COMPARATIVE ANALYSIS OF NET ENERGY BALANCE OF SATELLITE POWER SYSTEMS (SPS) AND OTHER ENERGY SYSTEMS

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SATELLITE POWER SYSTEM
Concept Development
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DEFINITIONS OF UNIT SYMBOLS

bbl: barrel

Btu: British thermal unit

°C: degrees centigrade

cm: centimeter

eV: electron volt

°F: degrees Fahrenheit

ft: foot

g: gram

gal: gallon

GW: gigawatt (i.e., 10^9 watts)

hr: hour

J: joule

K: Kelvin (temperature scale)

kg: kilogram

km: kilometer

kV: kilovolt

kWh: kilowatt hour

kWhe: kilowatt hour (electric)

kWht: kilowatt hour (thermal)

lb: pound

m: meter

mi: mile

MWe: megawatt (electric)

MWh: megawatt hour

μm: micrometer

s: second

SWU: separative work unit

t: metric ton (1,000 kg)

t-km: ton-kilometer (metric)

ton: English ton

ton-mi: ton-mile (English)

yr: year

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ABSTRACT

This report assesses the net energy balance of seven electric energy systems: two coal-based, one nuclear, two terrestrial solar, and two solar power satellites, with principal emphasis on the latter two systems. Solar energy systems require much less operating energy per unit of electrical output. However, on the basis of the analysis used here, coal and nuclear systems are two to five times more efficient at extracting useful energy from the primary resource base than are the solar energy systems. The payback period for all systems is less than 1.5 years, except for the terrestrial photovoltaic (19.8 yr) and the solar power satellite system (6.4 yr), both of which rely on energy-intensive silicon cells.

1 EXECUTIVE SUMMARY

A preliminary assessment of the net energy balance of seven electric energy systems was conducted, using existing data and methods, to identify differences and to recommend further work needed to improve the evaluation. Two of the systems are coal-based--a 747-MWe atmospheric fluidized bed combustion (AFBC) and a 741.5-MWe coal-gasification/combined-cycle (CG/CC) system; one is nuclear--a 1000-MWe light water reactor (LWR); two are terrestrial solar--a 100-MWe thermal and a 1000-MWe photovoltaic system; and two are satellite power systems--5000-MWe satellites using, respectively, silicon cells and gallium aluminum arsenide (GaAlAs) cells. The principal emphasis is on the satellite power system (SPS).

A combination of process analysis and input/output analysis was used to compute, for each system, the energy balance parameters: gross efficiency, operating efficiency, operating ratio, lifetime efficiency, lifetime ratio, and payback period. These parameters are defined in Table 1.1, which summarizes the basic results.

The coal and nuclear systems are two to five times more efficient than the solar energy systems, but use nonrenewable resources, which is undesirable when concern for resource depletion is important. The conversion efficiency of the system dominates the result: the calculation of efficiency is not

Table 1.1. Summary of Energy Balance Data

Parameter	Coal AFBC	Coal CG/CC	Nuclear LWR	Terrestrial Solar[a] Thermal	Terrestrial Solar[a] Photo-voltaic[b]	SPS[a] Silicon	SPS[a] GaAlAs
Gross Efficiency, %[c]	28.1	36.7	21.7	11.4	5.7	7.0	6.9
Operating Efficiency, %[d]	26.7	33.4	20.4	11.4	5.7	7.0	6.9
Operating Ratio[e]	5.33	3.67	3.32	26.74	27.34	16.67	77.89
Lifetime Efficiency, %[f]	26.4	33.0	20.3	11.3	5.4	6.9	6.9
Lifetime Ratio[g]	4.43	3.26	3.04	11.54	1.43	3.85	17.97
Payback Period (Electric Basis), yr[h]	1.30	1.11	1.14	1.48	19.82	6.38	1.30

[a]The data for the solar energy systems are limited and, in some cases, highly uncertain; conclusions should be drawn with caution.

[b]Silicon system.

[c]Gross Efficiency = Annual Net Output/Annual Primary Input.

[d]Operating Efficiency = Annual Net Output/Annual Primary + Operating + Internal Inputs.

[e]Operating Ratio = Annual Net Output/Annual Operating + Internal Inputs.

[f]Lifetime Efficiency = Lifetime Net Output/Lifetime Primary + Operating + Internal + Capital Inputs.

[g]Lifetime Ratio = Lifetime Net Output/Lifetime Operating + Internal + Capital Inputs.

[h]Payback Period is the time at which Net Output = Operating + Capital Inputs.

sensitive to gross, operating, or lifetime efficiency figures. Because efficiency parameters cannot take into account the fact that the solar energy systems operate from a renewable, effectively inexhaustible, resource base, whereas nuclear and coal systems operate from a nonrenewable resource base, one must conclude that efficiency is not a good measure of comparability between the solar and the coal and nuclear systems.

Although the operating ratio results demonstrate that the solar energy systems require substantially less operating energy per unit of electrical output, the large capital investment reduces their lifetime ratios significantly. For silicon-cell satellite power systems (SPS/Si) and terrestrial photovoltaic systems, the lifetime ratios are less than that of the best coal system.

The payback period for all systems except SPS/Si and terrestrial photovoltaic is less than 1.5 years. For both these exceptions, the long payback results primarily from the energy intensity of silicon production. For the SPS/Si system, several possibilities -- e.g., decreased energy requirements for cell production, use of solar-generated rather than conventional electrical power in cell manufacture, increased cell lifetime, and decreased silicon requirements -- could make the payback period comparable to that of the other systems. (The payback periods of the other systems could also be reduced slightly if solar electricity were substituted for conventional electricity in their manufacture.) In contrast, the best combination of conditions for the terrestrial photovoltaic system still would result in a payback of about six years. Figure 1.1 summarizes the range of payback conditions.

The difference between the SPS/Si and the terrestrial photovoltaic system occurs because the SPS/Si system would operate 24 hr/day, as compared to about 8-10 hr/day for the terrestrial system, and after the capital energy investment has been made in the silicon cells, the SPS would use the material more intensively and thus more efficiently.

The results of this study were compared to those from three earlier studies of the net energy balance of satellite power systems. Differences among the results arise primarily from different initial assumptions in the various studies. When these assumptions are resolved to the same set of conditions, the resulting net energy balance parameters from the different studies become comparable.
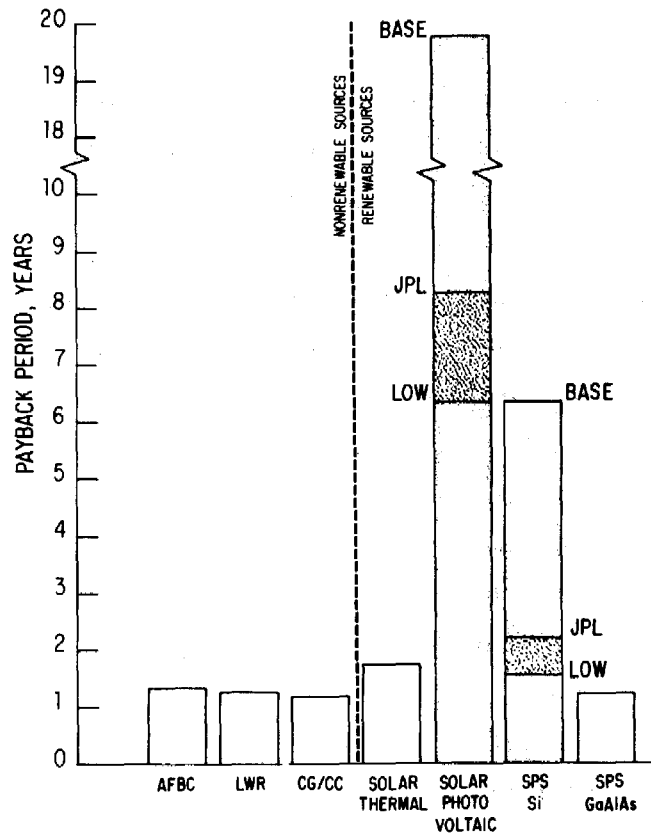
Fig. 1.1. Comparison of System Energy Payback Periods

Recommendations for future activity include the following:

1. No further analysis is recommended for the coal, nuclear, and terrestrial solar thermal systems, because their payback periods are so similar; little can be gained by further comparisons of SPS with these systems.

2. More detailed assessment of energy requirements for production of silicon cells is needed, because the results for SPS/Si and terrestrial photovoltaic systems depend so heavily on this energy input. A study of the potential for reducing such energy consumption is recommended, and the net energy balance parameters for SPS/Si

3. The energy inputs required for production of GaAlAs cells need study, and the net energy balance parameters for SPS/GaAlAs should be recomputed with the resulting new information. The information available at present is extremely limited, and although it suggests a very short paypack period the level of uncertainty dictates that is should be examined more carefully.

2 SCOPE AND METHODOLOGY

2.1 INTRODUCTION

Net energy analysis is a developing tool that is coming to be more widely used in energy research and decision making. Its goal is to estimate the quantity of energy that must be invested in an energy system to recover useful energy output. The concept of net energy analysis has not been important in decisions about conventional energy systems, because those systems traditionally have been considered to provide substantially more energy than was required to put them into operation. However, advanced technologies require more energy investment to recover each unit of usable energy, so the net energy yield becomes an important decision parameter. Net energy output is not the only variable on which decisions must be based; it must be considered in the light of economic, environmental, social, and other factors of interest, including use of renewable versus non-renewable resources and depletion of nonenergy mineral resources. All these factors are important in a comparative assessment, but they are beyond the scope of a net energy study. They are more appropriately addressed separately.

For satellite power systems (SPS), the issue of net energy analysis was raised by Herendeen,[1] who suggested that an SPS system might be close to the payback limit, i.e., might not return sufficient usable energy compared to the energy investment required. Other studies[2,3] have come to somewhat different conclusions. The objective of the present study, part of an overall comparative assessment of SPS and other energy technologies, was to conduct a preliminary evaluation of the net energy output for SPS and other technologies to draw some preliminary conclusions about how SPS compares with other systems and to identify where deficiencies in information exist. Available data and current analytic methods were used to obtain first-order estimates of the net energy balance parameters for the various systems; there has been no great effort to make detailed refinements of the calculations. This preliminary screening process will lead to a determination of where additional effort might best be spent to resolve differences in data and approach and to fill the information gaps.

Net energy analysis was applied to seven electrical energy systems: atmospheric fluidized bed combustion (AFBC) and coal gasification/combined-

cycle (CG/CC), both coal-based; light water reactors (LWR), two terrestrial solar energy systems (photovoltaic and thermal), and two satellite power systems, SPS/Si and SPS/GaAlAs, which use, respectively, silicon cells and gallium aluminum arsenide cells.

2.2 METHODOLOGICAL ALTERNATIVES

Basically, three methodologies can be used for net energy analysis. Reference 4 gives a concise review and critique of the alternatives.

Process analysis involves a detailed balance of energy flows into and out of a system. It is the most accurate and most involved methodology, and can be applied to situations where vast amounts of process-specific information are available.

Input/output analysis uses a procedure analogous to economic input-output analysis to determine the energy costs of any energy supply. It involves identifying the interactions among all sectors of the economy required to produce energy and translating the flow of goods and services among sectors into energy equivalents.

Ecoenergetics involves the assignment of energy values to various portions of the natural environment that are affected by the energy system. The process can be compared to a cost/benefit analysis in an economic evaluation.

In addition to the choice of analysis, several other decisions must be made to conduct a net energy analysis. Reference 4 classifies these decisions as follows:

Technical Issues

- Definition of system boundaries.
- Assignment of weights and quality factors to different forms of energy.
- Measurement of net energy.
- Treatment of temporal variations.

Philosophical Issues

- Evaluation of return on investment and discount rate.
- Treatment of labor requirements.
- Evaluation of sociological and institutional factors.
- Evaluation of environmental impacts.

2.3 APPROACH

2.3.1 Methodology

In this preliminary analysis, a combination of process analysis and input/output analysis, rather than the econenergetics approach, was used. These methodologies have been widely applied in other studies and therefore satisfy a primary guideline for this assessment, i.e., to use existing research.

Each of the systems chosen for evaluation can be described as a collection of system elements. Each element represents a particular piece of hardware, processing step, energy conversion step, or transportation mode. The energy balance of each system element can be described as shown in Fig. 2.1. The primary input is in the form of fuel (e.g., coal into a coal-processing plant) or energy (e.g., heat from a solar collector into a boiler). The ancillary operating inputs are those energy forms (fuel, electricity, or materials) required to keep the process operating (e.g., electricity to run pumps, gasoline for motor vehicles, or limestone for a combustor). The gross output is the energy or processed fuel that results from the system element. A portion of this may be used to meet internal energy requirements (e.g., electricity required at a power plant site to operate equipment). The balance is the net output that goes on to become the primary input of the next system element. The losses are the difference between the outputs and inputs.
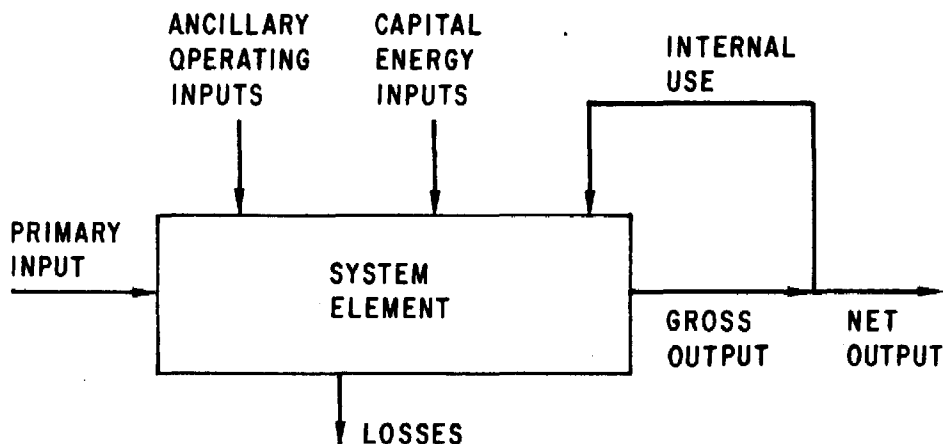
Fig. 2.1. Schematic of Energy Balance

For each system element, data on the quantities of materials, fuels, and electricity required to build and operate the system were compiled. Published data on energy requirements,[1,3,5,6] expressed either in joules per ton of material or joules per dollar cost of material, were used to convert the physical material quantity or material cost into an energy equivalent. Where the material cost was available, this conversion was based on an input/output table for each sector of the economy. For each type of material, an economic value of goods and services required from other sectors of the economy was computed, and an energy intensity figure was used to translate these economic costs into energy costs. In some cases, data already translated into energy equivalents in other net energy analyses were used. Because it was not deemed necessary at this time to perform a systematic check of the analytical processes used in these other studies, the potential exists for some inconsistencies among technologies in the calculation of indirect energy. These can be corrected in subsequent expansions of this work.

2.3.2 Resolution of Technical Issues

Several technical assumptions, discussed below, are implicit in the application of the analytical procedure.

System Boundaries. The boundary of each energy system was defined as extending from the primary resource (coal, uranium, or solar radiation) to electricity transmitted from the generating plant. The boundary includes environmental control systems and procedures to the extent that they are directly attributable to the energy system (e.g., cooling towers, particulate emission control, or strip mine reclamation). Materials, fuels, and electricity required for plant construction and operation enter the system from external sources, and the input/output analysis is the only method of dealing with their energy equivalents.

Energy Quality Factors. No attempt was made to attach a relative weight to the various forms of energy to account for the differences in quality and potential use. (For example, a joule-equivalent of a petroleum fuel is more useful than a joule-equivalent of coal). In the case of electricity required as ancillary operating input or as capital energy input, some adjustment must be made to reflect the basic resource cost of generating

electricity. Nominally, 2.5 to 3 times as much basic energy in the form of coal, oil, gas, or uranium is required to generate a given amount of electricity at the generating plant. In the present situation, the input of a given amount of electricity into construction of another energy system requires basic resources four times the energy equivalent. Details of this conversion are given in Appendix A.

Measurement of Net Energy. Results of a net energy analysis may be tabulated in various ways, according to the parameters used in Eqs.2.1 to 2.5:

$$\text{Gross Efficiency} = \text{NO/PI} \tag{2.1}$$

where:

NO = Net output, and
PI = Primary energy input (i.e., basic energy resources).

Gross efficiency is the basic measure of the amount of energy delivered per unit of input energy.

$$\text{Operating Efficiency} = \text{NO/(PI + AOI + IU)} \tag{2.2}$$

where:

AOI = Ancillary operating inputs,
IU = Internal use, and
NO and PI are as in Eq. 2.1.

Operating efficiency is a more complete measure of how effectively the basic energy resource is being utilized, i.e., how efficient a given technology is at extracting useful energy from a primary energy form. This value is of more critical concern to an assessment of nonrenewable resources. (The numerical value of these efficiencies is always less than unity.)

$$\text{Operating Ratio} = \text{NO/(AOI + IU)} \tag{2.3}$$

where NO, AOI, and IU are as in Eq. 2.2. The operating ratio eliminates the energy content of the primary resource from calculation. This parameter is a measure of how much useful energy can be extracted from a primary resource. It considers the primary resource as fundamentally unusable in its basic state and measures the amount of energy that must be expended to convert it to a usable form. The higher the value of this ratio, the better the system is from an energy balance standpoint; if the value is less than one, more energy is expended than is recovered. Although this is not the most desirable situation, it may be acceptable when other factors are considered.

$$\text{Lifetime Efficiency} = \frac{T \times NO}{T(PI + AOI + IU) + CI} \qquad (2.4)$$

where:

  T = System lifetime,

  CI = Capital energy inputs, and

  NO, PI, AOI, and IU are as in Eq. 2.2.

$$\text{Lifetime Ratio} = \frac{T \times NO}{T(AOI + IU) + CI} \qquad (2.5)$$

Where the notation is as in Eq. 2.4. The lifetime efficiency and lifetime ratio are entirely analogous to the operating efficiency and operating ratio of Eqs. 2.2 and 2.3. They include in the balance the capital energy investment, which represents the energy required to construct the system.

Temporal Variations. This preliminary analysis did not consider the time variation of energy expenditures or energy returns in constructing and operating an energy system; all calculations were made on an annual basis with capital investments adjusted by the system lifetime. However, several of the energy systems examined have significant variations in the time rate of energy investment and usable energy output. A temporal analysis could treat the problems arising from high energy demands early in system deployment, but such an analysis was considered unnecessary for this preliminary study.

2.3.3 Resolution of Philosophical Issues

As with the technical issues, some philosophical assumptions are implied in the analysis; these are discussed below:

Return on Investment. No attempt was made to prescribe and evaluate a desirable rate of return on energy investment or a suitable discount rate for estimating present value. No estimates were made of the relative value of an early expenditure versus a later one. The only assessment of this type that was carried out was the straightforward calculation of the payback period, i.e., the time required for the system to produce enough useful energy to match the energy invested in building and operating it. The payback period is that time at which the net output equals the capital energy input plus the cumulative ancillary operating inputs.

Treatment of Labor. No attempt was made to place an energy equivalent on human labor because this issue is outside the realm in which net energy analysis can supply useful insight.

Institutional/Sociological Considerations. No energy value can be placed on changes in institutional or social structures that are required or induced by an energy system. Institutional and social effects must be examined in other assessments of the technologies.

Environmental Impacts. The inclusion of direct requirements of energy for environmental control was discussed in defining system boundaries. No attempt was made to place energy values on such problems as ecosystem disturbance or withdrawal of land from natural ecological uses, because these concerns are outside the realm of net energy analysis.

3 ALTERNATIVE ENERGY SYSTEMS

3.1 COAL-BASED SYSTEMS

Both atmospheric fluidized-bed combustion (AFBC) and coal-gasification/ combined-cycle (CG/CC) generation are advanced technologies and are projected to be available for commercial use in about the same period as a satellite power system. Appendix B gives a detailed description of the configurations of these two coal-based systems selected for net energy evaluation.

3.1.1 Atmospheric Fluidized Bed Combustion (AFBC)

The system selected for analysis is a coal-fired AFBC steam generation system based on a design by the General Electric Company. A 747-MWe system was assumed, generating 4.25×10^9 kWhe/yr at a plant capacity factor of 65%.

The total system analyzed includes stripmining of coal, coal preparation and transportation, handling of both coal and limestone, combustion in an AFBC furnace, and conversion to power in a conventional steam-cycle system including a steam turbine, generator, condenser, and cooling tower.

Table 3.1 summarizes the energy parameters for the system. The power plant itself requires most of the capital energy investment, accounting for 85% of the total capital energy. It also requires almost half the operating energy investment. Other portions of the system are relatively small in the energy balance.

3.1.2 Coal Gasification/Combined Cycle (CG/CC)

The system studied is a gas-turbine/steam-turbine, combined-cycle unit, fired by the output of a low-Btu, fluidized-bed coal gasifier. The design, based on a Westinghouse system, is for a 741.5-MWe station generating 4.22×10^9 kWhe/yr at a plant capacity factor of 65%.

The overall system evaluated includes stripmining of coal, coal preparation and transportation, and the gasifier/cleanup unit, gas turbine, heat recovery system, and steam-cycle generator.

Table 3.2 summarizes the energy balance parameters for the system. As with AFBC, the power plant itself represents the largest energy invest-

Table 3.1. Summary of AFBC Energy Parameters

System Element	Annual Primary Input		Total Capital Inputs		Annual Operating Inputs		Annual Output		
	Type	Energy $(10^{15} J/yr)$	Type	Energy $(10^{15} J)$	Type	Energy $(10^{15} J/yr)$	Type		Energy $(10^{15} J/yr)$
Stripmining	Coal 2.35 x 10^6 t	54.629	Equipment and Construction	1.827	Electricity, fuel, supplies, maintenance, reclamation	0.541	Coal 2.11 x 10^6 t		49.166
Coal Preparation	Coal 2.11 x 10^6 t	49.166	Machinery, construction, water lines	0.270	Electricity, supplies, maintenance, water	0.082	Coal 1.86 x 10^6 t		43.266
Transportation (Railroad)	Coal 1.86 x 10^6 t	43.266	Rolling stock	0.531	Diesel oil	0.342	Coal 1.84 x 10^6 t		42.833
AFBC and Steam Cycle	Coal 1.84 x 10^6 t	42.833	Equipment, construction	15.016	Consumables, maintenance, limestone	0.780	Electricity	10^6 kWhe	
							Gross	4.56	16.455
							Internal	0.31	1.129
							Net	4.25	15.326
TOTAL		54.629[a]		17.644		1.745	Gross[b]		16.455
							Internal[b]		1.129
							Net[b]		15.326

[a] Input to entire cycle.

[b] Output from entire cycle.

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Table 3.2. Summary of Coal Gasification/Combined Cycle Energy Parameters

System Element	Annual Primary Input		Total Capital Inputs		Annual Operating Inputs		Annual Output	
	Type	Energy $(10^{15} J/yr)$	Type	Energy $(10^{15} J)$	Type	Energy $(10^{15} J/yr)$	Type	Energy $(10^{15} J/yr)$
Stripmining	Coal 1.78×10^6 t	41.442	Equipment and Construction	1.383	Electricity, fuel, supplies, maintenance, reclamation	0.410	Coal 1.61×10^6 t	37.298
Coal Preparation	Coal 1.61×10^6 t	37.298	Machinery, construction, water lines	0.207	Electricity, supplies, maintenance, water	0.062	Coal 1.42×10^6 t	32.822
Transportation (Railroad)	Coal 1.42×10^6 t	32.822	Rolling stock	0.402	Diesel oil	0.259	Coal 1.40×10^6 t	32.494
Gasifier/Cleanup	Coal 1.40×10^6 t	32.494	------(Included Below)------		Dolomite, internal air, steam, water, electricity	0.152 (2.746) [b]	Low Btu gas	33.771
Gas Turbine	Low Btu Gas	33.771	------------------------(Included Below)------------------------				Internal air, steam / Exhaust gas / Electricity	1.663 / 21.392 / 10.503
Heat Recovery System	Exhaust Gas	21.391	------------------------(Included Below)------------------------				Internal steam, water / Steam to turbine	0.657 / 14.352
Steam Cycle System	Steam	14.352	------------------------(Included Below)------------------------				Electricity	5.512
Power Transformer	Electricity	16.015	------------------------(Included Below)------------------------				Electricity 10^9 kWhe Gross 4.43 Internal 0.21 Net 4.22	15.938 0.735 15.203
Total Plant			Components	13.641	Routine and Special O & M	0.206		
TOTAL		41.442[a]		15.633		1.089	Gross[c] Internal[c,d] Net[c]	15.938 3.055 15.203

[a] Input to entire system.

[b] Internal use - included in output total only.

[c] Output from entire cycle.

[d] Internal includes electricity, steam, air, water

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ment. The energy balance is somewhat complicated by the internal energy use: air, steam, and water are supplied to the gasifier from the gas turbine and heat recovery system; electricity is supplied from the overall plant output. In general, the system is more efficient than the AFBC configuration, as it uses about 25% less coal to deliver about the same amount of electricity.

3.2 NUCLEAR SYSTEM

The nuclear system analyzed is a conventional 1000-MWe light-water reactor (LWR), assumed to generate 5.34×10^9 kWhe/yr at a plant capacity factor of 61%. Appendix C gives the details of this system.

The overall system includes uranium mining, milling, and transportation; conversion, enrichment, and fuel element fabrication; the reactor itself; spent fuel storage, and waste storage. Ordinary uranium ore, 0.208% U_3O_8 of which 0.71% is U^{235} with an enrichment tails assay of 0.2%, is assumed. Reprocessing for recovery of unused uranium and plutonium is not considered.

Table 3.3 summarizes the energy balance parameters. Although the reactor itself represents the largest energy investment, the enrichment process is the largest consumer of operating energy, most of which is in the form of electricity.

3.3 TERRESTRIAL SOLAR ENERGY SYSTEMS

Two terrestrial solar energy systems are considered: thermal and photovoltaic. Both are advanced technologies and could be available for commercial use at about the same time as an SPS. Appendix D gives the details of these systems.

3.3.1 Terrestrial Solar Thermal System

The terrestrial solar thermal system assessed is a 100-MWe central receiver (power tower), designed by the McDonnell-Douglas Company. Glass flat-plate heliostats (22,000) on tracking mounts focus sunlight on a receiver tower. The receiver/boiler and riser/downcomer provide heat and steam to the storage system and steam turbine; the storage system, designed to even out fluctuations in solar radiation, contributes about one-third of the input to the turbine. The turbine/generator and the balance of the electrical system use conventional components.

Table 3.3. Summary of LWR Energy Parameters

System Element	Annual Primary Input Type	Annual Primary Input Energy $(10^{15}J/yr)$	Total Capital Inputs Type	Total Capital Inputs Energy $(10^{15}J)$	Annual Operating Inputs Type	Annual Operating Inputs Energy $(10^{15}J/yr)$	Annual Output Type	Annual Output Energy $(10^{15}J/yr)$
Uranium Mining	Uranium 137.2 t	88.515	Electricity, fuels	0.647	Electricity, fuels, materials	0.095	Uranium 137.2 t	88.515
Uranium Milling	Uranium 137.2 t	88.515	Electricity, fuels, materials	0.169	Electricity, fuels, materials	0.118	Uranium 130.3 t	84.084
Conversion	Uranium 130.3 t	84.084	Electricity, fuels, materials	0.040	Electricity, fuels, materials	0.220	UF_6 191.7 t	84.084
Enrichment	UF_6 191.7 t	84.084	Electricity, fuels, materials	1.449	Electricity, fuels	4.069	Enriched uranium 22.8 t	60.515
Fuel Fabrication	Enriched uranium 22.8 t	60.515	Electricity, fuels, materials	0.037	Electricity, fuels, materials	0.155	Enriched uranium 22.8 t	60.515
Reactor	Enriched uranium 22.8 t	60.515	Electricity, fuels, materials	13.323	Electricity, fuels, materials	0.421	Electricity 10^9 kWhe Gross 5.54 Internal 0.19 Net 5.35	19.933 0.700 19.233
Spent Fuel Storage	Depleted uranium 22.8 M tons	NA	Electricity, materials	0.236	Electricity, fuels, materials	0.007	NA	
Waste Storage	Depleted uranium	NA	Electricity, fuels, materials	0.031	Electricity, fuels materials	0.008	NA	
Transportation		NA	Electricity, materials	0.150	Fuel	0.007	NA	
TOTAL		88.515[a]		16.082		5.100	Gross[b] Internal[b] Net[b]	19.933 0.700 19.233

[a] Input to entire cycle.

