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An Assessment of the Satellite Power System and Six Alternative Technologies

April 1981

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DOE/NASA
Satellite Power System
Concept Development
and
Evaluation Program

An Assessment of the Satellite Power System and Six Alternative Technologies

April 1981

Prepared by:
T. Wolsko, R. Whitfield, M. Samsa, L. S. Habegger,
E. Levine and E. Tanzman
Argonne National Laboratory
Argonne, IL 60439

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DEFINITIONS OF UNIT SYMBOLS

Btu: British thermal unit
°C: degrees celsius
Ci: curie (unit of radioactivity)
cm: centimeter
d: day
dB: decibel
dBa: decibel, adjusted
°F: degrees Fahrenheit
g: gram
GHz: gigahertz (10^9 cycles per second)
GW: gigawatt (10^9 watts)
h: hour
J: joule
kg: kilogram (10^3 grams)
kJ: kilojoule
km: kilometer
kV: kilovolt
kW: kilowatt
kWh: kilowatt-hour
L: liter
lb: pound
m: meter
mL: milliliter (10^{-3} liter)
mW: milliwatt
MeV: mega electron-volt (10^6 electron-volts)
MW: megawatt
MWe: megawatt (electric energy)
MWt: megawatt (thermal energy)
MW-yr: megawatt-year
μm: micrometer (10^{-6} meter)
N: newton (unit of force)
N/m^2:   newton per square meter
Pa: pascal (unit of pressure: 1 Pa = 1 N/m^2)
Q: quad (10^{15} Btu)
s: second
t: metric ton (1000 kilograms)
T: tesla (unit of magnetic force); also English ton
W: watt
yr: year

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EXECUTIVE SUMMARY

The SPS Concept Development and Evaluation Program (CDEP)[1] was established by the Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA) to generate information by which a rational decision could be made regarding the direction of the Satellite Power System (SPS) program after fiscal 1980. The four functional areas within the joint DOE/NASA CDEP are as follows:

- Systems Definition: development of the SPS reference system design.

- Environmental Assessment: evaluation of potential environmental effects of SPS.

- Societal Assessment· evaluation of potential societal effects of SPS.

- Comparative Assessment: development of a comparative data base on the SPS and six other energy technologies.

The results of the first three activities are inputs to the comparative assessment process as well as independent program assessments.

This report concerns the comparative assessment portion of the CDEP. The objective of the comparative assessment is to develop an initial understanding of the SPS with respect to a limited set of energy alternatives. This is consistent with the overall CDEP objective, that is, to determine whether or not the SPS concept is sufficiently attractive (presenting no insurmountable barriers) to receive further research investment.

In all comparative assessments it is vital that the assumptions, uncertainties, and significant differences between the systems being compared are clearly and objectively presented. Otherwise, the comparison may prove useless for making meaningful decisions. The key assumptions and ground rules made in this report are as follows:

1. The baseload electric generation technologies are projected to be on line in the year 2000, with an approximate availability date of 1990. Further, the R&D base and the infrastructure are assumed to be in place when required.

2. All data are traceable to publicly available information.

3. Each technology is treated as an independent variable. For example, if coal costs go up or down, the costs of the other technologies are assumed not to change for the same reasons.

4. When no historical data or basic reports were available, the analysts have specified the conditions they have chosen and presented their rationales for doing so. In cases where the chosen conditions have favored or disfavored a technology, the analysts have stated the bias.

The SPS, fusion, and central-station terrestrial photovoltaics technologies have received less engineering design and R&D than the other technologies examined in this assessment. Therefore, they are subject to larger uncertainty as well as greater optimism. Furthermore, the life cycle costs of these three technologies are reduced, since the R&D and infrastructure costs are not addressed explicitly, in keeping with the second part of the first assumption.

The third assumption tends to exaggerate cost overlap, but taking correlated characteristics into account was not feasible in this study except in a theoretical way. The choices made under the fourth assumption tend to favor the two solar technologies and fusion.

The intent of the data derived under these assumptions is to compare SPS to each of the other six technologies, or to subsets of the six, or to all six technologies together. The limitations resulting from the assumptions preclude other comparisons. Within these assumptions and ground rules, the six limited but representative energy technologies were selected, characterized, and documented. These data were normalized to unit bases, such as dollars per megawatt or environmental residuals per megawatt, and alternative futures were compared (i.e., possible technology mixes, supply and demand cases, and resultant environmental, resource, and cost uncertainties).

The technology alternatives selected for comparison with the SPS were limited to the following:

- Improved conventional coal technology

- Light water reactor (LWR)

- Coal gasification/combined cycle (CG/CC)

- Liquid-metal, fast-breeder reactor (LMFBR)

- Central station, terrestrial photovoltaic (TPV)

- Fusion (magnetically confined)

These selections were considered to be the most representative set of year-2000 energy technologies for comparison to the SPS reference system. It should be noted that the selections were not made by DOE, but by the Concept Development and Evaluation Program.

A six-step comparative methodology is described briefly in this report and more thoroughly in a companion report.[2] This assessment included only five of the six steps (i.e., selection of alternatives, issue selection, system characterizations, side-by-side analysis, and alternative futures analysis).

This assessment represents an update of the preliminary side-by-side comparative assessment[3] and has added an alternative futures analysis. The update includes changes in the technology descriptions as well as improvements in the comparative analyses.

Included in this document are a brief description of the comparative methodology, brief characterizations of the alternative technologies,

side-by-side comparisons in selected issue areas, alternative futures analysis for three different scenarios and most issues, and conclusions on the comparative viability of the SPS technology.

The issue areas used for comparisons were (1) cost and performance, (2) health and safety, (3) environmental welfare, (4) resources, (5) macroeconomic and socioeconomic, and (6) institutional. The comparisons were performed for technologies that are at different stages of development -- current, near-term, and advanced -- and which therefore have different degrees of information available (e.g., actual vs. projected construction data). Table 1 lists experience and uncertainty levels for the technologies evaluated in this assessment. Capital cost uncertainty factors and cost uncertainty issues are also listed. These cost uncertainty factors were developed on the basis of existing relevant documentation and on the judgments of the assessment participants.

As stated earlier, the information presented and developed in these comparisons has been derived from published research and information found in the literature for the various technologies. However, in some instances, data have not been available from such sources, and it has been necessary to develop these data either through analysis or on the basis of engineering judgment. In these instances, the rationales are explained and the inherent uncertainties duly noted.

Table 1 Developmental Status of the Technologies
Selected for Comparison

Technology	Units in Operation	Capital Cost Uncertainty Rating	Cost Uncertainty Issues
Conventional Coal	100	2	Fuel, ECT[a]
LWR	50	2	Fuel, ECT
CG/CC	5	3	Fuel
LMFBR	5	3	Fuel, ECT
TPV	0	4	Materials, cell efficiency
SPS	0	4-5	Materials, ECT, Space Transport, and Construction O&M
Fusion	0	4-5	Materials, Containment Design, ECT

[a]ECT - Environmental Control Technology.

Cost and performance characterization data for the alternative technologies are presented briefly in Sec. 3 and form the basis for the comparisons that are reported in Sec. 4. Cost data for the SPS were obtained from NASA-sponsored Boeing and Rockwell systems design efforts. Cost estimates for the alternative technologies were developed from reference design reports.

ALTERNATIVE TECHNOLOGY CHARACTERIZATIONS

Six alternative technologies were selected for comparison with the SPS; their major characteristics are displayed in Table 2. The general approach was to review a broad segment of the recent technical literature concerned with the characteristics of the individual technologies and their accompanying fuel cycles. This data base of information was then synthesized into the alternative technology reference characterizations by adapting the data into internally consistent energy and materials balances for each of the systems. Where appropriate, a nominal generating capacity of 1250 MWe was selected for the reference technologies. Only the terrestrial photovoltaic and fusion systems differ from this nominal capacity due to special considerations unique to ea h system.

An integral part of the energy and materials balances was the determination of natural resource requirements such as land, water, fuels, and other raw materials, and the determination of environmental residuals including air-borne emissions, liquid effluents, and solid and radioactive wastes. These parameters have been estimated for the main plant site and for major elements of the respective fuel cycles.

The final step in the characterization procedure was to estimate the capital construction costs, labor requirements, and annual nonfuel operation and maintenance (O&M) costs for each alternative reference system. Detailed lists of equipment, materials, and site labor requirements from the Energy Economic Data Base (EEDB) and other major references were used as the basis for estimating the direct and indirect capital construction costs and construction labor requirements for many of the systems. For technologies not included in the EEDB, similar data from other major references was used. All costs are presented in 1978 dollars.

Direct capital costs include the costs of all materials, components, structures, and direct labor necessary for construction of the reference facility at the plant site. Indirect costs include temporary site construction facilities, payroll insurance and taxes, and other construction services. Excluded are items sensitive to the particular policies of individual utilities, including owner's costs, fees and permits, interest on construction funds, contingency funds, and price escalation during construction.

Nonfuel O&M costs were derived on the basis of labor requirements, disposal and materials handling costs, and other factors applicable to the respective technologies. Decommissioning costs for each of the nuclear systems are also included. Fuel costs for each of the systems are scenario-dependent and will be estimated as part of the subsequent cost and performance analysis.

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Table 2 Major Characteristics of Alternative
Central Station Technologies*

Characteristic	Conventional Coal with Advanced FGD	LWR, Improved Fuel Use	CC/CC	LMFBR	TPV	Magnetic Confinement Fusion
Major Feature	Wellman-Lord SO_2 Removal	Fuel Burn up 50 MWd/kg U	32 Fixed-Bed Gasifiers	Uranium/ Thorium Fuel Cycle	Cell Efficiency Like SPS	NUWMAK Concept
Nominal Capacity (MWe)	1,250	1,250	2 @ 625	1,250	200	2 @ 660
Heat Rate (Btu/kWh)	9,546	10,224	8,865	9,330	NA	10,835
Conversion Efficiency (%)	35.8	33.4	38.5	36.6	14.2	31.5
Air Emissions						
Plant Site						
SO_2 (T/yr)	21,200	-	11,090	-	-	-
NO_x (T/yr)	22,000	-	2,320	-	-	-
Particulates	250	-	200	-	-	-
Radionuclides (Ci/yr)	-	4,100	-	155	NA	730.
Fuel Cycle						
SO_2 (T/yr)	290	6,040[a]	270	6	NA	-
NO_x (T/yr)	220	1,600[a]	205	23	NA	-
Particulates	1,300	1,550	1,200	1	NA	-
Radionuclides (Ci/yr)	-	95	-	409,500	NA	-
Solids and Sludges						
Plant Site						
Dry Sulfur (T/yr)	95,565	-	91,725	-	NA	-
Ash Sludge (T/yr)	426,490	-	317,060	-	NA	-
Other (T/yr)	18,400	b	18,600	b	c	b
Radionuclides (Ci/yr)	-	11,000	-	33,000	NA	9,000[d]
Fuel Cycle Solids (T/yr)	113,600	215	105,650	1	NA	-
Liquid Effluents						
Plant Site						
Total Solids (T/yr)	16,000	1,330	16,000	1,330	-	c
Radionuclides (Ci/yr)	-	405	-	482	NA	c
Fuel Cycle						
Total Solids (T/yr)	5,220	-	4,850	-	NA	-
Radionuclides (Ci/yr)	-	1,500	-	c	NA	-
Water Use (10^6 gal/day)	70	33	13	29	-	37
Land Use						
Plant Site (acres)	500	500	500	500	1,000	500
Fuel Cycle (acres/yr)	250	22	235	1	NA	-
Labor Requirements						
Plant Construction						
(10^6 man-hours)	9.3	15.5	13.4	12.7	1.7	17.4
Plant Operation (persons)	259	215	336	225	26	c
Fuel Cycle (persons)	650	225	605	c	NA	-
Costs (1978 dollars)						
Direct (10^6 $)	452.1	486.0	537.4	702.9	117.5	1,533.2
Indirect (10^6 $)	90.7	197.1	132.7	262.6	20.0	628.6
Total (10^6 $)	542.8	683.1	670.1	965.5	137.5	2,161.8
Total ($/kWe)	434.2	546.5	536.1	772.4	687.5	1,637.7
O & M Cost (mills/kWh)	3.1	2.2	2.7	2.9	3.4/4.6[e]	7.3
Operating Factor (%)	70	70	70	70	25.8/19.1[e]	70

NA: Not Applicable.   [c]Not estimated

-: Small or Negligible   [d]After 10 yrs of on-site storage

[a]98% due to supporting power production   [e]Values for Phoenix/Cleveland

[b]Quantified in terms of Ci/yr

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*Conversion factors: Btu x 1.06 = kJ; T x 0.907 = t; gal x 0.0038 = m^3; acres x 0.004 = km^2.

ALTERNATIVE FUTURES SCENARIOS

Since the objective of this comparative assessment is to compare technologies projected for the post-2000 era, a great number of assumptions are required. Most of these assumptions are highly uncertain and inter-dependent so that a single consistent set may not present the decision maker with an adequate comparative perspective of the future. The alternative future analysis was chosen as a means of providing a broader perspective of key parameters that may describe the future. The assumptions underlying the alternative futures analysis constitute a set of energy supply/demand futures or scenarios.

Six scenarios were created from a consistent economic model so that interdependencies between economic assumptions were preserved. Scenarios were selected as a means of exploring and analyzing, not predicting, the economic energy future. The scenarios were selected to represent a plausible future world, and no probabilities were assigned to any of them. Scenarios were selected to provide a comparative perspective on the negative and positive aspects of demand and mixes of supply technologies in the post-2000 era.

A model developed by Resources for the Future, Inc. (RFF)[4] was selected for this assessment on the basis of several selection criteria -- sectoral detail, endogenous treatment of both capital investment and final demand, and transferable experience in the form of existing model runs covering the desired time frame, 2000-2030.

One GNP trajectory was selected for all scenarios. For simplicity, three alternative price elasticities of aggregate demand for energy were considered, viz.,

H: High energy intensiveness, corresponding to low
   elasticity (-0.25);

I: Intermediate energy intensiveness, corresponding to
   intermediate elasticity (-0.4 for residential and
   housing demand, -0.7 for industry, 0 for feedstocks);

I: Low energy intensiveness, corresponding to high
   elasticity (-0.75).

Regarding constraints, two cases were selected:

U: Unconstrained supply of coal and nuclear power;

C: Constrained supply, due to health, safety,
   environmental, and other limitations on the rate
   of supply increase.

The three price elasticities and two different constraints resulted in the development of six scenarios. Each of these scenarios resulted in different supply-demand patterns and different fuel (i.e., coal and nuclear) price trajectories. Three of these six scenarios [i.e., unconstrained high energy (UH), unconstrained intermediate energy intensity (UI), and constrained intermediate energy intensity (CI)] were selected for the alternative futures comparisons.

COST AND PERFORMANCE

Table 3 shows the nominal capital costs and capital cost uncertainty factors that were developed for the SPS and the six alternative technologies. The following three factors were considered to include the major capital cost uncertainties and were used to derive the capital cost uncertainty ratios shown in Table 3.

1. Uncertainty about future costs of materials, supplies, and labor necessary to construct powerplant facilities;

2. Uncertainty about the future requirements and associated costs of environmental and safety equipment; and

3. Uncertainty about the capability of technologies to perform as conceptualized.

The analysis of the alternative energy supply/demand scenarios resulted in the range of fuel prices shown in Fig. 1. The range of coal prices seems to bracket forecasts made by others, and the light water reactor fuel price is similar to that in other projections.

The capital cost ranges and scenario-dependent fuel prices were used to calculate levelized energy cost ranges for each technology. Table 4 shows the levelized energy cost ranges for the SPS and the six alternatives for scenario CI (constrained coal and nuclear, intermediate energy demand). Similar energy cost ranges were calculated for other scenarios with similar cost ranges. These cost ranges were developed with independent reference costs so that the degree of overlap between coal and nuclear technologies and the SPS systems is not as large as shown in Table 4, because there is probably some correlation between the SPS cost base and coal/nuclear data bases that are not accounted for in these calculations.

