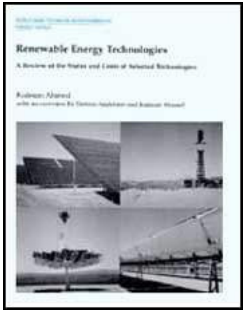

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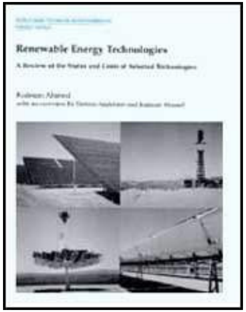

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KuIsum Ahmed
with an overview by Dennis Anderson and Kulsum Ahmed

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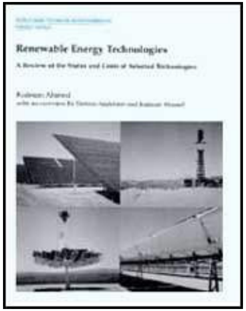

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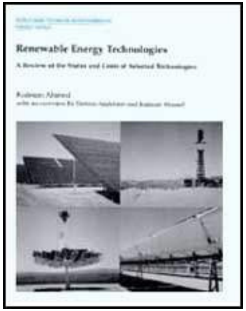

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Annex 1. Cost calculations and currency adjustments

The costs quoted in this paper are drawn from a variety of sources. Some are actual costs, whereas others are results of tabletop and engineering studies. Frequently, the sources quoted do not specify the details of their calculations and the assumptions made therein, such as discount rates and tax credits. Where these assumptions have been specified, I have attempted to note them. However, it is worth bearing in mind that this does cause difficulties in making direct cost comparisons.

Where data is available, the levelized cost of electricity has been calculated using the following standard formula

Cost of electricity (levelized) = $\frac{AC + (O\&M) + F}{E}$ (in $/kWh)

where

AC = Annualized capital cost (&/yr)
C = Total capital cost ($)

A = The annuity rate = $\frac{r(1+r)^n}{(1+r)^n - 1}$ **,**

where r = 0.10, i.e., a discount rate of 10%, and n = life of plant (yr)
(O&M) = Annual operating and maintenance cost ($/yr)
F = Annual fuel cost for plant ($/yr.)
E = Number of kilowatt hours produced annually (kWh/yr).

All currency values have been converted to 1990 currency figures using the Consumer Price Index (line 64) quoted in the IMFs International Financial Statistics. They have then been converted to U.S. dollars (1990) using the period average of the market exchange rate (rf) taken from the same document. For 1992 dollars, an average of the first three quarters of the market exchange rate (rf) has been used for conversion to 1990 dollars. Any variations from the methods given above are noted in the relevant section of the text.

The reader is referred to the International Energy Agency's Guidelines for the Economic Analysis of Renewable Energy Technology Applications or to the Electric Power Research Institute's Technical Assessment Guide (EPRI TAG) for more detailed cost analyses of these technologies.

Annex 2. Costs of ethanol production

	Reference	*Raw material*	*Production cost (as quoted)*	*Production cost (1990 US $/GJ)*	*Year*	*Notes*
1	U.S. Congress (1992)	sugarcane	10-11.80 $/GJ (1990)	10 - 11.8	1992	Based on operating experience-average production cost in Brazil.
2	U.S. Congress (1992)	sugarcane	9.0 $/GJ (1990)	9	1992	Based on operating experience of most efficient distilleries in Brazil.
3	U.S. Congress	sugarcane	8.5 $/GJ	8.5	2000	Technology could be available by 2000

	(1992)		(1990)			with concerted R,D&D effort; assumes biomass gasifier/gas turbine cogeneration; sale of surplus electricity, revenues credited against cost of ethanol.
4	U.S. Congress (1992)	cellulosic material	19-21 $/GJ (1990)	19 - 21	1992	Utilizing acid hydrolysis; technology commercially ready but not yet implemented commercially.
5	U.S. Congress (1992)	cellulosic material	15 $/GJ (1990)	15	2000	Technology could be available by 2000 with concerted R,D&D effort.
6	U.S. Congress (1992)	cellulosic material	9-11 $/GJ (1990)	9 - 11	1992	Enzymatic process; technology near-commercial.
7	U.S. Congress (1992)	cellulosic material	6-6.5 $/GJ (1990)	6 - 6.5	2000	Enzymatic process; technology could be available by 2000 with concerted R,D&D effort.
8	U.S. DOE (1990a)	corn	$1.28/gallon	16	1990	Assuming cost in 1990 $; corn feedstock represents half this cost; revenues from animal feed co-products include about half the total costs.
9	U.S. DOE (1990a)	cellulosic material	$1.35/gallon	17	1990	Assuming costs are in 1990 $; Cost based on technology of the time.
10	U.S. DOE (1990a)	cellulosic material	$0.60/gallon	7.5	1998	Assuming costs are in 1990 $; for enzymatic hydrolysis technology.
11	U.S. DOE (1990a)	not specified	17.4 $/MilBtu	16.6	1990	Assuming costs in 1990 $; levelized cost; states "approach to fuels is consistent with EPRI's required revenues (Fixed Charge Rate) methodology; Science Applications International Corp. (SAIC) model used for economic analysis."
12	U.S. DOE (1990a)	not specified	7.2 $/MilBtu	6.9	2000	Assuming costs in 1990 $; levelized cost assumes intensified R,D&D; states "approach to fuels is consistent with EPRI's required revenues (Fixed Charge Rate) methodology; SAIC model used for economic analysis."

Table A2.1. Costs of Ethanol Production

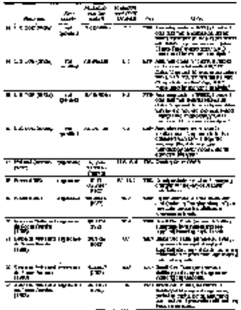


Table A2.1. Costs of Ethanol Production (continued on next page)

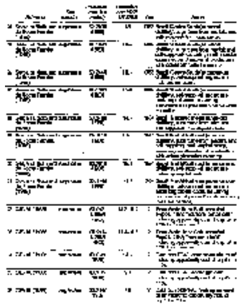
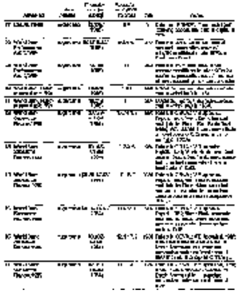


Table A2.1. Costs of Ethanol Production (continued on next page)



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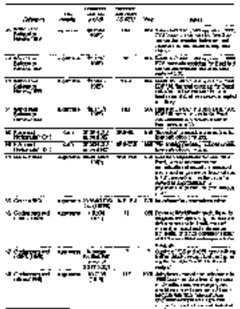


Table A2.1. Costs of Ethanol Production (continued on next page)

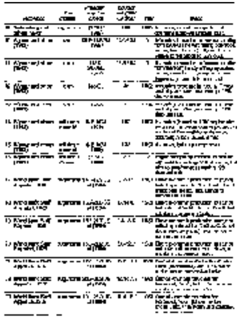


Table A2.1. Costs of Ethanol Production (continued on next page)

	Reference	Raw material	Production cost (as quoted)	Production cost (1990 US $/GJ)	Year	Notes
74	World Bank Staff Appraisal, 1985	sugarcane	20.0-25.2 US ¢/l (1984)	12-15.1	1983	Cost of ethanol production for New areas, Brazil, Incl. 11% return and standard conversion factor.

Table A2.1. Costs of Ethanol Production (continued on next page)

Annex 3. Costs of electricity from biomass

	Reference	Plant size in MWp	Capital cost	Interest rate (%)	Annualized capital cost	Lifetime (years)	Fuel cost	Efficiency (%)	O&M cost	Year	Cost of electricity: Units quoted	Cost of electricity: 1990 prices	Cost of electricity: USc/kWh (1990)	Notes
1	Elliott and Booth (1990)	37	1600-1700 $/kW	nq	nq	nq	2.8 $/ GJ LCV	42 (fuel)	nq	1990	6.0-7.0 US ¢/ kWh (1990)	6.0-7.0 US ¢/ kWh	6.0-7.0	Table study bioma gasifi
2	Elliott and Booth (1990)	37	1200-1300 $/ kW	nq	nq	nq	1.00 - 4.00 $/ GJ LCV	>42 (fuel)	nq	>1990 (Assume 2000)	4.0-6.0 US ¢/ kWh (1990)	4.0-6.0 US ¢/ kWh	4.0-6.0	Predic costs of tab study, bioma gasifi
3	Perlack, Ranney, and Russell (1991)	20	8000 yuan/ kW	10	0.215 (conversion plant) + 0.001 (road construction) yuan/ kWh	20	45 yuan/ dry Mg ($9.60/ dry Mg)	25 (overall)	120 yuan/ kW fixed maintenance, 6,000 yuan/ yr labor, 0.010 yuan/ kWh variable maintenance	1990	0.311 yuan/ kWh (1990)	0.311 yuan/ kWh	6.6	Cost e mates ORNL projec steam turbin
4	Perlack, Ranney, and Russell (1991)	20	5850 yuan/ kW	10	0.157 (conversion plant) + 0.001 (road construction) yuan/ kWh	20	45 yuan/ dry Mg ($9.60/ dry Mg)	35 (overall)	120 yuan/ kW fixed maintenance, 4,000 yuan/ yr labor, 0.010 yuan/ kWh variable maintenance	1990	0.236 yuan/ kWh or 5 US ¢/ kWh (1990)	0.236 yuan/ kWh	5	Cost e mates ORNL projec gas tu
5	Mahin (1989)	160 kW	DM 780,000 (installed gasifier power plant)	11.73 (over 13 yrs in case of plant)	DM 85,877	nq	na	nq	DM 146,877 (total annual operating cost)	1987	0.26 DM/ kWh (1987)	0.28 DM/ kWh	17.2	Comp gasifie with d plant, has to of pow 0.48 D kWh.

Table A3.1. Costs of Electricity from Biomass (continued on next page)

Plant size in	Capital	Interest	Annualized capital	Lifetime	Fuel	Efficiency	O&M	Cost of electricity: Units	1990	USc/kWh

	Reference	MWp	cost	rate (%)	cost	(years)	cost	(%)	cost	Year	quoted	prices	(1990)	Note
6	Grassi (1992)	2 to 30	2000 ECU/ kW	10	nq	25	50 ECU/ dry tonne/ 120 ECU/ TOE in table	20 (power gen.)	0.009 ECU/ kWh	1992	0.092-0.11 ECU/ kWh (assuming 1992)	_	11.8-14.1 (converted to US$ at Sept 1992 ECU exchange rate, and then to US$1990)	Exis syst
7	Grassi (1992)	large	1200-1300 ECU/ kW	10	nq	30	50 ECU/ dry tonne biomass and 170-176 ECU/ TOE biocrude oil prod.	35-38 (power gen.)	0.006 ECU/ kWh	1995	0.06-0.066 ECU/ kWh (assuming 1992)	-	7.7-8.4 (converted to US$ at Sept 1992 ECU exchange rate, and then to US$1990)	Proj cost ther stati by b or w char slurr
8	Grassi (1992)	100 to 500 kW	330 ECU/ kW	10	nq	20	50 ECU/ dry tonne biomass and 150 ECU/ TOE fuel	33-40 (power gen.)	0.008 ECU/ kWh	1997	0.05 ECU/ kWh (assuming 1992)	_	6.4 (converted to US$ at Sept 1992 ECU exchange rate, and ten to US$1990)	Proj cost dece elect dust firing biom der i gas
9	Grassi (1992)	<500 kW	900- 1200 ECU/ kW	10	nq	20	300 ECU/ TOE upgraded biocrude oil	55- 60 (power gen.)	0.01 ECU/ kWh	1997	0.068 ECU/ kWh (assuming 1992)	_	8.7 (converted to US $ at Sept 1992 ECU exchange rate, and then to US $1990)	Adva cond abov
10	Grassi (1992)	0.3-50	930 ECU/ kW	10	nq	20	50 ECU/ dry tonne biomass and 300 ECU/ TOE upgraded biofuel	50	0.004 (base) and 0.007 (peak) ECU/ kWh	1996	0.072 (base) and 0.085 (peak) ECU/ kWh (assuming 1992)	_	9.2 (base) and 10.9 (peak) (converted to US $ at Sept 1992 ECU exchange rate, and then to US $1990)	Proj cost tricit tion engi deriv turbi turbi bine fuele upgr

bloc

Note: na = not applicable; nq = not quoted; MW_p = peak megawatt

(Table A3.1 continued) (continued on next page)

	Reference	Plant size in MWp	Capital cost	Interest rate (%)	Annualized capital cost	Lifetime (years)	Fuel cost	Efficiency (%)	O&M cost	Year	Cost of electricity: Units quoted	Cost of electricity: 1990 prices	Cost of electricity: US¢/kWh (1990)	Notes
11	Grassi (1992)	1 to 30	2000 ECU/ kW	10	nq	20	50 ECU/ dry tonne/ 120 ECU/ TOE	40	0.009 ECU/ kWh	1996	0.067-0.068 ECU/ kWh (assuming 1992)	–	8.6-8.7 (converted to US $ at Sept 1992 ECU exchange rate, and then to US $1990)	Proje costs electi ducti gasifi biom use c engir deriv turbir turbir comb cycle
12	Grassi (1992)	nq	930 ECU/ kW	10	nq	20	500 ECU/ TOE	50	0.007 ECU/ kWh	1992	0.119 ECU/ kWh (assuming 1992)	–	15.2 (converted to US $ at Sept 1992 ECU exchange rate, and then to US $1990)	Proje costs ethar syste
13	Grassi (1992)	nq	600 ECU/ kW	10	nq	20	150 ECU/ TOE	30	0.008 ECU/ kWh	1997	0.071 ECU/ kWh (assuming 1992)	–	9.1 (converted to US $ at Sept 1992 ECU exchange rate, and then to US $1990)	Proje for bi powe syste
14	BTG (1992a)	880 kW gen-erator	estimated at ECU 490,000 (DM 1 min	nq	nq	nq	na	85% (gene-rator)	nq	1992	Sold to grid for 0.04 (peak) and	–	Sold at 3.5 (base) and 4.6 (peak) (converted	Woo fired gene

	... at 1980 prices)									0.03 (base) ECU/ kWh (1992)		to US $ at March 1992 ECU ex-change rate, and then to US $1990)	plant in 19 ECU 2.05 1992

Note: na = not applicable; nq = not quoted; MW_p = peak megawatt

(Table A3.1 continued) **(continued on next page)**

	Reference	Plant size in MWp	Capital cost	Interest rate (%)	Annualized capital cost	Lifetime (years)	Fuel cost	Efficiency (%)	O&M cost	Year	Cost of electricity: Units quoted	Cost of electricity: 1990 prices	Cost of electricity: US¢/kWh (1990)	Notes
15	BTG (1992b)	3.5 (gen-era-tor)	ECU 6.6 mln (DM 13.5 mln) for boiler and ECU 1.7 mln (DM 3.5 mln) for turbine and generator	nq	nq	nq	na	96% (gene-rator)	nq	1992	Est. at 0.02 ECU/ kWh (0.05 DM/ kWh)/ Sold to grid for 0.06 (peak) and 0.04 (base) ECU/ kWh (1992)		2.3 (0.02 ECU/ kWh converted to US $ at March 1992 ECU ex-change rate, and then to US $1990)	Wood-fired c eratio Cost c tion d includ ment f and m power (requi any ca
16	World Energy Council (1992)	na	na	na	na	na	1.9- 3.9 $/ GJ (1987) quot-ing Hall (1992); up to 4.9 $/ GJ in US in 1992 and est. 2.0$/ GJ by 2000	na	na	1992	Quotes 5-6 US ¢/ kWh (1989) in USA (Hall and others, 1991 and Johansson and others, 1993) Rosillo-Calle and Hall (1992) sug-gest est. 4 ¢/ kWh for elec. in Brazil (no dates)	6.3-6.3 (USA) and approx 4 (Brazil) US ¢/ kWh.	5.3-6.3 (USA) and approx. 4 (Brazil)	
17	Tarrado (1986)	3	2116 $/ kW (1984 $) (base in-stalled cost)	12	-	29	na	-	Detailed in ref-erence. Costs are for planta-tion and power plant.	1985	12.08 US ¢/ kWh (1984)	15.2 US ¢/ kWh	15.2	Cost e for dir combu steam 3 MW

18	Terrado (1985)	10	1705 $/ kW (1984 $) (base installed cost)	12	_	29	na	_	Detailed in reference. Costs are for plantation and power plant.	1985	8.41 US ¢/ kWh (1984)	10.6 US ¢/ kWh	10.6	Cost e for dir combu steam 10 MW
19	Terrado (1985)	50	1272 $/ kW (1984 $) (base installed cost)	12		29	na	_	Detailed in reference. Costs are for plantation and power plant.	1985	6.63 US ¢/ kWh (1984)	8.3 US ¢/ kWh	8.3	Cost e for dir combu steam 50 MW

Note: na = not applicable; nq = not quoted; MW_p = peak megawatt

(Table A3.1 continued) (continued on next page)

	Reference	Plant size in MWp	Capital cost	Interest rate (%)	Annualized capital cost	Lifetime (years)	Fuel cost	Efficiency (%)	O&M cost	Year	Cost of electricity: Units quoted	Cost of electricity: 1990 prices	Cost of electricity: USc/kWh (1990)	Notes
20	U.S. Congress (1992)	5-50,000 kW	1,900 $/ kW	7	nq	nq	$2/ GJ (1990)	nq	nq	1992	5-7 US ¢/ kWh (1990)	5-7 US ¢/ kWh	5 to 7	Electrici biomass steam tu numbers on oper perience
21	U.S. Congress (1992)	5 kW	1,200 $/ kW	7	nq	nq	$2/ GJ (1990)	nq	nq	1992	10 US ¢/ kWh (1990)	10 US ¢/ kWh	10	Electrici biomass biogas i combus gine; nu based o ing expe
22	U.S. Congress (1992)	5-100 kW	680-420 $/ kW	7	nq	nq	$2/ GJ (1990)	nq	nq	1992	24-15 US ¢/ kWh (1990)	24-15 US ¢/ kWh	24-15	Electrici biomass produce ternal cc tion eng numbers on opera perience

	Reference	Plant size in MWp	Capital cost	Interest rate (%)	Annualized capital cost	Lifetime (years)	Fuel cost	Efficiency (%)	O&M cost	Year	Cost of electricity: Units quoted	1990 prices	USc/kWh (1990)	Notes
23	U.S. Congress (1992)	50	1,150 $/ kW	7	nq	nq	$2/ GJ (1990)	nq	nq	1992	4-5 US ¢/ kWh (1990)	4-5 US ¢/ kWh	4 to 5	Electrici biomass produce turbines nology n commer tion.
24	U.S. Congress (1992)	100	800 $/ kW	7	nq	nq	$2/ GJ (1990)	nq	nq	2000	3-4 US ¢/ kWh (1990)	3-4 US ¢/ kWh	3 to 4	Electrici biomass produce turbines; nology p by 2000 concerte effort.
25	U.S. DOE (1990a)	50	$1,500/ kW; 2.5 ¢/ kWh levelized (constant 1988 $)	nq	nq	nq	1.00-2.00 $/ MilBtu; 1.2-2.4 ¢/ kWh levelized (constant 1988 $)	nq	0.5 ¢/ kWh levelized (constant 1988 $)	1990	4.2-5.4 ¢/ kWh levelized (constant 1988 $)	4.8-6.0 US ¢/ kWh	4.8-6.0	Depends cost bei proximat MilBtu.

Note: na = not applicable; nq = not quoted; MW_p = peak megawatt

(Table A3.1 continued) **(continued on next page)**

	Reference	Plant size in MWp	Capital cost	Interest rate (%)	Annualized capital cost	Lifetime (years)	Fuel cost	Efficiency (%)	O&M cost	Year	Cost of electricity: Units quoted	1990 prices	USc/kWh (1990)	Note
26	ESMAP (1987)	–	–	10% (real discount rate)	$246,790 (1985)	12 (diesel)/ 15 (steam)	$96,000/ yr	nq	$167,100/ yr	1985	19.2 US ¢/ kWh (1985) av. elec. cost	23.3 US ¢/ kWh	23.3	Financia of Ehani processi (Côte d'I
27	ESMAP (1987)	–	–	10% (real discount rate)	$327,450 (1985)	15 (steam)	0	nq	$470,980/ yr	1985	6.8 US ¢/ kWh (1985) average electricity cost	8.3 US ¢/ kWh	8.3	Financia mate for palm oil ing facili additiona ment to electricit

														tion is as Total pro electricity duction = GWh/ yr.
28	ESMAP (1987)	1.3	_	10% (real discount rate)	$259,332 / yr	_	0	nq	$181,100/ yr	1985	6.6 c/ kWh (1985)	8.0 US c/ kWh	8	Estimate potential wood ra large-sca integrate Analysis study, as use of ac equipme existing p Total pro elecricity tion = 6.
29	ESMAP (1987)	0.275	_	10% (real discount rate)	$76,904/ yr	_	0	nq	$34,600/ yr	1985	20.3 ¢/ kWh (1985)	24.6 US ¢/ kWh	24.6	Estimate potential wood res small-sca sawmills analysis plant for Sawmill, use of ac equipme existing p Total pro electricity duction = GWh/ yr.

Note: na = not applicable; nq = not quoted; MW_p = peak megawatt

(Table A3.1 continued) **(continued on next page)**

Reference	Plant size in MWb	Capital cost	Interest rate (%)	Annualized capital cost	Lifetime (years)	Fuel cost	Efficiency (%)	O&M cost	Year	Cost of electricity: Units quoted	1990 prices	USc/kWh (1990)	Notes

30	ESMAP (1987)	–	–	10% (real discount rate)	$152,341 / yr	–	0	nq	$82,399/ yr	1985	3.7 ¢/ kWh (1985)	4.5 US ¢/ kWh	4.5	Estimat ergy pol from col residues per total ity prod (6.38 G for Abol Coffee Decortic Plant. S assume tional ec to conve residue cess he electrici
31	ESMAP (1987)	–	–	10% (real discount rate)	$304,560 / yr	15	0	nq	$102,610/ yr	1985	17.4 ¢/ kWh (1985)	21.1 US ¢/ kWh	21.1	Estimat ergy pol from ric residue Financia sis of la Ivorian Scenari sumes r electrici duction GWh/ y
32	ESMAP (1987)	–	–	10% (real discount rate)	$50,430/ yr	15	0	nq	$26,220/ yr	1985	21.9 ¢/ kWh (1985)	26.6 US ¢/ kWh	26.6	Estimat ergy pol from ric residue (medium mill). Fi analysis model; I tion of g plant for posed e producti MWh/ u

Note: na = not applicable; nq = not quoted; MW_p = peak megawatt

(Table A3.1 continued) (continued on next page)

	Reference	Plant size in MWp	Capital cost	Interest rate (%)	Annualized capital cost	Lifetime (years)	Fuel cost	Efficiency (%)	O&M cost	Year	Cost of electricity: Units quoted	Cost of electricity: 1990 prices	Cost of electricity: US¢/kWh (1990)	Notes
33	ESMAP (1987)	-	-	10% (real discount rate)	$13,150/ yr	15	0	nq	$4,230/ yr	1985	38.6 ¢/ kWh (1985)	46.9 US ¢/ kWh	46.9	Estimate ergy pote from rice residues scale mil Financial sis of mo stallation comobile Propose tricity pro = 45 MW
34	ESMAP (1991a)	-	Rs. 65.4 million	Assume 10%	Rs. 11.2 million	Assume 15 years	Assume nil		Rs. 1.1 million	1991	Rs. 0.37/ kWh (1991)	-	Approx. 2.2	Calculati ried out b capital ar costs quo generate mum pos electricity excess e not inclu 2500 TC mill. Exp total elec productio 29,587 M
35	ESMAP (1991a)	-	Rs. 110.9 million	Assume 10%	Rs. 14.8 million	Assume 15 years	Assume nil		Rs. 1.5 million	1991	Rs. 0.39/ kWh (1991)	-	Approx. 2.3	Calculati ried out b capital ar costs quo generate mum pos

														electricity excess e not inclu 3500 TC mill. Exp total elec productio 41,423 M

Note: na = not applicable; nq = not quoted; MW_p = peak megawatt

(Table A3.1 continued) **(continued on next page)**

	Reference	Plant size in MWp	Capital cost	Interest rate (%)	Annualized capital cost	Lifetime (years)	Fuel cost	Efficiency (%)	O&M cost	Year	Cost of electricity: Units quoted	Cost of electricity: 1990 prices	Cost of electricity: USc/kWh (1990)	Notes
36	ESMAP (1991a)	–	Rs. 142.8 million	Assume 10%	Rs. 18.8 million	Assume 15 years	Assume nil		Rs. 1.9 million	1991	Rs. 0.35/ kWh (1991)	–	Approx. 2.1	Calculat rled out b capital a costs quo generate mum pos electricity excess e not inclu 5000 TC mill. Exp total elec productio 59,172 M
37	ESMAP (1988)	–	Details in ref.	10% (real discount rate)	Details in ref.	15 yrs	–	–	Details in ref.	1988	5.6 to 7.1 US ¢/ kWh (assuming 1988)	6.2-7.8 US ¢/ kWh	6.2-7.8	Estimate marginal costs for fueled co ated elec large saw Ghana.
38	Rajabapaiah and others (1993)	5 kW	$1,207/ kW (1990)	nq	nq	25	nil?	nq	nq	1992	>25 US ¢/ kWh (assuming [illegible]	>23.4 US ¢/ kWh	>23.4	Cost of b electricity ation for

											1992)			4.2 hours operation Pura villa study).
39	Rajabapaiah and others (1993)	5 kW	$1,207/ kW (1990)	nq	nq	26	nil?	nq	nq	1992	12 US ¢/ kWh (assuming 1992)	11.2 US ¢/ kWh	11.2	Estimate biogas el generatio approxim hours/ da ation (the village ca study).
40	International Energy Agency (1987)	5	$7,087,500 (not including cost of boiler)	5	_	20	_	_	$122,917	1987	4.1 US ¢/ kWh (assuming 1987)	4.7 US ¢/ kWh	4.7	Estimate ban garb eled pow tion in Ja

Note: na = not applicable; nq = not quoted; MW_p = peak megawatt

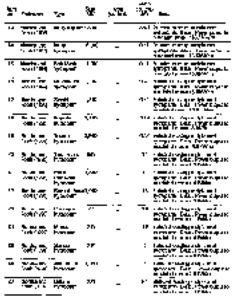
(Table A3.1 continued)

Annex 4. Land requirements for power stations

Item no.	*Reference*	*Type*	*Size MW*	*Area (sq. km)*	*Ratio sq. km / MW*	*Notes*
1	Terrado (1985)	Dendrothermal plantation	50	300	6	Land requirement for plantation under assumptions made in analysis.
2	IFC back-to-office report, 1991	Luz parabolic trough solar thermal system	80	483,960 sq. m. (0.48 sq. km.) of reflector covering approx. 1 sq. mile (2.59 sq. km.) area (text). Total land 416 acres (1.68 sq. km.) (annexure)	0.021	Ratio calculated on the basis of 416 acres.
3	De Laquil and	Solar One	10	Collector area	0.007	

3	De Laquil and others (1993)	Solar One solar-thermal central receiver plant	10	Collector area 71,084 sq. m.	0.007	
4	De Laquil and others (1993)	CESA-1 solar-thermal central receiver plant	1	Collector area 11,880 sq. m.	0.01	
5	De Laquil and others (1993)	Eurelios solar-thermal central receiver plant	1	Collector area 6,216 sq. m.	0.006	
6	Boes and Luque (1993)	PV concentrator power system	0.3	Total array area 3,806 sq. m.	0.013	Soleras, Saudi Arabia. Average annual DC efficiencies ~ 9%.
7	Boes and Luque (1993)	PV concentrator power system	0.225	Total array area 2,022 sq. m.	0.009	Sky Harbor, Phoenix, Arizona. Average annual DC efficiencies ~ 6.5%.
8	Boes and Luque (1993)	PV concentrator power system	0.025	Total aperture area 245 sq. m.	0.01	DFW, Dallas-Fort Worth, Texas. Electric and thermal efficiencies, 7% and 39%, respectively.
9	Moreira and Poole (1993)	Jaguari hydroplant	24	_	0.004	Selected existing and planned hydroplants, Brazil. Power output to inundated area = 2400 kW/ha
10	Moreira and Poole (1993)	Sapucaia hydroplant	300	_	0.014	Selected existing and planned hydroplants, Brazil. Power output to inundated area = 714 kW/ha
11	Moreira and Poole (1993)	Xingo hydroplant	5,000	_	0.017	Selected existing and planned hydroplants, Brazil. Power output to inundated area = 588.2 kW/ha
12	Moreira and Poole (1993)	Segredo hydroplant	1,260	_	0.065	Selected existing and planned hydroplants, Brazil. Power output to inundated area = 152.7 kW/ha

Table A 4.1. Land Requirements for Power Stations



(Table A4.1 continued)

Annex 5. The Luz experience

The bankruptcy of LUZ International Limited (Luz), the company responsible for setting up and running the Luz SEGS power plants in California, has raised many questions about the future of the technology. It should be noted, however, that the plants are still operating under new companies formed by groups of the SEGS plants' owners/investos (which include some U.S. utilities), and they continue to provide much information on technical performance and costs. A synopsis of the difficulties encountered by the Luz Corporation, along with comments, is presented below (see Lotker 1991, De Laquil and others 1993, and Kearney and Price 1992 for further information).

Each SEGS project was set up with private financing from investors, who benefited by receiving a return on their investment from revenues generated from electricity production; investors also benefited from certain financial incentives, such as Californian and U. S. Federal tax credits, that were in place at the time. The internal rate of return to investors was about 15 percent.

In 1991, Luz was unable to finance a tenth plant (SEGS X) because of financial and regulatory constraints. In the same year, the company was forced into bankruptcy. This

business failure had a number of causes:

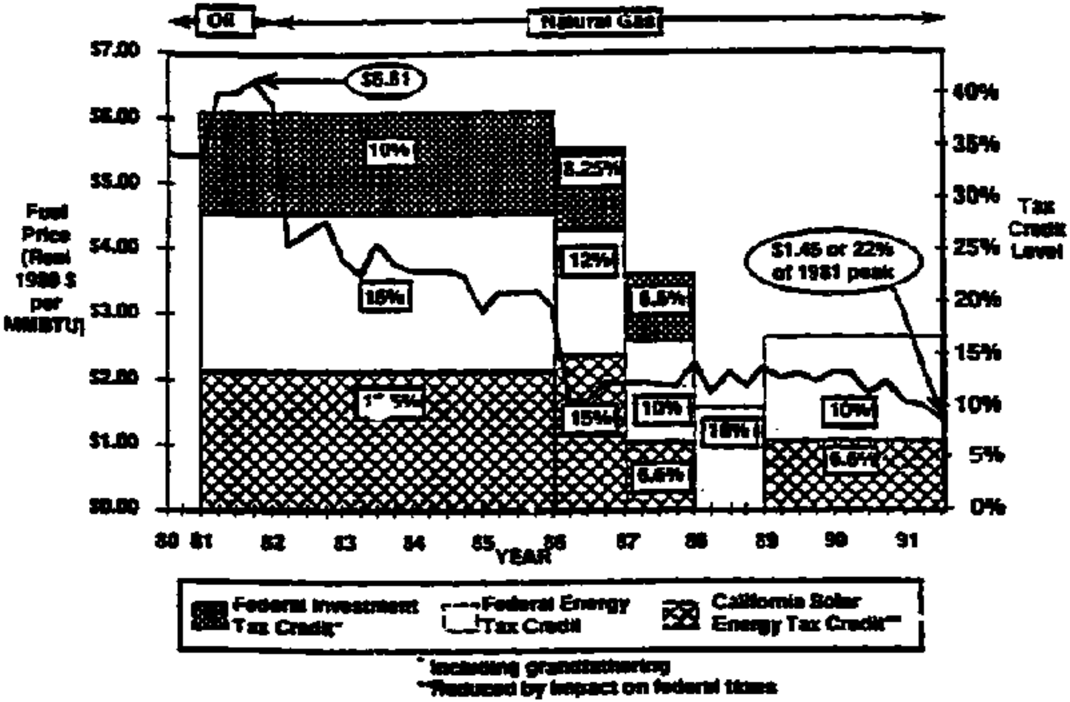
1. **The revenues generated from the sale of electricity were expected to cover the cash flow requirements of the plants, including operating and maintenance expenses. However, this sale price was linked to the price of natural gas, which progressively decreased from 1981 to 1991 (see figure), in real terms, by 78 percent This resulted in reduced electricity revenues.**

b. Financial incentives, such as Californian and U.S. federal tax credits, although still available, had decreased by about half over the period 1981-91 (see figure) The incentives could also change unpredictably. For example, tax credits were renewed annually; however, in 1989 these were only renewed for nine months, forcing Luz to reduce the construction period for the SEGS IX plant from a planned ten months to seven months. This was achieved, but it weakened the company financially, as investors demanded a higher rate of return on their investments because of the increased risk, while vendors of goods and services charged a higher risk premium for their services from the company. Ironically, the tax credits were later extended in late 1990 until December 1991.

c. The state of California recognized the greater land requirement of these solar plants compared with, say, a natural gas plant, and therefore exempted the solar field part of the plant from a state property tax. This exemption expired at the end of 1990 and was not reenacted until May 15, 1991; the delay meant that the tenth SEGS plant was also required to be constructed in about seven months (to get in under the December 31, 1991, expiration of the energy credits). Hence, Luz was further "squeezed"' after the shortened construction period of the SEGS IX plant.

A number of important lessons can be learned from the Luz experience. First, consistency and durability of policies is essential. It is a prerequisite at the early stage of any new

technology—particularly one that is highly capital-intensive. The unpredictable changes in this particular case not only squeezed Luz financially by causing it to accelerate construction of the SEGS IX plant from 10 to 7 months but also raised risks and deterred investors. Second, the wisdom of basing the price of electricity from a renewable energy technology on a mature fossil fuel price, such as natural gas, which is linked to other factors, must surely be questioned. Thus, not only were the positive environmental features of the technology not recognized in the price obtained for the electricity, generated but investors were deterred, because any investment was tantamount to "gambling" on future fossil fuel prices.



Source: Lotker (1991).

Figure A5.1. Energy Prices and Policy Support for Solar Energy, 1980-1991

Annex 6. Calculated cost of electricity from solar-thermal technologies

	Reference	System	Size	Capital costs ($/kW$_p$)	O&M costs	Lifetime of plant (years)	Capacity factor (%)	Calculated cost US¢/kWh (1990)	Quoted cost	Year	Notes
	PARABOLIC TROUGH TECHNOLOGY										
1	U.S. Congress (1992)	Parabolic trough/ natural gas hybrid	80 MW	3000	1.5 ¢/kWh	30	40	11.5	9.90 ¢/kWh (1990)	1990	Quoted cost assumes 7% and 0.90 ¢/kWh fuel costs
2	U.S. DOE (1992c)	Parabolic trough/ natural gas hybrid	80 MW	3100	2.2 ¢/kWh	30	40	12.5	–	1991	All costs in 1990 $. Net el output = 281,000 MWh/yr of $2,505,600/yr.
3	U.S. DOE (1992c)	Parabolic trough/ natural gas hybrid	80 MW	2875	1.26 ¢/kWh	30	40	10.1	–	1998	All costs in 1990 $. Net el output = 287,710 MWh/yr of $2,629,120/yr.
4	U.S. DOE (1992c)	Parabolic trough/ natural gas hybrid	Assume 80 MW	nq	15-20% of total level-ized costs	nq	nq		8.5 ¢/kWh (1990)	1992	Assume 1992. Levelized "according to Luz."
5	De Laquil and others (1993)	Parabolic trough	80 MW	2800-3500	1.8-2.5 ¢/kWh	Assume 30	25-22 (solar only)	14-20	11.8-15.7¢/kWh (solar); 13.0-9.3¢/kWh (hybrid, 25% natural gas)	1992	Assume costs are in 1992
6	De Laquil and others (1993)	Parabolic trough	80 MW	2400-3000	1.6-2.4 ¢/kWh	Assume 30	28-18 (solar only)	12 to 21	9.8-17.2 ¢/kWh (solar); 13.5-7.9 ¢/kWh (hybrid, 25% natural gas)	1995-2000	Assume costs are in 1992
7	De Laquil and others (1993)	Parabolic trough	80 MW	2000-2400	1.3-2.0 ¢/kWh	Assume 30	27-22 (solar only)	10 to 14	7.9-11.7 ¢/kWh (solar); 9.3-6.6 ¢/kWh (hybrid, 25% natural gas)	2000-2005	Assume costs are in 1992

Note: na = not applicable; nq = not quoted; kWp = peak kilowatts; Tech. = technology.

Table A6.1. Calculated Cost of Electricity from Solar-Thermal Technologies (continued on

next page)

	Reference	System	Size	Capital costs ($/kW$_p$)	O&M costs	Lifetime of plant (years)	Capacity factor (%)	Calculated cost US¢ /kWh (1990)	Quoted cost	Year	Notes
8	IFC back-to-office report, 1991	Parabolic trough/ 50% natural gas hybrid	80 MW	2813	1.30 ¢/kWh	Assume 30	63	7.4	6.80 ¢/kWh	1991	Luz data. Assume costs in 1
9	IFC back-to-office report, 1991	Parabolic trough/ 30% natural gas hybrid	80 MW	3708	2.22 ¢/kWh	Assume 30	37	13.8	14.67 ¢/kWh	1991	Author's calculations based Luz plants. Assume costs in
10	IFC back-to-office report, 1991	Parabolic trough	80 MW	3575	3.17 ¢/kWh	Assume 30	28	19	18.93 ¢/kWh	1991	Author's calculations based Luz plants. Assume costs in
11	IFC back-to-office report, 1991	Parabolic trough/ 50% natural gas hybrid	200 MW	2000	0.80 ¢/kWh	Assume 30	53	5.2	5.10 ¢/kWh	1991	Luz data. Assume costs in 1
12	IFC back-to-office report, 1991	Parabolic trough/ 50% natural gas hybrid	200 MW	2638	1.07 ¢/kWh	Assume 30	53	6.8	8.30 ¢/kWh	1991	Author's calculations based Luz plants. Assume costs in
13	IFC back-to-office report, 1991	Parabolic trough	200 MW	2500	2.15 ¢/kWh	Assume 30	26	13.2	13.62 ¢/kWh	1991	Author's calculations based Luz plants. Assume costs in
14	Kearney and Price (1992)	Parabolic trough/ natural gas hybrid	80 MW	3000	25% of total elec. cost	Assume 30	35	12.1	–	1992	Assume costs in 1992 $. Dat on Luz plants.
15	Kearney and Price (1992)	Parabolic trough	80 MW	3000	25% of total elec. cost	Assume 30	25	17	–	1992	Assume costs are in 1992 $ based on Luz plants.
16	Walton and Hall (1990)	Parabolic trough	nq, but based on Luz data	2100	1.21 US ¢/kWh (1990)	Assume 30	26	11	nq	1990	Based on Luz plant data. Co costs include allowance for g but capacity factor altered by exclude natural gas from ane

17	U.S. DOE (1990b)	Parabolic trough/ natural gas hybrid	80 MW	nq	nq	nq	nq	_	13 ¢/kWh	1990	Assume 1990 $. Calculated common economic assumpti fixed charge rate = 10.2%). capacity credits is not includ
18	U.S. DOE (1990b)	Parabolic trough/ natural gas hybrid	80 MW	nq	nq	nq	nq	_	12.2 ¢/kWh		5th plant to above. Assume Cost calculated "utilizing con economic assumptions (i.e., charge rate = 10.2%). Value capacity credits is not includ

Note: na = not applicable; nq = not quoted; kWp = peak kilowatts; Tech. = technology.