[b] Output from entire cycle.

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Table 3.4 summarizes the energy parameters for the system. The collector represents the largest energy investment, accounting for 40% of the total. Operating energy is in the form of auxiliary electricity that is generated by the plant itself.

3.3.2 Terrestrial Solar Photovoltaic System

A 1000-MWe (peak) photovoltaic facility, operating 10 hr/day at a capacity factor of 55%, was analyzed. The system has limited storage capacity in the form of lithium/sulfur batteries to compensate for loss of insolation. The solar cells, assumed to be silicon, occupy an area of 52 km^2; they are fitted with parabolic trough reflectors to concentrate solar radiation. Output from the cells is controlled by a power-conditioning module consisting of a DC collection network, regulator, controller, and inverter. An AC distribution system and a transformer for matching to a utility grid also are included.

Table 3.5 summarizes the net energy parameters of this system: the capital energy investment is overwhelmingly dominated by the energy required to produce the silicon cells--73% of the total, on the basis of the current state of the art of silicon manufacture. The implications of projected reductions in the cost of silicon cells and corresponding reductions in energy requirements will be discussed later. Steel required for the facility makes up an additional 17% of the capital energy investment.

3.4 SATELLITE POWER SYSTEM (SPS)

The SPS analyzed is based on the latest concept definition prepared by NASA under the DOE/NASA SPS Concept Development and Evaluation Program.[7] Two systems, using silicon cells and gallium aluminum arsenide cells respectively, were analyzed. Appendix E gives the details of the systems.

A single 5-GW satellite in geosynchronous orbit, transmitting power to earth via focused microwave beams, is assumed. The system includes the ground rectenna, which receives and rectifies the microwave power, and the launch vehicle and orbital construction equipment. An analysis of the entire system (projected to use 60 satellites) would prorate the launch vehicles and other orbital construction equipment over all the satellites rather than

Table 3.4. Summary of Terrestrial Solar Thermal Energy Parameters

System Element	Annual Primary Input		Total Capital Inputs		Annual Operating Inputs		Annual Output	
	Type	Energy $(10^{15} J/yr)$	Type	Energy $(10^{15} J)$	Type	Energy $(10^{15} J/yr)$	Type	Energy $(10^{15} J/yr)$
Collector	Solar radiation	10.775	Glass, steel, concrete	0.737	---------(Included Below)[a]--------		Heat	5.389
Receiver/Boiler	Heat	5.389	Steel, concrete	0.137			Heat	4.534
Riser/Downcomer	Heat	4.534	Steel	0.001	---------(Included Below)[a]--------		Heat to storage / Steam to turbine	1.777 / 2.711
Storage	Heat	1.777	Caloric HT43 oil, sand, gravel, steel	0.483	---------(Included Below)[a]--------		Steam to turbine	1.510
Turbine/Generator	Steam	4.221	Equipment	0.324	---------(Included Below)[a]--------		Electricity	
							10^8 kWhe	
							Gross 3.62	1.303
							Internal 0.13	0.046
							To transformer 3.49	1.257
Transformer/ Power Conditioner	Electricity	1.257	(Included in turbine/generator)				Electricity Net 3.42×10^8 kWh$_e$	1.230
Misc. Equipment			Electrical equipment, cooling tower, water transport	0.136				
TOTAL		10.775[b]		1.818		—[a]	Gross[c] / Internal[c] / Net[c]	1.303 / 0.046 / 1.230

[a]Operating inputs as internal electricity use.

[b]Input to entire cycle.

[c]Output from entire cycle.

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Table 3.5. Summary of Terrestrial Solar Photovoltaic Energy Parameters

System Element	Annual Primary Input		Total Capital Inputs		Annual Operating Inputs		Annual Output		
	Type	Energy (10^{15} J/yr)	Type	Energy (10^{15} J)	Type	Energy (10^{15} J/yr)	Type	10^9 kWhe	Energy (10^{15} J/yr)
Collector	Solar radiation 10 kWh$_e$	115.048	Silicon	94.580[a]	--------(Included Below)[b]--------		Electricity	2.18	7.830
Power Regulator, Controller, DC Collection Network	Electricity 2.18	7.830	Copper	0.027	--------(Included Below)[b]--------		Electricity To Battery To Inverter	0.70 1.43	2.508 5.165
Battery	Electricity 0.70	2.508	Lithium	6.480	--------(Included Below)[b]--------		Electricity To Inverter	0.56	2.006
Inverter	Electricity 1.99	7.171	Equipment	1.370			Electricity	1.89	6.814
AC Distribution Line System	Electricity 1.89	6.814	-------(Included Below)-------				Electricity Gross Internal To transformer	1.89 10.07 1.82	6.814 0.238 6.576
Transformer	Electricity 1.82	6.576	Equipment	1.940			Electricity Net	1.81	6.508
Entire Plant			Electrical equipment, steel, concrete	24.566					
TOTAL		115.048[c]		128.963		--[b]	Gross[d] Internal[d] Net[d]		6.814 0.238 6.508

[a] Based on state-of-the-art silicon production.

[b] Operating inputs as internal electricity use.

[c] Input to entire cycle.

[d] Output from entire cycle.

just the first one, but insufficient information was available to do so in the present study. The results, however, would not change much because vehicles and construction equipment make up a very small portion of the total materials energy required, and because the rocket fuel, which is a much larger portion of the construction energy required, was assessed for a single satellite only.

The energy parameters are summarized in Table 3.6. The energy needed for production of silicon cells dominates the balance, as was the case for terrestrial solar photovoltaic. The rectenna is the next largest consumer of capital energy for SPS/Si (it is the largest for SPS/GaAlAs) because of the aluminum and steel required.

Table 3.6. Summary of SPS Energy Parameters

System Element	Annual Primary Input Type	Energy (10^{15} J/yr)	Total Capital Inputs Type	Energy (10^{15} J)	Annual Operating Inputs Type	Energy (10^{15} J/yr)	Annual Output Type	Energy (10^{15} J/yr)
Solar Energy Collection System							10^9 kWhe	
Si	Solar Radiation	2079.410					Electricity 74.05	266.570
GaAlAs	Solar Radiation	2107.530					Electricity 74.05	266.570
Power Distribution System	Electricity 74.05 x 10^9 kWh$_e$	266.570					Electricity 66.77	240.360
Microwave Power Transmission System	Electricity 66.77 x 10^9 kWh$_e$	240.360					Electricity Gross 40.33 Internal NA Net 40.33	145.180 NA 145.180
System Components								
Satellite Si			Materials	406.906				
GaAlAs			Materials	37.393				
LEO/GEO Si			Materials	6.564				
Construction GaAlAs			Materials	NA				
Flight Si			Materials	13.504				
Vehicles GaAlAs			Materials	1.462				
Rectenna			Materials	118.553				
Other Si			Materials	325.719				
GaAlAs			Materials	28.816				
Entire System Si					Materials	8.712		
GaAlAs					Materials	1.864		
TOTAL Si		2079.410[a]		871.246		8.712[b]	Gross	145.180[c]
GaAlAs		2107.530[a]		186.224		1.864[b]	Internal Net	NA[d] 145.180[c]

[a] Input to entire system.

[b] Based on 30% of capital materials amortized over 30 year lifetime.

[c] Output from entire system.

[d] Not available.

4 RESULTS OF ANALYSIS

4.1 BASELINE CASE

Table 4.1 summarizes the energy inputs and outputs described in Sec. 3 for each of the systems considered. Because of the variation in system size (100 MWe for terrestrial solar thermal to 5000 MWe for SPS) and plant capacity factors, the values are not directly comparable. (In the net energy balance, discussed below, these differences disappear because the parameters of interest are normalized.)

All net output values are expressed in terms of electricity rather than as thermal equivalents; the importance of this will become apparent later. Likewise, all primary inputs are expressed as energy content of the fuel itself, with no adjustment factors applied. The capital and operating inputs, however, are computed using the net energy analysis techniques described in Sec. 2 and reflect both the energy cost of delivering materials to the facility and the energy content of the materials themselves.

The internal energy use includes electricity, compressed air, and steam. These differences in energy form, plus the differences in where internal electrical power is tapped in each system configuration, yield the consequence that the net output is not simply the difference between gross output and internal energy use.

Table 4.2 shows the energy balance parameters for the seven systems. The coal and nuclear systems are substantially more efficient than their solar counterparts in terms of gross, operating, and lifetime efficiency. However, the coal and nuclear systems operate from a nonrenewable resource base, whereas the solar energy systems operate from a renewable and effectively unlimited resource base, but the cost of resource depletion does not enter the calculation of efficiency. The three different measures of efficiency do not differ significantly because the numerator of each measure reflects the system output and the denominator includes the primary input, with various combinations of internal use and operating and capital inputs. The annual primary input is much larger, for all systems, than the annual operating input and internal use; also, the primary input is much larger than the capital input when both are expressed over the system lifetime for the lifetime efficiency calculation. The implication is that the efficiency with which the

Table 4.1. Summary of System Energy Inputs and Outputs

	Energy, 10^{15} J						
	Coal		Nuclear	Terrestrial Solar		SPS	
	AFBC 747 MWe	CG/CC 741.5 MWe	LWR 1000 MWe	Thermal 100 MWe	Photovoltaic 1000 MWe	S_i 5000 MWe	GaAlAs 5000 MWe
Annual Primary Input	54.629	41.442	88.515	10.755	115.048	2079.410	2107.530
Total Capital Input	17.644	15.633	16.082	1.818	128.963	871.246	186.224
Annual Operating Input	1.745	1.089	5.100	—[c]	—[c]	8.712	1.864
Annual Outputs							
Gross[a]	16.455	15.938	19.933	1.303	6.814	145.180	145.180
Internal Use[b]	1.129	3.055	0.700	0.046	0.238	NA	NA
Net[a]	15.326	15.203	19.533	1.230	6.508	145.180	145.180

[a]Expressed as electricity.

[b]Internal includes electricity, air, steam. Because of differences in where the internal energy use is tapped from the system, the net output is not necessarily equal to the difference between gross and internal.

[c]Internal electricity only.

Table 4.2. Summary of Energy Balance Data

Parameter	Coal		Nuclear	Terrestrial Solar		SPS	
	AFBC	CG/CC	LWR	Thermal	Photovoltaic[a]	Silicon[a]	GaAlAs[a]
1. Gross Efficiency, %	28.1	36.7	21.7	11.4	5.7	7.0	6.9
2. Operating Efficiency, %	26.7	33.4	20.4	11.4	5.7	7.0	6.9
3. Operating Ratio	5.33	3.67	3.32	26.74	27.34	16.67	77.89
4. Lifetime Efficiency, %	26.4	33.0	20.3	11.3	5.4	6.9	6.9
5. Lifetime Ratio	4.43	3.26	3.04	11.54	1.43	3.85	17.97
6. Payback Period (Electric Basis), yr	1.30	1.11	1.14	1.48	19.82	6.38	1.30

[a]The data for the solar energy systems are limited and, in some cases, highly uncertain. Therefore, conclusions should be drawn with caution.

primary energy resource is converted into electricity is relatively insensitive to the ancillary operating energy inputs and the capital energy inputs for these systems. The thermal or electric conversion efficiency of the system is thus the principal factor in determining system performance.

The situation is different with regard to the operating ratio and the lifetime ratio, both of which are computed without consideration of the primary resource input. Operating ratios of the solar energy systems are much higher than those of coal and nuclear systems, indicating that much less energy is used annually to convert each unit of primary resource into electricity. Over the lifetime of each system, however, the result changes dramatically. For the coal and nuclear systems, the operating and lifetime ratios differ by, at most, 17% (for AFBC), whereas for the solar energy systems, the difference is 57%-95%. The terrestrial photovoltaic and the SPS/Si systems show lifetime ratios that are lower than the best coal system (AFBC), whereas the terrestrial solar thermal and the SPS/GaAlAs systems have both operating and lifetime ratios higher than those of the coal and nuclear systems. The implication is that the capital energy investment required to build each of the solar energy systems greatly reduces the net useful output of the systems over their lifetimes. This is not true of the coal and nuclear systems because the capital energy investments required are not as great relative to the energy output. For the terrestrial photovoltaic and the SPS/Si systems, the decrease in net output makes them poorer performers than the best coal system. (As will be shown later, this is the result of the silicon production requirements.)

In contrast to the measures of efficiency, operating and lifetime ratios are relatively sensitive to the ancillary operating, internal, and capital energy requirements. Small changes in these data can make relatively large changes in the ratios. Therefore the ratio calculations must be viewed as only rough gauges of system performance.

The energy payback period of each system is a somewhat less sensitive measure of overall energy balance. The payback period for all systems except the terrestrial photovoltaic and SPS/Si is less than 1.5 yr, indicating that five of the systems will deliver significantly more energy over their nominal 30-yr lifetimes than was required to build them. Because the calculation is relatively insensitive to moderate changes in the data, it can be inferred

that payback from these systems is reasonable; but the results are so similar among the five systems with short payback periods that they do not provide a clear basis for choosing among these systems.

The results are not encouraging for the terrestrial photovoltaic and the SPS/Si systems. The SPS/Si system requires over six years of operation to return the energy invested—more than four times longer than the worst of the other systems. Although this is not necessarily an unacceptable situation, it does demand closer investigation of the possibility of reducing the capital energy required. The terrestrial photovoltaic system requires almost 2/3 of its entire lifetime to repay the energy investment. This slow payback, combined with a lifetime ratio of 1.43—little more than the breakeven point of 1.0—leads to some serious concern over the viability of such a system, at least in the configuration used here.

In the following sections, the uncertainties in some of the data used in this baseline analysis will be considered, and different approaches to net energy analysis will be discussed, to illustrate the sensitivity of the results to alternative data and methods.

4.2 EFFECT OF UNCERTAIN DATA

4.2.1 Energy Intensity of Silicon Cell Production

For both the terrestrial photovoltaic and SPS/Si systems, the relatively poor performance compared to the other systems was traced to the very high energy requirements of silicon cell production. As shown in Appendix A, the energy requirements for silicon solar cell production vary over a wide range $(1.0 \times 10^3$ to 26.0×10^3 kWht/kg).[1,2,8,9] The value used in the baseline case, 13.9×10^3 kWht/kg, is derived from Ref. 9 and falls in the middle of the range. This value represents the current state of the art in silicon production technology. Substantial reductions in the cost of silicon cell production, and presumably in the energy required, are projected for the period when SPS is to be operational. Therefore, the impact of these reductions on the energy balance needs to be investigated.

Figure 4.1 shows the effect of using different levels of silicon energy intensity on the energy parameters. Because of the dominance of the primary energy input, there is essentially no effect on the lifetime efficiency.
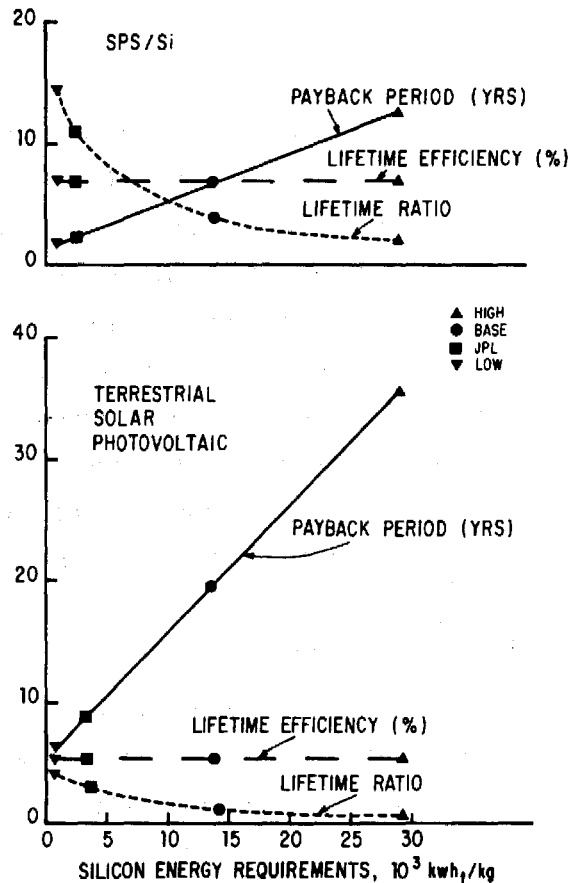
Fig. 4.1. Variation of Net Energy Parameters with
Silicon Energy Requirements

The lifetime ratio and the payback period could be significantly altered by reductions in this production energy. By assuming the silicon production energy used in Ref. 2, the SPS payback period is reduced to just over two years, and that of the terrestrial photovoltaic system to just over eight years. Use of the lowest estimates of production energy would put the SPS/Si system into the same payback class as the other energy systems and give the terrestrial photovoltaic system a somewhat more acceptable payback period of just over six years.

The difference between the SPS/Si and the terrestrial photovoltaic system occurs because the SPS/Si system would operate 24 hr/day, as compared to about 8-10 hr/day for the terrestrial system, and after the capital energy investment has been made in the silicon cells, the SPS would use the material more intensively and thus more efficiently.

4.2.2 Cell Lifetime

A fair amount of uncertainty exists as to the lifetime of silicon cells, either in geosynchronous earth orbit (GEO) or in the terrestrial environment. Reference 9 indicates a cell lifetime of ten years in terrestrial applications; Ref. 7 assumes a 30-yr lifetime in orbit with some cell repair necessary. Obviously, a three-fold difference in cell lifetime and, concomitantly, in the amount of silicon required, will affect the net energy balance similarly to a changed energy intensity of cell production. Experience is as yet insufficient to allow determination of the most realistic expected lifetime. For the purpose of this study it was assumed that the cells in both SPS/Si and terrestrial photovoltaic systems would have a 30-yr lifetime.

4.2.3 Energy Supply for Silicon Production

Most of the energy required for silicon production is needed as electricity for growing the crystals.[9] All of the estimates of production energy cited above consider the electricity to be supplied by conventional generators; thus all are limited by the thermal conversion efficiency of such equipment. (For input/output analysis as described in Appendix A, the energy cost of providing electricity is approximately four times the amount of electrical energy provided.) One method of reducing the energy requirements for silicon production would be to provide the electricity for cell manufacture from solar-power facilities instead of conventional fossil fuel or nuclear facilities. This would, in effect, reduce the silicon energy requirements by a factor of four. To account for this reduction, a dynamic analysis of the development of an entire solar electricity system would be needed, instead of the individual facility analysis made here. Although such a dynamic analysis is not within the scope of this study, a rough estimate of the impact of such a scenario may be obtained by simply viewing the use of solar electricity as a four-fold decrease in energy intensity and using Fig. 4.1 to determine the effect on the parameters. A four-fold decrease in the value used in this study for silicon production would reduce the payback period from 19.8 yr to about 9 yr for terrestrial photovoltaic, and from 6.4 yr to about 2 yr for SPS/Si. With a four-fold decrease in the lowest estimate of silicon production energy, the payback would be about six years for terrestrial solar and one year for SPS/Si. (Reductions of smaller magnitude could also be realized for all the other systems if solar electricity were substituted for conventional electricity.)

4.2.4 Quantity of Silicon Required

There is also some uncertainty, although of smaller magnitude, with respect to the amount of silicon required per MW of electrical output. Table 4.3 summarizes some of the different estimates. None of the different values would lead to a substantial difference in the outcome of the analysis, with the exception of the values for the average rather than peak power output for the terrestrial systems. In this analysis only values for the peak power rating were used.

4.2.5 Energy Intenstity of GaAlAs Cell Production

Uncertainties about the energy requirements for production of gallium alluminum arsenide photovoltaic cells are much greater than the uncertainties about silicon. None of the other analyses of net energy for solar systems included GaAlAs as a candidate system, so very little information is available. The data for this study were based on Ref. 8; no other sources were discovered in the course of this preliminary review. The estimated energy intensity of 5.5×10^3 kWht/kg is about half as much as that required for silicon production. The quantity of GaAlAs required is almost an order of magnitude less (1696 t versus 13,813 t), primarily as the result of the higher efficiency GaAlAs and the use of concentrators in the cell configuration. It appears that GaAlAs cells require a much smaller energy investment than silicon cells (34×10^{15} J versus 691×10^{15} J) for the same energy output.

Table 4.3. Differences in Silicon Requirements

System	Capacity (MWe)	Silicon Required (t)	Intensity (t/MWe)	Reference
SPS/Si	480,000	698,000	1.45	JPL[2]
SPS/Si	5,000	13,813	2.76[a]	NASA[7]
Terrestrial Photovoltaic (Peak)	4,500	11,000	2.44	EPA[9]
(Average)	900	11,000	12.22	
Terrestrial Photovoltaic (Peak)	1,000	1,890	1.89[a,b]	EPA[10]

[a]Used for this study.

[b]Based on use of parabolic concentrators.

Clearly, changes in the energy intensity or materials requirements of GaAlAs production will have a significant impact on the energy balance; however, more data are needed to evaluate the possible range of values.

4.2.6 Other Material Energy Requirements

Appendix A gives the ranges of energy intensity of the materials other than silicon that were analyzed. Because a complete materials list was not available for each of the technologies considered, a complete analysis of the effect of alternative ranges of energy intensity was not possible. However, a rough estimate can be made on the SPS requirements because a fairly comprehensive list of materials was available. Table 4.4 shows the effect on capital energy requirements and payback period, of using the low estimate and the high estimate of energy intensities from Appendix A, on the assumption that the silicon energy intensity is fixed at the baseline level. It is evident that variations in the energy requirements of other materials have very little effect on the payback period for either SPS/Si or SPS/GaAlAs.

4.3 EFFECT OF ALTERNATIVE METHODS: OTHER STUDIES

Reference 11 reviews the three earlier analyses of net energy that have been done on SPS.[2,3,12] All three were done for preliminary SPS configurations somewhat different from the ones analyzed here, and so they cannot be compared directly to results presented here; nevertheless, it is informative to review the results and to attempt to explain some of the differences.

The PRC study[12] was designed to be a rough, first-cut analysis of SPS energy balance and was conducted with input/output techniques only. All

Table 4.4. Effect of Energy Intensity Assumptions on SPS Energy Balance

Parameter	Units	Baseline Values		Low Intensity Values		High Intensity Values[a]	
		Si	GaAlAs	Si	GaAlAs	Si	GaAlAs
Total Capital Input	$(10^{15}J)$	871.246	186.224	787.892	124.835	1116.145	421.171
Annual Operating Input[b]	$(10^{15}J/yr)$	8.712	1.862	7.879	1.248	11.161	4.212
Payback Period	(yrs)	6.38	1.30	5.74	0.87	8.33	2.99

[a]Except silicon, which is held at baseline value.

[b]Changes because operating input is computed as a fraction of capital input.

SPS components were represented by cost figures and were converted to energy requirements using the standard approach. The calculation for a 5-GWe satellite using GaAlAs cells and a rectenna site, showed a capital energy requirement of 465 x 10^{15} J. This can be compared to the current study's estimate of 186 x 10^{15} J for the same size satellite and rectenna. The difference can be traced primarily to the energy intensity values used in the two studies. The PRC analysis used strictly system component costs, whereas the present current study used a materials list. Also, the materials and cost requirements are different for each system because of an evolving system definition. If the PRC estimate of capital energy is translated into a payback period on the same basis as in the current study, the result is 2.5 years, which is comparable to the 1.3 years computed here.

The Herendeen study[3] was conducted for an entire SPS consisting of 112 silicon-cell satellites of 10 GWe each. Several energy ratios are presented; the one that is closest to the lifetime ratio used here is referred to as the "Energy Ratio, at 3413 Btu/kWe, fuel excluded." This refers to the fact that the system output is expressed as electricity, and does not consider the efficiency of conventional power plants that generate the input electricity. The "fuel excluded" indicates that the primary resource input is not included in the calculation. Both of these assumptions are the same as those used in the present study to compute lifetime ratio. Herendeen's analysis shows a range of energy ratios from 0.5 to 3.9, using a randomized uncertainty in energy intensity; the present study shows a lifetime ratio of 3.85. Considering the major difference in the assumption about silicon cell life, the values are surprisingly close. Herendeen considers an exponentially decreasing power output as the cells deteriorate over the system lifetime; however, this study assumes constant power output with cell repairs over a 30-yr lifetime. Because the lifetime energy ratio is a relatively sensitive parameter, small changes in data make significant changes in the ratios.

The JPL study[2] is also for an entire SPS including 48 satellites of 10 GWe each. It also is based on an earlier system design using silicon cells only. JPL computed energy intensity values by starting with process energy requirements for materials and multiplying by a factor of 2.5 to derive total materials of energy requirements, instead of using an input/output analysis based on economic costs. The JPL study used a multiplier of 4 to

convert input electricity to total thermal energy equivalents, and a multiplier of 3 to convert output electricity to thermal equivalents. The first multiplier is basically consistent with the approach used here; but the second multiplier is not. Although it can be argued that the SPS output should be compared to the energy required to deliver that electricity from conventional generators, the across-the-board multiplication of the output by a factor of 3 appears arbitrary. Rather, it would seem more appropriate to consider the energy ratios as "joules of electricity output per joule of energy input" and to consider the payback period as the time over which the useful electrical output equals the useful thermal and electrical inputs. The JPL study[2] shows a payback period of 1.2 to 1.6 yr, depending on the rectenna materials chosen. If the factor of 3 were removed from the output energy, then the payback period would be 3.6 to 4.8 yr. This is comparable to the 6.4 yr reported here. The reason for the difference lies primarily in the values used for energy requirements for silicon production. The JPL value[2] is significantly lower (2.9 x 10^3 kWht/kg versus 13.9 x 10^3 kWht/kg) and represents projected improvements in the state of the art. Moreover, the quantity of silicon required is substantially less (1.45 t/MWe versus 2.76 t/MWe). These two factors yield the result that in the JPL study[2] the SPS energy balance is more heavily dominated by the choice of aluminum or steel for the rectenna than by the silicon requirements.

5 CONCLUSIONS AND RECOMMENDATIONS

Three preliminary conclusions can be drawn from the present analysis. First, the calculation of system efficiency shows that the coal and nuclear systems are 2 to 5 times more efficient at extracting useful energy from the primary resource base than are the solar energy systems. This efficiency difference remains whether one uses gross, operating, or lifetime parameters; it derives primarily from the electrical conversion efficiencies of the systems. However, because efficiency parameters cannot take into account the fact that the solar energy systems operate from a renewable and effectively inexhaustible resource base, whereas the nuclear and coal systems operate from a nonrenewable resource base, one must conclude that efficiency is not a good measure of comparability between the solar and the coal and nuclear systems.

Second, the operating ratio calculation shows that the solar energy systems require substantially less operating energy per unit of electrical output than do the coal and nuclear systems. Even the poorest of the solar energy systems (SPS/Si) has an operating ratio more than three times better than that of the best coal system (AFBC). The lifetime ratio, however, is greatly reduced (by 57%-95%) below the operating ratio because of the intensive capital energy investment. For SPS/Si and terrestrial photovoltaic, the reduction is enough to drop them below the best coal system in performance.

Third, the payback period is less than 1.5 yr, except for the terrestrial photovoltaic system (19.8 yr) and the SPS/Si (6.4 yr). In both cases, this poor performance is caused by the energy required for silicon cell production. Several possibilities, including reduction in the energy required for cell production, the use of solar-generated electricity in place of conventional electrical power, increased cell lifetime, and decreased silicon requirements, could reduce the SPS/Si payback period to a level that is comparable with the other systems considered (1-2 yr). However, for the terrestrial photovoltaic system, it appears that even the best combination of conditions would still require a payback period significantly longer than those of the other options (about 6 yr). (This is not necessarily a reason to consider terrestrial photovoltaic systems undesirable, as net energy balance is only one of several decision parameters.)