Table 3 Capital Cost Ranges for Technical and Regulatory Uncertainty ($/kW)

Costs	Coal	LWR	CG/CC	LMFBR	TPV	Fusion	SPS
1978 Costs (Nominal)	549	712	690	1037	344	2378	3340/3079
2000 Costs							
Low	647	886	813	1291	731	2378	3139/2874
Nominal	762	1100	957	1603	1057	3677	3646/3362
High	1605	2566	2623	5048	4229	?	16,698/ 15,398
Cost Ratios:							
2000 Low/1978 Nominal	1.18	1.24	1.18	1.24	0.87	1.00	0.94/0.94
2000 Nominal/2000 Low	1.18	1.24	1.18	1.25	1.45	1.55	1.16/1.16
2000 High/2000 Nominal	2.11	2.33	2.74	3.14	4.00	?	4.58/4.58

Table 4 Levelized Energy Cost Ranges for Scenario CI[a]

Technology	Cost, (1978) mills/kWh		
	Low	Nominal	High
SPS			
Si	45.6	52.1	218.1
GaAlAs	42.3	48.5	201.7
Coal			
Conventional, High-S	-	41.1	54.8
CG/CC	-	42.0	69.0
Nuclear			
LWR	-	30.0	53.8
LMFBR	-	35.1	90.9
TPV	36.6	51.4	195.7
Fusion (NUWMAK)[b]	-	74.0	-

[a]This constrained scenario represents continuation and augmentation of current regulatory trends concerning emissions, health, and safety. The price elasticity of energy demand is assumed to be moderate (intermediate), which is considered the most likely situation if constraints are maintained.

[b]No range was established for the cost of energy from fusion.
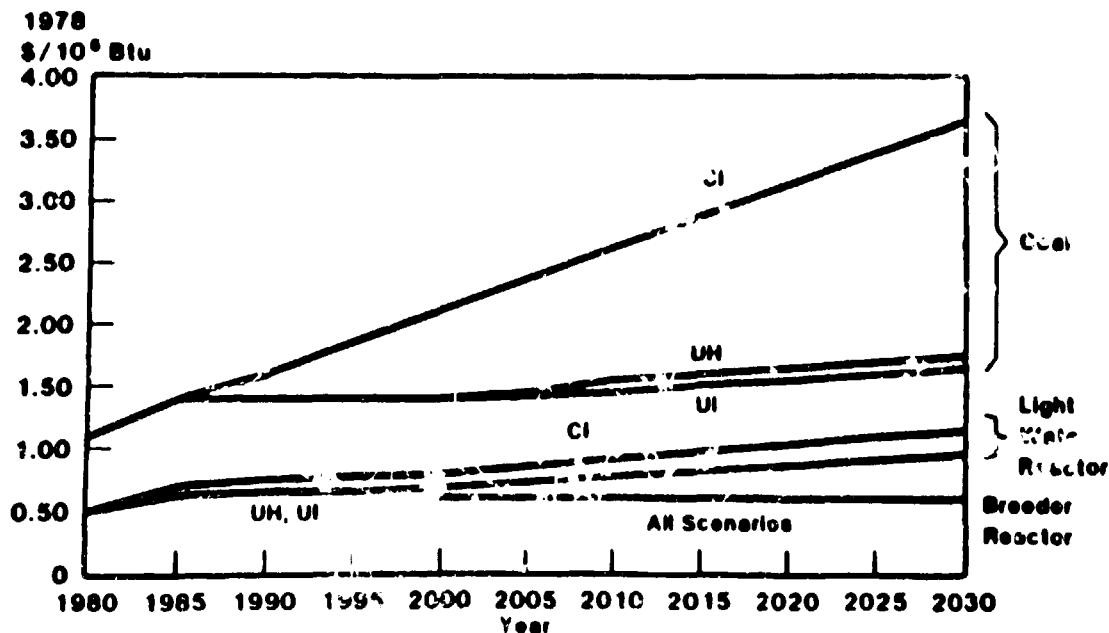
Fig. 1 Fuel Price Projections for Different Scenarios

DEVELOPMENT COSTS

Boeing[5] estimated development costs on the basis of the reference system scenario, which predicates a 20-year development schedule and a 30-year deployment schedule (for 60 5-GW satellites). These costs amount to $100-110 billion and are broken down as follows (Fig. 2):

- Research costs: mainly ground-based research to address environmental and social issues and alternative systems, resulting in a preferred system;

- Engineering: development and testing of prototype sub-systems, resulting in specifications for demonstration units and production facilities;

- Demonstration: flight tests of a 100-200 MW unit integrated with a commercial network;

- Investment: development of industrial infrastructure, e.g., transportation, photovoltaic, and klystron manuf.   ir facilities.

  Construction and implementation: the first 5-GW SPS   into place.

It is important to note that these cost estimates assume that all effor specific to the SPS. The benefits from generic research or from cost s. ing (e.g., industry or other federal program support for photovoltaics manufacturing facilities) have not been considered. Such cost modif.cations could amount to 50-70% of the $102.5 billion.[7]

Since comparable cost data for the other six technologies were not available, side-by-side comparisons of costs or of the benefits or disadvantages of public expenditures were not attempted.

Fig. 2   Development Costs of the SPS
(Source: Ref. 6)

HEALTH AND SAFETY

The comparison of health and safety aspects of advanced and current technologies is not possible on the basis of total quantified risk because of the uncertainties and unquantifiable impacts for all the technologies, even current coal and nuclear technologies. The health and safety issues can best be summarized as follows:

- All the technologies will have distinct health and safety impacts.

- It is difficult to quantify and assess the low-level and delayed impacts of all the technologies.

Assessing the health and safety risks required three major tasks: detailed characterization of each phase of the fuel cycle; analysis of the magnitude of risk associated with each identified issue; and accumulation of risks by technology, risk category, and generation scenario. Each segment of the energy cycle was considered, including component fabrication, plant construction, fuel extraction and processing, operation and maintenance, and waste disposal. In addition, an uncertainty index was assigned to each issue to reflect the uncertainty in the magnitude of the impact. Figure 3 shows the total quantified construction and O&M fatalities per MW/yr for SPS and five alternative technologies.
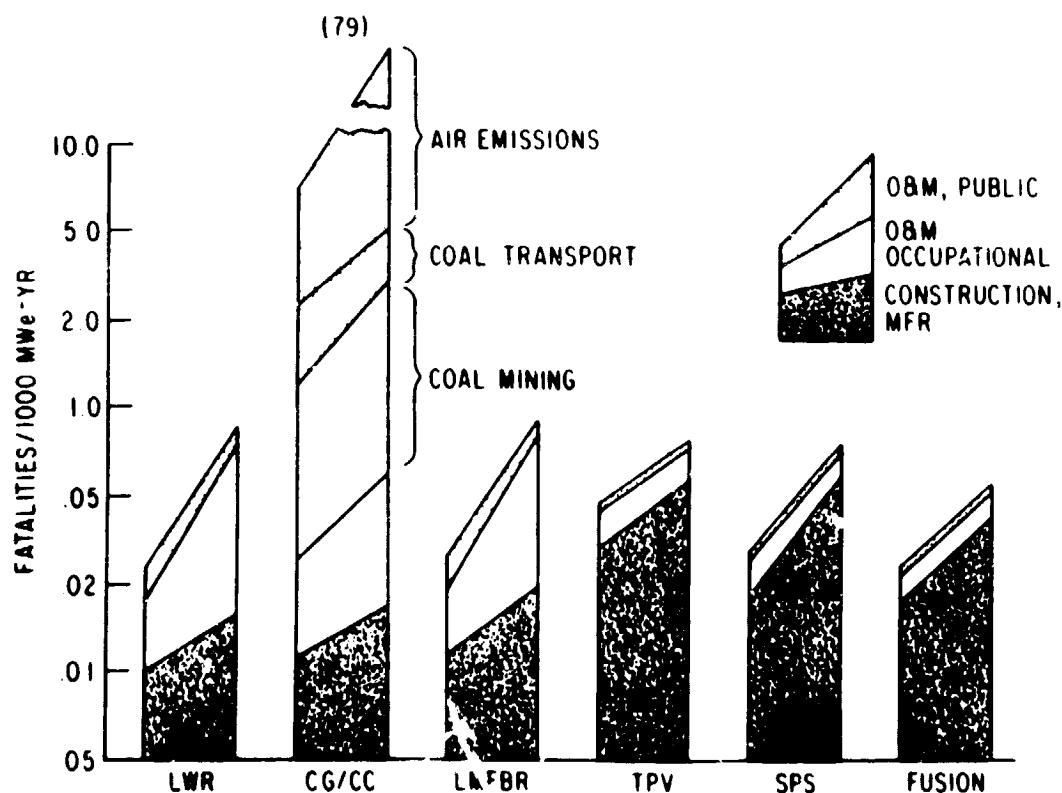
Fig. 3 Total Quantified Construction and
O&M Fatalities per 1000 MW-yr

Of the various systems considered, the coal technology has the largest overall quantified risk, primarily due to coal extraction, processing and transport, and air-borne emissions, although large uncertainties remain in the actual effect of the air-borne emissions. On the other hand, additional issues that are potentially major but remain largely unquantifiable were not identified for the coal system. Quantified risks from the remaining technologies (fission, fusion, SPS, and centralized terrestrial photovoltaic) are comparable within the range of quantified uncertainty. The occupational risks for component production, both direct and indirect, are a substantial fraction of the total risk, in particular for the advanced, capital-intensive solar and fusion technologies.

ENVIRONMENTAL WELFARE

Environmental effects not related to health and safety are classified here as environmental welfare effects, e.g., weather modification by carbon dioxide, materials degradation, electromagnetic interference with communications, aesthetics, and noise. Welfare effects were identified at each part of the fuel cycle and were categorized by the environmental impact (e.g., air pollution) that produced the welfare effect (e.g., crop damage). In summary, each technology produces environmental effects that affect society in different ways. With the exception of the CO_2 climatic effects from coal combustion, all the technologies appear to be equivalent with regard to environmental welfare problems.

RESOURCES/MACROECONOMIC/INSTITUTIONAL ISSUES

Three areas important in the comparative assessment of energy technologies are resource requirements, macroeconomic effects, and institutional considerations. The scenarios (alternative energy futures) developed as part of the SPS Concept Development and Evaluation Program were used to provide another perspective on the land and water resources required; macroeconomic results followed from the scenario development activity. The institutional analysis, completed before development of the scenarios, focused on regulatory issues.

Land requirements were first derived on a normalized basis for each of the energy technologies. The land requirements (in km^2 per 1,000 MW of installed capacity) used in this study are: 10 for coal, 3 for light water reactor (LWR), 2 for liquid metal fast breeder reactor (LMFBR), 20 for terrestrial photovoltaic (TPV), 35 for SPS, and 2 for fusion. These amounts include (where appropriate) land requirements for resource and fuel extraction, processing, the power plant site itself, and waste disposal. Transmission requirements are not included because they have been shown to be about the same for all technologies, particularly in view of studies indicating that 60 SPS rectennas can be sited within 300 miles of a load center. Scenario-driven results shown in Fig. 4 for the 1980 to 2030 time period in .ate that total land use (excluding transmission) increases 0-500% without SPS and 100-900% with SPS, whereas electrical energy demand increases 75-850% by the year 2030. The land required by SPS alone in the year 2030 is 2-6 times the total land in use for electrical generation in the United States today. The availability of additional land for power plant sites has not been determined.
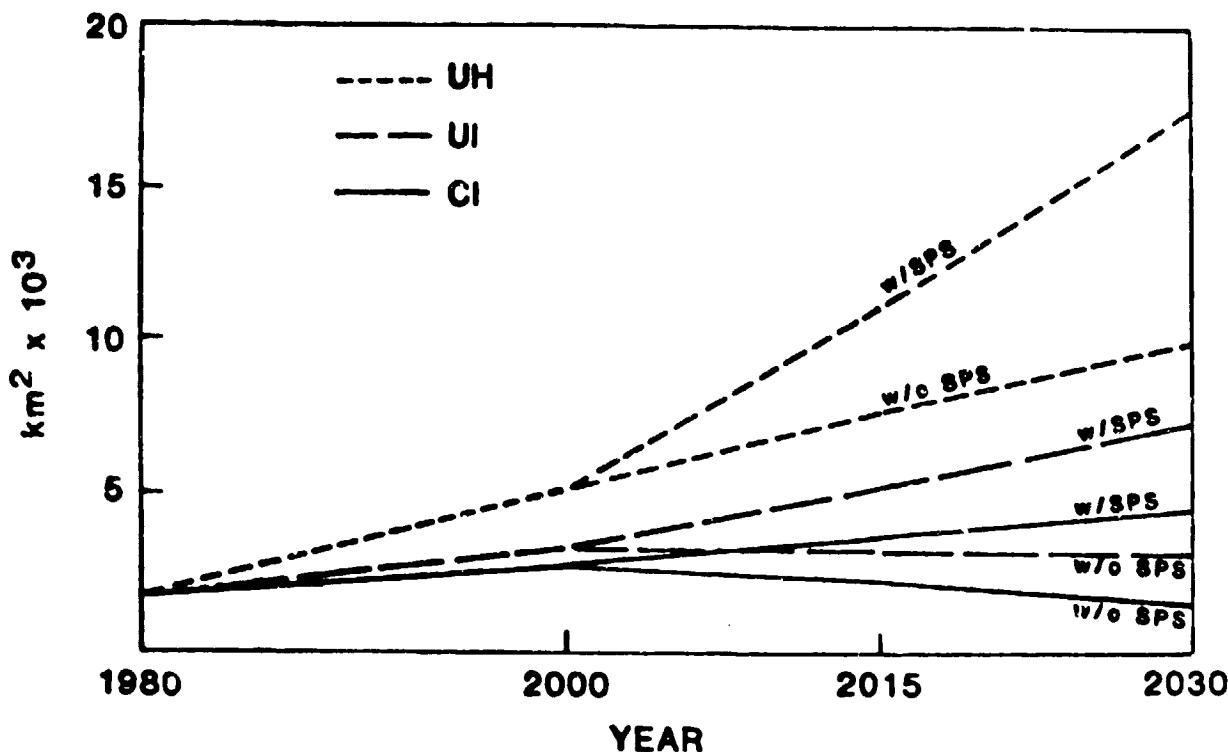
Fig. 4 Alternative Futures Analysis of Land Requirements

The need for large contigious areas, as for SPS rectennas, is a further complicating factor.

Water use in $m^3 \times 10^6/GW/year$, is 22 for coal, 60 for LWR, 22 for LMFBR, 12 for fusion and negligible for TPV and SPS. Total water requirements for the three scenarios, with and without SPS, are shown in Fig. 5. Results indicate that deployment of SPS can save large volumes of water; in scenario CI, SPS saves an amount equal to 40% of the total used in 1980 for baseload electrical generation by coal and nuclear; in scenario UH, the saving is 170% of today's total.

Due to large uncertainties in determining the resource/reserve levels for both the United States and the world, the analysis of materials problems was less quantitative than the land and water analyses. A screening methodology included a reliance on imports as a criterion as well as availability and total demand considerations. These screening factors identified gallium as being a material of serious concern. Gallium is used extensively in the GaAlAs solar cell option for SPS. Also of serious concern is tungsten, which is used both in SPS and coal technologies.

