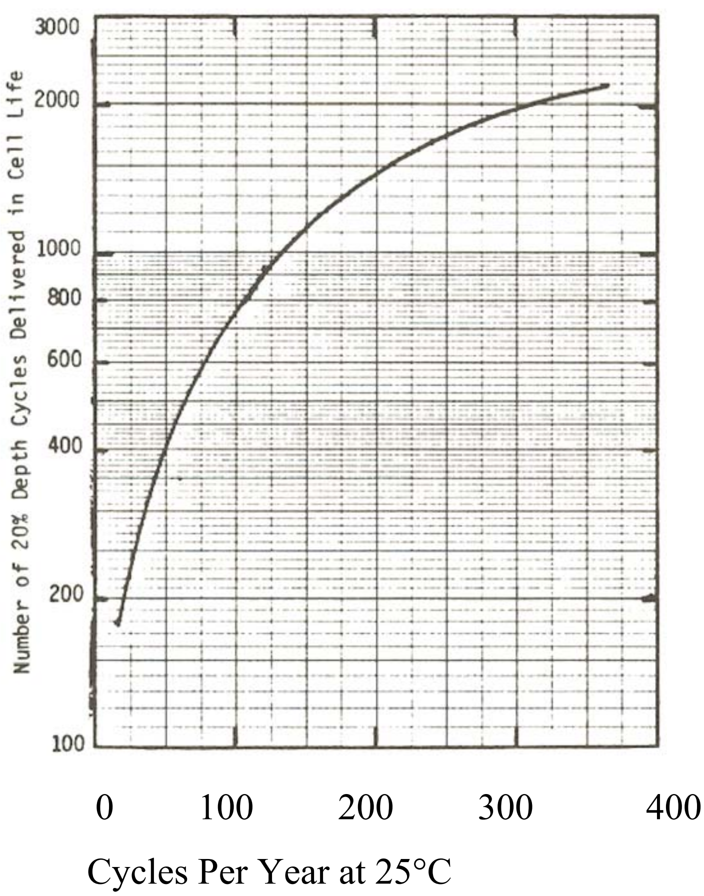

Figure 5-1 Shallow Cycle Life of Low Rate, Pure Lead Flat Plate Cells, Charge Retaining Type, 110-600 Ah Size Range

Industrial motorized truck batteries are designed for high cycle service. Table 5-6 sunmarizes output energy at the typical lift truck rate of 6-hours to 1.75V, delivered energy cost in $/kWh, and the accumulative stored energy cost for a line of 12 volt lead-antimony, tubular positive truck batteries in the capacity range 220-400Ah (5-7).

TABLE 5-6

Energy Output, Delivered and Stored Energy Cost
220-770 Ah Lead-Antimony Tubular Positive Motorized Truck Cells
(Costs are in 1981 $)

Nominal 6-Hour Capacity	Energy Output 6-Hour Rate to 1.75 V	Delivered Energy Cost	Stored Energy Cost $/kwh/cycle	
Ah	kWh	$/kwh	20% DOD[1]	80% DOD[2]
.220	2.58	207	.26	.17
330	3.84	171	.21	.14
440	5.16	157	.20	.13
550	6.42	151	.19	.13
660	7.68	148	.19	.12
770	9.00	144	.18	.12

Notes:

(1) 4000 cycles at 20% of rated 6-hour capacity

(2) 1500 cycles at 80% of rated 6-hour capacity on a WB-133B specification

Test 2 cycles per day at room ambient

Energy costs for an excellent general purpose lead-antimony tubular positive cell line, which thrives on cycling and float service, is given in Table 5-7 [5-8].

TABLE 5-7

Energy Output, Delivered and Stored Energy Cost
760-2130 Ah Lead Antimony, Tubular Positive General Purpose Cells
(in 1981 $)

Nominal 8-Hour Capacity	Energy Output-kwh (to 1.75VPC)			Delivered Energy Cost $/kwh			Stored Energy Cost $kwh/cycle (1)	
	72-h	8-h	1-h	72-h	8-h	1-h	20%DOD (8-h)	80%DOD (8-h)
760	2.08	1.44	0.59	149	215	524	.27	.18
1060	2.91	2.02	0.82	132	190	467	.24	.16
1370	3.74	2.60	1.06	124	178	438	.22	.15
1670	4.57	3.18	1.29	124	178	441	.22	.15
2130	5.83	4.04	1.64	120	174	427	.22	.15

Notes:
(1) Estimated cycle life at 25^0C to 80% rated 8-h capacity: 20%DOD, 4000 cycles; 80%DOD, 1500 cycles.

These cells are recommended for applications where cycling depth is not predictable, where variable rate discharges (1 minute to 3 hours) are expected and where a 22 year life expectancy in shallow cycling can be an advantage.