Concerning the application of these results, it can be concluded that the energy payback period is a significant decision parameter only with respect to the choice of SPS/Si or terrestrial photovoltaic systems over the other systems. For the others, the computed payback periods are so close as to be well within the range of error of the data, and it can be concluded that there is no difference. The operating and lifetime ratios show the expected results that the solar systems require much less operating energy than the coal or nuclear systems but that the capital energy requirements greatly reduce this advantage. The terrestrial photovoltaic system is the poorest performer in this category. Although the efficiency calculations show the conventional systems to have higher efficiencies than the solar systems, the nature of the renewable versus nonrenewable resource base makes the cross-comparison difficult.

Recommendations for future activity include the following:

1. No further analysis is recommended for the coal, nuclear, and terrestrial solar thermal systems, because their payback periods are so similar; little can be gained by further comparisons of SPS with these systems.

2. More detailed assessment of energy requirements for production of silicon cells is needed, because the results for SPS/Si and terrestrial photovoltaic systems depend so heavily on this energy input. A study of the potential for reducing such energy consumption is recommended, and the net energy balance parameters for SPS/Si and terrestrial photovoltaic should be recomputed using the results of that study.

3. The energy inputs required for production of GaAlAs cells need study, and the net energy balance parameters for SPS/GaAlAs should be recomputed with the resulting new information. The information available at present is extremely limited, and although it suggests a very short payback period the level of uncertainty dictates that it should be examined more carefully.

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APPENDIX A
DETAILS OF THE METHODOLOGY

A.1 BASIC STRUCTURE

The energy technology system to be analyzed is first described as a series of elements that fall into the following categories:

> Resource Extraction
> Processing
> Transportation
> Conversion
> Environmental Control

In the present analysis, the system boundary extends from the basic resource (e.g., coal in the ground or incident solar radiation) to the generation of electricity at the power plant. Specifically excluded from the analysis are the energy costs of exploration for resources and of research and development; these are beyond the scope of this preliminary evaluation.

Figure A.1 gives the basic structure of the net energy balance applied to each element of the system. The principal flows are the primary resource input; the ancillary operating inputs; the capital inputs; and the gross, net, and internal use outputs. The net output of one system element becomes the primary resource input to the next element in sequence.

The primary resource input is measured by a physical quantity and an energy content. In the case of coal, for example, the physical quantity is the tonnage of coal moved through the system; the energy content is the heating value of the coal. In the case of heat flow from a solar collector, the physical quantity is the volume of air or heat-exchange fluid, and the energy content is the heat content.

Ancillary operating inputs (A) are divided into three categories: electricity, fuels, and materials. These inputs represent the requirements for operating the system element on a daily basis. The ancillary electricity energy content (AEE) is the electricity that must be purchased from outside the element to run machinery, operate instruments, or provide energy for the process. In keeping with standard practice on net energy analysis, the energy content of the ancillary electricity must have associated with it an ancillary energy cost (AEC) that reflects the primary fuel resource required to generate that electricity. Details of this calculation are described in Sec. A.3.

Ancillary Operating Inputs, A

	Electricity	Fuels	Materials
Physical Quantity:	- -	$AFQ_1 \ldots AFQ_n$	$AMQ_1 \ldots AMQ_n$
Energy Content:	AEE	$AFE_1 \ldots AFE_n$	- - - -
Energy Cost:	AEC	$AFC_1 \ldots AFC_n$	$AMC_1 \ldots AMC_n$

Capital Inputs, C

	Electricity	Fuels	Materials
Physical Quantity:	- - -	$CFQ_1 \ldots CFQ_n$	$CMQ_1 \ldots CMQ_n$
Energy Content:	CEE	$CFE_1 \quad CFE_n$	- - - -
Energy Cost:	CEC	$CFC_1 \ldots CFC_n$	$CMC_1 \ldots CMC_n$

Internal Use   I   IE

System Element

	Primary Resource Input		Gross Output	Net Output
Physical Quantity:	PQ		GQ	NQ
Energy Content:	PE		GE	NE

Losses

	Resource Lost	Byproducts	Energy Lost
Physical Quantity:	RQ_o	$BQ_1 \ldots BQ_n$	- - - -
Energy Content:	RE_o	$BE_1 \ldots BE_n$	$LE_1 \ldots LE_n$

Fig. A.1.   Schematic Chart of System Element Energy Balance

Ancillary fuels (AF) input into the system element are measured by three parameters: AFQ, the physical quantity (e.g., m^3 of natural gas or gal of fuel oil); AFE, the energy content (e.g., the heating value of the fuel); and AFC, the energy cost required to produce and deliver the fuel to the system element. The first two items require straightforward calculations; Table A.1 presents the fuel heating values used here. To determine the conversion from physical units to energy costs requires the use of input/output analysis, which is also described in Sec. A.3.

Ancillary materials (AM) input is measured by AMQ, the physical quantity (e.g. tons of steel or tons of concrete). By definition, there is no heating value in the material itself. The energy cost (AMC), is the energy required to produce and deliver the material to the plant site. This is calculated using input/output analysis or the material energy intensities described in Secs. A.2 and A.4, respectively.

Capital inputs (C) represent the energy required to construct the system element. They are entirely analogous to the ancillary operating inputs, except that they are input over the lifetime of the system, in contrast to the annual inputs represented by the primary resource inputs and ancillary operating inputs. To incorporate capital inputs into the analysis, they are

Table A.1. Fuel Heating Values

Fuel	Heating Value	
	10^9 J/m^3	Btu/gal
Heavy Diesel Fuel	41.7	149,690
Diesel and Light Fuel	38.7	138,690
Gasoline	34.8	124,952
Other Petroleum Products	40.3	144,405
Oil	36.5	131,000
	10^7 J/kg	Btu/lb
Coal	2.32	10,000
Uranium	64,520	277.6 x 10^6
	10^7 J/m^3	Btu/ft^3
Natural Gas	3.92	1,051

either annualized by dividing by the system lifetime, or the other inputs are multiplied by system lifetime to obtain total energy flows. The simplifying assumption is used that level of operation is constant over the system lifetime. This is not an accurate reflection of actual conditions, but will suffice for this preliminary analysis.

Gross output (G) is the form of energy that results from operation of the system element. (Output may be in the same form as the primary resource input or it may be in a different form if the system element is a conversion process.) The internal use (IQ) is that quantity of the output product that is consumed internally (e.g., electricity from a power plant used to run equipment). The net output (NQ) becomes the primary resource input to the next system element.

Losses are included in the diagram for the sake of completeness, but they are not used directly in any of the calculations; they are derived quantities computed by balancing inputs and outputs.

The expressions for the energy balance parameters can be presented in terms of these energy flows (meaning of abbreviations is shown in Fig. A.1) as follows:

$$\begin{matrix} \text{System} \\ \text{Primary} \\ \text{Resource} \\ \text{Input} \end{matrix} = PE_0 \text{ (Input to first system element)}$$

$$\begin{matrix} \text{Ancillary} \\ \text{Operating} \\ \text{Inputs} \end{matrix} = A = \sum_{\text{elements}} \left[AEC + \sum_{\text{fuels}} AFC + \sum_{\text{materials}} AMC \right]$$

$$\begin{matrix} \text{Capital} \\ \text{Inputs} \end{matrix} = C = \sum_{\text{elements}} \left[CEC + \sum_{\text{fuels}} CFC + \sum_{\text{materials}} CMC \right]$$

$$\begin{matrix} \text{Internal} \\ \text{Use} \end{matrix} = IQ = \sum_{\text{elements}} IE$$

System
  Net   = NE_f (Net output from final system element)
Output

System
Lifetime   = τ

$$\text{Gross Efficiency} = \frac{NE_f}{PE_o}$$

$$\text{Operating Efficiency} = \frac{NE_f}{PE_o + A + IQ}$$

$$\text{Operating Ratio} = \frac{NE_f}{A + IQ}$$

$$\text{Lifetime Efficiency} = \frac{NE_f \times \tau}{(PE_o + A + IQ) \times \tau + C}$$

$$\text{Lifetime Ratio} = \frac{NE_f \times \tau}{(A + IQ) \times \tau + C}$$

$$\text{Payback Period} = \frac{C}{NE_f - A}$$

Note that the numerator in the operating and lifetime efficiency and ratio equations includes net output only and the denominator includes internal use. This is standard net energy analysis formulation and is based on the consideration that if the internal use energy were not supplied by the system, it would have to be supplied by another source. Therefore, it must be treated as an additional operating energy requirement.

A.2   INPUT/OUTPUT ANALYSIS

The details of an input/output analysis applied to net energy evaluation have been described in several studies.[1] The process involves the development of energy intensity values (expressed in Btu/$) that represent the quantity of energy required per unit of output of a given product. Basic data used in many studies comes from work done by Herendeen and Bullard,[5] in which a 357-sector input/output model of the U.S. economy was constructed and used to develop energy intensity values. These values are expressed in terms of the primary energy resources (coal and crude oil) and electricity required to deliver a given dollar value of materials or finished product. The electricity values are in terms of the U.S. national average of primary resources required for electricity generation, given the structure of the U.S. utility system.

Application of the input/output technique followed the procedure outlined by DSI, Inc.[1] In this procedure, several adjustments were made to the basic data from Herendeen and Bullard, which were derived for U.S. conditions in 1967. First, the electricity requirements were modified to account for a change in the structure of the utility system through the introduction of more nuclear and hydroelectric power since 1967. Second, the energy intensity of U.S. industry, which has changed since 1967, was factored in by adjusting the 1967 data by the energy consumption per dollar of GNP. Third, inflation was accounted for by adjusting the 1976 energy intensity values (Btu per 1967 dollar) to 1974 or 1975 dollars, depending on the data used. The inflation rates for various sectors of the economy were used to make the adjustment more accurate for the period 1967-1974. Only one set of factors was available to adjust from 1974 dollars to 1975 dollars; these are summarized in Table A.2.

These revised 1974 and 1975 energy intensity values were used for those system components that were expressed in terms of cost. For material components the energy intensities per physical quantity (i.e., kWht/kg) given in Sec. A.4 were used.

A.3   COMPUTATION OF ENERGY COSTS

In many of the data sources used for the various systems, some of the operating energy and/or capital energy requirements are reported in

Table A.2. Adjustments to Energy Intensity for
Input/Output Analysis

Cause of Adjustment	Cost Adjusted	Factor
Structure of Utility Sector	Electricity	0.61652
Energy Intensity of Industry	Coal	0.8838
	Crude Oil	1.0150
	Electricity	1.7869
Inflation (1967-1974)	Coal	-[a]
	Crude Oil	-[a]
	Electricity	-[a]
Inflation (1974-1975)	Coal	0.9203
	Crude Oil	0.9203
	Electricity	0.9203

[a]Varied with economic sector (see ref. 5).

physical units (e.g., kWh of electricity, bbl of oil, m^3 of gas). It is not
adequate, however, to include only the energy content of the fuels in the
energy balance; an accounting of the energy required to produce and deliver
those fuels is necessary also. The input/output methodology of Refs. 1 and
5 provides coefficients that permit computation of the energy costs of de-
livered fuel. These coefficients, shown in Table A.3, have the units of Btu
of primary energy required per Btu of fuel energy delivered in its final
form. The energy content of the fuel used in the process is multiplied by the
coefficient to account for the energy required to deliver that fuel. For this
analysis, the fuel heating values in Table A.1 were assumed. For electricity,

Table A.3. Energy Costs of Delivered Fuel

Fuel	Energy Cost (Btu required/Btu delivered)
Coal	1.0060
Refined Petroleum Products	1.2082
Gas	1.1005
Electricity	3.7963

Source: Ref. 1.

the quantity of electricity in kWh is first converted to Btu (3413 Btu/kWh) and then multiplied by the coefficient, which includes a factor for the thermal efficiency of electrical generation facilities. This process is applied only to the capital and operating energy requirements, and not to the primary energy input of the system.

A.4 THE ENERGY INTENSITY OF MATERIALS

A.4.1 General Materials

In some of the analyses, the quantities of materials involved in the construction and/or operation of a system are presented in physical units rather than in terms of energy costs. The energy intensities of these materials are shown in Table A.4 with the reported range of values and the value selected for this study.

Use of these intensities along with the intensities expressed in dollar costs in Sec. A.2 is consistent in that both represent total primary energy required at the point of manufacture. In the case of the Herendeen data[3] in Table A.4, an input/output economic analysis was used to develop the total energy requirements. In the case of the JPL data,[2] the direct process energy required in manufacturing is arbitrarily multiplied by a factor of 2.5 to account for total energy requirements.

A.4.2 Silicon Production

Silicon production requires coke and electric power. Coke is used to reduce quartz (SiO_2) to metallurgical grade silicon in an arc furnace that is approximately 50% efficient. The silicon reacts with hydrochloric acid to yield trichlorosilane ($SiHCl_3$), which is admitted to a chamber containing an electrically heated silicon rod. The heat of the rod (1370 K) causes the $SiHCl_3$ to decompose; the released Si deposits on the rod, which grows at about 1.44 cm/day. A suitable silicon ingot is produced in 3 to 4 days, and resistance heating of the rod during this period consumes about 70% of the electricity required by the process.

The electrical power required to produce 0.11×10^5 t of silicon cells annually (i.e., the quantity required for 4500 MWe peak output) is 4574 MWe.[9] This process is assumed to be continuous, so the annual energy requirement is

Table A.4. Material Energy Intensities

Material	Energy Intensity, kWht/kg[a]				
	Ref. 3 Range	Ref. 2 Range	Other References	Value Used	Rationale for Selection
GFRTP[b]	–	–	–	179	Use graphite value
Stainless Steel	–	–	–	26.5	Mean of steel values
Glass	–	49	3.22[c]	49/3.22	Use 49 for SPS, 3.22 for terres. solar-different types of glass
Silicon	1,900-26,000	2,920	1,000-13,900[d]	13,900	Current state-of-the-art
Copper	–	90	–	71	Mean of copper and electronic parts
Aluminum	66-83	154-225	–	145.5	Mean
Silver	–	76	–	76	
Molybdenum	–	76	–	76	
Mercury	–	–	–	50	Use "Other"
Tungsten	–	–	–	50	Use "Other"
Steel	14-19	27.2-39	7.53[c]	7.53	
Concrete	0.31-0.41	2.3	1.00[c]	1.00	
Gallium Arsenide	–	–	5,500[e]	5,500	
Titanium	–	–	–	50	Use "Other"
Ceramics	–	–	–	50	Use "Other"
Misc. Organics	–	–	–	50	Use "Other"
Argon	7-11	3.3	–	7.15	Mean
Hydrogen	1.4-2.3	11.7	–	6.55	Mean
Oxygen	3.3-4.2	0.6	–	2.40	Mean
Methane Fuel	14-15	0.8	–	7.9	Mean
Sapphire	–	–	–	38	Use "Insulation, Mylar, etc."
Teflon	–	–	–	38	Use "Insulation, Mylar, etc."
Kapton	–	–	–	38	Use "Insulation, Mylar, etc."
Graphite	–	179	–	–	Not used directly
Insulation	–	38	–	–	Not used directly
Mylar	–	38	–	–	Not used directly
Glue	–	38	–	–	Not used directly
Gold Kovar	–	38	–	–	Not used directly
Electronic parts-SPS	52-87	87	–	–	Not used directly
Mechanical Systems-SPS	–	50	–	–	Not used directly
Other	66-83	50	–	50	
Limestone	–	–	0.08[c]	0.08	
Dolomite	–	–	–	0.08	Use limestone value
Caloric HT43 oil	–	–	–	13,508[f]	Use refined petroleum prod. Table A.2
Sand and Gravel	–	–	0.036[c]	0.036	

[a]Primary energy requirement - thermal equivalent

[b]Glass fiber reinforced thermo plastic

[c]Ref. 6

[d]Ref. 8, 9 and Sec. A.4.2

[e]Ref. 9 and Sec. A.4.3

[f]kWht/m^3

4.007 x 10^{10} kWhe. This value yields an energy intensity of 3643 kWhe/kg of silicon cell, for a total energy cost (as discussed in Sec. A.3) of 13,800 kWht/kg. In addition, the process requires 21 kg of coke per kg of silicon cell. Assuming a heating value of 10,000 Btu/lb (23.24 x 10^6 J/kg) and using the energy cost of coal from Sec. A.3 yields 140 kWht/kg of silicon cell. Thus the total energy requirement is 13,900 kWht/kg of silicon cells. This is the value used in the present baseline analysis.

Figure A.2 illustrates potential reductions in energy requirements as silicon manufacturing technology advances;[8] the lower limit is about 1000 kWht/kg of cells.

In addition to the advances in silicon manufacturing technology projected in Ref. 8, different technologies are emerging that may significantly reduce the energy consumption in various phases of polycrystalline silicon production. In all cases the Si single cell is produced from polycrystalline Si. Four such processes are the Acheson Process,[13] Westinghouse Arc Heater Process,[14] Battelle Zinc Reduction Process,[15] and the Union Carbide Silane Process.[14]

The Acheson Process produces SiC (rather than metallurgical grade Si) from sand and sawdust using a very efficient resistance heating process with a
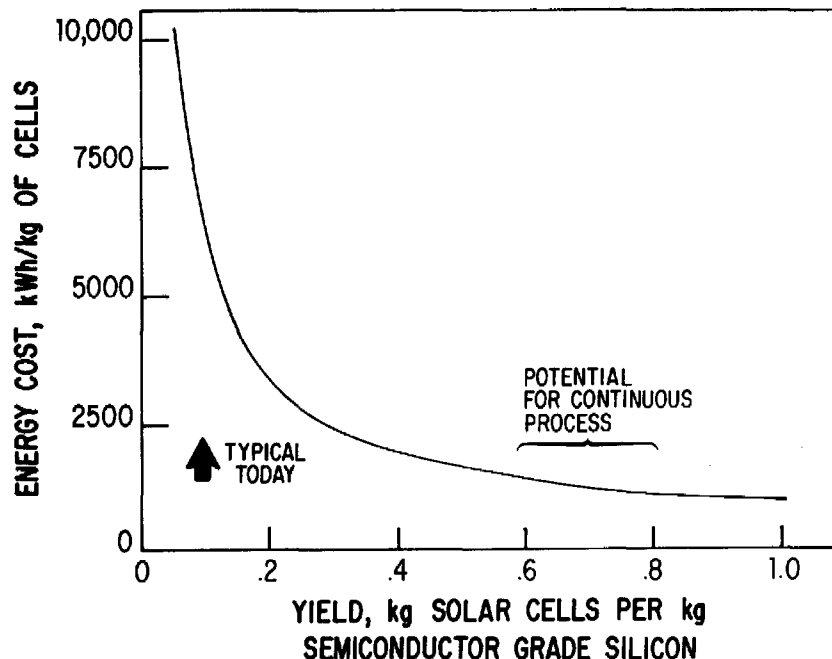
Fig. A.2. Potential for Reduction in Silicon Energy Requirements[8]

carbon rod. The Westinghouse Arc Heater Process starts with the preparation of $SiCl_4$ from SiC and produces polycrystalline silicon. The Battelle Zinc Reduction Process produces polycrystalline silicon starting with the reduction of $SiCl_4$ with zinc. The $SiCl_4$ can either be purchased or produced from metallurgical grade Si or SiC. The Union Carbide Silane process also produces polycrystalline Si, starting with metallurgical grade Si. All of these appear to have the potential for reducing the energy requirements of silicon production significantly below those used in this analysis.

A.4.3 Gallium Aluminum Arsenide Production

Very few data are available on gallium arsenide production requirements. The electrical power required for the annual production of enough GaAlAs to make cells to yield 100 MWe (peak power) of electricity is 57.98 MWe.[9] The process is assumed to be continuous, so the energy requirement is 5.08×10^8 kWhe. Cell requirements are 3.69 t per peak MWe, which yields an energy intensity of 1377 kWhe/kg of cells. Using the energy costs of electricity from Sec. A.3 yields 5500 kWht/kg of cells. This value was used here.

No information was available on potential energy reductions.

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APPENDIX B
COAL FUEL CYCLE SYSTEMS

APPENDIX B
COAL FUEL CYCLE SYSTEMS

This appendix will address two coal-based systems: atmospheric fluidized-bed combustion and gasification/combined-cycle facilities.

B.1 FLUIDIZED-BED COMBUSTION

B.1.1 Description of the Overall System

The system analyzed is a coal-fired steam generation cycle with the atmospheric fluidized-bed combustion (AFBC) furnace, designed by the General Electric Company. The system is designed to deliver electricity to a utility grid and includes a 747-MWe power plant generating $15{,}326 \times 10^{12}$ J/yr (4.25 x 10^9 kWh/yr) with a plant capacity factor of 65%.

Figure B.1 shows a simplified flow diagram of a coal fuel cycle for the AFBC system. In addition to mining, preparation, and transportation of coal, separate unit processes in the AFBC system are merged into two subsystems: the conversion system and the steam cycle system. These subsystems are used to calculate separate energy balances for the overall system performance. Energy balances for each subsystem are calculated on the basis of the electrical output of $15{,}326 \times 10^{12}$ J/yr.[1-3] The lifetime of a power plant is assumed to be 30 yr.

B.1.2 System Elements

The net energy analysis for a coal fuel cycle depends on many complex factors, such as geographic location, mining methods, coal-preparation options, transportation, prices of ancillary energy, capital requirements, manpower and material availabilities, and environmental regulations. In this section, the elements of the AFBC system are discussed briefly.

Resource Extraction. Two types of coal mining procedures are used in the United States: strip mining and underground mining. Some 545×10^6 t* of coal were mined in the U.S. in 1973.[4] This is a 14% increase since 1965;

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*t is the abbreviation for metric ton (1000 kg); the English ton is not abbreviated.
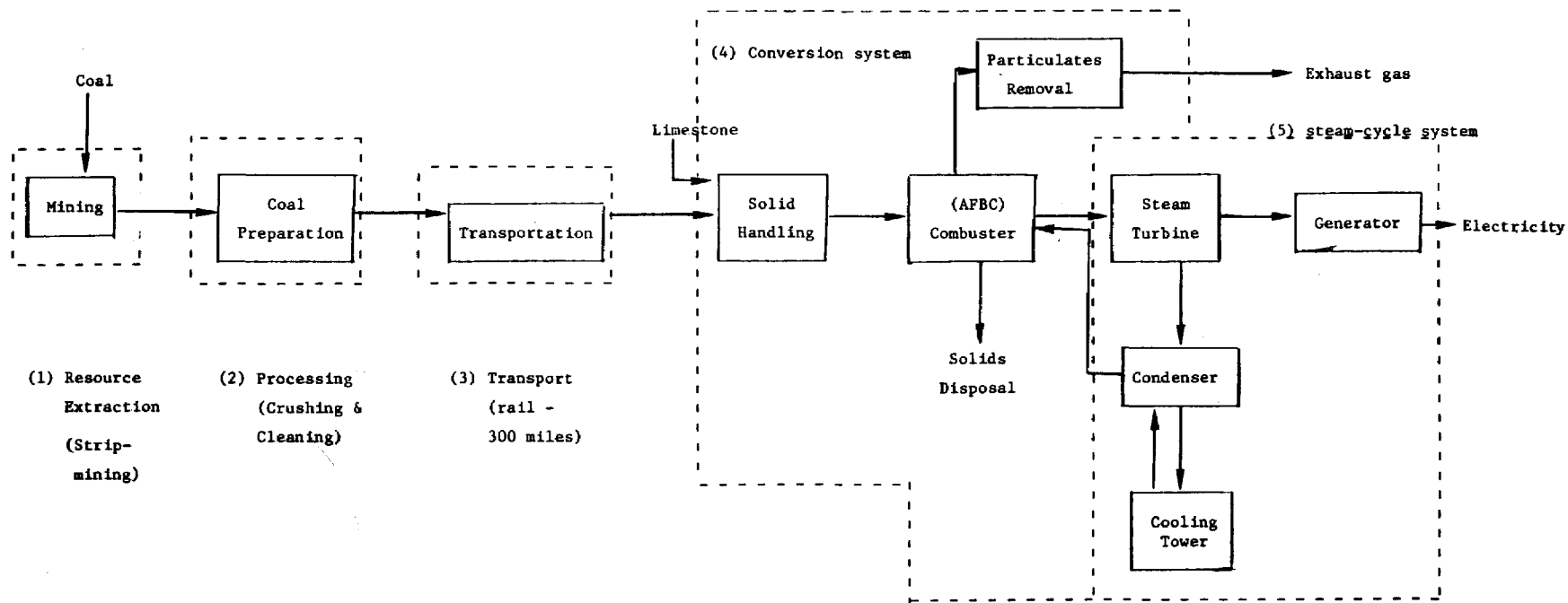
Fig. B.1. Simplified Flow Diagram of an AFBC Cycle

however, most of this increase has occurred in the western coal fields where surface mining methods are used, and total underground mining has decreased.[4] Therefore, only surface mining is considered in this study.

Typical energy contents of coal generally range from about 16.3 x 10^{9} J/t (7,000 Btu/lb) for lignite to over 32.6 x 10^{9} J/t (14,000 Btu/lb) for anthracite. The coal studied here is assumed to be a bituminous coal with a heating value of 23.2 x 10^{9} J/t (10,000 Btu/lb).

A typical strip-mined coal bed is 2 m wide with an overburden averaging 22 m.[1] The overburden is blasted with an ammonium nitrate-fuel oil mixture and removed by electric shovels of 92-m[3] capacity.[1] Overburden drills, stripping equipment, coal loading shovels, pumps, and lighting equipment are operated by electric power. About 90% of the deposited coal is assumed to be recovered in surface mines;[1-4] only 50% to 60% of the coal may be recovered in an underground mine using room-and-pillar methods.

Land reclamation costs, including handling and treatment of the preparation plant refuse, are estimated at $494,000 per km[2] ($2,000 per acre).[1]

Processing. Coal may be prepared (beneficiated) before transportation to upgrade its value and remove potential environmental pollutants. The preparation assumed in this study consists of mechanical cleaning and separation of particles of coal from impurities. (About 60% of total U.S. coal output undergoes some kind of mechanical cleaning and processing.)[5]

Coal preparation generally is accomplished at or near the mine site, and it involves any combination of the following steps:[5]

● Crushing and screening to achieve desired size range and to remove part of the impurities.

● Removal of dust and heavier mineral impurities (including pyritic sulfur) through techniques based on specific gravity, centrifugation, and differences in surface characteristics.

● Thermal drying to prepare the coal for shipping or use.

In this study, the coal preparation plant was assumed to be located at the mine mouth, and a 16 km (10 mi) pipeline to bring water to the plant is required. An allowance for a coal loading facility is included in the plant

costs. Rail tracks for coal transportation away from the plant are assumed to exist already. In the course of crushing and cleaning, 12% of the heating value was assumed to be lost.[1]

Transportation. Transportation options include rail, barge, slurry pipeline, truck, and conveyor. Trucks and conveyors normally are used either in conjunction with another mode of transportation or between mines and nearby conversion facilities; barges, of course, require the proximity of a river or canal. Slurry pipelines represent a reasonably new technology; their main disadvantages are high capital costs, substantial water requirements, and the inflexibility of pick-up and delivery points. Their major advantage is low operating cost for high-volume, long-distance coal transport. In 1974, about 75% of all U.S. coal was moved by rail; in 1972 the average haul distance distance was 453 km (283 mi).[4] In this study, coal was assumed to be transported 480 km (300 mi) by rail to a coal conversion plant. About 1% of coal was estimated to be lost during transportation.

Conversion. Fluidized-bed coal combustion is a technique for burning coal in a bed of granular, noncombustible material such as limestone or dolomite. The bed is supported by a distributor plate, and air is passed up through the distributor plate to suspend or fluidize the bed particles. Heat generated is removed by heat-transfer tubes placed in the bed. There are three types of fluidized-bed combustors: atmospheric fluidized-bed combustors (AFBC), pressurized fluidized-bed combustors (PFBC), and pressurized fluidized-bed adiabatic combustors.[6,7]

The system analyzed in this study is the AFBC process designed by the General Electric Co. for the ERDA-sponsored Energy Conversion Alternatives Study (ECAS) - Phase II studies.[2,3] AFBC was chosen for use here because it is a simpler process and is comparable with the other processes in terms of overall performance.

