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CO_2 Emissions from Coal-Fired and Solar Electric Power Plants

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PREFACE

This report presents estimates of the lifetime carbon dioxide emissions from coal-fired, photovoltaic, and solar thermal electric power plants in the United States. These CO_2 estimates are based on a net energy analysis derived from both operational systems and detailed design studies. The implications of the results for planning a national energy policy are also discussed.

The authors would like to thank Thomas D. Bath of the Solar Energy Research Institute (SERI) and Prof. R. E. West of the University of Colorado for their constructive criticism of the manuscript.

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1.0 INTRODUCTION

Human activities can affect the heat balance of the Earth, the atmosphere, and space. In particular, burning fossil fuels increases the carbon dioxide (CO_2) concentration in the atmosphere and thus induces global warming by virtue of a mechanism commonly referred to as the "greenhouse effect" (Ramanathan 1988). This is the mechanism by which the atmosphere controls the Earth's temperature. It depends on the high transmissivity of atmospheric gases to radiation in the short-wavelength range, in which the major part of incoming sunlight reaches the Earth, and the opaqueness of these same gases to the infrared (IR) radiation emanating from the Earth. The absorption of solar radiation warms the Earth's surface, whereas the IR radiation emitted by the surface tends to cool the Earth. But the atmosphere absorbs more and more of this IR energy as the concentration of CO_2 builds up, and more heat is trapped in the lower atmosphere. The temperature of the Earth then increases to maintain a heat balance between incoming and outgoing radiation.

Figure 1-1 shows the average global temperature deviation from the mean, the CO_2 concentration in the atmosphere, and annual carbon production as a function of time over the last 140 years. There are still questions about its exact magnitude, but all the available evidence points to a rise in the average global temperature as the CO_2 concentration increases. These data indicate that the burning of fossil fuels, coupled with the destruction of vast forests, have led to a rise in CO_2 concentration approximately 25% above the level that existed before humans began interfering with the Earth's natural heat balance.

According to Bath and Feucht (1990), current estimates of global CO_2 emissions from fossil fuel use (expressed as gigatons of carbon) are about 5.1 GT per year. Reductions of biologically fixed carbon, mostly from deforestation, add about 1 to 1.5 GT of carbon to the atmospheric input. Of this annual total of about 6.5 GT of carbon, roughly 3 to 3.5 GT are removed from the atmosphere by the oceans, leaving a net input of about 3 GT of carbon per year. This agrees with the observed rate of increase in atmospheric CO_2 (0.5% per year) and suggests with some confidence that a 50% reduction from current emission levels would bring the atmospheric carbon cycle back into balance, stabilizing the CO_2 concentration in the atmosphere (Bath and Feucht 1990). However, if we continue burning fossil fuels at current rates, the buildup of CO_2 in the atmosphere will trap increasing amounts of infrared radiation emitted by the Earth and result in a warming of the Earth's surface.

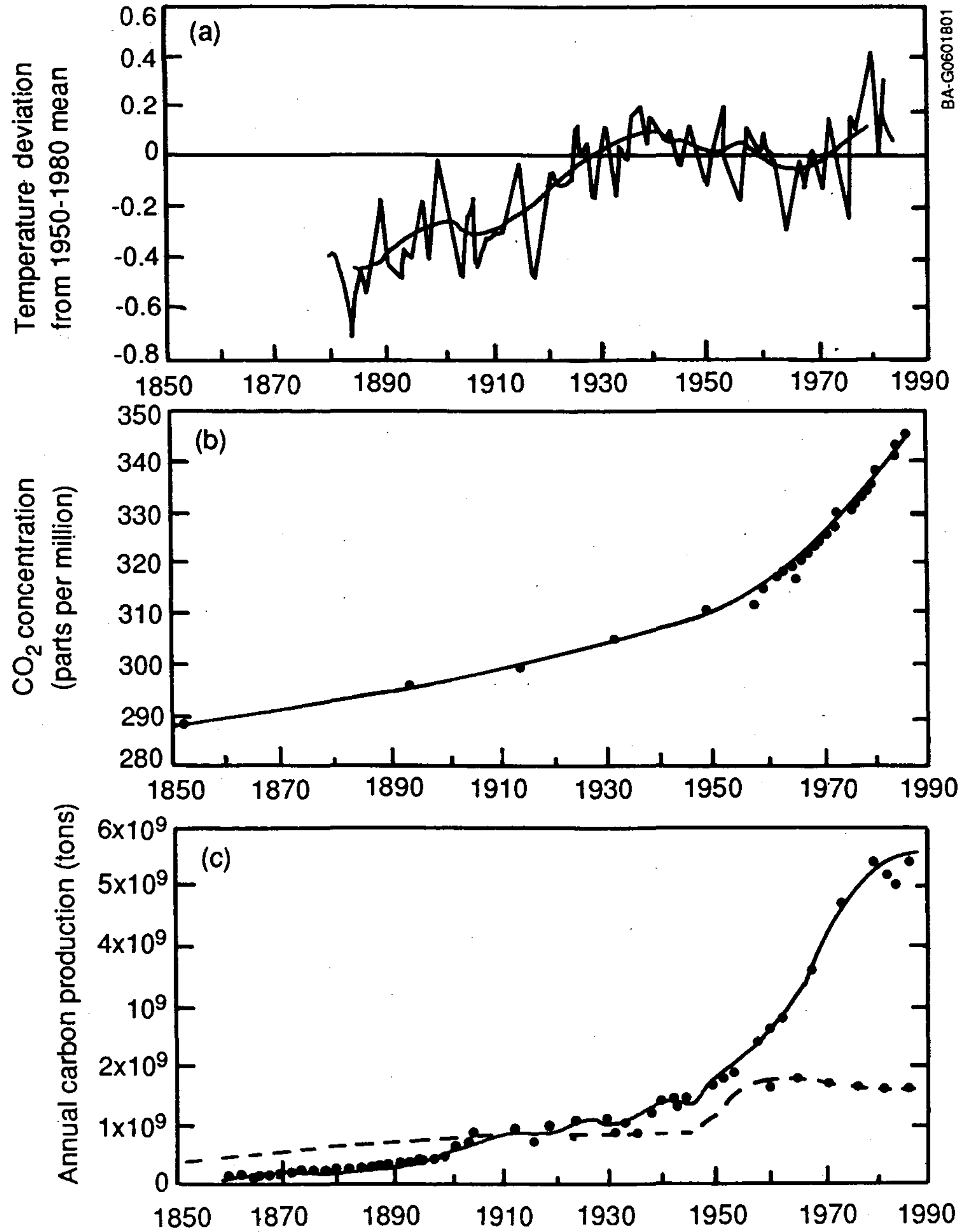

Figure 1-1. **Global temperature change, CO_2 concentration, and annual carbon production for the past 140 years.** Graph (a) shows the annual mean (spiky curve) and the 5-year mean (smooth curve) global temperature. Graph (b) shows the atmospheric CO_2 content. (Pre-1958 data come from analysis of air trapped in bubbles of glacial ice from around the world.) The annual production of carbon from fossil-fuel burning (solid line) and from changes in land use (dashed line) is shown in graph (c). (Source: Houghton and Woodwell 1989. Reproduced with permission.)

2.0 OPTIONS FOR REDUCING CO_2 GENERATION

Five basic options for reducing CO_2 generation have been proposed (Morrison 1989; Jaeger 1988). These are as follows:

1. *Increase the end-use efficiency of fuel use by conservation and improved energy conversion.* Technologies exist for energy conservation and improved utilization by measures such as better insulation, cogeneration, or increased gas mileage; a reduction in overall energy consumption of up to 50% is achievable with available means.

2. *Replace fossil fuels with renewable energy sources.* As this report shows, this is the only viable long-term strategy to provide power without curtailing growth. Appropriate technology is available, but the optimum system (e.g., wind, solar or nuclear energy for electric power, solar thermal energy for domestic hot water, etc.) depends on geographic location and end use. Implementing this option would require a national energy plan with appropriate regulations and economic incentives.

3. *Reverse the trend of deforestation.* As much as 20% of worldwide CO_2 emissions due to human activities comes from burning forests. Eliminating burning and instituting accelerated reforestation would reduce emissions and absorb atmospheric CO_2 as the trees grow and store carbon in their biomass. At present, however, it is estimated that only one tree is planted for every 11 or 12 trees cut down. In Brazil's Amazon Basin alone, 20,000 to 40,000 km^2 of forest land is cleared annually.

4. *Shift from coal to natural gas.* The combustion of natural gas produces about 40% to 50% less carbon dioxide per unit energy delivered than the combustion of coal (Marland and Rotty 1983). However, estimates of the amount of natural gas available in the United States have recently plummeted (Kerr 1989), and appreciable amounts of CO_2 would still be produced by natural gas systems. Hence, switching fuel is at best a temporary amelioration and not a long-term solution.

5. *Collect and dispose of CO_2.* Liquid solvents, solid adsorbents, and separation processes could be used to remove carbon dioxide from flue gases. Although CO_2 emissions from coal-fired power plants could be reduced by up to 90%, the power generation of those plants would thus be reduced by as much as 70%. In addition to the extreme cost, transportation and final disposal of the CO_2 present unresolved problems.

Concern about deleterious climate changes resulting from global warming has led to recommendations designed to reduce emissions of CO_2. The recommendations outlined above include energy conservation, reforestation, cogeneration, and substituting natural gas, nuclear, and solar energy for coal and oil. However, U.S. energy policy since 1973 has largely emphasized the substitution of coal for oil to protect national security interests. Hence, the goal of reducing CO_2 production could conflict with U.S. energy security measures. To avoid such a conflict, it is necessary to adopt a long-range energy policy that takes the various interests into account and reduces CO_2 production without curtailing economic activities. To develop such a policy it is necessary to know the amount of CO_2 that would be emitted from different energy conversion and conservation technologies. In this report we estimate the CO_2 production of solar thermal, photovoltaic, and coal-fired electric power plants operating in the "electricity only" mode and as cogeneration systems. This information may be useful to energy planners in developing realistic options for long-term energy policy.

2.1 A Method of Estimating CO_2 Emissions

A method for calculating the energy return on (energy) investment (EROI) for renewable energy conversion systems has been demonstrated by Kreith et al. (1987). Subsequently, Kreith and Norton (1989) showed how to apply the EROI to calculate CO_2 generation for renewable and nonrenewable energy sources.

In this approach, the total amount of CO_2 generated during the life of a power plant is calculated by adding the CO_2 generated during construction and decommissioning to the CO_2 generated from burning fossil fuels and from operation and maintenance (O&M) of the plant. The CO_2 generated during the construction of a power plant is calculated by multiplying the primary energy investment in each component of the plant by the average CO_2 production per unit of primary energy used by the U.S. energy infrastructure.

The CO_2 production per unit of primary fossil energy for coal, oil, and natural gas is calculated from the carbon content and the stoichiometric equations of combustion for each of the fossil fuels. Carbon dioxide production from coal, oil, and natural gas has been calculated by several sources, including the U.S. Department of Energy (DOE) and the Congressional Research Service (CRS) (Marland and Rotty 1983; Morrison 1989; Lovins et al. 1981; Kreith and Norton 1989). The results of these calculations agree within 10%. One reason for this discrepancy is the difference in assumptions about the carbon content in fossil fuels and the coal chemistry. The DOE data base of Marland and Rotty (1983) is the most extensive of these studies and will be used in our analysis. The U.S. fossil energy use distribution (Mackenzie 1988) is shown in the first column of Table 2-1 in GWh of energy from a given fossil fuel source per GWh of energy delivered from all fossil fuel sources. Multiplying the energy from a given fossil fuel per GWh from all fossil fuels by the metric tons of CO_2 per GWh for that fuel yields the tons of CO_2 produced per GWh of primary fossil fuel use. Summing the third column of Table 2-1 shows that an average of about 255 metric tons of carbon dioxide is produced for every GWh of primary fossil fuel energy used in the United States.

Kreith and Norton (1989) compared the CO_2 generation for residential photovoltaic and large wind energy conversion systems with the CO_2 generation from coal- and oil-fired electric power plants by the method described above. The data bases for these CO_2 generation estimates were the economic profiles of selected solar technologies prepared jointly in 1982 by Los Alamos National Laboratory (LANL) and the Solar Energy Research Institute (SERI) (Mann and Neenan 1982). Since the LANL-SERI

Table 2-1. U.S. Fossil Fuel Use Distribution and CO_2 Production per Unit of Primary Fossil Energy Used in the United States

	Fractional Energy from Fuel Sources per GWh of Primary Fossil Energy Used (U.S.) (Mackenzie 1988)	CO_2 Produced per GWh from Each Fuel Source of Primary Fossil Energy (Marland and Rotty 1983) (metric tons)	CO_2 Produced per GWh of Primary Fossil Fuel Energy Used (U.S.) (metric tons)
Coal	0.26 GWh	315	81.9
Oil	0.49 GWh	260	127.4
Natural gas	0.25 GWh	182	45.5
Total	1.00 GWh		254.8

Table 2-1 study did not include solar thermal power plants or large-scale photovoltaic plants, data bases for these electric generation technologies had to be developed in order to calculate their CO_2 generation.