(Table A6.1. continued) **(continued on next page)**

	Reference	System	Size	Capital costs ($/kW$_p$)	O&M costs	Lifetime of plant (years)	Capacity factor (%)	Calculated cost US¢ /kWh (1990)	Quoted cost	Year	Notes
19	U.S. DOE (1990b)	Parabolic trough/ natural gas hybrid	160 MW	nq	nq	nq	nq	_	9.9 ¢/kWh		5th 160 MW plant. Assume Cost calculated "utilizing com economic assumptions (i.e., charge rate = 10.2%). Value capacity credits is not includ
20	Kearney (1991) Data from Meridian Corp.	Parabolic trough/ natural gas hybrid	80 MW	nq	nq	nq	nq	_	10 ¢/kWh (1990)	1991	For SEGS IX.
	PARABOLIC DISH TECHNOLOGY										
21	U.S. DOE (1992c)	Parabolic dish (distributed)	0.5	780-2780	1.66-3.45 ¢/kWh	20	27-23	5.8-20.3	_	1998	All costs in 1990 $. Net elect output =1,115 to 969 MWh/yr
22	U.S. DOE (1992c)	Parabolic dish (modular)	30	1328	0.7 ¢/kWh	20	40	6.5	_	1998	All costs in 1990 $. Net elect output =105000 MWh/yr and of $1,391,040/yr.
23	De Laquil and others (1993)	Parabolic dish/ Stirling engine	3 MW/yr	3000-5000	2.5-5.0 ¢/kWh	Assume 20	22-16	19-44	14.6-32.8 ¢/kWh	1995-2000.	Assume 2000 on graph. Assume costs are in 1992 $.
24	De Laquil and others (1993)	Parabolic dish/ Stirling engine	30 MW/yr	2000-3500	2.0-3.0 ¢/kWh	Assume 20	26-20	12 to 25	8.8-18.6 ¢/kWh	2000-2005.	Assume 2005 on graph. Assume costs are in 1992 $.

	Reference	System	Size	Capital costs ($/kWp)	O&M costs	Lifetime of plant (years)	Capacity factor (%)	Calculated cost US¢/kWh (1990)	Quoted cost	Year	Notes
25	De Laquil and others (1993)	Parabolic dish/ Stirling engine	300 MW/yr	1250-2000	1.5-2.5 ¢/kWh	Assume 20	28-22	7 to 14	5.5-10.6 ¢/kWh	2005-2010.	Assume 2010 on graph. Assume costs are in 1992 $.
26	U.S. DOE (1990b)	Parabolic dish	25 kW	nq	nq	nq	nq	–	20 ; ¢/kWh	1985 tech.	Assume 1990 $. Calculated " common economic assumpti fixed charge rate = 10.2%). V capacity credits is not include
27	U.S. DOE (1990b)	Parabolic dish	5-25 kW	nq	nq	nq	nq	–	12.1¢/kWh (solar) and 10.5 ¢/kWh (20% gas, hybrid mode)		5-25kW stand-alone modules Assume 1990 $. Calculated " common economic assumpti fixed charge rate = 10.2%). V capacity credits is not include
28	U.S. DOE (1990b)	Parabolic dish	25kW modules for utility scale plant	nq	nq	nq	nq	–	5.4¢/kWh (solar) and 5.5 ¢/kWh (20% gas, hybrid mode)		25kW modules mass-produce utility Assume 1990 $. Calcu "utilizing common economic a tions (i.e., fixed charge rate = Value of capacity credits is n included."

Note: na = not applicable; nq = not quoted; kWp = peak kilowatts; Tech. = technology.

(Table A6.1. continued) (continued on next page)

	Reference	System	Size	Capital costs ($/kW$_p$)	O&M costs	Lifetime of plant (years)	Capacity factor (%)	Calculated cost US¢ /kWh (1990)	Quoted cost	Year	Notes
	CENTRAL RECEIVER TECHNOLOGY										
29	International Energy Agency (1987)	Central receiver	100 MW	2000	6,000,000 $/yr	30	nq	43 (see note)	23¢/kWh (1984) assuming 5% discount rate; 13¢/kWh (1984) assuming 3.15% discount rate + favorable tax credits	1986	1986 U.S. DOE 5-Yr. R&D Electricity production = 10 Note that calculated cost is (1984)/kWh or 43 ¢ (1990) 10% discount rate and 19. ¢(1984)/kWh with 3.15% d rate, with no tax credits.
30	International Energy Agency (1987)	Central receiver	100 MW	2200	3,000,000 $/yr	30	nq	23 (see note)	11.5¢/kWh (1984) assuming 5% discount rate	1995	1986 U.S. DOE 5-Yr. R&D decrease reflects increase i availability, and decrease in Electricity production = 148

											Note that calculated cost is (1984)/kWh or 23 ¢ (1990)/ 10% discount rate.
31	U.S. DOE (1992c)	Central receiver	200 MW	2961	0.51 ¢/kWh	30	70	5.6	–	1998	All costs in 1990 $. Net elec output = 1,226,561 MWh/yr.
32	International Energy Agency (1987)	Central receiver	50MW	nq	nq	nq	nq	–	$0.16/kWh	1984	Feasibility study by Zurich utility and SOTEL (Swiss co for favorable Swiss site and hours operation/yr under pe conditions.
33	De Laquil and others (1993)	Central receiver	100 MW	3000-4000	1.3-1.9 ¢/kWh	Assume 30	40-25	10 to 20	8.0-16.1 ¢/kWh	1995	Assume costs are in 1992 $
34	De Laquil and others (1993)	Central receiver	200 MW	2225-3000	0.8-1.2 ¢/kWh	Assume 30	40-30	7 to 12	5.8-10.1 ¢/kWh	2005	Assume costs are in 1992 $
35	De Laquil and others (1993)	Central receiver	200 MW	2900-3500	0.5-0.8 ¢/kWh	Assume 30	63-55	6 to 8	4.6-6.5 ¢/kWh	2005-2010.	Assume 2010 on graph. Ba Assume costs are in 1992 $.
36	De Laquil and others (1993)	Central receiver	200 MW	1600-2500	0.5-0.6 ¢/kWh	Assume 30	43-52	5 to 10	4.5-8.2 ¢/kWh	2005-2010.	Assume 2010 on graph. Adv receiver. Assume costs are i
37	U.S. DOE (1990b)	Central receiver	100 MW	nq	nq	nq	nq	–	14.2 ¢/kWh	1985 tech. (study)	Assume costs are in 1990 $. calculated "utilizing commor assumptions (i.e., fixed char 10.2%). Value of capacity cr included."

Note: na = not applicable; nq = not quoted; kWp = peak kilowatts; Tech. = technology.

(Table A6.1. continued) (continued on next page)

	Reference	System	Size	Capital costs $/kW$_p$	O&M costs	Lifetime of plant yrs	Capacity factor %	Calc. cost US¢ /kWh (1990)	Quoted cost	Year	Notes
38	U.S. DOE (1990b)	Central receiver	100 MW	nq	nq	nq	nq	–	10.8 ¢/kWh (solar) and 10.3 ¢/kWh (23% gas, hybrid mode)		1st 100 MW plant. Assume 1990 $. Cost calculated "uti common economic assump fixed charge rate = 10.2%). capacity credits is not inclu
39	U.S. DOE (1990b)	Central receiver	200 MW	nq	nq	nq	nq	–	7.9 ¢/kWh		1st 200 MW plant (5th CR p Assume 1990 $. Calculated common economic assump fixed charge rate = 10.2%). capacity credits is not inclu
40	U.S. DOE (1990b)	Central receiver	200 MW	nq	nq	nq	nq	–	5.7 ¢/kWh		1st 200 MW direct absorpti plant (6th CR plant) Assum Cost calculated "utilizing co economic assumptions (i.e. charge rate = 10.2%). Valu credits is not included."

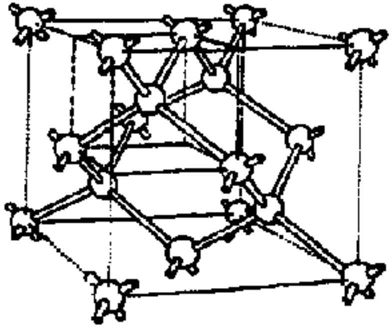
Note: na = not applicable; nq = not quoted; kWp = peak kilowatts.

(Table A6.1. continued)

Annex 7. The photovoltaic effect

Excellent descriptions of the photovoltaic effect may be found in the U.S. Department of Energy's Photovoltaic Fundamentals (U.S. DOE 1991), Kelly (1993), and other texts. This description is for the reader's convenience (diagrams are from U.S. DOE 1991}.

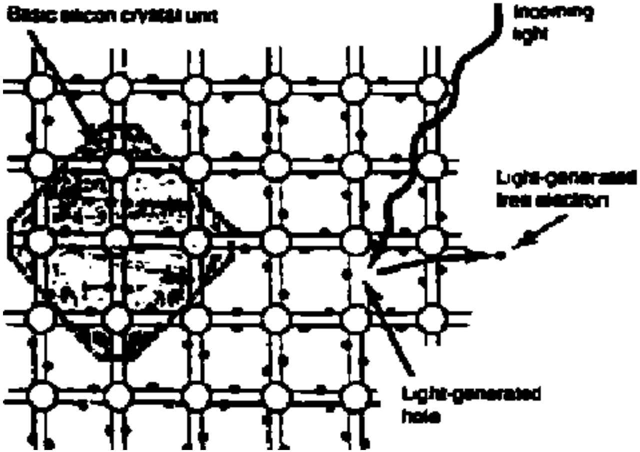
- **A silicon atom has 14 electrons with 4 electrons in its outermost orbit.**
- **These 4 valence electrons are shared by 4 other silicon atoms in a crystal.**
- **So silicon atoms form a lattice.**



A silicon atom

- **Light of a specific energy can dislodge a negative electron from a bond, creating a positive hole.**

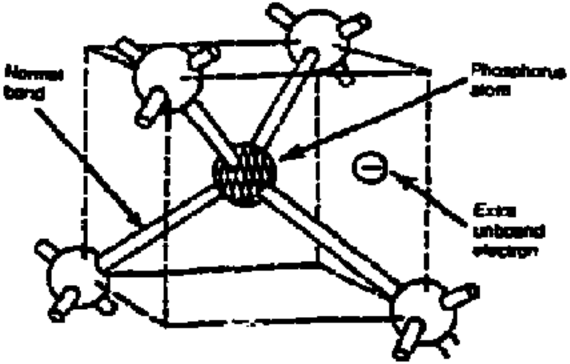
- **These negative and positive charges, which can move around freely, are the constituents of electricity.**



Negative and positive charges

- **Silicon can be droped with atoms of other elements to after the crystal's electrical properties.**
- **n-type material (e.g., phosphorus atom with 5 valence electrons) is "dopant."**

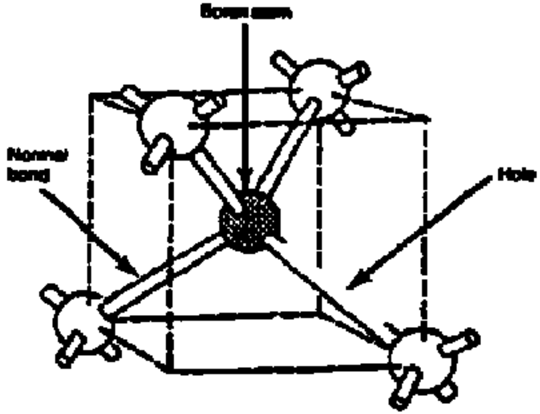
  - Results in the presence of an extra unbonded electron in crystal.
  - Electrons are the majority charge carriers.



N-type material

- **p-type material (e.g., boron atom with 3 valence electrons) is "dopant."**

  - Results in a hole in the crystal.
  - Holes are the majority charge carriers.

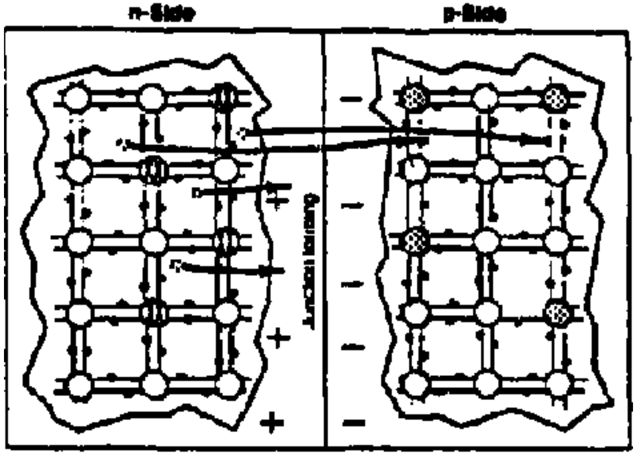


P-type material

- **When a p-type material is placed In contact with an e-type rnaterial, an electric field forms at the junction.**
- **This Is caused by two effects:**

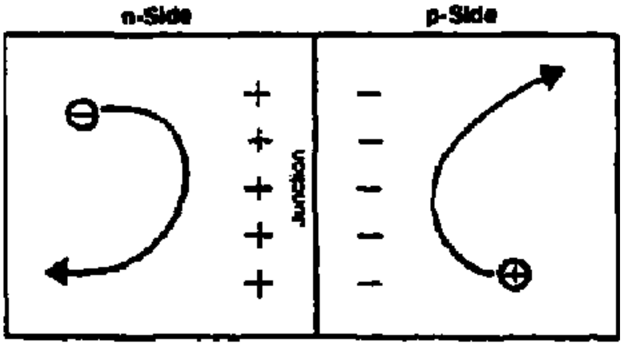
  a. Diffusion of the charge carriers from areas of high concentration to areas of low concentration.

  b. Electric attraction by the opposite charge of the majority canters across the junction.



Diffusion of the charge carriers

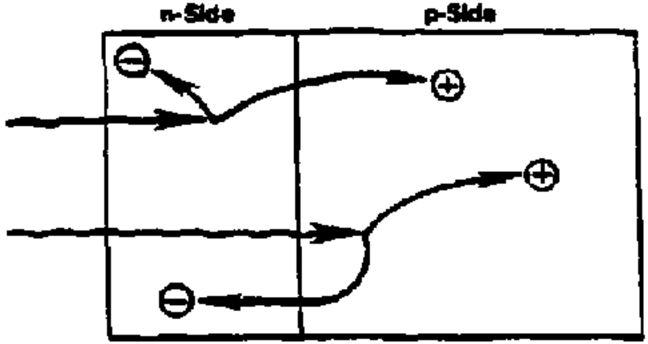
- **Eventually equilibrium is reached when any additional crossover is repelled.**
- **The strength of the field depends on the amount of dopant in the silicon.**



The amount of dopant in the silicon.

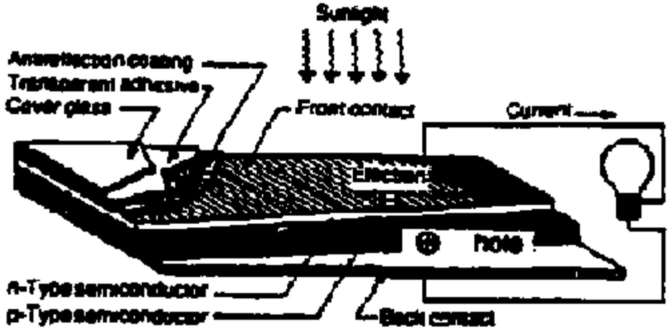
When sunlight of a specific energy (called the "band gap.") strikes the cell, charge carriers are created.

- **These carriers would normally recombine in a fraction of a second, however the cell is so designed that the electric field across the junction pushes electrons to one side and holes to the other.**



"Band gap."

- **If an external circuit is connected, current flows.**
- **Electrons from the n-layer can flow through the circuit to the p-layer and recombine with the holes.**



If an external circuit is connected, current flows.

Annex 8. Cost of electricity from photovoltaic systems

	Reference	Size (W)	Module life (yrs)	Efficiency (%)	Costs in current prices: O&M	BOS	Module	System	Electricity	Electricity cost, 1990 US¢/kWh	Year	Notes
1	Costello and Rappaport (1980)	–	–	–	–	–	< $10/ W_p (assume 1980 $)	–	~ $1-2/ kWh	158-317	1980	No details given.
2	Costello and Rappaport (1980)	=	=	=	=	=	~ $20/ W_p (assume 1975 $)	=	=	=	1975	1st large US federal for terrestrial use
3	Costello and Rappaport (1980)	–	–	–	–	–	~ $15-38/ W_p (assume 1978 $)	–	–	–	1978	Result of SERI surv commercial module 1978, sold in small
4	Costello and Rappaport (1980)	–	–	–	–	–	~ $10-15/ W_p (assume 1978 $)	–	–	–	1978	Result of SERI surv commercial module 1978, sold in large
5	Costello and Rappaport (1980)	–	–	–	–	–	–	$20-40/ W_p (assume 1979 $)	–	–	1978-79	

	Reference	Size (W)	Module life (yrs)	Efficiency (%)	O&M	BOS	Module	System	Electricity	Electricity cost, 1990 US¢/kWh	Year	Notes
6	Carlson (1990)	–	–	7 to 8 (module)	–	–	–	–	–	–	1976	Crystalline Si: avera commercial module (source: Solarex Co
7	Carlson (1990)	–	–	9 to 10 (module)	–	–	–	–	–	–	1980	Crystalline Si: avera commercial module (source: Solarex Co
8	Carlson (1990)	–	–	11 to 12 (module)	–	–	–	–	–	–	1985	Crystalline Si: avera commercial module (source: Solarex Co
9	Carlson (1990)	–	–	12 to 13 (module)	–	–	–	–	–	–	Assume 1990	Crystalline Si
10	Carlson (1990)	–	–	14.5-23.2 (cell)	–	–	–	–	–	–	Assume 1990	Crystalline Si (highe for single crystal)
11	Carlson (1990)	–	–	4 to 5 (module)	–	–	–	–	–	–	Assume 1990	Amorphous Si comn modules (after seve of operation)

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

Table A8.1. Cost of Electricity from Photovoltaic Systems (continued on next page)

	Reference	Size (W)	Module life (yrs)	Efficiency (%)	Costs in current prices: O&M	BOS	Module	System	Electricity	Electricity cost, 1990 US¢/kWh	Year	Notes
12	Carlson (1990)	–	–	11 to 12 (cell)	–	–	–	–	–	–	Assume 1990	Amorphous Si (in lab
13	Carlson (1990)	–	–	11 to 17 (cell)	–	–	–	–	–	–	Assume 1990	Amorphous Si (multi)
14	Carlson (1990)	–	–	11 to 14 (cell)	–	–	–	–	–	–	Assume 1990	Polycrystalline thin fi based solar cells
15	Carlson (1990)	–	–	20-27 (cell)	–	–	–	–	–	–	Assume 1990	Concentrators (Singl Si)
16	Carlson (1990)	–	–	29 (cell)	–	–	–	–	–	–	Assume	Concentrators (GaAs

	Reference	Size (W)	Module life (yrs)	Efficiency (%)	O&M	BOS	Module	System	Electricity	Electricity cost, 1990 US¢/kWh	Year	Notes
											1990	
17	Carlson (1990)	–	–	37 (cell)	–	–	–	–	–	–	Assume 1990	Concentrators (GaAs
18	Carlson (1990)	–	–	–	–	–	$4/ W_p (1987 $)	–	–	–	1988	Called solar cell cost but factory module pı graph.
19	Carlson (1990)	–	–	–	–	–	$100/ W_p (assume 1972 $)	–	–	–	Early 1970s Assume 1972.	Called solar cell cost but factory module pı graph.
20	Carlson (1990)	–	–	–	–	–	$15/ W_p (1987 $)	–	–	–	1980	Factory price for moc
21	Real Goods (1991)	48	–	–	–	–	$6.85-7.27/ W_p (1991)	–	–	–	1991	Mfr.: Hoxan (heliopo H-4810; single cryst sale price of module. price is for 1-3 modul for >20.
22	Real Goods (1991)	96	–	–	–	–	$4.47-4.99/ W_p (1991)	–	–	–	1991	Mfr.: Siemens; recycl modules (6-7 yrs old) crystal. Higher price modules; lower for >2
23	Real Goods (1991)	48	–	–	–	–	$8.73-9.35/ W_p (1991)	–	–	–	1991	Mfr.: Siemens; M-75; crystal; actual sale pı module. Higher price modules; lower for >2
24	Real Goods (1991)	53	–	–	–	–	$9.04-9.42/ W_p (1991)	–	–	–	1991	Mfr.: Siemens; M-55; crystal; actual sale pı module. Higher price modules; lower for >2

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

(Table A8.1 continued). **(continued on next page)**

Reference	Size (W)	Module life (yrs)	Efficiency (%)	Costs in current prices: O&M	BOS	Module	System	Electricity	Electricity cost, 1990 US¢/kWh	Year	Notes

25	Real Goods (1991)	40	–	–	–	–	\$8.98-9.73/ W_p (1991)	–	–	–	1991	Mfr.: Siemens; M-40; crystal; actual sale p module. Higher price modules; lower for >
26	Real Goods (1991)	43	–	–	–	–	\$9.51-10.21/ W_p (1991)	–	–	–	1991	Mfr.: Siemens; M-65; crystal; actual sale p module. Higher price modules; lower for >
27	Real Goods (1991)	22	–	–	–	–	\$11.32/ W_p (1991)	–	–	–	1991	Mfr.: Siemens; M-20; crystal; self-regulatin actual sale price of m
28	Real Goods (1991)	37	–	–	–	–	\$9.16-9.97/ W_p (1991)	–	–	–	1991	Mfr.: Siemens; M-35; crystal; actual sale p module. Higher price modules; lower for >
29	Real Goods (1991)	48	–	–	–	–	\$8.94-9.58/ W_p (1991)	–	–	–	1991	Mfr.: Siemens; M-50; crystal; actual sale p module. Higher price modules; lower for >
30	Real Goods (1991)	5	–	–	–	–	\$17.80/ W_p (1991)	–	–	–	1991	Mfr.: Siemens; T-5; s crystal; useful for sm applications; actual s of module.
31	Real Goods (1991)	2.5	–	–	–	–	\$23.60/ W_p (1991)	–	–	–	1991	Mfr.: Siemens; G-50; crystal; useful for ver applications; actual s of module.
32	Real Goods (1991)	51	–	–	–	–	\$7.82-8.22/ W_p (1991)	–	–	–	1991	Mfr.: Kyocera; K-51; multicrystal; actual s of module. Higher pr 1-3 modules; lower f
33	Real Goods (1991)	45.3	–	–	–	–	\$7.92-8.59/ W_p (1991)	–	–	–	1991	Mfr.: Kyocera; K-45; multicrystal; actual s of module. Higher pr 1-3 modules; lower f
34	Real Goods (1991)	62.7	–	–	–	–	\$8.60-8.92/ W_p (1991)	–	–	–	1991	Mfr.: Kyocera; K-63; multicrystal; actual s of module. Higher pr

1-3 modules; lower f

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

(Table A8.1 continued) **(continued on next page)**

	Reference	Size (W)	Module life (yrs)	Efficiency (%)	Costs in current prices: O&M	BOS	Module	System	Electricity	Electricity cost, 1990 US¢/kWh	Year	Notes
35	Real Goods (1991)	30	–	–	–	–	$13.30/ W_p (1991)	–	–	–	1991	Mfr.: Solarex; MSX Unbreakable Modu crystal; Thin, lightw portable; actual sal of module.
36	Real Goods (1991)	18.6	–	–	–	–	$12.85/ W_p (1991)	–	–	–	1991	Mfr.: Solarex; MSX Unbreakable Modu multicrystal; Thin, l portable; actual sal module.
37	Real Goods (1991)	10	–	–	–	–	$13.80/ W_p (1991)	–	–	–	1991	Mfr.: Solarex; MSX Unbreakable Modu crystal: Thin. lightw portable; actual sal of module.
38	Real Goods (1991)	60	–	–	–	–	$6.98-7.32/ W_p (1991)	–	–	–	1991	Mfr.: Solarex; MSX multicryst. Higher p 3 modules; lower f
39	Real Goods (1991)	56	–	–	–	–	$7.13-7.48/ W_p (1991)	–	–	–	1991	Mfr.: Solarex; MSX multicrystal; actual of module. Higher p 1-3 modules; lower
40	Real Goods (1991)	53	–	–	–	–	$6.77-7.34/ W_p (1991)	–	–	–	1991	Mfr.: Solarex; MSX multicrystal; actual of module. Higher p 1-3 modules; lower
41	Real Goods	40	–	–	–	–	$7.98-8.48/	–	–	–	1991	Mfr.: Solarex; MSX

	(1991)						W_p (1991)					multicrystal; actual of module. Higher p 1-3 modules; lower
42	Real Goods (1991)	10	–	–	–	–	$6.90/ W_p (1991)	–	–	–	1991	Mfr.: Chronar; amo originally rated 12V rating them as 10W 20% degradation i actual sale price of
43	U.S. Congress (1992)	70	–	–	–	–	–	$11,200/ kWp	–	–	1990	Actual retail prices *United States in 19*
44	U.S. Congress (1992)	190	–	–	–	–	–	$8,400/ kWp	–		1990	Actual retail prices United States in 19

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

(Table A8.1 continued) **(continued on next page)**

	Reference	*Size (W)*	*Module life (yrs)*	*Efficiency (%)*	*Costs in current prices* O&M	*BOS*	*Module*	*System*	*Electricity*	*Electricity cost, 1990 US¢/kWh*	*Year*	*Notes*
45	U.S. Congress (1992)	–	–	–	0.5 ¢/ kWh	–	–	–	–	–	Assume 1992	
46	U.S. Congress (1992)	–	20-30	–	–	–	–	–	–		Assume 1992	
47	U.S. Congress (1992)	–	30	10	0.7 ¢/ kWh	–	–	$6,000/ kWp	37.50 ¢/ kWh (based on 7% discount rate and 20% capacity factor)	35	Assume 1992	On-grid generation; capacity factor used calculations, it appe there is a misprint ir and that the system should read $8,000/ opposed to $6,000/
48	U.S. Congress (1992)	–	30	–	0.5 ¢/ kWh	–	–	$10,000/ kW	51 ¢/ kWh	47.7	Assume 1992	Off-grid generation. capacity factor as 2 system losses as 1(
49	U.S. Congress	38	–	–	–	Battery:	–	–	–	–	Assume	Small residential sy

	(1992)					$1,050/ kW (lasts 3-5 yrs); Electronic control equipment: $1,000/ kW					1992	Dominican Republic
50	U.S. Congress (1992)	200	–	–	–	Battery: $1,400/ kW (lasts 3-5 yrs); Mounting hardware; $800/ kW; Electronic control equipment: $1,800/ kW	–	–	–	–	Assume 1992	Residential mixed u system in the Unitec
51	U.S. Congress (1992)	–	–	–	–	–	$4,000-6,000/ kW_p (Assume 1992 $)	–	–	–	Assume 1992	UN Committee on D ment & Utilization of Renewable Sources $4,000/ kW_p price f line Si large orders (taxes and delivery); retailer: $6,000 for s orders; Dominican R $6,000/ kW_p for 38V

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arseaide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

(Table A8.1 continued) (continued on next page)

	Reference	*Size (W)*	*Module life (yrs)*	*Efficiency (%)*	*Costs in current prices* O&M	*BOS*	*Module*	*System*	*Electricity*	*Electricity cost, 1990 US$/kWh*	*Year*	*Notes*
52	U.S. Congress (1992)	–	–	–	–	–	$1,000/ kW_p (Assume 1990 $)	–	–	–	1995	PV industry reps. for 1995, according to SI 1990.
53	U.S. Congress (1992)	–	–	–	–	–	$1,500/ kW_p (Assume	–	–	–	1994	Electric Power Resea Institute estimate in 1

							1989 $)					large flat-plate syster
54	U.S. Congress (1992)	–	–	–	0.5 ¢/ kWh	–	–	–	–	–	Assume 1986	For small PV system according to 1986 es
55	U.S. Congress (1992)	–	–	–	0.39-1.44 ¢/ kWh	–	–	–	–	–	Assume 1989	For utility scale flat pl systems acc. to EPR: see items 239 and 2t reference quoted but values cited for O&M others refer to both fl and concentrator syst
56	U.S. DOE (1990a)	–	30	–	0.5 ¢/ kWh	–	–	$7,000/ kW (1988 $)	32 ¢/ kWh* (assume 1988 $)	35	1988	*Levelized cost of ele over 30 years at 6.1% rate (EPRI TAG [Tec Assessment Guide]), 25% capacity factor.
57	U.S. DOE (1990a)	–	30	–	0.2 ¢/ kWh	–	–	$3,600/ kW (BAU) and $2,325/ kW (R,D&D) (1988 $)	15 (BAU) and 10 (R,D&D) ¢/ kWh* (assume 1988 $)	17 (BAU) and 11 (R,D&D)	2000	BAU= Business-as-u: scenario and R,D&D= intensified R,D&D sc *Levelized cost of ele over 30 years at 6.1% rate (EPRI TAG), usi capacity factor.
58	U.S. DOE (1990a)	–	30	–	0.2 ¢/ kWh	–	–	$2,100/ kW (BAU) and $1,625/ kW (R,D&D) (1988 $)	9 (BAU) and 7 (R,D&D) ¢/ kWh* (assume 1988 $)	10 (BAU) and 8 (R,D&D)	2010	BAU= Business-as-u: scenario and R,D&D= intensified R,D&D sc *Levelized cost of ele over 30 years at 6.1% count rate (EPRI TAC 27.5% capacity facto
59	U.S. DOE (1990a)	–	30	–	0.2 ¢/ kWh	–	–	$1,400/ kW (BAU) and $1,150/ kW (R,D&D) (1988 $)	6 (BAU) and 5 (R,D&D) ¢/ kWh* (assume 1988 $)	7 (BAU) and 6 (R,D&D)	2020	BAU= Business-as-u: scenario and R,D&D= intensified R,D&D sc *Levelized cost of ele over 30 years at 6.1% count rate (EPRI TAC 27.5% capacity facto

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

(Table A8.1 continued) (continued on next page)

	Reference	Size (W)	Module life (yrs)	Efficiency (%)	Costs in current prices: O&M	BOS	Module	System	Electricity	Electricity cost, 1990 US¢/kWh	Year	Notes
60	U.S. DOE (1990a)	_	30	_	0.1 ¢/ kWh	_	_	$1,175/ kW (BAU) and $930/ kW (R,D&D) (1988 $)	5 (BAU) and 4 (R,D&D) ¢/ kWh* (assume 1988 $)	6 (BAU) and 4 (R,D&D)	2030	BAU= Business-as-u scenario and R,D&D intensified R,D&D sc *Levelized cost of el over 30 years at 6.1 count rate (EPRI TA 27.5% capacity facto
61	National Research Council (1976)	_	_	10	_	_	$20-30/ Wp	_	_	_	1976	
62	National Research Council (1976)	_	_	_	_	_	$30,000-70,000/ kW_p (array)	_	_	_	1976	Si solar cells
63	National Research Council (1981)	_	_	_	_	_	$22/ W_p (Assume 1976 $)	_	_	_	1976	In the US
64	National Research Council (1981)	_	_	_	_	_	$7-10/ W_p (Assume 1980 $)	_	_	_	1980	In the US with 2 MW production.
65	Hislop (1992)	_	_	_	_	_	$5/ W_p (MW_p orders), $10/ W_p (>1 kW_p orders), $25/ W_p (<100 W_p orders).	_	_	_	1991	
66	Falz (1978)	_	_	_	_	_	$20/ W_p (Assume 1975 $)	_	_	_	1975	Terrestrial PV yearly production volume o in 1975.
67	SERI (1989)	_	_	_	_	_	$600/ W	_	_	_	1950s	Cost of "silicon solar
68	SERI (1989)	_	_	_	_	_	$100-200/ W	_	_	_	1970	Not clear from the te cost is of modules o

												[illegible] probably the latter.
69	SERI (1989)	–	–	–	–	–	$20/ W (Assume 1977 $)	–	–	–	1977	
70	SERI (1989)	–	–	–	–	–	$4-5/ W (Assume 1988 $)	$8-10/ W	–	–	1988	

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

(Table A8.1 continued) (continued on next page)

	Reference	Size (W)	Module life (yrs)	Efficiency (%)	Costs in current prices: O&M	BOS	Module	System	Electricity	Electricity cost, 1990 US¢/kWh	Year	Notes
71	NREL (1992c)	–	–	–	–	–	$500/ W (Assume 1972 $)	–	–	–	1972	
72	NREL (1992c)	–	–	–	–	–	$4.00-4.50/ W	–	–	–	199[illegible]	
73	NREL (1992c)	–	–	11 to 17 (mod.)	–	–	–	–	–	–	1991	Efficiencies of 11 to for commercially av modules; experimer the laboratory have demonstrated effici high as 34%
74	NREL (1992c)	–	10 to 15	5 to 15	–	–	–	–	25-50 ¢/ kWh (1990)	25 to 50	1991	Installed capacity < utility power system MW; typical electrici consumer; remote,
75	NREL (1992c)	–	20	10 to 20	–	–	–	–	12-20 ¢/ kWh (1990)	12 to 20	1995	Mid-term goals for U States; utility power 50-100 MW; typical price: distributed; hi utility applications.

76	NREL (1992c)	–	30	15 to 25	–	–	–	–	5-6 ¢/kWh (1990)	5 to 6	2010-2030	Long term goals for power systems 10,0 MW; typical electrici central utility power.
77	NREL (1992c)	–	–	17 (cell)	–	–	–	–	–	–	Early 1980s	Assume 1983. Cryst cells.
78	NREL (1992c)	–	–	23 (cell)	–	–	–	–	–	–	1991	Crystalline Si labora
79	NREL (1992c)	–	–	1 (cell)	–	–	–	–	–	–	1974	Amorphous Si singl cell.
80	NREL (1992c)	–	–	12 (cell)	–	–	–	–	–	–	1991	Amorphous Si singl cell; initial efficiency
81	NREL (1992c)	–	–	>13 (cell)	–	–	–	–	–	–	1991	Amorphous Si multij cell; initial efficiency
82	NREL (1992c)	–	–	10 (sub-module)	–	–	–	–	–	–	1991	Amorphous Si subm
83	NREL (1992c)	–	–	4 to 6 (module)	–	–	–	–	–	–	1991	Amorphous Si; very modules (10 sq. fee

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

(Table A8.1. continued) **(continued on next page)**

	Reference	Size (W)	Module life (yrs)	Efficiency (%)	Costs in current prices: O&M	BOS	Module	System	Electricity	Electricity cost, 1990 US¢/kWh	Year	Notes
84	NREL (1992c)	–	–	14 (cell)	–	–	–	–	–	–	1991	CIS polycrystalline t cells
85	NREL (1992c)	–	–	11 (sub-module)	–	–	–	–	–	–	1991	CIS polycrystalline t submodules
86	NREL (1992c)	–	–	14.6 (cell)	–	–	–	–	–	–	1991	Experimental cells o CIS and amorphous
87	NREL (1992c)	–	–	12 (cell)	–	–	–	–	–	–	1991	CdTe polycrystalline cells

88	NREL (1992c)	–	–	7 (sub-module)	–	–	–	–	–	–	1991	CdTe polycrystalline submodules
89	NREL (1992c)	–	–	15 (cell)	–	–	–	–	–	–	1991	Thin film crystalline
90	NREL (1992c)	–	–	25 (cell)	–	–	–	–	–	–	1991	GaAs cells 'under o conditions.' Assume under regular light.
91	NREL (1992c)	–	–	30 (cell)	–	–	–	–	–	–	1991	GaAs cells under co light.
92	NREL (1992c)	–	–	25 (cell)	–	–	–	–	–	–	1991	Single crystal GaAs GaAs substrate.
93	NREL (1992c)	–	–	20 (cell)	–	–	–	–	–	–	1991	Single crystal GaAs germanium or Si sul
94	NREL (1992c)	–	–	22 (cell)	–	–	–	–	–	–	1991	Single crystal GaAs on a GaAs substrate removed after fabric
95	NREL (1992c)	–	–	>25 (cell); 30 (expected practical limit)	–	–	–	–	–	–	1991	Advanced Si concer from university labor incorporated into mc expected practical li
96	NREL (1992c)	–	–	>34 (cell); 40 (expected practical limit)	–	–	–	–	–	–	1991	Multijunction solar c concentrated light in research; expected limit, 40%.
97	NREL (1992c)	–	–	11-13 (22-23)	–	–	–	–	–	–	1991	Flat plate crystalline commercial modules laboratory cell efficie parentheses.