For the AFBC unit, there is no pressure differential to consider, and a conventional steam turbine can be used. For the pressurized units, a gas turbine is required in addition to the steam turbine to extract all the energy of combustion. This necessitates a high-temperature, high-pressure gas cleanup, which is more difficult than low-temperature, low-pressure gas cleanup.[7]

The AFBC and PFBC systems designed by G.E. have been compared,[2,3] and the results show that the overall efficiency of the AFBC system (35.8%) is about 3.4 percentage points lower than that of the PFBC system (39.2%). The cost of electricity (COE) of the AFBC (31.7 mills/kWh) is about 2.4 mills/kWh less than the PFBC's COE (34.1 mills/kWh).[3] Therefore, the AFBC system requires more ancillary energy but involves a lower cost to produce the same amount of electricity, mainly because of the lack of gas turbines operating in parallel with the steam cycle. According to a net energy analysis[2] for fluidized-bed systems, the rate of delivered energy output to total primary energy input is also favorable to the AFBC system.

Environmental Control. Three major pollutants are emitted by the burning of coal in a power plant: sulfur oxides, nitrogen oxides, and particulates.

For fluidized-bed combustion systems, the use of limestone or dolomite as the bed material provides a means for removing the SO_2 generated during coal combustion. Because the AFBC is operated under oxidizing conditions, complete combustion is possible, and SO_2 is removed as $CaSO_4$. Fluidized-bed systems also offer the potential for inherently low NO_x emissions because of lower combustion temperatures. In most cases SO_2 and NO_x emissions are below the present federal standards.[2-4]

The control of particulates is similar to that in conventional power plants. In general, control is accomplished by mechanical devices such as centrifugal collectors (cyclones), wet collectors, electrostatic precipitators, and baghouses. In this study, conventional cyclones and hot electrostatic precipitators were assumed as the furnace-gas cleanup equipment. Furthermore, for this energy balance study, the performance of the conversion system and environmental control system were merged.

Steam-Cycle System. The energy flow from an atmospheric fluidized-bed combustor has two major outlets: the flue-gas circuit and the water/steam circuit. The water/steam circuit generates the electricity using a steam turbine driving an electrical generator, whereas the flue-gas circuit is funneled through the environmental control equipment.

Water is converted to steam in tubes placed inside the combustor. The thermal energy of superheated steam is converted into mechanical energy by expansion in a steam turbine, and the mechanical energy is changed to electricity by the generator. After leaving the turbine, the low-pressure steam is converted back to water in a condenser. Energy is released during condensation and absorbed by water or air at a cooling tower, and then discharged into the atmosphere. This is the conventional steam-cycle system that is used in modern coal-fired power plants.

B.1.3 Energy Balance Parameters

Two types of energy flow are included in the net energy analysis of a coal fuel cycle: primary energy, and operating and capital energy.

The primary energy flow diagram of a fuel cycle for the AFBC from mining to busbar is shown in Fig. B.2. The nominal size of the unit chosen for study (747 MWe operating at a capacity factor of 65%) requires 2.35×10^6 t of bituminous coal per year with a heating value of 2.32×10^{10} J/t (10,000 Btu/lb); it is assumed to be strip-mined coal. After mining, preparation, and transportation losses are subtracted, the coal thermal input to the conversion system is $42,833 \times 10^{12}$ J (from 1.84×10^6 t of coal). Except for the energy loss in the conversion system, all the heat released in the combustor ($37,639 \times 10^{12}$ J) is transmitted to the steam cycle. The steam turbine generates $15,326 \times 10^{12}$ J of electric power (4.25×10^9 kWh).

Annual operating and capital energy requirements for the AFBC were normalized to the electric output of $15,326 \times 10^{12}$ J; results are summarized in Table B.1. The operating and capital energy consumption for coal extraction, preparation, and transportation, and for plant operation and construction materials has been calculated using the input/output methodology and the cost estimates of appropriate materials for each economic sector.[1,2]

B.1.4 Identification of Sensitive Data

The primary energy efficiencies for the present study were estimated from previous analyses. It is important to review the range for each of these parameters. for the identification of sensitive data. Table B.2 shows the range of available data on the efficiencies of the primary energy flow used for the system studied here. The most significant step for energy utilization

Coal
(2.35 x 10^6 t)

54,629 x 10^{12} joules

Recycled ancillary energy

Limestone
(473 x 10^3 t)

753 x 10^{12}
joules

376 x 10^{12}
joules

Electricity
15,326 x 10^{12}
joules

| Strip Mining | Physical Preparation | Transportation by rail (480 km) | Conversion System (AFBC) | Steam-Cycle System |

49,166 x 10^{12}
joules
(2.11 x 10^6 t)

43,266 x 10^{12}
joules
(1.86 x 10^6 t)

42,833 x 10^{12}
joules
(1.84 x 10^6 t)

(steam)

37,630 x 10^{12}
joules

(electricity)

16,542 x 10^{12}
joules

loss
5,463 x 10^{12}
joules

loss
5,900 x 10^{12}
joules

loss
433 x 10^{12} J

Combustion
loss
1,196 x 10^{12}
joules

Misc. losses
997 x 10^{12}
joules

Heat rejection
at Cooling
Tower
21,473 x 10^{12}
joules

Transformer
loss
87 x 10^{12}
joules

Stack gas
at 121°C
3,764 x 10^{12}
joules

Fig. B.2.   Primary Energy Flow Diagram of an AFBC Cycle

Table B.1. Energy Balance Parameters for AFBC System

Total Capital Input			Annual Operating Input			Annual Output		
Type	Quantity[a]	Energy $(10^{15}$ J$)^b$	Type	Quantity[a]	Energy $(10^{15}$ J$)^b$	Type	Quantity	Energy $(10^{15}$ J$)^c$
STRIPMINING: ANNUAL PRIMARY INPUT 2.35 x 10^6 t COAL, 54.629 x 10^{15} J[c]								
Shovels, Drills, etc.	$18,970,000	1.2030	Electricity	23.32 x 10^6 kWhe	0.3195	Coal	2.11 x 10^6 t	49.166
Industrial Vehicles	$ 6,110,000	0.3420	Oil	9635 bbls	0.0675			
Construction	$ 4,333,000	0.2820						
Total	–	1.8270	Explosives	$536,890	0.0916			
			General Supplies	$735,760	0.0296			
			Maintenance	$259,390	0.0096			
			Reclamation	$532,650	0.0231			
			Total	–	0.5409			
COAL PREPARATION: ANNUAL PRIMARY INPUT 2.11 x 10^6 t COAL, 49.166 x 10^{15} J[c]								
Machinery	$ 1,927,000	0.1260	Electricity	4.78 x 10^6 kWhe	0.0655	Coal	1.86 x 10^6 t	43.266
Construction	$ 1,927,000	0.1260	Supplies	$38,540	0.0014			
Water Lines	NA	0.0180	Maintenance	$19,270	0.0071			
Total	–	0.2700	Water	NA	0.0080			
			Total	–	0.0820			
RAIL TRANSPORT: ANNUAL PRIMARY INPUT 1.86 x 10^6 t COAL, 43.266 x 10^{15} J[c]								
Rolling Stock	NA	0.5310	Diesel Oil	45,923 bbls	0.3417	Coal	1.84 x 10^6 t	42.833
AFBC AND STEAM CYCLE: ANNUAL PRIMARY INPUT 1.84 x 10^6 t COAL, 42.833 x 10^{15} J[c]								
Electricity (material equivalents)			Electricity (from output)[d]	(0.31 x 10^9 kWhe)[d]	(1.129)[d]	Electricity Gross	4.57 x 10^9 kWhe	16.455
Major Components	2.99 x 10^8 kWhe	4.0956	Material equivalents:			Internal[d]	(0.31 x 10^9 kWhe)[d]	(1.129)[d]
Other Components	3.08 x 10^8 kWhe	4.2165	Consumables[e]	1.57 x 10^7 kWhe	0.2147	Net	4.25 x 10^9 kWhe	15.326
Construction	0.09 x 10^8 kWhe	0.1210	Maintenance	1.20 x 10^7 kWhe	0.1646			
Other Materials			Other Materials					
Major Components	NA	2.9118	Consumbables[e]	NA	0.0918			
Other Components	NA	2.9751	Maintenance	NA	0.1699			
Construction	NA	0.6963	Limestone	521,000 t	0.1385			
Total	–	15.0163	Total	–	0.7795			

[a]Dollar amounts in 1974 dollars.

[b]Capital and operating energy computed by I/O analysis as energy cost of fuels, materials, and electricity used.

[c]Energy input and output computed as heat content of fuels or joule equivalent of electricity generated.

[d]Internal use, included in output total only.

[e]Other than limestone.

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Table B.2. Energy Efficiencies for the Primary
Energy Flow in the AFBC System

Subsystem	Assumed Operating Efficiency, %	Range of Variation	References
Stripmining of Coal	90	5-10% loss in extraction	1,4,8
Coal Cleaning	88	10-15% loss of heating value	1,4,5
Coal Transport	99	Rail: 1% loss per 480-km haul	1
		1.6% loss per 800-km haul	8
		0.04% loss per unit train	8
		0.08% loss per conventional train	5
		Barge: 0.04% loss	5
		Pipeline: 2% loss	5
AFBC	36	35.8% (AFBC) to 40.0% (PFBC)	3,10
Conversion	88		
Steam Cycle	44		
Power Conditioning	93		
Overall Efficiency	28		

must be the AFBC system which has a 36% overall efficiency in this study. According to Refs. 3 and 7, however, there is not much room to improve the overall power plant efficiency.

Because of the lack of data, the range of operating and capital energy requirements is not shown.

B.2 COAL GASIFICATION/COMBINED CYCLE (CG/CC)

B.2.1 Description of the Overall System

The system studied is a coal-fired steam cycle using a Westinghouse gas-turbine/steam-turbine, combined-cycle system integrated with a low-Btu fluidized-bed gasifier. The analysis was based on a system required to

deliver electricity to a utility grid at a 741.5-MWe output, generating 15,203 x 10^{12} J/yr (4.222 x 10^9 kWh/yr) of electricity with a plant capacity factor of 65%.

Figure B.3 shows a simplified flow diagram of a coal fuel cycle for the Westinghouse integrated gasifier and combined cycle system (CG/CC). In addition to mining, preparation, and transportation of the coal, separate unit processes in the CG/CC system were grouped into the following subsystems to allow separate energy balances: the gasifier/cleanup system; and the combined cycle, consisting of the gas-turbine system, heat recovery system, and steam-cycle system. Energy balances for each subsystem were calculated on the basis of available references[1,9,3] and normalized to the electrical output of 15,203 x 10^{12} J/yr. The construction period and life of the power plant were assumed to be 5 yr and 30 yr respectively.[9]

B.2.2 System Elements

The mining, preparation, and transport of coal assumed for the CG/CC system are identical to the processes described in Sec. B.1.2. The other system elements, conversion (gasifier/cleanup) and the combined cycle system, are described briefly below.

Gasifier/Cleanup System. The conversion system is itself divided into other subsystems: coal and dolomite handling, gasification, and hot gas cleanup. A pressurized fluidized-bed gasifier with a hot gas cleanup system was analyzed.

The Westinghouse fluidized-bed gasifier is made up of two stages, one a 870°C (1666°F) desulfurizer/devolatizer bed; the other a 1093°C (2000°F) agglomerating gasifier bed.[9] Dry, crushed coal from the coal handling system is injected into the gas stream from the gasifier and devolatilized in the 870°C bed. Desulfurization is accomplished by injecting dolomite into the bed. The char and fines from this bed are gasified in the 1093°C bed in the presence of air and steam; the gas leaving the gasifier is recycled to fluidize the desulfurizer/devolatilizer bed. This gasification process must be able to operate at a temperature high enough to avoid tars in the resultant flue gas, but low enough to avoid volatilizing and carrying over alkali metals. The low-Btu gas leaving the gasifier vessels passes through a three-
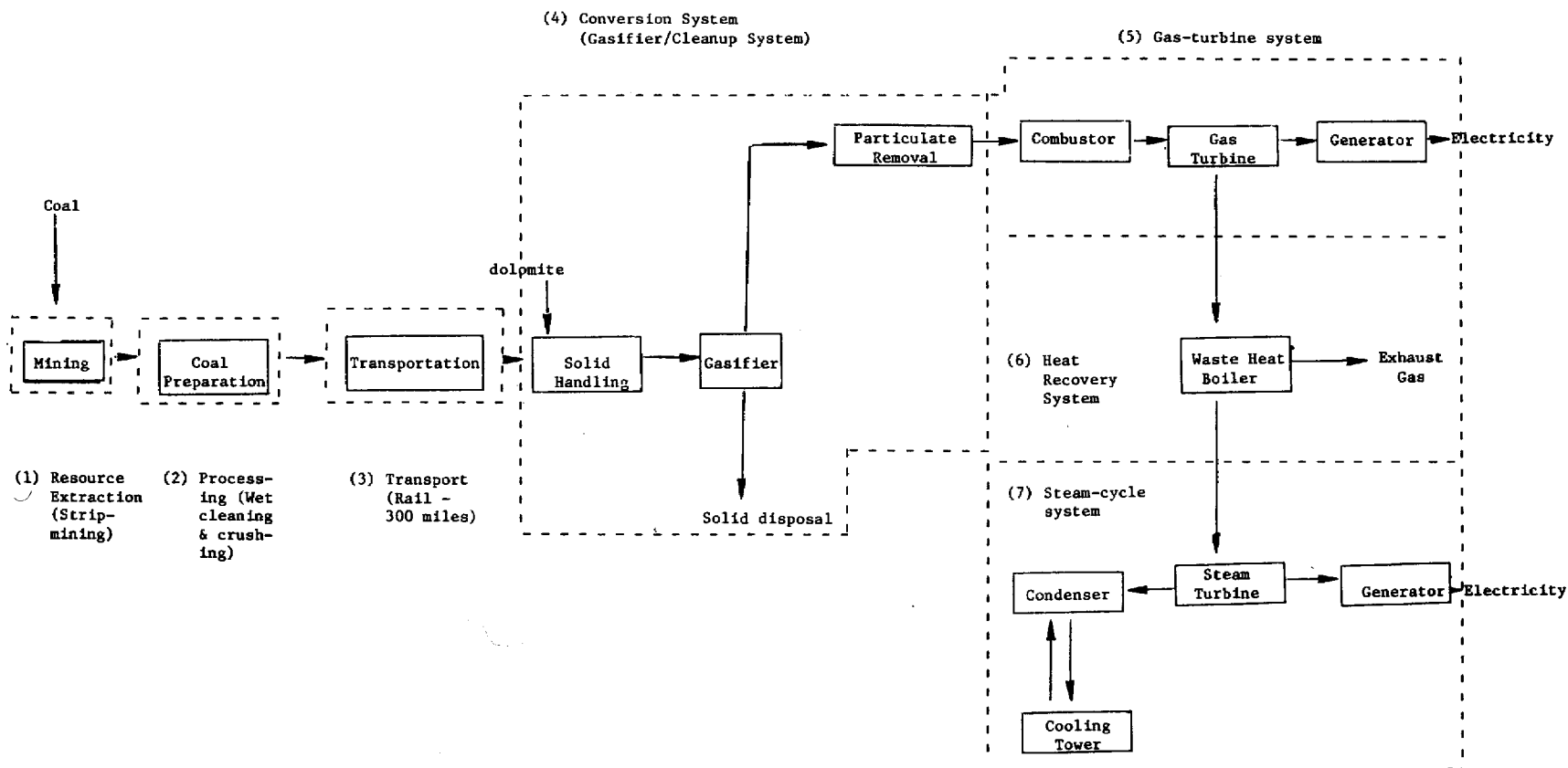
Fig. B.3. Simplified Flow Diagram of Low-Btu CG/CC System

stage particle cleanup system consisting of a cyclone, a multiclone unit, and a granular bed filter.

The plant requires 66.95 kg/s (265.7 tons/hr) of coal and 24.86 kg/s (98.6 tons/hr) of dolomite as inputs.[9] It emits 0.3096 g of SO_2, 0.2795 g of NO_x, and 0.00602 g of particulates per megajoule of input coal energy (respectively 0.91, 0.65, and 0.014 lb/10^6 Btu of input).[9] These emissions are respectively, 76%, 93%, and 14% of the relevant EPA emission limits.[9] The plant also discharges 24.22 kg/s (96.12 tons/hr) of solid wastes (ash and spent sorbent), which are disposed of in an on-site landfill.[9]

Three basic low-Btu gasification processes are available: fixed or moving bed (used by Lurgi, McDowell-Wellman, and G.E.); fluidized bed (used by IGT, Westinghouse, and BCR); and entrained flow (used by Foster Wheeler and Texaco).[7,9,10]

The G.E. fixed-bed process and the Westinghouse fluidized-bed process were chosen for this study because good data were available for both.[3,9] After results for the two systems were compared, the Westinghouse system was finally selected for analysis because it had better overall efficiency: the G.E. design for the integrated gasifier/combined cycle has an overall efficiency of 39.6%, whereas the Westinghouse design has an overall efficiency of 46.8%.[3] The difference in efficiency is attributable to the differing thermodynamic efficiencies of gas and steam turbines and to differences between the two gasifier/cleanup systems: in the G.E. cleanup system, a large portion of the sensible heat is lost when the gas is water-washed to remove tars, oils, and phenols, and is desulfurized, whereas the Westinghouse design uses in-bed desulfurization and hot-gas particulate cleanup, with the result that little of the sensible heat of the gas is lost.[3]

Combined-Cycle System. The combined-cycle system consists of a gas-turbine system, a heat recovery system, and a steam-cycle system. The net plant electrical output in this study is 15,203 x 10^{12} J/yr with a 65% plant capacity. About 66% of the net power is derived from the gas-turbine generators, and the remainder is from the steam-turbine generator.

A part of the gas turbine's compressor air is recycled and passed through a coupled, fluidized-bed gasifier with three stages of hot gas cleanup. The resultant low-Btu fuel gas is burned in the gas-turbine combustor. The products of combustion expand through the gas turbine and flow upward

through a heat-recovery steam generator, and then to the stack. Steam generated in the heat-recovery boiler is expanded through a steam turbine with an abbreviated feedwater heater system. Heat rejected from the steam turbine into the condenser is discharged to the atmosphere by means of mechanical-draft evaporative cooling tower.[9]

B.2.3 Energy Balance Parameters

Figure B.4 shows the primary energy flow diagram of the CG/CC system analyzed. The 741.5-MWe unit, operating at a 65% plant capacity factor, requires 1.78×10^6 t of bituminous coal annually, with a heating value of 2.32×10^{10} J/t (10,000 Btu/lb). Strip-mined coal is assumed; after mining, preparation, and transportation losses are deducted, the coal thermal input to the conversion system is $32,494 \times 10^{12}$ J (from 1.40×10^6 t of coal). Most of the heat released in the combustor is transmitted to the gas turbine, which produces $10,503 \times 10^{12}$ J (2.92×10^9 kWh) of electric power. After leaving the gas-turbine system, the combustion products move to heat-recovery boilers. The heat-recovery system delivers steam to the steam turbine, which generates $5,512 \times 10^{12}$ J (1.53×10^9 kWh) of electricity. After subtraction of recycled ancillary energy and transformer losses, a balance of $15,203 \times 10^{12}$ J (4.22×10^9 kWh) of electric power is produced by this system.

Operating and capital energy requirements for the CG/CC system were normalized to the electric output of $15,203 \times 10^{12}$ J; they are summarized in Table B.3. Annual operating and capital energy consumption for coal extraction, preparation, and transportation were calculated by using an input/output analysis and the cost estimates of appropriate materials for each economic sector.[1]

B.2.4 Identification of Sensitive Data

Because the energy efficiencies for this study were estimated from existing data, it is necessary to review the range of each of those parameters to identify sensitive data. Table B.4 shows all the available efficiency data for the primary energy flow used in the system studied. The most significantly limiting step is the gasifier/combined-cycle system, with 46.8% overall efficiency. According to Refs. 11 and 15, it seems that this efficiency is not likely to improve significantly in the near future.
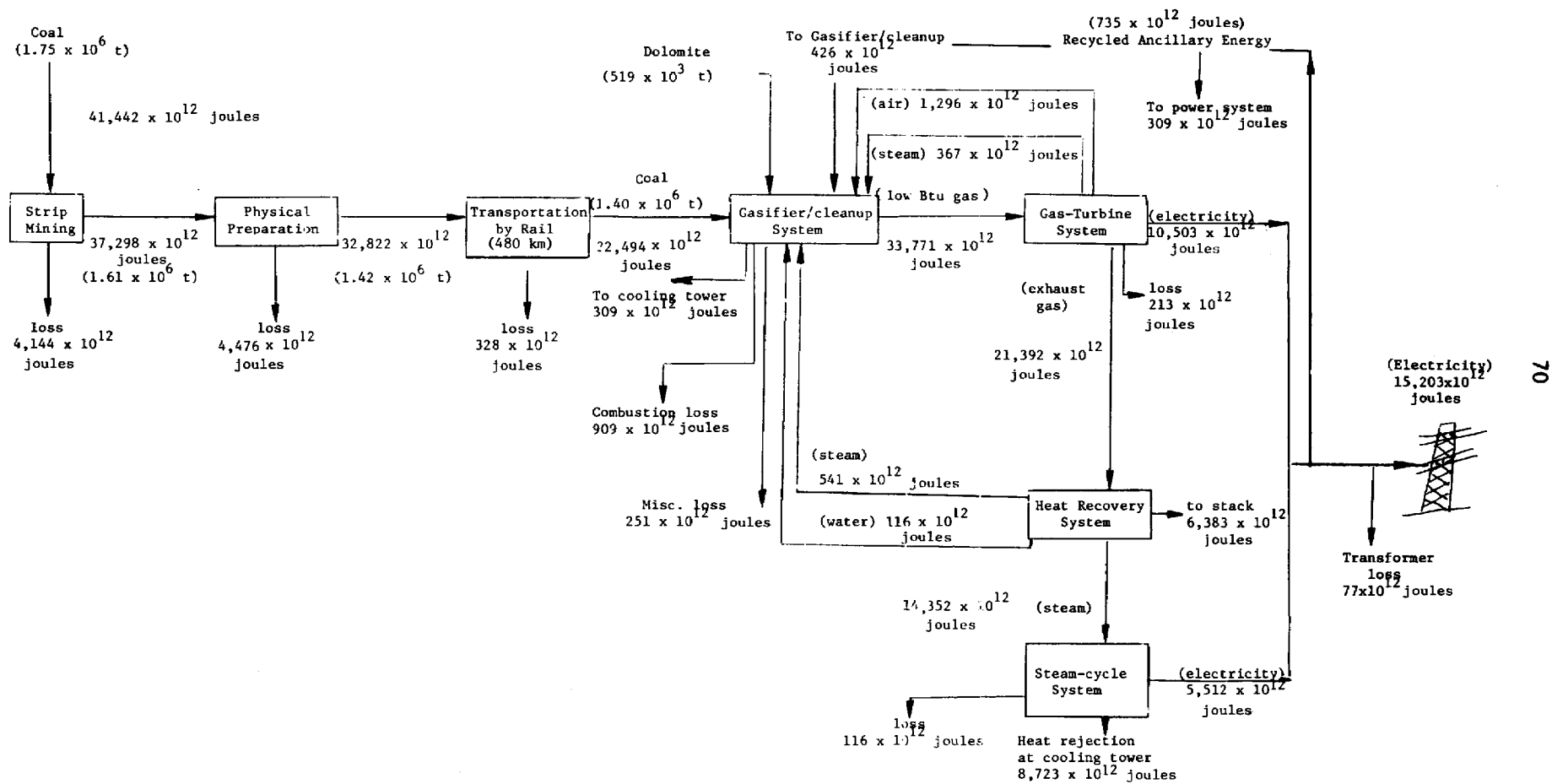
Fig. B.4. Primary Energy Flow in a Low-Btu CG/CC System

Table B.3. Energy Balance for CG/CC System

System Element	Annual Primary Input			Total Capital Inputs			Annual Operating Inputs[b]			Annual Output		
	Type	Quantity	Energy[a] $(10^{15}$ J)	Type	Quantity[b]	Energy[c] $(10^{15}$ J)	Type	Quantity	Energy[c] $(10^{15}$ J)	Type	Quantity	Energy[a] $(10^{15}$ J)
Stripmining	Coal	1.78×10^6 t	41.442	Shovels, drills, etc.	$14,385,000	0.9120	Electricity	17.68×10^6 kWhe	0.2422	Coal	1.61×10^6 t	37.298
				Industrial vehicles	$4,633,000	0.2580	Oil	7307 bbls	0.0512			
				Construction	$3,286,000	0.2130	Explosives	$197,000	0.0694			
				Total	–	1.3830	Gen. Supplies	$558,000	0.0225			
							Maintenance	$407,000	0.0073			
							Reclamation	$404,000	0.0175			
							Total	–	0.4101			
Coal Preparation	Coal	1.61×10^6 t	37.298	Machinery	$1,461,000	0.0960	Electricity	3.62×10^6 kWhe	0.0496	Coal	1.42×10^6 t	32.822
				Construction	$1,461,000	0.0960	Supplies	$29,000	0.0010			
				Water Line	NA	0.0150	Maintenance	$146,000	0.0054			
				Total	–	0.2070	Water	NA	0.0061			
							Total	–	0.0621			
Rail Transport	Coal	1.42×10^6 t	32.822	Rolling Stock	NA	0.4020	Diesel Oil	34,828 bbls	0.2592	Coal	1.40×10^6 t	32.494
Gasifier/Cleanup	Coal	1.40×10^6 t	32.494	---------------(Included below)---------------			Dolomite	518,989 t	0.1519	Low Btu Gas	–	33.771
							Gas Turbine: Air	–	(1.2960)[d]			
							Steam	–	(0.3670)[d]			
							Boiler: Steam	–	(0.5410)[d]			
							Water	–	(0.1160)[d]			
Gas Turbine	Low Btu Gas	–	33.771	---------------(Included below)---------------			Internal Elec.	–	(0.4260)[d]	Internal Use: Air	–	1.296
										Steam	–	0.367
										Exhaust to boiler	–	21.392
										Electricity	2.92×10^9 kWhe	10.503
Heat Recovery	Exhaust Gas	–	21.392	---------------(Included below)---------------			–	–	–	Steam to Gasifier	–	0.541
										To Turbine	–	14.352
										Water to Gasifier	–	0.116
Steam Cycle	Steam	–	14.352	---------------(Included below)---------------			–	–	–	Electricity	1.53×10^9 kWhe	5.512
Power Transformer	Electricity	4.45×10^9 kWhe	16.015	---------------(Included below)---------------			–	–	–	Electricity		
										Gross	4.43×10^9 kWhe	15.938
										To Gasifier	0.12×10^9 kWhe	0.426
										To Generator	0.09×10^9 kWhe	0.309
										Net	4.22×10^9 kWhe	15.203
Total Power Plant	–	–	–	Major Components	$217,100,000	9.1940	Routine O & M	$4,350,000	0.1570			
				Other Components	$105,000,000	4.4470	Special O & M	$1,385,000	0.0490			
				Total	–	13.6410	Total	–	0.3579			

[a] Energy input and output computed as heat content of fuels or joule equivalent of electricity generated.

[b] Dollar amounts in 1974 dollars.

[c] Capital and operating energy computed by I/O analysis as energy cost of fuels, materials, and electricity used.

[d] Internal use, included in output total only.