2.2 Solar Thermal Power Plants

The data base for solar thermal power plants was generated by Battelle Pacific Northwest Laboratory (PNL), using cost data supplied by the prime contractors listed in Table 2-2 for a design for a 100-megawatt (electric) (MW_e) solar thermal central-receiver electric power plant. The procedure is described in detail by Brown (1988); key results are given below.

Table 2-2. Prime Contractors Supplying Cost Data for the 100-MW_e Solar Thermal Power Plant (Brown 1988)

Arizona Public Service [1-3][a]
Bechtel [4-6]
Black and Veatch [7, 8]
El Paso Electric Company [9, 10]
Exxon [11]
General Electric [12]
Honeywell [13]
Jet Propulsion Laboratory [14]
Martin Marietta [15]
McDonnell Douglas [16, 17]
Northrup (ARCO) [18]
Rockwell International [19-21]
Sandia National Laboratories [22, 23]
Southern California Edison [24]
Stearns-Roger [25, 26]
U.S. Department of Energy [27]

[a] Numbers in brackets refer to references in D. R. Brown, "Cost Drivers for Solar Thermal Central Receiver Power Plants" (Brown 1988).

The central-receiver system analyzed is shown schematically in Figure 2-1. It uses an established technology based on a molten nitrate salt working fluid. Heliostats track the sun in two axes, redirecting the incident solar energy onto a tower-mounted receiver. The energy absorbed at the receiver heats the molten salt to 1050°F (840 K); the molten salt is then transported through pipes to the storage subsystem and subsequently to a four-shell recirculating steam generator that powers a water/steam Rankine-cycle heat engine.

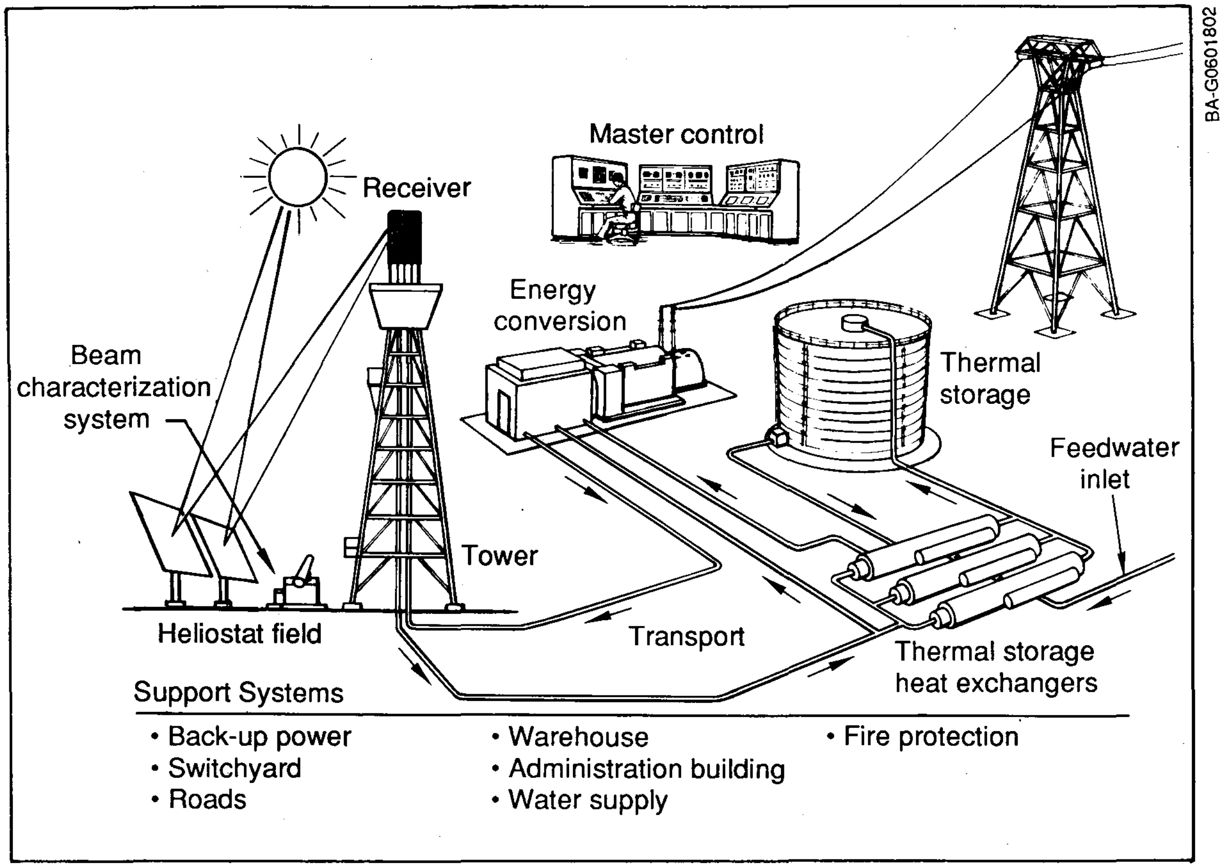

Figure 2-1. Schematic diagram of a molten-salt central receiver power plant (Source: US DOE 1985)

The heliostat field, which is the most energy-intensive component of the system, uses a 1600-ft^2 (148.6-m^2) glass mirror design developed by ARCO Solar Industries that was scaled up from a 1024-ft^2 (95.1-m^2) design described by Rockwell International (1983). Stretched-membrane heliostats use a more advanced design, which affords a radically lower cost, less energy investment, and less CO_2 production (Murphy 1986). But additional development is necessary to achieve the design maturity and reliability of the glass mirror design used in this analysis (Alpert and Houser 1989). A drawing of ARCO's 1600-ft^2 (148.6 m^2) heliostat is shown in Figure 2-2.

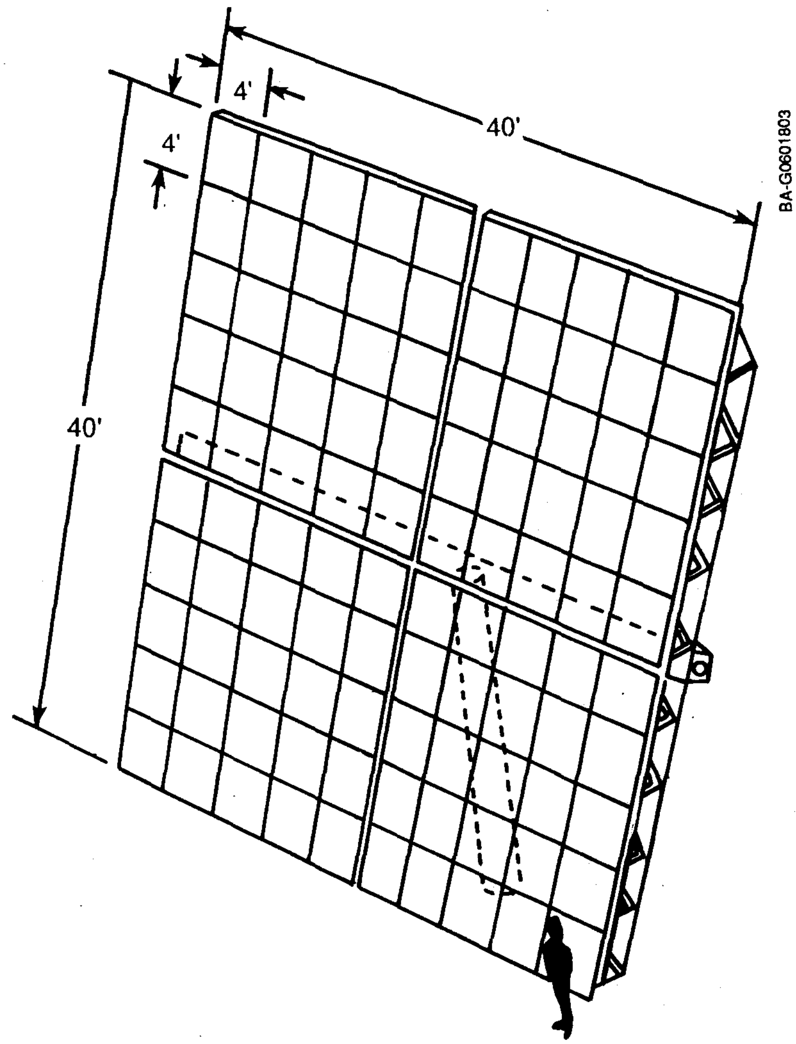

Figure 2-2. ARCO Solar Industries' 1600-ft^2 (148.6 m^2) glass mirror heliostat

The receiver design is described by Weber (1983). It uses a C-shaped cavity receiver with a vertical orientation for the absorber panels. The transport subsystem connects the receiver, storage, and steam generator subsystems. Principal components include the riser and downcomer within the receiver tower, ground-level piping, pumps, valves, and fittings. The storage subsystem consists of a "hot" tank for storing molten salt at 1050°F (839 K), a "cold" tank for storing molten salt at 550°F (561 K), and a salt treatment and makeup system. The steam generator is composed of preheating, evaporating, superheating, and reheating heat exchangers.

The design specifications and the predicted annual performance for the molten-salt central-receiver (MSCR) solar thermal power plant are summarized in Table 2-3. For the CO_2 generation calculation, the availability was taken as 90%, a level that is considered reasonable for a future mature system. Table 2-4 shows a breakdown of the costs of the receiver, the tower, the transport piping, the storage facility, the heliostat field (including support structures and controls), the energy conversion system, and the balance of the plant. Also included is the cost of labor for the assembly and installation of each component of the MSCR solar thermal system. The final item is the estimated yearly O&M cost for the system. All of the cost data in the second column of Table 2-4 are in 1977 dollars. They were obtained by applying the appropriate inflation factor to the cost estimates in 1984 dollars provided by Brown (1988), using data published by the U.S. Department of Commerce (West 1988). A detailed breakdown of the system costs and materials is contained in the appendix.

Table 2-3. Solar Thermal Power Plant System Design and Performance Specifications (Williams et al. 1987)

Construction time (years)	3
Net generating capacity (MW_e)	100
Heliostat field size (1000 m^2)	733
Storage capacity (MWh_t)	1139
Storage time (h)	4.4
Plant capacity factor	0.4[a]
Annual (solar) energy input (kWh_t/m^2)	2848
System annual efficiency (solar to electric)	18.6%[a]
Annual energy output (kWh_e)	3.883 E8[a]

[a]Assumes 100% availability.

The procedure for calculating the embodied energy of the subsystems in the third column of Table 2-4 is given in detail by Kreith et al. (1987) and is illustrated for the energy conversion subsystem in Table 2-5. The first column lists the item, the second column the cost in 1984 dollars ($1984), the third column the same cost in $1977, the fourth column the appropriate standard industrial code (SIC) of the item, the fifth column the SIC sector, and the sixth column the embodied energy per dollar for this SIC code, obtained from Hannon et al. (1985). The seventh column shows the embodied energy in that item based on the energy efficiency of the United States in 1977. However, U.S. energy consumption per dollar of gross national product (GNP) has decreased since 1977, as shown in Figure 2-3.

Table 2-4. Cost, Embodied Energy, and CO_2 Production of the Key Components of 100 MW_e Solar Thermal Power Plant

Component	Cost (10^7 \$1984)	Cost (10^7 \$1977)	Embodied Energy (GWh of primary energy)	CO_2 Production (metric tons of CO_2)	Percent of Total CO_2
A.1 Receiver[a]	1.7	1.1	121	30,831	6.6
A.2 Tower	0.6	0.4	75	19,110	4.4
A.3 Heliostats	7.3	4.6	581	148,039	33.3
A.4 Transport	1.0	0.5	60	15,288	3.3
A.5 Storage	1.6	1.0	170	43,316	9.3
A.6 Energy conversion	3.8	2.4	172	43,826	9.9
A.7 Balance of plant[b]	2.6	1.6	103	26,244	6.0
A.8 30 years of operation and maintenance	11.4	7.0	478	121,794	27.4
Total for 30-Year Life	30.0	18.6	1760	448,448	100

[a] Notations A.1, A.2, etc., refer to the corresponding tables in the appendix that give the cost breakdown for each component.