Net energy analysis shows that the payback period for most of the technologies studied is small (less than 1.5 years). The payback periods for the SPS GaAlAs option, coal, and the nuclear options are about one year, and those for the SPS Si option and TPV (silicon cells) are about 6 and 20 years, respectively. Thus, the GaAlAs design affords SPS with an option that compares favorably with conventional technologies on a net energy basis.
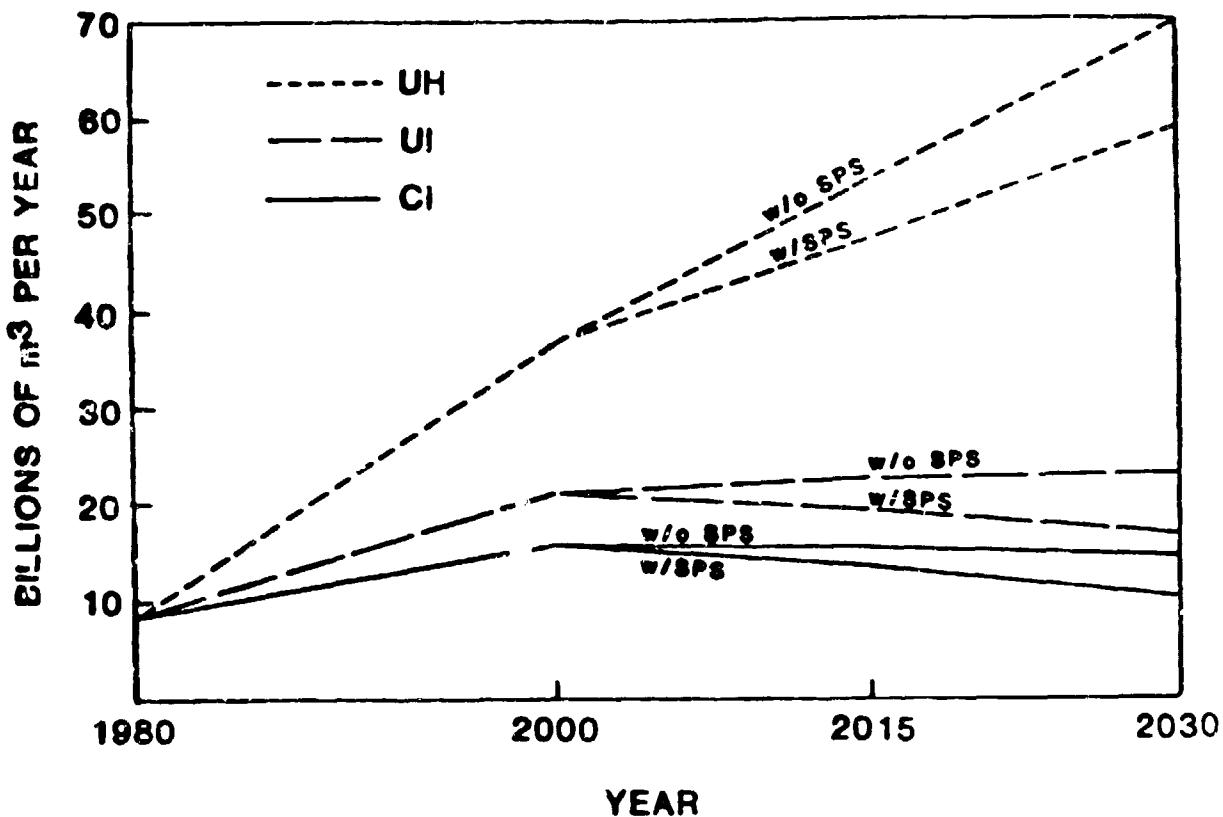
Fig. 5   Alternative Futures Analysis of Annual Water
Consumption for Baseload Electricity Generation

Macroeconomic analyses included the calculation of changes in GNP for
the year 2000 and, in qualitative terms, the effect on inflation due to
deployment of the SPS. Using a target GNP of $3.7 trillion (all figures in
1978 dollars) for the year 2000, deployment of 10 GW of SPS power will require
$20 to $50 billion of excess investment compared to the least expensive option
(coal). This is 10 to 15% of $200 billion, the amount available for financing
economic growth of about 2.3% per annum. Compounded to the year 2030, such a
reduction would result in a $200 to $500 billion reduction in the target GNP
of $7 trillion.

If uranium and coal fuel supplies are much more contrained than
presently envisioned, then deployment of SPS would reduce consumption of these
scarce items and possibly reduce their prices. This could in turn reduce
total energy expenditures, as indicated in Table 5. For the UH and UI
scenarios, SPS energy costs of about 40-50 mills/kWh would result in a
breakeven from the point of view of total energy expenditures.

The institutional analysis focused on the regulatory aspects of
electricity generation by coal, nuclear, and the SPS. The technologies were
characterized relative to one another, and justifications for regulation, the
level of governmental responsibility, and the cost of regulation were con-
sidered. Studies estimate that the annual cost of regulating the nuclear
industry is about $6 billion, versus about $3.4 billion for coal. In view of
the changing regulatory environment (e.g., the decentralization movement and
the growth of power on the local level), SPS regulatory costs may look more
like nuclear regulatory costs than coal regulatory costs. Regulatory costs

Table 5   Net Change in Annual Energy Expenditures
Due to the SPS (1978 $ x 10^9)

Year	Scenario (mills/kWh)					
	UH		UI		CI	
	60	120	60	120	60	120
2015	8	79	4	34	-12	11
2025	14	132	6	56	-20	19
2030	16	158	8	67	-25	23

for SPS could be significant compared to SPS investment costs, particularly in a low deployment rate (3.3 GW/yr) scenario.

CONCLUSIONS

This comparative assessment analyzed each technology issue by issue (side-by-side analysis), and then evaluated the technologies, given different post-2000 economic climates and the economic trajectories that would lead to those climates (alternative futures analysis). Conclusions were formed separately for these two types of analyses and are summarized in the following tables. Tables 6 to 11 summarize the comparison among the seven technologies issue-by-issue. Comparisons are described in terms of key issues, uncertainty about the understanding of those issues and a concluding comparative statement that cuts across all technologies for that issue area.

Table 12 describes the six mixes of technologies that were analyzed in terms of meeting the energy demand for two different scenarios (i.e., UH and CI). Tables 13 and 14 summarize comparative conclusions about mixes of technologies from an energy supply/demand perspective. In these tables, the comparative analyses are described briefly, issue by issue, for each of the energy supply alternatives.

Table 6 Cost and Performance: Key Issues, Uncertainties, and Comparative Conclusions

System	Key Issues	Uncertainties	Comparative Conclusions
Coal (Conventional, CG/CC)	Capital cost expected to escalate only slightly but coal price would raise energy price substantially.	Coal price uncertain but dependent on amount of demand and environmental regulations.	SPS is economically competitive with coal and nuclear if fuel prices rise sharply and environmental regulations raise the capital cost of these technologies. However, if the regulatory climate is severe for coal and nuclear it may also affect SPS. The probability that SPS will be cost competitive with coal is very small until well after 2000.
Nuclear (LWR, LMFBR)	Capital cost will probably escalate due to environmental and safety regulations. Uranium prices expected to increase.	Capital cost increases are uncertain.	
TPV	Costs depend strongly on cell production cost.	Large improvements required in cell cost.	SPS has approximately the same cost range as TPV and fusion, but the range is very large and no judgments can be made regarding any cost advantages. More detailed cost evaluations and design studies would be required to evaluate the relative economic viability of the advanced technologies.
SPS	Capital cost and system efficiency dominate energy cost.	Cell cost; transportation cost, and system performance are all uncertain.	
Fusion	Containment costs cannot be estimated very well.	Plasma containment cost is highly uncertain. System performance and reliability unknown.	

Table 7 Health and Safety: Key Issues, Uncertainties, and Comparative Conclusions

System	Key Issues	Uncertainties	Comparative Conclusions
Coal (Conventional, CG/CC)	Coal extraction, transportation and air pollution are the main contributors to impacts. All issues are well-defined.	Data still not accepted for air pollution but more defined than other issues.	SPS has no health advantage over other technologies. Problems are different and less defined. Quantified impacts of coal are highest but this is the most studied technology. The problem of SPS microwave impacts is similar to low-level ionizing radiation and low-level air pollution: it is difficult to quantify the impact, but it will concern many people. This is a potential problem for SPS that does not have a short-term solution.
Nuclear (LWR, LMFBR)	Most impacts are occupational. Low-probability catastrophic impacts affect the perception of this technology.	Low-level radiation impacts are uncertain.	
TPV	Extraction of materials for and manufacture of solar cells are the main contributors to impacts. Construction and maintenance of facilities will have large safety impacts.	The production industry may have large impacts.	
SPS	Extraction of raw materials and component manufacture are key problems. Other problems of key concern remain unquantified or undetermined.	Impacts on space worker health are uncertain. Low-level microwave effects are uncertain.	
Fusion	Tritium release.	Tritium pathways are not well-defined.	

Table 8 Environmental Welfare: Key Issues, Uncertainties, and Comparative Conclusions

System	Key Issues	Uncertainties	Comparative Conclusions
Coal (Conventional, CG/CC)	CO_2 climate impacts dominate the issues.	CO_2 uncertainty.	Each technology has a different set of environmental welfare problems. The CO_2 problem has the greatest catastrophic potential, but CO_2 from electricity production is only a small part of the overall problem. Microwave problems will not be solved for many years, possibly not until after a system is built and operated.
Nuclear (LWR, LMFBR)	Radiation waste disposal. Safeguards problems.	Waste disposal technology performance is unproven.	
TPV	No significant environmental welfare issues were identified.		
SPS	Electromagnetic interference is a large issue. Microwave radiation may have ecological impacts on agriculture.	Microwave impacts (e.g., communications interference, ecological impacts) are highly uncertain.	
Fusion	No significant issues were identified because the technology is not completely defined.		

Table 9 Resources: Key Issues, Uncertainties, and Comparative Conclusions

System	Key Issues	Uncertainties	Comparative Conclusions
Coal (Conventional, CG/CC)	Water contamination is the only issue.	No large uncertainties.	Large contiguous land consumption is the biggest resource issue for SPS. No other resource problem is as important with the possible exception of uranium fuel supplies for the LWRs.
Nuclear (LWR, LMFBR)	Uranium supply could be limited after 2000.	Uranium supply is uncertain for LWR.	
TPV	Large land areas are required. Energy payback is low.	Energy intensity of cell production is uncertain.	
SPS	Large contiguous land use. Some materials problems.	Microwave health and safety regulations may require an even larger buffer zone - even more total land.	
Fusion	No serious problems.		

Table 10 Economic/Societal Issues: Key Issues, Uncertainties, and Comparative Conclusions

System	Key Issues	Uncertainties	Comparative Conclusions
Coal (Conventional, CG/CC)	Regional economic impacts are a problem in the West, but have been well-studied.		Because it is a new technology entailing many new industries, SPS would require a large investment in the infrastructure. This, coupled with the capital intensiveness of the technology, would mean that SPS could have the largest effect on the GNP and the economy. Regional impacts of implementing nuclear technology (fission, fusion) are less significant than those of other technologies.
Nuclear (LWR, LMFBR)	Possible opposition to wide deployment of nuclear technology by some sectors of the public.		
TPV	Regional implementation expected. Large capital requirements.	Industrial infrastructure not described.	
SPS	Capital cost and infrastructure investments could affect GNP. Regional effects are likely. Possible public opposition.		
Fusion	No estimates of infrastructure and R&D costs.		

Table 11 Institutional Issues: Key Issues, Uncertainties, and Comparative Conclusions

System	Key Issues	Uncertainties	Comparative Conclusions
Coal (Conventional, CG/CC)	Coal is heavily regulated.	Regulations may increase or decrease.	Although regulations on coal and nuclear technology have been important, SPS faces perhaps the largest challenge because of its far-reaching nature. The international restraints due to orbit ownership, microwave transmission, and space transportation are probably the most serious.
Nuclear (LWR, LMFBR)	Regulations have and will affect designs, deployment, and operation.	How inhibiting future regulations will be is uncertain.	
TPV	Regulatory impacts are undefined, but hazardous materials are sure to fall under strong regulations.		
SPS	Regulations could affect SPS severely because of many areas of impact (e.g., transportation, orbits, microwave transmission).	International regulatory action is highly uncertain.	
Fusion	Not addressed.		

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Table 12 Energy Supply Options

	Supply Option	Description
S1	Conventional	Conventional coal combustion and combined-cycle plants and nuclear LWRs with advancement to LMFBRs make up this supply option. Coal and uranium would be continually used in conventional systems until they are replaced by improved systems, e.g., combined-cycle coal gasification and the LMFBR.
S2	Conventional fuel utilization plus SPS	This supply option includes the use of coal, with nuclear only in the form of the LWR, replaced by the SPS when fuel prices for uranium either rise too high or the resource is depleted.
S3	Conventional fuel sources plus fusion	This option utilizes coal, with nuclear in the form of both the LWR and LMFBR, and replaces these systems with fusion. If fusion is not available when the LWR fuels are running low, the MFBR would be utilized until fusion technology is available.
S4	This is the same as Supply Option 1.	
S5	Conventional systems plus SPS.	Same as Supply Option 2.
S6	Conventional systems plus fusion	In this case since the energy demand is expected to be low, only nuclear LWRs would be used until fusion would be available. Since the energy demand is low, it is expected that the uranium fuel would last until fusion technology could be applied.

Table 13 Evaluation of Energy Supply Options S1-S3 for Demand Scenario UH – Unconstrained, High Demand

Scenario Definition			
Energy Demand	**Energy Supply**	**Issue**	**Comparative Analysis**
Electrical energy demand is high because coal and nuclear energy remain relatively cheap. Regulation impositions will not get much larger. Conservation and subsitution do not penetrate to a great degree.	S1 – Conventional Coal (Conv. and CG/CC) Nuclear (LWR, LMFBR) Continued use of conventional sources with improved systems. LMFBR could provide energy for many years.	Energy Cost	Low because costs of conventional sources remain relatively lowest of all scenarios .
		Health & Safety	Possible impact of further coal use and nuclear safeguard issues.
		Environmental Welfare	Welfare: CO_2 could become a problem after 2000.
		Resource	Nonrenewable fuel supplies continue to be depleted.
		Economic/ Societal	Continued development of coal mining and technology in western states.
		Institutional	Minimal impact because role of regulatory bodies will remain relatively constant.
	S2 – Conventional + SPS (Coal, LWR, SPS) Conventional systems will be used until the SPS is implemented.	Energy Cost	Higher energy cost than S1 because of depleting uranium stocks and the introduction of a new technology.
		Health & Safety	Many new health issues associated with SPS, but conventional problems decreased.
		Environmental Welfare	Potential CO_2 impact is no. changed because of other uses; several new SPS issues.
		Resources	Increased land consumption, continued uranium depletion.
		Economic/ Societal	New technology will affect the economy because of large investments; western states could go through a boom/bust cycle with cost
		Institutional	A whole new set of interactions will develop because of SPS.
	S3 – Conventional + Fusion (Coal, LWR, LMBFR, and Fusion) Conventional systems including some form of breeder until fusion technology is available.	Energy Cost	Higher than S1, slightly lower than S2.
		Health & Safety	New radiation problems.
		Environmental Welfare	Same as S1.
		Resource	Same as S1.
		Economic/ Societal	Similar to S2 but probably not as great.
		Institutional	Nuclear fission regulatory bodies will probably handle fusion.

Table 14 Evaluation of Energy Supply Options S4-S6 for Demand Scenario CI - Constrained, Intermediate Demand

Scenario Definition		Issue	Comparative Analysis
Energy Demand	Energy Supply		
Elect ical energy demand is low because regulations and fuel prices have driven up the cost of energy. Conservation and other supply substitutions are selected, thereby lessening the demand for electrical energy.	**S4 - Conventional** (Coal, LWR, LK?BR) Because of low electrical demand, conventional supply systems could be used for many years (i.e., fuel stretchout). Breeder could be implemented when fuels are depleted (e.g., 2030).	Energy Cost	High because of restrained conventional sources.
		Health & Safety	Better than S1 because of decreased use of conventional technologies.
		Environmental Welfare	Not much different than S1.
		Rest rce	Depleting fuel supplies but at a low rate.
		Economic/ Societal	Moderate development of western states.
		Institutional	Strong regulation.
	S5 - Conventional + SPS (Coal, LWR, and SPS) Because of low demand for electricity, SPS would not be required until later (e.g., 2020).	Energy Cost	Lower than S4 because replacement technology will hold down fuel prices somewhat.
		Health & Safety	Same as S2.
		Environmental Welfare	Same as S3.
		Resource	Land consumption, depleting fuels.
		Economic/ Societal	Same as S2 but boom/bust would be less.
		Institutional	Same as S2.
	S6 - Conventional + Fusion (Coal, LWR, LMFBR, and Fusion) Because of low demand for electricity, fusion would not be needed until later (e.g., 2020).	Energy Cost	Lower than S4, maybe less than S5.
		Health & Safety	New radiation problems.
		Environmental Welfare	Same as S1.
		Resource	Same as S1.
		Economic/ Societal	Similar to S2 but diminished boom/bust.
		Institutional	Same as S3.