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

(Table A8.1 continued) **(continued on next page)**

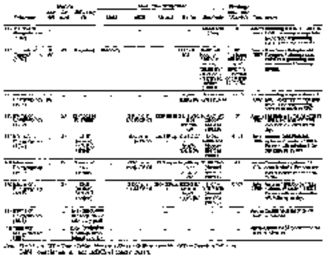
	Reference	Size (W)	Module life (yrs)	Efficiency (%)	Costs in current prices					Electricity cost, 1990 US$/kWh	Year	Notes
					O&M	BOS	Module	System	Electricity			

98	NREL (1992c)	–	–	14-15 (25)	–	–	–	–	–	–	1995	Flat plate crystallin commercial module laboratory cell effici parentheses.
99	NREL (1992c)	–	–	>18 (>26)	–	–	–	–	–	–	2010-2030	Flat plate crystallin commercial module laboratory cell effici parentheses.
100	NREL (1992c)	–	–	4-6 (12-14)	–	–	–	–	–	–	1991	Flat plate thin film c modules; laborator efficiencies in paren
101	NREL (1992c)	–	–	6-10 (15-18)	–	–	–	–	–	–	1995	Flat plate thin film c modules; laborator efficiencies in paren
102	NREL (1992c)	–	–	>15 (>20)	–	–	–	–	–	–	2010-2030	Flat plate thin film c modules; laborator efficiencies in paren
103	NREL (1992c)	–	–	14-17 (27-32)	–	–	–	–	–	–	1991	Concentrators; com module efficiencies cell efficiencies in parentheses.
104	NREL (1992c)	–	–	18-20 (35)	–	–	–	–	–	–	1995	Concentrators; com module efficiencies cell efficiencies in parentheses.
105	NREL (1992c)	–	–	>25 (>40)	–	–	–	–	–	–	2010-2030	Concentrators; com module efficiencies cell efficiencies in parentheses.
106	NREL (1992c)	–	5-15, mods	–	–	–	–	–	–	–	1991	BOS component re 5 yrs.
107	NREL (1992c)	–	15-20, mods	–	–	–	–	–	–	–	1995	BOS component re >15 yrs.
108	NREL (1992c)	–	>30, mods	–	–	–	–	–	–	–	2010-2030	
109	Thornton and						$4.00-8.00/W		25-40 ¢/kWh	24-38	1991	

Brown (1992)	_	_	_	_	_	[illegible]	_	[illegible]	[illegible]	[illegible]

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

(Table A8.1 continued) (continued on next page)



(Table A8.1 continued) (continued on next paged

	Reference	Size (W)	Module life (yrs)	Efficiency (%)	Costs in current prices O&M	BOS	Module	System	Electricity	Electricity cost, 1990 US¢/kWh	Year	Notes
119	International Energy Agency (1991)	_	_	10-15 (production efficiency); 15-18 (laboratory goal)	_	_	_	_	_	_	Assume 1991	Polycrystalline Si cel efficiencies.
120	International Energy Agency (1991)	_	_	11-14 (production efficiency); 14-16 (laboratory goal)	_	_	_	_	_	_	Assume 1991	Si ribbon cell efficien
121	International Energy Agency (1991)	_	_	5-8 (production efficiency); 8-10 (laboratory goal)	_	_	_	_	_	_	Assume 1991	Amorphous Si flat pl efficiencies.
122	International Energy Agency (1991)	_	_	13 (laboratory goal)	_	_	_	_	_	_	Assume 1991	Amorphous Si (aSi): aSi/ aSi multijunction efficiency.
123	International	_	_	12-15	_	_	_	_	_	_	Assume	Amorphous Si (aSi):

	Reference	Size (W)	Module life (yrs)	Efficiency (%)	O&M	BOS	Module	System	Electricity	Electricity cost, 1990 US¢/kWh	Year	Notes
	Energy Agency (1991)	–	–	(laboratory goal)	–	–	–	–	–	–	1991	aSi/ CIS multijunctio efficiency.
124	International Energy Agency (1991)	–	–	24 (laboratory goal)	–	–	–	–	–	–	Assume 1991	GaAs: thin film cell e
125	International Energy Agency (1991)	–	–	29 (laboratory goal)	–	–	–	–	–	–	Assume 1991	GaAs: concentrator c efficiency.
126	International Energy Agency (1991)	–	–	30 (laboratory goal)	–	–	–	–	–	–	Assume 1991	GaAs: concentrator multijunction cell effic
127	International Energy Agency (1991)	–	–	8-10 (laboratory goal)	–	–	–	–	–	–	Assume 1991	CIS cell efficiency.
128	International Energy Agency (1991)	–	–	6 (laboratory goal)	–	–	–	–	–	–	Assume 1991	CdTe cell efficiency.
129	Tsuchiya (1992)	–	–	–	–	–	7,000 yen/ Wp	–	–	–	1979	Assume cost is in 19 currency.
130	Tsuchiya (1992)	–	–	–	–	–	4,000 yen/ Wp	–	–	–	1980	Assume cost is in 19 currency.
131	Tsuchiya (1992)	–	–	–	–	–	3,500 yen/ Wp	–	–	–	1981	Assume cost is in 19 currency.
132	Tsuchiya (1992)	–	–	–	–	–	2,200 yen/ Wp	–	–	–	1982	Assume cost is in 19 currency.
133	Tsuchiya (1992)	–	–	–	–	–	1,800 yen/	–	–	–	1983	Assume cost is in 1

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

(Table A8.1A. continued) **(continued on next page)**

Costs in current prices: O&M, BOS, Module, System, Electricity

						Wp					currency.
134 Tsuchiya (1992)	_	–	–	–	–	1,500 yen/ Wp	–	–	–	1984	Assume cost is in 1 currency.
135 Tsuchiya (1992)	_	–	–	–	–	1,200 yen/ Wp	–	–	–	1985	Assume cost is in 1 currency.
136 Tsuchiya (1992)	_	–	–	–	–	1,100 yen/ Wp	–	–	–	1986	Assume cost is in 1 currency.
137 Tsuchiya (1992)	_	–	–	–	–	1,000 yen/ Wp	–	–	–	1987	Assume cost is in 1 currency.
138 Tsuchiya (1992)	_	–	–	–	–	900 yen/ Wp	–	–	–	1988	Assume cost is in 1 currency.
139 ESMAP (1989)	103	15	11.5	Rs 100/ yr	Rs 700/ kWh (battery); Rs 1,300 (controller); Rs 400 (cable); Rs 200 (connection cost).	Rs. 104/ W_p (assume 1989)	–	Rs 25.77/ kWh (real levelized electricity cost) (assume 1989)	129 (Currency adjusted to 1990 Pakistan rupees, and then to 1990 $ as described in Annex 1)	1989	Decentralized DC s land costs; assump including insolation sq. m/ day (worst c storage requiremen certain battery and lifetimes (2 and 8, respectively).
140 ESMAP (1989)	3423	15	11.5	Rs 18,000/ yr	Rs 2,200/ kWh (battery); Rs 3,500 (controller); Rs 9,000 (cable); Rs 900/ connection (connection cost; 30 connections); Rs 85,000 (site civil cost).	Rs. 104/ W_p (assume 1989)	–	Rs 35.44/ kWh (real levelized electricity cost) (assume 1989)	178 (Currency adjusted to 1990 Pakistan rupees, and then to 1990 $ as described in Annex 1)	1989	Centralized DC sys connections per un costs; assumptions insolation = 3.5 kW day (worst case), 2 storage requiremen certain battery, inv controller lifetimes (respectively).

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

{Table A8.1 continued) (continued on next page)

	Reference	Size (W)	Module life (yrs)	Efficiency (%)	Costs in current prices: O&M	BOS	Module	System	Electricity	Electricity cost, 1990 US¢/kWh	Year	Notes
141	ESMAP (1989)	114	15	11.5	Rs 100/ yr	Rs 700/ kWh (battery); Rs 1,300 (controller); Rs 400 (cable); Rs 200 (connection cost); Rs 5,200 (inverter).	Rs. 104/ W_p (assume 1989)	–	Rs 38.75/ kWh (real levelized electricity cost) (assume 1989)	195 (Currency adjusted to 1990 Pakistan rupees, and then to 1990 $ as described in Annex 1)	1989	Decentralized AC sy land costs; assumpt including insolation = sq. m/ day (worst ca storage requirement certain battery and c lifetimes (5 and 8 re
142	ESMAP (1989)	3423	15	11.5	Rs 16,000/ yr	Rs 2,200/ kWh (battery); Rs 2,500 (controller); Rs 9,000 (cable); Rs 900/ conn. (connection cost; 30 connections); Rs 85,000 (site civil cost); Rs 200,000 (inverter).	Rs. 104/ W_p (assume 1990)	–	Rs 49.60/ kWh (real levelized electricity cost) (assume 1989)	249 (Currency adjusted to 1990 Pakistan rupees, and then to 1990 $ as described in Annex 1)	1989	Centralized AC syst connections per unit costs; assumptions i insolation = 3.5 kWh day (worst case), 2 c storage requirement certain battery, inver controller lifetimes (5 respectively).
143	*Cody and Tiedje (1992)*	–	–	*7.2 (peak system conversion efficiency)*	–	–	–	–	*$0.40/ kWh (1988)*	*44*	*1988*	*Assumptions such a* life and 7.5% rate of insolation for genera southwest location ir United States (Cap f etc.
144	Cody and Tiedje (1992)	–	–	15 (system)	–	–	–	–	$0.06-0.10/ kWh (1988)	7 to 12	2010	Predictions for cost c electricity from PVs l of 40% and 20% anr growth in sales betw and 2010.
145	Cody and Tiedje (1992)	–	–	12 (single cell); 22 (fundamental [illegible]	–	–	–	–	–	–	1987	Amorphous Si.

146	Cody and Tiedje (1992)	–	–	24 (single cell); 33 (fundamental limit)	–	–	–	–	–	–	1990	Crystalline Si.

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

(Table A8.1 continued) (continued on next page)

	Reference	Size (W)	Module life (yrs)	Efficiency (%)	Costs in current prices: O&M	BOS	Module	System	Electricity	Electricity cost, 1990 US¢/kWh	Year	Notes
147	Cody and Tiedje (1992)	–	–	25 (single cell); 33 (fundamental limit)	–	–	–	–	–	–	1990	Crystalline GaAs.
148	Cody and Tiedje (1992)	–	–	14 (single cell); 29 (fundamental limit)	–	–	–	–	–	–	1988	Tandem cell with tw amorphous layers.
149	Cody and Tiedje (1992)	–	–	21 (single cell); 47 (fundamental limit)	–	–	–	–	–	–	1982	Tandem cell with tw crystalline layers.
150	Perlack, Jones and Waddle (1990)	–	–	–	–	–	$4-5/ Wp	–	–	–	1990	Costs of larger syste lower.
151	UNDP (1992)	–	–	–	–	–	$4/ W (cell cost)	–	–	–	Assume 1992	Imported cells by SOLARCOMM into 2
152	UNDP (1992)	–	–	–	–	–	$4/ W (module cost for large consignments, 50 MW)	–	–	–	Assume 1992	International price fo per container load.
153	UNDP (1992)	–	–	12-13 (module)	–	–	–	–	–	–	Assume 1992	Module efficiency of SOLARCOMM mod
154	UNDP (1992)	–	–	–	–	–	$ 12.17/ W (1991)	–	–	–	1991	Solematic module p
155	UNDP (1992)	–	–	–	–	–	$ 9.22/ W	–	–	–	1991	Battery World modul

						(1991)					
156 UNDP (1992)	–	–	–	–	–	$ 9.27/ W (1991)	–	–	–	1991	Solarcomm module
157 ESMAP back-to-office report, 1992	50 W	–	–	–	–	$5.21/ W_p (total $260.69)	–	–	–	Assume 1992	
158 ESMAP (1991b)	90 Wp	15	11.5 (module), 6 (overall system)	$5/ yr fixed	$265 (Battery: $70/ kWh; Controller: $75; cables: $30; 3 *fluorescent* lamps and fixtures: $90)	$5.5/ W_p (total $495)	$760	$1.44/ kWh	144	1990	Assumptions includi storage requirement *discount rate*; 4 kWh day insolation (worst 80% battery energy 70% max. depth of c 2 yr battery lifetime; controller lifetime; 0. day system load; etc

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

(Table A8.1 continued). (continued on next page)

(Table A8.1 continued)

Reference	Size (W)	Module life (yrs)	Efficiency (%)	Costs in current prices: O&M	BOS	Module	System	Electricity	Electricity cost, 1990 US¢/kWh	Year	Notes
159 Terrado, Mendis and Fitzgerald (1989)	–	–	–	–	–	$12/ W_p (installed array)	–	–	–	1989	
160 Meridian Corporation (1992)	–	–	–	–	–	$30/ W (currency yr not specified; assume 1975 $)	–	–	–	1975	From Maycock (199
161 Meridian Corporation (1992)	–	–	–	–	–	$13/ W (currency yr not specified; assume 1980 $)	–	–	–	1980	From Maycock (199
162 Meridian Corporation	–	–	–	–	–	$7/ W (currency yr not specified;	–	–	–	1985	From Maycock (199

	(1992)						assume 1985 $)					
163	Meridian Corporation (1992)	–	–	–	–	–	$4/ W (currency yr not specified; assume 1990 $)	–	–	–	1990	From Maycock (199
164	Meridian Corporation (1992)	–	–	–	–	–	$3/ W (currency yr not specified; assume 1992 $)	–	–	–	1995	Projected values fro Maycock (1991).
165	Meridian Corporation (1992)	–	–	–	–	–	$2/ W (currency yr not specified; assume 1992 $)	–	–	–	2000	Projected values fro Maycock (1991).
166	Meridian Corporation (1992)	–	–	–	–	–	$1.4/ W (currency yr not specified; assume 1992 $)	–	–	–	2005	Projected values fro Maycock (1991).
167	Meridian Corporation (1992)	–	–	–	–	–	$1/ W (currency yr not specified; assume 1992 $)	–	–	–	2010	Projected values fro Maycock (1991).
168	Meridian Corporation (1992)	nq	nq	nq	3% (PV & pump), 2% (PV & domestic) and 2% (PV & street lighting) of total cost	Rs 20 (1988)/ W_p (domestic system) and Rs 10 (1988)/ W_p (street lighting); Rs 20 (1988)/ W_p (PV motor & pump)	Rs 90 (1988)/ W_p (no import duty; Rs 155/ W_p with duty)	–	–	–	Assume 1988	Costs for subcompo PV systems in India 1988). Also storage 2/ kWh.
169	Meridian Corporation (1992)	–	–	11-13 (commercial cell efficiencies)	–	–	–	–	–	–	Assume 1992	Single-cell (monocry

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

(Table A8.1 continued). **(continued on next page)**

	Module Size	Module life	Module Efficiency	Costs in current prices	Electricity cost, 1990

	Reference	(W)	(yrs)	(%)	O&M	BOS	Module	System	Electricity	US¢/kWh	Year	Notes
170	Meridian Corporation (1992)	–	–	10-12 (commercial cell efficiencies)	–	–	–	–	–	–	Assume 1992	Polycrystalline Si
171	Meridian Corporation (1992)	–	–	4-7 (commercial cell efficiencies)	–	–	–	–	–	–	Assume 1992	Thin film amorphou
172	Meridian Corporation (1992)	–	–	14-17 (commercial cell efficiencies)	–	–	–	–	–	–	Assume 1992	Concentrators
173	Meridian Corporation (1992)	250 kW	–	–	–	–	–	–	12.5-21.3 (1990 ¢/ kWh)	12.5-21.3	Assume 1998	Costs are based or projections.
174	Meridian Corporation (1992)	–	–	–	–	–	$5.30-10.50/ W	$8.00 - 26.00/ W	–	–	Assume 1992	Estimate for stand-i systems.
175	Meridian Corporation (1992)	–	20	–	–	$1,756/ kW (batteries); $59/ kW (wiring/ controls); $1,171/ kW (labor, profit).	$5,854/ kW (1992 $)	–	$0.96/ kW (1992 $)	90	1990	Levelized cost of gı independent systen discount rate; assu including 5 yr batte and 10 year control
176	Meridian Corporation (1992)	–	20	–	–	$1,756/ kW (batteries); $59/ kW (wiring/ controls); $937/ kW (labor, profit).	$3,512/ kW (1992 $)	–	$0.81/ kWh (1992 $)	76	1995	Levelized cost of gı independent systen discount rate; assu including 5 yr batte and 10 yr controls l
177	Meridian Corporation (1992)	–	30	–	–	$1,756/ kW (batteries); $59/ kW (wiring/ controls); $585/ kW (labor, profit).	$2,342/ kW (1992 $)	–	$0.47/ kWh (1992 $)	44	2000	Levelized cost of gı independent systen discount rate; assu including 8 yr batte and 15 year control
178	Meridian Corporation (1992)	–	30	–	–	$1,756/ kW (batteries); $59/ kW (wiring/ controls); $585/ kW (labor, profit).	$1,756/ kW (1992 $)	–	$0.44/ kWh (1992 $)	41	2010	Levelized cost of gı independent systen discount rate; assu including 8 yr batte and 15 year control
179	Meridian	–	20	–	–	$820/ kW (wiring /	$4,683/ kW	–	$0.46/ kWh	43	1990	Levelized cost of gı

Corporation (1992)					controls); $937/ kW (labor, profit).	(1992 $)		(1992 $)			connected system; discount rate; assur including 5 year bat and 10 yr controls li

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

(Table A8.1 continued). (continued on next page)

Reference	Size (W)	Module life (yrs)	Efficiency (%)	Costs in current prices: O&M	BOS	Module	System	Electricity	Electricity cost, 1990 US¢/kWh	Year	Notes
180 Meridian Corporation (1992)	_	20	_	_	$468/ kW (wiring / controls); $585/ kW (labor, profit).	$2,342/ kW (1992 $)	_	$0.25/ kWh (1992 $)	23	1995	Levelized cost of gri connected system; discount rate; assun including 5 yr battar 10 yr controls life.
181 Meridian Corporation (1992)	_	30	_	_	$351/ kW (wiring / controls); $351/ kW (labor, profit).	$1,756/ kW (1992 $)	_	$0.16/ kWh (1992 $)	15	2000	Levelized cost of gri connected system; discount rate; assun including 8 yr batter 15 yr controls life.
182 Meridian Corporation (1992)	_	30	_	_	$351/ kW (wiring / controls); $351/ kW (labor, profit).	$1,405/ kW (1992 $)	_	$0.14/ kWh (1992 $)	13	2010	Levelized cost of gri connected system; discount rate; assun including 8 yr batter 15 yr controls life.
183 U.S. DOE (1992c)	250 kW	30 (system)	_	0.585 ¢/ kWh	_	_	1,080,000 ($4.32/ Wp)	_	_	1998	Daggett, demand sic management; 31% factor; net electricity 690 MWh/ yr.
184 U.S. DOE (1992c)	500 kW	30 (system)	_	0.216-0.613 ¢/ kWh	_	_	$1,660,000-2,600,000 ($3.32-5.2/ Wp)	_	_	1998	Daggett, distributed 28-31% capacity fac electricity output = 1 MWh/ yr.
185 U.S. DOE	10	30	_	0.613 ¢/ kWh	_	_	42,260,000	_	_	1998	Daggett, modular sy

Reference	Size (W)	Module life (yrs)	Efficiency (%)	O&M	BOS	Module	System	Electricity	Electricity cost, 1990 USc/kWh	Year	Notes
(1992c)	MW	(system)					($4.2/ Wp)	–	–		capacity factor; net e output = 24840 MWI
186 U.S. DOE (1992c)	10 MW	30 (system)	–	0.585 ¢/ kWh	–	–	41,760,000 ($4.2/ Wp)	–	–	1998	Denver, modular sys capacity factor; net e output – 24922 MWI
187 U.S. DOE (1992c)	5,000	20	–	$0.02/ kWp	$1,500/ kW$_p$ (controls/ inverter); $150/ kW$_p$ (battery); $1,000/ kW$_p$ (installation).	$5,000/ kW$_p$ (array)	$7,650/ kWp	–	–	1991	Remote power syste assumptions includir battery storage, 80% depth of discharge, 5 battery life and 10 ye controls/ inverter life
188 U.S. DOE (1992c)	5,000	30	–	$0.01/ kWp	$1,000/ kW$_p$ (controls/ inverter); $125/ kW$_p$ (battery); $500/ kW$_p$ (installation).	$2,500/ kW$_p$ (array)	$4,125/ kWp	–	–	2000	Remote power syste assumptions includir battery storage, 80% depth of discharge, 8 battery life and 15 ye controls/ inverter life.

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(Table A8.1 continued). (continued on next page)

Reference	Size (W)	Module life (yrs)	Efficiency (%)	Costs in current prices: O&M	BOS	Module	System	Electricity	Electricity cost, 1990 USc/kWh	Year	Notes
189 Carlson (1992)	–	–	–	–	–	$5/ W$_p$ (for large quantities)	–	$0.35-0.45/ kWh	35-45	1990	
190 Carlson (1992)	–	–	–	–	–	about $20/ W$_p$ (Assume 1980 $)	–	–	–	1980	
191 Remy and Durand (1992)	–	–	–	–	–	$5.3/ W$_p$ (selling price), $8.3/ W$_p$ (installed price—no storage, but inverter included)	–	–	–	1990	1990 (current) price

Reference	Size (W)	Module life (yrs)	Efficiency (%)	O&M	BOS	Module	System	Electricity	Electricity cost, 1990 US¢/kWh	Year	Notes
192 Remy and Durand (1992)	–	–	–	–	–	$2.6/ W_p (selling price), $4.1/ W_p (installed price—no storage, but inverter included)	–	–	–	1995	Projected price assu absence of large (ut markets but expecti "natural" doubling of every 5 years.
193 Kimura (1992)	–	–	–	–	–	Yen 600-700/ W_p ($4.60-5.40/ W_p)	–	–	–	1990	Production level of
194 Kimura (1992)	–	–	–	–	–	Yen 500/ W_p ($3.9/ Wp)	–	–	–	1990	Cost prediction in 19 production level wa yr.
195 Kimura (1992)	–	–	–	–	–	Yen 200/ W_p ($1.5/ W_p on basis of currency conversions above)	–	–	–	2000	Prediction by Japan Photovoltaic Specia government staff in production level of 1
196 Kimura (1992)	–	–	–	–	–	–	60-120% higher than module cost.	–	–		–
197 Kimura (1992)	–	–	–	–	–	–	–	Yen 150/ kWh ($1.2/ kWh)	120	1990	Prediction for first h decade, making PV practical as auxiliary supply sources in is
198 Kimura (1992)	–	–	–	–	–	–	–	Yen 70-120/ kWh (~ $0.6-1.0/ kWh on basis of currency conversion above)	60-100	1995	Prediction for 1995 thereabouts, making systems directly co against diesel powe generation.

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(Table A8.1 continued). (continued on next page)

Reference	Size (W)	Module life (yrs)	Efficiency (%)	Costs in current prices: O&M	BOS	Module	System	Electricity	Electricity cost, 1990 US¢/kWh	Year	Notes

199 Kimura (1992)	–	–	–	–	–	–	–	Yen 20-30/ kWh (~ $0.2-0.3/ kWh on basis of currency conversion above)	20-30	2000	Prediction for 2000, a large scale grid conn systems, with PV mo mounted on roofs of houses.
200 Hankins (1993)	18	–	–	–	–	–	$350	–	–	Assume 1992	Cost for 18 W_p two l system in Sri Lanka; at 12 V (DC).
201 Hankins (1993)	35	–	–	–	10.15% (battery), 2.89% (controller), 7.65% (wiring and switches), 17.33% (lights), 4.53% (installation) of total cost.	57.46% (module and support) of total cost. ($9.85/ Wp)	$600	–	–	Assume 1992	Suntec data for typic home system in Sri L
202 Hankins (1993)	47	–	–	–	–	–	$1,000	–	–	Assume 1992	Cost for 47 W_p four l system in Zimbabwe operating at 12 V (D
203 Hankins (1993)	50	–	–	–	–	–	US$1,500 (including labor, excluding transport)	–	–	Assume 1992	Solarcomm home lig system with a 100 A a 50 W_p module, fou fluorescent lamps, a controller, and assoc wiring and switches i Zimbabwe.
204 Hankins (1993)	507	–	–	–	–	–	US$700-2,000	–	–	Assume 1992	PV systems in Zimba
205 Hankins (1993)	–	–	–	–	–	US$13-15/ Wp				Assume 1992	PV module price to c in Zimbabwe.
206 Hankins (1993)	–	–	–	–	8.21% (battery), 5.22% (controller), 1.82% (wiring and switches), 11.94% (lights), 4.97% (installation) of total cost.	67.84% (module and support) of total cost.	–	–	–	Assume 1992	Component cost of representative home Zimbabwe; data fron Zimbabwe Min. Ene

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

(Table A8.1 continued). (continued on next page)

Reference	Size (W)	Module life (yrs)	Efficiency (%)	Costs in current prices: O&M	BOS	Module	System	Electricity	Electricity cost, 1990 US¢/kWh	Year	Notes
207 Hankins (1993)	48	_	_	_	7.65% (battery), 5.22% (control/ junction box), 9.57% (lamps, wiring switches), 3.48% (installation, labor), 23.65% (dealer margin) of total cost.	50.43% (module and support) of total cost. ($7.35-7.88/ Wp)	$700-750	_	_	1992	Data from Enersol A 48 W PV lighting sys breakdown, Dominic Republic; operating (DC).
208 Hankins (1993)	40	_	_	_	_	_	$800-850	_	_	Assume 1992	A typical 40 W_p sola system with four fluo tube lights, a locally battery, a control, a and mounting equip Kenya.
209 Hankins (1993)	_	_	_	_	14.23% (battery), 11.14% (controller), 8.05% (wiring and switches), 15.70% (lights), 8.72% (installation) of total cost.	42.16% (module and support) of total cost.	_	_	_	Assume 1992	Cost component dat Alpa Nguvu, Inc., Na
210 Hankins (1993)	_	_	_	_	_	$9.38/ W_p (assume 1992 $)	_	_	_	Assume 1992	Typical price for stan module in Dominican
211 Hankins (1993)	_	_	_	_	_	$7.80/ W_p (assume 1992 $)	_	_	_	Assume 1992	Typical price for stan module in Kenya.
212 Hankins (1993)	_	_	_	_	_	$10.40/ W_p (assume	_	_	_	Assume 1992	Typical price for stan module in Sri Lanka.

						1992 $)					
213 Hankins (1993)	–	–	–	–	–	$14.34/ Wp (assume 1992 $)	–	–	–	Assume 1992	Typical price for stan module in Zimbabwe
214 Charters (1991)	–	–	–	–	–	–	–	$30/ kWh (assume 1970 $)	10100	1970	
215 Charters (1991)	–	–	–	–	–	–	–	$0.30/ kWh (assume 1990 $)	30	1990	

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

(Table A8.1 continued). **(continued on next page)**

Reference	Size (W)	Module life (yrs)	Efficiency (%)	Costs in current prices: O&M	BOS	Module	System	Electricity	Electricity cost, 1990 US¢/kWh	Year	Notes
216 Charters (1991)	–	–	–	–	–	–	–	$0.10/ kWh (assume 1991 $)	10	2000	Forecast by informal
217 Charters (1991)	–	–	–	–	–	–	–	$0.04/ kWh (assume 1991 $)	4	2030	Forecast by informal
218 Kelly (1993)	–	–	–	–	–	$20/ Wp (1989 $)	–	–	–	1976	The average selling flat-plate photovoltai
219 Kelly (1990)	–	–	–	–	–	$7.1/ Wp (1989 $)	–	–	–	1984	The average selling flat-plate photovoltai
220 Kelly (1993)	–	–	–	–	–	$6.2/ Wp (1989 $)	–	–	–	1990	The average selling flat-plate photovoltai
221 Kelly (1993)	–	–	–	–	–	–	$10-15/ Wp	–	–	Assume 1992	Recently installed P
222 Kelly (1993)	–	–	10-12 (modules, field experience),	–	–	–	–	–	–	Assume 1992	Flat plate crystalline photovoltaic cell.

			17.8 (prototype), 24.2 (experimental), 30-33 (theoretical limit).									
223 Kelly (1993)	–	–	8-9 (modules, field experience), 18.2 (experimental)	–	–	–	–	–	–	Assume 1992	Flat plate polycrysta *photovoltaic cell.*
224 Kelly (1993)	–	–	3-5 (modules, field experience), 5 (prototype), 6 (experimental), 27-29 (theoretical limit).	–	–	–	–	–	–	Assume 1992	Flat plate single-junc amorphous Si photo cell; stabilized efficie
225 Kelly (1993)	–	–	15-20 (experimental)	–	–	–	–	–	–		Future projection. Fl single-junction amor photovoltaic cell; init efficiency.
226 Kelly (1993)	–	–	6 (modules, field experience), 8 (prototype), 10 (experimental)	–	–	–	–	–	–	Assume 1992	Flat plate *multijuncti* amorphous Si photo cell; stabilized efficie

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

(Table A8.1 continued). **(continued on next page)**

Reference	*Size (W)*	*Module life (yrs)*	*Efficiency (%)*	*Costs in current prices*					*Electricity cost, 1990 US¢/kWh*	*Year*	*Notes*
				O&M	*BOS*	*Module*	*System*	*Electricity*			
227 Kelly (1993)	–	–	7-8 (modules, field experience)	–	–	–	–	–	–	Early 1990s	Assume 1993. Flat junction amorphous photovoltaic cell; sta efficiencies.
228 Kelly (1993)	–	–	10 (modules, field experience)	–	–	–	–	–	–	Mid-1990s	Assume 1995. Flat junction amorphous photovoltaic cell; sta

efficiencies.

229	Kelly (1993)	–	–	15.6 (experimental), 12.3 (prototype), 42 (theoretical)	–	–	–	–	–	–	Assume 1992	Flat plate mechanic stacked amorphous photovoltaic cell; init stabilized, efficienci
230	Kelly (1993)	–	–	16 (modules, field experience)	–	–	–	–	–	–	After 2005	Amorphous Si/ CIS amorphous Si-based multijunction cell; st efficiency.
231	Kelly (1993)	–	–	11.1 (prototype), 14.6 (experi-mental), 23.5 (theoretical limit).	–	–	–	–	–	–	Assume 1992	Flat plate CIS photo
232	Kelly (1993)	–	–	10 (prototype), 15.8 (experi-mental), 27-28 (theoretical limit).	–	–	–	–	–	–	Assume 1992	Flat plate CdTe phot cell.
233	Kelly (1993)	–	–	22 (prototype), 28 (experimental)	–	–	–	–	–	–	Assume 1992	GaAs concentrator photovoltaic cell.
234	Kelly (1993)	–	–	34 (experimental)	–	–	–	–	–	–	Assume 1992	GaAs)on gallium an (GaSb) concentrator photovoltaic cell.
235	Kelly (1993)	–	–	–	–	–	$500/ sq. m ($4/ W_p at 12.5% efficiency)	–	–	–	Assume 1992	Approximate produc polycrystalline photo modules using curre (conventional) meth
236	Kelly (1993)	–	–	–	–	–	$1.70-2.66 / W_p (7% efficient mod., 10 kW_p production/ yr)	–	–	–	Assume 1992	Production cost of th modules (tabletop st

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

(Table A8.1 continued). (continued on next page)

Module	Costs in current prices	Electricity

Reference	Size (W)	life (yrs)	Efficiency (%)	O&M	BOS	Module	System	Electricity	cost, 1990 US¢/kWh	Year	Notes
237 Kelly (1993)	–	–	–	–	–	$1.19-1.86 / W_p (10% efficient mod., 100,000 sq. m production/ yr)	–	–	–	Assume 1992	Production cost of th modules (tabletop st
238 Kelly (1993)	–	–	–	–	$400-500/ sq. m	–	–	–	–	Assume 1992	System costs exclus modules and power conditioners. Note a dependence.
239 Kelly (1993)	–	–	–	From table: 0.39-1.44 ¢/ kWh (flat plate) & 4.81-6.87 ¢/ kWh (concentrator). Values in text do not match table (11-15 and 2-3 ¢/ kWh respectively).	–	–	–	–	–	Assume 1989	Data from EPRI bas operating experienc photovoltaic system items 55 and 256.
240 Green (1993)	–	–	17 (cell)	–	–	–	–	–	–	1974	Terrestrial Si crystall
241 Green (1993)	–	–	18 (cell)	–	–	–	–	–	–	1983	Terrestrial Si crystall
242 Green (1993)	–	–	19 (cell)	–	–	–	–	–	–	1984	Terrestrial Si crystall
243 Green (1993)	–	–	20 (cell)	–	–	–	–	–	–	1985	Terrestrial Si crystall
244 Green (1993)	–	–	23-24 (cell)	–	–	–	–	–	–	1992	Terrestrial Si crystall
245 Green (1993)	–	–	–	–	–	$5/ W_p (1989 $)	–	–	–	1989	Average module pric
246 Zweibel and Barnett (1993)	–	–	10 (experimental cell)	–	–	–	–	–	–	1980	CIS cells.
247 Zweibel and Barnett (1993)	–	–	9.8 (experimental cell)	–	–	–	–	–	–	1985	CIS cells.
248 Zweibel and Barnett (1993)	–	–	5 (prototype module)	–	–	–	–	–	–	1986	CIS.
249 Zweibel and Barnett (1993)	–	–	11.1 (prototype module)	–	–	–	–	–	–	1988	CIS.

250 Zweibel and Barnett (1993)	–	–	14 (cell)	–	–	–	–	–	–	1991	CdTe solar cells.

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

(Table A8.1 continued). (continued on next page)

Reference	Size (W)	Module life (yrs)	Efficiency (%)	Costs in current prices O&M	BOS	Module	System	Electricity	Electricity cost, 1990 USc/kWh	Year	Notes
251 Zweibel and Barnett (1993)	–	–	10 (1 sq. ft. prototype modules)	–	–	–	–	–	–	1991	CdTe.
252 Zweibel and Barnett (1993)	–	–	9 (cell)	–	–	–	–	–	–	1986	CdTe solar cells.
253 Zweibel and Barnett (1993)	–	–	5 (1 sq. ft. prototype module)	–	–	–	–	–	–	1986	CdTe.
254 Zweibel and Barnett (1993)	–	–	12.3 (cell)	–	–	–	–	–	–	1989	CdTe solar cells.
255 Zweibel and Barnett (1993)	–	–	7.3 (prototype module)	–	–	–	–	–	–	1989	CdTe.
256 Zweibel and Barnett (1993)	–	–	12.7 (cell)	–	–	–	–	–	–	1991	CdTe solar cells.
257 Zweibel and Barnett (1993)	–	–	8.1 (1 sq. ft. module)	–	–	–	–	–	–	1991	CdTe.
258 Zweibel and Barnett (1993)	–	–	6.5 (4 sq. ft module)	–	–	–	–	–	–	1991	CdTe.
259 Zweibel and Barnett (1993)	–	–	6.9 (cell)	–	–	–	–	–	–	1985	*Thin film Si on stee solar cell.*
260 Zweibel and Barnett (1993)	–	–	9.6 (cell)	–	–	–	–	–	–	1985	Thin film Si on stee solar cell.
261 Zweibel and Barnett (1993)	–	–	10.2 (cell)	–	–	–	–	–	–	1987	Thin film Si on cera substrate solar cell

262 Zweibel and Barnett (1993)	–	–	15.7 (cell)	–	–	–	–	–	–	1988	Thin film Si on cera substrate solar cell
263 Zweibel and Barnett (1993)	–	–	16 (module)	–	–	–	–	–	–	Assume 1992	Thin film Si
264 Zweibel and Barnett (1993)	–	–	9.7 (module)	–	–	$200/ sq. m ($2.06/ W_p using quoted efficiency of 9.7%) (assume 1992 $)	–	–	–	Assume 1992	CIS

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

(Table A8.1 continued). (continued on next page)

Reference	Size (W)	Module life (yrs)	Efficiency (%)	Costs in current prices: O&M	BOS	Module	System	Electricity	Electricity cost, 1990 US¢/kWh	Year	Notes
265 Zweibel and Barnett (1993)	–	–	6.5 (module)	–	–	$150/ sq. m ($2.31/ W_p using quoted efficiency of 6.5%) (assume 1992 $)	–	–	–	Assume 1992	CdTe
266 Zweibel and Barnett (1993)	–	–	15 (module), 12 (system)	$0.005/ kWh	$80/ sq. m (fixed array), $20/ sq. m (power conditioning), $4/ sq. m (land), 33% of direct costs (indirect costs)	$400/ sq. m ($3.08/ W_p using quoted efficiency of 13%) (assume 1992 $)	–	$0.40/ kWh (assume 1992 $)	37	Assume 1992	Location assumes av sunlight of 1,800 kW year for a fixed flat pl
267 Zweibel and Barnett (1993)	–	–	13 (module), 10 (system)	$0.001/ kWh	$50/ sq. m (fixed array), $10/ sq. m (power conditioning),	$60/ sq. m	–	$0.06/ kWh	–	?	Projected cost; locati assumes average US of 1,800 kWh/ sq. m/ fixed flat plate.

					$4/ sq. m (land), 25% of direct costs (indirect costs)							
268 Firor, Vigotti, and Iannucci (1993)	–	–	–	$0.004-0.07/ kWh (average $0.023/ kWh)	–	–	–	–	–	Assume 1989	Results of EPRI com study of 7 medium-sc PV projects. Three of systems produced m MW of power, and th substantially lower O Also see items 55 an
269 Costello and Rappaport (1980)	–	–	16 (cell)	–	–	–	–	–	–	Assume 1980	Efficiencies achieved experimental semicry Si cells.
270 Costello and Rappaport (1980)	–	–	8-12 (cell)	–	–	–	–	–	–	Assume 1989	Efficiencies achieved Si cells.

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

(Table A8.1 continued). (continued on next page)

Reference	Size (W)	Module life (yrs)	Efficiency (%)	Costs in current prices: O&M	BOS	Module	System	Electricity	Electricity cost, 1990 US¢/kWh	Year	Notes
271 Costello and Rappaport (1980)	–	–	19-28.5 (cell)	–	–	–	–	–	–	Assume 1980	Efficiencies achievec concentrator cells (th is for Si cells under 3 and the latter for gall aluminum arsenide a cells illuminated thro beam splitter at 167 .
272 Costello and Rappaport (1980)	–	–	24.7 (cell)	–	–	–	–	–	–	Assume 1980	Best efficiency for a : junction device at 17
273 Carlson (1990)	–	–	11 to 13	–	–	–	–	–	–	Assume	Assume 1990. Polyc

				(cell)							1990	thin film CdTe-based cells
274	Boes and Luque (1993)	300 kW	–	9 (average annual DC system efficiency)	–	–	–	–	–	–	Assume 1992	Soleras PV concentr power system in Sau operational since 19
275	Boes and Luque (1993)	225 kW	–	6.5 (average annual DC system efficiency)	–	–	–	–	–	–	Assume 1982	Sky Harbor PV conc system in Phoenix, A set up in 1982. It wa dismantled, as plann several years of ope System experienced inverter, module and problems.
276	Boes and Luque (1993)	25 kW	–	7 (system electrical efficiency)	–	–	–	–	–	–	1982-1987	Assume 1985. DFW concentrator system Fort Worth, Texas; s 1982. Has not been operational for sever because of inverter p
277	Boes and Luque (1993)	–	–	15 (average peak module efficiency); 13 (array field operational efficiency).	–	–	–	–	–	–	Assume 1992	ENTECH-3M Austin Austin, Texas. Opera concentrator system, 1989.

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

(Table A8.1 continued). **(continued on next page)**

	Reference	*Size (W)*	*Module life (yrs)*	*Efficiency (%)*	*Costs in current prices: O&M*	*BOS*	*Module*	*System*	*Electricity*	*Electricity cost, 1990 US¢/kWh*	*Year*	*Notes*
278	SERI (1989)	–	–	–	–	2,000 battery (storage for 5 days);100 wiring	7,000 (module including racks)	–	–	–	1987	All costs in $(1987)/ Actual cost of remot alone (1 kW) installe

						wiring controls; 1,500 labor.	racks)					
279	SERI (1989)	–	–	–	–	1,500 battery (storage for 5 days); 50 wiring controls; 1,000 labor.	5,000 (module including racks)	–	–	–	1990	All costs in $(1987)/ Predicted cost of ren stand-alone (1 kW) i system.
280	SERI (1989)	–	–	–	–	1,500 battery (storage for 5 days); 50 wiring controls; 800 labor.	3,000 (module including racks)	–	–	–	1995	All costs in $(1987)/ Predicted cost of ren stand-alone (1 kW) i system.
281	SERI (1989)	–	–	–	–	1,500 battery (storage for 5 days); 50 wiring controls; 500 labor.	2,000 (module including racks)	–	–	–	2000	All costs in $(1987)/ Predicted cost of ren stand-alone (1 kW) i system.
282	SERI (1989)	–	–	–	–	500 power conditioning; 500 wiring; 1,000 labor.	5,000 (module including racks or tracker)	–	–	–	1987	All costs in $(1987)/ Actual cost of large, i grid-tied system.
283	SERI (1989)	–	–	–	–	400 power conditioning; 300 wiring; 800 labor.	4,000 (module including racks or tracker)	–	–	–	1990	All costs in $(1987)/ Predicted cost of lar installed, grid-tied sy
284	SERI (1989)	–	–	–	–	200 power conditioning; 200 wiring; 500 labor.	2,000 (module including racks or tracker)	–	–	–	1995	All costs in $(1987)/ Predicted cost of lar installed, grid-tied sy

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

(Table A8.1 continued). (continued on next page)

	Reference	Size (W)	Module life (yrs)	Efficiency (%)	Costs in current prices: O&M	BOS	Module	System	Electricity	Electricity cost, 1990 US¢/kWh	Year	Notes
285	SERI (1989)	–	–	–	–	150 power conditioning; 150 wiring; 300 labor.	1,500 (module including racks or tracker)	–	–	–	2000	All costs in $(1987)/ Predicted cost of la installed, grid-tied sy
286	U.S. DOE (1991)	–	–	31	–	–	–	–	–	–	1988	Mechanically stack cell on single crystal under concentrated
287	Meridian Corporation (1992)	–	–	28.2 (Si concentrator cell)	–	–	–	–	–	–	1992	Si concentrator cell suns.
288	Meridian Corporation (1992)	–	–	15-17 (commercial concentrator Si module)	–	–	–	–	–	–	1992	Commercial concent module at 20 suns.

Note: Si = Silicon; CIS = Copper Indium Diselenide; GaAs = Gallium Arsenide; CdTe = Cadmium Telluride; O&M = operation and maintenance; BOS = balance of system.

(Table A8.1 continued)

Annex 9. Photovoltaic efficiencies

Year	Crystalline Silicon: Field module	Prototype module	Laboratory cell	Theoretical limit	Concentrator: Laboratory cell	Concentrator: Theoretical limit	Concentrator: Field module	Polycrystalline Silicon, Thin film: Laboratory cell	Field module	On steel lab. cell	O…
1974			17								
1976	7 to 8										

1980	9 to 10		8 to 12							
1980										
1982			17							
1983			18							
1984			19							
1985	11 to 12		20							6.9
1985										9.6
1986										
1987										
1988										
1989										
1990	12 to 13		14.6 to 23.2	33	20 to 27					
1990			24							
1991	11 to 13		22 to 23		>25	30		15		
1991			23							
1991										
1992	10 to 12	17.8	24.2	30 to 33	28.2		15-17		16	
1992			23 to 24							
1993										
1995	14 to 15		25							
1998										
2005										
2010										
2030	>18		>26							

Note: All values are from Annex 8 and are figures quoted by different sources in the literature reviewed.
All figures are percentages. s-c = single crystal; ns = not specified; in = initial value; st = stabilized value.