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Table B.4. Energy Efficiencies for the Primary
Energy Flow in the CG/CC System

Subsystem	Assumed Operating Efficiency, %	Range of Variation	References
Stripmining of Coal	90	5-10% loss in extraction	1,4,8
Coal Cleaning	88	10-15% loss of heating value	1,4,5
Coal Transport	99	Rail: 1% loss per 480-km haul	1
		1.6% loss per 800-km haul	8
		0.04% loss per unit train	8
		0.08% loss per conventional train	5
		Barge: 0.04% loss	5
		Pipeline: 2% loss	5
CG/CC	46.8	39.6% (G.E., fixed-bed) to 42.2% (IGT,fluidized-bed)	3,10
Overall Efficiency	36.7		

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APPENDIX C

NUCLEAR FUEL CYCLE

C.1 DESCRIPTION OF THE OVERALL SYSTEM

This appendix describes the direct energy, process energy, and con-
struction energy inputs required in each stage of the nuclear fuel cycle.
These requirements, which include the energy use associated with mining of the
ore and transport and storage of the wastes, are those necessary to support
the annual operation of a 1000-MWe light water reactor (LWR). Most of the
data were developed by the Institute for Energy Analysis (IEA) of Oak Ridge
Associated Universities[1] and adjusted according to the assumptions used by
the Energy Research and Development Administration.[2]

The use of conventional uranium ores (0.208% U_3O_8, of which 0.71% is
U^{235}) with an enrichment tails assay of 0.2% is assumed. Reprocessing of
wastes for recovery of unused uranium and plutonium is not considered. The
reactor is assumed to have a service life of 30 years, during which it pro-
duces an average of 19,240 x 10^{12} J/yr (5.343 x 10^9 kWh/yr) at a capacity
factor of 61%. Figure C.1 shows a simplified schematic diagram of the nuclear
fuel cycle considered.

C.2 SYSTEM ELEMENTS

C.2.1 Mining

Most of the uranium produced domestically is recovered from high-grade
sandstone deposits in the western United States. The ores found in this
region contain 0.1% to 0.5% uranium. Both open pit and underground mining
methods are utilized; the choice depends on the depth and nature of the rock
strata of the overburden covering the ore.

Current mining practices are mechanized and highly efficient operations
that extract almost all of the uranium. Electric and fuel purchase require-
ments have been determined by the Institute for Energy Analysis (IEA)[1] from
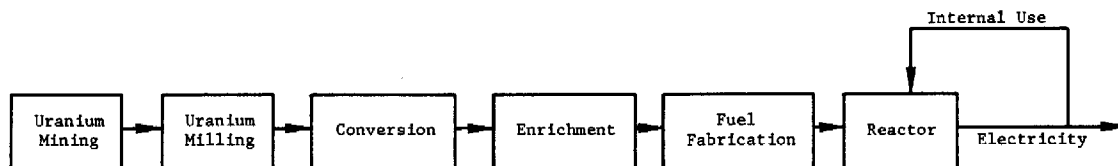
Fig. C.1. Simplified Flow Diagram of Nuclear Fuel Cycle

1973 Bureau of Mines (BOM) survey data. The annual direct electrical purchase that is required to support a 1000-MWe light water reactor is 1,586 MWh. Petroleum products needed for mine operation are divided into categories of heavy fuel oil, diesel and light fuel oil, gasoline, and other petroleum products. These fuel quantities and the energy content required for the mining of 65,950 t of ore (137.16 t uranium) are listed in Table C.1.

One common recovery technique is room and pillar mining, in which material is tunnel-bored and transported to the surface where it is crushed. Equipment used in underground mining usually includes drills, boring machinery, loaders, and explosives. Open-pit mining generally is done by tractors with rippers, scrapers, tractor pushers, drill-powered shovels, and large truck fleets.[3] Beneficiation of the ore before shipment to the mill is relatively uncommon at uranium mines.

The energy content of the process materials was estimated by IEA as 30.6×10^{12} J. Explosives are the largest class in the process materials requirement; their value was adjusted to reflect the 1974 ratio of surface to underground mining (59% of uranium surface-mined and 41% deep-mined); however, these percentages vary annually.

The construction energy requirements for the mining operation were developed by amortizing the costs over an expected 10-yr mine lifetime.

Table C.1. Uranium Mining - Direct Energy Requirements[a]

Energy	Quantity (per yr)	Energy (10^9 J/m^3)	Electricity (MWh/yr)	Energy (10^{12} J/yr)
Electricity	1,586 MWh	–	1,586	–
Heavy Diesel Fuel	25.1 m^3	41.7	–	1.0
Diesel & Light Fuel	789.9 m^3	38.7	–	30.6
Gasoline	46.7 m^3	34.8	–	1.6
Other Petroleum	38.2 m^3	40.3	–	1.5
Natural Gas	20,051 m^3	0.0392	–	0.8
Other Energy	1 MWh	–	1	–
Total	–	–	1,587	35.5
Per Metric Ton of Uranium	–	–	11.62	0.26

[a]Quantity adjusted to show the amount needed to support a 1000-MWe LWR for each year of service using conventional ore containing 0.208% U_3O_8, of which 0.71% is U^{235}.

These requirements, adjusted to reflect the amount needed annually for an 1000-MWe LWR, were 207 MWh of electricity and 15.5×10^{12} J of other fuels.

The total energy requirements for mining are listed in Table C.2; they represent about 2% of the entire nuclear fuel cycle energy requirements.

IEA did not indicate whether land reclamation costs were included in the energy values presented above. However, because they derived much of the information from 1973 mining industry surveys, these values are likely to have included direct and operating energy requirements for reclamation that were in effect during that year.

This analysis did not consider any resource loss to occur during the mining operation, because strip-mining is very efficient in extracting the ore, and uranium ores left behind in deep mines are not, strictly speaking, lost. The energy content of the 137.16 t uranium delivered to the mill site is $88,515 \times 10^{12}$ J.

C.2.2 Milling

Extraction of the uranium from its ore (which contains, on the average, 5 lbs U_3O_8 per ton of ore) is performed at the mill site. The milling operation comprises mechanical and chemical processing, from crushing and grinding the ore to the precipitation of yellowcake.

Ores are crushed and ground in ball-and-rod mills. The uranium is extracted from the ore by chemical leaching, using either sulfuric acid or an alkaline solution (usually sodium carbonate/sodium bicarbonate). The acid treatment is more common because most ores are low-lime types amenable to acid leach.[3] Uranium in the leach solution is purified by either solvent extrac-

Table C.2. Uranium Mining - Total Energy Requirements

Energy Requirement	Electricity (MWh/yr)	Other Energy (10^{12} J/yr)
Direct	1,587	35.5
Process Materials	–	30.6
Mine Construction	207	15.5
Total	1,794	81.6

tion or ion exchange; solvent extraction is the more common process. Yellow-cake, the final product, contains from 70% to 90% U_3O_8 after it is calcined to remove the excess water.

Direct energy requirements were calculated by IEA[1] on the basis of Bureau of Mines data, which accounted for fuels and electricity purchased in 1973 for the milling of 91% of the yellowcake produced domestically. Annual electricity, fuel oil, and natural gas requirements for supporting a 1000-MWe LWR amount to 2,248 MWh/yr of electricity, 11.8 x 10^{12} J/yr of petroleum products, and 34.4 x 10^{12} J/yr of natural gas, as indicated in Table C.3. The milling operation considered in this analysis is projected to process 137.16 t of uranium annually in support of the LWR. The process is assumed to be 95% efficient in its extraction.

The energy content of the process materials was determined on the assumption of a 330,000-t/yr mill with a service life of ten years. Large quantities of sulfuric acid are required for the acid leach treatment: 34 kg (75 lb) of acid per ton of ore processed, which results in an annual require-ment of 2,482 t H_2SO_4 per 1000-MWe LWR. This amount of acid has an energy value of 7.4 x 10^{12} J/yr. Other materials and supplies are estimated to have an energy value of 27.2 x 10^{12} J/yr. These other supplies include the sodium chlorate and manganese dioxide oxidants required for acid leaching.[3]

Amortized over the life of the plant, the capital energy needed for the mill was divided into two categories: the energy in construction materials

Table C.3. Uranium Milling – Direct Energy Requirements

Energy	Quantity (per yr)	Energy (10^9 J/m^3)	Electricity (MWh/yr)	Energy (10^{12} J/yr)
Electricity	2,248 MWh	–	2,248	–
Heavy Fuel Oil	68.3 m^3	41.7	–	2.8
Diesel & Light Fuel	200.5 m^3	38.7	–	7.8
Gasoline	6.3 m^3	34.8	–	0.2
Other Petroleum	25.6 m^3	40.3	–	1.0
Natural Gas	877,920 m^3	0.0392	–	34.4
Total	–	–	2,248	46.2
Per Metric Ton of Uranium	–	–	16.39	0.34

and the direct energy used in construction. These amounted to 3.65 MWh of electricity, 0.9×10^{12} J/yr in fuels, and 4.5×10^{12} J/yr in material energy requirements.

Table C.4 summarizes the energy requirements of the milling operation; the total represents 2.2% of the entire energy requirement of the nuclear fuel cycle.

As indicated earlier, the milling operation was assumed 95% efficient in extracting the uranium from its ore. This 5% loss represents about 6.9 t of uranium and has an energy content of $4,431 \times 10^{12}$ J. The remaining material represents 130.3 t of uranium with an energy content of $84,084 \times 10^{12}$ J. This reported efficiency is close to the milling industry average of 93.2% U_3O_8 recovery in the 16 producing mills operating in 1974.[3]

C.2.3 Purification

Uranium used in reactor fuel must be free of impurities capable of capturing neutrons. Thus further purification beyond the production of yellowcake is required. The process involves conversion of yellowcake to uranium hexafluoride (UF_6), which can be purified and enriched in the gaseous state.

Conversion of U_3O_8 to UF_6 is usually a three-stage operation. In the first stage, the yellowcake feed is dissolved in nitric acid; the resulting uranium nitrate solution is heated to 550-600°C and decomposed to UO_3, which is then reduced with hydrogen or dissociated NH_3 to UO_2. During the second stage, the UO_2 is converted to UF_4 with anhydrous hydrogen fluoride at 450-650°C and then to crude UF_6 with elemental fluorine at 350-500°C. The third step entails the removal of impurities by fractional distillation.

Table C.4. Uranium Milling - Total Energy Requirements

Energy Requirement	Electricity (MWh/yr)	Other Energy (10^{12} J/yr)
Direct	2,248	46.2
Process Materials	–	34.6
Mill Construction	3.65	5.4
Total	2,252	86.2

IEA analyzed the energy requirements for the process, and concluded that the direct energy used, mostly as natural gas, constituted the major part of the total energy required. The energy requirements for direct energy, process material, and plant construction are given in Table C.5 for a plant assumed to produce 9,090 t/yr of UF_6 (6,180 t/yr of U). These values represent an assumed plant service life of 30 years. Purification of uranium uses approximately 4% of the entire nuclear cycle energy requirements. IEA assumed 100% efficiency in the purification of U_3O_8; thus uranium enters and exits from this operation with a resource energy equivalence of 84,084 x 10^{12} J.

C.2.4 Enrichment

The gaseous diffusion enrichment process concentrates crude UF_6 containing about 0.7% U^{235} to the desired concentration of about 3%. The process makes use of the different rates at which gases of differing molecular weights will diffuse through a porous barrier. The lighter UF_6 molecules containing U^{235} diffuse through the barrier relatively faster than the heavier UF_6 molecules containing U^{238}, thereby separating the UF_6 into two streams, one slightly enriched in the U^{235} isotope and the other slightly depleted. The degree of separation in a single diffusion stage is low, but the effect can be amplified by repeating the process with many stages arranged in cascades.

Table C.5. Energy Requirements of Uranium Purification

Energy Requirement	Electricity (MWh/yr)	Other Energy (10^{12} J/yr)
Direct		
Electricity	1,327.76	–
Natural Gas	–	169.7
Process Materials	553.78	15.0
Plant Construction		
Construction Material	19.55	0.8
Direct Construction		
Energy	0.78	0.2
Total	1,901.9	185.7

The quantity of feed material and of separative work units (SWU)* needed to produce reactor grade U^{235} depends on the U^{235} concentration in the feed material and in the tails. The optimum tails assay varies from 0.2% to 0.3% U^{235}. A higher tails assay would require a greater quantity of feed material to achieve the desired amount of enriched U^{235}, but would reduce the processing time and energy requirement. It is estimated that increasing the tails assay from 0.2% to 0.3% U^{235} would require about 70 additional tons of uranium to be processed for the first fueling of a 1000-MWe LWR.[3]

Energy requirements developed by IEA for the enrichment process were based on a plant capacity of 8.75×10^6 SWU/yr. A conservative value of 2.81 MWhe/SWU was assumed, although this value represents the high end of the probable range (2.3 to 2.8 MWhe/SWU). Table C.6 summarizes the enrichment energy needed to support a 1000-MWe LWR requiring 104,133.3 SWU/yr.

Table C.6. Enrichment Energy Requirements

| Energy Requirement | Electricity (MWh/yr) | Other Energy | | |
		Material Quantity per year[a]	Energy Content (J/m^3 or J/t)	Input Energy (10^{12} J/yr)
Diffusion Process:				
Direct	292,614.7	–	–	–
Plant Fuels				
Gasoline	–	11.5 m^3	34.8×10^9	0.4
Diesel Fuel	–	10.1 m^3	38.7×10^9	0.4
Propane	–	1.2 m^3	26.6×10^9	0.03
Coal	–	1289 t	27.9×10^9	36.0
Process Materials	603.97	–	–	15.1
Construction:				
Direct	31.24	–	–	7.7
Materials	770.6	–	–	28.0
Total	294,020.51	–	–	87.6
Energy/SWU	2.82	–	–	0.84×10^{-3}

[a]A 30-yr plant life is assumed.

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*SWU, separative work unit, is a measure of the energy required to perform the separation of uranium isotopes into two streams.

The enrichment process involves large capital expenditures and consumes enormous amounts of electric power, with much of the power being used for recompression of the gas before each diffusion stage. Enrichment accounts for about 71% of the total energy input required for the nuclear fuel cycle, and more than 97% of the total electrical input required. Energy requirements for operation and construction are small compared with the direct energy inputs.

An enrichment operation converting 0.71% U^{235} to 3.0% U^{235} will lose 28.17% of the U^{235} input. This amounts to 36.71 t of U with an energy equivalence of 23,685 x 10^{12} J/yr. The output from this operation is 22.77 t of enriched uranium, representing an energy equivalence of 60,515 x 10^{12} J.

C.2.5 Fuel Fabrication

Fuel fabrication consists in converting the enriched UF_6 to a form usable as reactor fuel. Pelletized uranium dioxide (UO_2) is the most common fuel form used in LWR. The enriched UF_6 is hydrolized to UO_2F_2, reacted with NH_3 to form ammonium diuranate, calcined to UO_3, and finally reduced with hydrogen to UO_2 at 800°C.[4]

Fabrication of a fuel assembly involves screening and compacting the raw UO_2, pelletizing it under high pressure, and sintering it at high temperature. After the uranium content is determined, the high-density pellets are inserted into cladding tubes. The preferred cladding materials are aluminum for moderate-temperature reactors and stainless steel or zircalloy for high-temperature reactors.

In 1975, ten fuel fabrication facilities of three types were operating: four plants were equipped to produce UO_2 pellets, three encased the pellets, and three were designed for integrated operations.[2] For the IEA study,[1] an integrated facility was assumed.

The energy requirements were evaluated for a plant producing 600 t/yr of enriched uranium in fuel elements, with a service life of 30 years. The energy requirements shown in Table C.7 are scaled to the needs of a 1000-MWe LWR, and represent the annual fabrication of 22.77 t of enriched uranium into fuel elments.

Material requirements of the process represent the major energy use, attributable to the required cladding materials. The fuel fabrication step

Table C.7. Energy Requirements for LWR Fuel Fabrication

Energy Requirement	Electricity (MWh/yr)	Other Energy (10^{12} J/yr)
Direct		
Electricity	2257.7	-
Natural Gas (135,398 m^3, 38.4 x 10^6 J/m^3)	-	5.2
Process Materials	4572	55.5
Plant Construction		
Construction Material	20.2	0.7
Direct	0.95	0.2
Total	6850.85	61.6
Per Metric Ton of Enriched Uranium	300.9	2.71

represents 2.8% of the fuel cycle energy requirements. No loss of enriched uranium is assumed; therefore, the material energy equivalent leaving this step remains at 60,515 x 10^{12} J.

C.2.6 Reactor

The reactor analyzed is assumed to be a 1000-MWe light water reactor (LWR) operating at an average capacity factor of 61% over a service life of 30 years. The lifetime electrical output from such a facility is 160,300,000 MWh (577,085 x 10^{12} J); 3.5% of this power is used in operating the station. The capacity schedule of this projected facility is as follows:

Five-month period before commercial operation: 40%
First two years of commercial operation: 65%
Years 3 through 15: 70%
Last 15 years (2% decrease per year): 68% to 40%

The direct energy requirements and process materials energy were estimated by IEA[1] using data scaled for a 1000-MWe facility. The direct fuel consumption is primarily for operation of the auxiliary equipment, which must remain operational even when the reactor is not functioning. Fuel consumption amounts to 344 m^3/yr (90,900 gal/yr) of diesel fuel.

The largest requirements for process materials energy are for fabrication and replacement of metal products such as valves, pipes, and supports, and chemicals required in water treatment in the boiler-turbine cycle. These

annual operating expenses are comparable to the 30-yr amortized values for plant construction energy.

The amounts of energy required for reactor construction that were used in this report were provided by the IEA study,[1] augmented as necessary with data from Bechtel.[5] These two studies differed in that IEA considered a reactor using once-through cooling whereas Bechtel assumed that cooling towers were used. The two studies nevertheless arrived at similar estimates of total energy input.

The IEA study did not specify the precise categories and amounts of materials on which its estimates of construction material energy were based; those unrecorded details were taken from an SRI study that was not readily available. To give some indication of the material requirements for reactor construction, other studies[5,6] were consulted. Table C.8 shows a breakdown, for various functional subsystems, of amounts of construction materials estimated by Noguchi[6] for a 1000-MWe LWR installation; Table C.9 shows the major categories of equipment included in each subsystem. For comparison, Table C.10 shows total construction materials estimated by Bechtel[5] (scaled to a 1000-MWe LWR); these estimates include raw materials for construction and materials contained in finished equipment procured for installation. The two sets of estimates in Tables C.8 and C.10 differ appreciably in their material requirements; however, if these materials were converted to energy value equivalents they would likely bracket the energy values reported by IEA and used in this study.

Table C.8. Major Material Requirements for a 1000-MWe LWR[a]

Materials	Material Requirements, t				
	Reactor	Turbine/Generator	Auxilliary	Shared	Total
Concrete	85,071	26,079	35,515	21,985	168,650
Carbon Steel	11,191	9,215	2,891	2,973	26,270
Stainless Steel	2,207	1,645	712	--	4,564
Copper	18	144	10	39	211
Aluminum	--	--	--	81	81

[a]Source: Ref. 6.

Table C.9. Major Categories for Plant Groupings Shown in Table C.8

Reactor	Turbine/Generator	Auxiliary	Shared

Building
Auxiliary Reactor
  Building
Reactor Equipment
Main Heat Transfer
  System
Instruments and
  Controls
Other Equipment
	Building
	Tur/Gen Equipment
	Feedwater System
	Condensing System
	Instrument and
	  Control
	Other Equipment
		Fuel Storage Bldg.
		Safeguard Cooling
		  System
		Rad. Waste and
		  Disposal
		Fuel Handling and
		  Storage
		Circulating Water
		  System
		Intake and Discharge
		  Structures
			Site Improve-
			  ments and
			  Facilities
			Misc. Buildings
			Electrical
			  Plant Equip-
			  ment

Table C.10. Major Material Requirements (Metric tons) for a 1000-MWe LWR[a]

Carbon Steel	47,800	Steel Castings	315
Low-Alloy Steel	4,860	Aluminum Castings	47
Stainless Steel	2,025	Brass & Bronze Castings	80
Copper	2,305	Iron & Steel Forgings	372
Aluminum	670	Structural Steel Shapes	8,263
Manganese	413	Steel Plate (1.5 in)	5,652
Chromium	477	Steel Plate (1.5 in)	1,796
Nickel	82	Cement	59,575
Cast Iron	900	Concrete	562,815

[a]Source: Ref. 5.

Use of cooling towers instead of once-through cooling systems would increase the energy requirements for the reactor. Although the actual energy increases were not readily available, the differences would be approximately as follows:

● Direct energy requirements for all auxiliaries would increase by about 1% to approximately 4 to 5%.

● Cooling towers would become the most energy-intensive auxiliary in the reactor operation.

● Most of the direct energy would go towards operation of six to eight 3100-HP pumps.

● Process material requirements would increase because the cooling tower would require additional water treatment to inhibit scaling, corrosion, and biofouling.

- Construction energy would increase to include the energy content in the superstructure, pumps, fans, and pipe materials.

Table C.11 provides the annual energy requirements for a 1000-MWe LWR. The reactor portion of the nuclear cycle represents the second largest energy use, amounting to more than 16% of the total energy input.

The reactor was assumed 33% efficient in production of electricity, yielding a gross power output of $19,933 \times 10^{12}$ J/yr. Allowing 3.5% of the power for internal results in a net power output of $19,235 \times 10^{12}$ J/yr.

C.2.7 Spent Fuel Storage

Between one-third and one-quarter of the reactor fuel elements are removed and replaced with new fuel bundles annually. Although only a portion of the fissionable material is depleted in the fuel elements that are removed, the accumulated fission products in them reduce operating efficiency by absorbing neutrons.

The spent fuel rods removed from the reactor are highly radioactive and are therefore submerged in water for cooling and decay of short-lived products. They are generally stored at the reactor site for several months to several years. The bulk of the material resources required for storage facilities is concrete and steel. Most storage systems consist of a pool, fuel storage racks, pool makeup system, pool cooling and filtering system, and a remote-controlled fuel-handling system with jib cranes, grapples, and slings.

Table C.11. Annual Energy Requirements for a 1000-MWe LWR

Energy Requirement	Electricity (MWh/yr)	Other Energy (10^{12} J/yr)
Direct		
Diesel Fuel (344 m^3 at 38.7 $\times 10^9$ J/m^3)	--	13.3
Process Materials	8,551	287.6
Plant Construction		
Materials	6,543	271.6
Direct	288	65.3
Total	15,382	637.8

Fuel storage racks are of stainless steel, aluminum, and neutron-absorbing materials. A stainless steel rack will use from 150 to 250 tons of stainless steel; aluminum racks require about 75 to 150 tons of aluminum.[7]

Many new or expanded storage plants currently are using a neutron-absorbing material as an integral part of rack construction. The commonly used materials are Boral plate (boron carbide dispersed in aluminum) or boron stainless steel.[7]

Direct process and capital energy requirements were developed by ERDA in Appendix B of their National Plan for Energy Research, Development and Demonstration.[2] The basis for their estimates for the storage of 22.77 t of depleted uranium (containing about 0.8% U^{235}) each year was not reported in that document.

It is assumed that the estimates represent interim waste fuel storage at the reactor facility and longer-term storage either at another plant in the utility system or at a commercial storage facility.

A summary of the energy requirements for spent fuel storage, as developed by ERDA,[2] appears in Table C.12. This portion of the nuclear cycle represents less than 0.3% of the cycle's total energy requirements.

The IEA values for this portion of the nuclear pathway are summarized in Table C.13. The values represent the energy requirements for the handling, packaging, and storing of the estimated ten canisters of waste accumulated each year. The dominant energy requirement is for the process materials:

Table C.12. Annual Fuel Storage Requirements

Energy Requirement	Electricity (MWh/yr)	Other Energy (10^{12} J/yr)
Direct		
Electricity	242.7	–
Other Fuels	–	0.16
Process Materials	81	2.26
Facility Construction		
Materials	–	6.13
Direct Construction	129.3	–
Total	453.0	8.55

Table C.13. Waste Storage Annual Requirements

Energy Requirement	Electricity (MWh/yr)	Other Energy (10^{12} J/yr)
Direct		
Electricity	4.35	--
Liquid Fuel (Diesel: $2m^3$ at 38.7 x 10^9 J/m^3)	--	0.07
Process Materials	151.9	5.56
Plant Construction		
Materials	9.8	0.43
Direct Construction	0.8	0.37
Total	166.85	6.43

hydraulic cement and steel. These requirements amount to 6.43 x 10^{12} J/yr and represent about 0.2% of the full nuclear cycle energy requirements.

Terminal decommissioning of the reactor was not included in the analysis because no data are available.

C.2.8 Waste Storage

Low-level and intermediate-level radioactive wastes are generated during routine plant operation. These wastes include contaminated filter and adsorption materials, ion exchange resins contaminated during purification of the primary water system, and other radioactive materials, e.g., spent reactor parts. Liquid wastes are generally treated to reduce their volume before storage; solid wastes are packaged and shipped to burial sites.

High-level radioactive wastes are principally those accumulated during the purification stage of fuel reprocessing. Because this operation is not required in the state-of-the-art nuclear cycle (no reprocessing is currently taking place), energy values for reprocessing are used in lieu of storage and disposal of the low and intermediate level wastes that are evaluated.

C.2.9 Transportation of Nuclear Materials

The transportation of nuclear material occurs throughout all stages of the fuel cycle. Regulations adopted by the Department of Transportation and NRC emphasize the design of packaging and shipping containers, to protect the public and the workers. Radioactive waste is shipped by truck or rail

over public transportation routes, and the regulations result in extra energy costs for the transport of fuel material and containers.

The transportation energy requirements reported by ERDA categorize transportation in two cycles, the first being the pre-enrichment transport of natural uranium and the second being the transport of enriched fuel or enriched uranium.

The transportation distances between the mine and the mill site are considered small since the mill is usually located near the mine site. The energy requirements for the trucks and fuels were slight and were included as part of the energy requirements of the milling operation.

The energy requirement for the transport of U_3O_8 from the mill to the purification plant was computed by assuming a typical travel distance, which was multiplied by a transportation intensity value (J/t-km) and a "shipment factor." This shipment factor is the ratio of total cargo to total uranium. A distance of 1290 km (800 miles) was assumed, with an intensity factor of 1.96 x 10^6 J/t-km (2720 Btu/ton-mi) for truck haulage and a shipment factor of 1.5 to account for the containers, equipment, and oxygen content of the U_3O_8. This results in an estimate of 3.44 x 10^9 J/t of uranium for transportation from the mill to the purification plant.

The energy requirement for material transport from the purification plant to the enrichment plant was calculated similarly. A shipment factor of 2.24 was used to account for the containers required in the shipment of UF_6 gas. The mileage between processing plants was assumed to be 1290 km (800 miles) and the transport performed by truck; the direct energy required amounts to 5.2 x 10^9 J. This information, scaled from the IEA report, is presented in Table C.14.

The direct transportation energy requirement includes the necessary shipping containers and other protective equipment. The indirect energy includes the energy content of the trucks and all loading, unloading, and docking facilities.

Post-enrichment transportation energy was similarly developed, but now represents enriched fuel rather than natural uranium. Also, transport by rail is included, with an energy intensity factor of 0.40 x 10^6 J/t-km (550 Btu/ton-mile). The data are shown in Table C.15.

Table C.14. Transportation Energy Requirements: Ore
Mill to Enrichment Plant

Transport Energy	Shipment Factor	Distance (km)	Energy Intensity (10^6J/t-km)	Electricity (MWh/yr)	Other Energy (10^{12} J/yr)
Indirect	-	-	-	13.7	0.86
Direct (Total)	-	-	-	-	1.12
Mill to Purification	1.5	1,290	1.96	-	0.45
Purification to Enrichment	2.24	1,290	1.96	-	0.67
Total Energy	-	-	-	13.7	1.98

Table C.15. Transportation Energy Requirements: Enrichment to
Storage or Reprocessing of Waste

Transport Energy	Shipment Factor	Distance (km)	Energy Intensity (10^6 J/t-km)	Electricity (MWh/yr)	Other Energy (10^{12} J/yr)
Indirect	-	-	-	51.5	3.24
Direct (Total)	-	-	-	-	4.24
Enrichment to Fabrication	4.0	1,290	1.96	-	0.84
Fabrication to Reactor	7.0	805	1.96	-	0.23
Reactor to Reprocessing:				-	
Truck	100	480	1.96	-	1.96
Rail	30	1,770	0.4	-	0.44
Waste Shipment	10	1,610	1.96	-	0.65
Recycle of U + Pu	2.25	1,290	1.96	-	0.12
Total Energy	-	-	-	51.5	7.48

The transport of fuel does not have a sizeable impact upon the nuclear cycle's energy requirements; it amounts to about 0.2% of the total. Therefore, the above values would not change appreciably if reprocessing energies were not substituted for low-level waste storage.