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1 INTRODUCTION

1.1 BACKGROUND

The SPS Concept Development and Evaluation Program (CDEP)[1] was established by the Department of Energy and the National Aeronautics and Space Administration to generate information from which a rational decision could be made regarding the direction of the Satellite Power System (SPS) Program after fiscal 1980. The comparative assessment program is one of four functional areas within the joint DOE/NASA CDEP. The other CDEP functional areas are:

- Systems definition: reference system design, alternative and advanced concept design, and critical supporting studies.

- Environmental assessment: evaluation of human health and safety, ecological, atmospheric, and electromagnetic interference issues pertaining to microwave transmission, power-line transmission, transportation activities, construction, and operation of the SPS.

- Societal assessment: evaluation of international issues, institutional issues (e.g., utility interfacing), resource issues, and public outreach.

The results of these three activities are inputs to the comparative assessment process as well as to program assessments. These four areas form the basis for the CDEP assessment of the technical possibility, economic viability, and environmental and social acceptability of the SPS concept.

1.2 OBJECTIVE AND APPROACH

The objective of the assessment is to provide an initial, traceable and consistent comparison of the SPS and selected current, near-term, and advanced energy technologies. To achieve this objective, the comparative assessment was divided into four parts:

1. Energy alternatives characterization: terrestrial alternatives were selected, and their cost, performance, and environmental and societal attributes were specified for use in the comparison with the SPS in the post-2000 era.

2. Methods: the framework for comparisons was established.

3. Evaluation: the SPS was compared with alternative systems in terms of key issues such as life-cycle cost and environmental impacts.

4. Management and integration: the results of the assessments were assembled and integrated into a consistent comparative assessment.

Data on alternative technologies were sought from previous research and from other comparisons, and data on the SPS developed by other parts of the program were evaluated and used for the comparative assessment. Traceable data were gathered on alternative technologies, evaluated, and normalized to some consistent power or energy level and then synthesized into a format convenient for comparison.

A comparative assessment such as this cannot proceed without a large number of initial assumptions. Furthermore, a group of technologies that is representative, for which data exist, and of a size reasonable for study must be selected from a larger set. These assumptions and technologies were selected on the basis of an objective selection procedure and the subjective judgments of the assessors and their program staff. The documentation of this assessment was prepared to provide the reader who strongly objects to some assumptions or data with ample information for reanalysis of the comparison with other data or assumptions. However, the many assumptions and data selections supporting this report were made carefully and thoughtfully.

This final comparative assessment is a revision and expansion of a preliminary assessment and represents a culmination of the CDEP program in this area. Some of the information from the preliminary assessment has not changed either because it represented the best comparative information available on a particular issue or because the issue was not considered as important as others and was therefore de-emphasized. The goal of the preliminary assessment was to gather some initial comparative information on a limited set of technologies. The objective of the present assessment is to finalize these comparisons on all key issues on the basis of state-of-the-art knowledge and to point out data deficiencies that affect the conclusions, as well as to add comparisons based on alternative future scenarios.

The preliminary assessment[2] evaluated six centralized baseload technologies: conventional coal; light water reactor (LWR); coal gasification/combined cycle (CG/CC); liquid-metal, fast-breeder reactor (LMFBR); central-station, terrestrial photovoltaic (TPV); the satellite power system (SPS); and fusion. For the final comparative assessment, some minor modifications were introduced into this group of technologies; most notably, an improved emission control system for the conventional coal technology and an improved fuel utilization cycle for the LWR were assumed.

The technologies compared with the SPS in this assessment vary in their stages of development and, therefore, in their degree of definition. This variability was handled by qualifying the data wherever possible: for example, a technological uncertainty factor was applied to data used in the cost and performance comparison.

The assessment framework or methodology is described briefly in this report and in more detail in a companion report.[3] This assessment follows the structure of the first five steps of the methodology, but the sixth (integration/aggregation techniques) was not carried out. Instead of a formalized procedure for reducing the comparative information to a specific, condensed format for decision-making, the information is presented in its entirety; it was assumed that decision makers would use their own procedures for summarizing and evaluating the information.

All issues included in the methodology taxonomy are addressed in this assessment. The side-by-side assessment reported here is a normalized comparison (i.e., per unit of energy output, such as per megawatt year) based on assumptions about the economic conditions in the beginning of the 21st century. This alternative-futures comparison defines plausible economic and energy futures and makes comparisons on the basis of the energy and economic climate pertinent to these futures.

Reported in this document are a brief description of the comparative methodology; brief characterizations of the alternative technologies; side-by-side comparison, by issue; alternative futures comparison, by issue; and conclusions about the assessment.

2 ASSESSMENT FRAMEWORK

2.1 OVERVIEW

This section describes a framework for comparing the SPS with various projected alternative energy sources on the basis of technical possibility, economic viability, and social and environmental acceptability. A more detailed description of the approach and method used in the assessment is contained in the methodology report for the comparative assessment.[3]

The analysis in the comparative methodology is composed of the following steps (Fig. 2.1):

1. Comparative issues selection and organization. Key issues from the deployment of the SPS and the alternative systems are selected and organized into an appropriate taxonomy.

2. Energy alternatives selection. Alternatives similar in utility to SPS are selected. Many possible issues and alternatives are examined, and these selections provide an initial focus for the remaining steps in the comparative assessment.

3. Energy system characterization. The energy system characterization provides reference data on technology costs and performance, resource use, and environmental residuals.

4. Side-by-side analysis of energy systems. Side-by-side analysis normalizes the energy output from each system to allow comparison of alternative technology impacts.

5. Alternative futures analysis. The alternative futures analysis incorporates the results of the side-by-side impact analysis into future energy supply/demand and state-of-the world scenarios that are not forecasts but are designed to examine specific issues and potential problems over a range of possible futures.

6. Development and application of integration/aggregation techniques. The development of formal techniques for integrating and aggregating the large amounts of data and information provided by the analysis will aid the decision maker in formulating SPS program recommendations.

Only the first five steps have been carried out in this comparative assessment. The following sections describe each of these six steps of the comparative assessment framework in more detail.

2.2 COMPARATIVE ISSUES

The selection of issues for the comparative assessment must be guided by the idea that not only should the issues structure be general enough to
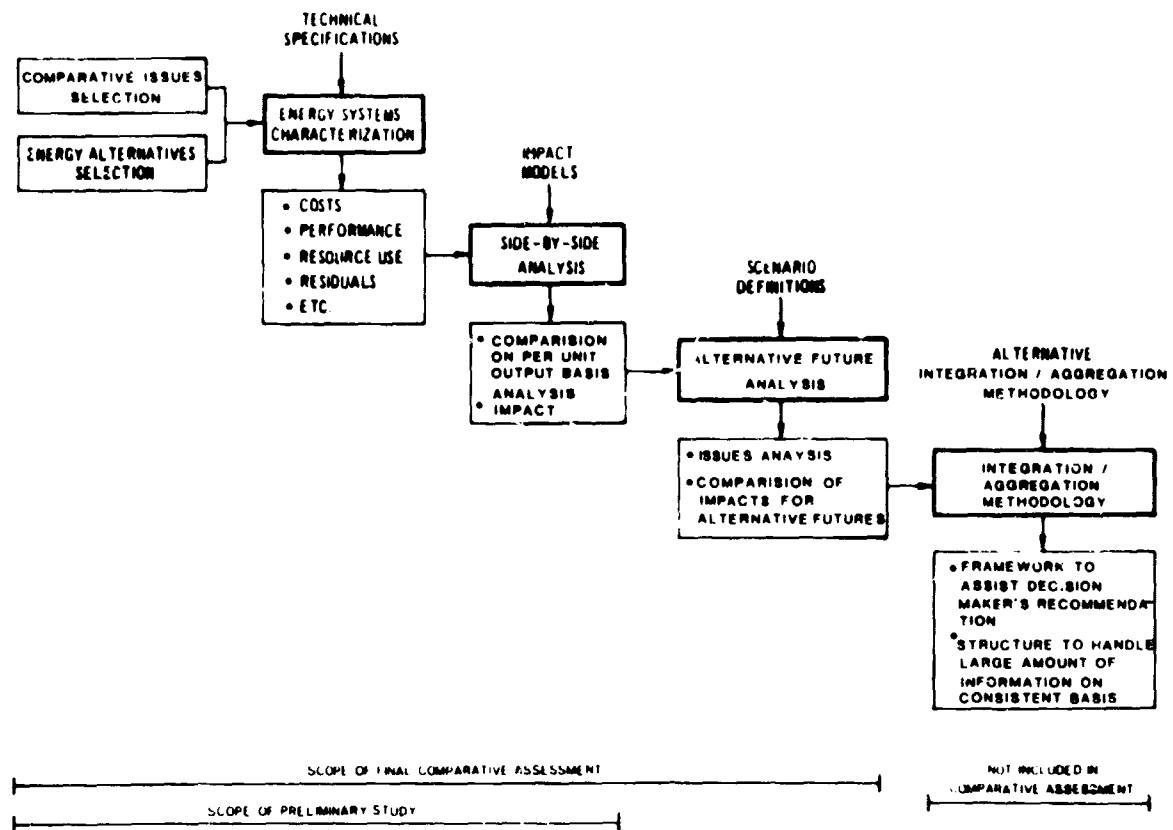
Fig. 2.1. Analysis Sequence for Comparative Assessment

accommodate different impacts that result from the alternative technologies, but it should also be specific enough so that comparisons between technologies are feasible and commensurate.

The classification system for the comparative assessment is shown in Fig. 2.2. The major issue categories are cost and performance, environmental, economic and societal, resource, and institutional.

In the cost and performance category, the life-cycle cost and system performance are compared. The R&D cost comparison between technologies was not considered because of the inability to develop an acceptable methodology or accurate data. Life-cycle cost includes development, construction, operation, maintenance, and decommissioning. Reliability is an example of an important system performance issue. The costs being compared are projected, and it is important to specify the uncertainty in these projections so that conclusions can be drawn in perspective.

Environmental issues are divided into two subcategories: health and safety issues and welfare issues. Health and safety is subdivided into public and occupational issues. In this context, health refers to chronic impacts (e.g., respiratory illness), whereas safety refers to the effects of accidents such as launch malfunctions, spills, and unexpected releases of hazardous pollutants. Welfare impacts are those that result from disruptions of the physical environment, such as damage to buildings from air pollution, degradation of radio-frequency communication due to
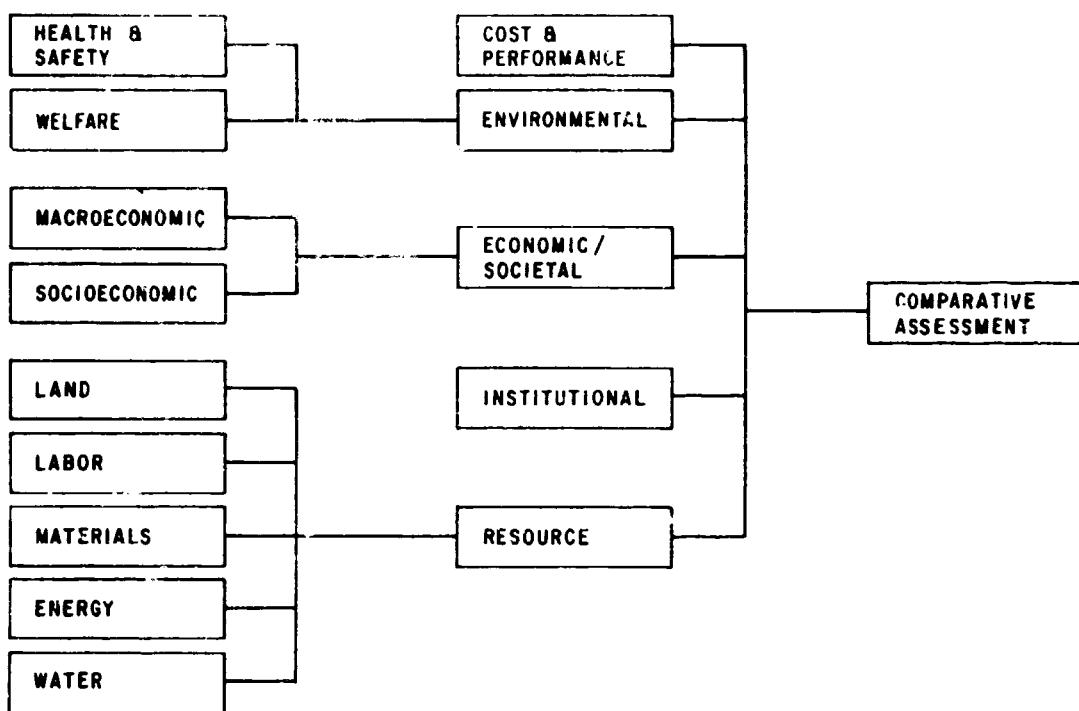
Fig. 2.2. Comparative Assessment Classification System

microwave interference, and changes in land value because of deployment of an energy technology.

The economic and societal category is divided into two parts: macroeconomic and socioeconomic. The macroeconcmic issues deal with national and regional macroeconomic impacts (e.g., trade, GNP, capital availability, and employment'. Socioeconomic issues concern the monetary impact and social stresses on the localities where power systems are sited.

Institutional comparisons deal with the effects of existing and potential institutions on the deployment of a technology (regulatory impacts). International institutional issues are addressed in terms of their regulatory impact on energy systems. The resource category includes five subcategories: land, labor, materials, energy, and water. Here, key concerns include resource limits, production limits, dependence on foreign resources, and need for new skilled labor.

2.3 SELECTION OF ENERGY ALTERNATIVES

The technologies initially considered for comparison with the SPS listed in Table 2.1 include six fossil options, ten nuclear technologies (including two fusion options), five solar technologies, and three geothermal technologies. The list was narrowed to six technologies according to the following criteria:

● Technical data must be available in sufficient detail to allow adequate technical characterization and comparison.

- The candidates must be central-station, baseload technologies.

- The technology should be available for commercial application by year 2000.

- Include improved current baseload technologies.

- Include representative advanced technologies currently being engineered.

- Include alternative (nonspace) applications of photovoltaic solar energy technology.

- Include alternatives that show potential as long-term energy sources after 2000.

- Fuel must be available for a long period (e.g., 2000-2050).

The energy alternatives selected were conventional coal with stack scrubber, coal gasification/combined cycle, the light water reactor, the liquid-metal breeder reactor, fusion, and the photovoltaic solar central station. Missing from this list are wind, biomass, decentralized solar (e.g., space heating and cooling, process heating and cooling, water heating; and photovoltaics for electrical energy production), and OTEC. These technologies were not included in the final list because they are not large central-station-baseload options or they have only regional application.

2.4 CHARACTERIZATION OF ENERGY SYSTEMS

Following the selection of energy alternatives and the preliminary selection of comparative issues, the reference energy systems were defined and described, and data on cost, performance, and environmental impact were collected from published sources for issue comparisons.

The ground rules for this data collection included the following:

- Characterizations should use readily available information.

- Characterizations should be performed and documented by persons who are knowledgeable about alternative technologies and DOE programs.

- Each technology characterization should be internally consistent.

- The set of characteristics should be consistent enough, overall, to facilitate comparisons with the SPS concept.

- There should be enough information to allow adequate evaluation of issues (failing this criterion, a candidate technology may have to be dropped).