Table A9.1. Photovoltaic Efficiencies (continued on next page)

	Polycrystalline Si	*Copper Indium Diselenide (CIS)*	*CIS and Amorphous Silicon*			
			Multi-	*Multifunct.*	*Multifunct.*	*Multi-*

Year	Field module	Laboratory cell	Field module	Prototype module	Laboratory cell	Theoretical limit	junctional lab. cell	prototype module	theoretical limit	junctional field module
1974										
1976										
1980		16			10					
1980										
1982										
1983										
1984										
1985										
1985										
1986				5	9.6					
1987										
1988				11.1						
1989										
1990					11 to 14					
1990										
1991				11	14		14.6			
1991										
1991										
1992	8 to 9	16.2	9.7	11.1	14.3	23.5	15.6 (in)	12.3 (in)	42	
1992										
1993										
1995										
1998										
2005										18 (st)
2010										
2030										

Note: All values are from Annex 8 and ar figures quoted by different sources in the literature reviewed.

All figures are percentages. s-c = single crystal; ns = not specified; in = initial value; st = stabilized value.

(Table A9.1 continued) **(continued on next page)**

	Cadmium Telluride (CdTe)				Amorphous Silicon						
Year	Field module	Prototype module	Laboratory cell	Theoretical limit	Field module	Prototype module	Laboratory cell	Theoretical limit	Multi-junctional lab. cell	Multi-junctional field module	Mu pr m
1974							1 (in)				
1978											
1980											
1980											
1982											
1983											
1984											
1985											
1985											
1986		5	9								
1987							12 (ns)	22			
1988											
1989		7.3	12.3								
1990			11 to 13		4 to 5 (st)		11 to 12 (ns)		11 to 17 (ns)		
1990											
1991	6.5	8.1	12		4 to 5 (ns)	10 (ns)	12 (in)				
1991		10	12.7				>13 (in)				
1991			14								
1992	6.5	10	15.8	27 to 28	3 to 5 (st)	5 (st)	6 (st)	27 to 28	10 (st)	6 (st)	[illegible]
1992											
1993										7 to 8 (st)	
1995										10 (st)	

1998	
2005	
2010	
2030	

Note: All values are from Annex 8 and are figures quoted by different sources in the literature reviewed.
All figures are percentages. s-c = single crystal; ns = not specified; in = initial value; st = stabilized value.

(Table A9.1 continued) (continued on next page)

	Gallium Arsenide (GaAs)								*Not specified*		
		Concentrator			*Grown on:*		*Crystalline GaAs*				
Year	*Prototype module*	*Laboratory cell*	*On s-c Si multijunct. lab. cell*	*On GaSb multijunct. lab. cell*	*Si or Ge support (lab. cell)*	*GaAs support, then removed (lab. cell)*	*Laboratory cell*	*Theoretical limit*	*Com-mercial modules*	*Cells*	*Fl con m*
1974											
1976									10		
1980											
1980											
1982											
1983											
1984											
1985											
1985											
1986											
1987											
1988			31								
1989									11.5		
1990		29		37		22	25	33	10		
1990									11.5		

1991		30		20	25	11 to 17	34	
1991					25	5 to 15		
1991								
1992	22	28	34			12 to 13		
1992						15		
1993								
1995						10 to 20		
1998								1
2005								
2010								
2030						15 to 26		

Note: All values are from Annex 8 and are figures quoted by different sources in the literature reviewed.
All figures are percentages. s-c = single crystal; ns = not specified; in = initial value; st = stabilized value.

(Table A9.1 continued) (continued on next page)

	Multijunctional concentrator		*Flat plate thin film*		*Concentrators*		*Tandem cell*			
							2 amorphous layers		*2 crystalline layers*	
Year	*Lab. cells*	*Lab. cells; theor. limit*	*Comm'l modules*	*Lab. cells*	*Comm'l modules*	*Lab. cells*	*Lab. cells*	*Theoretical limit*	*Lab. cells*	*Theoretical limit*
1974										
1976										
1980						19 to 28.5				
1980						24.7				
1982									21	47
1983										
1984										
1985										
1986										
1986										

1987					17			
1988							14	29
1989								
1990								
1990								
1991	>34	40	4 to 6	12 to 14	14 to 17	27 to 32		
1991								
1991								
1992					15			
1992								
1993								
1995			8 to 10	15 to 18	18 to 20	35		
1998					23 to 29			
2005								
2010								
2030			>15	>20	>25	>40		

Note: All values are from Annex 8 and are figures quoted by different sources in the literature reviewed.
All figures are percentages. s-c = single crystal; ns = not specified; in = initial value; st = stabilized value.

(Table A9.1 continued) (continued on next page)

	System		
Year	*Flat plate*	*Con-centrator*	*Type not specified*
1974			
1976			
1980			
1980			
1982		6.5	

1983			
1984			
1985		7	
1985			
1986			
1987	10	14.4	8
1988			7.2
1989			
1990	9		
1990			
1991			
1991			
1991			
1992		9	12
1992			
1993			
1995			
1998	11.7 to 15.3	20.7 to 26.1	
2005			
2010			15
2030			

Note: All values are from Annex 8 and are figures quoted by different sources in the literature reviewed.
All figures are percentages. s-c = single crystal; ns = not specified; in = initial value; st = stabilized value.

(Table A9.1 continued)

Annex 10. Photovoltaic module costs

Item*	Reference	Module cost	Module cost [$(1990)/$W_p$] Size of order: <1000 W_p	1 kW_p-1 MW_p	>1 MW_p	"Large" quantity	"Small" quantity	Size not specified	W_p	Year	Notes
1	Costello and Rappaport (1980)	< $10/$W_p$ (assume 1980 $)						15.85	_	1980	Module cost
2	Costello and Rappaport (1980)	~ $20/$W_p$ (assume 1975 $)				48.53			_	1975	First large US federal of modules for terrest
3	Costello and Rappaport (1980)	~ $15-36/$W_p$ (assume 1978 $)					30.01-72.03		_	1978	Result of SERI survey commercial module p 1978, sold in small qu
4	Costello and Rappaport (1980)	~ $10-15/$W_p$ (assume 1978 $)				20.01-30.01			_	1978	Result of SERI survey commercial module p *1978, sold in large qu*
18	Carlson (1990)	$4/$W_p$ (1987 $)						4.59	_	1988	Called solar cell cost factory module price
19	Carlson (1990)	$100/$W_p$ (assume 1972 $)						312.28	_	Early 70s	Assume 1972. Called cost in text, but factor price in graph.
20	Carlson (1990)	$13/$W_p$ (1987)						14.93	_	1980	Factory price for mod
21	Real Goods (1991)	$6.85-7.27/$W_p$ (1991)	6.97	6.57					48 ea.	1991	Manufacturer (Mfr.): (heliopower); H-4810; crystal; actual sale pri module. Higher price modules; lower for >2
22	Real Goods (1991)	$4.47-4.99/$W_p$ (1991)	4.79	4.29					96 ea.	1991	Mfr.: Siemens; recycle modules (6-7 yrs old); crystal; actual sale pri module. Higher price modules; lower for >2

*Item = item from Annex 8. W_p = peak Watts.

Table A10.1. Photovoltaic Module Costs (continued on next page)

			Module cost [\$(1990)/W_p] *Size of order*								
Item[a]	*Reference*	*Module cost*	*<1000 W_p*	*1 kW_p- 1 MW_p*	*>1 MW_p*	*"Large" quantity*	*"Small" quantity*	*Size not specified*	*W_p*	*Year*	*Notes*
23	Real Goods (1991)	\$8.73-9.35/W_p (1991)	8.97	8.37					48 ea.	1991	Mfr.: Siemens; M-75; si crystal; actual sale pric module. Higher price is modules; lower for >20
24	Real Goods (1991)	\$9.04-9.42/W_p (1991)	9.03	8.67					53 ea.	1991	Mfr.: Siemens; M-55; si crystal; actual sale pric module. Higher price is modules; lower for >20
25	Real Goods (1991)	\$8.98-9.73/W_p (1991)	8.61-9.33						40 ea.	1991	Mfr.: Siemens; M-40; si crystal; actual sale pric module. Higher price is modules; lower for >20
26	Real Goods (1991)	\$9.51-10.21/W_p (1991)	9.12-9.79						43 ea.	1991	Mfr.: Siemens; M-65; si crystal; actual sale pric module. Higher price is modules; lower for >20
27	Real Goods (1991)	\$11.32/W_p (1991)	10.86						22	1991	Mfr.: Siemens; M-20; si crystal; self-regulating r actual sale price of mod
28	Real Goods (1991)	\$9.16-9.97/W_p (1991)	8.78-9.56						37 ea.	1991	Mfr.: Siemens; M-35; si crystal; actual sale pric module. Higher price is modules; lower for >20
29	Real Goods (1991)	\$8.94-9.56/W_p (1991)	9.17	8.57					48 ea.	1991	Mfr.: Siemens; M-50; si crystal; actual sale pric module. Higher price is modules; lower for >20
[illegible]	Real Goods (1991)	[illegible]	[illegible]						[illegible]	1991	[illegible]

30	Real Goods (1991)	$17.80/$W_p$ (1991)	17.07						5	1991	Mfr.: Siemens; T-5; sin crystal; useful for small applications; actual sal module.
31	Real Goods (1991)	$23.60/$W_p$ (1991)	22.63						2.5	1991	Mfr.: Siemens; G-50; si crystal; useful for very s applications; actual sal module.

(Table A10.1 continued) (continued on next page)

Item*	Reference	Module cost	Module cost [$(1990)/$W_p$] Size of order: ≤1000 W_p	1 kW_p- 1 MW_p	>1 MW_p	"Large" quantity	"Small" quantity	Size not specified	W_p	Year	Notes
32	Real Goods (1991)	$7.82-8.22/$W_p$ (1991)	7.88	7.5					51 ea.	1991	Mfr.: Kyocera; K-51; multicrystal; actual sal module. Higher price f modules; lower for >20
33	Real Goods (1991)	$7.92-8.59/$W_p$ (1991)	7.59-8.24						45.3 ea.	1991	Mfr.: Kyocera; K-45; m crystal; actual sale pri module. Higher price f modules; lower for >20
34	Real Goods (1991)	$8.60-8.92/$W_p$ (1991)	8.55	8.25					62.7 ea.	1991	Mfr.: Kyocera; K-63; m crystal; actual sale pri module. Higher price f modules; lower for >20
35	Real Goods (1991)	$13.30/$W_p$ (1991)	12.75						30	1991	Mfr.: Solarex; MSX30 Unbreakable Module; crystal; Thin, lightweig portable; actual sale p module.
36	Real Goods (1991)	$12.85/$W_p$ (1991)	12.32						18.6	1991	Mfr.: Solarex; MSX18; able Module; multicrys lightweight, portable; a

Item*	Reference	Module cost	<100 W_p	1 kW_p-1 MW_p	>1 MW_p	"Large" quantity	"Small" quantity	Size not specified	W_p	Year	Notes
											price of module.
37	Real Goods (1991)	$13.90/$W_p$ (1991)	13.33						10	1991	Mfr.: Solarex; MSX10; able Module; multicrys lightweight, portable; a price of module.
38	Real Goods (1991)	$6.98-7.32/$W_p$ (1991)	7.02	6.69					60 ea.	1991	Mfr.: Solarex; MSX60; crystal; actual sale pri module. Higher price f modules; lower for >2(
39	Real Goods (1991)	$7.13-7.48/$W_p$ (1991)	7.17	6.84					56 ea.	1991	Mfr.: Solarex; MSX56; crystal; actual sale pri module. Higher price i modules; lower for >2(

*Item = item from Annex 8. W_p = peak Watts.

(Table A10.1 continued) (continued on next page)

Item*	Reference	Module cost	Module cost [$(1990)/$W_p$] Size of order: <100 W_p	1 kW_p-1 MW_p	>1 MW_p	"Large" quantity	"Small" quantity	Size not specified	W_p	Year	Notes
40	Real Goods (1991)	$6.77-7.34/$W_p$ (1991)	7.04	6.49					53 ea.	1991	Mfr.: Solarex; MSX53 crystal; actual sale pri module. Higher price i modules; lower for >2
41	Real Goods (1991)	$7.86-8.48/$W_p$ (1991)	7.65-8.13						40	1991	Mfr.: Solarex; MSX40; crystal; actual sale pri module. Higher price i modules; lower for >2
42	Real Goods (1991)	$6.90/$W_p$ (1991)	6.62						10	1991	Mfr.: Chronar; amorph originally rated 12W, l rating them as 10W to 20% degradation in fir

Item*	Reference	Module cost	<1000 W_p	1 kW_p- 1 MW_p	>1 MW_p	"Large" quantity	"Small" quantity	Size not specified	W_p	Year	Notes
											actual sale price of m
51	U.S. Congress (1992)	\$4,000-6,000/kW_p (assume 1992 \$)				8.74	5.61		–	1992	Assume 1992. UN Co on Development & Uti New & Renewable So Energy: \$4000/kW_p p crystalline silicon larg (excl. taxes and deliv retailer: \$6000 for sma Dominican Republic: \$6000/kW_p for 38W p
52	U.S. Congress (1992)	\$1,000/kW_p (assume 1990 \$)						1	–	1995	PV industry reps. fore according to SERI.
53	U.S. Congress (1992)	\$1,500/kW_p (assume 1989 \$)				1.56			–	1994	EPRI estimate for larg plate system.
61	National Research Council (1976)	\$20-30/Wp						45.87-68.81	–	1976	
63	National Research Council (1981)	\$22/W_p (assume 1976 \$)						50.46	–	1976	In the U.S.
64	National Research Council (1981)	\$7-10/W_p (assume 1980 \$)						11.09-15.85	–	1980	In the US with 2 MW p

*Item = item from Annex 8. W_p = peak Watts.

(Table A10.1 continued) **(continued on next page)**

Item*	Reference	Module cost	Module cost [\$(1990)/W_p] Size of order: <1000 W_p	1 kW_p- 1 MW_p	>1 MW_p	"Large" quantity	"Small" quantity	Size not specified	W_p	Year	Notes
65	Hislop (1992)	\$5/W_p (MW_p orders), \$10/W_p (>1 kW_p orders), \$25/W_p (<100	23.98	9.59	4.79				–	1991	

		W_p orders).				
66	Palz (1978)	$20/$W_p$ (assume 1975 $)	46.53	_	1975	Terrestrial PV yearly pı volume 100 kW in 197
69	SERI (1989)	$20/W (assume 1977 $)	43.06	_	1977	
70	SERI (1989)	$4-5/W (assume 1988 $)	:.42-5.52	_	1988	
71	NREL (1992c)	$500/W (assume 1972 $)	1,561.39	_	1972	
72	NREL (1992c)	$4.00-4.50/W	4-4.5	_	1990	
109	Thornton and Brown (1992)	$4.00-8.00/W (assume 1991 $)	3.84-7.67	_	1991	
113	International Energy Agency (1987)	$550/sq. m ($4.40/W_p using quoted 12.5% efficiency) (1982 $)	5.95	_	1987	Assume 1987. Flat plat systems. All costs in 1 For area with solar ins 6 kWh/sq. m/day.
114	International Energy Agency (1987)	$40-75/sq. m ($0.24-0.58/W_p using quoted 13-17% efficiency) (1982 $)	0.32-0.78	_	Late 90s	Assume 1998. Flat pla systems. All costs in 1 For area with solar ins 6 kWh/sq. m/day.
115	International Energy Agency (1987)	$750/sq. m ($4.41/W_p using quoted 17% efficiency) (1982 $)	5.97	_	1987	Assume 1987. Concen systems. All costs in 1 For area with solar ins 6 kWh/sq. m/day.

*Item = item from Annex 8. W_p = peak Watts.

(Table A10.1 continued) **(continued on next page)**

Module cost [$(1990)/$W_p$]
Size of order

Item*	Reference	Module cost	<1000 W_p	1 kW_p-1 MW_p	>1 MW_p	"Large" quantity	"Small" quantity	Size not specified	W_p	Year	Notes
116	International Energy Agency (1987)	$90-100/sq. m ($0.31-0.43/W_p using quoted 23-29% efficiency) (1982 $)						0.42-0.66	_	Late 90s	Assume 1998. Conce systems. All costs in 1 For area with solar ins 6 kWh/sq. m/day.
129	Tsuchiya (1992)	7,000 yen/Wp						63.84	_	1979	Assume cost is in 197 rency. Adjusted to 199 then to 1990 $ (see Ar
130	Tsuchiya (1992)	4,000 yen/Wp						33.78	_	1980	Assume cost is in 198 rency. Adjusted to 199 then to 1990 $ (see Ar
131	Tsuchiya (1992)	3,500 yen/Wp						28.18	_	1981	Assume cost is in 198 currency. Adjusted to 1 then to 1990 $ (see Ar
132	Tsuchiya (1992)	2,200 yen/Wp						17.25	_	1982	Assume cost is in 198 rency. Adjusted to 199 then to 1990 $ (see Ar
133	Tsuchiya (1992)	1,800 yen/Wp						13.67	_	1983	Assume cost is in 198 rency. Adjusted to 199 then to 1990 $ (see Ar
134	Tsuchiya (1992)	1,500 yen/Wp						11.3	_	1984	Assume cost is in 198 rency. Adjusted to 199 then to 1990 $ (see Ar
135	Tsuchiya (1992)	1,200 yen/Wp						8.86	_	1985	Assume cost is in 198 rency. Adjusted to 199 then to 1990 $ (see Ar
136	Tsuchiya (1992)	1,100 yen/Wp						8.07	_	1986	Assume cost is in 198 rency. Adjusted to 199 then to 1990 $ (see Ar
137	Tsuchiya (1992)	1,000 yen/Wp						7.33	_	1987	Assume cost is in 198 rency. Adjusted to 199

then to 1990 $ (see Ar

*Item = item from Annex 8. W_p = peak Watts.

(Table A10.1 continued) (continued on next page)

Item*	Reference	Module cost	Module cost [$(1990)/$W_p$] Size of order: <1000 W_p	1 kW_p-1 MW_p	>1 MW_p	"Large" quantity	"Small" quantity	Size not specified	W_p	Year	Notes
138	Tsuchiya (1992)	900 yen/Wp						6.55	_	1988	Assume cost is in 198 rency. Adjusted to 19 then to 1990 $ (see A
139	ESMAP (1989)	Rs. 104/W_p (assume 1989)	5.22	5.22					103 / 3,423	1989	Decentralized DC sys land costs; assumptio insolation = 3.5 kWh/ (worst case), 2 day st requirement, and cert and controller lifetime resp.). Adj. to 1990 P then to 1990 $ (see A
150	Perlack, Jones, and Waddle (1990)	$4-5/Wp						4 to 5	_	1990	Costs of larger systen lower.
152	UNDP (1992)	$4/W (module cost for large consignments, 50 MW)			3.74				50 MW	1992	Assume 1992. Interna price for modules per load.
154	UNDP (1992)	$12.17/W (1991)	11.67						_	1991	Solematic module pri
155	UNDP (1992)	$9.22/W (1991)	8.84						_	1991	Battery World module
156	UNDP (1992)	$9.27/W (1991)	8.89						_	1991	Solarcomm module p
157	ESMAP back-to-office report, 1992	$260.69 ($5.21/Wp)	4.87						50	1992	Assume 1992
158	ESMAP (1991b)	$495 ($5.5/Wp)	5.5						90	1990	Assumptions incl. 1 kV

											age requirement; 10% rate; 4 kWh/sq. m/day (worst case); 80% bat energy efficiency; 70% depth of discharge; 2 lifetime; 8 yr controlle 0.25 kWh/day system
160	Meridian Corporation (1992)	\$30/W (currency year not specified) (assume 1975)						72.8	_	1975	From Maycock (1991)

*Item = item from Annex 6. W_p = peak Watts.

(Table A10.1 continued) (continued on next page)

Item*	Reference	Module cost	Module cost [\$(1990)/W_p] Size of order: <1000 W_p	1 kW_p-1 MW_p	>1 MW_p	"Large" quantity	"Small" quantity	Size not specified	W_p	Year	Notes
161	Meridian Corporation (1992)	\$13/W (currency year not specified) (assume 1980)						20.6	_	1980	From Maycock (1991).
162	Meridian Corporation (1992)	\$7/W (currency year not specified) (assume 1985)						8.5	_	1985	From Maycock (1991).
163	Meridian Corporation (1992)	\$4/W (currency year not specified) (assume 1990)						4	_	1990	From Maycock (1991).
164	Meridian Corporation (1992)	\$3/W (currency year not specified) [illegible]						2.8	_	1995	Projected values from M (1991).

		(assume 1992)									
165	Meridian Corporation (1992)	$2/W (currency year not specified) (assume 1992)						1.87	_	2000	Projected values from M (1991).
166	Meridian Corporation (1992)	$1.4/W (currency year not specified) (assume 1992)						1.31	_	2005	Projected values from M (1991).
167	Meridian Corporation (1992)	$1/W (currency year not specified) (assume 1992)						0.93	_	2010	Projected values from M (1991).
168	Meridian Corporation (1992)	Rs. 90 (1988)/W_p						5.95	_	1988	Assume 1988. In India Adjusted to 1990 Indian and then to 1990 $ as c in Annex 1.
174	Meridian Corporation (1992)	$5.30-10.50/W						4.95-9.81	_	1992	Assume 1992. Estimate stand-alone systems.

*Item = item from Annex 8. W_p = peak Watts.

(Table A10.1 continued) **(continued on next page)**

			Module cost [$(1990)/$W_p$] Size of order								
Item*	Reference	Module cost	<1000 W_p	1 kW_p-1 MW_p	>1 MW_p	"Large" quantity	"Small" quantity	Size not specified	W_p	Year	Notes
175	Meridian Corporation (1992)	$5,854/kW (1992 $)					5.47		_	1990	Levelized cost of grid independent system; 1 discount rate; assumpt 5 yr battery life and 10 controls life. Assume "s quantity of modules re

176	Meridian *Corporation (1992)*	$3,512/kW *(1992 $)*		3.26	_	1995	Levelized cost of grid *independent system; 1* discount rate; assumpl 5 yr battery life and 10 controls life. Assume "a quantity of modules re
177	Meridian Corporation (1992)	$2,342/kW (1992 $)		2.19	_	2000	Levelized cost of grid independent system; 1 discount rate; assumpl 8 yr battery life and 15 controls life. Assume "a quantity of modules re
178	Meridian Corporation (1992)	$1,756/kW (1992 $)		1.64	_	2010	Levelized cost of grid independent system; 1 discount rate; assumpt 8 yr battery life and 15 controls life. Assume "a quantity of modules re
179	Meridian Corporation (1992)	$4,683/kW (1992 $)	4.38		_	1990	Levelized cost of grid c system; 10% discount assumptions incl. 5 yr l life and 10 yr controls l Assume "large" quanti modules required.
180	Meridian Corporation (1992)	$2,342/kW (1992 $)	2.19		_	1995	Levelized cost of grid c system; 10% discount assumptions incl. 5 yr l life and 10 yr controls l Assume "large" quanti modules required.

*Item = Item from Annex 8. W_p = peak Watts.

(Table A10.1 continued) **(continued on next page)**

Module cost [$(1990)/$W_p$]

Item*	Reference	Module cost	Size of order <1000 W_p	1 kW_p-1 MW_p	>1 MW_p	"Large" quantity	"Small" quantity	Size not specified	W_p	Year	Notes
181	Meridian Corporation (1992)	$1,756/kW (1992 $)				1.64			–	2000	Levelized cost of grid system; 10% discour assumptions incl. 8 y life and 15 yr control Assume "large" quan modules required.
182	Meridian Corporation (1992)	$1,406/kW (1992 $)				1.31			–	2010	Levelized cost of grid system; 10% discour assumptions incl. 8 y life and 15 yr control Assume "large" quan modules required.
189	Carlson (1992)	$5/$W_p$ (for large quantities)				5			–	1990	
190	Carlson (1992)	About $20/$W_p$ (assume 1980 $)						31.69	–	1980	
191	Remy and Durand (1992)	$5.3/$W_p$ (selling price)						5.3	–	1990	1990 (current) prices
192	Remy and Durand (1992)	$2.6/$W_p$ (selling price) (assume 1990 $)						2.6	–	1995	Projected price assur absence of large (util markets but expectin doubling of sales eve
193	Kimura (1992)	Yen 600-700/W_p ($4.60-5.40/Wp)						4.6-5.4	–	1990	Production level of 3-
205	Hankins (1993)	US$13-15/Wp	12.15-14.02						–	1992	Assume 1992. PV m to customer in Zimba
210	Hankins (1993)	$9.38/$W_p$ (assume 1992 $)	8.77						–	1992	Assume 1992. Typica standard module in D Republic.
211	Hankins (1993)	$7.80/$W_p$	7.29						–	1992	Assume 1992. Typica

		(assume 1992 $)				standard module in R
212	Hankins (1993)	$10.40/$W_p$ (assume 1992 $)	9.72	–	1992	Assume 1992. Typica standard module in S

*Item = item from Annex 8. W_p = peak Watts.

(Table A10.1 continued) **(continued on next page)**

Item*	Reference	Module cost	Module cost [$(1990)/$W_p$] Size of order ≤1000 W_p	1 kW_p-1 MW_p	>1 MW_p	"Large" quantity	"Small" quantity	Size not specified	W_p	Year	Notes
213	Hankins (1993)	$14.34/$W_p$ (assume 1992 $)	12.4						_	1992	Assume 1992. Typical standard module in Zi
218	Kelly (1993)	$20/$W_p$ (1989 $)						21.06	_	1976	The average selling p plate photovoltaic moc
219	Kelly (1993)	$7.1/$W_p$ (1989 $)						7.48	_	1984	The average selling p plate photovoltaic moc
220	Kelly (1993)	$6.2/$W_p$ (1989 $)						6.53	_	1990	The average selling p plate photovoltaic moc
245	Green (1993)	$5/$W_p$ (1989 $)						5.27	_	1989	1989. Average module
264	Zweibel and Barnett (1993)	$200/sq. m ($2.06/W_p using quoted efficiency of 9.7%) (assume 1992$)						1.93	_	1992	Assume 1992. Copper diselenide
265	Zweibel and Barnett (1993)	$150/sq. m ($2.31/W_p using quoted efficiency of 6.5%) (assume 1992$)						2.16	_	1992	Assume 1992. Cadmi telluride
266	Zweibel and Barnett (1993)	$400/sq. m ($3.08/W_p using quoted efficiency of 13%) (assume 1992$)						2.88	_	1992	Assume 1992. Locatio assumes average US of 1600 kWh/sq. m/yr flat plate.

*Item = item from Annex 6. W_p = peak Watts.

(Table A10.1 continued)

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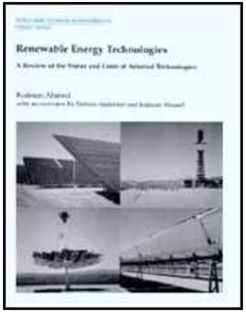

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Foreword

Major advances in recent year-are have led to improvements in efficiency of renewable energy technologies and reductions in costs. These developments, the establishment of the Global Environment Facility in 1991, and the World Bank's operational initiatives on environmentally sustainable development are providing new opportunities for the finance of renewable energy investments.

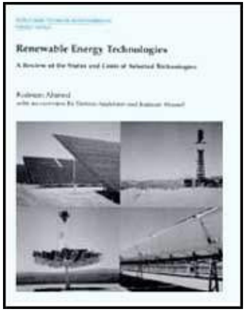
This is the first in a series of reports on renewables. It reviews the cost and status of renewable energy technologies, concentrating on the use of biomass for fuel and electricity, solar-thermal technologies, and photovoltaics. Parallel studies currently under

way in the Bank include one on costs and markets and others reporting on operating experience with renewable energy technologies in various countries and regions.

These studies resect the growing interest of the World Bank Group in renewable energy technologies. There are three reasons for this interest. First, from an economic point of view, renewables have good prospects of giving good returns to investment, and indeed they are already economically attractive for an increasing number of small-scale applications. With further development, large-scale applications should follow. That renewables generally have short lead times is another economically attractive feature. Second, as many have noted, solar schemes m particular are environmentally attractive. Third, renewable energy technologies are well-suited to the circumstances of developing countries. For example, because most developing countries are in tropical or subtropical regions, their levels of incident solar energy per square kilometer are twice the levels found in many industrial countries; moreover, the day to day quality of the insolation is superior, and seasonal variations are less.

This report is also among the first in a new Energy Series within the ongoing World Bank technical papers volumes. The new Energy Series technical papers will replace the Industry and Energy Department's "pink" series energy working papers. We are making this shift to take advantage of the World Bank's global distribution network for what we believe will be publications of significance and widespread interest

Richard Stem
Director
Industry and Energy Department



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Abstract

This paper examines the evidence on the historic and projected costs of selected renewable energy technologies and assesses developments. It reviews estimates of more than 50 studies and expresses the costs on a common basis for photovoltaics, solar-thermal, and biomass for liquid fuels and electricity production.

Findings show that them has been a decline in the cost of ethanol production since the 1970s, attributable to technology improvements and a shift toward cheaper crops. The technology developments to convert low-cost cellulosic materials to ethanol promise further reductions in cost.

The costs of electricity from biomass show great variability. Costs me site-specific and

vary with raw material costs but still compare well with the costs of fossil-fired generation and even hydro generation in favorable situations.

Costs of electricity from solar-thermal technologies show much variability because with the notable exception of the parabolic trough technology all are in the experimental stage. However, experience to date and engineering analysis both point consistently to costs in the 5 to 10 cents per kilowatt hour range in the next generation of schemes. Furthermore, the possibilities for low cost storage, high conversion efficiencies, and short lead times make this an attractive option

Costs of photovoltaic modules have deceased by a factor of 10 over the past fifteen years and by more than 50 since the early 1970s. The possibilities for further cost reduction are far from being exhausted Key developments with concentrator cells and multijunction devices, commercialization of new thin-film devices, and introduction of batch production processes in manufacturing promise further inductions.

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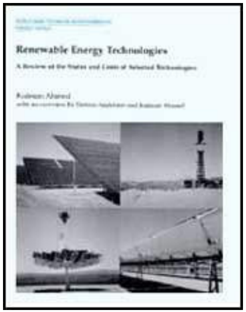

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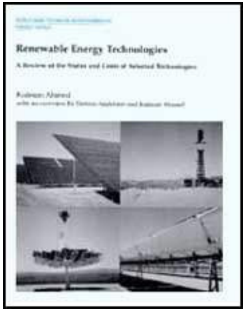

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Abbreviations and acronyms

AC	alternating current
BAU	business as usual
BOS	balance of system
CdTe	cadmium telluride
CENAL	Executive Secretariat of the National Alcohol Commission
CIS	copper iridium diselenide
CO_2	carbon dioxide
DC	direct current
DM	deutsche made
DOE	Department of Energy
EC	European Community
ECU	European Currency Unit
EPRI	Electric Power Research Institute Technical Assessment Guide

TAG	
ESMAP	Energy Sector Management Assistance electron volts Programme eV
GaAs	gallium arsenide
GEF	Global Environment Facility
GJ	gigajoules or 1,000,000,000 joules
GWh	gigawatt-hour (1,000,000 kilowatt-hours)
ha	hectare (= 0.01 square kilometers)
kW/m_2	kilowatts per square meter kWh kilowatt-hours
kWp	peak kilowatt
MilBtu	million British Thermal Units
MW	megawatt
MWp	peak megawatt
NOx	oxides of nitrogen
O&M	operating and maintenance
ORNL	Oak Ridge National Laboratory
PEICCE	Proyecto Energtico Istmo Centroamericano
PURPA	Public Utility Regulatory Policies Act
PV	photovoltaic
R&D	research and development
R. D & D	research, development and demonstration
Rs.	rupees
SERI	Solar Electric Research Institute
SRWC	short rotation woody crop sun unit used cell, defined as the solar radiation incident on the

	cell divided to describe the intensity of illumination on a PV by the solar radiation that would be incident on the cell under" one standard sun" (i.e., under sunlight with a total intensity of 1 kW/m^2 and a standard spectrum).
TCD	tons cane per day
TOE	ton of oil equivalent ton 1,000 kilograms
U.S.	United States
Wp	peak watts

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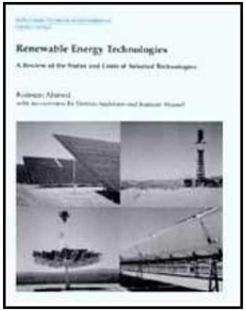

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Renewable Energy Technologies: A Review of the Status and Costs of Selected

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1. Overview

Introduction

Several studies have reported significant declines in the unit costs of renewable energy technologies over the past two decades in photovoltaics, solar-thermal, wind, and the use of biomass for producing electricity and liquid fuels and it is now clear that further reductions in costs can be expected with technical progress and market growth. Changes in relative costs are beginning to alter the comparative economics of the production of energy from fossil, nuclear, and renewable resources in important ways.

This paper examines the evidence on the historic and projected costs of selected renewable energy technologies and assesses developments. It reviews estimates from more than 50 studies and expresses the costs on a common basis. There are many excellent studies available, and those familiar with them will also be familiar with the results presented here. On reviewing the material, we found that it frequently estimated costs in different ways, used different discount rates, and included or excluded particular components of cost. Moreover, some of the works were tabletop studies, whereas others used actual costs and commercial data Hence, to assess how costs are actually changing and to assess prospects for further developments, we tried to iron out these inconsistencies. It was not possible do this completely in every case, and some inconsistencies and ambiguities in the costs remain' but the uncertainties, we think have been reduced, and the trends are fairly clear. Yet even when this is done, unit costs differ appreciably because they relate to different technologies in different stages of development, as would be expected for newly emerging technologies and when the competition among approaches is both intense and economically healthy.

This paper was prepared for the Global Environment Facility (GEE:), as an input to its

inquiries on cost-effective options for abating emissions of carbon dioxide. It concentrates on three types of renewable energy: photovoltaics, solar-thermal, and the use of biomass for producing electricity and liquid fuels. Developments of other renewables, such as wind and ocean systems, also have been notable but are left for a separate study. Brief descriptions and analyses of the various technologies are provided, but these, it should be noted, are no substitute for the excellent and encyclopedic edition of studies, Renewable Energy: Sources for Fuel and Electricity (Johansson and others 1993).

Costs have been calculated in 1990 prices. All relevant data, assumptions, and sources are tabulated in the annexes. The estimates presented below are actual figures up to 1992 and projections thereafter.

Findings

The costs of ethanol from biomass

Figure 1.1 summarizes the main findings. The data' mostly from Brazil and the United States, show the costs of ethanol production from different raw materials ore, sugarcane, and cellulosic materials compared with the ex-refinery costs of gasoline. The large variance in costs is mainly caused by the differing; costs of the raw materials, which account for 60 to 80 percent of total costs.

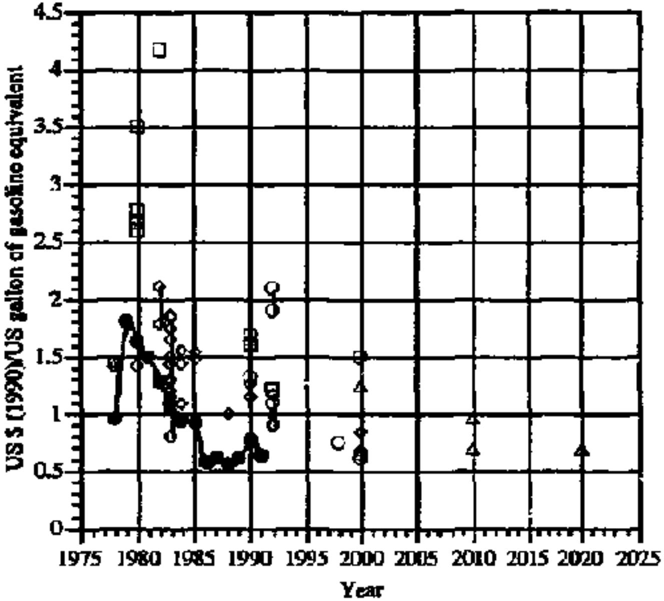

Figure 1.1. Cost of Ethanol Production Compared with Gasoline Prices, 1977-2020

The decline in costs since the 1970s has been significant and is attributable to technology improvements and a shift toward cheaper crops. The outliers in the 1970s were corn crops in the United States, the costs of ethanol from sugarcane in Brazil being much lower; but costs have since declined for both types of material. The recent emergence of low-cost cellulosic materials—woody materials and agricultural residues—for ethanol production has been made possible by advances in biotechnology for converting the sugars in the materials to ethanol, and these advances promise further reductions in costs. Cellulosic materials have the advantage of not competing with food crops for land, which also helps

to reduce costs. The costs of ethanol were beginning to compare well with gasoline until the collapse of oil prices in the mid-1980s.

The costs of electricity from biomass

The costs of electricity from biomass show great variability, even for co-generation plants using waste materials and residues. The boiler and generator technologies now in use are standard, have been used for many decades, and have seen no obvious decline in costs in recent years. Costs are site specific and vary with raw material costs; but, as Figure 1.2 shows, they compare well with the costs of fossil-fired generation and even hydro generation in favorable situations; some are as low as 2 to 4 cents per kilowatt hour.

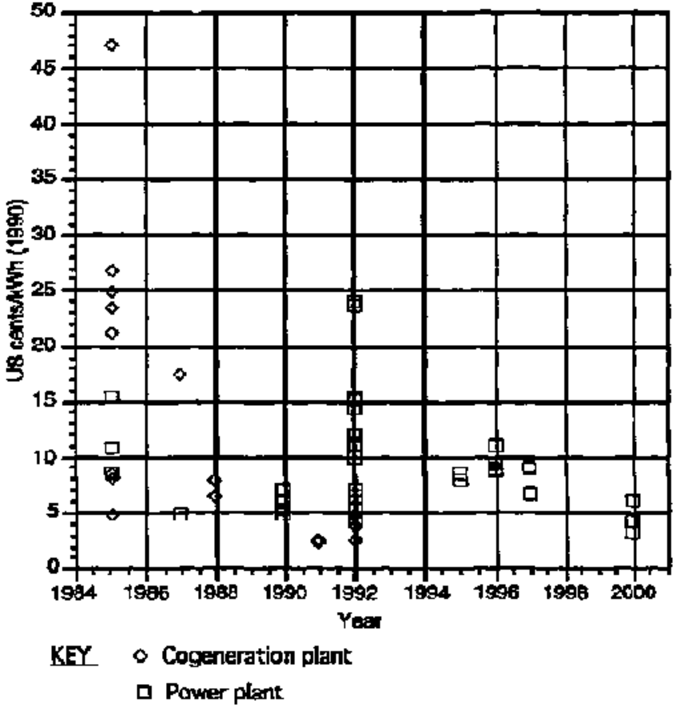

Figure 1.2. Cost of Electricity from Biomass. 1985-2000

The recent proposals to use biomass gasification combined-cycle technologies show much promise for reducing costs for large-scale power generation again in areas where wood yields are good. Another much-discussed way of reducing net costs (not studied here) is to use the schemes where they can serve more than one purpose, such as reforestation, restoration of degraded land, protection of watersheds, and generation of electricity.

Solar-thermal technologies for power generation

Recent experience with solar-thermal dates back only to the mid-1980s. Costs show much variability because—with the notable exception of the parabolic trough technology—all are in the experimental stage. Figure 13 shows the current and projected costs of generation from the three main technologies for larger-scale generation of about 50 MW and up wardpabolic trough, central receiver, and parabolic dish. Experience to date and engineering analysis both point consistently to costs in the 5 to 10 cents per kilowatt hour range in the next generation of schemes.