C.3 ENERGY BALANCE PARAMETERS

This analysis has discussed the energy requirements for each stage of the nuclear fuel cycle as it exists today, including all fuel processing, transportation, and waste storage needed for supplying a 1000-MWe light water reactor with a 30-yr service life and an enrichment tails assay of 0.2%, and excluding reprocessing of the residual uranium and plutonium in the spent fuel.

Figure C.2 shows an energy flow diagram for the nuclear cycle with resources, energy equivalence values, and losses. The energy flow values were based on the total power output of the plant operating according to the efficiencies described previously, i.e., a one-year annualized output of 1.92 x 10^{16} J. The residual energy remaining in the depleted fuel rods was considered as lost energy for purposes of this analysis.

Table C.16 summarizes the energy requirements for the entire fuel cycle, with electricity and fuel use converted to energy equivalents using the methodology of Appendix A.

C.4 IDENTIFICATION OF SENSITIVE DATA

Some possibilities exist for decreasing the overall energy requirements of the fuel cycle. Increasing the plant capacity from 61% to 75% would reduce the energy input requirements by about 5%. Increasing the enrichment tails assay from 0.2% to 0.3% would reduce the energy input by approximately 15%. Addition of fuel reprocessing would lower the energy input requirements by more than 20% (assuming no major changes in the system components), with the bulk of the energy reduction occurring from a decrease in the quantity of fuel requiring enrichment.

Reactor decommissioning and ultimate disposal of high-level wastes and spent fuel would add another step in the fuel cycle and slightly increase the energy input requirements reported here.

The greatest potential for increasing the net efficiency of the LWR fuel cycle is likely to occur in the enrichment operation. This report considers the enrichment operation by the gaseous diffusion process. However, gas centrifugation processes hold promise for drastically reducing direct-energy requirements. The electrical input for centrifugation has been esti-

65.942 t ore

137.16 t U   137.16 t U   130.3 t U   191.7 tUF_6

| MINING | | MILLING | | CONVERSION | | ENRICHMENT |

88.515×10^{15} J 88.515×10^{15} 84.084×10^{15} J 84.084×10^{15} J

4.431×10^{15} J

23.569×10^{15} J

(3.5%)
0.700×10^{15} J

22.77 t U*   22.77 t U*

| FUEL FAB. | | REACTOR |

60.515×10^{15} J 60.515×10^{15} J $19.93^{3} \times 10^{15}$ J 19.233×10^{15} J

40.582×10^{15} J
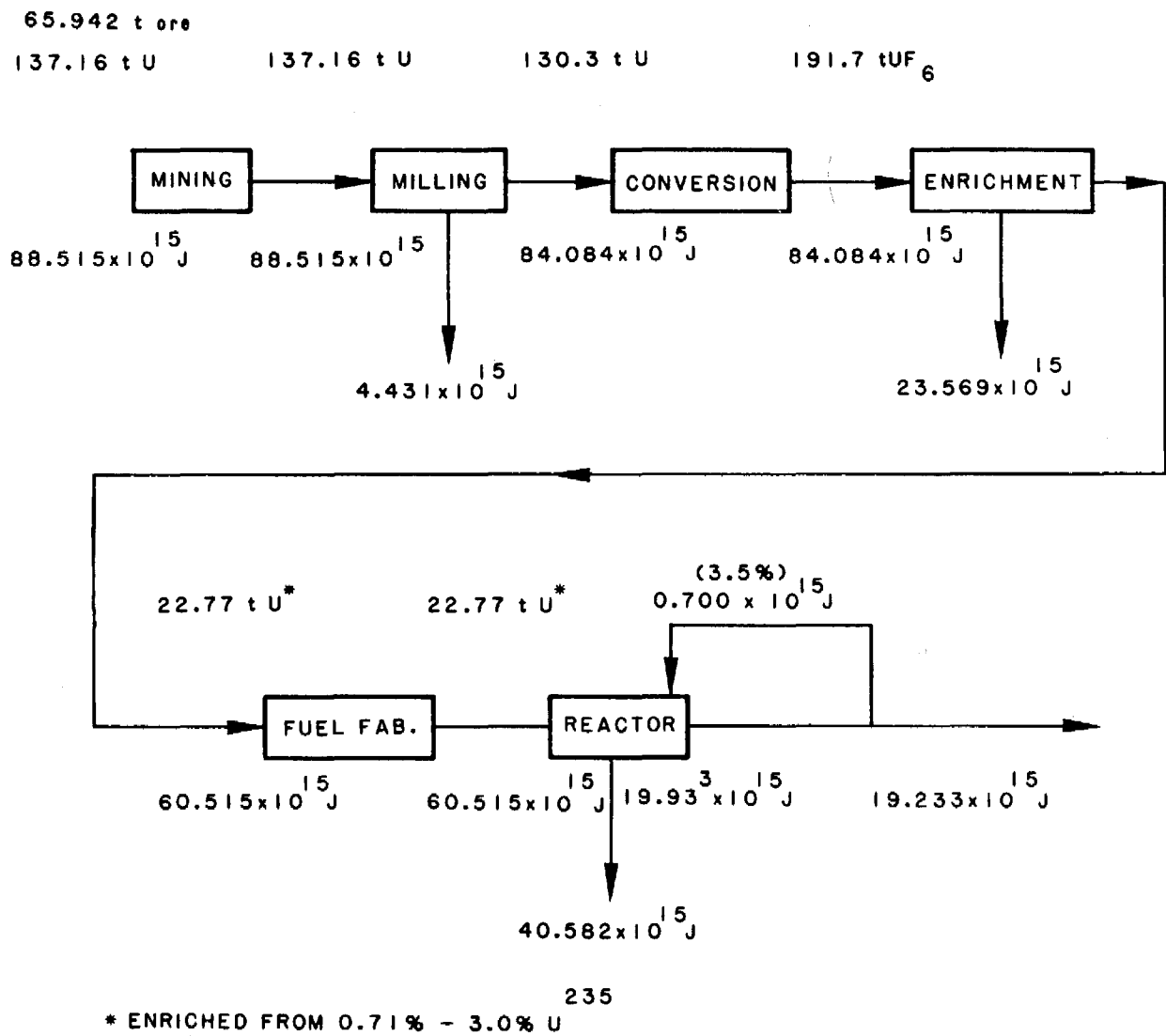
* ENRICHED FROM 0.71% − 3.0% U^{235}

Fig. C.2.   Energy Flow Pathway − Nuclear Fuel Cycle

Table C.16. Energy Balance Parameters for Nuclear LWR System

System Element	Annual Primary Input Type	Quantity (t)	Energy[a] (10^15 J)	Total Capital Inputs Type	Quantity	Energy[b] (10^15 J)	Annual Operating Inputs Type	Quantity	Energy[b] (10^15 J)	Annual Primary Output Type	Quantity	Energy[a] (10^15 J)
Uranium Mining	Uranium	137.2	88.515	Electricity	6.21×10^6 kWhe	0.0852	Electricity	1.59×10^6 kWhe	0.0217	Uranium	137.2t	88.515
				Fuels	465.0×10^{12} J	0.5618	Heavy fuel oil	25.1 m^3/yr	0.0012			
				Total	–	0.6470	Diesel fuel	789.9 m^3/yr	0.0370			
							Gasoline	46.7 m^3/yr	0.0019			
							Other petroleum	38.20 m^3/yr	0.0018			
							Natural gas	20,051 m^3/yr	0.0009			
							Process materials	NA	0.0306			
							Total	–	0.0951			
Uranium Milling	Uranium	137.2	88.515	Electricity	0.11×10^6 kWhe	0.0015	Electricity	2.25×10^6 kWhe	0.0308	Uranium	130.3t	84.084
				Fuels	27.0×10^{12} J	0.0326	Heavy fuel oil	68.3 m^3/yr	0.0034			
				Materials	NA	0.1350	Diesel fuel	200.5 m^3/yr	0.0094			
				Total	–	0.1691	Gasoline	6.3 m^3/yr	0.0002			
							Other petroleum	25.6 m^3/yr	0.0012			
							Natural gas	877,920 m^3/yr	0.0379			
							Sulfuric acid	NA	0.0074			
							Other materials	NA	0.0272			
							Total	–	0.1175			
Conversion	Uranium	130.3	84.084	Electricity	0.023×10^6 kWhe	0.0003	Electricity	1.33×10^6 kWhe	0.0182	UF$_6$	191.7t	84.084
				In materials	0.587×10^6 kWhe	0.0081	Natural gas	4.33×10^6 m^3/yr	0.1868			
				Fuels	0.2×10^{12} J	0.0073	Process materials	NA	0.0150			
				Materials	NA	0.0240	Total	–	0.2200			
				Total	–	0.0397						
Enrichment	UF$_6$	191.7	84.084	Electricity	0.94×10^6 kWhe	0.0129	Electricity	292.6×10^6 kWhe	4.0088	Enriched Uranium	22.8t	60.515
				In materials	23.12×10^6 kWhe	0.3168	In materials	0.6×10^6 kWhe	0.0083			
				Fuels	231.0×10^{12} J	0.2790	Gasoline	11.5 m^3/yr	0.0005			
				Materials	NA	0.8400	Diesel Fuel	10.1 m^3/yr	0.0005			
				Total	–	1.4487	Propane	1.2 m^3/yr	0.00004			
							Coal	1289 t/yr	0.0362			
							Process materials	NA	0.0151			
							Total	–	4.0694			
Fuel Fabrication	Enriched Uranium	22.8	60.515	Electricity	0.03×10^6 kWhe	0.0003	Electricity	2.26×10^6 kWhe	0.0309	Enriched Uranium	22.8t	60.515
				In Materials	0.61×10^6 kWhe	0.0084	In materials	4.57×10^6 kWhe	0.0626			
				Fuels	6.0×10^{12} J	0.0073	Natural gas	0.14×10^6 m^3	0.0057			
				Materials	NA	0.0210	Process materials	NA	0.0555			
				Total	–	0.0370	Total	–	0.1547			
Reactor	Enriched Uranium	22.8	60.515	Electricity	8.64×10^6 kWhe	0.1185	Electricity	$(0.19 \times 10^9$ kWhe)[c]	(0.7000)[c]	Electricity Gross	5.54×10^9 kWhe	19.933
				In materials	196.30×10^6 kWhe	2.6892	In materials	8.55×10^6 kWhe	0.1172	Internal[c]	$(0.19 \times 10^9$ kWhe)	(0.700)
				Fuels	1.959×10^{15} J	2.3669	Diesel fuel	344 m^3	0.0161	Net	5.35×10^9 kWhe	19.233
				Materials	NA	8.1480	Process materials	NA	0.2876			
				Total	–	13.3226	Total	–	0.4209			
Spent Fuel Storage	Depleted Uranium	22.8	NA	Electricity	3.88×10^6 kWhe	0.0531	Electricity	0.25×10^6 kWhe	0.0033		NA	
				Materials	NA	0.1830	In materials	0.08×10^6 kWhe	0.0011			
				Total	–	0.2361	Fuels	0.2×10^{12} kWhe	0.0002			
							Process materials	NA	0.0023			
							Total	–	0.0069			
Waste Storage	–	–	NA	Electricity	0.02×10^6 kWhe	0.0003	Electricity	0.004×10^6 kWhe	0.0006		NA	
				Fuels	12.0×10^{12} J	0.0144	In materials	0.15×10^6 kWhe	0.0021			
				Materials	NA	0.0120	Diesel fuel	2 m^3/yr	0.0012			
				Total	–	0.0306	Process materials	NA	0.0056			
							Total	–	0.0079			
Transport	–	–	NA	Electricity	1.96×10^6 kWhe	0.0267	Fuel	5.36×10^{12} J	0.0065		NA	
				Materials	NA	0.1230						
				Total	–	0.1497						

[a]Energy input and output computed as heat content of fuels or joule equivalent of electricity generated.

[b]Capital and operating energy input computed by I/O analysis as energy cost of fuels, materials, and electricity used.

[c]Internal use, included in output totals only.

mated at between 4%[1] and 10%[8] of current diffusion power requirements (100 to 250 kWh/SWU versus 2500 kWh/SWU). Moreover, a 30% increase in enrichment capacity could be handled by existing utility grids.[8] Although centrifugation offers lower power consumption, it does not show a commensurate reduction in total cost per SWU. However, it still is thought to be more economical.

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APPENDIX D
TERRESTRIAL SOLAR ENERGY SYSTEMS

This appendix describes the details of the terrestrial solar power systems used in the analysis. Both photovoltaic and thermal systems are discussed.

D.1 PHOTOVOLTAIC SYSTEM

D.1.1 Description of the Overall System

The conceptual design[1] for the photovoltaic plant analyzed calls for an estimated peak capacity of 1000 MWe and a capacity factor of 55%, with limited storage to compensate for loss of insolation. The plant is assumed to be operational 329 days (i.e., 90%) of the year. With lithium/sulfur batteries capable of storing 6.097×10^{12} J/day, the plant would operate 10 hr/day to yield a total of 1.978×10^{13} J/day or 6.058×10^{15} J/yr given a daily mean insolation of 3.150×10^{14} J/day. The plant's net efficiency for days of operation is 6.28%. Plant lifetime is assumed to be 30 years, battery lifetime to be 5 years,[1] and silicon cell lifetime to be 30 years. All capital inputs are stated for a 30-yr plant lifetime.

D.1.2 System Elements

Figure D.1 gives a schematic diagram of the elements of the system.

Insolation. Insolation is a diffuse energy source that varies with nearness to the equator and with regional climate factors such as cloud cover. The mean daily insolation is that solar energy which is normal to the earth's surface. The terrestrial photovoltaic plant analyzed is assumed to be situated in Barstow, California,[2] where the mean daily insolation is approximately 480 langleys (i.e., 2.01×10^7 J/m^2-day). The insolation used for this analysis is based on an average for the winter solstice, equinoxes, and summer solstice, assuming the use of a tracking reflector system that captures solar radiation equal to 3.39×10^7 J/m^2-day, somewhat more than the mean insolation of 2.01×10^7 J/m^2-day.

Solar Array Module. The solar array is composed of 50,000 single-axis modules spaced on 32.9-m centers in a NS-EW grid pattern occupying 52 km^2 (12,840 acres). Each module is composed of 14 linear-focus, reflective con-
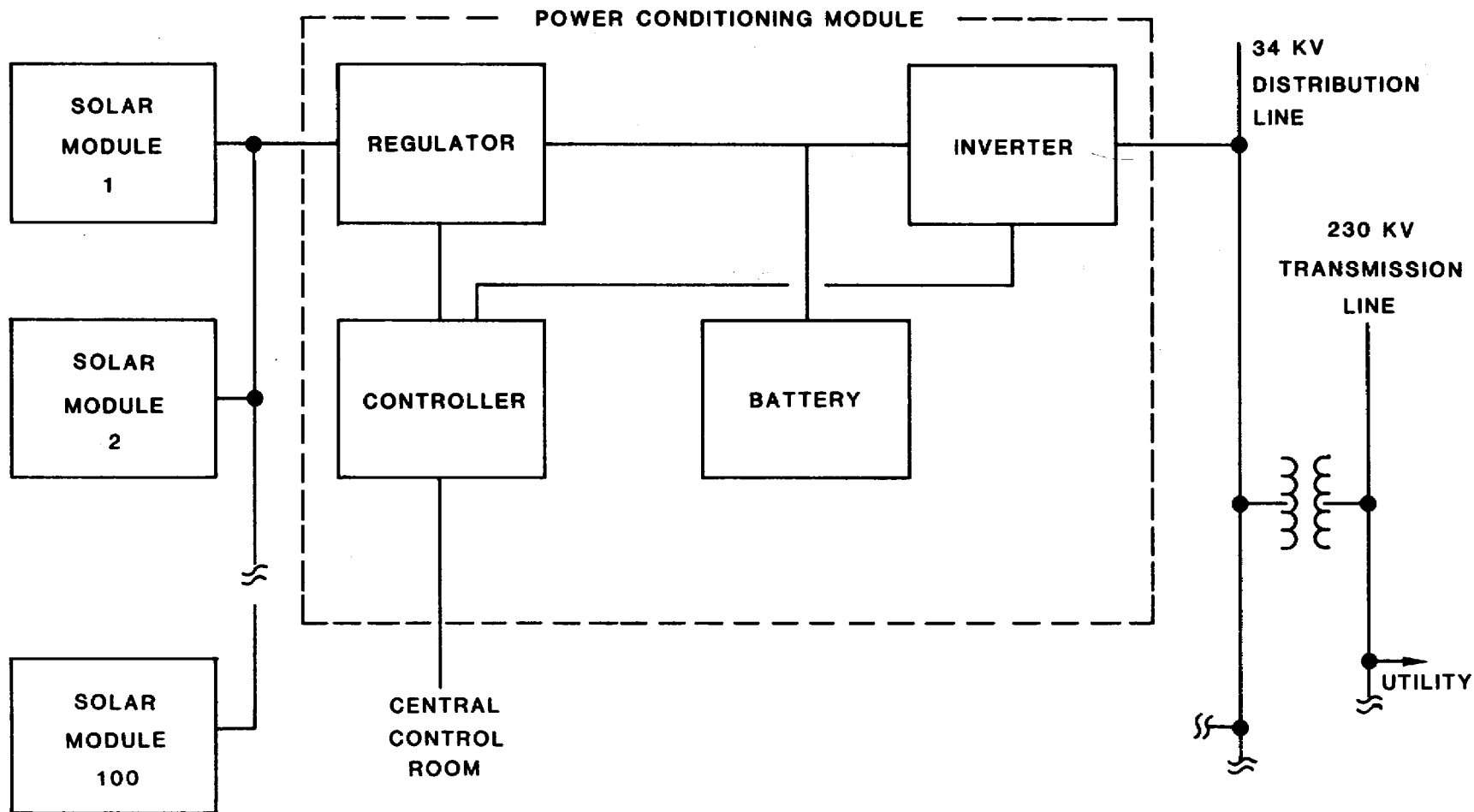
Fig. D.1. Power Conditioning Module Functional Block Diagram[1]

centrators (i.e., parabolic troughs). The troughs are arranged side by side on a plane inclined 45° from the horizontal. The primary concentrator is 1.2 m x 12.2 m, with a 12.7 cm x 12.2 m absorber strip mounted directly over the focal point of the trough. The total collector area of each module (less the surface area shaded by the absorber) is 186 m^2. The geometric solar concentration ratio of the collector to absorber is 18.

The absorber has a 6.1-cm x 12.20-m strip of single silicon cells contained within a Winston-type concentrator with a 12.2 cm aperture. The absorber containing the silicon cells is passively cooled by ambient convection. Nominal cell temperature is 100°C.

This solar array module was selected as representative of the current and near-term state of the art. Other photovoltaic materials as well as collector designs are currently being developed for possible commercialization in the future.

The primary energy input is 3.150 x 10^{14} J/day, assuming the average daily insolation per year available with the tracking system in Barstow, California. The ancillary energy input is electrical energy used to rotate the solar modules; this energy is part of the 7.235 x 10^{11} J/day (3.5% of gross output) tapped from plant output as total auxiliary power. The principal capital input is 1.89 x 10^6 kg of pure monocrystalline silicon.

System output is 2.380 x 10^{13} J/day as electricity (6.61 x 10^6 kWh/day), assuming the silicon cells are 16% efficient at 60°C.[3] The linear temperature correction equation for cell efficiency[4] reduces the single cell efficiency to 13% at the operating temperature of 100°C. The matrix of single cells (including the conductive bridge) occupies 85%[3] of the total absorber area. Series resistance of the cell matrix results in a 10% energy loss.[3] The parabolic trough collector has an efficiency of 69% with north-south tracking. The overall efficiency is the product of the efficiencies of the cell, the module, and the collector, which is equal to 7.55%. Losses are reflected solar energy and heat released to the atmosphere, which total 2,914 x 10^{14} J/day.

Power Regulator, Controller, and DC Collection Network. The power regulator, in conjunction with the controller's microcomputer, follows the characteristics of the solar module for variations in solar input and temper-

ature to maximize power output for each solar module. The power regulator and controller are part of the power conditioning module. There are 500 power conditioning modules, each servicing 100 solar modules. The power regulator consists of a smoothing reactor, and interphase reactor, and the direct current (DC) collection network.

The daily input to the collection network is 2.380×10^{13} J/day from the solar array. The ancillary energy inputs are in the form of electrical energy for operating switches and cooling fans; this ancillary energy is supplied by the plant.

Capital material inputs[1] have been aggregated for the entire plant: 835×10^6 kg steel, 260×10^6 kg cement, 1.4×10^5 m^3 water for cement, and 1.08×10^5 kg copper for the DC collection network. The gross ouput, at an overall efficiency of 98%,[5] is 2.33×10^{13} J/day of electrical energy. About 4.75×10^{11} J/day is lost in electrical resistance and released to the environment as heat.

Lithium/Sulfur Storage Batteries.

Lithium/sulfur batteries[1] will be located in a 3.7 m x 16.8 m battery building, an all-steel construction with a 15 cm-thick reinforced concrete floor. The battery bank will be 2.4 m x 12.2 m x 3.1 m high with a nominal weight of 79 t. The cells operate at 450°C, but the batteries are insulated so that the exterior surface temperature is 32°C. Auxiliary resistance heaters are embedded in the battery banks for reheat in the event of an idle period exceeding two days. Normally, however, self-generated heat will maintain the batteries within their operating temperature range, and no additional power will be needed. (Waste heat is removed by circulating air.) Should heat be required, the auxiliary heaters will expend about 1 kW/100 kW generating capacity.

The primary energy input to the batteries is 7.624×10^{12} J/day (2.12×10^6 kWh/day) for charging them. The major capital material input is 14.4×10^6 kg of lithium, assuming a 5-yr battery life.

The net output is 6.097×10^{12} J/day (1.69×10^6 kWh/day). About 6.08×10^{11} J/day (8% of the input) is lost on charging, and 9.14×10^{11} J/day (about 12% of the input) is lost on discharging the batteries. These losses are expended to atmosphere as heat.

DC/AC Inverter. The DC/AC inverter converts regulated DC to 60 Hz AC at 34 kV. An inverter is included in each of the 500 power conditioning modules. Total input is 6.097×10^{12} J/day from battery storage and 1.570×10^{13} J/day directly from the power regulators, for a total of 2.1797×10^{13} J/day (6.06×10^6 kWh/day). Thus about 72% of the total input to the inverters comes directly from the solar module; there are no ancillary inputs. Data on capital input materials were not available. Only the total inverter cost was available (29.51×10^6 in 1975 dollars[5]). This cost was converted to an energy equivalent using the input/output method described in Appendix A.

Transformer. Transformers are also included in the power conditioning modules; they convert the 34 kV to 230 kV for the AC transmission network. Total input is 1.999×10^{13} J/day. There are no ancillary inputs. Data on capital inputs were limited to costs (34.63×10^6 in 1975 dollars[5]).

Output is 1.978×10^{13} J/day or 6.508×10^{15} J/yr assuming 329 operating days per year and 99% efficiency.[5] Losses are 1.999×10^{11} J/day, as heat due to electrical resistance.

D.1.3 Energy Balance Parameters

Figure D.2 gives a schematic description of the energy flows in the terrestrial photovoltaic system. Table D.1 give the values of the parameters used in the net energy balance.

D.1.4 Identification of Sensitive Parameters

This section will describe some of the more sensitive data and indicate the ranges of possible values.

Insolation. The area chosen for the plant site is in the Southwest, which is the most suitable part of the U.S. for terrestrial solar energy. The Southwest has an average daily insolation of approximately 1.88×10^7 J/m^2-day. Some areas (El Paso, Phoenix, Tucson, etc.) receive as much insolation as 2.41×10^7 J/m^2-day. The Midwest, North and East Coast have much lower average insolation levels of 1.5×10^7 J/m^2-day. Moreover, indirect insolation from cloud cover cannot be effectively utilized by a tracking

Table D.1. Energy Balance Parameters for Terrestrial Solar Photovoltaic System

System Element	Annual Primary Input Type	Quantity (kWhe)	Energy[a] (10^{15} J)	Total Capital Inputs Type	Quantity[b]	Energy[c] (10^{15} J)	Annual Output Type	Quantity (kWhe)	Energy[a] (10^{15} J)
Collector[d]	Solar Radiation	–	115.048	Silicon	1,890 t	94.580[e]	Electricity	2.18×10^9	7.830
Power Regulator Controller, DC Collection Network[d]	Electricity	2.18×10^9	7.830	Copper	108 t	0.0272	Electricity to Battery to Inverter	0.70×10^9 1.43×10^9	2.508 5.165
Battery[d]	Electricity	0.70×10^9	2.508	Lithium	2,400 t	6.480	Electricity to Inverter	0.56×10^9	2.006
Inverter	Electricity	1.99×10^9	7.171	Equipment	$29,510,000	1.370	Electricity	1.89×10^9	6.814
AC Distribution Line System	Electricity	1.89×10^9	6.814	----------(Included below)----------			Electricity Gross Internal[d] Net	1.89×10^9 $(0.07 \times 10^9)^d$ 1.82×10^9	6.814 $(0.238)^d$ 6.576
Transformer	Electricity	1.82×10^9	6.576	Main transformers Substation transformers	$28,570,000 $ 6,060,000	1.601 0.339	Electricity	1.81×10^9	6.508
Entire Plant	–	–	–	Miscellaneous Electrical Equipment Steel Cement	$24,380,000 835,000 t 260,000 t	1.130 22.500 0.936			

[a] Energy input and output is computed as heat content of fuels or joule equivalent of electricity generated.

[b] Dollar amounts are in 1975 dollars.

[c] Capital energy input computed by I/O analysis as energy cost of fuels, materials, and electricity used.

[d] Annual operating input consists solely of auxiliary electricity tapped from output for internal use; the total is shown as "Electricity-Internal" under Annual Output.

[e] Based on 13,900 kWht/kg; current state-of-the-art of manufacturing.

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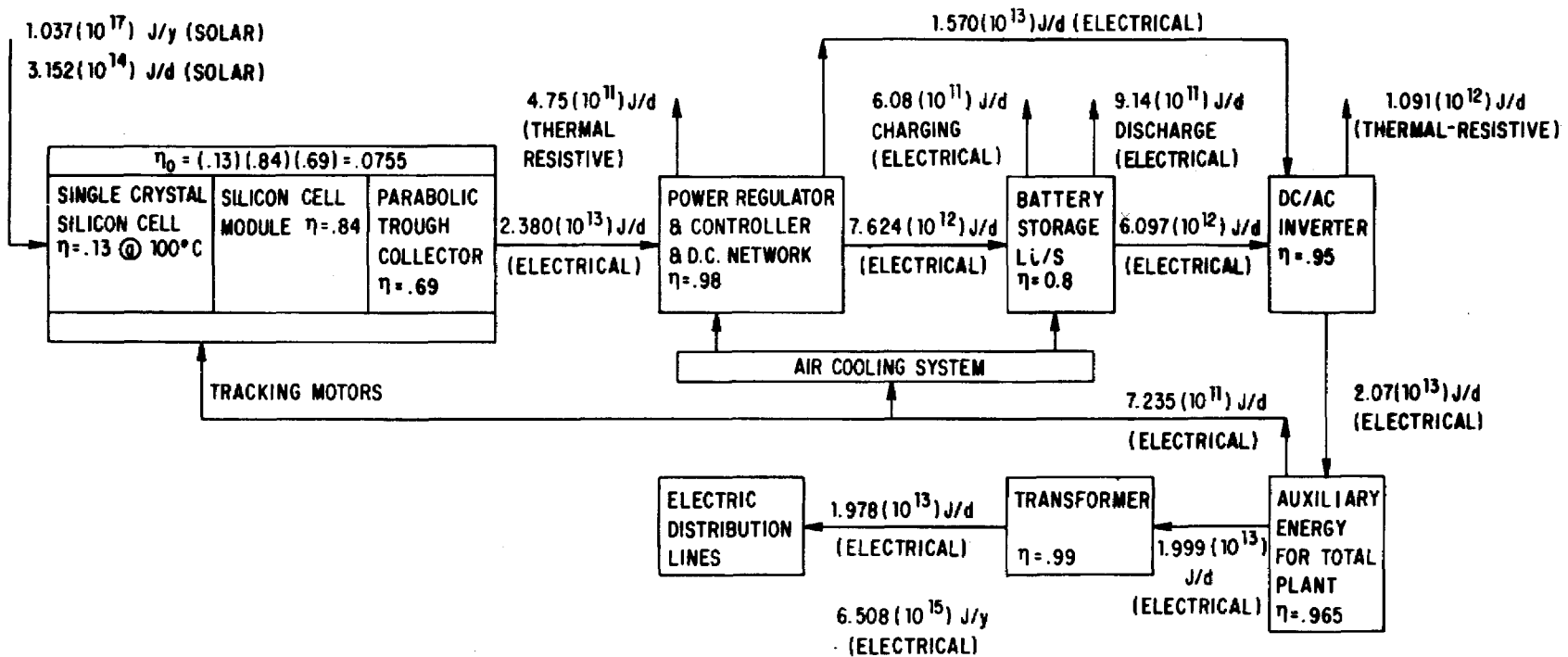
Fig D.2. Energy Flow of 1000-MWe Solar Photovoltaic Plant in Barstow, California

system. If the representative plant were located in Chicago, where the average insolation is 1.47 x 10^7 J/m^2-day, the resulting daily output of electricity would be almost 30% less, although the energy investment in materials would be the same.