[b] Balance of plant includes land and land-related costs, buildings, fences, master control, service facilities, power conditioning, and spare parts.

Table 2-5. Energy Investment in the Energy Conversion Subsystem of the Solar Thermal Power Plant

Parts	$1984	$1977	SIC Code	SIC Sector	Energy Intensity (Btu/$1977 GNP)	1977 Energy Investment (10^{10} Btu)	1989 Energy Investment[a] (10^{10} Btu)
Turbine generator	15,500,000	9,650,000	530400	Motors, Generator	33556	32.38	25.1
Cooling tower, condenser, and ancillary Rankine equipment	15,500,000	9,650,000	490700	General Ind. Mach.	28793	27.79	21.5
Carbon steel preheater	1,150,000	716,000	400300	Heating Equipment	33553	2.40	1.9
Low-alloy steel evaporator	2,350,000	1,460,000	400300	Heating Equipment	33553	4.91	3.8
Stainless steel superheater	2,030,000	1,264,000	400300	Heating Equipment	33553	4.24	3.3
Stainless steel preheater	1,790,000	1,114,000	400300	Heating Equipment	33553	3.74	2.9
							Total: 5.85×10^{11} Btu primary energy = 172 GWh primary energy

[a]The figures in the preceding column for the energy investment in 1977 were corrected to reflect the 22.5% reduction in energy used per dollar of GNP between 1987 and the beginning of 1989.

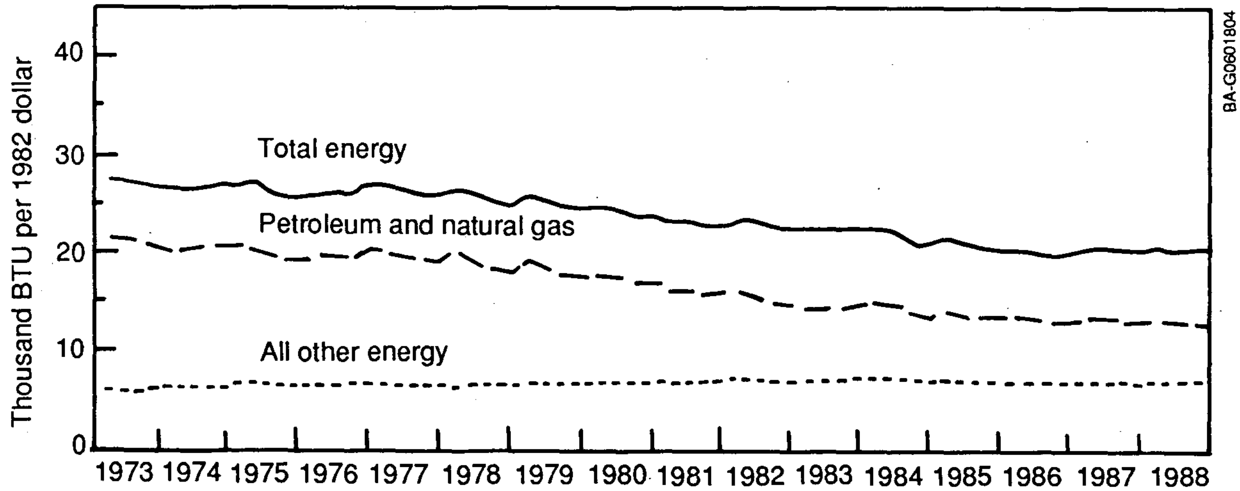

Figure 2-3. Energy consumption per dollar of gross national product (Source: Energy Information Administration 1988)

The United States now produces one dollar of GNP with 22.5% less energy than it did in 1977 (Energy Information Administration 1988). Therefore, the embodied energy based on the 1977 data must be reduced by 22.5% to obtain the embodied energy for a system built in 1989. This adjusted embodied energy is listed in the last column of Table 2-5. The CO_2 production for each component of the system is then calculated by multiplying the average CO_2 per unit of primary energy for the U.S. energy infrastructure by the embodied energy of that component.

Note that the energy efficiency correction is approximate because the energy utilization pattern has changed as a result of a realignment of U.S.-produced goods and those imported from other countries. For example, a considerable portion of the decline in U.S. energy intensity was the result of rising imports of energy-intensive goods such as automobiles and machinery, of higher new-car fuel efficiencies, and of reduced levels of energy used in heating and cooling buildings. Also, this method does not include "non-energy" CO_2, which may be important in processes such as cement production, where CO_2 from calcining CO_3 rock also produces CO_2.

2.3 Photovoltaic Power Plants

Two data bases were used to study photovoltaic power plants; one is a small system in operation at Austin, Tex., and the other is a conceptual design. A comparison of these two systems provides both an indication of economies of scale and the improvement that occurs between a current, state-of-the-art system and a next-generation system that can draw on operational experience in its design. The cost and performance data for the City of Austin's 300-kW_e plant were obtained from Panico (1989) and Hoffner (1989), respectively. Although this is a relatively small system by electric utility standards, it is of interest because actual cost and performance data are available. The data for a conceptual design for a large, 100-MW_e photovoltaic power plant were obtained from a study conducted by the Electric Power Research Institute (EPRI) (Levy and Stoddard 1984).

The City of Austin Electric Utility Department has been operating its nominal 300-kW_e photovoltaic plant since December 1986. A full year of data for 1988 has been recorded and analyzed by Hoffner (1989). The plant has been highly reliable, with an availability greater than 99% and a 22% yearly capacity factor based on the actual-to-rated plant output. During 1988, the plant had an alternating-current (AC) net efficiency of 8.5% with a total net output of 484,957 kWh_e-AC. The maintenance costs for the plant were \$0.004/kWh_e (\$1988). The plant consists of a 3.5-acre field of 2620 m^2 (gross) of single-crystal silicon cells. The cells are mounted on 42 single-axis passive trackers that rotate around a north-south, horizontal axis. The system uses a 300-kW Toshiba inverter with a design peak efficiency of 96% and is connected to the city's electric distribution system of 12,500 V AC. The total installed cost of the plant was \$3 million in 1986. Figure 2-4 shows a photograph of the system.

The costs, the embodied energy, and the CO_2 production for the 300-kW_e photovoltaic system components are presented in Table 2-6. A more detailed breakdown of the component materials, material costs, SIC sectors, energy intensity, and embodied energy is contained in the appendix.

EPRI performed a design study of the performance and cost of 100-MW_e photovoltaic central stations using fixed flat-plate, one-axis tracking flat-plate, two-axis tracking flat-plate, and two-axis tracking high-concentration collectors in the southwestern and southeastern United States (Levy and Stoddard 1984). The study concluded that the three flat-plate systems are potentially viable in the Southwest, but only the fixed and one-axis tracking systems are potentially economical in the Southeast. For this report, only the flat-plate one-axis tracking design was analyzed for CO_2 production at both locations. The key design characteristics of this system are listed in Table 2-7. The plant layout and panel structural concept are shown in Figures 2-5 and 2-6, respectively. The construction of the plant is slightly different for the two locations, owing to variations in soil conditions and wind loading. Higher labor rates in the Southwest also cause a difference in systems costs.

The Southwest site is at Barstow, Calif. The total net annual energy generation for the plant at this site is 228 GWh_e. The total cost estimate of the plant at Barstow is \$97 million (\$1982). The Southeast site is at Bay Minette, Ala. The plant at Bay Minette has an estimated net annual output of 178 GWh_e and a cost of \$86 million (\$1982). The annual operation and maintenance costs for this system were estimated to be \$2.30/m^2 (\$1982) of photovoltaic panel. The costs, embodied energy, and

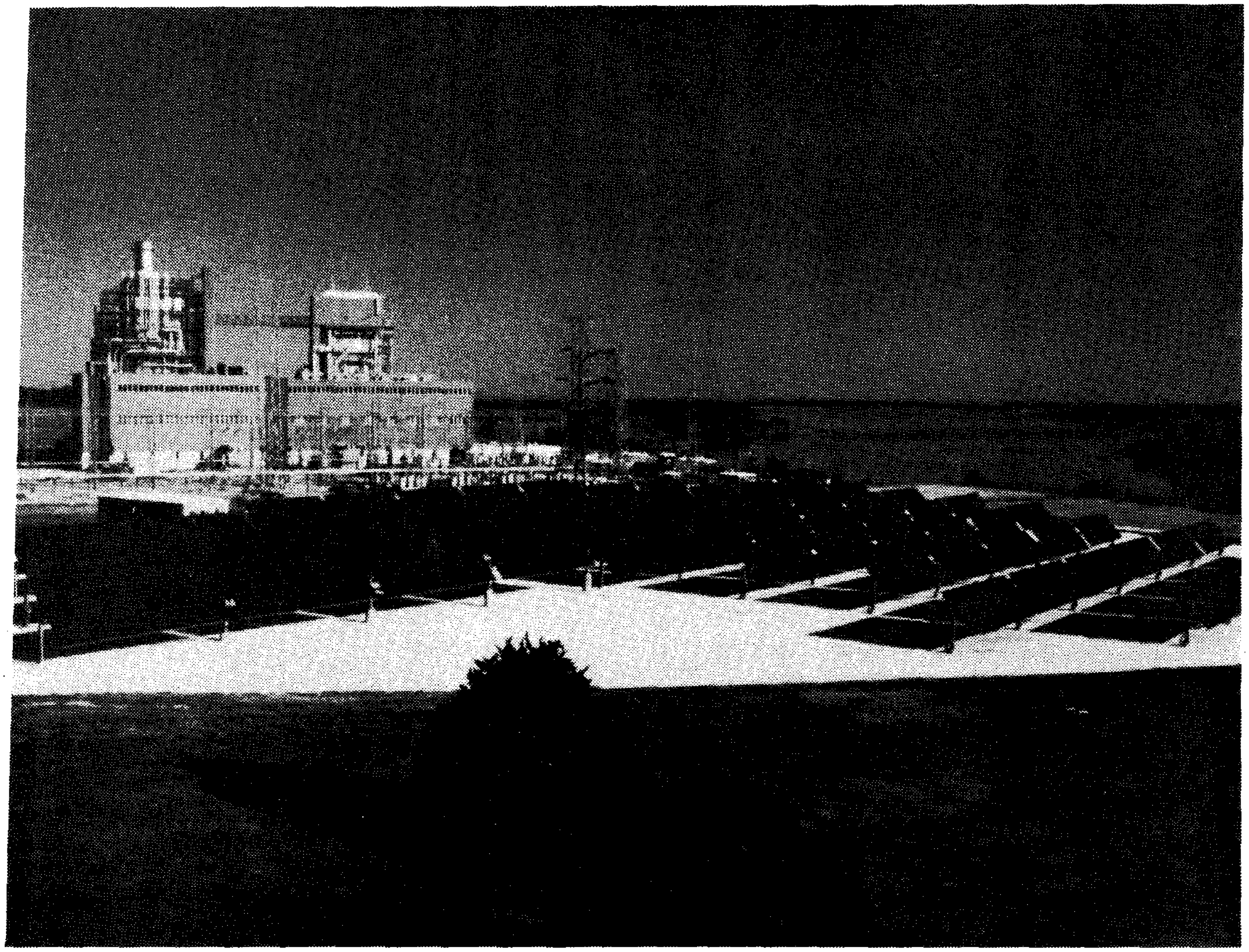

Figure 2-4. The City of Austin's PV300 (300-kW$_e$) photovoltaic power plant

CO_2 production of the key components of the plants are shown in Tables 2-8 and 2-9. Materials, material costs, SIC sectors, energy intensity, and embodied energy are shown in detail in the appendix.

2.4 A Comparison of Solar and Coal-Fired Electric Power Plants

The lifetime CO_2 production from construction, operation, and maintenance and the net electric power output for the three solar power plants are shown in Table 2-10, for a 30-year lifetime. Also shown in the table are the power output and CO_2 production for a 747-MW$_e$ fluidized-bed, coal-burning power plant. The performance of this type of coal plant was analyzed by Perry et. al (1977) and the CO_2 production was calculated with the DOE data (Marland and Rotty 1983). These results are shown graphically in Figure 2-7.