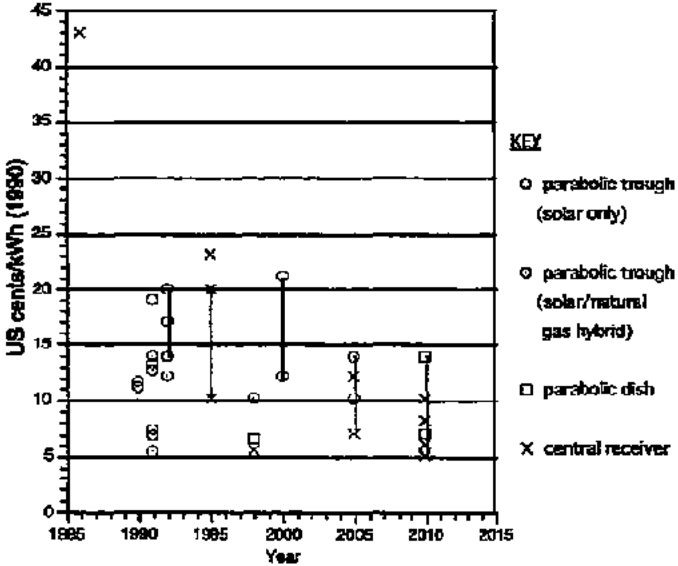

Figure 1.3. Calculated Cost d Electricity from Large-Scale Solar-Thermal Technologies, 1906 2010

Three other factors deserve special mention: the possibilities for low-cost thermal storage, so schemes can be operated in the evenings or on cloudy days; the high temperatures the central receiver technologies now being tested, which promise high conversion efficiencies; and short lead times for construction and installation (recent parabolic trough schemes in California were installed and operating within a year).

Photovoltaics

Costs of photovoltaic modules have decreased by a factor of 10 over the past 15 years and by more than 50 since the early 1970s (Figure 1.4). The dispersion in the cost data shown in the figure reflects the wide range of modules now under development; the size of the consumer's order also has an effect on unit costs. The general decrease in costs is clear from the data and can be attributed to technical progress in materials, to cell design and manufacturing methods, and to scale economies in manufacturing and gains in PV production experience. Large gains have also been made in conversion efficiencies, from about 7 percent for crystalline silicon modules in 1976 to 13 percent today. For amorphous silicon, stabilized efficiencies of mono-junctional laboratory cells rose from less than 1 percent to more than 6 percent in the same period.

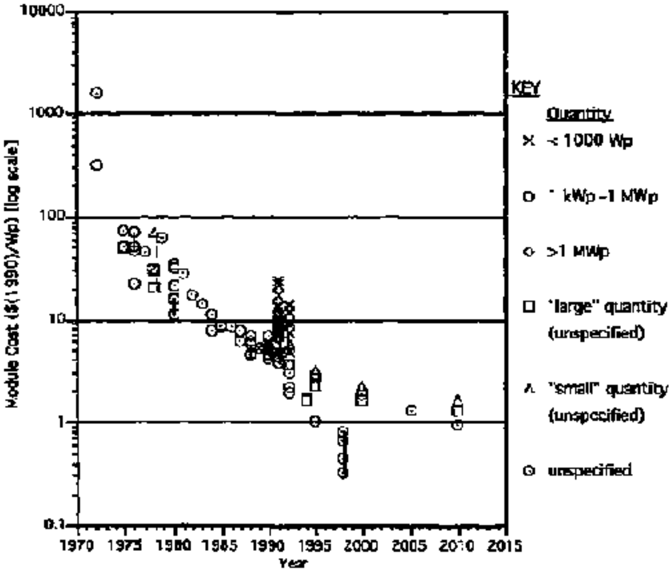

Figure 1.4. Costs of Photovoltaic Nodules 1972-2010

The possibilities for reducing costs further are far from being exhausted. The following are among the key developments taking

- **The use of multijunction devices to improve conversion efficiencies**
- **Further developments in concentrator cells (already achieving efficiencies of more than 28 percent with crystalline silicon and 27 to 30 percent with gallium arsenide)**
- **New materials for thin-film devices, now ready for commercial production**

- **Improvements in cell design to improve photon capture and reduce resistive losses**
Introduction of batch production processes in manufacturing, which should also lead to significant scale economies.

The world market for PVs is still small, having increased from less than 1 MW in 1978 to 57.9 MW in 1992, and it is generally expected that the above developments will tend to appreciable reductions in costs as the market expands further and manufacturers move to larger production volumes. Numerous small-scale applications are now economical (see chapter 4).

Wind

Wind energy technologies are not reviewed here, but their costs fall into the same pattern as that for the other renewable energy technologies discussed, and for much the same reasons—technical progress in the design of the machines, short lead times, and scale economies in manufacture. Costs have declined to the range of 6 to 10 cents per kWh in the past eight years, and wind turbines are becoming established as a commercial source of supplementary power in areas with favorable wind regimes. Figure 1.5 shows some data for California, taken from Cavallo, Hock, and Smith (1993), who project costs in the 4 to cents per kilowatt hour range with the new generation of technologies. Offshore systems are also under development.

Conclusions and implications

Progress in renewable energy technologies has been positive; the reported reductions in costs, improvements in conversion efficiencies, and technical progress in manufacturing are all well founded, and there are convincing engineering economic reasons for expecting efficiencies to improve and costs to fall further. By financing applications of renewables in electricity generation, the GEF and the World Bank will help to develop markets, reduce

costs, and demonstrate the technologies.

The applications are likely to be on a small scale in the near term, although with "bundling" the potential applications are sufficiently numerous that large-scale programs could be formulated Solar-thermal would be suitable for larger-scale generation already if there were a greater commitment to its development and application in national R&D and demonstration programs.

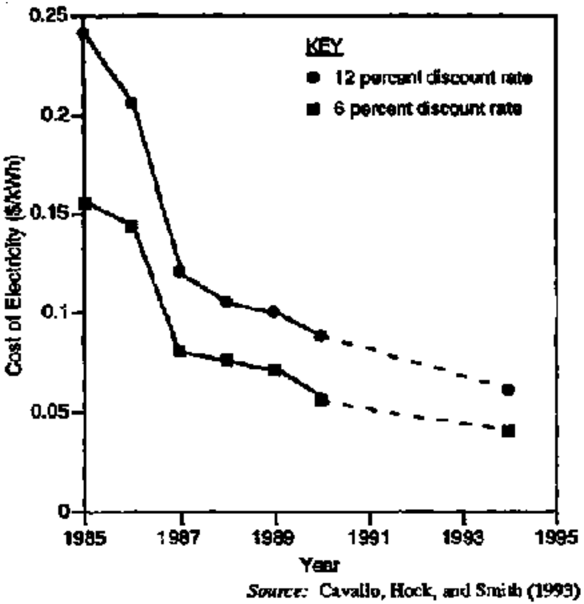

Figure 1.5. Cost of Electricity from Wind Turbines In California, 1985-1995

- **Specific types of investments that can be recommended confidently on the basis**

of this review include the following:

- **Expanded use of PVs for small-scale applications in high-insolation areas. For many purposes they are already the least-cost option. Costs and performance compare well with diesel generation, for example, and sometimes with grid-supplied electricity in rural areas, depending on the community's distance from the grid.**

- **Use of PVs to provide supplementary power on grid-connected distribution systems, if the peak load matches solar insolation. (Wind energy, which is not reviewed below, also shows much promise for this purpose and could also be a good complement to existing hydro schemes.)**

- **Expanded use of thermal-solar schemes for power generation on pilot basis. A series of 100 to 200 MW of pilot projects in selected countries, financed on a concessionary basis, and perhaps built and operated under collaborative international arrangements, would do much to establish the technology. It is already competitive with nuclear energy, and prospectively with hydro energy.**

- **Use of biomass for power generation. Modeled on the forthcoming GEF project in Brazil, this type of activity is another promising area of investment.**

Costs considered in this review are hardware costs. In the comparisons of costs with conventional energy sources at a particular site, four factors are especially important to bear in mind. First, since markets are still small, transaction costs tend to be a large component of overall costs. These include the installation, operational, and reaming costs of setting up and using a technology for the first time and of providing customer services. The GEF is to make a special study of this problem. The general assessment, however, is that these costs will decline appreciably as markest increase.

Second, scale economies and the gains from technical progress as applications increase are likely to be large during the next two decades. This means that marginal costs will be much less than average costs, and there is a good case for public policies to support the development and use of the technologies through tax incentives, financial support through public R&D programs, and other financial facilities such as the GEF. It is in fact remarkable how much has been accomplished over the past two decades, given the limited financial support for renewables. In the industrial countries, solar energy receives minuscule funding compared with fossil and nuclear technologies (about 5 percent of public R&D in energy), despite its promise.

Third, the analysis of investments needs to take into account the environmental costs and benefits of the technologies.

Fourth, attention will need to be given to deformities in energy prices. The sad fact is that the "playing field is not lever' when it comes to competition between renewables and conventional fuels. Aside from the distortions just noted in public R&D policies, two further examples will suffice to make the point. One is the absence of peak-load pricing for electricity. The costs of meeting peak demands are two to three tunes those of meeting base-load demands in many countries. Peak-load costs are about 15 to 20 gents per kilowatt hour, depending on the system and the patterns of demand, compared with average costs of about 5 to 8 cents per kilowatt hour (for a base-load plant). The adoption of peak-load pricing would provide a significant stimulus to the development of short-term storage technologies for solar energy. The other example is rural electrification, which is widely subsidized, again making it difficult for the renewable energy alternatives (and PVs in particular) to compete in applications for which they would otherwise be, for consumers, the financially more attractive alternative. Removing such distortions in public policy will do much to facilitate the development and use of renewable energy.

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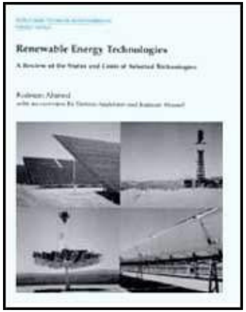

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Biomass Energy

Introduction

Biomass is the term used to describe all plant-derived material. It may be used to generate energy by direct combustion or by conversion to either a liquid or a gaseous fuel.

Plane materials use the sun's energy to convert atmospheric carbon dioxide to sugars during photosynthesis. On combustion of the biomass, energy is released as the sugars are converted back to carbon dioxide.

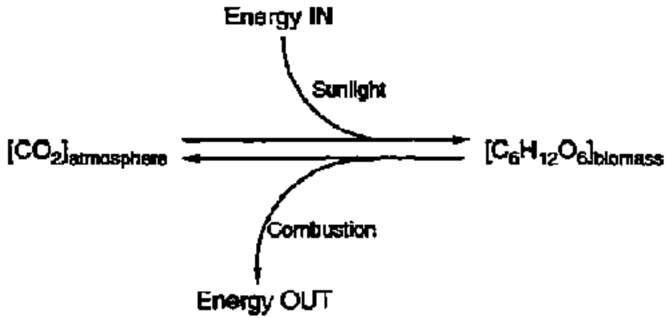
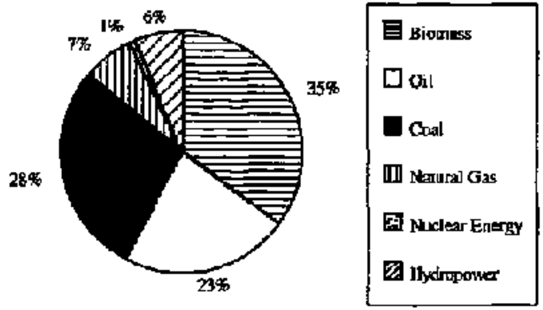


Figure 2.1 Energy from Biomass

Thus, energy is harnessed and released in a shore time frame, making biomass energy a renewable energy source. Fossil fuels have also ultimately been derived from atmospheric carbon dioxide, as they are degraded residues of plant and animal sources. However, the tune frame is very long—in the order of millions of years rather than a few years, as in the case of biomass.

Biomass has been used as a source of energy for centuries, and even today is the major type of energy source in the developing world. As is illustrated in Figure 2.2, biomass forms 35 percent of total sources of energy in developing countries. This energy is mainly used for cooking and heating.



Source: World Development Report 1992 (World Bank 1992): based on Hall, background paper.

Figure 2.2. Sources of in Developing Countries, 1987

In some "renewables intensive" scenarios, a number of studies show biomass as a major player (see Johansson and others 1993, chap. 1; U.S. DOE 1990a; and World Energy Council 1992). Several reasons are given for this. The foremost, perhaps, is the versatility of biomass. It may be converted directly to electric power by burning, or it may be converted to liquid or gaseous fuel by physical or biological means. It is also amenable to storage. In many respects it can be compared to fossil fuels. However, it is worth noting that its energy density is lower. Hall and others (1993) quote heating values of 17.5 to 20 gigajoules per ton (on a dry weight basis) for biomass compared with 30 to 35 gigajoules per ton for bituminous coals and 23 to 26 gigajoules per ton for lignite. Therefore, transport and storage costs play a significant part in cost evaluations.

The main growth in energy demar is expected to occur in developing countries (World Bank 1992). It is worth noting that biomass combustion is a familiar idea in most of these countries, and this familiarity could play an important part when the feasibility of biomass projects, albeit on a larger and more efficient scale compared to current uses, is considered in these countries.

Efficiency is perhaps the key determinant of costs. To begin, therefore, the following looks at some points presented in the current Iiterature on the efficiency with which (a) biomass is created and (b) biomass is converted to commercially usable energy.

Formation of biomass

The limiting factor is the efficiency with which sunlight is converted to biomass energy. The maximum theoretical value quoted is 6.7 percent; this is for C4 plants (so called because the first product of photosynthesis is a 4 carbon sugar), such as maize, sorghum, and sugar-cane, which grow best in relatively hot climates. A value of 3.3 percent is given for C3 plants, such as wheat, rice, and trees, which account for 95 percent of global plant biomass. Once factors such as temperature, leaf cover, disease and pests, and presence of adequate nutrients and water are taken into account, however, the real values become much lower (2 to 3 percent and 1 percent of incident sunlight are quoted for C_4 and C_3, respectively, by one authority and 0.2 to 0.3 percent by another). Another point of interest is the possible effect of increased carbon dioxide levels, and therefore resulting climatic change, on growth. This is an important issue, and work on it includes some studies being carried out currently at Oak Ridge National Laboratory (ORNL; information is from the Environmental Sciences Division of ORNL and from discussions with ORNL staff on their Global Environmental Studies research).

The main point illustrated by the theoretical photosynthetic efficiency is the high land intensity of biomass energy compared with other sources of energy, such as photovoltaics, which have a solar energy to electricity conversion percentage of 3 to 17 percent in the field and even higher experimental efficiencies ((i to 34 percent) and theoretical efficiencies (47 percent for a tandem cell with two crystalline layers; see chapter 4). This raises the issue of whether the land might be better used for something else, such as crop production, given that increases in the world's population in the coming decades seem likely to place increasing pressures on land resources, even allowing for

increases in crop yields (for discussion, see chapter 7 of the World Development Report 1992 [World Bank 1992]). Particular cases need to be considered in detail, however. Examples are growth of biomass for restoration of degraded land, as a by-product of afforestation schemes, and as a new livelihood for farmers in some developed countries in order to replace food production of excess capacity. An example of this high land requirement is the figure quoted in an Energy Department Working Paper of 600 hectares of plantation per megawatt or 30,000 hectares (300 square kilometers) for a 50 MW dendro thermal plant, quite a small plant by conventional fossil-fuel standards (Terrado 1985). These figures, although not completely up-to dam, illustrate that the use of biomass for commercial energy production will place significant demands on land and forestry management.

Several factors play an important part in determining the "efficiency" and therefore cost effectiveness of a biomass plantation (Terrado 1985; Hall and others 1993; and literature from ORNL Environmental Sciences Division). These include site establishment, including species selection, land cost, and equipment costs; plantation running cost - for example, costs of labor, fertilizer, and herbicides; and transport costs to the site of energy conversion. Naturally, the species selection and crop rotation play an important part, since the biomass energy density, leaf cover, productivity, water requirements, nutrient requirements, soil erosion, susceptibility to diseases, and effect on the biodiversity of the plantation and its surroundings are all related to this one factor. The United States Department of Energy's Oak Ridge National Laboratory (ORNL) has carried out extensive research on crop selection and rotation.

Aside from using plantations for energy production, there are many examples some going back many years—of the use of biomass residues for the production of energy. These are instances where crop residues are used, usually by the industry producing them, to generate both heat and power for use within the plant, with excess electricity being sold to the utility. These are called cogeneration plants. These plants can be very cost-

effective, especially if the residue has no other value, and a good price (say, based on avoided costs as in the United States under the Public Utility Regulatory Policies Act [PURPA]) can be obtained from the utility. Lately, an increase in the availability of second-hand boilers is making the coatings feasible for cogeneration facilities in a number of developing countries, resulting in a flourishing private industry (Willem Floor, personal communication, 1992). However, because of subsidies in many countries, the cost of power from the grid can be artificially low, and thus setting up a cogeneration plant may not necessarily be economically feasible (see ESMAP 1988 for an example). Other problems may include electricity boards refusing to take privately generated power at all, imposing a sales tax on self-generated electricity, or even decreasing the maximum power available to industries with cogeneration facilities and providing no backup power (U.S. Congress 1992).

Energy from biomass

Biomass can be converted to energy by a variety of methods: direct combustion and use of the heat generated for space heating and cooking, combustion of biomass or biomass-derived products to generate steam, which in turn is used to drive steam turbines for power generation, and biochemical or thermochemical degradation of biomass to form biogas and liquid fuels. These in turn may either be used directly as fuel or converted to electric power by combustion in an internal combustion engine or in a gas turbine to obtain shaft power, which in turn can be coupled to a generator.

Liquid fuels from biomass

The fermentation of sugars to produce ethanol is an age-old process and essentially forms the basis for the production of alcohol from biomass. Both methanol and ethanol may be produced from biomass. Ethanol may be produced from sugars (such as sugarcane), starches (such as corn?, or cellulosic material. In the first case, the sugar is directly

fermented to produce ethanol, with the waste bagasse sometimes being burned for cogeneration. In the latter two cases, the material has first to be broken down into sugars before fermentation. This is done either by using acids or hydrolytic enzymes. These two processes, scarification and fermentation, may be carried out in "one pot" (see Johansson and others 1993 and U.S. Congress 1992 for details of the latest technologies).

In cases other than sugarcane, fossil-fuel energy is also required, and therefore prices vary significantly according to the method of production. The main cost, however, is that of the raw material. According to most sources, this makes up 60 to 80 percent of the total cost of ethanol production (World Bank data; see also Hall and Overend 1987: 318). Brazil is most well known for use of ethanol as a transport fuel (Goldemberg, Monaco, and Macedo 1993; Monaco 1989; CENAL 1988; and unpublished World Bank data). Ethanol, of course, has other uses for example, in the chemical and beverage industries—but these are not considered here.

Methanol can be made by a thermochemical degradation reaction in the presence of oxygen to form "synthesis gas:' followed by a shift-gas reaction to obtain a precise mixture of hydrogen and carbon monoxide, and finally by passage through a pressurized catalytic reactor to form liquid methanol. This is not a commercial process as yet (see Johansson and others 1993 and U.S. Congress 1992 for details of the latest technologies).

Ethanol and methanol may of course be burned to generate energy or electricity. However, this is not economically desirable in normal situations. Their main use is as an additive to gasoline, and ethanol is considered to be more desirable in that respect than methanol in the United States, in terms of its physical properties, as on blending the ethanol mixture has a lower Reid Vapor Pressure than the methanol blend (Wyman and others 1993).6 "Pure" ethanol can either be used in its hydrated form (95:5 ratio of ethanol to water) as a transport fuel, or its anhydrous form can be blended with gasoline. The latter is naturally more expensive, because it involves the extra step of distilling the hydrated ethanol.

Electricity from biomass

The conversion efficiency of biomass to heat for cooking and heating—the traditional role is highly inefficient, being only a few percent. Considerable work has been carried out on the improvement of domestic stoves to improve efficiency (see Johansson and others 1993 or World Bank 1992, for example).

Most of the components of a direct combustion system plant are the same as in a conventional fossil-fuel-fired thermal plant. The main exception is the fumace, as biomass has a lower energy density and requires a furnace designed to cope with the higher moisture content of the fuel and the greater quantity of ash generated. The technology, nevertheless, is well developed, and a number of different types of commercial furnaces for firing wood in boilers are available (Terrado 1985; Johansson and others 1993; and U.S. Congress 1992 all describe the technology further).

Biomass may be converted to producer gas by thermochemical means or to biogas by anaerobic digestion; these, in turn, are used to generate electricity by combustion in an internal combustion engine. A number of small-scale facilities of this type already exist, particularly in Brazil (producer-gas-based) and in China and India (biogas-based). The cost of producing electricity from these systems is given in the section on cost of electricity from biomass, below. The technology utilizing biomass fuels in gas turbines is under development (see Elliott and Booth 1990; Johansson and others 1993; and U.S. Congress 1992 for detailed description of technologies). The heart of the technology already exists, but technological advances are needed to cope with the high ash and impurity content of the biomass-derived gaseous fuel and its consequent low efficiency. Elliott and Booth (1990) quote a current figure of 42 percent fuel efficiency. They also provide a lucid account of the technology advances needed to increase efficiencies and decrease capital costs. These include technology to cope with the low calorific value of the gas, the higher ash content from combustion of biomass compared with coal, and the

higher concentration of alkali metals in the ash. This volatile ash can carry over and causes rapid deterioration of the turbines. There is one scheme, however, in which a ceramic heat exchanger separates combustion gas from heated air to drive a gas turbine (Edwin Moore, personal communication 1993}. The U.S. Congress's Office of Technology Assessment (1992) feels that some of these problems may already be resolved and describes technologies that are near commercialization, as well as others that may be available by the end of the century with a concerted R&D effort. These are all larger-scale operations than internal combustion engines. Estimated costs of electricity using these technologies are also discussed in the section, Cost of Electricity from Biomass.

Environmental effects

For environmental reasons, the "recycling" of carbon dioxide is important. There is no net increase in the short term of atmospheric carbon dioxide from burning biomass or biomassderived fuels a factor that is becoming increasingly important in the context of discussions about imposing a "carbon tax" because of the greenhouse effect. Biomass also has a far lower sulfur content than coal (0.01 to 0.1 percent sulfur by weight for typical biomass feedstocks compared with 0.5 to 5 percent for coal; Hall and others 1993). Thus, acid deposition from sulfur dioxide emissions on combustion are significantly lower than for coal. Some work is being carried out at Oak Ridge National Laboratory (ORNL), in conjunction with the Tennessee Valley Authority, on the co-combustion of wood and coal in coal-fired plants to reduce sulfur dioxide emissions. The NOX emissions of biomass, however, are higher than those of coal, and this may be something to consider in terms of their effect on the atmosphere. Biomass power plants also have far higher particulate emissions than conventional coal-fired plants (Terrado 1985).

The environmental aspects of burning ethanol as a fuel are also worth noting. First, the net quantity of carbon dioxide released to the atmosphere is zero if the initial capture of carbon dioxide from the atmosphere by the biomass is taken into account, and carbon

monoxide emissions are lower than for gasoline. Second, ethanol does not contain lead additives (unlike gasoline), and therefore lead emissions are zero for "neat" ethanol use. Hydrocarbon emissions are also lower compared with gasoline. Opinion varies on whether NOx emissions are different, and in which direction. However, aldehyde emissions are significantly greater; this may prove to be a serious problem, as aldehydes are reactive species; acetaldehyde, for example, is a known irritant and possible carcinogen, and formaldehyde is a known carcinogen. Finally, the burning of sugarcane residues on plantations (preharvest burning of dry leaves to promote pest control and lower harvesting costs, and postharvest burning of residues to expedite replanting) does cause concern. The problem is made worse in some countries by the proximity of the plantations to urban areas (Goldemberg, Monaco, and Macedo 1993). Initially, on the introduction of the Proalcool program in Brazil, pollution of waterways increased in several cases because of the discharge of stillage from distilleries directly into the waterways. This is no longer a problem, as the stillage is now being used as fertilizer or being treated before discharge (World Bank data).

The cost of biomass energy

The costs of producing liquid fuels from biomass are considered first, followed by the costs of producing electricity.

Cost of liquid fuel production from biomass

Annex 2 gives some of the costs quoted in the literature for the production of ethanol from various biomass sources. Figures 2.3 to 2.5 provide a graphical presentation of the data Before interpreting these results, a note of caution needs to be sounded. First, the quoted costs vary in their assumptions, and this is one reason why estimates vary so much Examples are as follows:

a. **It is not stated in all cases whether the cost of anhydrous or hydrous ethanol is**

being quoted. The former is mere expensive than the latter, as it involves the extra production step of distillation. Nevertheless, both have been plotted on the graph without any adjustments.

b. Capital costs are treated as sunk costs in some cases and are not included in the cost of production. These cases, where known, are noted in the table in Annex 2, but they have not been plotted on the graph.

c. It is not always clear whether the cost quoted includes government subsidies and credits from sale of byproducts of ethanol production. By-products include stillage for fertilizer, electricity from bagasse in the case of sugarcane, and carbon dioxide and animal feeds from corn.

d. The scale of production is rarely mentioned.

e. It is worth noting that the cost of setting up a distillery will vary depending on whether the plantation already exists, as this is a major cost. Also, the proximity of the plantation to the distillery is important because of high transport costs.

f. In the case of ethanol production from sugarcane, the data presented here is mainly from Brazil, and the following should be noted:

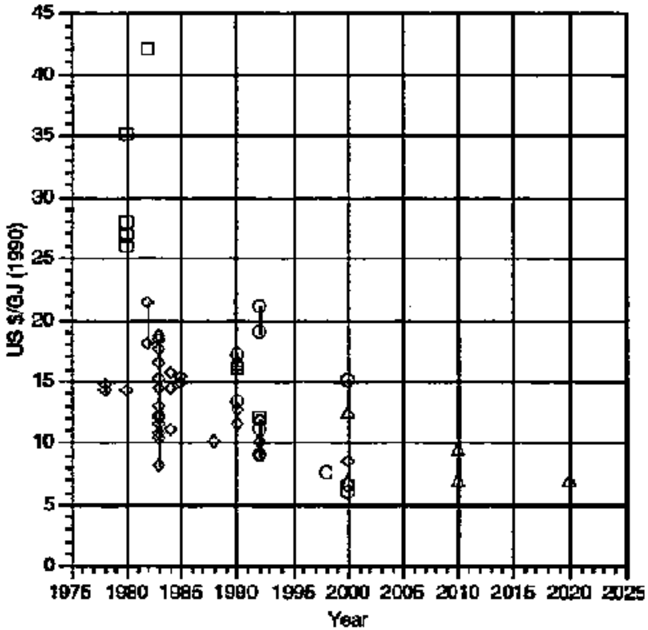
- **Details such as the variation in pace caused by the number of rattoons (cuttings) per year or the proportion being sold directly as sugar in different distilleries are not taken into account and only averages are presented.**

- **Official data from Copersucar (the cooperative of sugarcane, ethanol, and sugar producers responsible for one-third of Brazilian sugar-cane production) tend to be on the high side. Copersucar estimate that making adjustments for the over-valued exchange rate and lowering the land value**

to reflect existence of large uncultivated areas could lead to a 20 percent reduction in costs (Goldemberg, Monaco, and Macedo 1993).

g. Costs given for ethanol production beyond 1992 are predictions that vary depending on the scenario assumptions. For example, some are based on a business-as-usual scenario, whereas others are based on an intensified R. D, & D scenario. These are noted in the table in Annex 2.

h. Costs shown for ethanol production up to and including 1992 are either actual costs or are results of engineering studies based on the technology of the time.



All values for years up to and including 1992 are costs from actual facilities or are costs from engineering studies based on the technology of the time.

KEY
Raw Material: ◇ sugar-cane
□ corn
○ cellulosic material
△ not specified

Figure 2.3. Cost of Ethanol Production from Different Raw Materials

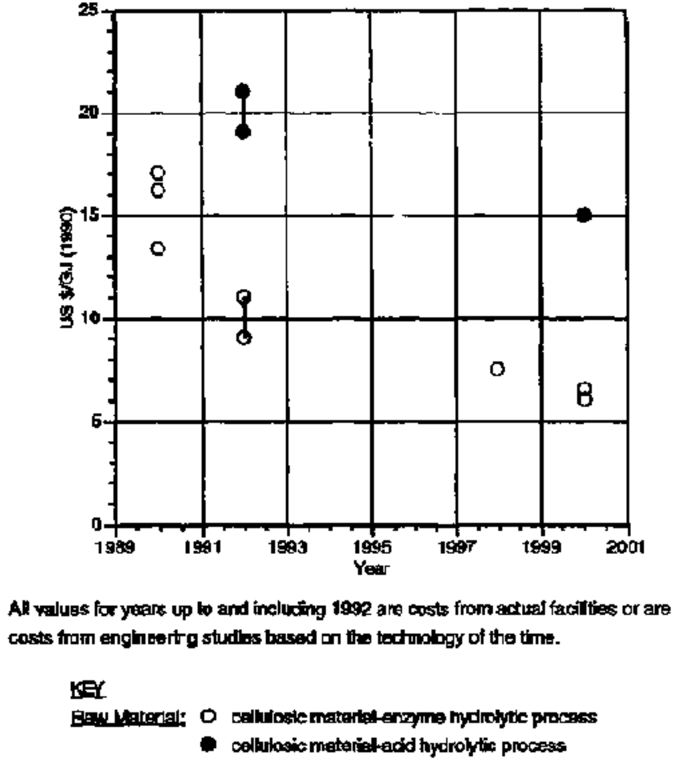
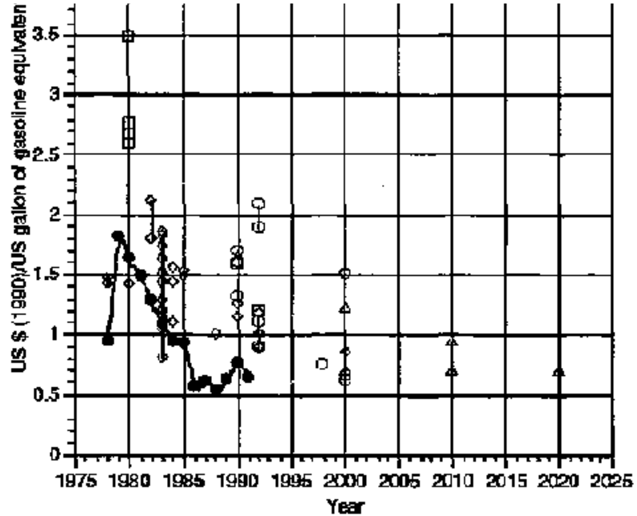


Figure 2.4. Cost of Ethanol Production from Cellulosic Material Using Different Hydrolytic Processes



All values for years up to and including 1992 are costs from actual facilities or are costs from engineering studies based on the technology of the time.

KEY Cost of ethanol production from the following raw materials:

- ◇ sugarcane
- ○ cellulose
- □ corn
- △ not specified
- ● Price of a gallon of premium gasoline based on spot prices (Rotterdam) from International Energy Agency, "Oil and Gas Information 1989-1991" (1992) converted to 1990 dollars.

Figure 2.5. Cost of Ethanol Production Compared with Gasoline Prices

Second, the following must be taken into account when converting all production costs to

1990 U.S. dollars {using the procedure described in Annex 1):

a. Different constituents of the production cost such as machinery, land, labor, and raw materials will have increased by different inflation rates over time. The method used for converting costs to 1990 dollars does not take this into account.

b. The conversion of the Brazilian cruzado to its foreign exchange equivalent poses special problems. It is overvalued, and thus quite distinct official and black market rates exist. Not all sources mention how this conversion is dealt with when quoting Brazilian ethanol costs in U.S. dollars.

c. In most cases, the source material gives the year of the price. Where it does not, this is noted in Annex 2, and the document's publication date is used as the year.

The following data from Annex 2 has not been plotted on the graphs:

a. Items 21, 23, 25, 27, 29, 31, 49, 51, and 67 to 70 have not been plotted as the quoted values do not include capital costs.

b. The data from CENAL (items 32 to 37}, World Bank data (items 42 to 47), and item 56 from Goldemberg, Monaco, and Macedo (1993) have not been plotted. The source data has been plotted instead (items 71, 72, and 74).

c. Items 57, 60 to 61, and 66 (from Wyman and others 1993) have not been plotted, as the data has not been specified for a particular year, and the sources from which the numbers are derived span several years.

d. Item 73 teas not been plotted, as the labor costs have been shadow- priced.

Despite the reservations discussed, which are illustrated by the dispersion in the graphs,

these conclusions may be drawn on the basis of the data in Figures 2.3 to 2.5:

a. There has been a reduction in the cost of production of ethanol in the last 15 years (Figure 2.3).

b. Presently, ethanol from sugarcane is cheaper than that from corn and cellulosic material (the latter has yet to be commercialized; Figure 2.3).

c. For cellulosic materials, acid hydrolysis is more expensive than enzymatic hydrolysis (Figure 2.4).

d. Ethanol from cellulosic material is expected to become the cheapest alternative by the year 2000.

Let us now examine these in a little more detail. As discussed earlier, the delivered cost of the raw material accounts for 60 to 80 percent of the cost of production. This is the main reason why ethanol from cellulosic materials (e.g., woody materials and agricultural residues), which are more abundant and lower in cost, is expected to be the cheapest alternative in the future (Hall and Overend 1987; U.S. DOE 1990a; Wyman and others 1993; and U.S. Congress 1992). This is not currently the cheapest source of ethanol, as the technology needs further

Woody materials and starch crops (such as corn) need first to be broken down (or hydrolyzed) to sugars before fermentation (the process is shown in simplified form in Figure 2.6; Hall and Overend 1987; U.S. DOE 1990a; Wyman and others 1993; and U.S. Congress 1992). As the figure shows, either enzymes or acids are used as catalysts in the reaction Of the two processes, enzymatic hydrolysis is preferable, as it is more specific, and only one product is formed, unlike acid hydrolysis, in which competing side reactions decrease the yield of product and lead to higher production costs. In either case, the sugars are then fermented to form ethanol. For woody materials, this process is more

difficult, and not all the sugars formed can be easily converted into ethanol, resulting in a lower yield of ethanol per ton of material. Advances in biotechnology have opened up some solutions that show promise for future lowcost ethanol production (Wyman and others 1993), but further evaluation is required before these methods are commercialized.

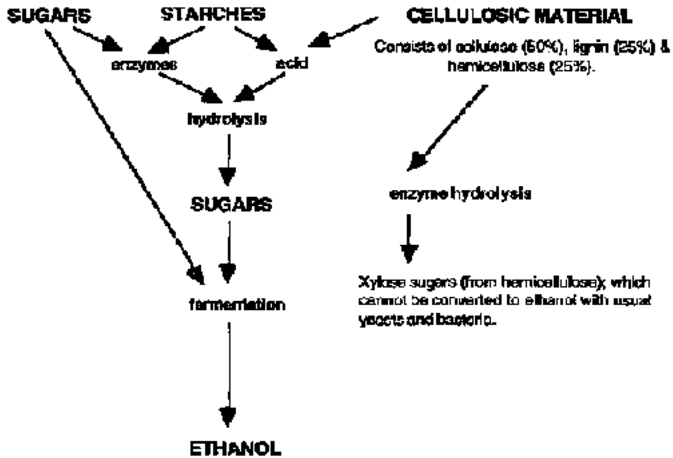


Figure 2.6. Formation of Ethanol (Simplified Scheme)

The costs quoted are for ethanol production from sugarcane in Brazil and from corn in the United States. In both cases, the distillery is one part of an operation that also sells the raw material as is, or other products derived from it. Thus, it is difficult to break up the cost estimate accurately. Various co-products are formed as a result of ethanol formation (see Wyman and others 1993 for a comprehensive summary). In the case of corn, carbon dioxide and animal feed are sold as by-products. However, the U.S. Department of Agriculture projects that as ethanol production increases, the cost of corn will rise and that of co-products will drop (Wyman and others 1993). For sugarcane, the stillage from

fermentation is used as a fertilizer on the plantation, and bagasse residues are used for cogeneration purposes, with surplus electricity being sold to the grid (Goldemberg, Monaco, and Macedo 1993). Naturally, this revenue is not likely to decrease in the same way as that from corn co-products. In corn derived ethanol, fossil fuels are required to generate energy. Other points of difference between corn- and cane-derived ethanol are the extra processing (hydrolysis) of corn to produce ethanol, and differences in the simple costs of raw material production in Brazil versus the United States, such as the price of land (Goldemberg, Monaco, and Macedo 1993; Geller 1985; Hall and Overend 1987). Corn may be processed to produce ethanol either by wet or dry milling. The former is the cheaper alternative (Flaim and Hertzmark 1981 and Wyman and others 1993 give costs).

Finally, as can be seen from Figure 2.5, the cost of producing ethanol has decreased over the last 15 years. However, since the ethanol is replacing gasoline, its cost relative to gasoline is crucial. Figure 2.5 gives the same data from Figure 2.3, but converted to $/U.S. gallon of gasoline equivalent by applying a simple multiplier. The price of a gallon of premium gasoline based on spot prices (Rotterdam) over the same period is also shown up to the present (International Energy Agency 1992). Note that the cost of producing ethanol was beginning to compare well with gasoline prices before the collapse of oil prices in 1986.

Methanol and synthetic petroleum can also be derived from biomass. Neither of these are commercial processes at present. Calculations show that gasoline could be produced from biomass for $0.85 to $1.00 per gallon (U.S. DOE 1990a). In the case of methanol, current cost estimates range from $7 to $20 per GJ.

Cost of electricity from biomass

Annex 3 summarizes data from a variety of sources. Figures 2.7 to 2.9 illustrate this data in graphical form. As in the discussion on liquid fuels from biomass, a note of caution

needs to be sounded. The figures being compared on the graphs vary in their underlying assumptions. The following are examples:

a. The graphs show costs for cogeneration facilities as well as and-connected plants, although Figure 2.7 distinguishes between the two.

b. Costs of actual facilities and engineering study estimates are given (Figure 2.8).

c. The costs are for plants based at different locations worldwide.

d. The method used for power generation ranges from direct combustion, to biogas gas turbines, to producer-gas internal-combustion engines.

e. The plant sizes vary from 5 kWp to 100 MWp. Figure 2.9 highlights larger units.

f. The method and underlying assumptions for the cost calculations (such as discount rates used) are not always specified in detail.

g. The revenues from sale of surplus electricity to the grid in the examples of cogeneration facilities may or may not be taken into account when quoting a cost for electricity generation. Furthermore, the sale of the electricity may have been accounted for at different rates.

h. The type of biomass used for power generation varies in the examples given.

Furthermore, this biomass will have been acquired in different ways, such as in entry number 19 the biomass is grown on a plantation on the premises and costs take into account the setting up of this plantation, whereas, in the case of entry 38, the biomass is purchased municipal solid waste. Entry 34, on the other hand, utilizes bagasse from an adjoining sugar mill. i. Costs given for electricity generation beyond 1992 are predicted

costs which vary in terms of technology being utilized and scale of production. j. In the case of cogeneration plants, capital costs may only include the cost of additional equipment, rather than all equipment to generate electricity.

The hazards of converting currencies to 1990 U.S. dollars (using the procedure in Annex 1, unless specified differently in the table) in order to compare costs are again worth considering. For example, some currencies are overvalued, and inflation may affect different parts of the estimate in different ways. In most cases, the year of the currency is given in the source material. Where it is not, the price is assumed to be that obtained in the year of publication and is noted to this effect in Annex 3.

With the above caveats, in mind, data from Annex 3 were plotted in Figures 2.7 to 2.9. The value of this type of analysis is that quoted costs for the production of electricity from biomass are being compared. Each situation is different, and therefore attempts to make the calculations uniform may not be any more meaningful and may suffer in terms of other aspects.

Figure 2.7 distinguishes between cogeneration facilities and power plants. As the graph shows, the costs span a wide range of values. The lowest costs are for electricity generated in cogeneration facilities. However, some of the highest costs are also for electricity from cogeneration facilities. Although no distinct pattern is evident, there may be a slight decrease in costs over time. The range of costs in a particular year does appear to decrease, but this probably represents a reflection of the data collected rather than a real effect.