Photovoltaic Cells. Critical properties of photovoltaic materials are the bandgap energy, internal resistance, and cell temperature. All these properties affect the generation of electricity.

Photovoltaic material is relatively transparent to light of wavelengths longer than the value of the bandgap energy level.[8] For sunshine at ground level, optimum bandgap energy is about 1.45 electron volts (eV), which is very close to the value for gallium arsenide (1.43 eV at 20°C) and somewhat greater than that for silicon (1.2 eV at 20°C). Therefore gallium arsenide is able to convert more of the solar energy into electrical energy than silicon. Also, absolute heat-sink temperatures can be about 20% higher for gallium arsenide than for silicon.[8] This means that the output of electricity would decrease 20% less for gallium arsenide than for silicon as the temperature increases above reference temperature. Gallium arsenide is also unusual in that, at temperatures as high as 200°C, it still has an efficiency of 14% with a 270-fold concentration of solar radiation (i.e., geometric concentration ratio).

Table D.2 shows currently achieved and theoretical efficiencies of photovoltaic cells, and the efficiency goals set by DOE, which may be achievable with further development. The upper bound of efficiency of photovoltaic materials is 26% at 60°C and about 17.6% at 100°C. The efficiency of the photovoltaic material is the critical efficiency (i.e., smallest efficiency) among the components of a photovoltaic generating plant. Replacement of silicon cells with gallium arsenide cells would increase plant output to 2.678 x 10^{13} J/day, giving the plant a new net efficiency of 8.5% as opposed to 6.28%.

Collector. The efficiency of the collector may be increased by using a different design or more efficient materials (e.g., reducing reflected losses, or providing more accurate tracking of the sun). Improving the collector efficiency to 80% would increase output (all else being the same) to

Table D.2. Solar Cell Efficiencies[a,b]

Cell Type	Efficiency, %		
	Achieved	Goal	Theoretical
Silicon			
Single Crystal	16	18	22
Polycrystalline	10	15	22
Amorphous	5	$\geqslant$ 10	unknown
Gallium Arsenide			
Single Crystal	18	20	26
Cadmium Sulfide			
Vacuum Deposition	8	12	14-16[c]
Spray	5	10	unknown[d]

[a]Source: Ref. 3.

[b]Without concentration and at reference temperature, 60°C.

[c]Theoretical understanding is still in formative stages.

[d]Should approach that of vacuum-deposited cells.

2.293 x 10^{13} J/day, raising the net plant efficiency to 7.28%. However, increasing the solar flux at the absorber would increase the cell temperature and (especially for silicon) decrease electrical production. Also, if the photovoltaic cells were actively cooled, energy would have to be expended for cooling fluid or fans.

Concentration Factor of Collector. A collector with greater concentrating ability would increase the incident solar flux on the photovoltaic cell, and thus increase the electric energy generated per unit area of cell; however, the temperature would also increase, which reduces power generation (more so for silicon than for gallium arsenide). Also, as the current per cell increases with solar flux, so does the power lost through the cell's resistance. The usual resistance of solar cells is in the vicinity of 1 to 10 ohm-cm. The optimum resistance of the bulk material is about 0.1 to 0.3 ohm-cm. A variety of designs are under consideration that would reduce the resistance of the solar cell.[10] These involve changing the geometry of the conventional planar cell in such a way that the series resistance is decreased. For instance, laboratory studies have indicated that use of a thick layer of aluminum gallium arsenide provides an improved series resist-

ance by reducing the series resistance components.[10] Another low-resistance design is the edge-illuminated silicon cell, which has multiple series-connected junctions that are perpendicular to the front surface. Solid contacts and elimination of the need for current travel along a thin diffused sheet results in a greatly improved series resistance.

Energy Consumption for Si Production. The input energy requirements for silicon production have already been discussed in Appendix A.

D.2 THERMAL SYSTEMS

D.2.1 Description of the Overall System

The terrestrial solar thermal electric plant is based on a two-year research and development program to develop technology for a 10-MWe central-receiver pilot plant, which is currently being built in Barstow, California under the sponsorship of DOE. The system evaluated is a 100-MWe design which has been designated as the commercial scale plant. Under the sponsorship of DOE and the technical management of Sandia Laboratories, three contract teams, headed by Honeywell, Martin Marrietta, and McDonnell Douglas, completed parallel and competing programs to develop conceptual designs for a pilot plant of 10 MWe as a basis for a 100-MWe commercial plant. The McDonnell Douglas design was chosen, and was used as the basis for this evaluation.

D.2.2 System Elements

Figure D.3 gives a schematic diagram of the system elements described below.

Insolation. The representative terrestrial thermal plant is assumed to be situated in Barstow, California, where average insolation is 3.39×10^7 J/m^2-day, as discussed in Section D.1.2.

Collector. The collector is a flat glass plate heliostat with a front-surface silver coating under an acrylic coating. The heliostat has a reflective area of 38 m^2 (6.1 m square) with a net reflectivity of 91%. Heliostats have motor drives to position them both vertically and horizon-

INCIDENT
INSOLATION

RECEIVER

ELECTRICAL POWER
TRANSMISSION
NETWORK

REFLECTED
INSOLATION

TOWER

STEAM TURBINE

ELECTRIC
GENERATOR

TRACKING HELIOSTATS

THERMAL
STORAGE

COOLING
TOWER
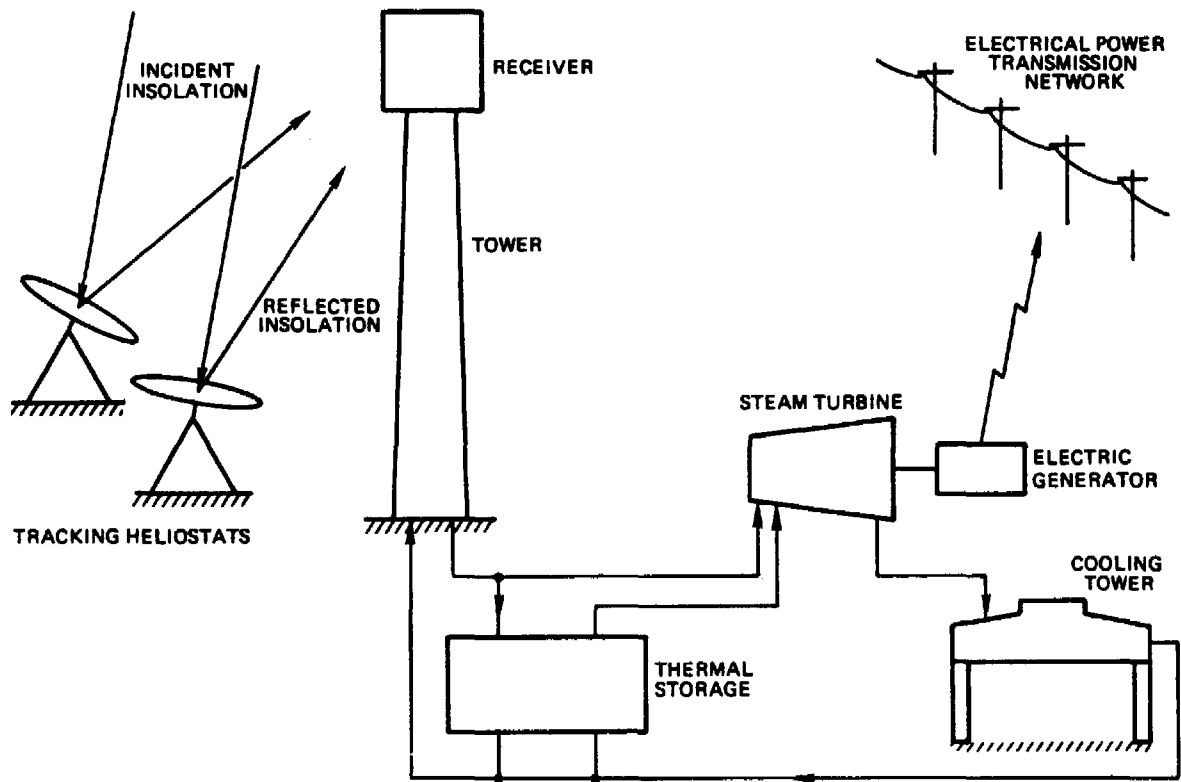
Fig. D.3.   Schematic Diagram of Solar Thermal Plant

tally. The collector array consists of 22,914 heliostats spaced around a central receiver tower in a staggered radial pattern. The heliostats total 869,586 m^2 of glass, and occupy 3.66×10^6 m^2 of land.

Primary energy input to the heliostats is 2.95×10^{13} J/day, assuming tracking of daily insolation averaged for the winter solstice, equinoxes, and summer solstice. This amounts to 1.077×10^{16} J/yr for direct sunshine 90% of the year (329 days/yr). Ancillary energy inputs include electrical power to drive the heliostat tracking motors, rated at 12 watts per heliostat. This power is taken from the plant output, and is part of an estimated total ancillary power need of 3.5% of total plant output.[6]

The capital material inputs are glass (1.088×10^7 kg), steel (1.998×10^7 kg), and concrete (1.888×10^7 kg).

The heliostat output is 1.638×10^{13} J/day of solar energy reflected to the receiver, assuming a net collection efficiency of 55.5%.[13] About 1.314×10^{13} J/day of solar energy is lost by being reflected into the atmosphere.

Receiver and Boiler. The receiver consists of 24 panels of Incoloy 800 tubing. Twenty panels are external, single-pass-through superheat boilers, and four are preheating panels, located on the south side of the receiver. The tubes are coated with Pyromark paint, which has 95% absorptivity over a wide range of wavelengths. The boiler tubes cover a cylinder 421 m in diameter, mounted atop a 242-m tower located in the optimum focal center of the collector array.

The primary energy input to the receiver is 1.638×10^{13} J/day of solar energy reflected by the tracking heliostats. There are no operating energy inputs.

The capital inputs[4] are: receiver steel (94.64×10^3 kg), tower steel (1.426×10^6 kg), and tower concrete (2.6491×10^7 kg).

The system output is 1.378×10^{13} J/day as pressurized steam from a receiver designed for an incident peak flux of 0.31 MW/m^2.[13] This yields a net efficiency of 84%; 2.61×10^{12} J/day are lost to the atmosphere as radiant heat energy.

Riser/Downcomer System. The riser and downcomer are two pipes, 242 m long, contained within the tower for circulation to storage and to the turbine.

The primary energy input is 1.378×10^{13} J/day of thermal energy from the receiver and boiler. The operating energy needed to pump cooled water from the cooling tower to the receiver is part of the overall ancillary energy requirement of 3.5% of plant output.

The capital input[4] is 27.60×10^3 kg of steel.

The net output is 1.3639×10^{13} J/day of thermal energy, of which 39.62%, or 5.403×10^{12} J/day, goes to storage and 8.236×10^{12} J/day goes directly to the turbine as steam at 510°C and 1800 psia. This output is based on an assumed piping efficiency of 99%.

Storage. The McDonnell Douglas single-stage sensible heat system, using a dual storage medium of rock and oil, is assumed to be used for heat storage. The system consists of four tanks 18.3 m (60 ft) tall and 27.6 m (90.5 ft) in diameter, used in parallel. The basic heat-transfer fluid is Caloric HT 43, which has excellent stability and compatibility with rocks and construction materials up to 316°C (600°F).

The primary energy input is 5.403×10^{12} J/day of thermal energy in the form of pressurized steam from the receiver. The ancillary input is the electrical power, taken from plant output, to operate pumps for the heat exchanger.

The capital inputs[5] are Caloric HT 43 heat-transfer oil (9400 m^3), sand and gravel (8.10×10^7 kg), and steel for the tanks (5.53×10^5 kg).

The output of the storage system is 4.59×10^{12} J/day of thermal energy, with a net efficiency of 85%.[3] Thermal energy amounting to 8.099×10^{11} J/day is lost by radiation.

Turbine, Condenser, Cooling Tower and Generator. A 3600-rpm dual admission turbine from G.E. is used.[13] The primary energy input is 8.236×10^{12} J/day of thermal energy in steam at 1800 psia and 950°F (510°C) directly from the receiver and 4.59×10^{12} J/day in steam at 550°F (288°C) and 500 psia from storage, for a total of 12.826×10^{12} J/day. Ancillary electrical energy

to drive pumps and fans for cooling towers and other equipment is part of the total internal electrical energy supplied by plant output.

The capital energy equivalent input for the various pieces of equipment include 324.0×10^{12} J for the turbine and generator, 22.68×10^{12} J for the condenser and other electrical equipment, 93.0×10^{12} J for the wet cooling tower, and 20.19×10^{12} J for makeup water and transport.

The net output is 3.95×10^{12} J/day of electrical energy, assuming a net operating efficiency of 33% for input from the receiver and 27% for input from storage. Because of the lower temperature and pressure of steam from storage, the turbine is derated slightly. A total of 8.869×10^{12} J/day of thermal energy is lost in the cooling tower output.

Transformer, AC Feeder Network, Power Conditioning. These components are conventional equipment for making the electrical characteristics (e.g., voltage and frequency) of the power compatible with the AC distribution network. The energy input to the power conditioning system is 3.819×10^{12} J/day; the output is 3.74×10^{12} J/day, assuming an efficiency of power conditioning of 98%.[5] Radiant heat equivalent to 7.56×10^{11} J/day is lost due to electrical resistance.

D.2.3 Energy Balance Parameters

Figure D.4 gives a schematic description of the energy flows in the system. Table D.3 gives the values of the parameters used in the net energy balance.

D.2.4 Identification of Sensitive Parameters

Insolation. The solar thermal system is as sensitive to the variation in insolation as is the photovoltaic system. This sensitivity has been discussed already in Sect. D.1.4.

Collector. Boeing Engineering and Construction, Seattle, Washington, under contract with DOE, has developed a preliminary design of a heliostat collector subsystem using circular membrane reflectors. The reflectors are "gravity focused" by controlling the tension in the reflective membranes.
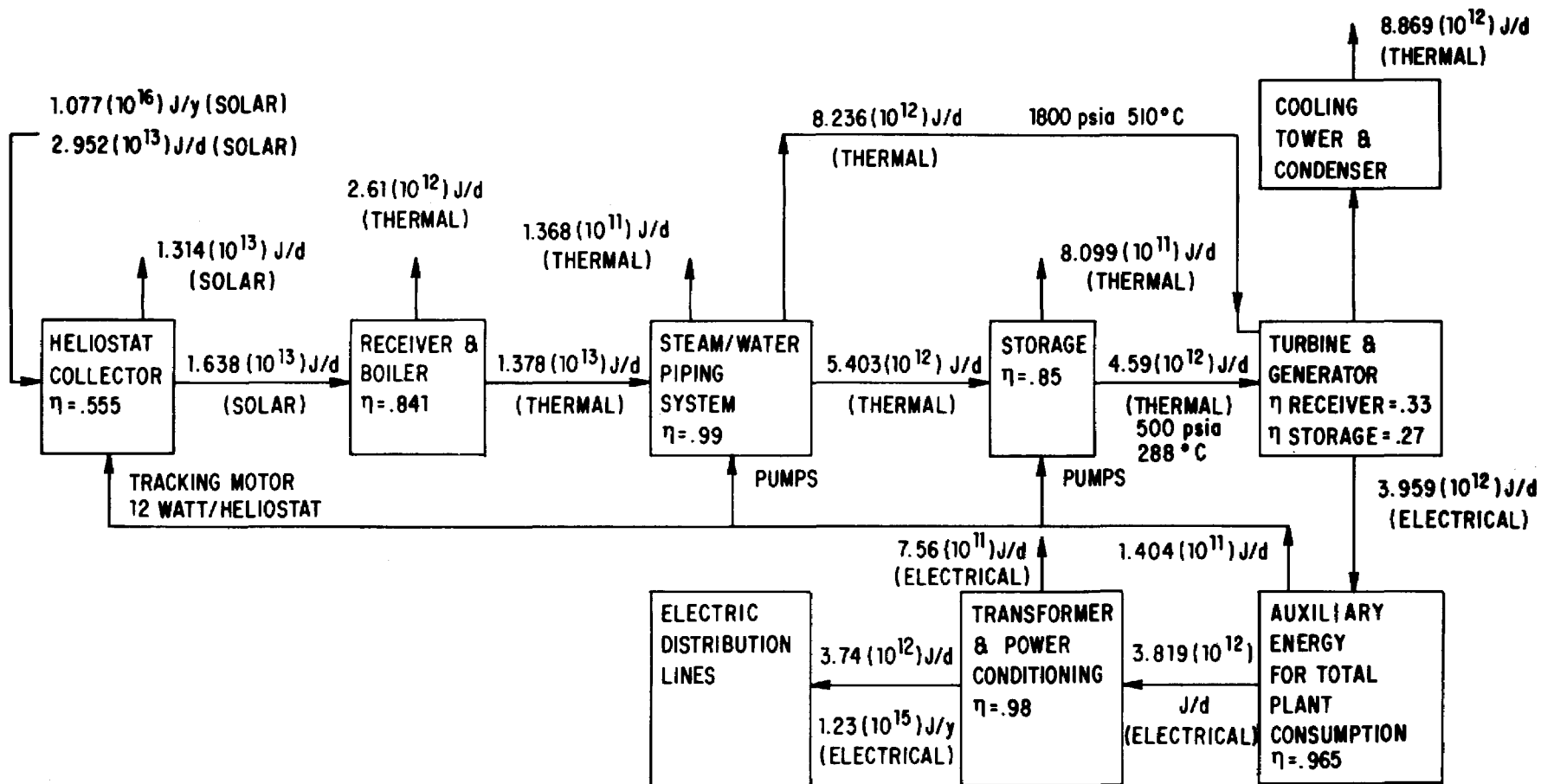
Fig. D.4. Energy Flow of 100-MWe Solar Thermal Plant in Barstow, California

Table D.3. Energy Balance Parameters for Terrestrial Solar Thermal System

System Element	Annual Primary Input			Total Capital Inputs			Annual Output		
	Type	Quantity (kWhe)	Energy[a] (10^{15} J)	Type	Quantity	Energy[b] (10^{15} J)	Type	Quantity (kWhe)	Energy[a] (10^{15} J)
Collector[c]	Solar Radiation	–	10.775	Glass	10,880 t	0.1260	Heat	–	5.389
				Steel	19,980 t	0.5430			
				Concrete	18,980 t	0.0684			
				Total	–	0.7374			
Receiver/Boiler	Heat	–	5.389	Steel			Heat	–	4.534
				Receiver	94.64 t	0.0025			
				Tower	354 t	0.0094			
				Tower Base	1072 t	0.0297			
				Concrete					
				Tower	2,031 t	0.0073			
				Tower Base	24,461 t	0.0881			
				Total	–	0.1370			
Riser/Downcomer[c]	Heat	–	4.534	Steel	27.60 t	0.0007	Heat to Storage	–	1.777
							Steam to Turbine	–	2.711
Storage[c]	Heat	–	1.777	Caloric HT43 oil	9,400 m^3	0.4571	Steam to Turbine	–	1.510
				Sand & Gravel	81,000 t	0.0106			
				Steel	555 t	0.0150			
				Total	–	0.4827			
Turbine/Generator[c]	Steam	–	4.221	General Equipment	NA	0.324	Electricity		
							Gross	3.62×10^8	1.303
							Internal[c]	(0.13×10^8)[c]	(0.046)[c]
							Net	3.49×10^8	1.257
Transformer/Power Conditioner	Electricity	3.49×10^8	1.257	----------(Included above)------------			Electricity	3.42×10^8	1.230
Miscellaneous Equipment	–	NA	–	Condenser & Other Electrical Equipment	NA	0.0227			
				Wet Cooling Tower	NA	0.0930			
				Makeup Water Transport	NA	0.0202			
				Total	–	0.1359			

[a]Energy input and output is computed as heat content of fuels or joule equivalent of electricity generated.

[b]Capital energy input computed by I/O analysis as energy cost of fuels, materials, and electricity used.

[c]Annual operating input consists solely of auxiliary electricity tapped from output for internal use; the total is shown as "Electricity-Internal" under Annual Output.

Transparent air-supported plastic-bubble enclosures protect the light-weight reflectors. Measurements were conducted in 1977[1] on individual heliostats and on a group of three heliostats over a 4.5 month period. Results showed a nominal average efficiency of 69% to 72%; after five months without cleaning, the reflectors still had a nominal average efficiency of 65%, which is appreciably better than the 55.5% efficiency of the McDonnell Douglas system.

Receiver and Boiler. The present receiver/boiler system, which uses once-through forced flow, has a rated efficiency of 84.1%[13], given an incident energy flux from the collector of 0.31 MW/m^2. The original commercial-scale plant has a predicted design efficiency of 89.8%, assuming an incident energy flux of 0.85 MW/m^2; however, the life of the receiver tubes at this higher energy flux is uncertain. Mechanical oscillations may be induced by the severe temperature stress of this level of energy flux, which could cause early failure of the tubes due to structural fatigue. Once-through boilers have been built and operated at flux levels of 0.3 MW/m^2, but apparently no once-through boiler has ever been built to operate at a flux as high as 0.85 MW/m^2.

Liquid Sodium System. The potential for higher plant efficiency has led to consideration of a second-generation solar thermal system using either a hot-gas or a liquid-metal cycle.[11] Recent studies have confirmed the technical feasibility of using the exceptional heat-transfer capability of liquid sodium in a solar thermal power plant.

The system as conceived would use liquid sodium in the receiver/boiler, with sodium at 594°C (1,100°F) going directly to storage. Heat exchangers would be employed to transfer the heat to water, producing steam for the turbine. Having hot sodium in storage would allow the system to operate in steady-state condition during periods of cloud cover. Peak energy flux at the receiver is limited to 1.7 MW/m^2 to achieve an assumed tube life of not less than 10,000 cycles; however, this level of energy flux is twice that of the McDonnell Douglas design (0.85 MW/m^2).

The predicted turbine efficiency for a 100-MWe liquid sodium plant with six hours operating energy in storage is 39.4%[7], as compared with turbine efficiencies of 33% (turbine feed from receiver) and 27% (turbine feed from

storage) for the water system. (In the sodium system the turbine would always be fed from storage, so there is only one efficiency value to consider.)

The advantage of liquid sodium as a receiver coolant is that scale formation is not a problem, as it is with water in the receiver. In addition, less pumping power is needed, and the low receiver pressure allows use of smaller-gauge tubing. This plus sodium's excellent heat-transfer characteristics substantially reduces the possibility of thermal fatigue in the receiver tubes, which can be a real problem in water systems at heat fluxes higher than 0.6 MW/m^2.

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APPENDIX E
SATELLITE POWER SYSTEM

E.1 DESCRIPTION OF OVERALL SYSTEM

The satellite power system was suggested in 1968 by P.E. Glaser.[1] It is a solar power cycle that involves generating electrical power from photovoltaic solar panels in geosynchronous orbit, transmitting the power to earth via focused microwave beams, and collecting and converting the beams into useful electricity on the earth's surface.

The system analyzed in this report[2,3] is designed as a 5-GW DC power unit that is connected to a conventional utility grid on the earth. The size of the satellite power system (SPS) is dictated primarily by the efficiency chain of the various elements in the system. Figure E.1 shows a simplified flow diagram and the end-to-end efficiency chain of the present SPS concept.[3] Two options are currently under consideration for converting solar energy into electrical energy: gallium aluminum arsenide (GaAlAs) solar cells with a concentration ratio of 2 and silicon (Si) solar cells with no concentration. The quoted efficiency is the minimum efficiency for a 30-yr lifetime, including the worst-case factor for solar radiation at the summer solstice (0.9675), the seasonal variation (0.91), and the end-of-life efficiency of solar cells, assuming annealing.[3]

The capacity factor of the plant designed to provide 5 GW of DC power to utility busbars is estimated to be 92%, with a downtime of 696 hours (87 day/yr x 8 hr/day) for maintenance.[4] As a result, the electricity generated by the 5-GW SPS is expected to be 145.18×10^{15} J/yr (40.32×10^9 kWh/yr).

E.2 SYSTEM ELEMENTS

The separate elements of the SPS illustrated in Fig. E.1 can be categorized into three groups: the solar energy collection system, the power distribution system, and the microwave power transmission system. The material requirements and the space transportation system to construct and operate a SPS are also key elements in studying the net energy balance. In this section these topics are briefly discussed, mainly on the basis of data in Ref. 3.

E.2.1 Solar Energy Collection System

The solar energy collection system has the function of collecting the dispersed solar energy in sufficient quantities for conversion to electrical energy.