Table 2-6. **Cost, Embodied Energy, and CO_2 Production of the Key Components of the City of Austin's 300-kW_e Photovoltaic Plant**

PV300 Plant Components	Actual Cost (10^4 \$1986)	Cost (10^4 \$1977)	Embodied Energy (GWh of primary energy)	CO_2 Production (metric tons of CO_2)	Percent of Total CO_2
Photovoltaic panels	167.5	98.6	7.0	1784	42.5
Power conditioning unit	23.4	13.7	1.2	306	7.1
Structural subsystem	27	15.9	4.6	1172	27.8
Electrical subsystem	10.8	6.4	0.6	153	3.8
Nonessentials	10.8	6.4	0.5	127	3.3
Site preparation	9	5.3	1.0	255	6.1
Installation	29.7	17.5	1.4	357	8.5
30 years of operation and maintenance	5.8	3.4	0.2	51	0.9
Total for 30-year lifetime	286.9	168.9	16.5	4205	100.0

Table 2-7. Key Design Characteristics for the EPRI Flat Plate, One-Axis, Tracking Photovoltaic Central Station Design

Time for construction:	2 years
Peak capacity:	97 MW_e
Net peak plant output:	86 MW_e (Southwest site)
	76 MW_e (Southeast site)
Collector aperture:	799,000 m^2
Number of panels:	26,880
Array arrangement:	North-South rows, horizontal axis with ±50° rotation
Structural concept:	Torque tube, linear actuator
Nominal panel voltage:	60 VDC
Nominal panel current:	63 A
Laminate efficiency:	15% (at a cell temperature of 28°C)

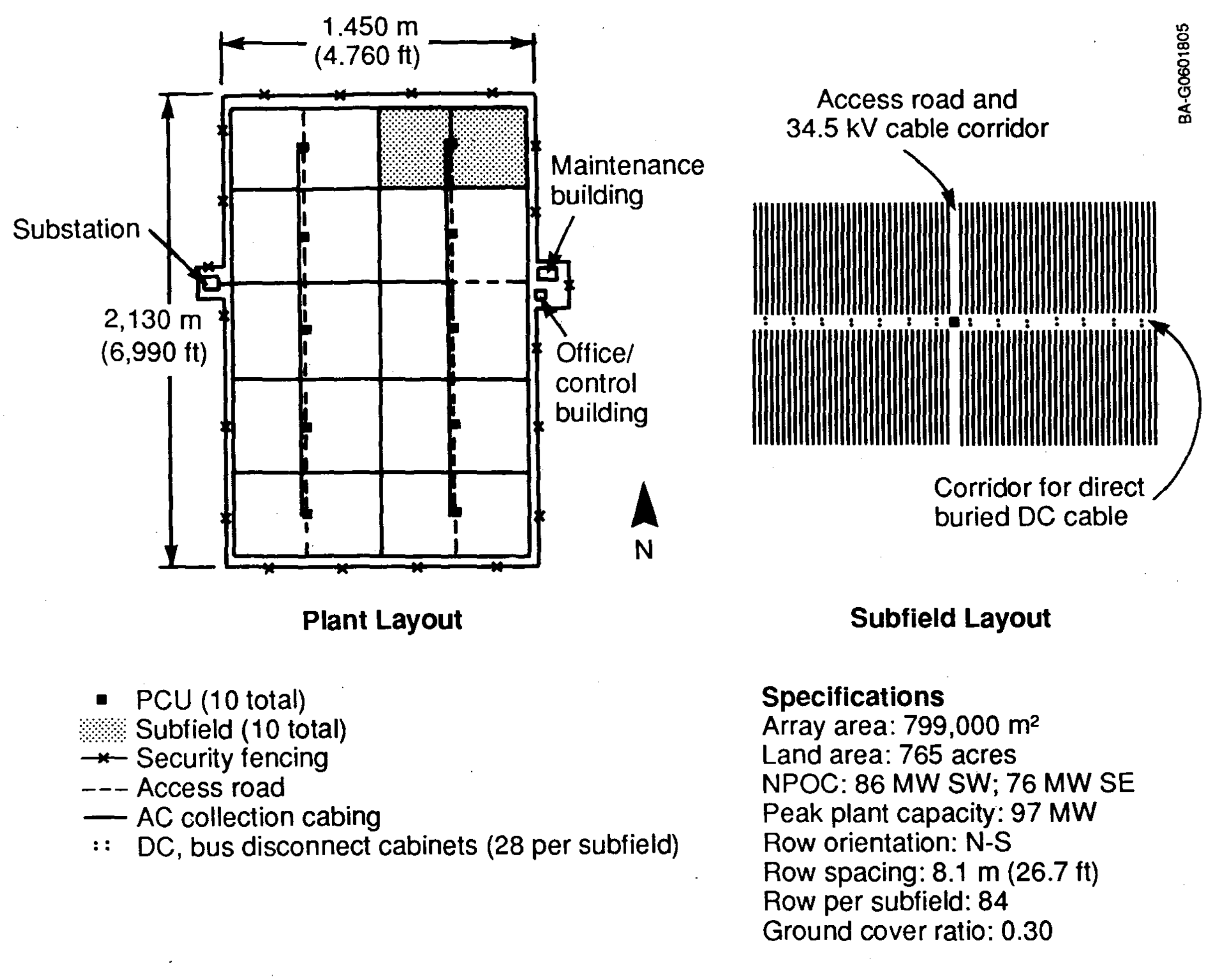

Figure 2-5. EPRI's plant arrangement for the one-axis, tracking, flat-plate photovoltaic power plant (Source: Levy and Stoddard 1984)

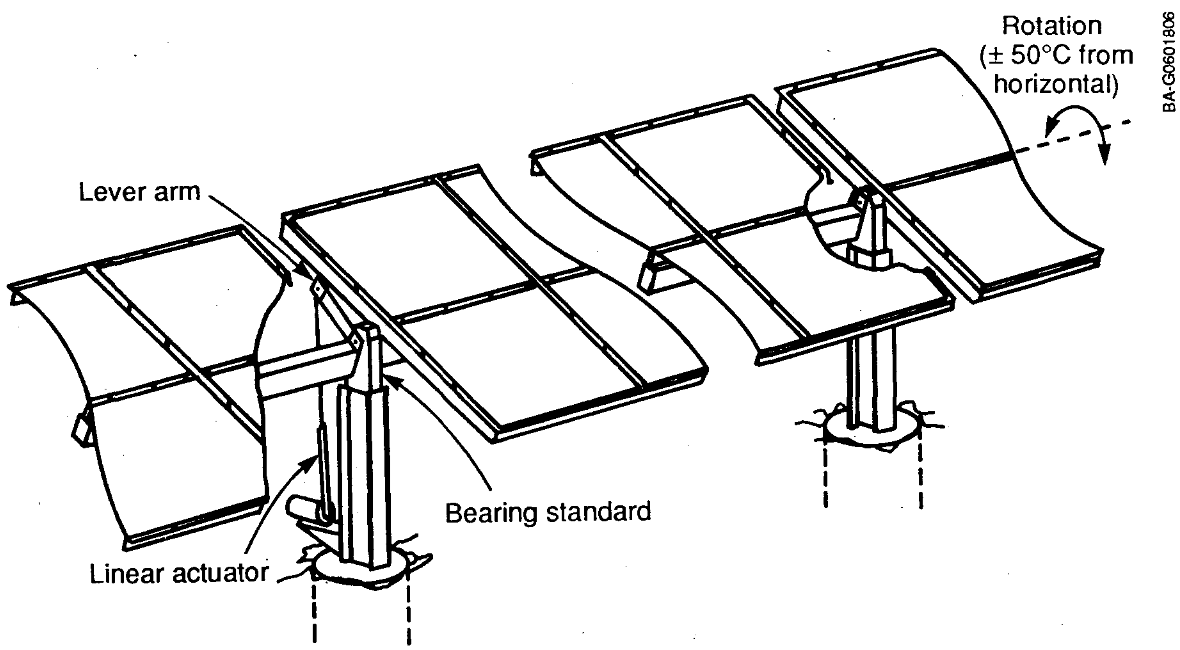

Figure 2-6. EPRI's one-axis, tracking, flat-plate system structural support concept (Source: Levy and Stoddard 1984)

A fluidized-bed, coal-burning power plant was chosen as the fossil technology for comparison with the solar plants because it represents an advanced but state-of-the-art design that is economical and widely used. At present, coal is the predominant type of fossil fuel used for baseload electric power production in the United States, while oil and natural gas are used only for peaking load. Nuclear energy accounts for about 20% of the U.S. electric power production, or 7% of the total primary energy used in the United States (Energy Information Administration 1988).

The numbers in the first column of Table 2-10 were calculated by multiplying the net annual output of the plant by the assumed lifetime. The second, third, and fourth columns are simply the total carbon dioxide produced during construction, operation and maintenance, and fossil-fuel burning, respectively, divided by the net lifetime energy output. In the last column, the total CO_2 production per GWh_e from the three contributions is shown.

For the solar technologies, the majority of carbon dioxide production occurs during construction. In contrast, 97% of the CO_2 generated by the fluidized-bed coal-burning plant is produced during operation as a consequence of fossil-fuel combustion. All of the solar systems produce considerably less CO_2 over a 30-year lifetime than the coal plant. The 100-MW_e solar thermal and photovoltaic systems produce only 4% and 3%, respectively, of CO_2 per GWh_e of that of the coal plant for a lifetime

Table 2-8. Cost, Embodied Energy, and CO_2 Production of the Key Components of the EPRI Single-Axis, Tracking Photovoltaic System at the Southwest Site
(Figures do not include tax, indirect costs, or contingency costs)

System Components (Southwest site)	Cost Estimate (10^4 \$1982)	Cost (10^4 \$1977)	Embodied Energy (1977) (GWh)	Corrected[a] Embodied Energy (GWh)	CO_2 Produced (metric tons)	Percent of Total CO_2
Land						
Acquisition	153.0	103.0	0.0	0.0	0	0.0
Site preparation	269.0	181.0	16.4	12.7	3,239	2.0
Power conditioning system	746.9	502.7	46.5	36.1	9,191	5.6
Foundation - electrical equipment	1.7	1.1	0.3	0.2	53	0.0
Panel components (structural)	1,352.1	910.0	172.2	133.6	34,034	20.6
Panel components (electrical)	408.7	275.1	33.4	25.9	6,594	4.0
Panel assembly	1,050.8	707.2	88.1	68.3	17,414	10.6
Pedestal (steel)	205.6	138.4	20.1	15.6	3,962	2.4
Pedestal installation	453.6	305.3	38.6	29.9	7,621	4.6
Panel installation	133.5	89.8	11.2	8.7	2,218	1.3
DC field wiring	188.6	126.9	21.4	16.6	4,225	2.6
DC system switchgear	412.9	277.9	20.9	16.2	4,137	2.5
AC power system	97.8	65.8	12.3	9.5	2,422	1.5
AC substation	115.0	77.4	8.8	6.8	1,733	1.1
DC system station/tracking power	190.4	128.1	18.8	14.6	3,717	2.3
Master control	140.0	94.2	6.5	5.0	1,278	0.8
Buildings/enclosures	122.0	82.1	7.7	6.0	1,529	0.9
Spare parts/equipment	37.7	25.4	4.8	3.8	957	0.6
O&M equipment	29.0	19.5	2.0	1.6	403	0.2
30 years of operation and maintainence	5,513.1	3,710.3	304.7	236.3	60,212	36.5
Total for a 30-year lifetime	11,621.4	7,821.2	834.7	647.3	164,939	100.0

[a]These figures were corrected to reflect the 22.5% less energy needed per 1982 dollar of GNP at the beginning of 1989 than in 1977.

Table 2-9. Cost, Embodied Energy, and CO_2 Production of the Key Components of the EPRI Single-Axis, Tracking Photovoltaic System at the Southeast Site
(Figures do not include tax, indirect costs, or contingency costs)

System Components (Southeast site)	Cost Estimate (10^4 \$1982)	Cost (10^4 \$1977)	Embodied Energy (GWh)	Corrected[a] Embodied Energy (GWh)	CO_2 Produced (metric tons)	Percent of Total CO_2
Land						
Acquisition	153.0	103.0	0.0	0.0	0	0.0
Site preparation	296.0	199.2	16.3	12.6	3,215	2.0
Power conditioning system	746.9	502.7	46.5	36.1	9,191	5.7
Foundation - electrical equipment	1.4	0.9	0.2	0.2	41	0.0
Panel components (structural)	1,352.1	910.0	172.2	133.6	34,034	21.8
Panel components (electrical)	408.8	275.1	33.4	25.9	6,594	4.2
Panel assembly	758.6	510.5	63.3	49.1	12,500	8.0
Pedestal (steel)	174.2	117.2	17.0	13.2	3,361	2.1
Pedestal installation	334.3	225.0	28.4	22.1	5,620	3.6
Panel installation	105.2	70.8	8.8	6.8	1,745	1.1
DC field wiring	188.5	126.9	21.4	16.6	4,225	2.6
DC system switchgear	413.0	277.9	21.0	16.3	4,143	2.6
AC power system	97.7	65.8	12.3	9.5	2,428	1.5
AC substation	115.0	77.4	8.8	6.8	1,733	1.1
DC system station/tracking power	190.4	128.1	18.8	14.6	3,717	2.3
Master control	140.0	94.2	6.5	5.0	1,278	0.8
Buildings/enclosures	122.0	82.1	7.7	6.0	1,529	1.0
Spare parts/equipment	37.4	25.2	4.8	3.7	951	0.6
O&M equipment	29.0	19.5	2.0	1.6	403	0.3
30 years of operation and maintainence	5,513.1	3,710.3	304.7	236.3	60,212	38.4
Total for a 30-year lifetime	11,149.6	7,521.9	794.1	616.0	156,922	100.0

[a]Figures were corrected to reflect the 22.5% less energy needed per 1982 dollar of GNP in the beginning of 1989 than in 1977.