Figure 2.8 highlights the values based on actual operating facilities. The small number illustrates the general lack of actual data available and the degree to which even well-known authorities values on the basis of tabletop studies when discussing electricity generation from biomass.

Figure 2.9 shows the cost of electricity from plants greater than or equal to 30 megawatts (peak). The costs are lower for these cases, because of economies of scale. The higher costs for 1992 and those for 1995-96 are from a European source (Grass) 1992). Costs of electricity generation from biomass tend to be greater in Europe than in other areas, particularly compared with the United States. However, it is worth noting that the dominant part of the 9,000 MW of power generated in the United States from biomass is from cogeneration facilities, where the biomass source is mainly residue from the pulp and paper industries. Table 2.1 shows the type of biomass utilized by percentage in the United States for power generation (U.S. DOE 1992a).

Table 2.1. Power Generation in the United States by Type of Biomass

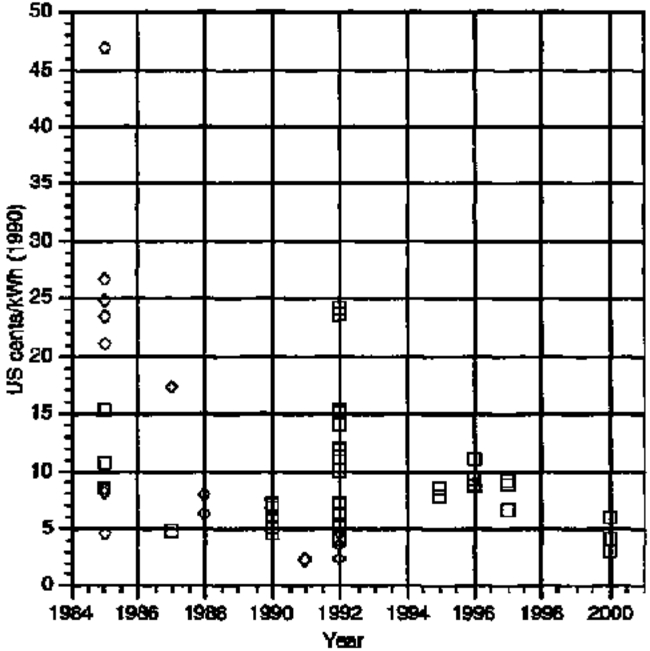
Percentage of total biomass capacity	
Type of biomass fuel	
Wood	88
Landfill gas	8
Agricultural waste	3
Gas from anaerobic digesters	1

The low costs turn out to be heavily dependent on the biomass being purchased at a price of $2/MilBtu or less (U.S. DOE 1990a). First, consider the cost calculation formula shown in Annex 1. This may be written in a more simplified form, for the purpose of discussion, as follows:

Cost of electricity = Capital cost factor + O&M factor + Fuel factor (cost + efficiency)

The operating and maintenance (O&M) costs are generally considered a fraction of the capital costs (about 4 percent). Capital costs vary with the technology being used to

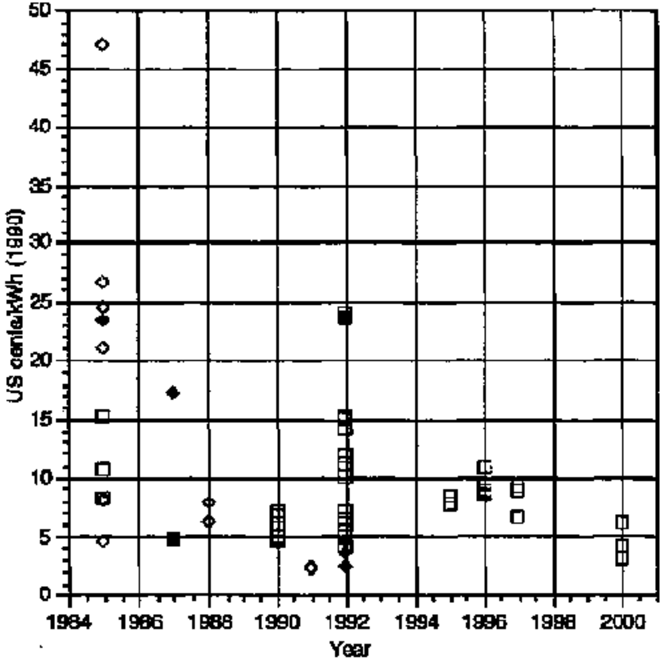
generate power, and for the larger plants also vary between the biomass gasifier plant and the conventional steam turbine plant.



All values for years up to and including 1992 are either actual costs for plants or are based on studies using the technology of the time. Costs after 1992 are projected values.

KEY ◇ Cogeneration plant
□ Power plant

Figure 2.7, Cost of Electricity from Bomass



All values for years up to and including 1992 are either actual costs for plants or are based on studies using the technology of the time. Costs after 1992 are projected values.

Highlighted values are based on actual operating facilities.

KEY ◇ Cogeneration plant
□ Power plant

Figure 2.8. Cost of Electricity from Biomass (Operating Facilities versus Engineering

Studies and Projections)

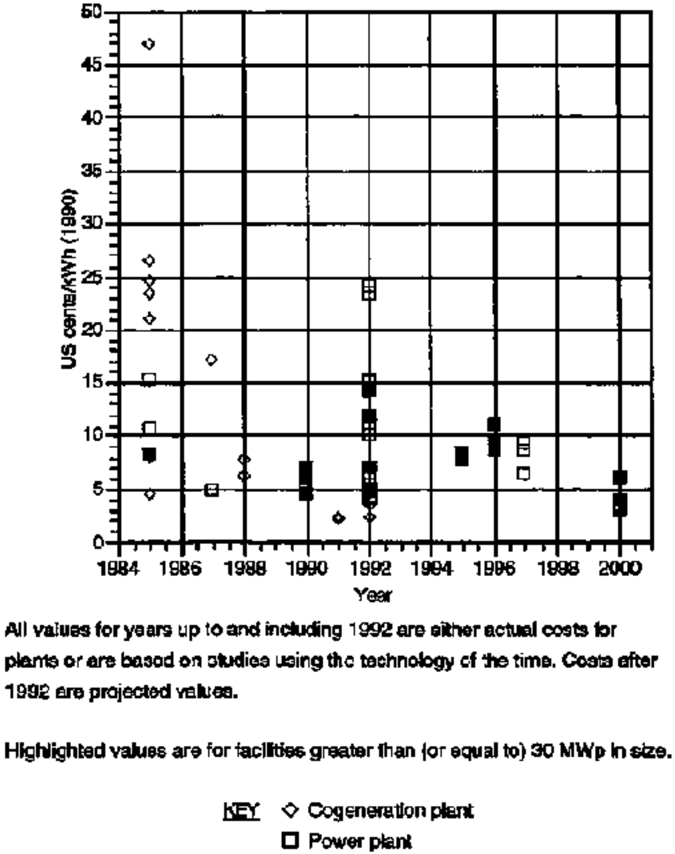


Figure 2.9. Cod d Electricity from Biomass (Large" versus Small-Scale Plants)

Table 2.2 shows some historical current capital costs (taken from Annex 3), for plants greater than 20 MWp. They have been converted to 1990 dollars, using the methods described in Annex 1. The costs in Table 2.2 are from only four sources, all based on theoretical calculations rather than on a particular power plant. It is also necessary to take into account that the capital cost in the case of item 19 includes the setting up of the plantation (about $1,000/kW (1990) for 50 MW power plant only, excluding plantation), and in the case of items 1 through 4 and 20 appears to be the cost of the plant only. Clearly, no conclusions may be made on the basis of the above limited data regarding change in costs with time, other than the range of costs being quoted by different authorities. The only point that can be made is that the capital costs of the biomass gasifier plant are expected to be lower in the very near future compared with the steam turbine technology. Predicted costs for the gasifier technology range from $1,200 to $1,300/kW to as low as $870/kW, for the biomass-integrated gasifier/intercooled steam injected gas turbine by the year 2000 (EIIiot and Booth 1990 for the former figure, Johansson and others 1993 for the laker).

Table 2.2. Capital Costs for Large Scale (>20 MW) Biomass Energy Plants l

Reference from			
Annex 3	Type of technology	Cost (1990 $/kWh)	Year
19	Steam turbine	1,599	1985
3	Steam turbine	1,695	1990
20	Steam turbine	1,900	1992
1	Biomass gasifier	1,600- 1,700	1990
4	Gas turbine	1,239	1990
2	Biomass gasifier	1,200-1,300	>1990

The delivered fuel cost is the other main factor that contributes significantly to the cost of the biomass-generated electricity. This consists of two factors, the transport cost and the cost of the biomass. The former is dependent on the distance of the biomass source from the power plant and the energy density and hence bulk quantity of fuel. The cost of the biomass is not only the cost of producing the biomass (i.e., land costs, plantation costs, and labor costs) but also the perceived cost of the biomass in terms of its other uses. For example, using maize for biomass power generation would mean a fuel cost the same as the market price for maize as a food crop rather than the actual cost of growing the crop. On the other hand, municipal solid waste could have a negative fuel cost, as burning it in a power plant would be a means of disposal. These are two extreme cases, however. Consider a short-rotation woody crop (SRWC) plantation. First, the setting up of any plantation will result in a large increase in the total capital cost of a biomass power plant/plantation (Terrado 1985). Second, the price of land is a major factor in developed countries and may be an important factor in developing countries future as population increases. Hall (1991) quotes an estimated cost of $56.36/ton (1990 dollars), equivalent to $2.9/GJ, for the total delivered cost of wood chips from poplar plantations in the United States. Earlier estimates for the delivered cost for SRWC were in the range of $3 to $4.10/GJ (1985 dollars) using the technology of the time (Hall 1991). This indicates considerable progress. Hall feels that $2/GJ is achievable for the United States. Note, however that the value of $2/MilBtu (equivalent to $1.9/GJ) is used in a number of estimates quoted earlier, although that value is an average and is probably heavily weighted by the cost of biomass residues (U.S. DOE 1990a; U.S. Congress 1992). Nevertheless, these figures are for current establishment of a SRWC site, and perhaps future figures may require the use of a higher value for land costs.

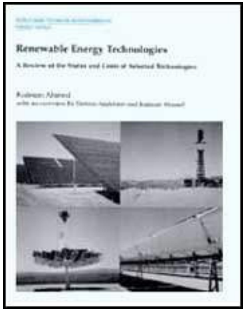
The future of biomass energy

For ethanol production from biomass sources, costs have decreased over the last 15 years. The production of ethanol from cellulosic material promises another significant decrease

in costs in the future.

The gasifier/gas turbine technology does appear to offer a cost-effective method of power generation in the future. The land intensity, however does remain an important factor, together with associated problems of utilizing large amounts of land for producing biomass such as competition over land for food crops. However, each individual case requires particular attention, and in some cases, biomass for power generation will be the best alternative. An example is the ORNL/China project, where the setting up of the plantation/power plant serves a dual purpose: reforestation and electricity generation (Perlack, Ranney, and Russell 1991).

Cogeneration plants appear to be much more viable, especially if there are no fuel costs and the surplus electricity can be sold to the grid. Another important requirement is that the grid electricity is not already subsidized heavily. However, their use is limited to the quantity of "free" fuel available.



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3. Solar-thermal

Introduction

The earth continuously receives a power input of 1.73 x 1014 kW from the sun. This translates to 1.5 x 1018 kWh/year, which is about 10.000 times the world's current annual energy consumption (Dunn 1986). The conversion of this huge renewable energy resource directly to electrical energy is the topic of this chapter and that of chapter 4.

Solar-thermal power plants use the sun's rays to heat a fluid, from which heat transfer systems may be used to generate steam that in turn is used to drive a turbo-generator. Or, the fluid may be used to operate an engine directly. At the outer atmosphere, the solar energy constant (indicative of the power density) is 1.373 kW/m2. Energy is then absorbed and scattered by the earth's atmosphere. The final incident sunlight is diffuse, with a peak power density of only 1 kW/m2 at the earth's surface at noon in the tropics (International Energy Agency 1987). The insolation available for conversion to energy

varies with factors such as the location of the sun in the sky (daily and seasonally), atmospheric conditions, altitude of the site, and number of daylight hours. Therefore, it is usually concentrated first by the use of mirrors. Three main technologies for concentration are in use or under development and are described in the section entitled Solar-Thermal Electric Technologies. Their current and prospective costs for electricity generation are discussed in the subsequent section.

It is worth pointing out that the methods of solar-thermal power generation are essentially the same as conventional technologies, except that the "fuel" is direct heat energy rather than stored energy in the form of fossil fuels, from which the heat energy needs to be released by combustion. This has led to criticism of the technology for its inability to store energy, unlike fossil fuels or biomass. However, storage of thermal energy is possible, and a number of systems are under development. These are discussed in more detail in the technology sections. Furthermore, as shown in the section on costs, thermal storage may help to reduce the unit cost of electricity generation from thermal-solar plants by improving the capacity utilization of the turbo generating and electrical plants. In addition, thermal storage could be unnecessary if thermal-solar plants were used in conjunction with existing hydro schemes; use of the solar plants would reduce the rate of drawdown of the reservoirs in the dry seasons.

The land requirement of solar-thermal plants is also worth consideration. Annex 4 gives land intensities of a dendro thermal plantation (based on an engineering study); an operating parabolic trough solar-thermal plant; and the collector areas of three existing central receiver test facilities. For completeness, the array area of three photovoltaic concentrator schemes is also given. These arc compared with the inundated area of several existing or planned hydro plants in Brazil. The data are also shown in Figure 3.1 below.

As can been seen, the range of sizes in the case of hydroplants is large, and the collector

or array area of solar plants is at the lower end of this range; whereas that of a dendrothermal plant is at the higher end of the range. This is only a rough comparison, and a comparison of total area occupied by the plant to the kilowatt hours generated by the plant would be more accurate (see Anderson 1992). However, Figure 3.1 does provide a comparison of the areas involved; this is unlikely to be altered significantly even if the areas are changed to allow for spacing.

The land requirements for solar-thermal plants, when compared with dendrothermal plants and hydroelectric dams, therefore, are not high; furthermore, solar-thermal plant sites are likely to be desert areas with low land values. Many experts feel that thermal-solar schemes, relative to hydro and biomass, are an attractive option for these very reasons, as they can be sited away from populous agricultural areas. This is particularly important when arable land is scarce or resettlement issues are controversial.

From an environmental viewpoint, solar-thermal technologies are benign. There are no emissions to the atmosphere. There is a water requirement, since areas of high insolation are usually dry (U.S. Congress 1992; unpublished IFC data). However, that problem can be minimized by using recycling systems (such as those commonly used in thermal power plants).

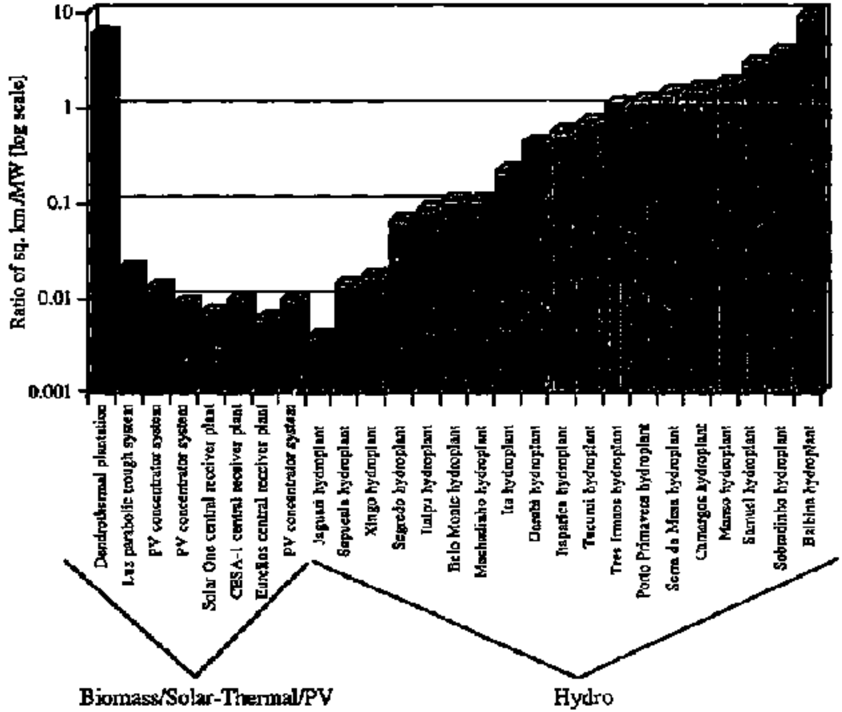


Figure 3.1. Land Requirements for a Biomass Plantation, Solar-Thermal Plants, and the PV Array Areas of Existing Solar Plants Compared with the Inundated Area of Hydroplants

Solar-thermal electric technologies

The three main types of system in use for concentrating and collecting diffuse sunlight are shown in Figure 3.2.

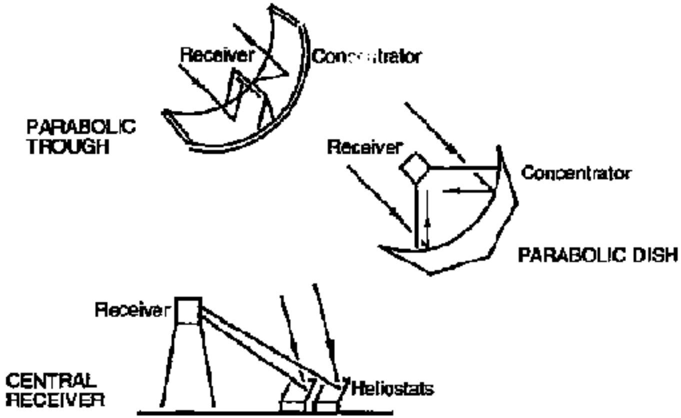


Figure 3.2. Concentrator and Receiver Systems for Solar-Thermal Electric Technologies

Parabolic trough

Currently, the most advanced of the "concentrator" systems is the parabolic trough This is the technology used in the largest commercial grid-attached solar-thermal power plants, which together make up 90 percent of the world's solar electric capacity (U.S. DOE 1990a). These have a total net capacity of 354 MWp and are based in Southern California They were installed by Luz International Limited and operated by that company until March 1992, when operation and maintenance were taken over by new operating companies, such as the Kramer Junction Operating Company for the Kramer-based plants, after Luz suffered financial difficulties (Kearney and Price 1992; Lotker 1991). These difficulties are summarized in Annex 5. The plants are still generating electricity and continue to provide information on technical performance and costs.

Parabolic troughs track the sun along one axis, concentrating the energy onto a receiver

tube located at the trough's focal line. Concentration ratios of 10 to 100 are typically achieved, with operating temperatures of about 400° C. In commercial plants, the receiver tube usually has water or oil running through it as the heat transfer medium This fluid is then piped from each of the parabolic trough assemblies to a central area, where the energy is converted to electricity (De Laquil and others 1993; U.S. DOE 1992b;

International Energy Agency 1987). Research is being carried out on direct steam generation (DSG), which is expected to cut costs further as it eliminates the need for the heat transfer fluid as well as centralized oil-heated steam generators (De Laquil and others 1993). Commercialization of DSG technology was planned for 1996 by Luz, which launched a major program to develop the technology in 1989. This is now in doubt, however, because Luz has filed for bankruptcy (see Annex 5). In commercial plants, electricity demand when solar radiation intensity is low is currently met by the use of auxiliary gas-fired boilers or heaters. Thermal storage systems do exist but are not cost effective so far; however, three new concepts that promise to be cheaper than current alternatives have been identified, although they still need significant development to reach technical readiness (De Laquil and others 1993).

The lack of economical storage and the combustion of a fossil fuel on cloudy days to maintain the output has prevented the technology from being a fully independent alternative to fossil fuel plants. The Luz plants are all 25 to 30 percent natural gas hybrids. This has not only helped to maintain their electrical output on cloudy days but has also helped to increase the capacity factor and reduce costs, resulting in a more economic scheme for the sale of power to the grid under U.S. PURPA regulations on the basis of avoided costs (Kearney and Price 1992).

Parabolic dish

A parabolic dish operates on the same principle as the parabolic trough, but it tracks the

sun on two axes, concentrating the energy at the focal point of the dish because it is always pointed at the sun. The parabolic dish's concentration ratios are considerably higher than the trough's. Dish ratios are 600 to 2,000, and operating temperatures can exceed 1,500°C (De Laquil and others 1993). The power-generating equipment for use with parabolic dishes may be mounted at the focal point of the dish itself, or, as with the trough, energy may be collected from a number of separate installations and converted to electricity at a central point (International Energy Agency 1987). The former option is perhaps the most promising use of the dish technology, making it very well suited to remote or stand-alone applications.

The two most promising engines for mounting at the focal point appear to be the Brayton cycle engine and the Stirling-cycle engine (De Laquil and others 1993). These convert the heat to power as heat is continuously supplied to a gas in a closed system, which in turn drives a piston as it cycles between hot and cold spaces in the engine. Extremely high solar-toelectricity efficiencies have been achieved for this technology; the record is 29.4 percent for the Vanguard parabolic dish-Stirling engine 25 kWp module in California, which was tested jointly by the U.S. Department of Energy and the Advanco Corporation between 1984 and 1985 (De Laquil and others 1993). Several parabolic dish test facilities have been constructed and operated; of these, some are still operational, but others have been disassembled (De Laquil and others 1993). The U.S. Department of Energy, in a joint venture with Cummins Power Generation, is working on the development and commercialization of a 5 kW dish/engine system and intends to initiate another project, involving the utilities, on 25 kW dish/engine systems (U.S. DOE 1992b).

Central receiver

This is a very promising technology for large-scale grid-connected power generation, even though it is at an early stage of development compared with parabolic trough technology. In this case, flat tracking mirrors, called heliostats, concentrate the sun's energy onto a

central receiver tower. Concentration ratios are 30() to 1,500, and systems can operate at temperatures of 500 to 1,500° C (De Laquil and others 1993). Energy losses from thermal-energy transport are also minimized as solar energy is being directly transferred by reflection from the heliostats to a single receiver rather than being moved through a transfer medium from several receivers to one central point, as with parabolic troughs. Solar-to-electric efficiencies for test systems are in the 8 to 13 percent range (De Laquil and others 1993). There are several test facilities in operation in both Europe and the United States. Work has been carried out on a number of different heat-transfer media, such as water/steam, molten sodium, air, and molten salt. The latter two are especially promising, as they could provide an economical energy storage system Currently, the largest demonstration of the molten salt technology has been in France on the THEMIS 2 MWp central receiver system, using Hitec molten salt, giving the plant six hours of electricity production capability without the sun. This experimental facility completed its operation in 1986, having achieved lower annual power production than expected, but having demonstrated the advantages of the new technology and highlighted problems that needed further resolution (De Laquil and others 1993; International Energy Agency 1987)

The U.S. Department of Energy, in collaboration with a consortium headed by Southern California Edison, is currently converting the successful 10 MW Solar One (water/steam) central receiver pilot-plant to Solar Two (U.S. DOE 1992b). The Solar Two project will use molten nitrate salt as the heat transfer and storage system and will be able to provide power for about four hours after sundown or during cloudy periods. The molten nitrate salt technology has been validated at Sandia National Laboratory, but the Solar Two pilot will be the first largescale field demonstration of the technology. It will highlight technical issues that appear to require further resolution, such as crystallization of the molten salt and energy losses from the salt during piping. New stretch-membrane heliostats will also be added to the existing heliostat field to increase the system's energy output. New improved heliostat design and new receiver technologies continue to be tested in the United States with a view to improving performance (see U.S. DOE 1992b and De Laquil

and others 1993). The U.S. Department of Energy believes that the Solar Two project will lead to the utilities setting up as many as four 100 MW central receiver plants by 1997-98 (discussions with R.H. Annan, Director, Office of Solar Energy Conversion, U.S. DOE, Washington, D.C.).

Another project under development uses air as the heat transport medium, with heat storage in a porous ceramic material. The work is being carried out by a European industry group called the PHOEBUS Consortium (De Laquil and others 1993; Grasse 1992). The advantages of this system are great because of its suppler design, ease of operation and maintenance, and lower cost. However, current disadvantages are the heat losses from the open receiver and the low effectiveness of the storage system. Plans are under way to construct a 2.5 MW experimental facility in Spain by 1993 to validate the system before building a 30 MW central receiver/fossil fuel hybrid plant with about three hours storage capability (due to solar only) near Aqaba, Jordan, in 1995.

Cost of electricity generation from solar-thermal electric technologies

Costs of electricity production using solar-thermal electric technologies are given in Annex 6. The "calculated cost" is calculated from the quoted capital cost, quoted operating and maintenance cost, and quoted fuel cost (natural gas only) using the formula given in Annex 1, assuming a 10 percent discount rate. The cost has then been converted into 1990 dollars according to the method described in Annex 1. The "quoted cost" is the cost exactly as given in the reference.

Two points need to be emphasized. First, all costs, other than those listed in entries 9, 10, 14, 15, and 16, are predicted costs. Those noted above are based on the Luz plants operating in Southern California. The Luz SEGS {Solar Electric Generating System) power plants in California are the main source of cost data, because they are the main example of commercial grid-attached electricity production from solar-thermal technologies. Other

plants do exist, but are smaller in scale and, in the main, experimental; because of the significant R&D expenditure involved, their power production costs (which are often not quoted) are not indicative of actual production costs.

Second, the graphs in this section have been plotted using the "calculated costs" (i.e., costs calculated on a common basis) rather than the quoted costs for electricity generation, in order to remove discrepancies caused by different assumptions. For example, for entry 29, the cost of electricity generation using central receiver technology assuming a 5 percent discount rate is 23 cents/kWh (1984 currency), but 34 cents/kWh (1984 currency) with a 10 percent discount rate, with all other parameters equal. On a less obvious note, for the same system, the study quotes a cost of electricity generation of 13 cents/kWh (1984 currency), assuming a 3.15 percent discount rate with "favorable tax credits." Recalculating the same using the formula in Annex 1, with the same 3.15 percent discount rate but no tax credits, gives 19.5 cents/kWh (1984 currency). When the cost could not be calculated because of insufficient data, the relevant references, together with quoted costs, were given in the table in Annex 6 but were not plotted on the graphs.

Figure 3.3 shows the calculated costs of electricity production from parabolic trough (solar/natural gas hybrid and solar only operation), parabolic dish, and central receiver solarthermal technologies. The costs are for large-scale generation of about 50 kW and upward. Discussion on the costs of electricity production by each of the individual technologies follows.

Cost of electricity generation from parabolic trough solar-thermal technology

Figure 3.4 shows the calculated costs of electricity production using parabolic trough technology (Annex 6, entries I to 16). The highlighted values are based on the Luz plants. The following may be noted from the graph:

a. The current calculated cost for electricity production (solar with 25 to 30 percent

natural gas) at the SEGS plants varies between 11 to 14 US¢/kWh (1990) due to the difference in quoted capital costs.

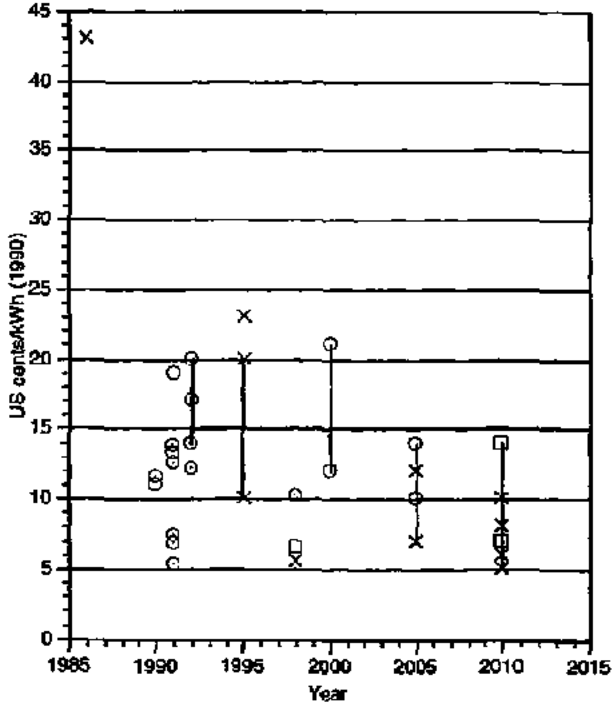
b. The solar only values are higher, ranging from 13 to 20 US¢/kWh (1990), because of the lower capacity factor. The outlier based on data from entry 16, of 11 US¢/kWh (1990), stems from an usually low quoted capital cost compared with the other data and does not appear to be representative (Walton and Hall 1990).

c. As the natural gas contribution is increased to 50 percent, the cost decreases further because of the increase in the capacity factor.

d. The cost of electricity production is expected to decrease further to 10 to 14 US ¢/kWh (1990) for solar only use by 2005. Thus, correspondingly, the cost of electricity production from the natural gas hybrid will also decrease. This decrease is caused by a decrease in capital costs and by a decrease in operating and maintenance costs, which constitute as much as 15 to 25 percent of the total cost of electricity production (Kearney and Price 1992; U.S. DOE 1992b). The U.S. Department of Energy is currently working on a project with the SEGS plants' owners and operators to reduce the latter, not only to make these plants more economical, but also with a view to using the lessons learned in other solar-thermal technologies, especially central receivers (U.S. DOE 1992b).

e. Economies of scale in manufacture should result in further lowering of costs. This is illustrated in the dispersion of costs in 1991 in Figure 3.4. Entries 11 to 13 in Annex 6 are for 200 MW plants; all others (entries 1 to 10, 14 to 16) are for 80 MW plants. As can be seen, this results in a 30 percent decrease in costs from the 80 MW plants. (Compare entries 8 and 10 with 11 and 13, respectively). The coatings for the 200 MW plants are based on technology proven on an experimental scale only, but one that Luz felt confident enough to offer to prospective clients in

1991 (IFC data 1991).



Costs for years up to and including 1992 are based on the technology of the time; costs for years after 1992 are from projected data

KEY O parabolic trough (solar only)
⊙ parabolic trough (solar/natural gas hybrid)

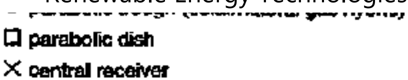
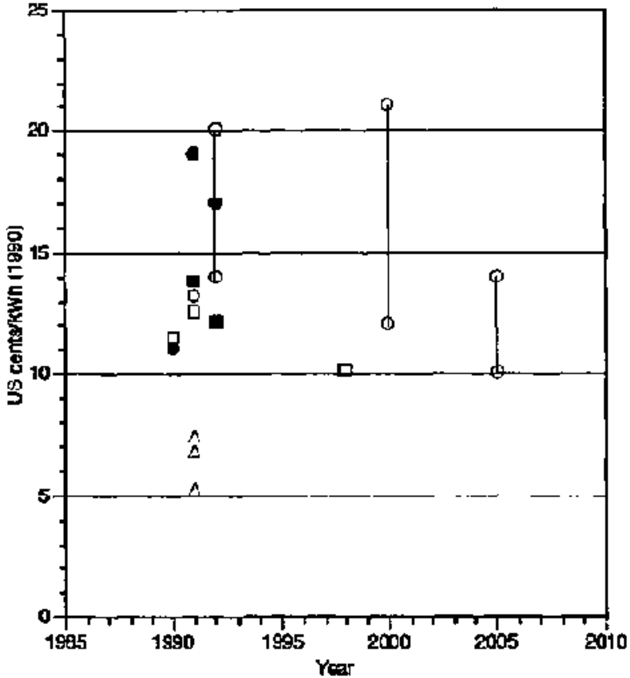


Figure 3.3. Calculated Cost d Electricity from Large Scale Solar-Thermal Technology



Highlighted values are based on data from the Luz plants in California.

Costs for years up to and including 1992 are based on the technology of the time; costs for years after 1992 are from projected data

KEY O solar only
□ solar/natural gas (25-30%) hybrid
Δ solar/natural gas (50%) hybrid

Figure 3.4. Calculated Cost of Electricity from Parabolic Trough Solar-Thermal Technology

Cost of electricity from parabolic dish solar-thermal technology

Figure 3.5 shows the expected decrease in costs over time for electricity generation from the parabolic dish system. The data points were obtained from only two sources (De Laquil and others 1993; U.S. DOE 1992c) and an all predicted costs. As shown by its predictions for 1998, the DOE expects the cost to fail faster than do De Laquil and others. The DOE's reasoning is based on an increase in production for a utility-scale market. The range quoted (5.8 to 20.3 US¢/kWh in 1990 dollars) is for a distributed system, whereas the single value (6.5 US¢/kWh in 1990 dollars) is for a modular system. This may be as a result of their projects for the development and commercialization of 5 kW and 25 kW dishes, as described in the section on parabolic dish technology.

Entries 26 to 28 in Annex 6 give more projections for costs from the U.S. DOE in terms of increasing market. The decrease in cost appears to stem both from improved technology and from increased production. According to the U.S. DOE (1992c) the cost of dishes has fallen from $1500/m2 in 1978 to $150/m2 in 1992. In comparison, Charters (1987) quotes $300/m2 in 1987, and De Laquil and others (1993) use a figure of $300 to &500/m2 in 1995-2000, with the cost decreasing to $150 to 200/m2 in 2005-10.

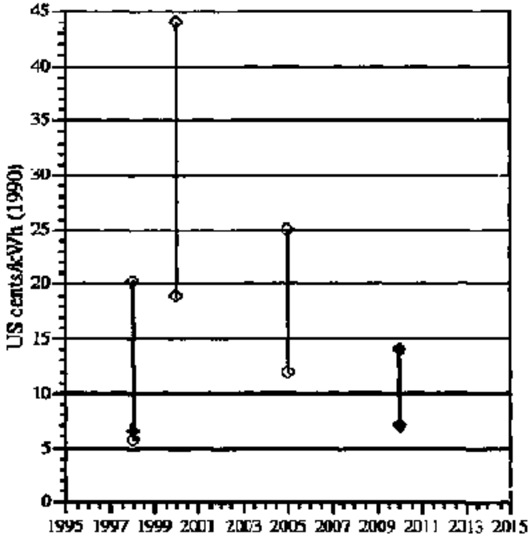
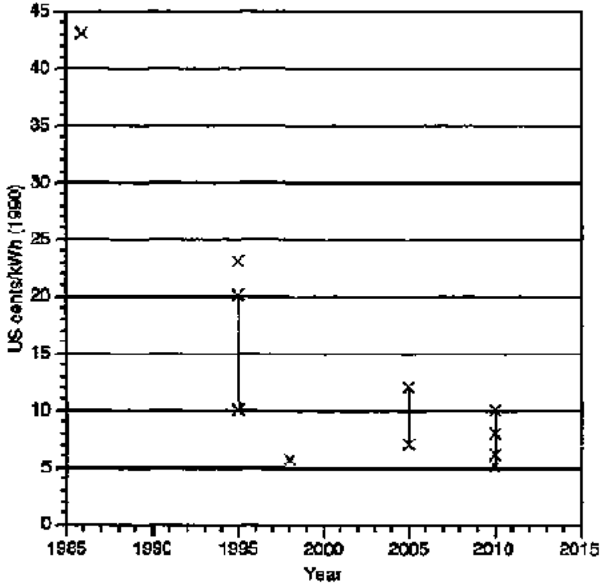


Figure 3.5. Calculated Cost of Electricity from Parabolic Dish Solar-Thermal Technology

Cost of electricity generation from central receiver solar-thermal technology

Figure 3.6 shows the costs of electricity production using central receiver technology (data from Annex 6). As can be seen, the predictions for the costs of electricity generation have decreased substantially in the last few years and are expected to decrease further. The outlier on the graph, 5.6 US¢/kWh (1990 dollars) in 1998, is the latest projection by the U.S. DOE, on the basis of current projects in progress. Entries 37 to 40 in Annex 6 show the expected decrease in costs with increasing market, according to the U.S. DOE. Thus, the main difference between the other predictions and that of the DOE is a faster

expansion of the market, with a 200 MW plant being set up as early as 1998, compared with 2005, according to De Laquil and others (1993).



Costs through 1992 are based on the technology of the time; those after 1992 are projected.

Figure 3.6. Calculated Cost of Electricity from Central Receiver Solar-Thermal Technology

Let us look at reasons for this expected decrease. First, capital costs of central receiver solar-thermal power plants from several sources are given in Table 3.1 and Figure 3.7. As can be seer:, the costs do not show as marked a trend as the decrease in cost of electricity. This is because recent studies have taken account of storage capability for plants. Storage adds to capital costs but improves the utilization of the turbogenerator,

and, since it costs much less than the latter, it reduces generation costs.

Table 3.1. Capital Costs of Central Receiver Plants

	Quoted capital cost		**Capital cost**	
Reference	($/kWp)	($/kWp, 1990)	Year	Notes
Palz (1978)	930 (1975)	2257	1975	
International Energy Agency (1987)	2900 (1984)	3645	1986	Study In 1986 U.S. DOE Five Year Research and Development Plan Overnight construction cost. (i.e. ignoring interest during construction); based on data from Luz
Walton and Hall (1990)	2100 (1990)	2100	1990	
International Energy Agency (1987)	2200 (1984)	2765	1995	Study in 1986 U.S. DOE Five Year Research and Development Plan
De Laquil and others (1993)	3000-4000 (assume 1992)	2804-3738	1995	
U.S. DOE (1992c)	2961 (1990)	2961	1998	
De Laquil and	3000-	2079-	2005	

De Laquil and others (1993)	3000-2225 (assume 1992)	2079-2804	2005	
De Laquil and others (1993)	2900-3500	2710-3271	2005	
	(assume 1992)	2010		
De Laquil and others (1993)	1800-2500	1682-2336	200	
	(assume 1992)	2010		

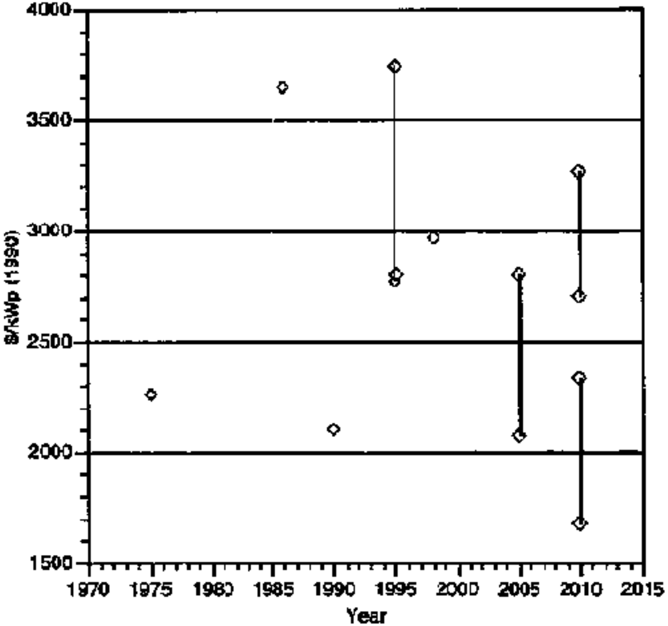


Figure 3.7. Capital Cods of Central Receiver Solar-Thermal Plants

The capability for storage has a significant effect on the capacity factor and decreases the overall cost of electricity production markedly. For example, entry 30 in Annex 6 utilizes a capacity factor of 17 percent, compared with entry 31, which has a capacity factor of 70 percent. Both are originally from U.S. Department of Energy studies, the former in 1986 and the latter in 1992. The details are compared in Table 3.2. Note the higher capital cost of the more recent estimate but the lower overall cost of electricity production because of the higher capacity factor.

The single largest cost component of the system is the heliostat field. In the United States, this exhibits an "86 percent" learning curve, with costs decreasing by 14 percent as production doubles (International Energy Agency 1987). The U.S. DOE (1992c) describes a tenfold decrease in costs from $1,000/m2 in 1978 to just over $100/m2 today, with costs expected to decrease to between $65/m2 and 85/m2 on mass production of the new stretched membrane heliostats currently under development. De Laquil and others (1993) use similar values for heliostat costs in their estimates. It appears, however, that the time scale for achieving these technological improvements and for setting up the larger scale plants is shorter in the case of the U.S. DOE's costings.