2.5 SIDE-BY-SIDE ANALYSIS OF ENERGY SYSTEMS

The objective of the side-by-side analysis is to compare the alternatives on the basis of single units normalized to the same power level, using a

Table 2.1 Candidate Alternative Technologies

Fossil

  Coal-Steam, Conventional
    with Improved Environmental Controls
    with Atmospheric Fluidized Bed
  Pressurized Fluidized Bed
  Gas Turbine, Closed-Cycle
    Open-Cycle, Low-Btu Gasifier
    Open-Cycle, Synthetic Liquid Fuel
  Metal Vapor Topping Cycle
  Molten Carbonate Fuel Cell
  Magnetohydrodynamic, Open-Cycle
    Closed-Cycle

Nuclear Fission

  Light Water Reactor, Conventional
    with Improved Fuel Utilization
    with Mixed-Oxide Fuel
  High Temperature Gas-Cooled Reactor
  Advanced High Temperature Reactor
  Liquid-Metal, Fast-Breeder Reactor
  Gas-Cooled, Fast-Breeder Reactor
  Light Water Breeder Reactor
  Electronuclear Breeder
  Fusion-Fission System

Fusion

  Magnetic Confinement
  Inertial Confinement

Solar

  Terrestrial Thermal
  Terrestrial Photovoltaic
  Ocean Thermal Energy
  Wind Energy
  Biomass Fuels

Geothermal

  Hydrothermal
  Geopressurized
  Hot Dry Rock

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consistent set of ground rules for all units. This was the first analytical step of the comparative assessment, and it entailed listing information (some detailed, some summary) for each of the energy systems. Information categories cover the technical, economic, environmental, and societal issues mentioned earlier.

Two important functions of the side-by-side analysis are: (1) providing the decision maker and analyst with a normalized comparison,* and (2) functioning as an intermediate step between the technology characterizations and the alternative futures analysis.

2.6 ALTERNATIVE FUTURES ANALYSIS

The alternative futures analysis compared alternative energy-supply systems (i.e., alternative mixes of coal, nuclear, and SPS technologies) under different levels of energy demand (i.e., alternative supply-demand patterns). This analysis addressed synergistic impacts or those that result from aggregation of single-plant effects. An integral part of the analysis was the creation of scenarios (e.g., statements about future supply, demand, lifestyle, resources, and regulation) to serve as inputs to other analyses.

The primary objective of the alternative futures analyses was to provide a comparison of the impacts of alternative technologies under several different assumptions of future conditions.

The following criteria were considered in the choice of scenarios that drive the alternative futures:

- A limited number of scenarios should be used, and they should be credible and representative;

- They must illustrate a suitably large range of alternative policies, and economic and social conditions (or at least those of major concern or interest);

- They must not produce a flood of data that would tend to overwhelm analysts and the decision-making process;

- They should highlight or identify major categories of issues for further analysis; and

- Uncertainty should be included in a consistent and efficient manner, conveying useful information to the decision maker.

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*The term "normalized comparison" simply means that quantifiable impacts are expressed in amount of impact per unit output of electrical energy, e.g., per megawatt-year (MW-yr). Thus, a 5-MW system that provides energy continuously for one year and expels 1,000 tons of pollutants to the environment in the process will be characterized by the normalized amount of 200 (= 1,000 ÷ 5) tons of pollutant per MW-yr of electrical energy; similarly, a 1 MW plant that operates for half a year and produces 50 tons of pollutants is assigned the normalized amount of 100 (= 50 ÷ 1/2) tons of pollutants per MW-yr.

Although a scenario must be plausible, it does not necessarily have a probability of occurrence associated with it, but instead addresses key issues and, perhaps, reveals other problems that result from specific future models.

2.7 ASSESSMENT INTEGRATION/AGGREGATION TECHNIQUES

The objective of integration/aggregation techniques is to analyze and focus the data assembled for the comparison of SPS with terrestrial technologies. A further objective is to begin reducing the complexity of the decision-making problem (which is aggravated by the large amounts of supporting data for each technology) by using techniques such as formal incorporation of preferences.

There are a number of criteria for deciding the appropriate level at which to carry out such integration/aggregation techniques. These include:

- The number of measurement categories desired;

- The number of alternatives desired;

- The manner in which views of priorities are deter-
  mined, represented, and inco-porated into the
  decisiou-making process;

- The use of uncertainty;

- The degree of inclusion of interactions between
  variables and priorities; and

- The suitability of the aggregated information for
  describing dynamic and time-varying conditions.

The degree of appropriateness of any of these criteria is determined by the degree of quantification of variables and effects that is achievable. Cost-risk-benefit analysis, total social cost, minimum energy cost with environmental constraints, and decision analysis are some of the techniques that may be considered. These approaches are formalized techniques that require value judgments. Since these value judgments would mainly be those of the analysts, it was decided to present the comparative information in its entirety and permit the reader to use his or her own values for arriving at any aggregate evaluation.

3 CHARACTERIZATIONS OF THE SPS AND ALTERNATIVE TECHNOLOGIES

This section contains brief descriptions of each of the technologies considered. More detailed characterizations are contained in the SPS CDEP Reference System Report[1] and in the alternative technology characterization reports.[4,5] The objective of the technology characterizations was to collect and develop a consistent and traceable set of characterization parameters for the SPS and other possible post-2000 baseload systems. The characterizations represent "first-order" characteristics that define systems in sufficient detail for the cost and environmental analyses.

3.1 SELECTION OF ALTERNATIVE TECHNOLOGIES

The preliminary list of 29 technologies (Table 3.1) was initially screened according to two sets of criteria. The list was reduced to a subset of systems that were then further screened by more restrictive criteria to a final subset of alternatives. Decentralized technologies were excluded from the comparative assessment, since the focus was on baseload alternatives to SPS. A more detailed description of the technology screening and selection process is presented in another report.[6]

Initial screening was both qualitative and quantitative. The qualitative screening procedure included the following criteria for selection of an initial and representative subset of candidate electrical power generation systems:

A. The initial set should include improved conventional systems (e.g., coal and LWR systems).

B. It should represent the following classes of advanced systems:

1. Advanced coal combustion and synfuels,
2. Solar,
3. Fission,
4. Fusion, and
5. Geothermal.

C. It should include the principal energy systems most suitable for large, central-station baseload generation within each class of inexhaustible energy sources.

D. It should reflect the consensus about which candidates are most likely to be viable in the year 2000.

A group of qualified energy technology researchers was asked to judge the candidate technologies according to the listed criteria, and their choices of the most viable candidate technologies for the year 2000 constituted the qualitative screening selections.

The quantitative screening technique explicitly considered five major technology factors and numerous subfactors (Table 3.2). The following criteria were used in the final alternative technology selection:

Table 3.1 Technologies Considered in Initial Screening

Energy Source	Conventional Systems	New Systems
Exhaustible Resource Technologies		
Coal	Coal-steam plants with flue-gas desulfurization	- Coal-steam plants with improved environmental controls - Atmospheric fluidized-bed combustion (AFBC) - Pressurized fluidized-bed combustion (PFBC) - Low-Btu gasifier/open cycle gas turbine, combined cycle - Closed cycle gas turbine - Metal vapor topping cycle - Open cycle magnetohydrodynamics (MHD) - Closed cycle magnetohydrodynamics - Molten carbonate fuel cell with gasifier (MCFC) - Synthetic fuels for advanced power cycles
Fission	Light water reactors with once-through fuel cycle	- Light water reactors (LWR) with improved fuel utilization efficiency - Light water reactors with mixed oxide fuels - High temperature gas-cooled reactors - Advanced high temperature reactors
Geothermal	Dry steam	- Liquid-dominated hydrothermal - Geopressure
Renewable or Essentially Inexhaustible Resource Technologies		
Solar	Hydroelectric Wood-fired steam	- Solar thermal electric with storage - Solar photovoltaic with storage - Ocean thermal energy conversion - Wind energy conversion with storage - Biomass fueled (other than wood-fired steam)
Fission		- Liquid-metal, fast-breeder reactor (LMFBR) - Gas-cooled, fast-breeder reactor - Light water breeder reactor - Electronuclear breeder - Fusion-fission systems
Fusion		- Magnetic confinement fusion - Inertial confinement fusion
Geothermal		- Hot dry rock (HDR)

1. Technical data must be available in sufficient detail to allow adequate technical characterization and comparison.

2. The candidates must be central-station, baseload technologies.

3. The technology should be available for commercial application by the year 2000.

4. Include improved current baseload technologies.

5. Include representative advanced technologies currently being engineered.

6. Include alternative (non-space) applications of photovoltaic solar energy technology.

7. Include alternatives that show potential as long-term energy sources after 2000.

8. Fuel must be available for a long period (e.g., 2000-2050).

The details of the qualitative and quantitative screening procedures are reported in a supporting document.[6]

Table 3.2   Quantitative Screening of Energy Systems

Factors	Subfactors
Technology Availability	Technology Feasibility Fuel or Energy Resource Availability Regional Limitations Status of Development
Economic Attractiveness	RD&D Costs Capital and O&M Costs Fuel Costs Plant Availability and Reliability Utility Compatibility
Environmental Impacts	Air and Water Pollutants Land Use or Disturbance Public Health and Safety Reversible vs. Irreversible Impacts
Critical Resource Requirements	Energy, Materials Land, Water Capital, Manpower
Socioeconomic Impacts	Economic Industrial Infrastructure Social International

The light water reactor (LWR) and coal technologies best satisfy the applicable criteria and thus were included in the final list of technologies to be compared with the SPS. Only one technology, terrestrial photovoltaics (TPV), meets the special criterion (No. 6) established to provide for a direct comparison of photovoltaics in space and terrestrial applications.

The combined-cycle system had the highest rating of the three advanced coal systems and thus was selected for the comparative assessment.

The liquid-metal, fast-breeder reactor (LMFBR), although controversial, has great potential, is close to demonstration, and has received worldwide backing; it was thus included in the comparative assessment.

Fusion is a technology of high scientific interest and potential. Therefore, it was selected to fill a position as a baseload alternative, even though DOE's Fusion Review Panel has stated that a date for a commercially competitive prototype reactor cannot now be established.

3.2 BRIEF TECHNICAL DESCRIPTION OF ALTERNATIVE GENERATION SYSTEMS

The characteristics of each of the alternative generation systems have been derived primarily through a synthesis of data and information obtained from available technical literature. The best self-contained system characterizations available in single documents were chosen as primary data sources. Where deficiencies were noted, available supplemental material was obtained or input from reviewers was solicited.

In most cases, the available data are for nominal systems that differ in some respects from the reference alternatives chosen for comparison. Usually, these differences are a result of varying assumptions about system generating capacity, cooling type, or, in some cases, even the site or fuel characteristics. Thus, in some cases, the reference characterizations required engineering judgment to adjust data to the system capacities and basic assumptions being used. The subsequent analyses are generally not sensitive to small variations in the system parameters derived in this fashion. However, the analysis is broad enough to allow reasonable conclusions to be drawn.

The parameters addressed in the system characterizations include those that relate to the physical system design and operating factors, capital and operating costs, reliability and availability, resource requirements, and environmental residuals. Table 3.3 briefly summarizes the characterization parameters for the technologies. Studies conducted by TRW[4] and United Engineers and Constructors[5] provide the basis for the non-SPS technical, environmental, and cost characterizations summarized in the following sections of this chapter.

3.2.1 Satellite Power System

The satellite power system characterization is based on data available in the SPS CDEP Reference System Report,[1] supplemented by additional studies

Table 3.3   Characterization Parameters for Plant Site and Fuel Cycle

Physical System Characteristics	Capital and Operating Cost
- Plant Configuration	- Construction Schedule
- Thermodynamic Cycle Characteristics	- Construction Cash Flow
- Capacity Factor	- Direct and Indirect Capital Cost
- Environmental Controls	- O&M Costs
- Mass & Energy Balances	- Decommissioning Costs
Environmental Residuals	Natural and Human Resource Requirements
- Air-Borne Emissions	- Fuel Use
- Liquid Effluents	- Water Use
- Solid Wastes	- Land Use
- Radionuclides	- Construction Labor
- Waste Heat	- Operating Labor

performed for NASA by Boeing[7] and Rockwell.[8]   The satellite power system consists of three basic elements: the first two, in geosynchronous orbit at 36,000 km, are the solar collector, which receives energy from the sun and converts it to electrical energy, and a microwave antenna, which transmits that energy to the third element, an earth-based rectifying antenna (rectenna).   The reference system is sized for 5 GW of DC power output to a conventional utility grid   The satellite has one end-mounted antenna, as illustrated in Fig. 3.1.

The satellite consists of a ` planar solar array structure of graphite composite material.   Two conversion options (Fig. 3.2) are presently being considered: one is the use of single-crystal gallium aluminum arsenide (GaAlAs) solar cells with a concentration ratio of 2; the other is the use of single-crystal silicon (Si) solar cells with no concentration.

The size of the solar array is dictated primarily by the efficiency chain of the various elements in the system.   Figure 3.3 shows the end-to-end efficiency chain for the GaAlAs and silicon cell options.   The satellite is designed to provide 5 GW of DC power to the utility busbar, and with an overall efficiency of approximately 7%, it is necessary to size the solar arrays so that approximately 70 GW of solar energy will be intercepted. The efficiency assumed is the minimum efficiency, including the worst-case summer solstice factor (0.9675), the seasonal variation (0.91), and the end-of-life (30-year) solar cell efficiency (assuming annealing in the silicon case).   For the GaAlAs case, the end-of-life (30-year) concentrator reflectivity is 0.83.   Since only half of the intercepted solar energy is reflected by the concentrators, the equivalent lifetime average efficiency is 0.915.

The GaAlAs option is a five-trough configuration with a solar blanket area of 26.52 km^2, a reflector area of 53.04 km^2, and an overall planform area of 55.13 km^2.   The silicon option has the solar blanket with no concentration, resulting in a blanket area of 52.34 km^2 and a planform area of 54.08 km^2.   Table 3.4 lists the cell and planform power characteristics for each cell type.
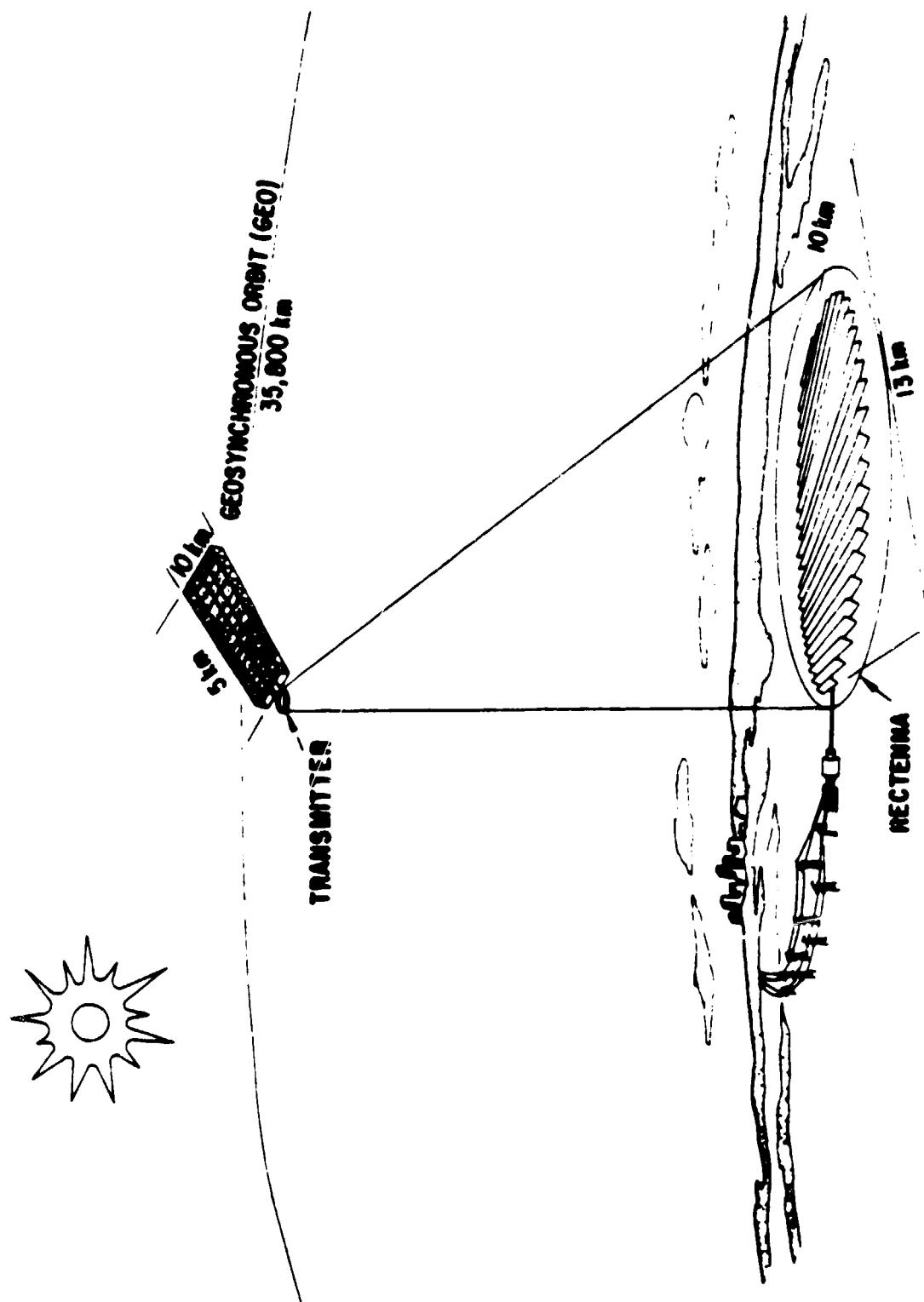
Fig. 3.1 Satellite Power System Concept (Source: Ref. 1)