Table 2-10. Net Lifetime Energy Output and CO_2 Production per GWh_e for Electric Power Plants with a 30-Year Lifetime

Technology	Net Lifetime Energy Output (10^2 GWh_e)	CO_2 Contribution from Construction (metric tons/GWh_e)	CO_2 Contribution from Operation and Maintenance (metric tons/GWh_e)	CO_2 Contribution from Fossil Fuel Input (metric tons/GWh_e)	Total CO_2 Production (metric tons/GWh_e)
Battelle 100-MW_e Molten Salt Central Receiver	105.0	31	12	--	43
Austin 300-kW_e PV System	0.15	277	3	--	280
EPRI 100-MW_e PV System					
Southwest site	68.4	15	9	--	24
Southeast site	53.4	18	11	--	29
Fluidized-bed coal	1075.0	5	28	1008	1041

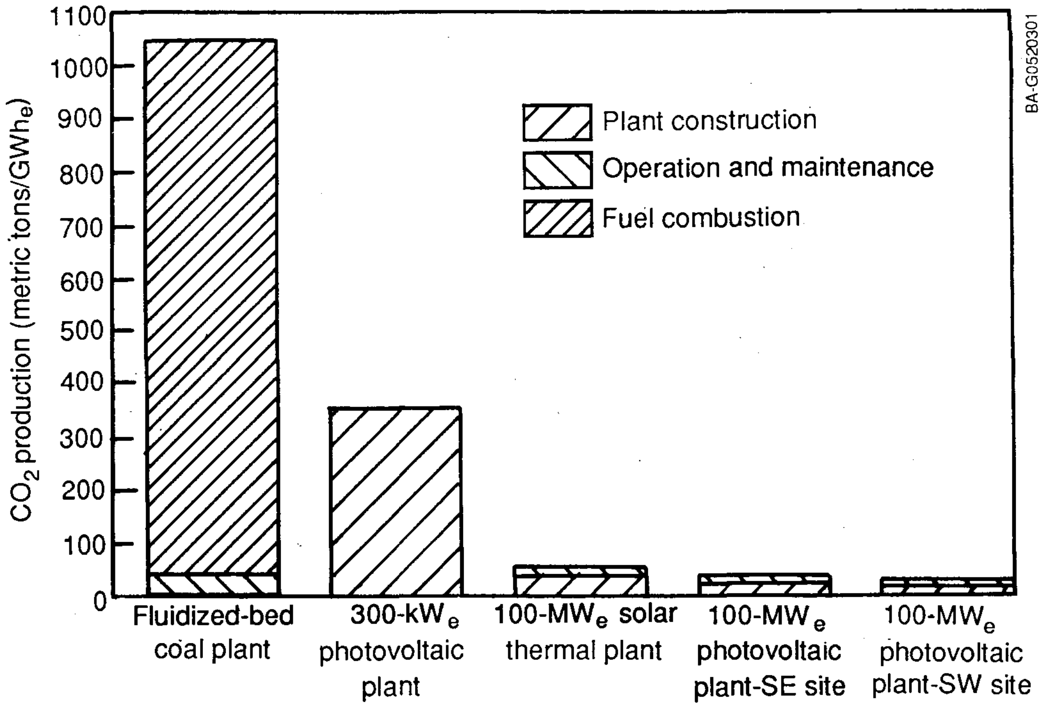

Figure 2-7. **Total CO_2 production per GWh_e of output energy.** CO_2 production for the coal plant is due primarily to fuel combustion. For the solar plants, CO_2 is produced primarily during construction of the plant.

of 30 years. Substituting advanced natural gas systems for coal can reduce the CO_2 production up to 50% (Morrison 1989). But this reduction would come with a considerable increase in cost and without achieving a long-term solution to global warming. However, substituting solar technology in favorable solar climates for coal-fired power plants could over time reduce CO_2 generation. For example, if a solar thermal or photovoltaic power plant were built instead of a coal-fired unit, CO_2 production during the first 30 years of operation of the solar plant would be less than 5% of that of the baseline coal plant. Moreover, once solar technology is in place on a large scale, it could become a "solar energy breeder." In other words, part of the energy it produced could be used to build more power plants and eventually eliminate global warming caused by electric power generation (Grimmer 1981).

The CO_2 production per unit energy for the City of Austin's 300-kW_e photovoltaic plant is considerably greater than that for the EPRI 100-MW_e photovoltaic plant designs. This shows the significance of economies of scale and suggests caution in using the data for a small, first-generation system to determine the viability of a technology. The difference in the results for the EPRI photovoltaic designs located in the Southwest site and those for the less favorable Southeast site is only 20%. This indicates that renewable energy systems will produce electric power with considerably less CO_2 generation than fossil systems even at less favorable solar sites.

2.5 The Potential of Cogeneration for Reducing CO_2 Production

The combined generation of heat and power, generally called cogeneration, is a cost-effective, reliable method for increasing the overall efficiency of fuel utilization (Horlock 1987). The most widely used method of combining the generation of heat and power uses the heat rejected from a turbine to supply thermal energy for an industrial process or for heating and cooling of buildings. Since with the same hardware more energy is produced per unit of fossil energy used, the CO_2 production per unit output of energy can be reduced by using cogeneration. Two cycles that could be applied to a fluidized-bed coal system as well as to a solar thermal central-receiver system are the extraction condensing cycle and the back-pressure cycle shown schematically in Figure 2-8. Cogeneration can also be applied to solar energy conversion systems. Extensive conceptual design studies of solar thermal cogeneration systems have been conducted by Sandia National Laboratories (1982). These studies have shown that for a given energy output, cogeneration systems require less collector or heliostat area than two separate systems (one for heat and the other for power). In principle, cogeneration can also be used with photovoltaic power systems, but the thermal output is too low in temperature to be thermodynamically useful.

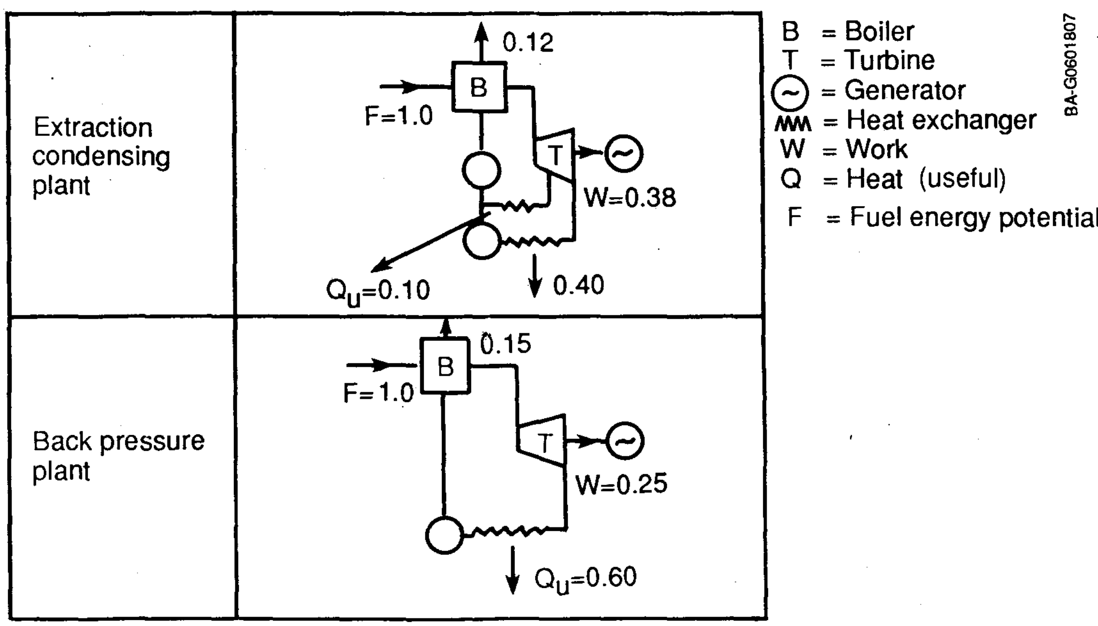

Figure 2-8. Schematic diagrams of combined heat (Q_u) and electricity (W) cogeneration systems (Source: Horlock 1987)

The potential reduction in CO_2 achievable with a cogeneration system over separate heat and electricity systems with the same output is shown in Table 2-11. Since CO_2 production for a given power plant with a given lifetime is proportional to the energy output of the plant, the reduction in CO_2 production due to cogeneration is directly proportional to the energy savings. The potential reduction in CO_2 production achieved by cogeneration, shown in the last column of Table 2-11, is thus simply the difference between the sum of the energy requirements of the separate systems and the cogeneration system divided by the energy requirement of the separate systems. We see that 29% less CO_2 is produced by a back-pressure cogeneration system than that produced by two separate systems with the same heat and power rating.

Table 2-11. Potential for Reducing CO_2 by Using Cogeneration Systems
(see Figure 2-8)

Cogeneration System	Thermal Output per Unit Thermal Input (kWh_t/kWh_t)	Electrical Output per Unit Thermal Input (kWh_e/kWh_t)	Ratio of Thermal Input for Two Separate Systems to That for a Cogeneration System $(kWh)_s/(kWh)_{CG}$ [a]	Potential Reduction in CO_2 Production by Cogeneration
Extracting condensing system	0.10	0.38	1.06	6%
Back-pressure system	0.60	0.25	1.29	29%

[a] (kWh)s = Thermal input to the separate systems with the same output as the cogeneration systems.
$(kWh)_{CG}$ = Thermal input to the cogeneration system.
Calculations are based on system efficiencies of 90% for the thermal system and 40% for the electrical system.

3.0 DISCUSSION

This report compares CO_2 production per unit energy output during a 30-year lifetime from a fluidized-bed, coal-fired power plant, a small and a large solar photovoltaic plant, and a solar thermal central-receiver power plant. The approach used in making these calculations starts with an energy analysis that accounts for the energy embodied in all of the components of the plants, the energy required for the operation and maintenance of the plants, and the fossil-fuel energy used to operate them. The method uses an input/output table that shows the monetary flows into and out of all sectors in the U.S. national economy. To convert the monetary costs of the components, labor, and fuel to energy units in this approach, one attaches energy flows, which can be obtained from a national energy balance, to the monetary flows in an input/output table. Then, a matrix based on the energy flows and their respective monetary values can be formulated, as shown by Hannon et al. (1981). This energy consumption matrix reveals the amount of primary energy (including all energy expenditures) necessary to produce one unit of monetary value in a given economic sector of the input/output matrix.

Conventional net energy analysis has been widely used as a supplement to standard economic analyses based on a monetary assessment of cost and benefits (Spreng 1988). It takes into account not only direct energy consumption but also the indirect energy consumption involved in the totality of an economic system. Once we know the energy input for the construction, operation, and maintenance of a system during its 30-year lifetime, we can calculate the CO_2 production.

An analysis of CO_2 production from several energy technology systems has also been performed recently by a DOE contractor (Meridian Corporation 1989). The approach Meridian used was a process chain analysis. As the name implies, a complex production chain is broken into its various steps, and for each step the relevant energy inputs and outputs are identified and evaluated. At the end of this chain is the physical system in which all the energy expenses have been accumulated. Then, the energy required to operate the system during its lifetime is added to that required to construct it, and the total energy during 30 years of power production is obtained. San Martin (1989) states that this approach views "the environmental effects of energy production at all stages of the energy production cycle as a direct function of generating the final energy product," and that "by analyzing the complete cycle these effects can be fully and consistently evaluated. . . . By investigating the impact of each stage of the energy production process the analysis attempts to normalize the differences between material- and fuel-intensive technologies to provide a fair basis for comparison."

Both the approach used in this report and the process chain approach have advantages and disadvantages. The latter estimates the CO_2 emissions associated with each stage of energy production, from fuel extraction through construction, operation, and decommissioning, as part of a system designed to produce energy. The advantage of this approach is that current methods of operation in each step of the process can be fed directly into the process chain during the analysis. The disadvantage, however, is that it is not only tedious but also extremely difficult to include all the steps in the process chain. The analysis is also very time-consuming and expensive to perform.