Table 3.2. Comparison of Two Estimates for a Large-Scale Central Receiver Plant

Entry from		Capital		O&M	Capacity	Calculated	Quoted cost		
		Size	cost	costs	factor	cost US¢/			
Annex 6	Reference	(MW)	(S/kWp)	($/yr)	(%)	kWh(1990)	US ¢/kWh	Year	
30[a]	International Energy Agency (1987)	100	2,200[b]	3000000[b]	17[c]	23	11.5[b]		1995
				(0.02 cents/ kWh)					
31	U.S. DOE (1992c)	200	2,961[d]	625464000 d,e	70	5.6	—		1998
				(0.51 cents/ kWh)					

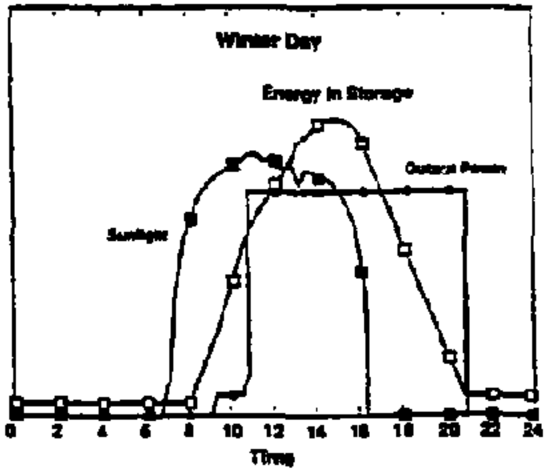
[a] **From study In 1986 by U.S. DOE, Five Year Research and Development Plan..**

b Costs are in 1984 dollar'.

c Capacity factor derived from quoted value for electricity production of 148 GWh/yr.

d Costs are in 1990 dollars.

e O&M costs derived from quoted value of 0.51 cents/kWh.



Source: U.S. DOE (1992d) "Solar Thermal Electric Five-Year Plan" Draft.

Figure 3.8. Load Dispatching Capability of Central Receiver Plants

The future of solar-thermal electric energy

Parabolic trough systems have so far been the most thoroughly tested of the solarthermal

technologies. The Luz plants have demonstrated and continue to demonstrate the capability of the technology to deliver power reliably to the grid. The capital costs, however, are high (13 to 20 US¢/kWh in 1990 dollars for solar-only operation). Some cost reductions are considered possible from economies of scale if the approach is expanded and if Direct Steam Generation (DSG) technology is developed and tested successfully. Costs are predicted to fall to 10 to 14 US¢/kWh (1990) by 2005.

The parabolic dish appears lo be best suited for remote application, because of its modular nature. However, the technology still has not been commercialized. Costs are predicted to be in the range 7 to 14 US¢/kWh (1990) by the year 2010.

Central receiver systems (with thermal storage) have considerable promise. Cost projections are as low as 7 to 12 US¢/kWh (1990) in the next 10 years or so, and 5 to 10 US¢/kWh (1990) in the long term. However, the technology has still not been commercialized, and therefore the most important factor affecting future prospects is the time scale in which initial test facilities can be set up and operational problems can be highlighted and investigated. Some confirmation of the ability to reduce costs is the tenfold decrease just mentioned in the unit costs of heliostats over the period 1978 to 1992. Test facilities (with no storage capability) have been operated successfully, but these were never scaled up to commercial size. This may be because of the high capital cost, which stems from the inherently greater size of the plants, compared with the other solar-thermal technologies.

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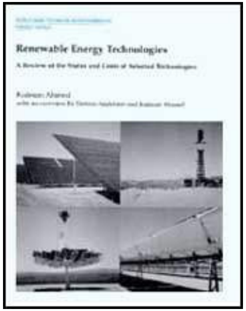

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4 Photovoltaics

Introduction

The previous two chapters have described the conversion of solar energy to electricity through either the combustion of the product of photosynthesis to generate heat energy or the use of direct solar energy to heat a fluid and drive a turbo generator. This chapter

describes a completely different way of generating electricity from sunlight: converting light energy directly to electrical energy using photovoltaic (PV) devices.

Photovoltaic devices work by using an effect first discovered in 1839 by Becquerel but not used in commercial applications until the 1950s (see Annex 7; "The Photovoltaic Effect"}. These early applications were in the space industry, and development of photovoltaics for terrestrial use began only in the 1970s. In the last two decades, however, development of photovoltaics has been nothing short of remarkable. The technology is described briefly and then discussed in relation to costs.

The recent and rapid advances in photovoltaic technology have been driven by technical innovations and contributions from several distinct scientific disciplines, including materials sciences, solid-state (semiconductor) physics, and optics. The technology is also notable for the variety of approaches being pursued by different laboratories and manufacturers, resulting in a healthy competition of ideas among innovators and in significant progress in the laboratory and in manufacturing.

The world market for photovoltaics was 57.9 MW in 1992, having increased from less than 1 MW in 1978 (Figure 4.1). Current uses of photovoltaic modules include the following:

- **Lighting (e.g., street lights, highway signs, parking lots, health clinics, and homes).**

- **Electricity for facilities in remote locations (e.g., refrigeration in remote health clinics or homes).**

- **Communications (e.g., telephones, radio communications, and emergency call boxes).**

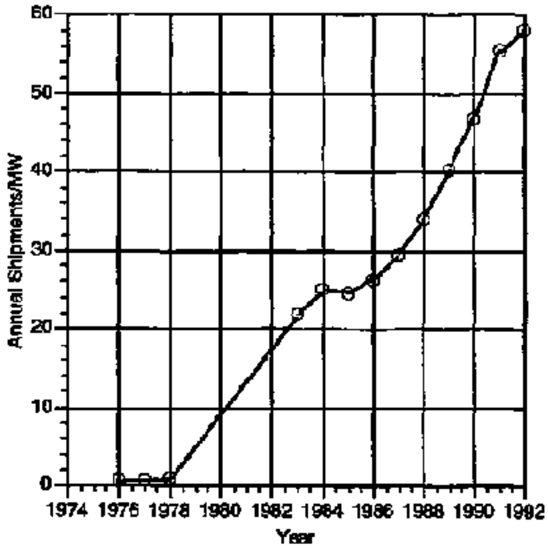
- **Water pumping (e.g., village water supply, irrigation and drainage).**

- **Warning signals (e.g., navigational beacons such as buoys and lighthouses, audible signals, railroad signals, and aircraft warning beacons).**

- **Monitoring at remote sites (e.g., seismic recording, meteorological information, structural conditions and scientific research).**

- **Cathodic protection (e.g., preventing corrosion of pipelines, bridges, and buildings).**

- **Battery charging for vehicles.**



Sources: Maycock (1985, 1986, 1993); Carlson (1990); Costello and Rappaport (1980).

Figure 4.1. Global Photovoltaic Market, 1976-1992

Photovoltaic manufacturing and technology

Photovoltaic modules are made from a number of materials and fabricated in a variety of different designs. An understanding of the designs and the direction of further improvements requires some knowledge of the principle of the Photovoltaic effect (Annex 7 explains the effect for single-crystal silicon; the principle is the same for other semiconductor materials). In brief, when sunlight shines on these materials, it frees electrons from fixed sites. The wavelength of the sunlight absorbed depends on the "band gap" of the material. The materials are designed so that the electrons cannot return to these sites easily except by flowing through an external circuit, thus generating a current. A typical solar cell consists of a layer of semiconductor material sandwiched between conducting top and bottom layers. Photovoltaic modules are made up of several interconnecting solar cells, as the individual PV cells do not provide much power. PV modules are generally less than 1m2 in size and deliver between 50 and 150 W of electric power Thornton and Brown 1992). The whole is encapsulated in a clear, waterproof coating to protect the cells from the environment. Modules can be further interconnected to form arrays. These are generally of two types: "non-tracking" arrays that remain in a fixed position and "tracking" arrays that follow the sun's movement across the sly. The latter are more complex and more expensive, but they can optimize the system's performance (Thornton and Brown 1992).

Efficiency

The efficiency of a solar cell is measured by the percentage of solar energy incident on the cell that is converted to electrical energy. This percentage varies with cell materials and design. Strategies for increasing cell efficiencies include the following (Kelly 1993; U.S. DOE 1991):

- **The surface of the cell is textured with small, pyramidal shapes that allow light reflected off the surface to reflect back into the cell so that it can be absorbed.**

- **Electrical contacts on the front of the cell are designed so that the maximum amount of light can reach the semiconductor (e.g., top contacts can either be transparent or in the form of a metal grid with thin, conductive "fingers").**

- **The amount of light that passes through the material without colliding with an electron can be minimized by selecting materials that are good light absorbers.**

- **Light-generated electrons and holes recombine easily if they reach a flaw or an impurity in the crystal. These flaws are minimized in polycrystalline or amorphous silicon by inaction with hydrogen.**

- **Electrical resistance within the cell can be minimized by good cell design.**

- **Stacking of cells with different band gaps can ensure that a broader range of the solar spectrum is captured, despite restrictions imposed by the band gaps of individual cells. These stacked configurations are called multifunctional devices.**

A number of approaches are therefore available for increasing the efficiency of photovoltaic cells. However, there are trade-offs between increases in efficiency and resulting increases in costs. For example, gallium arsenide has a near-ideal band gap for single-junction devices, is a particularly good light absorber. But its cost is considerably greater than that of silicon. Hence, gallium arsenide has yet to penetrate the terrestrial market significantly. Similarly, although single-crystal silicon modules have achieved higher efficiencies (10 to 13 percent) than amorphous silicon modules (stabilized efficiency of 3 to 5 percent), the manufacturing cost of the latter is much lower. Thus, despite their lower efficiency, the amorphous silicon modules have captured a third of the world market.

Annex 8 summarizes data relating to photovoltaics from a large number of sources. Annex 9 shows only the efficiency data extracted from Annex 8, with the exception of items 117 to 128, 168 to 172, 225, and 267. These have not been used because in items 117 to 128 and 168 to 172 it is not clear whether the values are for cells or modules. In the case of items 225 and 267, the date for these projected efficiency values is not given. The data have then been plotted in several graphs according to semiconductor material (figures 4.2 to 4.6). Figure 4.7 shows efficiencies of cells and modules where the semiconductor material has not been specified.

The following points need to be noted with regard to interpretation of these data and estimates:

Efficiencies quoted for years after 1992 are projected; those quoted up to and including 1992 are actual values.

- **Cell efficiencies, experimental efficiencies, and laboratory efficiencies have been taken to mean efficiency values obtained in the laboratory for individual cells.**

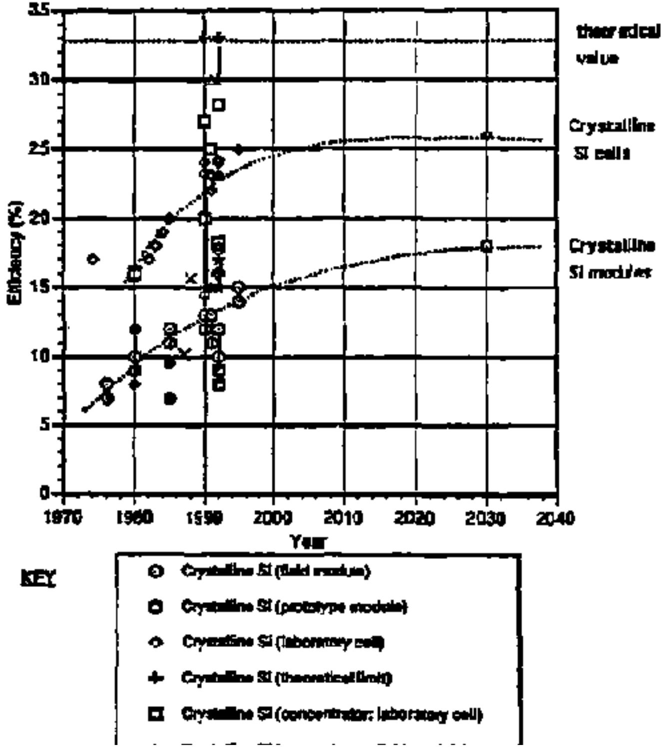
- **Module efficiencies and commercial module efficiencies have all been assumed to be field module efficiencies. Distinctions between prototype and field modules have been noted, if they have been specified by the source. The latter tend to be lower because of the effects of dust and other factors experienced in the field.**

- **Sub-module efficiencies. where specified as such (i.e., for smaller modules), have been noted as prototype module efficiencies.**

- **Light-induced degradation occurs when amorphous silicon devices are operated, thus reducing the initial efficiency to a stabilized value after a few months of operation (see the explanation in the section on thin-film solar cells). The efficiencies have been noted as such in Figure 4.3.**

- **Efficiency also varies with manufacturing method. For example, a single-crystal silicon cell manufactured by the dendritic web method differs in efficiency from the same cell made by the Czochralski method (see the section on "thick-film" cells).**

- **The lines drawn on the graphs are only to aid the reader in visualizing trends and are not based on actual efficiency values.**



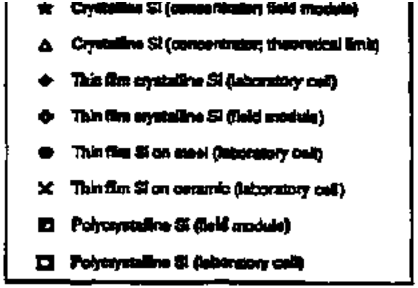
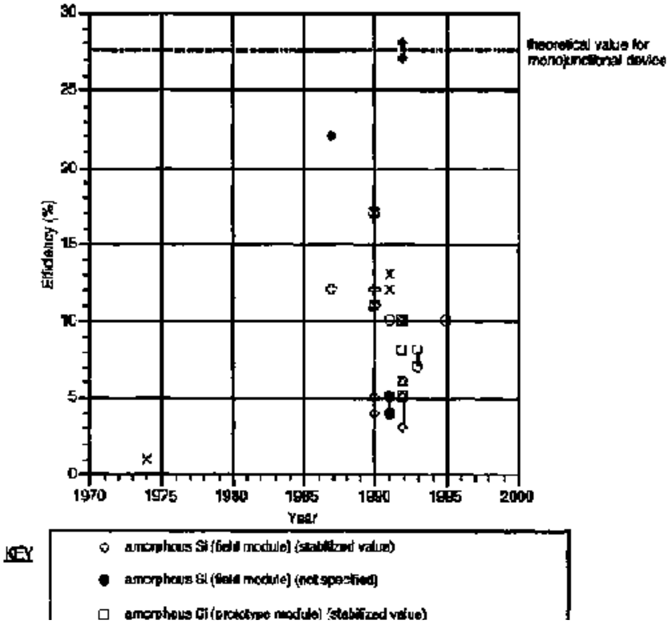
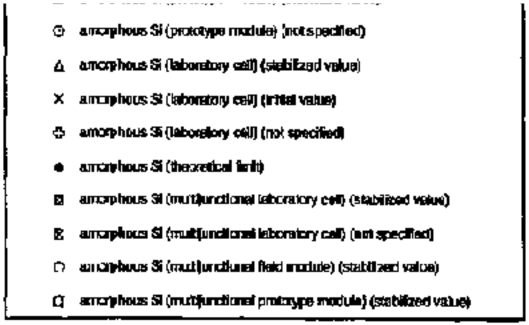


Figure 4.2. Efficiencies of Crystalline Silicon Calls and Modules





All efficiencies through 1992 are actual; those after 1992 are projected.

Figure 4.3. Efficiencies of Amorphous Silicon Cells and Modules

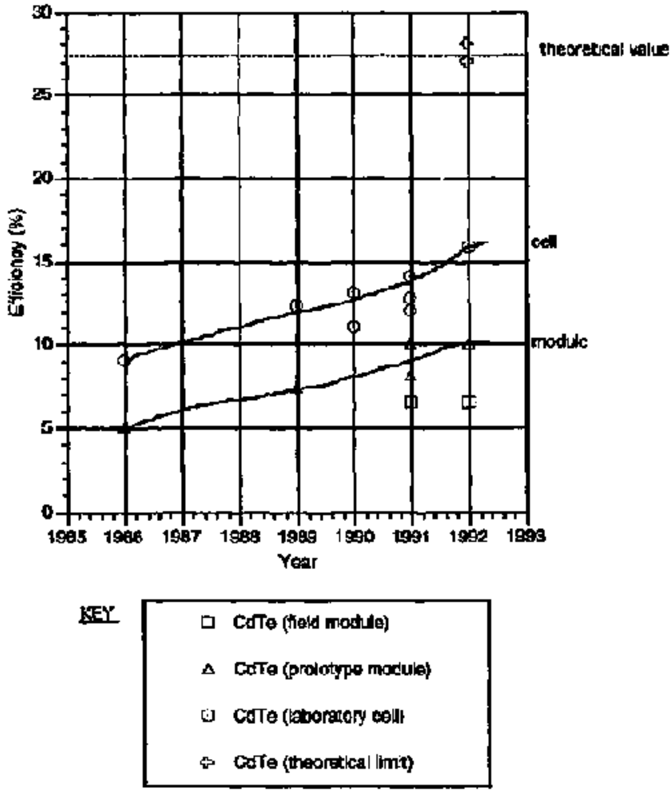
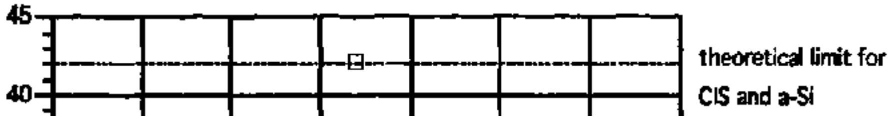
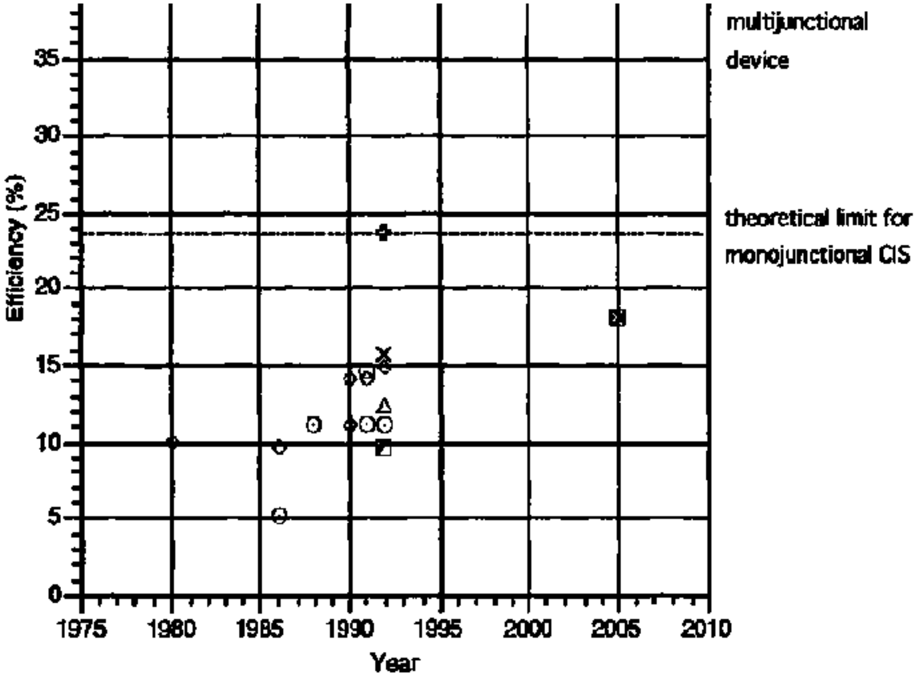


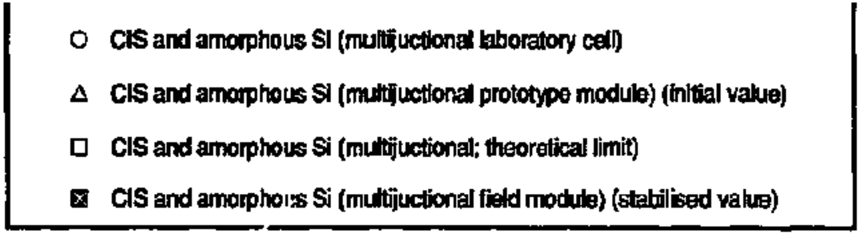
Figure 4.4. Efficiencies of Cadmium Telluride (CdTe) Cells and Modules





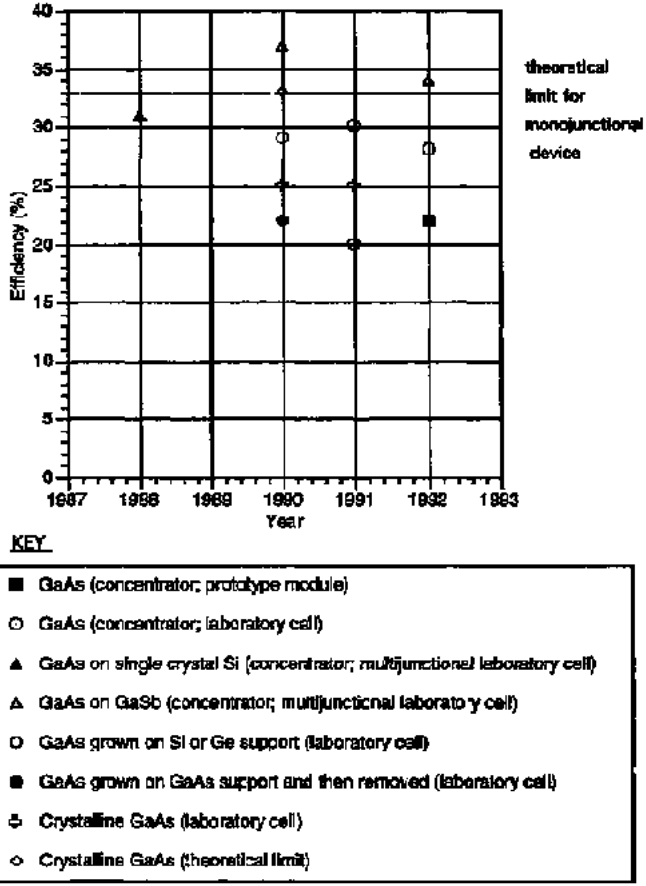
KEY

- CIS (field module)
- CIS (prototype module)
- CIS (laboratory cell)
- CIS (theoretical limit)
- CIS and amorphous Si (multijuctional laboratory cell) (initial value)



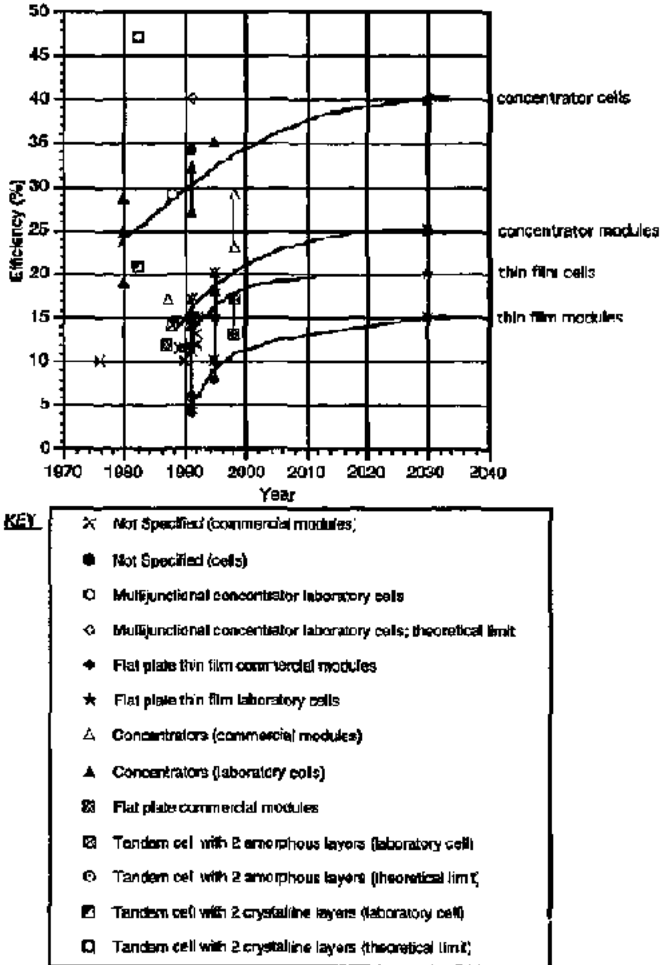
All efficiencies for years up to and including 1992 are actual; those after 1992 are projected.

Figure 4.5. Efficiencies of Copper Indium Diseienide (CIS) Cells and Modules



All efficiencies for years up to and including 1992 are actual.

Figure 4.6. Efficiencies of Gallium Arsenide (GaAs) Cells and Modules


Efficiency (%)
Year
concentrator cells
concentrator modules
thin film cells
thin film modules
KEY
Not Specified (commercial modules)
Not Specified (cells)
Multijunctional concentrator laboratory cells
Multijunctional concentrator laboratory cells; theoretical limit
Flat plate thin film commercial modules
Flat plate thin film laboratory cells
Concentrators (commercial modules)
Concentrators (laboratory cells)
Flat plate commercial modules
Tandem cell with 2 amorphous layers (laboratory cell)
Tandem cell with 2 amorphous layers (theoretical limit)
Tandem cell with 2 crystalline layers (laboratory cell)
Tandem cell with 2 crystalline layers (theoretical limit)

All efficiencies through 1992 are actual; those after 1992 are projected.

Figure 4.7. Efficiencies of Photovoltaic Cells and Modules

The following general conclusions may be drawn from the graphs:

- **Efficiencies increased in the last few years. For example, efficiencies of crystalline silicon modules have increased from 7 to 8 percent in 1976 to 10 to 13 percent in 1992 (Figure 4.2); for cadmium telluride thin-film prototype modules, from 5 percent in 1986 to 10 percent in 1992 (Figure 4.4); and for CIS thin-film prototype modules, from 5 percent in 1986 to 11 percent in 1992 (Figure 4.5).**

- **Cell efficiencies are greater than module efficiencies. The time lag is not only different for different types of photovoltaic module but is also different for different time periods. For example, in the case of crystalline silicon, the time lag appears to have been about five years between 1980 and 1985; but modules are not expected to reach efficiencies of 17 percent (achieved by cells in 1984) till 2030 (Figure 4.2).**

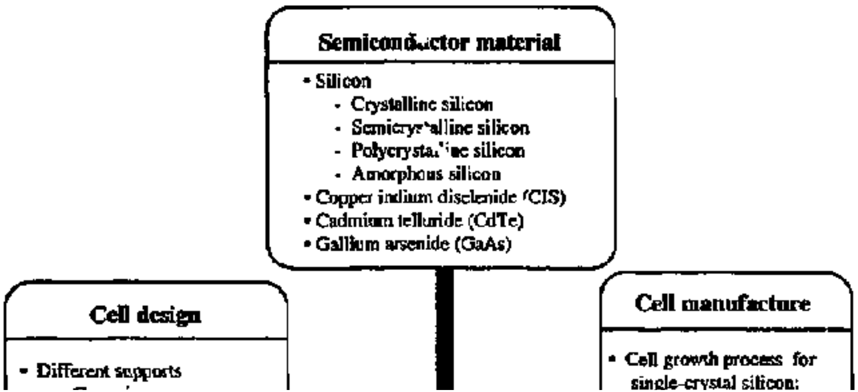
- **Concentrator and multifunctional cells are more efficient than monojunctional cells operating under regular light. For example, amorphous silicon monojunctional cells have stabilized efficiencies of 6 percent, whereas the multifunctional cells have stabilized efficiencies of 10 percent (Figure 4.3). This is also partly because stacking reduces light-induced cell degradation. Crystalline gallium arsenide cells under regular light have exhibited efficiencies of 25 percent, whereas the concentrator cells have efficiencies of 27 to 30 percent (Figure 4.6). Similarly, under regular light, crystalline silicon cells have efficiencies of 22 to 24 percent, whereas the concentrator cells have achieved efficiencies of 28 percent (Figure 4.2).**

The scope for further efficiency improvements is significant. Practical theoretical

efficiencies for monojunctional cells, under regular light, are about 30 to 33 percent for crystalline silicon, 27 to 28 percent for amorphous silicon, 27 to 28 percent for thin-film cadrnium telluride, 23.5 percent for thin-film copper indium diselenide, and 33 percent for crystalline gallium arsenide. Theoretical values are given in the literature of 40 percent for multifunctional concentrator cells, 29 percent for a tandem cell with two amorphous layers, 47 percent for a tandem cell with two crystaline layers, and 42 percent for mechanically stacked amorphous silicon and copper indium diselenide.

Details in Figures 4.2 to 4.6 are discussed further in the following sections.

The scale of the variety in solar cell manufacture and design is illustrated by Figure 4.8 and can be seen in the charts on efficiency (Figures 4.2 to 4.7). Many devices are also being investigated and manufactured, and allowing for these makes the total range of approaches being followed by scientists and engineers in research laboratories and in commercial companies even larger. As noted, no dominant approach has emerged, and the competition among ideas is intense and healthy. Some common types of solar cells are described in more detail below.



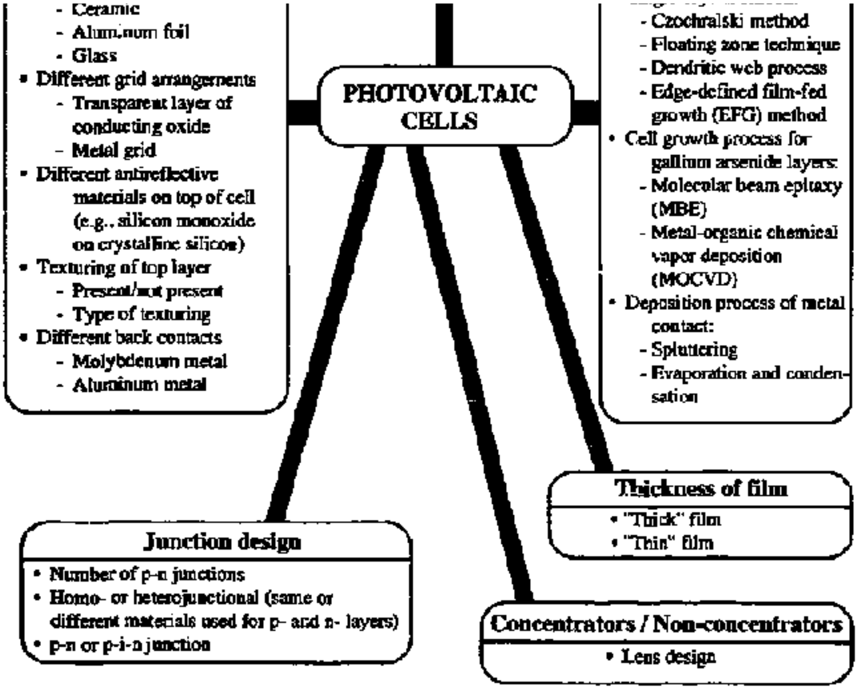


Figure 4.8. Variety In Photovoltaic Cells and Manufacturing Processes

Crystalline sillicon solar cells (''Thick'' Film)

Single-Crystal Sllicon. In 1980, single-crystal silicon cells accounted for 90 percent of commercial PV cells. In 1990, they were only 35 percent of the total world market, with amorphous silicon at 31 percent and semicrystalline silicon at 33 percent.

The cell contains a wafer cut from a single crystal of silicon. The raw material is waste

silicon from the semiconductor industry, which PV manufacturers purchase at a reduced price (Remy and Durand 1992; Kelly 1993). The silicon is melted and regrown into large crystals. The two most established methods for this are the Czochralski method and the floating-zone technique. In the former, a seed crystal is dipped into a reservoir of molten silicon and slowly drawn from it to form a large cylindrical crystal; in the latter, a rod of polysilicon is placed above a seed crystal, and movable heating coils are used to melt the polysilicon rod at the interface, allowing it to resolidify as a single crystal (see U.S. DOE 1991; Green 1993 for descriptions of the methods). These crystals are then sliced into wafers.

This process results in the waste of much silicon, as the cylindrical ingots are much larger in diameter than the required wafers. Alternative methods that minimize waste and cut manufacturing costs, such as the use of thinner saws to slice the wafers or direct growth of thin crystalline sheets or ribbons of silicon are being investigated actively to reduce manufacturing costs (see Green 1993; Carlson, 1990; and U.S. DOE 1991). These methods include (a) the dendritic web approach, in which two dendrites a few centimeters apart are drawn from the melt, trapping a thin sheet of molten silicon in between, which solidifies; (b) the edge-defined film-fed (EFG) growth method, in which molten silicon moves by capillary action between two faces of a graphite die and a thin sheet is drawn from the top of the die; and (c) the S-Web approach, in which a carbon web is coated with silicon as it is drawn through a silicon melt.

One potential problem in PV manufacture is that the quantity of silicon that will be required in the near future, as the market of photovoltaics increases, is in excess of the current silicon waste produced by the semiconductor industry, indicating that silicon production specifically for the PV industry will be required. Silicon is the second most abundant element on Earth, but it is present in the form of silica (silicon and oxygen) and silicates (compounds of silicon, oxygen, metals, and possibly hydrogen). Silica is processed into silicon, which is then refined. The silicon used in PV manufacture can be

less pure than that needed for semiconductors, but current production procedures are expensive, and some work is being carried out to develop new, low-cost methods for silicon production (U.S. DOE 1991; Green 1993). However, some authorities feel that this matter merits more attention (Remy and Durand 1992; and Pistella 1992).

Efficiencies of single-crystal cells and modules are shown in Figure 4.2. Currently, efficiencies of experimental cells are 22 to 24 percent, and those of modules (based on field experience) are 11 to 13 percent. Theoretical efficiencies for single-crystal silicon are 30 to 33 percent. A multifunction of a mechanically stacked gallium arsenide cell on top of a singlecrystal silicon cell is reported to have achieved 31 percent efficiency under concentrated light in 1988 (see the section on solar concentrator cells; U.S. DOE 1991).

Polycrystalline Silicon Polycrystalline silicon is also used for PV cell manufacture. Here, the semiconductor material consists of many crystals of silicon. The associated problems in terms of increased electrical resistance caused by the electrons and holes meeting at cell boundaries and recombining are overcome to a certain extent by reaction with hydrogen or oxygen to fill the broken bonds at the grain boundaries or by heating and cooling the material so that the crystals are enlarged further, thus reducing the number of cell boundaries within the material (U.S. DOE 1991). Nevertheless, polycrystalline cells are less efficient than singlecrystal silicon cells, with efficiencies of 8 to 9 percent for field modules and 18 percent for experimental cells (Figure 4.2).

However, the corresponding decrease in efficiency is compensated to a certain extent by the lower cost of manufacture for these cells. Silicon wafers are manufactured by cooling molten silicon in a crucible in a controlled manner to form an ingot, which is then cut into smaller blocks and sliced into wafers. Methods for producing thin films of silicon on different supports (such as ceramic and steel) are also being investigated, with the intention of reducing costs, as less silicon is use d in these devices.

Thin-film solar cells

Thin films require substantially less active material than single-crystal silicon. Films are typically of thicknesses 0.001 to 0.002 mm, as opposed to about 0.3 mm for a typical thickfilm single crystal or polycrystalline silicon cell (Thornton and Brown 1992). Manufacturing techniques are also different, with thin layers of different materials being deposited sequentially, in a continuous process, on top of each other on a substrate (usually glass), from the back electrical contact (usually a thin layer of transparent oxide) to the semiconductor material to the antireflective coating to the front electrical contact, to eventually make up the module. The sheets are then divided into individual (interconnected) cells by scoring with a laser beam (U.S. DOE 1991). The manufacturing procedures are potentially much less costly than growing single crystals, because in addition to using as little as 1 percent of active material compared with the latter, they hold great potential for low-cost, automated, large-scale production (Kelly 1993; Zwiebel and Barnett 1993; U.S. DOE 1991).

Amorphous Silicon. Amorphous silicon (a glassy alloy of silicon and about 10 percent hydrogen) was regarded as an insulator until 1974, when it was demonstrated to be a semiconducting material. By '990, amorphous silicon PV cells formed 31 to 32 percent of the world market for PVs (Carlson and Wagner 1993; U.S. DOE 1991). The active cell has slightly different construction, with a neutral layer of amorphous silicon (the "i" or intrinsic layer) present between the thin, highly doped, top p-layer and the bottom e-layer. It is here that the electron-hole pairs are generated, thus facilitating their movement, as electrons and holes are far less mobile in amorphous silicon than crystalline silicon, and doping worsens this situation (U.S. DOE 1991).

The first cell had an initial efficiency of I percent in 1974, which decreased on exposure to light to as little as 0.25 to 0.5 percent (Carlson and Wagner 1993). Efficiencies for amorphous silicon cells are shown in Figure 4.3. It is worth noting that a decrease of 10 to

20 percent from the initial efficiency occurs in the first few months of use because of light-induced degradation of the amorphous silicon (Carlson and Wagner 1993; U.S. DOE 1991). Currently, stabilized monojunctional experimental cell efficiencies are about 6 percent, and stabilized field module efficiencies are in the range of 3 to 5 percent. Estimates in the literature for theoretical efficiency limits for single-junction amorphous silicon cells are 22 percent and 27 to 28 percent (Cody and Tiedje 1992 for the lower value; Kelly 1993 for the higher).

Multijunctional devices, with higher efficiencies, have also been developed for amorphous silicon. Use of this configuration not only improves the overall efficiency of the cell but, in the case of amorphous silicon, results in a further increase in the overall efficiency of the individual cells because the thinner layers of material result in less light-induced degradation (International Energy Agency 1987; U.S. DOE 1991). The band gap of amorphous silicon can be altered by the formation of alloys with germanium, carbon, tin, and nitrogen. Thus, typically three amorphous silicon cells with different band gaps are stacked to form a multifunctional cell. Multijunctional amorphous silicon cells have stabilized laboratory efficiencies of 10 percent (6 percent for field modules; Figure 4.3). An amorphous silicon cell has also been stacked on top of a CIS cell, achieving initial efficiencies in the laboratory of 16 percent and 12 percent for submodules (Figure 4.5).

The lower efficiency of the modules relative to single-crystal silicon is balanced by their significantly lower cost per unit area due to the smaller quantity of active material needed because of its high absorptivity (40 percent greater than single-crystal silicon), as well as the lower temperatures required for production and the use of low-cost substrates for deposition of the active material (U.S. DOE 1991).

Cadmium Telluride (CdTe). Efficiencies of cadmium telluride-based laboratory PV cells are in the range of 12 to 16 percent, with prototype modules having efficiencies of 8 to 10 percent (see Figure 4.4.). Theoretical efficiencies are estimated at 27 to 28 percent. CdTe

cells do not show the light-induced instability found in amorphous silicon. Two cell designs are predominant. In the first, CdTe forms the p-layer, and cadmium sulfide forms the elayer. However, CdTe is highly resistive when doped, and this problem has been circumvented in another design that makes CdTe into an intrinsic layer, sandwiched between pzinc telluride and e-cadmium sulfide (U.S. DOE 1991). Cadmium telluride-based cells are about to be commercialized, after benefiting from the experience of research in the late 1970s and early 1980s, when several companies unsuccessfully attempted to commercialize these cells (Zweibel and Barnett 1993).

Copper Indium Diselenide (CIS). Efficiencies of copper indium diselenide PV cells are in the range of 14 to 15 percent, with prototype modules demonstrating efficiencies of 11 percent (see in Figure 4.5). The theoretical efficiency for single-junction thin-film CIS cells is estimated as 23.5 percent by one source (Kelly 1993). These cells consist of a p-layer of CIS and an e-layer of cadmium sulfide (U.S. DOE 1991). Copper indium diselenide is also both being used in various designs of multijunctional cells (U.S. DOE 1991). An amorphous silicon cell has also been stacked on top of a CIS cell, achieving initial efficiencies in the laboratory of 16 percent (12 percent for submodules; Figure 4.5).