SOLAR ENERGY COLLECTION SYSTEM

Ga
71.77 GW
(SOLAR)

70.81 GW
Si

69.43 GW	63.18 GW
SUMMER SOLSTICE FACTOR	SEASONAL VARIATION
0.9675	0.91

68.51 GW   62.34 GW

Ga

57.81 GW	10.50 GW	9.97 GW	9.45 GW
REFLECTOR REFLECTIVITY EQUIVALENT	CELL TEMP DEGRADATION @125°C	PACKING FACTOR	ARRAY DESIGN FACTOR
0.915	0.908	0.95	0.901

Ga

Si

10.79 GW	10.29 GW	10.19GW	9.79 GW
SOLAR CELL EFF @ AMO 28°C	CELL TEMP DEGRADATION @ 38°C	CELL-TO-CELL MISMATCH	ARRAY DESIGN FACTOR
0.173	0.954	0.99	0.951

Si

POWER DISTRIBUTION SYSTEM   MICROWAVE TRANSMISSION

Ga

9.08 GW
0.96
ULTRAVIOLET & RADIATION DEGRADATION
0.9273

Si

9.08 GW

8.50 GW	8.50 GW	8.18 GW
ARRAY POWER DISTRIBUTION	SLIP RINGS	ANTENNA POWER DISTRIBUTION
0.9368	0.9995	0.963

6.98 GW	6.72 GW
DC-RF CONVERSION	TRANSMITTING ANTENNA
0.85	0.9653

6.58 GW	5.79 GW	5.15 GW		
ATMOSPHERIC LOSSES	RECTENNA ENERGY COLLECTION	RECTENNA ENERGY CONVERSION	GRID INTERFACES	UTILITY BUSBAR 5 GW
0.98	0.89	0.88	0.97	

MICROWAVE TRANSMISSION SYSTEM

OVERALL EFFICIENCY = 6.97% Ga   MPTS EFFICIENCY = 63.0%
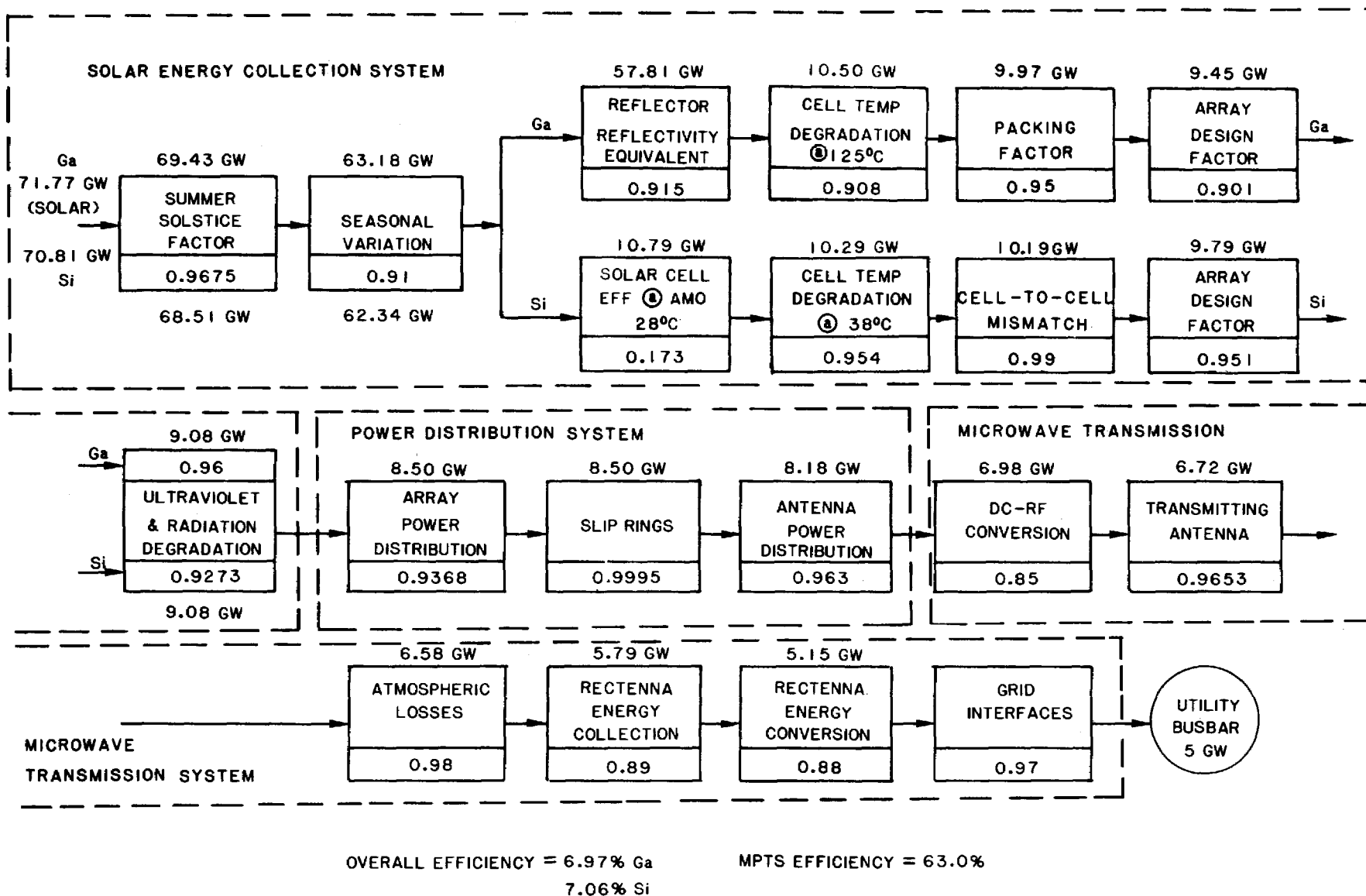7.06% Si

Fig. E.1.   Simplified Flow Diagram and Efficiency Chain of SPS (Ga CR=2 and Si CR=1)[6]

In order to determine the most favorable energy collection/conversion system, a variety of studies were performed during 1974-1976, including solar photovoltaic systems, thermal conversion systems (solar Rankine cycle, solar Brayton cycle), orbiting nuclear power systems, and orbiting solar reflector systems.[5] After a review of those systems, the photovoltaic system, using either single-crystal Si or GaAlAs cells, was chosen as the reference energy-conversion device. A concentration ratio of one (CR 1) is preferred for Si-cell systems, whereas GaAlAs cells may be more advantageous with a concentration ratio of two (CR 2). Based on the analyses conducted to date, the results indicate the photovoltaic systems would be less complex and have lower mass than the thermal conversion systems regarded as competitive. The major disadvantages of thermal systems are the need to contain fluid, wear in rotating equipment, complexity of construction, and relatively high mass.

The solar array consists of the deployed solar cell blankets and their support structure. The basic GaAlAs solar cell consists of a 5-μm-thick GaAs PN cell with a 0.03 to 0.05-μm-thick GaAlAs front-side window. The blanket material is 25-μm-thick Kapton. The area of the blanket is 25.52 km^2, deployed in a total area of 55.13 km^2 for the GaAlAs system with CR2, which includes the solar reflectors mounted on each side of the solar cell blankets. The projected cost of the blankets is \$71/m^2.

The Si-cell blanket consists of 50-μm-thick single-crystal Si cells with a borosilicate covering electrostatically bonded to the front and back. The area of the blanket for the Si system with CR 1 is 52.34 km^2, deployed in a total area of 54.08 km^2. The projected cost of the Si blankets is \$35/m^2.

The primary structure for both types of solar cells is of open-truss design made of thermoplastic reinforced with graphite fiber. The basic truss elements are designed for automatic fabrication in space.

E.2.2 Power Distribution System

The prime function of the power distribution system is to collect, regulate, and control power from the solar-array sections; to control, condition, and transmit this power to microwave generators on the transmitting antenna; to provide for energy storage during occultations of the sun by the earth or moon, or during system maintenance; and to provide for detection and monitoring of faults and disconnecting faulty sections.

Power from the solar array is controlled by high-voltage circuit breakers near the buses, depending on load requirements. Two sections of the array provide the required voltage (45.5 kV) at the sliprings, using the sheet-conductor voltage drop to achieve this voltage.

Power is transferred from sections of the solar array to the microwave attenna via rotary joints using slipring/brush assemblies. Conductors from the slipring brushes are tied to DC/DC convertors through switchgear that allow isolation of a section when it is under maintenance. Conductors are then tied between voltage-summing buses through other switchgear for transmitting the required power to the DC-RF generators.

Batteries for energy storage are located on the microwave antenna structure, with a bus routed along the regular network to provide power when the solar array is not operating. About 12 MWh of electrical energy would be stored.

E.2.3 Microwave Power Transmission System

The transfer of energy from geosynchronous orbit to earth, in the present SPS concept, would be accomplished by means of microwave transmission. Power transfer is a 3-step process: (1) converting the power from DC to microwaves; (2) focusing and transmitting the microwaves to earth's surface; and (3) collecting the microwave power on earth and converting it to DC power. The overall efficiency of this system is about 63%; a breakdown of the efficiencies of the subsystems is given in Fig. E.1.

The studies performed by contractors on the microwave power amplifiers (DC to RF converters) have focused primarily on investigation of the klystron (a linear beam amplifier) and the amplitron (a crossed-field amplifier). According to these studies,[6] the klystron is preferred because of better performance, including much higher power per tube, higher operating voltage, lower noise levels, and much lower phase-control drive power.

The microwave transmission system assumed has a phased-array transmitting antenna 1 km in diameter. This antenna is composed of 7,220 subarrays with slotted waveguides as the radiating surface and DC-RF power tubes mounted on the back. Both the primary and the secondary structure of the antenna are composed of a graphite/epoxy material. The primary structure is an open A-frame truss, and the secondary structure is a deployable cubic truss which

provides support for installation of the microwave subarrays. The slotted waveguides are assumed to be made of aluminum.[6]

The present configuration of the ground rectenna, which receives and rectifies the power beam, has half-wave dipoles feeding Schottky barrier diodes.[6] Two-stage, low-pass filters between the dipoles and diodes suppress harmonic generation and provide impedance matching. For economic reasons, the rectenna is a series of serrated panels perpendicular to the incident beam rather than a continuous structure. RF power collected at the rectenna is converted to DC power to be used in utility power levels through the unit processes such as RF-DC conversion, DC power interface, and DC/DC processing.

E.2.4 Material Requirements

The materials needed for the SPS program are presented in Table E.1.[6] These requirements have been estimated for individual system components, such as the satellite station, ground station, and various transport vehicles.

The satellite station requirements are separated into three major segments: a 5-GW satellite system, low earth orbit (LEO) staging, construction of an orbital transfer vehicle (OTV), and construction in geosynchronous orbit (GEO). The satellite masses, which are shown in Table E.2,[6] consist of the solar array, the microwave antenna, and array/antenna interfaces. The GaAlAs option in the solar array uses a radiation concentration ratio of 2, which reduces the required blanket area and therefore the blanket mass.

The rectenna is the main part of the ground unit. It is composed of steel panels supported by steel columns in concrete footings; aluminum conductors are used for the power collection system. According to the present concept report,[6] the projected cost for the rectenna structure is over 20% of the total SPS program, even though a recent redesign of the rectenna eliminated over 75% of the aluminum from the original 1976 design. This component needs further study to bring costs down.

E.2.5 Space Transportation System

This section describes the space transportation vehicles assumed in the present study. The vehicles are distinguished by their primary payload, either cargo or personnel, and their area of operation, i.e., between earth and low earth orbit (LEO), or between LEO and geosynchronous earth orbit (GEO).

Table E.1. Materials Requirements (Metric Tons) for SPS

Subsystem	Resources Dependent on Cell Type		Resources Independent of Cell Type
	Si Cells (CR=1)	GaAs Cells (CR=2)	
Satellite (Total)	50,618	34,159	-
GFRTP[a]	6,359	7,680	-
Stainless Steel	5,723	5,305	-
Copper	6,873	4,834	-
Sapphire	0	3,376	-
Aluminum	2,204	4,122	-
Gallium Arsenide	0	1,354	-
Teflon	0	1,152	-
Kapton	0	2,719	-
Silver	37	928	-
Mercury	89	89	-
Tungsten	646	646	-
Glass	19,271	0	-
Silicon	7,903	0	-
Miscellaneous	1,880	1,947	-
Staging and Construction in LEO (Total)	2,405	110[b]	-
GFRTP[a]	640	-	-
Aluminum	1,433	-	-
Stainless Steel	108	-	-
Copper	26	-	-
Glass	20	-	-
Silicon	9	-	-
Construction in GEO (Total)	8,353	6,000[b]	-
GFRTP[a]	2,551	-	-
Aluminum	4,694	-	-
Stainless Steel	390	-	-
Copper	110	-	-
Glass	30	-	-
Silicon	13	-	-
Miscellaneous	565	-	-
Cargo Orbital Transfer Vehicle (Total)	1,100	679	-
Aluminum	3	369	-
Gallium Arsenide	0	38	-
Teflon	0	32	-
Sapphire	0	93	-
Kapton	0	66	-
GFRTP[a]	126	0	-
Copper	67	15	-
Silicon	256	17	-
Stainless Steel	14	40	-
Glass	623	0	-
Miscellaneous	11	9	-
Heavy Lift Launch Vehicle (Total)	-	-	1,170
Aluminum	-	-	470
Titanium	-	-	248
Stainless Steel	-	-	232
Ceramic	-	-	103
Copper	-	-	17
Miscellaneous	-	-	100
Personnel Launch Vehicle (Total)	-	-	264
Aluminum	-	-	106
Titanium	-	-	56
Stainless Steel	-	-	52
Ceramic	-	-	23
Copper	-	-	4
Miscellaneous	-	-	23
Personnel Orbital Transfer Vehicle (Total)	-	-	116
Aluminum	-	-	81
Stainless Steel	-	-	23
Copper	-	-	2
Miscellaneous	-	-	10
Rectenna (Total)	-	-	2,962,009
Steel	-	-	1,492,000
Concrete	-	-	1,330,000
Aluminum	-	-	140,000
Gallium Arsenide	-	-	9

[a]Graphite-Fiber-Reinforced Thermoplastic.

[b]Only estimates of totals currently available.

Source: Ref. 6.

Table E.2. Masses of SPS Subsystems

	Mass. 10^6 kg	
Subsystem	GaAlAs CR = 2	Silicon CR = 1
Solar Array	13.798	27.258
Primary Structure	4.172	3.388
Secondary Structure	0.581	0.436
Solar Blankets	6.696	22.051
Concentrators	0.955	–
Power Distribution and Conditioning	1.144	1.134
Information Management and Control	0.050	0.050
Attitude Control and Stationkeeping	0.200	0.200
Antenna	13.382	13.382
Primary Structure	0.250	0.250
Secondary Structure	0.786	0.786
Transmitter Subarrays	7.178	7.178
Power Distribution and Conditioning	2.189	2.189
Thermal Control	2.222	2.222
Information Management and Control	0.630	0.630
Attitude Control	0.128	0.128
Array Antenna Interfaces[a]	0.147	0.147
Primary Structure	0.094	0.094
Secondary Structure	0.003	0.003
Mechanisms	0.033	0.033
Power Distribution	0.017	0.017
Subtotal	27.327	40.787
Contingency (25%)	6.832	10.197
Total	34.159	50.984

[a]Rotary joint, slip rings, antenna yoke.

Source: Ref. 6.

Heavy Lift Launch Vehicle (HLLV). The reference HLLV is a two-stage (booster and orbiter), vertical take-off, horizontal landing, fully reusable, winged launch vehicle. The vehicle uses 16 liquid methane/liquid oxygen engines on the booster (first stage) and 14 standard Space Shuttle Main Engines (SSME) on the orbiter (second stage). Cargo is transported from the earth's surface to LEO by the HLLV.

Personnel Launch Vehicle (PLV). The PLV provides for the transportation of personnel and priority cargo between earth and LEO. The reference vehicle is derived from the current space shuttle system. It uses methane-fueled, winged flyback boosters with smaller external tanks than those on the existing shuttle. The booster employs 4 methane/oxygen engines similar to those on the HLLV booster.

Cargo Orbital Transfer Vehicle (COTV). The function of the COTV is to deliver SPS cargo to GEO from the LEO staging area. The basic concept involves constructing a fleet of reusable round-trip vehicles powered by solar-electric arrays in LEO. The vehicles would use ion-bombardment thrusters, with cryogenic argon as the propellant.

Personnel Orbital Transfer Vehicle (POTV). The functions of the POTV are to deliver personnel and priority cargo from LEO to GEO and to return personnel from GEO and LEO at 90-day intervals. The reference vehicle has two stages and is fueled with oxygen and hydrogen; it could make the trip in about one day.

E.3 ENERGY BALANCE PARAMETERS

Figure E.2 shows the primary energy flow for the GaAlAs and Si cell options, with the satellite designed to provide 5 GW of DC power to the utility busbar and overall efficiencies of 6.9% and 7.0%, respectively. The system, based on a 5-GWe unit operating at a plant factor of 92%, generates 145.18×10^{15} J/yr (40.32×10^9 kWh/yr). It is necessary to size the solar arrays to intercept approximately $2,100 \times 10^{15}$ J of solar energy as indicated in Fig. E.2.

Table E.3 summarizes the energy balance parameters. Table E.4 summarizes the system materials requirements, and Table E.5 shows the conversion

				REFLECTOR REFLECTIVITY DEGRADATION	CELL TEMP DEGRADATION @ 113°	PACKING FACTOR	ARRAY DESIGN FACTOR	

2107.53
GaAlAs
CR = 2

SUNLIGHT IN
Si CR = 1
2079.41

2039.04 — 68.49 / 67.58 — SUMMER SOLSTICE FACTOR — 2011.83

1855.52 — 183.52 / 181.06 — SEASONAL VARIATION — 1830.77

GaAlAs:
1697.80 — REFLECTOR REFLECTIVITY DEGRADATION — 157.72
308.32 — CELL TEMP DEGRADATION @ 113° — 1389.48
292.91 — PACKING FACTOR — 15.41
277.67 — ARRAY DESIGN FACTOR — 15.24 — GaAlAs

Si:
SOLAR CELL EFF @ AMO 28°C — 1514.05
CELL TEMP. DEGRADATION — 14.57
CELL-TO-CELL MISMATCH — 2.02
PANEL LOST AREA — 11.66 — Si
316.72 — 302.15 — 299.13 — 287.47

277.67 GaAlAs
266.57 — 11.10 / 20.90 — ULTRAVIOLET & RADIATION DEGRADATION — 266.57
287.47 Si

249.72 — ARRAY POWER DISTRIBUTION — 16.85
249.60 — SLIP RINGS — 0.12
240.36 — ANTENNA POWER DISTRIBUTION — 9.24
204.31 — DC-RF CONVERSION — 36.05
197.22 — TRANSMITTING ANTENNA — 7.09

197.22 — ATMOSPHERIC LOSSES — 3.95
193.27 — RECTENNA ENERGY COLLECTION — 23.19
170.08 — RF-DC CONVERSION — 20.41
149.67 — GRID INTERFACES — 4.49

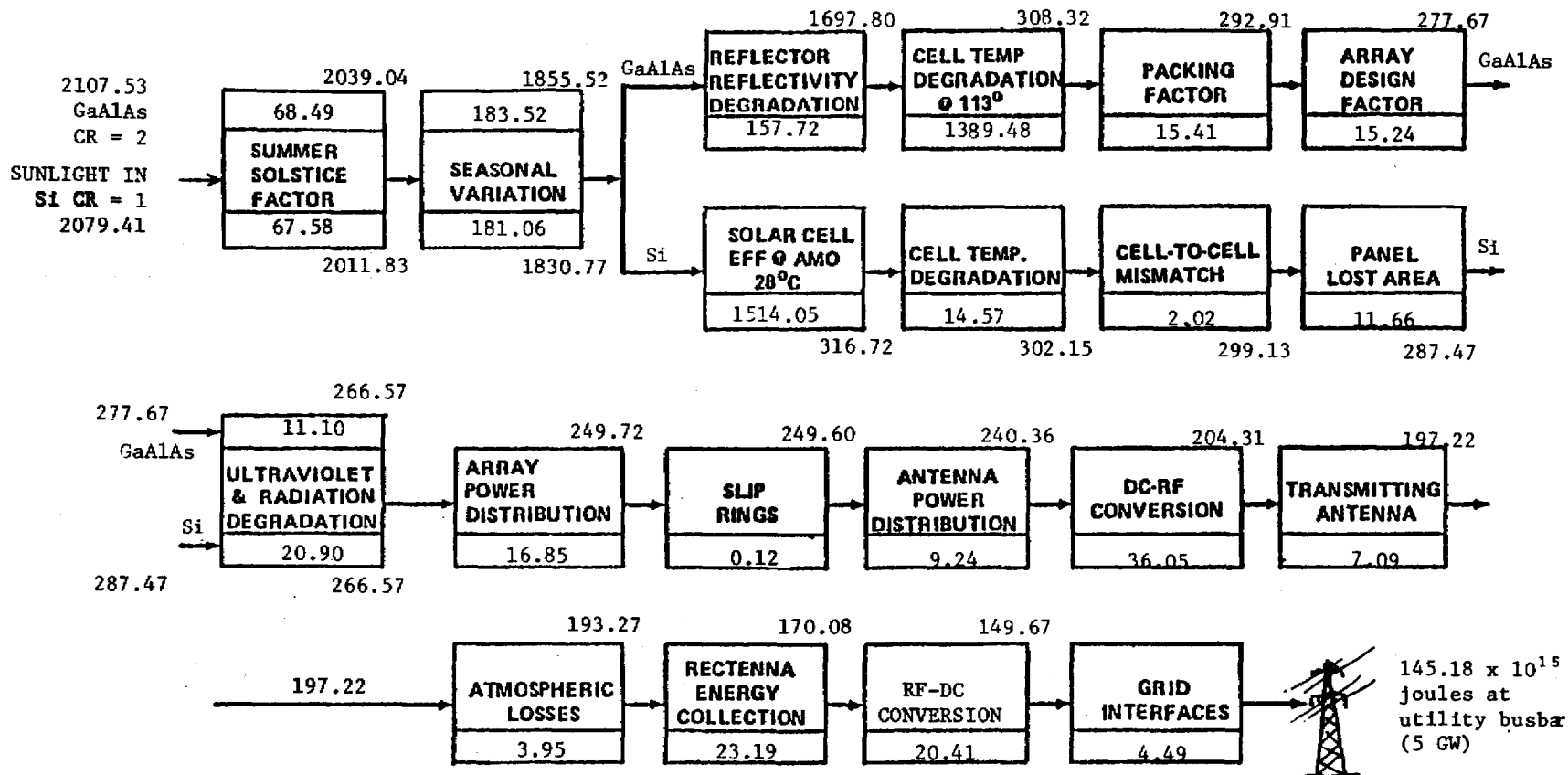145.18 x 10^{15} joules at utility busbar (5 GW)

Fig. E.2. Primary Energy Flow Diagram for SPS (10^{15} J/yr)

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Table E.3. Energy Balance Parameters for SPS

System Element	Annual Primary Input			Total Capital Input: Energy $(10^{15}$ J)	Annual Operating Input: Energy[b] $(10^{15}$ J)	Annual Output, Electricity	
	Type	Quantity $(10^9$ kWhe)	Energy[a] $(10^{15}$ J)			Quantity $(10^9$ kWhe)	Energy[a] $(10^{15}$ J)
Collection System							
Si	Solar Radiation	–	2079.41	–[c]	–	74.05	266.57
GaAlAs	Solar Radiation	–	2107.53	–[c]	–	74.05	266.57
Power Distribution	Electricity	74.05	266.57	–[c]	–	66.77	240.36
Microwave Transmission	Electricity	66.77	240.36	–[c]	–	40.33[d]	145.18[d]
Entire System							
Si	–	–	–	871.246[c]	8.712[b]	–	–
GaAlAs	–	–	–	186.403[c]	1.867[b]	–	–

[a] Energy input and output is computed as the heat content of fuels and materials or joule equivalent of electricity generated.

[b] Annual operating input is assumed to be 30% of capital input, amortized over a 30-yr system lifetime.

[c] Details are shown in Tables E.4 and E.5.

[d] Gross and net: none of the output is tapped for internal use.

Table E.4.   Total Masses of All SPS Program Components

Satellite Program Materials	Mass, Metric Tons			
	Through First 5-GW SPS[a]		Two 5-GW Satellites/Year	
	Si (CR=1)	GaAlAs (CR=2)	Si (CR=1)	GaAlAs (CR=2)
GFRTP	12,447	7,680	12,716	15,360
Stainless Steel	7,621	6,511	11,446	10,610
Glass	33,650	0	38,542	0
Silicon	13,813	0	15,806	0
Copper	8,630	5,030	13,746	9,668
Aluminum	150,654	149,227	284,408	288,244
Silver	37	928	74	1,856
Molybdenum	2	0	4	0
Mercury	89	89	178	178
Tungsten	646	646	1,292	1,292
Steel	1,492,000	1,492,000	2,984,000	2,984,000
Concrete	1,330,000	1,330,000	2,660,000	2,660,000
Gallium Arsenide	7	1,696	14	2,708
Titanium	1,104	856	248	124
Ceramics	458	355	103	52
Misc. & Organics	3,084	8,663[b]	3,700	3,984
Argon[c]	20,559	4,876	18,690	4,664
H_2[c]	107,406	61,227	128,547	80,920
O_2[c]	2,268,033	1,164,528	2,728,506	1,680,710
CH_4[c]	540,572	265,539	651,599	379,930
Sapphire	0	4,213	0	6,752
Teflon	0	1,441	0	2,306
Kapton	0	3,313	0	5,438

[a]The first satellite includes not only transportation and rectenna, but also the orbital staging and construction bases, plus the construction of the cargo orbital vehicles.

[b]Also included is total mass estimates for LEO and GEO construction bases and OTV construction.

[c]Propellants of space transport used for the construction.

Source: Refs. 1 and 6.

Table E.5. Total Capital Inputs for SPS

Material	Satellite[a] Si System t	Si System 10^{15} J	GaAlAs System t	GaAlAs System 10^{15} J	LEO/GEO Construction[b] Si System t	Si System 10^{15} J	Flight Vehicles Si System t	Si System 10^{15} J	GaAlAs System t	GaAlAs System 10^{15} J	Rectenna (both systems) t	10^{15} J	Other Si System t	Si System 10^{15} J	GaAlAs System t	GaAlAs System 10^{15} J
GFRTP[c]	6,359	4.100	7,680	4.950	3,191	2.060	126	0.080	--	--	--	--	2,771	1.785	--	--
Stainless Steel	5,723	0.550	5,305	0.510	498	0.048	321	0.031	347	0.033	--	--	1,079	0.103	859	0.082
Glass	19,271	3.399	--	--	50	0.009	623	0.110	--	--	--	--	13,706	2.418	--	--
Silicon	7,903	395.466[d]	--	--	22	1.101[d]	256	12.810[d]	--	--	--	--	5,632	281.825d	--	--
Copper	6,873	1.757	4,834	1.236	136	0.035	90	0.023	38	0.010	--	--	1,531	0.391	158	0.040
Aluminum	2,204	1.154	4,122	2.159	6,127	3.209	660	0.346	1,026	0.537	140,000	73.332	1,663	0.871	4,079	2.137
Silver	37	0.010	928	0.254	--	--	--	--	--	--	--	--	--	--	--	--
Molybdenum	--	--	--	--	--	--	--	--	--	--	--	--	2	0.001	--	--
Mercury	89	0.016	89	0.016	--	--	--	--	--	--	--	--	--	--	--	--
Tungsten	646	0.116	646	0.116	--	--	--	--	--	--	--	--	--	--	--	--
Steel	--	--	--	--	--	--	--	--	--	--	1,492,000	40.433	--	--	--	--
Concrete	--	--	--	--	--	--	--	--	--	--	1,330,000	4.788	--	--	--	--
Gallium Arsenide	--	--	1,354	26.810	--	--	--	--	38	0.752	--	--	--	--	295	5.841
Titanium	--	--	--	--	--	--	304	0.055	304	0.055	--	--	800	0.144	552	0.099
Ceramics	--	--	--	--	--	--	126	0.023	126	0.023	--	--	332	0.060	229	0.041
Misc. & Organics	1,880	0.338	1,947	0.350	565	0.102	144	0.026	142	0.026	--	--	495	0.089	6,574	1.183
Argon	--	--	--	--	--	--	--	--	--	--	--	--	20,559	0.529	4,876	0.126
Hydrogen	--	--	--	--	--	--	--	--	--	--	--	--	107,406	2.533	61,227	1.444
Oxygen	--	--	--	--	--	--	--	--	--	--	--	--	2,268,033	19.596	1,164,528	10.062
CH4	--	--	--	--	--	--	--	--	--	--	--	--	540,572	15.374	265,539	7.552
Sapphire	--	--	3,376	0.462	--	--	--	--	93	0.013	--	--	--	--	744	0.102
Teflon	--	--	1,152	0.158	--	--	--	--	32	0.004	--	--	--	--	257	0.035
Kapton	--	--	2,719	0.372	--	--	--	--	66	0.009	--	--	--	--	528	0.072
TOTAL	--	406.906	--	37.393	--	6.564	--	13.504	--	1.462	--	118.553	--	325,719	--	28.816

[a]One 5-GW satellite and one rectenna site.

[b]The LEO/GEO construction requirements of the GaAlAs satellite are not completely defined.

[c]Glass fiber reinforced thermoplastic.

[d]Based on 13,900 kWhe/kg for silicon production; current state-of-the-art of manufacturing.

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of these requirements into capital energy investment using the intensity factors from Appendix A.

E.4 IDENTIFICATION OF SENSITIVE DATA

Because of the uncertainties and limitations of data, it is extremely important, but also very difficult at this time, to perform a sensitivity analysis of the SPS. The impact of silicon energy requirements and the energy intensity of other materials have already been discussed in Sect. 4.

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