The advantage of the approach used in this report is that it is relatively simple, and it automatically encompasses all the functions of the U.S. economy. The disadvantage is that the last comprehensive energy matrix converting from monetary to energy units was prepared in 1985 using the Bureau of Economic Analysis input/output data for 1977, and its accuracy has not been demonstrated quantitatively. Also, it is necessary to correct the embodied energy for the increase in energy efficiency of the U.S. economy between 1977 and 1989 to estimate the energy embodied in a plant built in 1989. This correction can be obtained from the yearly statistics about energy use and GNP on a SIC basis, but it does not reveal detailed shifts in the energy consumption pattern, such as, for example, the increase in imports of energy-intensive products.

A comparison of our results and those of other studies (Meridian Corporation 1989; San Martin 1989) reveals essential agreement for the fossil system, but some substantial differences in the CO_2 production predicted for the solar energy systems. The results are displayed in Table 3-1 for an assumed lifetime of 30 years. We see that there is essential agreement between the results for the coal-fired power plant and that all the studies indicate that renewable energy sources, be they photovoltaic or solar thermal, will produce per unit output less than 5% of the CO_2 generated by the coal plant during their lifetimes. However, our results predict larger CO_2 production for the renewables than the DOE study, even after the 22.5% correction for the efficiency increase is applied. A reason for this difference may be that in Meridian's study, which does not show the intermediate steps in the process chain, some steps have been omitted. Moreover, only the CO_2 production associated with the aluminum, glass, steel, and concrete in the power plants is included (Meridian 1989). All other energy inputs, including labor, are omitted because of a lack of available information on the process requirements. This could be a serious omission, since our analysis, as shown in Table A-10 in the appenix, indicates that 55% of the primary energy required to construct a photovoltaic plant comes from materials that are not included in the chain analysis. Since the majority of CO_2 production from the renewable plants occurs during construction, a simplified chain analysis leads to a significant underestimation of the total CO_2 production for all renewable energy systems. Moreover, energy expenditures for operation and maintenance in solar thermal and photovoltaic plants have also been omitted.

A net energy analysis for the major materials contents of a 100-MW_e solar thermal power plant has also been conducted by Vant-Hull (1988), who used a process chain method approach. However, he used stretched-membrane heliostats and included only the thermal part of the plant. Vant-Hull estimated that 372 GWh of energy are embodied in the material used to construct that system. Our analysis indicated that the construction of the thermal portion of the central-receiver plant, using glass heliostats, would require about 1061 GWh of primary energy. The discrepancy seems largely due to the difference in heliostat technology and Vant-Hull's analysis having omitted the energy costs of labor and the control system.

Table 3-1. Comparison of CO_2 Production per GWh_e Net Lifetime Energy Output for Various Electric Power Technologies (metric tons of CO_2)

System	DOE (Meridian Corporation 1989)	DOE (San Martin 1989)	Kreith and Norton[a] (1989)	This Study
Fluidized-bed coal	1059	963		1041
Oil-fired plant		726	937	
Gas-fired plant		484	687	
Boiling water reactor	9	8		
Wind energy		7	47	
Photovoltaics	6	5		24
Solar thermal		4		43

[a] The data presented earlier by Kreith and Norton (1989) were modified to reflect CO_2 production from fossil fuels from the DOE studies (Marland and Rotty 1983) and the increased energy efficiency of the U.S. economy between 1977 and 1988.

The CO_2 production due to construction of the solar thermal electric power plant, using Vant-Hull's analysis and assuming an embodied energy in the electric conversion and balance of plant equal to that in our analysis, is 18 metric tons of CO_2 per GWh_e. This is about 58% of the 31 metric tons of CO_2 per GWh_e CO_2 production due to construction estimated in this study. If glass heliostats were used and labor energy cost were included, Vant-Hull's CO_2 production estimate would be of the same order of magnitude as that of this study.

The estimation of annual operation and maintenance costs of solar thermal power plants is uncertain, as illustrated by the estimates ranging from \$1.00 to \$17.30/m^2 (\$1984) presented by various sources (Williams et al. 1987). The data base for the solar thermal power plant analyzed in this paper includes an annual operation and maintenance cost of \$5.17/m^2 (\$1984). The CO_2 production due to operation and maintenance is thus 12 metric tons of CO_2/GWh_e, bringing the total CO_2 production from the plant to 43 metric tons of CO_2/GWh_e.

It is important to note that CO_2 production from nuclear and solar systems is of the same order of magnitude, according to the chain analysis of San Martin (1989). Recently, interest has been renewed in building more nuclear power plants in the United States, and reducing CO_2 emissions has been given as a reason for shifting from coal to nuclear power. Europe's experiences have demonstrated that nuclear power is a viable option, but the costs of dismantling obsolete plants and disposing of radioactive waste remain unresolved problems. Moreover, after the accidents at Three Mile Island and Chernobyl, public fears understandably cloud the nuclear option in the United States, although it is available.

4.0 IMPLICATIONS FOR A NATIONAL ENERGY POLICY

Although there are discrepancies in the details, the basic agreement between our analyses and others (Meridian 1989; San Martin 1989; Vant-Hull 1989) is sufficient from a broad policy perspective. The results of all these studies show that any serious efforts to reduce CO_2 production from electric power plants would require a major shift from fossil fuels to renewable energy sources. The use of cogeneration and fossil-fuel switching from coal to natural gas may be helpful in ameliorating CO_2 production in the short run, but they cannot solve the global warming problem in the long term.

The approach for calculating greenhouse-gas emissions illustrated in this report for electric power production and in an earlier paper for wind energy, passive solar, and water heating (Kreith & Norton 1989) could of course also be applied to conservation and other energy production technologies. We have made some preliminary calculations based on a previous study by Pilati (1977), and the results indicate that for the short term the most effective way to reduce CO_2 production is by introducing conservation measures that reduce energy requirements, rather than by increasing energy production to meet increased energy demands. Japan today produces a dollar's worth of GNP for less than half the primary energy input required by the U.S. economy (International Energy Agency 1987). Consequently, a desirable first step in a long-term energy plan would be to improve the energy efficiency of the United States by introducing energy conservation and mature renewables while continuing to develop new types of these plants to improve their efficiency and reduce their cost.

As illustrated in this report, once the net energy analysis for an energy generation or conservation system has been performed, it is a simple matter to calculate its lifetime CO_2 production. From this information it is then possible to estimate with existing and developing computer simulation models the social costs (Hohmeyer 1988) or the extent of global warming that different policies would create (Jaeger 1988). We have shown in this report that energy conservation measures and shifting from fossil to renewable energy sources offer significant long-term potential to reduce CO_2 production caused by energy generation. Many of these CO_2 reduction measures can be justified on their own merits, irrespective of their possible effect on reducing global warming (Schneider 1989). In view of the long lead time required for conservation and renewable technologies to be brought into the energy infrastructure on a large scale, policies that can be justified on their own merit and also reduce greenhouse-gas emissions should be initiated as soon as possible. There is a risk in delaying such actions since the costs of reducing CO_2 emissions are likely to increase if the urgency for their implementation should grow.

5.0 REFERENCES

Alpert, D. J., and R. M. Houser, 1989, "Evaluation of the Optical Performance of a Prototype Stretched Membrane Mirror Module for Solar Central Receivers," *J. Sol. En. Eng.*, 111:37-43.

Bath, T. D., and D. L. Feucht, 1990, "Renewable Energy as a Response to Global Warming Concerns," *Greenhouse Mitigation*, A.E.S. Green, ed., American Society of Mechanical Engineers, FACT, Vol. 7.

Brown, D. R., 1988, "Cost Drivers for Solar Thermal Central Receiver Power Plants," *J. Sol. En. Eng.*, 110:156-164.

Energy Information Administration, 1988, *Monthly Energy Review*, U.S. Department of Energy, Washington, DC, December.

Grimmer, D. P., 1981, "Solar Energy Breeders," *Solar Energy*, 26:49-53.

Hannon, B., R. A. Herendeen, and T. S. Blazeck, 1981, *Energy and Labor Intensities for 1972*, Energy Research Group, University of Illinois at Urbana-Champaign.

Hannon, B., S. P. Caster, and T. S. Blazeck, 1985, *Energy Intensities for the U.S. Economy—1977*, Energy Research Group, University of Illinois at Urbana-Champaign.

Hoffner, J. E., 1989, "Analysis of the 1988 Performance of Austin's 300-kilowatt Photovoltaic Plant," Proceedings of the 1989 Conference of the American Solar Energy Society, Denver, Colorado.

Hohmeyer, O., 1988, *Social Costs of Energy Consumption*, Springer-Verlag, Berlin, West Germany.

Horlock, J. H., 1987, *Cogeneration: Combined Heat and Power*, Pergamon Press, Oxford, England.

Houghton, R. A., and G. M. Woodwell, 1989, "Global Climatic Change," *Scientific American*, 260:36-44, April.

International Energy Agency, 1987, "Energy Conservation in IEA Countries," Paris: Organization for Economic Operation and Development.

Jaeger, J., 1988, "Developing Policies for Responding to Climatic Change," WMO/TD-No. 225, Beijer Institute, Stockholm, Sweden.

Kerr, R. A., 1989, "Oil and Gas Estimates Plummet," *Science*, 245:1330-3331.

Kreith, F., and P. Norton, 1989, "The Potential of Solar Technologies to Reduce the Greenhouse Effect," Proceedings of the 1989 Annual Conference of the American Solar Energy Society, M. I. Coleman, ed., pp. 385-391, Denver, CO.

Kreith, F., R. E. West, and C. J. Cleveland, 1987, "Energy Analysis for Renewable Energy Technologies," *ASHRAE Trans.*, 91:999-1010.

Levy, S. L., and L. E. Stoddard, 1984, *Integrated Photovoltaic Central Station Conceptual Designs*, EPRI AP-3264, Electric Power Research Institute, Palo Alto, CA.

Lovins, A. B., L. H. Lovins, F. Krause, and W. Bach, 1981, *Least-Cost Energy, Solving the CO_2 Problem*, Brick House Publishing, Andover, MA.

Mackenzie, J. J. 1988, *Breathing Easier: Taking Action on Climate Change, Air Pollution, and Energy Insecurity*, World Resources Institute, Washington, DC.

Mann, G., and B. Neenan, 1982, *Economic Profiles of Selected Solar Energy Technologies for Use in Input-Output Analysis*, LA-9083-TAES, Los Alamos National Laboratory, Los Alamos, NM.

Marland, G., and R. M. Rotty, 1983, *Carbon Dioxide Emissions from Fossil Fuels: A Procedure for Estimation and Results for 1950-1981*, DOE/NBB-0036, Oak Ridge, TN: Oak Ridge Associated Universities.

Meridian Corporation, 1989, *Energy Systems and Material Requirements*, prepared for the U.S. Department of Energy Office of Renewable Energy, Washington, DC, February.

Morrison, R. E., 1989, *Global Climate Change*, Congressional Research Service, Library of Congress, Washington, DC, Order Code IB 81005.

Murphy, L. M., 1986, "Stretched Membrane Heliostat Technology," *J. Sol. En. Eng.*, 108:230-238.

Nierenberg, W. A., 1989, "Atmospheric CO_2: Causes, Effects, and Options," *Chem. Eng. Prog.*, 85:27-36.

Panico, D., 1989, private communication, City of Austin Electric Utility Department.

Perry, A. M., et al., 1977, *Net Energy Analysis of Five Energy Systems*, ORAV/IEA(R)-77-12, Oak Ridge, TN: Oak Ridge Associated Universities.

Pilati, P. A., 1977, "Energy Analysis of Electricity Supply and Energy Conservation Options," *Energy*, 2:1-7.

Ramanathan, V., 1988, "Greenhouse Theory of Climate Change," *Science*, 240:293-299.

Rockwell International, 1983, *Preliminary Design of the Carrisa Plains Solar Central Receiver Power Plant*, ESG-DOE-13404, Rockwell International, Inc., Canoga Park, CA.

Sandia National Laboratories, 1982, *Solar Cogeneration*, Livermore, CA, April.

San Martin, R. L., 1989, *Environmental Emissions from Energy Technology Systems: The Total Fuel Cycle*, U.S. Department of Energy, Washington, DC, April.

Schneider, S. H., 1989a, "The Greenhouse Effect: Science and Public Policy," *Science*, 243:771-780, February.

Schneider, S. H., 1989b, "The Changing Climate," *Scientific American*, 261:70-79, September.