SILICON CR = 1
BLANKET AREA = 32.34 km²
PLANFORM AREA = 54.08 km²

5200m

470m

650m
TYPICAL

10,400m

GaAlAs CR = 2
BLANKET AREA = 26.52 km²
PLANFORM AREA = 55.13 km²

5250m

1050m

10,500m

525m

463m

525m

525m
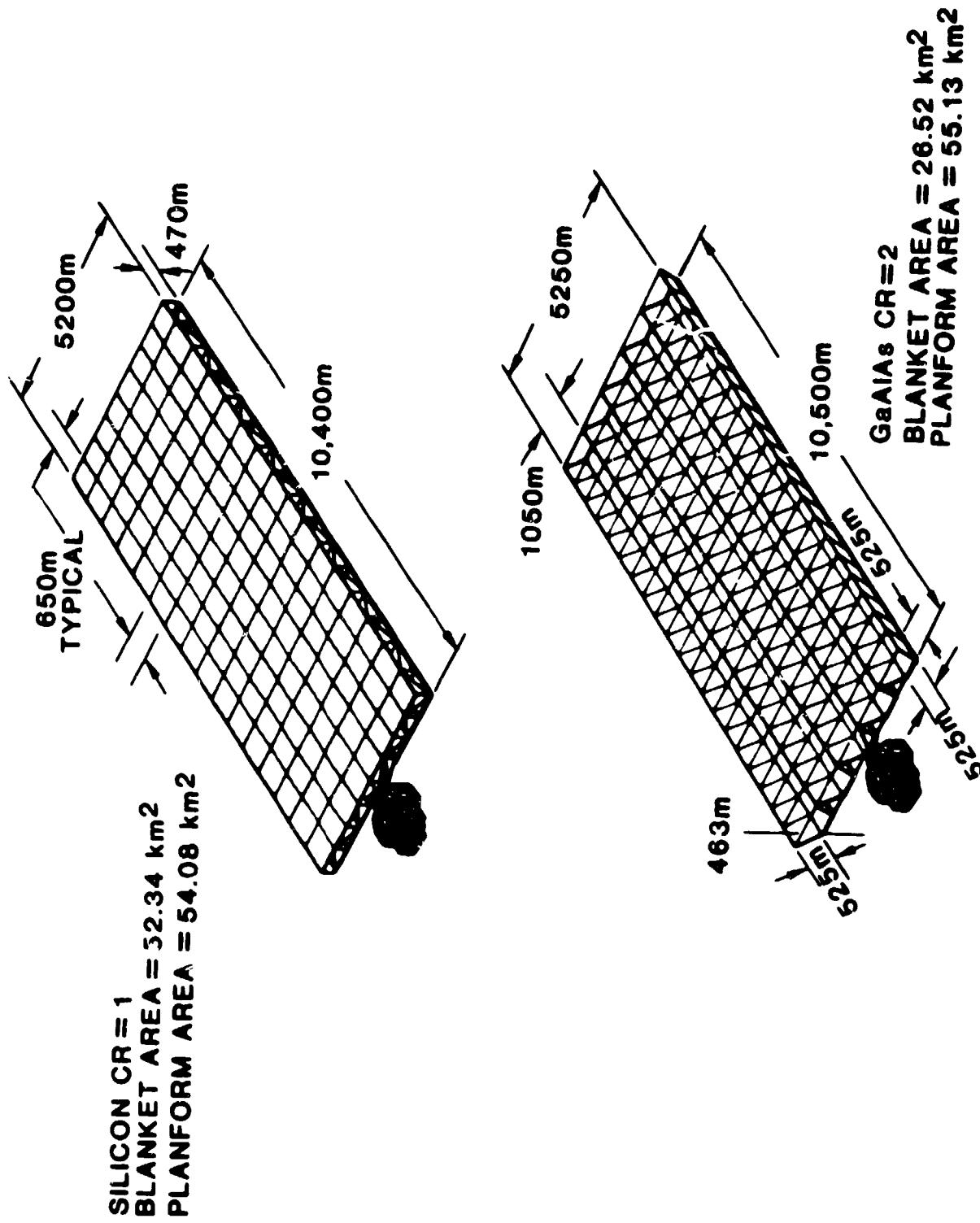
Fig. 3.2 SPS Satellite Configurations (Source: Ref. 1)

18
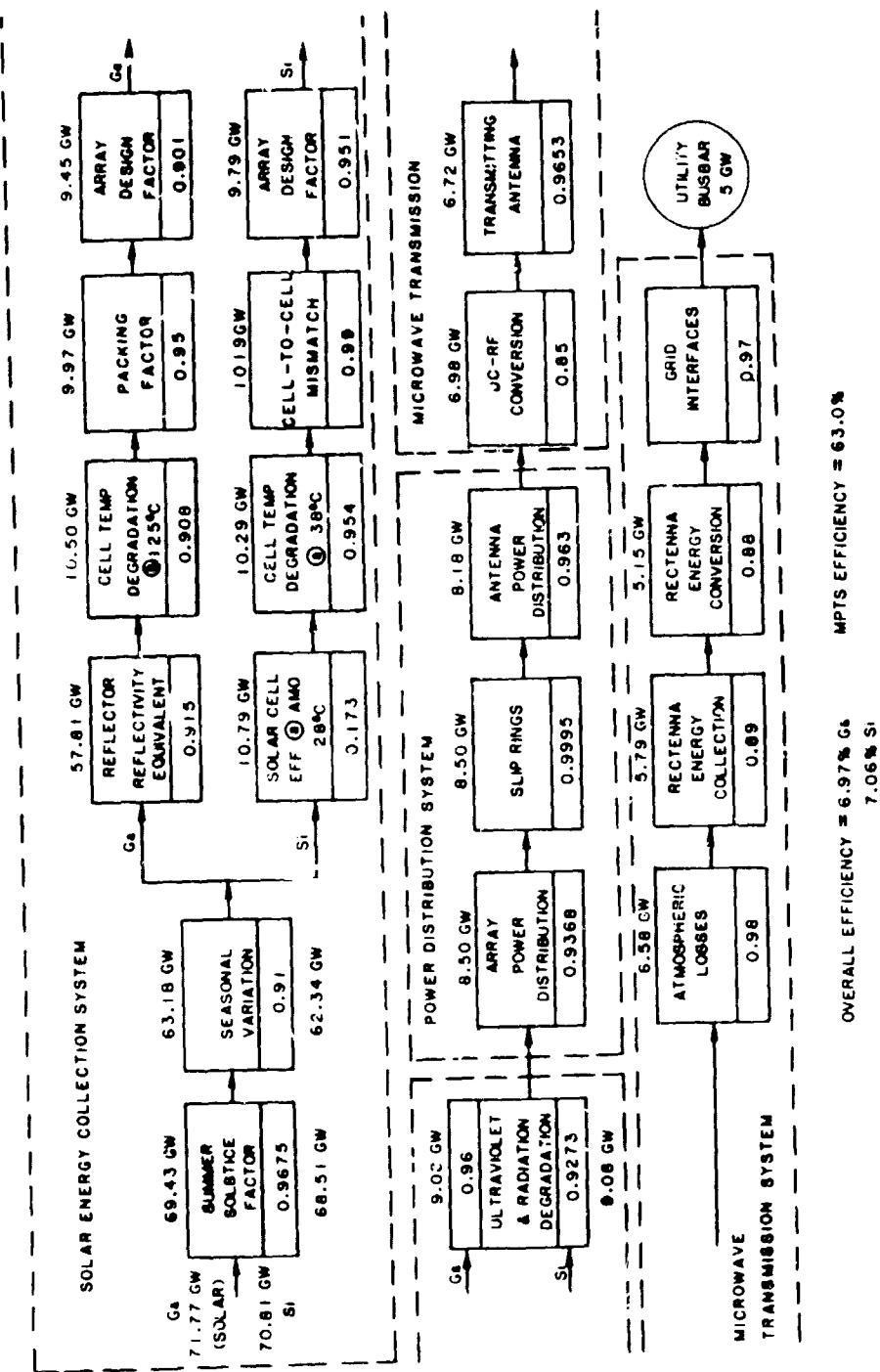
Fig. 3.3 SPS Efficiency Chain.* GaAlAs (CR = 2) and Si (CR = 1)
(Source: Ref. 1)

*Individual efficiencies are approximate and may be expected to
change with additional analysis.

Table 3.4   SPS Cell and Planform Power Characteristics

Cell Type	GaAlAs	Silicon
Concentration ratio	2	1
Solar power available	1,353 W/m^2	1,353 W/m^2
Solar power on cell at maximum off-sun pointing	2,414 W/m^2	1,190 W/m^2
Cell conversion efficiency at 28°C AMO (in vacuum)	20%	17.33%
Blanket power output		
Beginning of life	380 W/m^2	186 W/m^2
End of life	370 W/m^2	149 W/m^2
Planform power output		
Beginning of life	185 W/m^2	186 W/m^2
End of life	171 W/m^2	149 W/m^2

Source: Ref. 1.

The end-mounted microwave antenna is a phased-array transmitter of 1-km diameter. The phase control system utilizes an active, retrodirective array with a pilot beam reference for phase conjugation. Klystrons are used as the baseline power amplifier with slotted waveguides as the radiating element. The ground rectenna has subarray panels with an active element area of 78.5 km^2. At 35° latitude, the total rectenna area, including the buffer zone, would be 149 km^2.

The construction of the satellite in geosynchronous orbit (GEO) is estimated to require six months. The initial estimates of construction crew size are 555 for the silicon option [480 in GEO and 75 in low earth orbit (LEO)] and 715 for the GaAlAs option (680 in GEO and 35 in LEO).

The transportation system assumed for the NASA contractor reference system consists of four major components: the heavy-lift launch vehicle (HLLV), the cargo orbit-transfer vehicle (COTV), the personnel launch vehicle (PLV), and the personnel orbit-transfer vehicle (POTV). The HLLV is a two-stage, vertical launch, winged, horizontal landing, reusable vehicle with a 424-metric ton payload to low earth orbit. The Kennedy Space Center was chosen as the reference earth launch site. The COTV is an independent, reusable, electric engine-powered vehicle, which transports cargo from the HLLV delivery site in low earth orbit to the geosynchronous earth orbit. For the GaAlAs option, the COTV is powered by GaAlAs solar cells, whereas a silicon solar cell power supply is assumed for the silicon option.

Personnel for the orbital construction and support functions are transported to LEO by the PLV, which is a modified space shuttle orbiter with a passenger module. The POTV, a two-stage, reusable, chemical-fuel vehicle, is used to transfer personnel from LEO to GEO and vice versa. Additionally, a LEO operations base would be constructed and used for temporary storage of supplies and propellant.

Power conversion equipment converts the direct current (DC) power from the collectors into high density microwave (RF) power; the microwave antenna transmits it to the ground-based rectifying antenna, called the rectenna. The microwave antenna is a phased-array transmitter of 1-km diameter and contains 7,220 subarrays or power modules. The antenna transmits 6.85 GW of power at 2.45 GHz.

The subarrays are arranged to provide a 10-dB Gaussian power distribution cross the array surface. The power density varies from 22.14 kW/m^2 at the center module to 2.45 kW/m^2 at the outer edge. At the earth's surface, the power is 23 mW/cm^2 at the rectenna center and 0.08 mW/cm^2 in the first sidelobe.

Each subarray covers 108 square meters and contains from 4 to 50 klystrons, depending on the power output of the subarray. Each klystron converts DC to 70 kW of RF. An alternative concept described in the SPS CDEP Reference System Report would use a 50-kW klystron tube that would result in the use of 6 to 50 tubes per subarray (Ref. 1, p. 30). The subarray radiates power through slotted waveguides on the surface. Electronic phasing equipment in each subarray processes a beam-phasing signal from the ground and focuses the microwave beam. Waste heat is dissipated by radiation. The subarray also includes power distribution and conditioning equipment, waveguides, amplifiers, and frequency-control electronics.

The rectenna consists of a dipole network and diode rectifiers, which receive and rectify the microwave power; a power distribution and conditioning system, which collects and delivers the rectified DC power to the utility interface; and the structure that provides support to the dipole rectenna panels and components of the distribution system. The support structure also provides a ground plane for the microwave power.

At 35° latitude, the rectenna area of 10 km by 13 km contains 814 rows of rectenna panels tilted 40° from the horizontal, providing an active intercept area of 78.5 km^2. A total of 436,805 panels will be assembled on site and erected. In order to minimize electrical wiring from the rectenna panel area, two electrical switchyards will be employed, each with its own converter and relay building. The rectenna site, including auxiliary buildings and the buffer zone, has been estimated to be an elliptical plot 12 km by 15.8 km, with a total area of 149 km^2.

The configuration of the ground-based rectenna, which receives and rectifies the downlink power beam, has half-wave dipoles feeding Schottky barrier diodes. Two-stage, low-pass filters between the dipoles and diodes suppress harmonic generation and provide impedance matching. The rectenna is a series of serrated panels perpendicular to the incident beam, rather than a continuous structure. Each panel has a steel-mesh ground plane with 75-80% optical transparency. This mesh is mounted on a steel framing structure, supported by steel columns in concrete footings. Aluminum conductors are used for the electrical power collection system.

3.2.2 Central-Station Terrestrial Photovoltaic System

The reference terrestrial photovoltaic (TPV) alternative is a 200-MW system in which silicon cells are mounted in fixed-tilt, flat-plate arrays, in eight 25-MW modular components. The reference system, which does not include storage, is based primarily on designs published in a 1978 EPRI study.[9] That study defined the cost and performance goals for utility photovoltaic conversion devices and assessed the effects of photovoltaic generation on electric utility systems.

The reference TPV system is assumed to have a silicon-cell efficiency equal to that of the SPS silicon cell, or 19%. (A cell efficiency of 12% was assumed in the EPRI study.) This modified assumption alters the EPRI design, in that it reduces by approximately 37% the number of solar cells required to generate 200 MW. Figure 3.4 shows the energy efficiency chain for this system.