Energy costs for a line of lead-antimony pasted flat plate cell designs for industrial motive power and lift trucks are given in Table 5-8 (5-9).

TABLE 5-8

Energy Output, Delivered and Stored Energy Cost
225-1200 Ah Lead-Antimony, Pasted Flat Plate Motive Power Cells

Nominal 6-Hour Capacity	Energy Output 5-Hour Rate to 1.70VPC	Delivered Energy Cost	Stored Energy Cost $/kWh/cycle (1) 1981 $		
Ah	kWh	$/kWh	20% DoD	50% DOD	80% DOD
225	0.44	180	0.18	0.11	0.11
450	0.87	134	0.13	0.082	0.084
675	1.30	127	0.13	0.078	0.079
900	1.74	124	0.12	0.076	0.078
1200	2.33	120	0.12	0.074	0.075

Notes: (1) Estimated cycle life to 80% rated 5-hour capacity: 20% DOD, 5,000 cycles; 50% DoD, 3,250 cycles; 80% DOD, 2,000 cycles on a WB 133B test regime.

Cells of this type have a construction ideally suited for continuous cycling at a rate of 1-2 deep (80%) cycles per day.

Cycling tests on lead-calcium motive power cells are in progress and some product lines have been introduced to customers.

Their cycle life, when properly charged by special methods required for the lead-calcium system, is expected to approach two-thirds of the cycle life of lead-antimony cells of a similar type cycled to the same depth. The higher stored energy costs resulting from a lower cycle life will be compensated by lower water consumption and lower maintenance costs. Golf cart and electric vehicle batteries are designed for 1-2 years service of one relatively deep cycle per day under ambient conditions. Cycle life varies with golf course terrain and average operating temperature. Electric vehicle battery development is aimed at increasing cycle life and energy density, not cost reduction; however, mass production of this battery type provides competitive costs attractive to the solar PV system designer. One manufacturer limits wet life to 500 days [(5-10)]. This restriction limits cycle life in the typical PV system to 500 cycles at one cycle per day. Table 5-9 gives estimated delivered and stored energy costs for two popular golf cart, EV 6V batteries. At 80% depth of discharge their lowest stored energy cost is 14-15 cents (in 1981 $) per kilowatt-hour per cycle.

NICKEL-CADMIUM SYSTEM ENERGY COSTS

Delivered and stored energy costs for pocket plate type nickel-cadmium cells are given in Table 5-10. These cells are designed primarily for standby and starter service but also provide a reasonable cycle life (5-11).

Depth of Discharge %	Number of Cycles (25°C)
100	500
60	1100
20	2500

Nickel-cadmium cells of this type have been in service for more than **40** years. Annual energy costs nevertheless are equal to or greater than comparable lead-acid size cells

TABLE 5-9
Energy Output, Delivered and Stored Energy Cost
6 volt Electric Vehicle Type Lead-Antimony Flat Plate Batteries

Nominal 3-Hour EV Capacity Ah	Discharge Rate h	Energy Output to 1.70VPC (1) KwH	Delivered Energy Cost (1-Cycle) (2) $/kWh	Stored Energy Cost $/kWh/Cycle (3) (in 1981 $) 20% DOD	50% DOD	80% DOD
110	72	1.09	48.5	1.70	0.68	0.42
	24	0.99	53.6	0.80	0.32	0.20
	12	0.89	59.7	0.60	0.24	0.15
	6	0.79	67.2	0.67	0.27	0.17
	3	0.64	83.0	0.83	0.33	0.21
133	72	1.22	48.0	1.68	0.67	0.42
	24	1.11	52.7	0.79	0.32	0.20
	12	1.01	57.9	0.58	0.23	0.14
	6	0.91	64.3	0.64	0.26	0.16
	3	0.77	76.0	0.76	0.30	0.19

Notes:

1. Golf cart and electric vehicle type cell design, 3 cells per battery.
2. GSA prices late 1980, Zone 1 delivery
3. Assumes l2-hour recharge, 500 days maximum wet life, and no more than 1 cycle per day.

TABLE 5-10

NiCd Pocket Plate Cell Output Energy And Stored Energy Costs vs. Discharge Rate in 1981 $

Nominal 5-Hour Capacity to 0.9V (1)	Discharge Rate	Energy Output to 0.9V	Delivered Energy Cost (1-Cycle) (2)	Stored Energy Cost $/kwh/cycle	
Ah	h	Wh	$/kwh	20% DOD[3]	60% DOD[4]
7.5	500	11.2	1060		
	50	11.0	1080		
	10	9.6	1230	2.46	1.86
	5	8.9	1335	2.67	2.02
	1	6.3	1890		
85	500	129	395		
	50	125	410		
	10	110	460	.92	.70
	5	103	495	.99	.75
	1	72	710		
300	500	450	350		
	50	440	360		
	10	385	410	.82	.62
	5	360	440	.88	.67
	1	250	630		
480	500	710	330		
	50	690	340		
	10	605	390	.78	.59
	5	565	415	.83	.63
	1	395	600		