CIS not only has high absorptivity, absorbing as much as 99 percent of the incident light, but also displays good stability with regard to light degradation (U.S. DOE 1991). CIS modules are amenable to low-cost, large-scale manufacture and are seen by many as the "model" thin film. It is worth noting, however, that indium supply may become an issue if CIS modules enter large-scale production. Indium is thought to be as abundant as silver, but current supply capacity cannot meet heavy future demand. This could well lead to an increase in indium prices that would impede growth of CIS module production. However, several companies have expressed interest in producing sufficient supplies of indium (Zweibel and Barnett 1993).

Concentrator solar cells

The high cost of the active semiconductor material has stimulated research into methods to reduce this cost further. One innovative idea is the concentrator cell (floes and Luque 1993). Here, mirrors or Fresnel lenses are used to concentrate the sunlight onto a smaller-area photovoltaic cell, allowing low-cost mirrors or lenses to replace high-cost PV cells. Furthermore, because only a small area of PV cell is required, one can pay a slightly higher price for it and still have a lower overall cost compared with a conventional PV cell of the same material. Both single-crystal silicon and single-crystal gallium arsenide have been used in concentrator cells, as well as in various multijunctional cells. Cell efficiency also appears to increase in concentrator cells, although the increase seems to depend on factors such as cell material and design (U.S. DOE 1991). However, concentrator cells, unlike conventional cells, cannot use diffuse sunlight and thus require direct-beam insolation, which is more variable than the total (diffuse plus direct) insolation at a particular site.

Silicon. Several silicon PV concentrator systems have been installed and are operational (Boes and Luque 1993). The efficiencies of laboratory concentrator cells are in the range 21) to 28 percent and of commercial concentrator modules under 20 suns are 15 to 17 percent (Figure 4.2).

Gallium. Gallium arsenide is an excellent active material for use in PV cells because its band gap of 1.43 eV is near ideal for single-junction solar cells; it also has high absorptivity, and it is relatively insensitive to heat (U.S. DOE 1991). The last factor is particularly important in concentrator devices, where the cell is subjected to high temperatures. Single-crystal gallium arsenide, however, is very costly, and therefore its use in concentrator devices is more economical than its operation under regular light. To date, because of its high cost, gallium arsenide has been used primarily in modules for applications in space rather than for large-scale terrestrial uses. Approaches to reduce module costs include fabrication of cells on cheaper substrates, such as silicon or germanium (U.S. DOE 1991). Efficiencies for gallium arsenide cells under regular light are

20 to 25 percent; efficiencies for concentrator cells are in the range 28 to 30 percent, with concentrator prototype modules showing efficiencies of 22 percent (Figure 4.6). It is worth noting that gallium arsenide devices show little difference between module and cell efficiencies..

Much of current research on multijunctional cells focuses on gallium arsenide as either one or as all of the component cells. In 1988, the record for the highest efficiency (31 percent) PV device was set by a gallium arsenide cell on top of a single crystal silicon cell under concentrated light (U.S. DOE 1991). The current record for the highest efficiency cell is also held by a multifunction device consisting of a gallium arsenide cell on top of a gallium antimonide cell. Under concentrated light of 100 suns, an efficiency of 34.2 percent was achieved.

Environmental effects

From an environmental point of view, the use of photovoltaics for electricity generation is a benign operation.

The solar cells themselves are made from either silicon or certain heavy metals, such as gallium arsenide. cadmium telluride, and copper indium diselenide. Silicon is obtained from silica by reaction with hydrogen, to form silicon and carbon dioxide (U.S. DOE 1991). Thus, a small quantity of carbon dioxide, dependent on the amount of silicon, is released to the atmosphere. However, when compared with the amount of carbon dioxide released from a fossil fuel power station over its life, this quantity is negligible. At the manufacturing stage, silicon dust is an important occupational hazard, but its risk can be minimized with careful handling (Holdren, Morris, and Mintzer 1980). In the case of disposal, silicon solar cells are thought not to pose any apparent health and safety risk (Zweibel and Barnett 1993).

The toxicity of the other heavy metals is worth some consideration. Cadmium telluride,

cadmium sulfide, copper indium diselenide, and gallium arsenide pose occupational risks and a hazard to the public if the arrays are consumed by fire (see both

Holdren, Morris, and Mintzer 1980 and Zweibel and Barnett 1993). Arsenic, a constituent of gallium arsenide solar cells, is very poisonous (U.S. DOE 1991).

Hydrogen selenide, used as a feedstock in copper indium diselenide thin-cell manufacture, is an extremely toxic gas. It can be used safely, however, if documented safety procedures are followed. Research is being conducted to find a substitute to replace the use of the gas altogether. After manufacture, sealed modules of copper indium diselenide contain small quantities of selenium, sandwiched between glass layers. This selenium could threaten groundwater if modules are disposed of improperly (Zweibel and Barnett 1993).

Tests have been conducted by the U.S. Environmental Protection Agency on copper indium diselenide solar cells (which also contain a layer of cadmium sulfide; see the section on thin-film cells). On grinding the cells and suspending them in various solutions, it was found that tests for leaching of cadmium, selenium, and other substances were within limits. Thus, under present U.S. laws, these modules are not considered hazardous waste (Zweibel and Barnett 1993; and discussions with R.H. Annan, Director, Office of Solar Energy Conversion, U.S. Department of Energy, Washington D.C.).

Cadmium is another toxin; it is both poisonous and a possible carcinogen. Both at the manufacturing stage and at the disposal stage, health and safety issues and environmental concerns must be addressed, as the technology matures, for cadmium telluride solar cells. Recycling procedures are being studied (U.S. DOE 1991). However, it is worth bearing in mind that the quantities are small compared with the amounts of cadmium waste from disposal of nickel-cadmium batteries and the cadmium entering the food stream from phosphate fertilizers. For example, in the United States 1,000 tons of cadmium enters the waste stream yearly from discarded batteries, this is equivalent to the waste that would

be created from 20 billion watts of discarded PV modules (Zweibel and Barnett 1993). Coal burning also produces some cadmium waste (about one kilogram/GWh of electricity, equivalent to 150 m2 of cadmium sulfide/cadmium telluride modules producing the same 1 GWh in 30 years; Zweibel and Barnett 1993).

The cost of photovoltaic power

The cost of electricity from photovoltaics is dependent on the following factors:

- **Insolation at the site. This determines the amount of electricity generated from a specific system, as it is analogous to the amount of fuel available.**

- **Module and system efficiency. The system efficiency is important, as it is the percentage of available energy converted to electrical energy, after energy losses during electricity generation. Data taken from Annex 8 on system efficiencies are shown in Figure 4.9. Values beyond 1992 are projected; the others are values used in calculations of various photovoltaic schemes. System efficiencies have increased with time. The main component of the system efficiency is the module efficiency.**

For most PV systems, the system efficiency is about 70 to 85 percent of the module efficiency. The module efficiency varies considerably between different PV modules, as illustrated in Figures 4.2 to 4.7. The module efficiency is also of importance in its contribution other costs, because generating a specific amount of power, will require different amounts of land, and will therefore result in different total area-related costs for modules with differing efficiency..

- **Module cost. The module cost depends on the cost of the materials comprising the module, the particular technique used to manufacture it, and the size of the module order. Costs are discussed in detail in the next subsection.**

- **Balance-of-system (BOS) cost. This can include the cost of the supporting structure, power conditioners (to convert the DC power to AC current), control devices, electrical wiring, batteries for storage, site preparation, installation, and the secondary system (such as lights or a water pump). Different sources differ about what constitutes the balance-of-system costs, and these inconsistencies make it difficult to compare BOS costs directly unless the costs of the individual constituents are given. These BOS costs can account for approximately 40 to 60 percent of the total capital cost according to varying sources. Balance-of-system costs are discussed in more detail in the cost subsection,**

- **System life. The life of the system is also important. Most sources quoted in this report assume a photovoltaic life of 30 years in calculations. One PV manufacturer has recently increased its warranty to 20 years, but most currently guarantee only 10 years, even though modules are expected to function longer (Real Goods 1991).**

National Renewable Energy Laboratory (1992c) report; current module lifetimes as 10 to 15 years. These are expected to increase to 20 years by 1995-2000 and to 30 years by 2010-2030, according to the U.S. DOE's Photovoltaics Program Plan (NREL 1992c). The International Energy Agency (1991) states that the technology has already approached a 30-year lifetime for single-crystal silicon.

- **Interest rate. The main distinguishing feature of this technology is the high capital cost and the zero fuel cost, unlike conventional technologies, in which fuel costs are high and the initial investment is low. For example, a conventional system may have a capital cost of $1,S00/kW and an operating cost (including fuel) of 4 cents/kWh, whereas a PV system can have a capital cost which is six times higher ($10,000/kW) but an operating cost which is six times lower (0.6 cents/kWh) than the conventional system.**

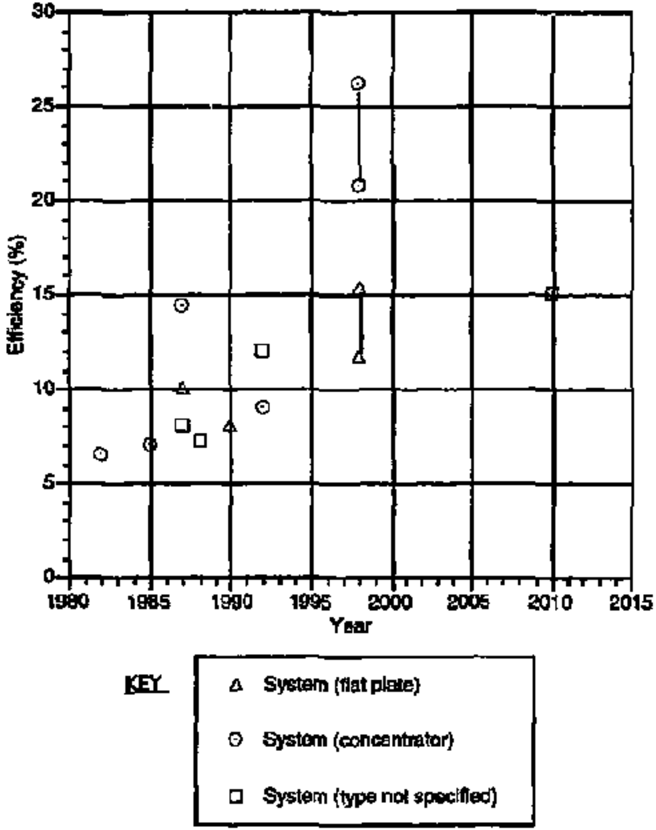


Figure 4.9. System Efficiencies

Operating and Maintenance Cost. Operating and maintenance (O&M) costs are generally low, because of the absence of moving parts in the electricity- generating components.

Items 54 and others in Annex 8 quote O&M costs of about 0.5¢/kWh for small PV systems. This is small relative to the O&M costs of a small diesel system (about 1.0 to 1.5¢/kWh for maintenance and about 5.0 cents/kWh for fuel). Operating and maintenance costs of 0.39 to 1.44/kWh are found for utility scale flat-plate systems (U.S. Congress 1992). Another source quotes a study of seven medium-scale U.S. PV projects as having O&M costs of 0.4 to 7.0¢/kWh (Kelly 1993). These arc shown below in Table 1 and may be divided into flat plate (0.39 to 1.44 ¢/kWh) and concentrator systems (4.81 to 6.97¢/kWh). In tie case of concentrator systems, almost 40 percent of the O&M cost in Arizona was for the tracker, whereas in Texas, 80 percent resulted from problems with the power conditioner.

Table 4.1. The Operating Experience of Large PV Systems

O&M costs (¢/kWh)						
	Power		Observed		Potential	
Site	(MW)	System type	Tracker only	Total	Best parts	Double efficiency
Lovington, CA	0.10	FP/OD	0.00	0.39	0.13	0.11
Washington, DC	0.30	FP/OD	0.00	1.44	0.14	0.12
Sacramento, CA	2.00	FP/1D	0.02	0.61	0.15	0.13
Carissa Plains, CA	6.50	FP/2D	0.18	0.80	0.29	0.20
Lugo, CA	1.00	FP/2D	0.37	1.10	0.29	0.20
Phoenix, AZ	0.23	C/2D	1.78	4.81	0.53	0.30
Dallas / Fort Worth, TX	0.03	C/2D	0.82	6.97	0.73	0.35

Notes. FP = flat plate;
C = concentrator;
OD = no tracking;
1D = one-dimensional tracking;

2D = two dimensional tracking.

Source: Electric Power Research Institute, Photovoltaic Operation and Maintenance Evaluation, EPRI GS-6625, December 1989, cited in Kelly (1993).

“Potential using best parts" corrects known design defects and assumes use of parts with proven low O&M costs Potential using "double efficiency" assumes best parts are used but module output is doubled by improved sell design (affects only some O&M).

Of O&M in Dallas/Fort Worth system, 80% resulted from problems with the power conditioner. More than half of the Sly Harbor (Phoenix} costs result from moisture leakage into the arrays, forcing extensive component replacement. The design defect has been corrected with improved seals.

Costs in detail

The following subsections look at module costs, balance-of-system costs, and electricity generation costs in more detail.

Modules costs

Module costs, both historic and future, according to various sources in the literature, are given in Annex 10. These were obtained from Annex 8, except items 62, 67 to 68, 159, 187 to 188, 194 to 195, 201, 207, 235 to 237, 267, and 278 to 285, which were excluded for one of the following reasons:

- **Costs for arrays were excluded, because they may also include the cost of the racks for supporting the modules.**
- **Tracker or racking (support) costs were included in the quoted cost**

- **It was not clear from the text whether the cell or module cost was being stated.**

- **Costs were based on achieving a particular production level (this necessitates certain assumptions about the rate of market increase).**

- **Costs were cited, but it was not possible to ascertain the date of the quote.**

- **Costs were projected for years up to and including 1992.**

The costs in Annex 10 were converted into 1990 U.S. dollars per peak watt using the methods described in Annex 1. These costs then were plotted in Figures 4.10 to 4.13. The following must be noted with regard to these graphs:

- **Only photovoltaic module costs are shown. BOS costs (e.g., mounting costs, storage costs) are not included but are discussed in the next section.**

- **In most cases, the year of the module cost quoted is from the source material.**

Where it is not, the publication date of the document is used, unless noted otherwise.

- **Similarly, the year of the price quoted is usually stated. Where this is not so, the year of the quoted cost is taken as the year of the currency. Beyond 1992, the year of publication of the document is taken as the currency year.**

- **The size of the module system/order is different in each case, with prices for both 2.5 Wp orders as well as megawatt orders being shown.**

Figures for 1992 and earlier are actual; those after 1992 am projections.

- **Both production costs as well as selling prices are shown. Prices may differ from production costs for several reasons; producers may have a higher implicit**

discount rate to provide for risks, taxes, recovery of R&D, and other factors. This adds to dispersion on the graphs.

Type of module is rarely specified; thus, no differentiation was made in the graphs.

The varying "quantities" (i.e., total peak wattage) of modules, as specified by the source, are shown in the graphs. In addition, Figure 4.11 shows only the module costs where the total sale is less than 1,000 Wp, as well as those bought in "small quantities." Figure 4.12 shows the module cost when the quantity being purchased is 1,000 Wp or greater, or when "large quantities" are being purchased. Figure 4.13 shows the data (the largest data set) for those costs where the wattage is not specified.

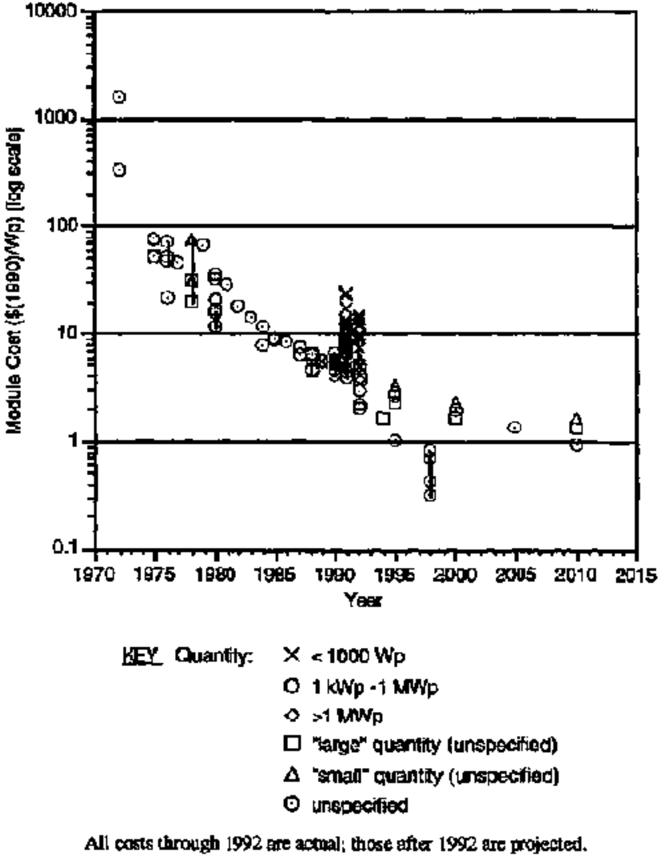
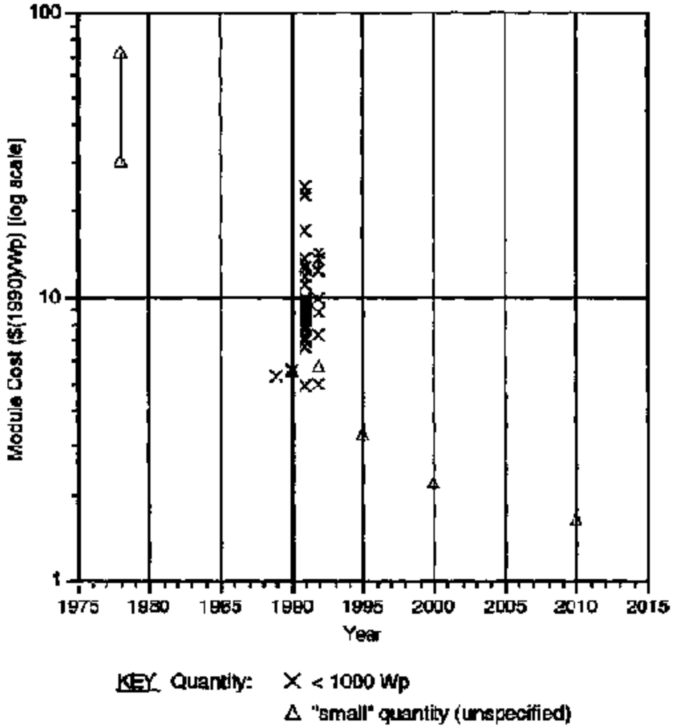


Figure 4.10. Photovoltaic Module Costs by Size of Order



All costs through 1992 are actual; those after 1992 are projected.

Figure 4.11. Photovoltaic Module Costs for Small Orders

The following may be deduced from the graphs:

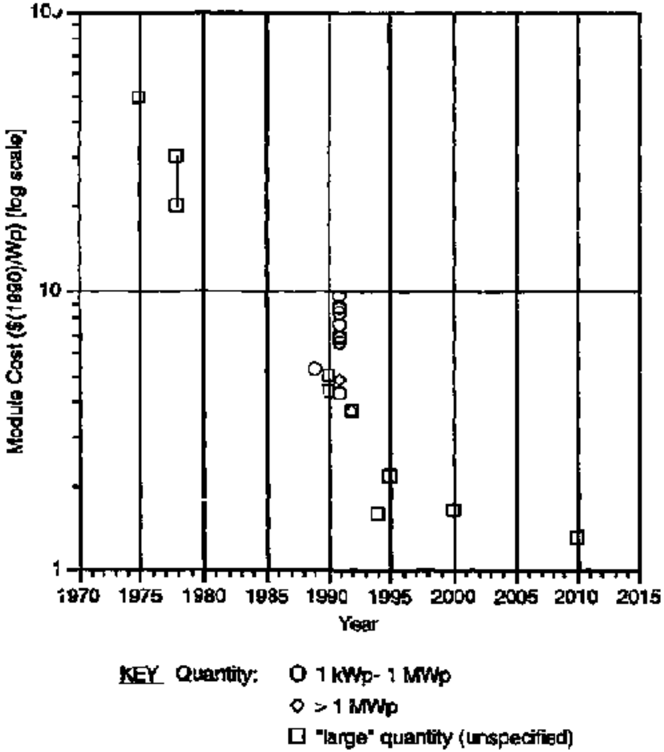
- **The costs of photovoltaic modules have decreased from about $300/Wp (1990 prices) in the early 1970s to $4 to 11/Wp (1990 prices) in 1992. An outlier figure**

of over $1,000/Wp (1990 prices) appears in the early 1970s, which may be due to the small scale of the application. There are also outlier figures of $2 to 3/Wp (1990 prices) in 1992; these may be actual production costs.

- **The costs vary with the total quantity (in terms of wattage) required, with larger quantities being cheaper.**

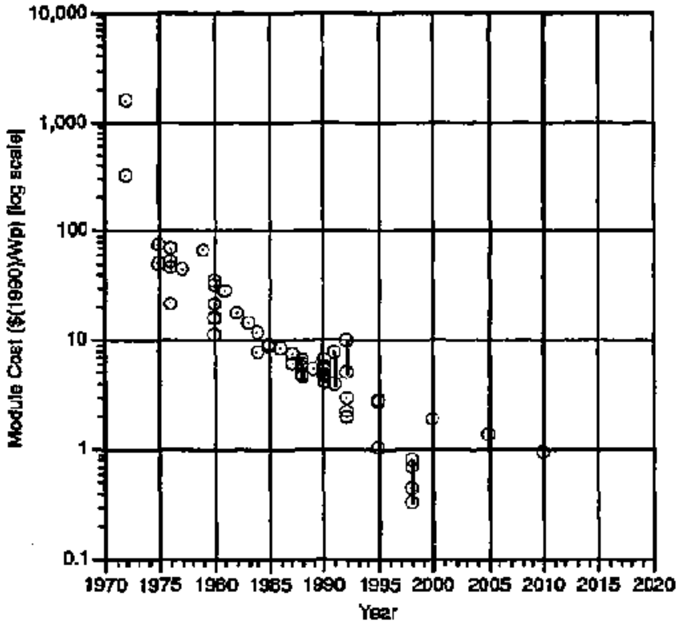
- **Projections for future cost reductions show that the cost is expected to drop to $1 to 2/Wp (1990 prices) by the beginning of the next century. The outliers for 1998 are based on projections made in the 1980s (Items 114 and 116) and appear optimistic.**

- **The costs are spread over a range for both 1991 and 1992. This probably stems from the range of data collected. This includes both actual module prices in a developing country, Zimbabwe, as well as actual module prices in the United States (from Real Goods, a commercial publication). On the other hand, the costs quoted by Zweibel and Barnett (1993; items 264-66) appear to be actual manufacturing costs. Furthermore, the latter are for thin-film PV modules, whereas the former are for crystalline silicon PV modules (except for item 42), which have a higher manufacturing cost.**



All costs through 1992 are actual; those after 1992 are projected.

Figure 4.12. Photovoltaic Module Costs for Large Orders



All costs through 1992 are actual; those after 1992 are projected.

Figure 4.13. Photovoltaic Module Costs for Unspecified Order Sizes

All costs through 1992 - are actual:; those after 1992 are projected.

From Figure 4.10, it appears that module costs are expected to drop further with time. Indeed, as noted earlier, a number of authorities quote decreases in price with respect to market size (i.e., values for module costs have been projected for a particular market size). This illustrates the extent to which economies of scale and the gain in manufacturing experience are expected to play a part in reducing future costs. Indeed, the

"learning curve" for photovoltaics has been calculated by several authorities (Cody and Tiedje 1992; and Tsuchiya 1992). This is a measure of the decrease in price with increasing production because of economies of scale and technological progress and is defined by the following relationship:

$Y = aX^b$ **or** $\log Y = \log a + b \cdot \log X$

where Y = Unit production cost for accumulated production X

X = Accumulated production
a = Cost of a unit at first production
b = Learning parameter (a negative number)

From this equation, a doubling in the accumulated production leads to a reduction in the unit cost by a factor, called the progress ratio, which is usually expressed as a percentage.

Cody and Tiedje (1992) found their data to yield a "77 percent learning curve" for "silicon solar cells" between 1976 and 1988; that is, that a doubling of production resulted in costs decreasing to 77 percent of their initial level. Cody and Tiedje (1992) also report Maycock as identifying a learning curve parameter as 90 percent for silicon solar cells up to 1965 and 80 percent between 1965 and 1973. Interestingly, Tsuchiya (1992) found a similar result for Japanese photovoltaic production between 1979 and 1988 (i.e., a nearly "80 percent learning curve"). although he does not specify the type of photovoltaic module.

These reductions in costs may be attributed to several factors:

- **The steady progress in the efficiency of cells and modules as noted earlier. For example, efficiencies of crystalline silicon modules have increased by 50 percent from 1976 to 1992; that is, from 7 to 8 percent to 10 to 13 percent. Furthermore, as**

discussed earlier, further gains in efficiency are still possible and likely.

- **Increases in the scale of manufacturing, and with this changes in cell design and manufacturing technologies. The 60-fold increase in the market from 1976, albeit from very small levels has permitted manufacturers to introduce methods more amenable to large-scale, low-cost production. Examples are the introduction of thin-film modules that are amenable to automated manufacturing processes, and the innovative methods being used for the production of single-crystal silicon wafers, such as the dendritic web approach which minimize silicon waste.**

Balance-of-system costs

As described earlier, the term balance-of-system can include supporting structure, power conditioners (to convert the DC power to AC current); control devices; electrical wiring; batteries for storage; site preparation; installation; and the secondary system, such as lights or a water pump. Sources differ in their definition of what exactly constitutes the balanceof-system, and these inconsistencies make it difficult to compare BOS costs directly, unless the costs of the individual components are given. These BOS costs can account for approximately 40 to 60 percent of the total capital cost according to varying sources. Annex 8 does give an indication of costs of certain BOS items. These are specified either a percentage of the total cost, or a total area-related ($/sq. m.) and a total power-related ($/kW) cost, or as individual component costs. The following should be noted with regard to these costs:

- **The BOS differs in different applications, from photovoltaics for water pumping to photovoltaics for generating electricity. Second, further variance is found between a grid-attached PV system and an individual unit for a house, both producing electricity. The situation can then become more complicated: Hankins (1993) gives a number of examples of PV power in developing country situations, where the**

system is only required to deliver DC electricity, unlike, say, for a home in the United States thus eliminating the need for power converters.

- **The BOS component parts are usually made or obtained locally, and thus even further variation is found in the cost of individual components depending on the site of the PV scheme. See, for exarnple, items 49 and 50 which compare costs between the Dominican Republic and the United States (U.S. Congress 1992).**

Battery cost is $1,050/kW (lasts 3 to 5 years) in the former, and $1,400/kW (lasts 3 to 5 years) in the latter. Similarly. the cost of electronic control equipment is $1,000/kW in the Dominican Republic and $1,800/kW in the United States. In addition, mounting hardware, with a cost of $800/kW, is required in the latter, unlike the former

- **The cost of the land and the cost of labor for installation of the PV scheme are again very much dependent on the site.**

- **Batteries can make up a large part of the cost. Variation in cost will be found depending on whether these are needed for a particular application. An example of an application that may not require batteries is a utility-based, grid-attached PV plant supplying only peak power.**

Significant reductions in future BOS costs are expected with increases in:

Module efficiency; this is with regard to area-related BOS costs, which will decrease as the area requirement is reduced with increasing module efficiency.

- **Market size, which lead to scale economies.**

Table 4.2 shows U.S. DOE ((1992c) and SERI (1989) assessments. The main reductions are expected to be in power conditioning, wiring and labor {installation) costs. Increases

in inverter and battery life are also projected.

*Item**	*Reference*	*System size (W)*	*BOS costs $/kW$_p$*	*Module cost $/kW$_p$*	*System cost $/kW$_p$*	*Year Notes*
187	U.S. DOE (1992c)	5,000	1,500 (controls/ inverter); 150 (battery); 1,000 installation	5,000 (array)	7,650	1991 Remote power systems; assumptions incl. 3-day battery storage, 80% max. depth of discharge, 5 yr battery life, and 10 yr controls/ inverter life
188	U.S. DOE (1992c)	5,000	1,000 (controls/ inverter); 125 (battery); 500 installation	2,500 (array)	4,125	2000 Remote power systems; assumptions incl. 3-day battery storage, 80% max. depth of discharge, 8 yr battery life, and 15 yr controls/ inverter life
278	SERI (1989)	-	2,000 battery (storage for 5 days); 100 wiring controls; 1,500 labor	7,000 (module incl. racks)	-	1987 All costs in 1987$/kWp (DC). Actual cost, remote stand-alone (1kW) system.
279	SERI (1989)	-	1,500 battery (storage for 5 days); 50 wiring controls; 1,000 labor	5,000 (module incl. racks)	-	1990 All costs in 1987$/kWp (DC). Predicted cost, remote stand-alone (1kW) system.
280	SERI (1989)	-	1,500 battery (storage for 5 days); 50 wiring controls; 800 labor	3,000 (module incl. racks)	-	1995 All costs in 1987$/kWp (DC). Predicted cost, remote stand-alone (1kW) system.
281	SERI (1989)	-	1,500 battery (storage for 5 days); 50 wiring controls; 500 labor	2,000 (module incl. racks)	-	2000 All costs in 1987$/kWp (DC). Predicted cost, remote stand-alone (1kW) system.
282	SERI (1989)	-	500 power conditioning; 500	5,000 (module	-	1987 All costs in 1987 $/kWp

			wiring; 1,000 labor	incl. racks or tracker)		(AC). Actual cost of large, installed, grid-tied system.
283	SERI (1989)	-	400 power conditioning; 300 wiring; 800 labor	4,000 (module incl. racks or tracker)	-	1990 All costs in 1987 $/kWp (AC). Predicted cost of large, installed, grid-tied system.
284	SERI (1989)	-	200 power conditioning; 200 wiring; 500 labor	2,000 (module incl. racks or tracker)	-	1995 All costs in 1987 $/kWp (AC). Predicted cost of large, installed, grid-tied system.
285	SERI (1989)	-	150 power conditioning; 150 wiring ;300 labor	1,500 (module incl. racks or tracker)	-	2000 All costs in 1987 $/kWp (AC). Predicted cost of large, installed, grid-tied system.

Note: *Item from Annex 8

Table 4.2. Balance-of-System Costs for Photovoltaic Systems

Cost of photovoltaic electricity

Figures 4.14 and 4.15 show the cost of photovoltaic electricity as calculated by a variety of different sources taken from the table in Annex 8. The costs have all been converted to 1990 dollars per kilowatt hour using the procedure described in Annex 1. Figure 4.14 distinguishes between cases where the details are given in the reference on the calculative assumptions made; and Figure 4.15 shows the same data but distinguishes between on-grid and off-grid generation, as specified by the reference. It is assumed that costs quoted up to and including 1992 are based on actual component prices, lifetimes, and efficiencies; though this is not always specified in the text. Costs beyond 1992 are based on projected component costs, lifetimes, and so on, and in some cases the basis for these projected values is given in the text.

The graphs show that the cost of electricity is decreasing. However, it is difficult to arrive

at conclusions about the rate of decrease, because different assumptions have been made by different sources for their calculations. These range from different insolation values, to different interest rates, to different types and size of schemes; furthermore, because scale economies are significant, projected costs are particularly dependent on the scale of the markets assumed. Nevertheless, some trends can be seen. The figures below compare the cost of photovoltaic electricity (in the same units) as quoted by different authorities. Current estimates for PV electricity generation range from 25 to 300 cents (1990)/kWh. Figure 4.15 illustrates the lower cost of on-grid PV electricity generation compared with remote systems. This Is partly because of economies of scale (as illustrated earlier by the lower cost of modules for large quantities) and may also be because storage costs (i.e., batteries) were not included for on-grid generation. Current cost estimates for off-grid generation are in the range 25 to 250 cents (1990)/kWh, whereas those for on-grid generation (where specified as such) are in the range 30 to 40 cents (1990)/kWh.

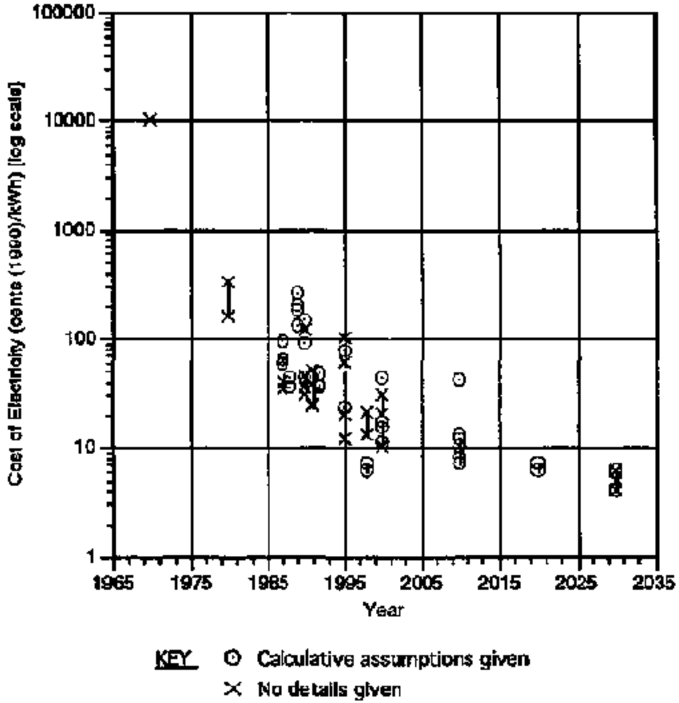


Figure 4.14. Cost of Electricity from Photovoltaics

As described earlier in this section, the cost of electricity depends on several factors, such as insolation, system efficiency, lifetime, capital costs, O&M costs, and interest rates. The method for calculating the levelized cost of electricity is shown below:

Cost of electricity (levelized) = $\frac{AC + (O\&M)}{E}$ **(in $/kWh)**

where AC = Annualized capital cost ($/yr)
C = Total capital cost ($)
A= The annuity

$$rate = \frac{r(1+r)^n}{(1+r)^n - 1},$$

where r=0.01,i.e. a discount rate of 10%, and n = life of plant (yr)
(O&M) = Annual operating and maintenance cost ($/yr)
E = Number of kilowatt hours produced annually (kWh/yr)

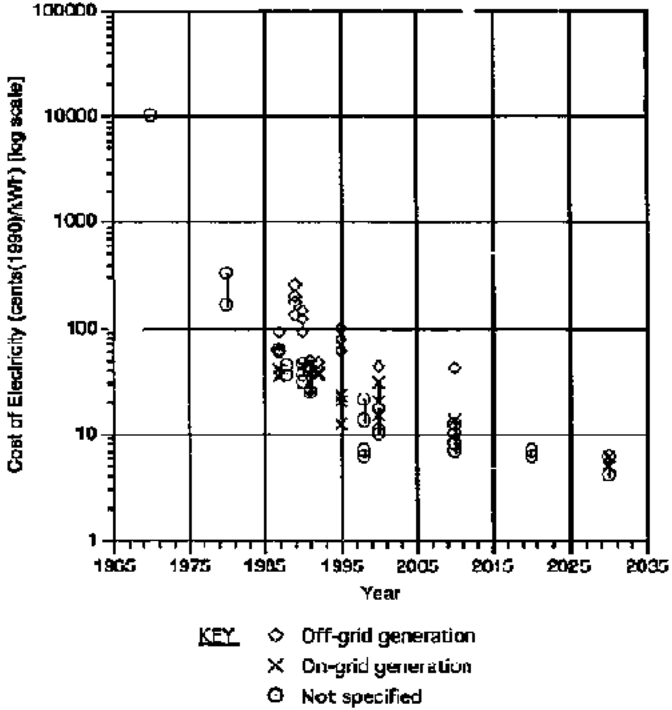


Figure 4.15. Cost of Electricity from Photovoltaics (Remote and Grid-Attached Generation)

In the case of photovoltaics, the fuel cost is zero. The term (AC/E) can be written as the sum of three terms: MOD (PV module component) + BOS(A) (area-related balance-of-system component} + BOS(P) (power-related balance-of-system component), where

$$MOD = \frac{A(r, n_M) \times C_M(\$/kW) \times 1(kW/m^2, \text{peak solar power incident on system}) \times Eff_M}{Eff_S \times insol}$$

$$BOS(A) = \frac{A(r, n_A) \times C_A(\$/m^2)}{Eff_S \times Insol.}$$

$$BOS(P) = \frac{A(r, n_p) \times C_p(\$/kW) \times I(kW/m^2, \text{peak solar power incident on system})}{Insol.}$$

Insol. where

n_M = module life (years)
n_A = life of area-related balance of system components (years)
n_p = life of power-related balance of system components (years)
C_M = module cost ($/kW)
C_A = cost of area-related balance of system components ($/m^2)
C_p = cost of power-related balance of system components ($/kW)
Eff_M = module efficiency (%)
Eff_S = system efficiency (%) = Eff_{Bos} x Eff_M
EffBOS - balance-of-system efficiency (%)
Insol. = Annual solar insolation at site (kWh/m$_2$).

As can be seen, longer component lifetimes, higher insolation, and lower component costs all result in lowering the cost of electricity generation. It is interesting to see the part played by the module efficiency.. As discussed earlier, the system efficiency is about 70 to 85 percent of the module efficiency. Thus, in the module component term, MOD, it is only the ratio of the two (EffM/EffS} that is of importance as the quoted module cost in $/Wp already accounts for the module efficiency.. The power-related balance-of-system components, BOS(P), are a function of capacity requirements and being "downstream" cf the system are not affected by module efficiency.. However, the area-related balance-of-system, BOS(A), is affected by both module efficiency, EffM, and system efficiency, Effs.

First, the system efficiency is of importance in determining the electricity generated. Second, the area-related balance of system costs are linked to the module area and therefore the module efficiency far a required peak wattage.

The future of photovoltaics

There is no doubt that costs of photovoltaic modules have decreased by a factor of 10 over the past 15 years or so and a factor of over 50 since the early 1970s. This decrease has been as a result of both technological progress and gain in PV production experience. There has also been an increase in PV module efficiencies. The "bottom line" is the cost of electricity. This too has decreased, as a result of lower module costs and higher module efficiencies. Indeed, it is already competitive with the cost of electricity from conventional technologies in certain instances. Remote sitings are the main example of this, particularly for small loads, due to the high costs of grid extension. For example, Waddle and Perlack (1991) found that in Guatemala, PV systems were less expensive than grid extension when loads were less than 15 to 25 kWh/day and the distance to the nearest tie-point was 6 to 10 km.

The extent of interest and technological research in the field of photovoltaics appears to offer prospects for further cost reductions, in particular with the large-scale commercialization of heterojunctional thin-film modules and multijunctional PV modules, as well as with advances in PV concentrator technology. Increases in the PV market will also play an important part in cost reduction because of scale economies and in the creation of incentives for further technical innovation in manufacturing. The incentive to PV manufacturers to decrease costs substantially will occur only if the market increases are large enough to enable the industry to recoup its investment in PV research and development. Other future issues of importance in the photovoltaic industry are the supply of raw materials, as the crystalline silicon PV market expands beyond the "waste" silicon available from the semiconductor industry.

The emphasis to date, however, has been on photovoltaic modules, when the balance-ofsystem components form 40 to 60 percent of the total cost. Economies of scale and extensions in component lifetimes are expected to be the main two factors in reducing these costs further. Batteries, especially, are mentioned as being a particularly expensive component because of their short lifetime (3 to 5 years) and consequent need for regular replacement. This, however, is mainly an issue for remote systems; grid-attached PV systems for the provision of peak power (if peak insolation and peak demand match) or PV schemes used in conjunction with an existing hydro scheme have less need for storage.