Eight 25-MW modules of photovoltaic arrays are connected radially to a 34.5-kV switchyard, which, in turn, supplies the transmission grid through a step-up transformer. Each module contains 48.9 x 10^6 cells measuring 6 cm x 6 cm. Each module is composed of the solar array field and its connecting DC cables and main b.s, the DC-to-AC converter station, and the AC medium-voltage connection to the 34.5-kV switchyard. Within each module, the photovoltaic cells are connected in series and parallel to provide as high a voltage as

Efficiency Chain (%)		
	Component	Cumulative
Solar Cell	19.00	19.00
Encapsulation	90.50	17.20
Packing Factor	93.95	16.12
Connections	98.00	15.80
DC/AC Converter	92.00	15.53
Step-up volt/line losses	98.00	14.24
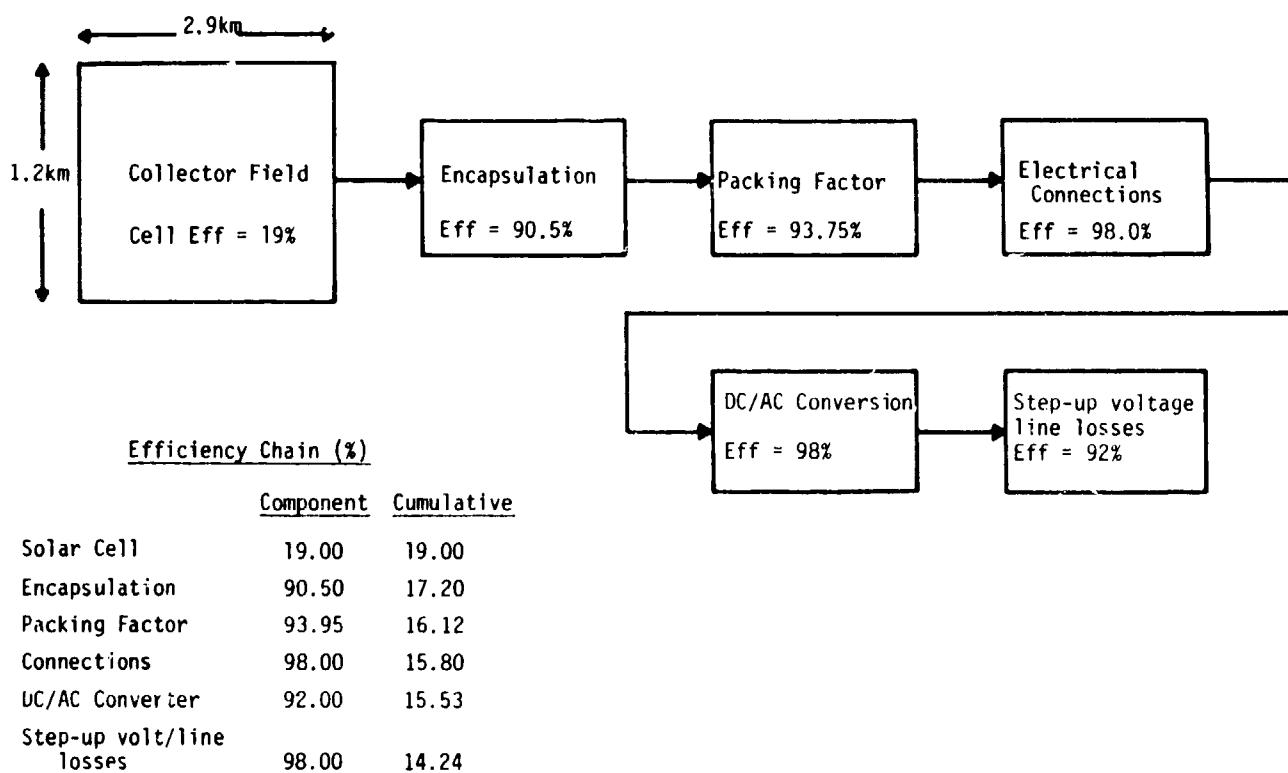
Fig. 3.4 Efficiency Chain of the Central-Station Photovoltaic System

practical. This produces improved inverter efficiency and minimizes DC cable losses. The arrangement is such that $\pm$ 5,200 V DC and 2,438 V AC are provided at the inverter input.

The plant capacity factor can be highly variable, since it is critically dependent on the plant's geographic location. Capacity factors have been estimated to range from nearly 25.8% in the Phoenix area to just under 18% in Boston. The Phoenix site was chosen for this analysis.

The reference system is designed to occupy a 4-km^2 (1000-acre) site, which houses the solar arrays, switch gear, transformer station, and personnel buildings. Excluding periodic maintenance crews, the staff requirement is about 26 persons.

Environmental residuals from the plant site should be minimal under normal operating conditions. No gaseous emissions should result from the normal operation of the system, and any waste heat should be removed from the arrays by natural convection. Small amounts of waste and garbage would be generated by personnel on site and small amounts of combustion products would be produced by on-site maintenance vehicles. An unquantified but small amount of runoff would result from cleaning of the solar arrays. Some environmental residuals would be generated as a result of the cell manufacturing process, but these effects have not yet been characterized.

3.2.3 Conventional Coal-Fired Power Plant

The reference, high-sulfur coal-combustion system is a single-unit facility. The steam plant uses a cross-compound turbine generator with two parallel shafts and has a net plant capacity of 1250 MW. The basic steam cycle is modeled after a 1232-MW concept designed by United Engineers and Constructors (UE&C), as described in their report "Commercial Electric Power Cost Studies."[10] The UE&C design utilizes a conventional lime flue-gas desulfurization system for stack gas cleaning and a mechanical draft cooling tower for removing condensate heat.

The characterization represents high-sulfur coal-combustion technology and SO_2 removal as projected to be available in 2000. The plant capacity factor is assumed to be 70%. It is also assumed that all of the plant's stack gases are processed to remove 90% of the SO_2 (recent EPA regulations). Thus the reference high-sulfur coal facility for the year 2000 is assumed to use a Wellman-Lord SO_2 removal system. The Wellman-Lord process has recently been demonstrated by the EPA,[11] and it is expected that this or a similar technology will be the preferred option in the year 2000. The Wellman-Lord system reduces the area of land required, but the processing of all stack gases decreases the net plant efficiency. Therefore, the plant capital cost is higher than that for the UE&C design.[10] These factors have been fully accounted for in the characterization.

Figure 3.5 is a simplified schematic of the functional plant components. The combustion boiler produces steam at 26.5 x 10^6 N/m^2 (3845 psi) and 543°C (1010°F). Turbine power is produced with throttle steam of 24.2 x 10^6 N/m^2 (3515 psi) at 540°C (1000°F) for the high pressure turbine and steam at 4.1 N/m^2 (600 psi) at 540°C for the intermediate pressure turbine.
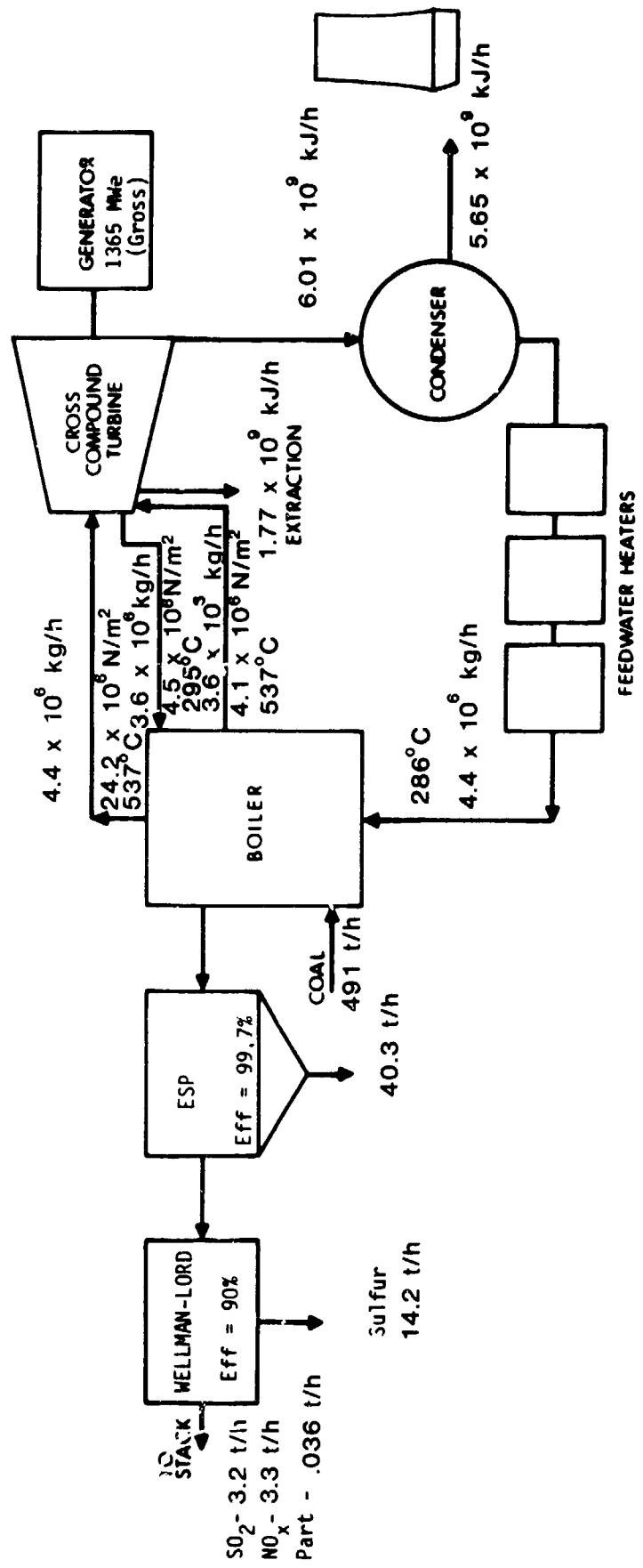
Fig. 3.5 Generation of 1250 MW, High-Sulfur Coal, Wellman-Lord Process

GENERATOR
1365 MWe
(Gross)

CROSS
COMPOUND
TURBINE

CONDENSER

6.01 x 10⁹ kJ/h

5.65 x 10⁹ kJ/h

FEEDWATER HEATERS

4.4 x 10⁸ kg/h

24.2 x 10⁸ N/m²
537°C 3.6 x 10⁸ kg/h

4.5 x 10⁸N/m²
295°C
3.6 x 10³ kg/h

4.1 x 10⁸ N/m²
537°C

1.77 x 10⁹ kJ/h
EXTRACTION

286°C
4.4 x 10⁶ kg/h

BOILER

COAL
491 t/h

40.3 t/h

ESP
Eff = 99.7%

Sulfur
14.2 t/h

WELLMAN-LORD
Eff = 90%

STACK
SO₂ - 3.2 t/h
NOₓ - 3.3 t/h
Part - .036 t/h

Gross Generation   1365 MWe
Aux Use   115 MWe
Net Generation   1250 MWe

Figure 3.5 illustrates the generation of a net capacity of 1250 MW with an assumed capacity factor of 70%, from typical eastern high-sulfur bituminous coal. The amount of pulverized coal yielding 10.1×10^3 kJ is required to generate one kWh of net output; this corresponds to a net plant efficiency of 35.75%. The coal characteristics assume a higher heating value of 25.6×10^3 kJ/kg of coal on an as-received basis. At this rate, an average of 8245 metric tons (t) of coal would be needed at the site each day. Because coal storage requirements are estimated at full capacity factor, a 3-day live storage stock pile would contain 35.3×10^3 t of coal, and a 57-day reserve storage would contain 67.2×10^4 t of coal. A 9.1-m-high active storage and a 15.24-m-high reserve storage pile results in a site area of 56×10^3 m^2 devoted to coal storage.

Other fuel in the form of natural gas is also required for reducing sulfur dioxide (SO_2) from the Wellman-Lord scrubber system (Fig. 3.6) to elemental sulfur. This process requires about 148×10^6 kJ/h of natural gas at full plant capacity or, at 70% capacity and 34×10^3 kJ/m^3 of gas, about 2.7×10^6 m^3 of natural gas per year.

The design has hot electrostatic precipitators sized for the removal of 99.7% of the flyash particulates emitted from the combustion furnace boiler. Auxiliary electric power of 13.9 MW is required for effective operation of the electrostatic precipitators.[12,13]

The combustion of 4.9×10^5 kg/h of coal with an ash content of 10.29% by weight produces 40×10^3 kg/h of flyash, assuming an 80% flyash/20% bottom ash proportion. (About 10^4 kg/h of bottom ash would be produced.) Removal of 99.7% of this flyash leaves 120 kg/h of flyash to be sent downstream for further processing in the Wellman-Lord SO_2 removal system.

The sludge wastes from the electrostatic precipitators and bottom ash total 63,120 kg/h for the 1250 MW reference coal facility at 100% capacity.

Downstream from the electrostatic precipitators is the Wellman-Lord flue-gas desulfurization system. This system uses a regenerable process in which SO_2 is removed from flue gases with a sodium sulfite scrubbing solution. The concentrated SO_2 stream that is produced can be processed into elemental sulfur or sulfuric acid, both of which are marketable industrial products.

The Wellman-Lord process consists of the four basic steps shown schematically in Fig. 3.6. These steps are (1) flue gas pretreatment, (2) SO_2 absorption, (3) purge treatment, and (4) sodium sulfite regeneration. A fifth step, the processing of SO_2 into marketable sulfur by-products, is not part of the Wellman-Lord process, but is generally associated with Wellman-Lord installations.

Tables 3.5 and 3.6 show the air pollutants and solid waste products emitted by this 1250 MW facility.

The normal construction period would take a total of seven years. Two years would be taken up for site selection, design, and preparation, and five years for on-site construction. Operation of the plant would require a staff of 259.
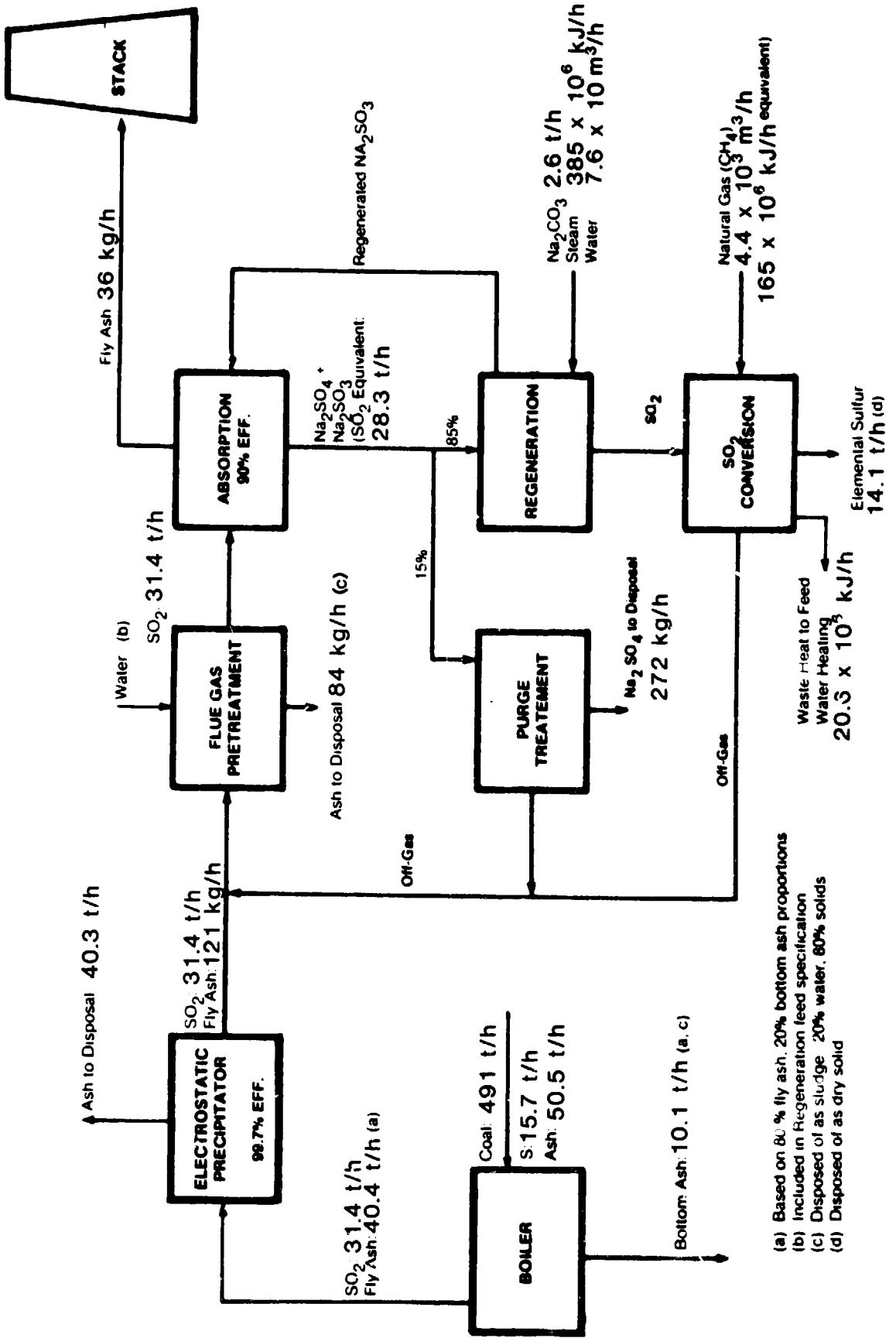
Fig. 3.6 Wellman-Lord Process (Adapted from Ref. 5)

Table 3.5 Air Pollutants from a 1250-MW Coal Facility

Pollutant	100% Capacity Factor		70% Capacity Factor		
	kg/h	t	kg/h	t	kg/10^6 kJ
SO$_2$	3136	27,605	2203	19,323	0.26
Particulates	36	318	25	223	0.003
NO$_x$	3254	28,537	2278	19,978	0.27

Table 3.6 Solid and Sludge Wastes from a 1250-MW
Coal Facility, 70% Capacity Factor

Solid Waste	Accumulation Rates at 70% Capacity Factor			Land Area[a]
	kg/h	t/yr	10^3 m^3/yr	10^3 m^2
Elemental Sulfur[b]	9,917	86,964	44	190
Ash Sludge[c]	44,260	388,105	269	1,145
Sodium Sulfite/ Sodium Sulfate	2,909	16,744	8.6	40.5
Total	–	–	–	1,375.5

[a]Assumes 8-m disposal depth typical of current practices.