Spreng, D. T., 1988, *Net Energy Analysis and the Energy Requirements of Energy Systems*, Praeger Publishers, New York, NY.

U.S. Department of Energy, 1985, *Solar Thermal Technology, Annual Evaluation Report, Fiscal Year 1984*, Solar Technical Information Program, Washington, DC, June.

Vant-Hull, L. L., 1988, "Solar Thermal Electricity, An Environmentally Benign and Viable Alternative," Energy and The Environment Conference, Denver, CO, September.

Weber, E. R., 1983, *Preliminary Design of a Solar Central Receiver for a Site-Specific Repowering Application (Saguaro Power Plant)*, DOE/SF/11675-T1, Arizona Public Service Company, Phoenix, AZ.

West, R. E., 1988, "Inflation Adjustment," in *Economic Analysis of Solar Thermal Systems*, R. E. West and F. Kreith, eds., MIT Press, Cambridge, MA.

Williams, T. A., et al., 1987, *Characterization of Solar Thermal Concepts for Electricity Generation*, PNL-6128, Pacific Northwest Laboratory, Richland, WA.

APPENDIX
Component Costs for Molten-Salt Central Receiver and Photovoltaic Systems

In this appendix, the costs and/or material requirements for a 100-MW_e molten-salt central receiver system, a 300-kW_e photovoltaic system, and a 100-MW_e photovoltaic power plant are itemized.

All cost data for the central receiver are in 1984 dollars and represent direct costs for equipment, material, and labor. Total capital costs were estimated by adding an additional 25% for indirect costs and 10% for contingency (indirect and contingency = 35% of the direct cost). Indirect costs represent expenses for temporary construction facilities, field supervision, management, clerical services, equipment rental, engineering, construction fee, and other cost elements not directly related to the construction of any single piece of equipment. The detailed cost and material figures documented in Tables A-1 through A-8 were developed from one design point of the system evaluated in a report by Williams et al. (1987). Specific design and annual performance data are summarized in Table 2-3 of the report.

The costs and material requirements for the City of Austin's 300-kW photovoltaic system are itemized in Table A-9. The itemization of the components and their integration into standard industrial code (SIC) sectors was provided by D. Panico (1989) of the City of Austin Electric Utilities Department. The actual costs are presented in Table A-9 along with the costs deflated to 1977 dollars and the embodied energy.

The construction details and costs of a 100-MW_e, single-axis tracking, flat-plate photovoltaic system were analyzed for two sites—one in the southwestern United States (Barstow, Calif.) and another in the southeastern United States (Bay Minette, Ala.)—by EPRI in 1984. Table A-10 shows the cost estimates in 1982 dollars and deflated to 1977 dollars, the appropriate SIC sector, the energy intensity, and the embodied energy for the components of the southwestern system. The same details are shown in Table A-11 for the southeastern location.

Table A-1. Receiver Component Costs and Weights of Material for the Solar Thermal System (Receiver shop and field labor = 265,000 manhours)

Components	Cost ($1984)
Absorber	11,926,000
Structure	3,148,000
Circulation	1,533,000
Instrumentation and control	1,243,000
Total installed cost	$17,850,000

Material	Weight (lb)
Absorber tubes (Incoloy 800H)	143,600
Misc. piping (50% carbon steel, 50% stainless steel)	143,600
Surge tanks (1 carbon steel, 1 stainless steel)	143,600
Structural steel	861,600
Misc. steel	143,600
Insulation	143,600
Molten salt	287,200
Miscellaneous items	143,600

Table A-2. Tower Component Costs for the Solar Thermal System (Installation labor = 90,000 hours)

Components	Cost ($1984)
Accessories (elevator, lighting, stairs, ladders, lightening protection, and platforms)	430,000
Concrete and rebar (concrete volume = 18,000 cubic yards, rebar weight = 900 tons)	5,419,000
Total installed cost	$5,849,000

Table A-3. Heliostat Material Cost for the Solar Thermal System (Labor = 92 hours per heliostat)

Component	Materials	Cost ($1984)
Mirror module	1600 ft^2 of thin, low iron fusion glass with silver and copper coatings	1496
	1600 ft^2 of polyvinyl butylate adhesive sheet	479
	1600 ft^2 of float glass	698
	118 lb of glass/metal "contact cement"	491
	3063 lb of steel hat sections	764
	281 lb of steel braces	70
	56 lb of bolts	50
Support structure (all steel except the paint)	1207 lb of truss chords	376
	275 lb of truss tubing	86
	860 lb of truss bracing	268
	1924 lb of torque tubes	600
	238 lb of torque tube brackets	74
	77 lb of torque tube flanges	37
	36 lb of bolts	65
	2 gal. of paint	42
Pedestal	3464 lb steel pipe	1080
	91 lb steel flange	40
	2 gal. of paint	36
Drive unit	Primarily built from steel materials	1500
Controls and wiring	Heliostat control	265
	Power and control cabling	465
	Array control	51
	Beam characterization	20
Transportation	600 miles via semi-truck and trailer	394
Site assembly building overhead	--	264

Note: The direct material and labor requirements listed are for a single heliostat and must be multiplied by 4932, the number of heliostats in the reference system. The total installed cost is $73,300,000, which includes all overheads and profits associated with heliostat manufacturing.
The total manufacturing plant capital equipment cost is 1.9×10^7 $1984.

Table A-4. Transport System Material Costs for the Solar Thermal System
(Labor hours = 188,000)

Material	Cost ($1984)
Heat tracing	184,000
Carbon steel pipe	95,000
Stainless steel pipe	812,000
Carbon steel pump	2,301,000
Expansion joints	619,000
Ground support	11,000
Carbon steel and stainless steel fittings	100,000
Carbon steel and stainless steel valves	144,000
Stainless steel valves insulation	785,000
Total installed cost	$5,052,000

Table A-5. Storage System Component Costs for the Solar Thermal System

Component	Installed Cost ($1984)
Molten salt (23.7 E6 lb)	5,291,000
Carbon steel tanks	943,000
Concrete foundation	1,151,000
Insulating brick	971,000
Nickel alloy liner	854,000
Insulation	1,134,000
Aluminum siding	51,000
Carbon steel pipe	214,000
Stainless steel pipe	747,000
Carbon steel and stainless steel fittings	480,000
Heat tracing	201,000
Pipe supports	19,000
Carbon steel and stainless steel valves	1,386,000
Conveyor and storage bins	582,000
Misc. piping	338,000
Melting tank and heater	516,000
Sump and drain	520,000
Instrumentation and control	538,000
Misc. equipment	55,000
Total installed cost	$15,990,000

Table A-6. Energy Conversion System Component Costs for the Solar Thermal System

Components	Installed Cost ($1984)
Turbine-generator	15,500,000
Cooling tower, condenser, and ancillary rankine cycle equipment	15,500,000
Carbon steel preheater (10,680 ft^2)	1,150,000
Low-alloy steel evaporator (12,980 ft^2)	2,350,000
Stainless steel superheater (6,930 ft^2)	2,030,000
Stainless steel reheater (5,650 ft^2)	1,790,000
Total installed cost	$38,320,000

Table A-7. Balance-of-Plant Costs for the Solar Thermal System

Cost Element	Installed Cost ($1984)
Land (1055 acres)	
Purchase and permits	5,589,000
Survey, clear and grub, grade, roads, ditches (mostly labor and equipment rental)	9,686,000
Structures (control room, administrative offices, maintenance shop, warehouse, and fencing)	834,000
Master control	2,636,000
Spare parts	2,944,000
Power conditioning	2,814,000
Service facilities	
Vehicles	324,000
Communications	22,000
Protection systems (fire, security)	150,000
Water supply	110,000
Feedwater treatment	638,000
Total installed cost	$25,747,000

Table A-8. Operation and Maintenance Costs for the Solar Thermal System

Cost Element	Cost ($1984)
Direct production (all labor)	619,000
Direct maintenance (labor and materials)	2,560,000
Plant overhead (mostly labor)	477,000
Molten salt replacement (mostly material)	134,000
Total annual O&M cost	$3,790,000

Table A-9. Cost and Embodied Energy of the City of Austin's 300-kW Photovoltaic Plant

PV300 Plant Component	Qty/Unit	Actual Cost ($1986)	Cost ($1977)	SIC Sector	SIC Code	Energy Intensity (Btu/$1977)	Embodied Energy (10^8 Btu)
Photovoltaic Panels							
Solar cells	28190 ft^2	1595089	939188	Semiconductors	570200	29749	279.4
Encapsulation	58212 lbs.	76846	45247	Glass	350100	58274	26.4
Freight	--- lot	3200	1884	Motor freight trans.	650300	29196	0.6
Power Conditioning Unit							
Inverter	1 ea.	168630	99289	Electrical equip.	580500	38118	37.8
Transformer	1 ea.	24900	14661	Transformer	530200	42591	6.2
AC switchgear	1 ea.	20560	12106	Switchgear	530300	25728	3.1
Field engineering	21 days	12720	7490	New Construction	110250	35535	2.7
Freight	--- lot	7190	4233	Motor freight trans.	650300	29196	1.2
Structural Subsystem							
Concrete	66792 lb	125000	73600	Cement	360100	216613	159.4
Steel sup. struct.	114380 lb	107000	63002	Fab struc. steel	400400	49469	31.2
Metal bldg.	704 ft^2	20000	11776	Fab struc. steel	400400	49469	5.8
Rebar	227534 lb	10000	5888	Iron, stl. foundries	370200	48498	2.9
Bearings	154 ea.	8000	4710	Bearings	490200	42638	2.0
Electrical Subsystem							
Conduit, steel & PVC	2500 ft.	39455	23231	Pipe	420800	37637	8.7
Wire, copper	1690 lb	8565	5043	Fab. wire products	420500	71355	3.6
Misc. electrical	--- lot	59980	35316	Electrical equip.	580500	38118	13.5
Nonessential							
Lavatory	1 ea.	26500	15603	Plumbing fixtures	360600	60670	9.5
Water line	1000 ft	19800	11658	NCNST water	110306	30950	3.6
Sewer line	1000 ft	35822	21092	NCNST sewer	110307	27520	5.8
Remote control line	700 ft	25878	15237	NCST elec. util.	110303	30648	4.7
Site Preparation							
Clearing and grading	--- lot	16780	9880	Const. machinery	450100	34534	3.4
Gravel	6270264 lb	47020	27685	Stone	361500	39667	11.0
Paved road	463820 lb	26200	15427	Asphalt	310300	184121	28.4
Installation		297000	174874	New construction	110250	35535	62.1
Design/Proj. Management		198000	116582				0.0
Administration		120000	70656				0.0

Total Embodied Energy = 7.13×10^{10} Btu (21 GWh)

Table A-10. Cost and Embodied Energy of the EPRI Single-Axis Tracking Photovoltaic System at the Southwest Site

EPRI One-Axis Tracking System Components (Southwest site)	Cost Estimate ($1982)	Cost ($1977)	SIC Sector	SIC Code	Energy Intensity (Btu/$1977)	Embodied Energy (10^9 Btu)
Land						
Acquisition	1530000	1029690				
Site preparation	2690000	1810370	NCST Elec. Util.	110303	30648	55.48
Power Conditioning System	7469000	5026637	Power trans. equip.	490500	31569	158.69
Foundation - Elec. Sys.	17100	11508	Ready-mix concrete	361200	80909	0.93
Panel Comp. (structural)						
Gasket tape	698880	470346	Misc. plastics	320400	63281	29.76
Torque tube	4139520	2785897	Fab. struc. steel	400400	49469	137.82
Torque tube pedestal conn'n	3198720	2152739	Steel prod.	370100	115724	249.12
Linear actuator	833280	560797	General ind. mach.	490700	28793	16.15
Cross members	1263360	850241	Fab. struc. steel	400400	49469	42.06
Longitudinal and center members, keeper bars, fasteners	3386880	2279370	Fab. struc. steel	400400	49469	112.76
Panel Comp. (elect.)						
Nylon 12 chutes	96768	65125	Misc. plastics	320400	63281	4.12
Busbar	1567104	1054661	Wiring devices	550300	40586	42.80
Bypass diode/heat sink	2150400	1447219	Electronic comp.	570300	31502	45.59
Cover plate	274176	184520	Steel prod.	370100	115724	21.35
Panel Assembly						
Labor	10059410	6769983	NCST non. bldg.	110704	43107	291.83
Equipment	421600	283737	General ind. mach.	490700	28793	8.17
Vehicles	28000	18844	Motor veh. & parts	590300	35846	0.68
Pedestal (steel)	2056320	1383903	Fab. struc. steel	400400	49469	68.46
Pedestal Installation						
Surveying (labor)	214500	144359	NCST non. bldg.	110704	43107	6.22
Auger holes (labor)	3089164	1406007	NCST non. bldg.	110704	43107	60.61
Place concrete (labor)	1183812	796705	NCST non. bldg.	110704	43107	34.34
Place and align. pedestal	1018164	685224	NCST non. bldg.	110704	43107	29.54
Pedestal tests	30000	20190	NCST non. bldg.	110704	43107	0.87
Panel Installation (labor)	1247600	839635	NCST non. bldg.	110704	43107	36.19
Install. equipment (vehicles)	88000	59224	Motor veh. & parts	590300	35846	2.12