Notes:

(1) Low rate cell type

(2) GSA prices late 1980, Zone 1 delivery

(3) Estimated cycle life 2500 cycles

(4) Estimated cycle life 1100 cycles

SUMMARY OF ANNUAL AND STORED ENERGY COST ESTIMATES

Data from Tables 5-1 through 5-10 are summarized in Table 5-11A and B to compare the delivered one-cycle energy cost, the annual energy cost and the accumulative stored energy cost for each of the two electrochemical systems (lead-acid and nickel-cadmium) and for each of the construction types. From this data the solar PV system designer can select the lowest cost battery which is most likely to perform best to the system requirements.

TABLE 5-11A

Summary of Battery Subsystem Annual and Stored Energy Costs
Lead-Acid System

Battery Type and Service DOD	Capacity Range (1) Ah	Discharge Rate at 25°C h	Delivered Energy Cost (2) $/kwh	Annual Energy Cost (3) $/kWh/Yr	Stored Energy Cost $/kwh/Cycle (4) 20% DOD	50% DOD	80%
• Float Service							
Pasted Flat Plate							
Pb-Ca	500-200	500	130-200			Float Service	
		8	180-400	9-20		Float Service	
	1020-3700	500	92-125			Float Service	
		8	160-180	7-9		Float Service	
Pb-Sb	50-200	500	130-300			Float Service	
		8	140-170	7-9		Float Service	
• Shallow Cycle Service							
Pure Lead	110-600	500	94-130		.20	.50	.90
Low Rate					.75	1.00	1.80
General Purpose Cycle Service							
Pb-Sb, Tubular	760-2130	72	120-149				
Positive Plate		8	174-215	8-10	.22		.15
		1	427-524				
• Motive Power							
Heavy Cycle Service							
Pb-Sb, Tubular	220-770	6	144-207	10-17	.18-.26		.12-.17
Pb-Sb, Flat Plate	225-1200	5	120-180	10-15	.12-.18		.08-.ll
Pb-Sb, EV	110-133	12	58-60		.58	.23	.14
		3	76-83		.76	.30	.19

Notes:
1. (1) 3-8 hour rate depending upon service condition
2. (2) Energy delivered to 1.70 VPC at rated discharge current, 25°C
3. (3) Delivered energy cost per year of estimated wet life
4. (4) Initial battery price divided by accumulated energy output during cycle life at 25°C.

TABLE 5-1lB

Summary of Battery Subsystem Annual and Stored Energy Costs

Nickel-Cadmium System

(in 1981 $)

Battery Type and Service	Capacity Range (1) Ah	Discharge Rate at 25°C h	Delivered Energy Cost (2) $/kWh	Annual Energy Cost (3) $/kWh/yr	Stored Energy Cost $/kWh/Cycle (4) 20% DOD	80% DOD
Pocket Plate	85-480	500	330-395	8-10		
		50	340-410			
		10	390-460			
		5	415-495	10-12		
		1	600-710		.80-.99	.63-.75

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Notes:
(1) 5-hour rate to 0.9VPC

(2) Energy delivered to 0.9VPC on rated capacity test new at 25°C

(3) Delivered energy cost per year of estimated float life at 25°C

(4) Initial cell price divided by accumulated energy output during cycle life at 25°C.

REFERENCES

5-1 Exide Stationary Batteries and Chargers, Calcium Flat Plate Types LC-CC, Section 51.10.

5-2 IBID, Types GU, Section 51.45.

5-3 IBID, Antimony Flat Plate Types LA-CA, Section 52~l0

5-4 IBID, Antimony Flat Plate Types GT, Section 52.40.

5-5 WISCO Charge Retaining Batteries, WISCO Division, Exide Corporation, 2510 North Boulevard, Raleigh, North Carolina, 27604.

5-6 Evaluation of Lead-Acid Secondary Batteries for Application in U.S. Coast Guard Aids to Navigation, WQEC/C80-32, Weapons Quality Engineering Center, Crane, Indiana, 47522.

5-7 Exide Batteries and Chargers for Industrial Trucks, Section 20.02.

5-8 Exide Stationary Batteries and Chargers, Lead Antimony Tubular Positive Plate Type, Section 53.15.

5-9 Exide Batteries and Chargers for Industrial Trucks, Dynaclad Type Lead-Acid Cells, Section 20.10.

5-10 Exide Renewable Energy Batteries, Section 93.10, March 1981, Exide Corporation 101 Gibraltar Road, Horsham, Pennsylvania, 19044

5-11 NIFE Incorporated Batteries and Power Systems, NiCd Block Battery Technical Data, Lincoln, R. I., 02865.