Table A-10. Cost and Embodied Energy of the EPRI Single-Axis Tracking Photovoltaic System at the Southwest Site (Continued)

EPRI One-Axis Tracking System Components (Southwest site)	Cost Estimate ($1982)	Cost ($1977)	SIC Sector	SIC Code	Energy Intensity (Btu/$1977)	Embodied Energy (10^9 Btu)
DC field wiring						
Interpanel jumpers	40320	27135	Fab. wire product	420500	71355	1.94
Labor	479052	322402	NCST non. bldg.	110704	43107	13.90
Neutral Cable I	147692	99397	Fab. wire product	420500	71355	7.09
Terminate	840	565	Fab. wire product	420500	71355	0.04
Labor	153387	103229	NCST non. bldg.	110704	43107	4.45
Neutral Cable II	37607	25310	Fab. wire product	420500	71355	1.81
Terminate	4200	2827	Fab. wire product	420500	71355	0.20
Labor	128648	86580	NCST non. bldg.	110704	43107	3.73
Grouping cable	52500	35333	Fab. wire product	420500	71355	2.52
Terminate	62765	42241	Fab. wire product	420500	71355	3.01
Trench and backfill	39404	26519	NCST non. bldg.	110704	43107	1.14
DC Bus Disc. Cab.	567561	381969	Fab. wire product	420500	71355	27.26
Terminate	47796	32167	Fab. wire product	420500	71355	2.30
Trench and backfill	123054	82815	NCST non. bldg.	110704	43107	3.57
DC System Switchgear						
Bus discon. cabinet	1705480	1147788	Switchgear	530300	25726	29.53
Subfield cabinet	186400	125447	Switchgear	530300	25726	3.23
Subfield switchgear	2238000	1506174	Switchgear	530300	25726	38.75
AC Power System						
Power cable	776250	522416	Fab. wire product	420500	71355	37.28
Trench and backfill	12002	8077	NCST non. bldg.	110704	43107	0.35
Tap vaults, etc.	40000	26920	Power trans. equip.	490500	31596	0.85
AC power cable	4500	3029	Fab. wire product	420500	71355	0.22
Terminate	6000	4038	Fab. wire product	420500	71355	0.29
Electronic recloser	138500	93211	Electronic comp.	570300	31502	2.94
AC Substation						
34.5 kV OCB	190000	127870	Electronic comp.	570300	31502	4.03
Switches	80000	53840	Switchgear	530300	25726	1.39
Buswork	85000	57205	Wiring devices	550300	40586	2.32
Relaying, metering, etc.	110000	74030	Electronic comp.	570300	31502	2.33
Transformer	675000	454275	Transformers	530200	42591	19.35
Grounding	10000	6730	Fab. wire product	420500	71355	0.48

Table A-10. Cost and Embodied Energy of the EPRI Single-Axis Tracking Photovoltaic System at the Southwest Site (Concluded)

EPRI One-Axis Tracking System Components (Southwest site)	Cost Estimate ($1982)	Cost ($1977)	SIC Sector	SIC Code	Energy Intensity (Btu/$1977)	Embodied Energy (10^9 Btu)
DC System Station/Tracking Power						
Transformers	65000	43745	Transformers	530200	42591	1.86
34.5 kV aux. and tracking cable	4500	3029	Fab. wire product	420500	71355	0.22
Terminate	6000	4038	Fab. wire product	420500	71355	0.29
480 V aux. and tracking cable	60000	40380	Fab. wire product	420500	71355	2.88
480 V aux. power and array power cable	9360	6299	Fab. wire product	420500	71355	0.45
Terminate	9600	6461	Fab. wire product	420500	71355	0.46
Tracking power panel boards	39720	26732	Power trans. equip.	490500	31596	0.84
Array tracking power cable	380271	255922	Fab. wire product	420500	71355	18.26
Terminate	20160	13568	Fab. wire product	420500	71355	0.97
Labor	1309080	881011	NCST non. bldg.	110704	43107	37.98
Master Control	140000	942200	Ind. controls	530500	23412	22.06
Buildings/enclosures	1220000	821060	NCST indust. bldg.	110201	32103	26.36
Spare Parts/Equipment	377000	253721	Misc. metal work	400900	65247	16.55
O&M Equipment						
Vehicles	240000	161520	Motor veh. & parts	590300	35846	5.79
Tools and equipment	50000	33650	Handtools	420200	34863	1.17
					Total:	1.8×10^{12} Btu (528 GWh)

Table A-11. Cost and Embodied Energy of the EPRI Single-Axis Tracking Photovoltaic System at the Southeast Site

EPRI One-Axis Tracking System Components (Southeast site)	Cost Estimate ($1982)	Cost ($1977)	SIC Sector	SIC Code	Energy Intensity (Btu/$1977)	Embodied Energy (10^9 Btu)
Land						
Acquisition	1530000	1029690				
Site preparation	2690000	1810370	NCST elec. util.	110303	30648	55.48
Power Conditioning System	7469000	5026637	Power trans. equip.	490500	31569	158.69
Foundation - Elec. Sys.	13600	9153	Ready-mix concrete	361200	80909	0.74
Panel Comp. (structural)						
Gasket tape	698880	470346	Misc. plastics	320400	63281	29.76
Torque tube	5322240	3581868	Fab. struc. steel	400400	49469	177.19
Torque tube pedestal conn'n.	3198720	2152739	Steel prod.	370100	115724	249.12
Linear actuator	833280	560797	General ind. mach.	490700	28793	16.15
Cross members	1747200	1175866	Fab. struc. steel	400400	49469	58.17
Longitudinal and center members, keeper bars, fasteners	3386880	2279370	Fab. struc. steel	400400	49469	112.76
Panel Comp. (Elect.)						
Nylon 12 chutes	96768	65125	Misc. plastics	320400	63281	4.12
Busbar	1567104	1054661	Wiring devices	550300	40586	42.80
Bypass diode/heat sink	2150400	1447219	Electronic comp.	570300	31502	45.59
Cover plate	274176	184520	Steel prod.	370100	115724	21.35
Panel Assembly						
Labor	7136490	4802858	NCST non. bldg.	110704	43107	207.04
Equipment	421600	283737	General ind. mach.	490700	28793	8.17
Vehicles	28000	18844	Motor veh. & parts	590300	35846	0.68
Pedestal (steel)	1742160	1172474	Fab. struc. steel	400400	49469	58.00
Pedestal Installation						
Surveying (labor)	185000	124505	NCST non. bldg.	110704	43107	5.37
Auger holes (labor)	1229760	827628	NCST non. bldg.	110704	43107	35.68
Place concrete (labor)	880320	592455	NCST non. bldg.	110704	43107	25.54
Place and align. pedestal	1018164	685224	NCST non. bldg.	110704	43107	29.54
Pedestal tests	30000	20190	NCST non. bldg.	110704	43107	0.87

Table A-11. **Cost and Embodied Energy of the EPRI Single-Axis Tracking Photovoltaic System at the Southeast Site** (Continued)

EPRI One-Axis Tracking System Components (Southeast site)	Cost Estimate ($1982)	Cost ($1977)	SIC Sector	SIC Code	Energy Intensity (Btu/$1977)	Embodied Energy (10^9 Btu)
Panel Installation (labor)	964100	648839	NCST non. bldg.	110704	43107	27.97
Install. equipment (vehicles)	88000	59224	Motor veh. & parts	590300	35846	2.12
DC Field Wiring						
Interpanel jumpers	40320	27135	Fab. wire product	420500	71355	1.94
Labor	479052	322402	NCST non. bldg.	110704	43107	13.90
Neutral Cable I	147692	99397	Fab. wire product	420500	71355	7.09
Terminate	840	565	Fab. wire product	420500	71355	0.04
Labor	153387	103229	NCST non. bldg.	110704	43107	4.45
Neutral Cable II	37607	25310	Fab. wire product	420500	71355	1.81
Terminate	4200	2827	Fab. wire product	420500	71355	0.20
Labor	128648	86580	NCST non. bldg.	110704	43107	3.73
Grouping cable	52500	35333	Fab. wire product	420500	71355	2.52
Terminate	62765	42241	Fab. wire product	420500	71355	3.01
Trench and backfill	39404	26519	NCST non. bldg.	110704	43107	1.14
DC Bus Disc. Cab.	567561	381969	Fab. wire product	420500	71355	27.26
Terminate	47796	32167	Fab. wire product	420500	71355	2.30
Trench and backfill	123054	82815	NCST non. bldg.	110704	43107	3.57
DC system switchgear						
Bus discon. cabinet	1705480	1147788	Switchgear	530300	25726	29.53
Subfield cabinet	186400	125447	Switchgear	530300	25726	3.23
Subfield switchgear	2238000	1506174	Switchgear	530300	25726	38.75
AC Power System						
Power cable	776250	522416	Fab. wire product	420500	71355	37.28
Trench and backfill	12002	8077	NCST non. bldg.	110704	43107	0.35
Tap vaults, etc.	40000	26920	Power trans. equip.	490500	31596	0.85
AC power cable	4500	3029	Fab. wire product	420500	71355	0.22
Terminate	6000	4038	Fab. wire product	420500	71355	0.29
Electronic recloser	138500	93211	Electronic comp.	570300	31502	2.94

Table A-11. Cost and Embodied Energy of the EPRI Single-Axis Tracking Photovoltaic System at the Southeast Site (Concluded)

EPRI One-Axis Tracking System Components (Southeast site)	Cost Estimate ($1982)	Cost ($1977)	SIC Sector	SIC Code	Energy Intensity (Btu/$1977)	Embodied Energy (10^9 Btu)
AC Substation						
34.5 kV OCB	190000	127870	Electronic comp.	570300	31502	4.03
Switches	80000	53840	Switchgear	530300	25726	1.39
Buswork	85000	57205	Wiring devices	550300	40586	2.32
Relaying, metering, etc.	110000	74030	Electronic comp.	570300	31502	2.33
Transformer	675000	454275	Transformers	530200	42591	19.35
Grounding	10000	6730	Fab. wire product	420500	71355	0.48
DC System Station/Tracking Power						
Transformers	65000	43745	Transformers	530200	42591	1.86
34.5 kV aux. and tracking cable	4500	3029	Fab. wire product	420500	71355	0.22
Terminate	6000	4038	Fab. wire product	420500	71355	0.29
480 V aux. and tracking cable	60000	40380	Fab. wire product	420500	71355	2.88
480 V aux. power and array power cable	9360	6299	Fab. wire product	420500	71355	0.45
Terminate	9600	6461	Fab. wire product	420500	71355	0.46
Tracking power panel boards	39720	26732	Power trans. equip.	490500	31596	0.84
Array tracking power cable	380271	255922	Fab. wire product	420500	71355	18.26
Terminate	20160	13568	Fab. wire product	420500	71355	0.97
Labor	1309080	881011	NCST non. bldg.	110704	43107	37.98
Master Control	1400000	942200	Ind. controls	530500	23412	22.06
Buildings/Enclosures	1220000	821060	NCST indust. bldg.	110201	32103	26.36
Spare Parts/Equipment	374000	251702	Misc. metal work	400900	65247	16.42
O&M Equipment						
Vehicles	240000	161520	Motor veh. & parts	590300	35846	5.79
Tools and equipment	50000	33650	Handtools	420200	34863	1.17

Total: 1.725×10^{12} Btu (504 GWh)

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15. Supplementary Notes

16. Abstract (Limit: 200 words)

This report presents estimates of the lifetime carbon dioxide emissions from coal-fired, photovoltaic, and solar thermal electric power plants in the United States. These CO_2 estimates are based on a net energy analysis derived from both operational systems and detailed design studies. It appears that energy conservation measures and shifting from fossil to renewable energy sources have significant long-term potential to reduce carbon dioxide production caused by energy generation and thus mitigate global warming. The implications of these results for a national energy policy are discussed.

17. Document Analysis

a. Descriptors Solar power plants ; solar thermal power plants ; photovoltaic power plants ; fossil-fuel power plants ; air quality ; air pollution abatement

b. Identifiers/Open-Ended Terms

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