[b]Disposal density = 1953 kg/m^3.

[c]80% ash, 20% water, density = 1440 kg/m^3. Solids content is 40,100 kg/h from bottom ash, and 85 kg from Wellman-Lord pretreatment.

3.2.4 Coal-Gasification/Combined-Cycle Power Plant

The coal-gasification/combined-cycle plant is an integrated system whose primary components are a gasifier, an open-cycle gas turbine, and a Rankine bottoming cycle. The basic plant is modeled after a 579-MW plant described in the ECAS study;[14] the design was augmented with information from the EPRI Preliminary Design study.[15] The plant design was scaled to 1250 MW net plant output (2 units at 625 MW each).

The reference facility is fired with eastern high-sulfur bituminous coal with heat content of 25,646 kJ/kg (11,026 Btu/lb). The overall net plant efficiency, which accounts for in-plant auxiliary steam and electrical consumption, is 38.5%. Figure 3.7 displays the major pieces of plant equipment in a simplified cycle schematic and energy flow diagram of the reference design.
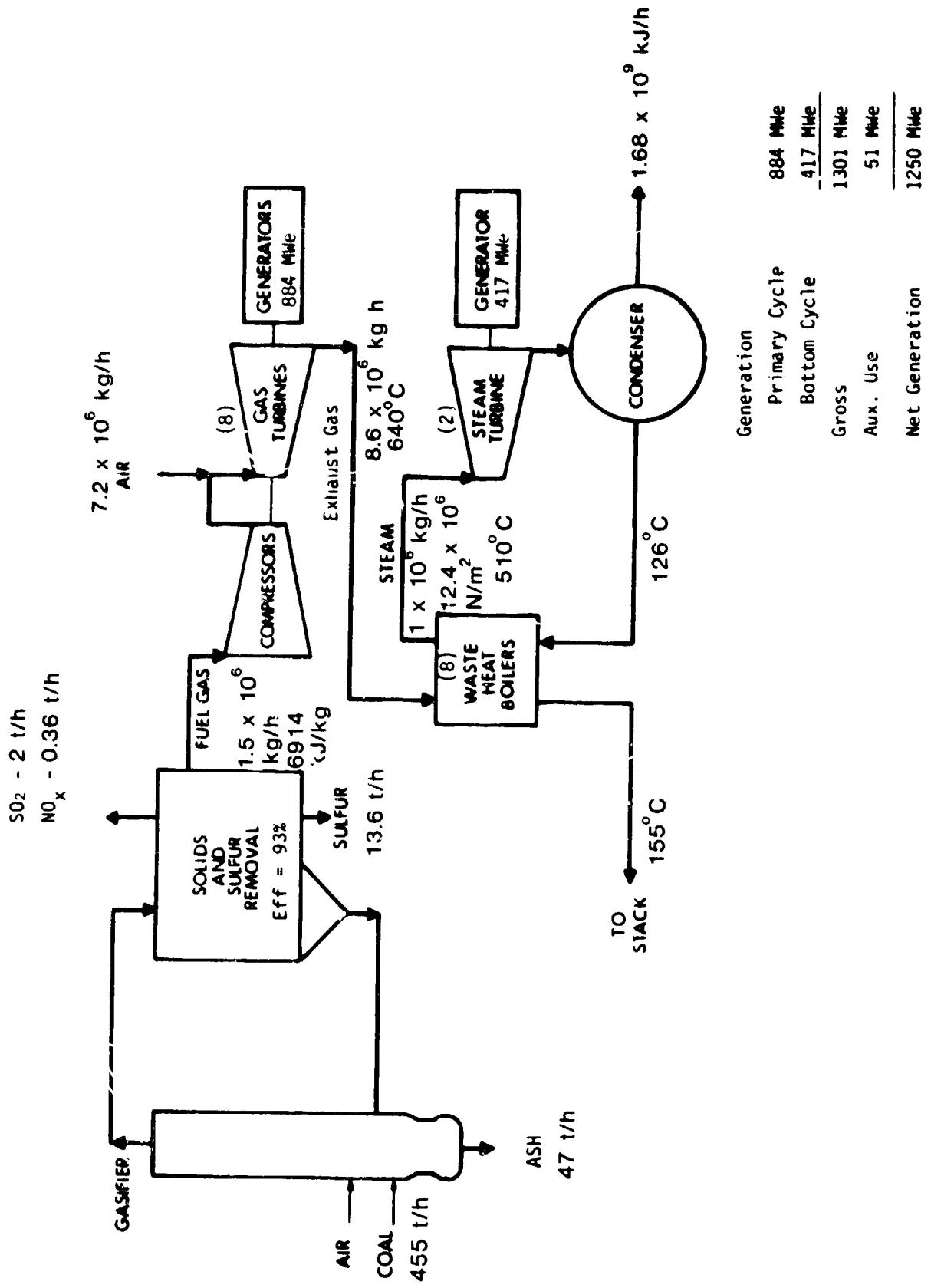
Fig. 3.7 1250 MW Coal-Gasification/Combined-Cycle System

The prime cycle consists of eight air-cooled gas turbine generator units, with a 12:1 compressor pressure ratio and 1315°C firing temperature (that is, the temperature at the inlet of the first-stage rotor). The prime cycle generates two-thirds of the total electrical power output. The gas turbine exhaust temperature is 640°C.

The bottoming cycle includes eight heat-recovery steam generators (HRSG) and two steam turbines. The HRSGs extract thermal energy from the gas turbine exhaust stream. The steam is supplied to steam-turbine generators, which contribute about one-third of the total power output. At full capacity, coal feed is required at a rate of 455 t/h or 2.8×10^6 t/yr at 70% capacity factor. At this rate, an average of 7650 t of coal would be required at the site each day; as coal storage requirements are estimated at full capacity factor, a 3-day live storage stock pile would contain 22,950 t of coal, and a 57-day reserve storage would contain 435,000 t of coal.

The average storage density of utility coal in live storage is 700 kg/m^3 and reserve storage density averages 865 kg/m^3. The assumption of 9.15-m-high active storage and 15.25-m-high reserve storage yields an area of about 36×10^3 m^2 devoted to coal storage and handling.

Figure 3.8 depicts the major environmental pollutants that arise from the impurities in the fuel and water used by the plant. The major impurities in the fuel are the sulfur and nitrogen compounds and incombustible ash. In the gasification step, almost all of the ash is separated from the coal, so it does not show up as a potential air pollutant. Similarly, about 93% of the sulfur is removed from the process stream by the combined Alkazid-Claus process. Another 1.3% is disposed of in the scrubber sludge from the wet limestone scrubber. The remaining sulfur appears as SO_2 in the stack gas from the various plant flues and exhausts. NO_2 control is effected by removing most of the NH_3 from the fuel gas streams before combustion.

Water used for plant cooling is also a source of environmental pollution. As the water is evaporated, concentrations of dissolved solids increase. This brackish "blowdown" water must be specially handled, to avoid pollution of local water systems.

The cleanup system must remove enough sulfur as elemental sulfur so that the sum of the SO_2 emitted from incinerator flues and the SO_2 emitted from the power plant flues will be no greater than allowed by EPA standards. The carbonyl sulfide (COS) formed in the gasifier and entering with the raw gas is almost completely hydrolyzed to hydrogen sulfide (H_2S) before entering the Alkazid plant. Five percent of the H_2S removed by the Alkazid plant will not be converted to elemental sulfur in the Claus plant. The tail gas is treated in the Wellman-Lord plant, which allows 90% of the sulfur to be recycled back to the Claus process. The Alkazid plant removes 95% of the H_2S entering with the raw gas. Only 5.6% of the total sulfur is emitted to the atmosphere as SO_2.

Nitrous oxides are formed by combustion of ammonia, and to a limited extent by oxidation of N_2 gas diluent. To meet the emission standards, 0.14 kg of NO_2 may be emitted to the atmosphere per million kJ of gaseous fuel.
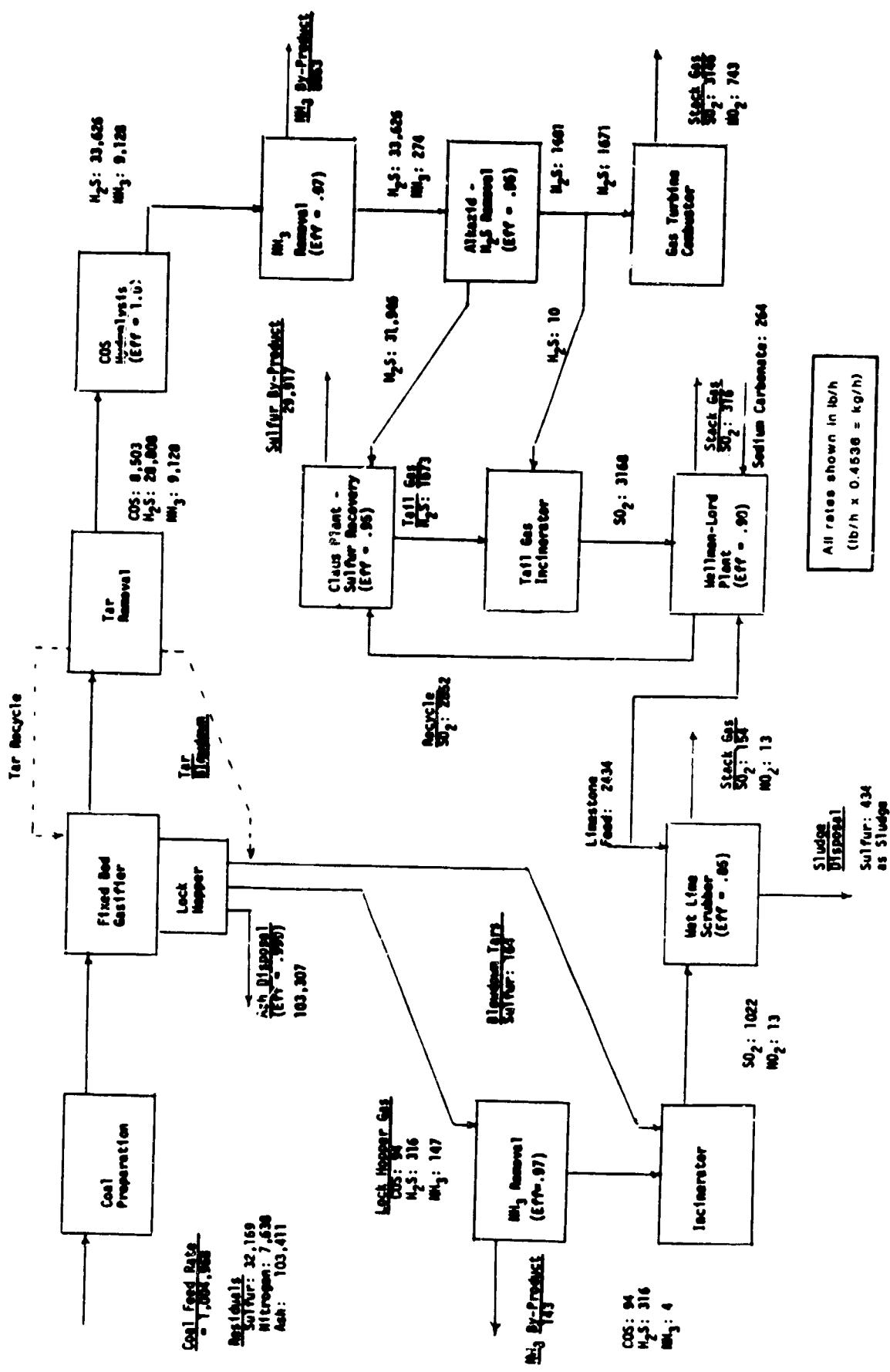
Fig. 3.8 Summary of Emissions from a 1250-MW, Low-Btu Gasifier, Combined-Cycle Plant

In the cleanup system, foul water condenses from the gas during dewatering. A foul process water enters with oil and phenol from the gasifier washer-coolers. These foul waters contain dissolved H_2S, NH_3, CO_2, and phenols. The water separated from the oil and phenol is returned to the washer-coolers where some additional makeup water is located. This makeup water evaporates and enters the cleanup systems with the saturated gas.

The construction period for a large coal-fired electric generation facility of the type characterized here would take a total of seven years. This includes a two-year period of fairly low level of effort for site selectiu , design and preparation, and a five-year period of actual on-site construction. During the on-site construction period, an estimated 8.1 million person-hours of direct craft labor would be required. The operating personnel requirement (336 persons) for this plant were estimated from experience with conventional plants.

3.2.5 Light Water Reactor Power Plant

The reference light water reactor (LWR) power plant[16-20] is a 1250-MW single-unit facility consisting of a pressurized water reactor supplying superheated steam to a conventional turbine generator. Condenser cooling is accomplished with a cooling tower.

The reference reactor as shown schematically in Fig. 3.9 was scaled up to 3750 MWt from a basic Westinghouse 3450-MWt design. At the present time, nuclear fuel is being discharged from reactors after an average burnup of 25,000 to 30,000 megawatt days per metric ton of fuel (MW-d/t). LWR technology has a goal[21] of achieving 50,000 MW-d/t, and therefore this value was assumed to be achieved by the year 2000 for the purpose of this characterization.

The nuclear steam supply system (NSSS) consists of a light-water-moderated nuclear reactor having a reactor core containing low-enriched uranium oxide fuel, approximately 4.15% U-235, in approximately 193 fuel assemblies. Loaded in the core are 98,000 kg of fuel. The core is refueled by replacing approximately one-third of the total set of fuel elements at roughly one-year intervals. The spent fuel is stored on site in a special fuel handling building. This building .s also a repository for fresh fuel prior to its insertion in the core.

The NSSS produces approximately 3750 MWt at nominal full power. The power generation system consists of the reactor core and vessel, its associated pressurizer, and four primary reactor coolant loops and four steam generators. Primary coolant (water) is heated from 295°C to 330°C by the nuclear reaction taking place in the core. The nominal coolant pressure is 15.5 x 10^6 Pa (or N/m^2). The high pressure is maintained in the primary system by a pressurizer to prevent boiling in the core. This hot water is then passed through the steam generators (u-tube heat exchangers) where water on the secondary side of the heat exchanger is heated to produce steam. Water on the primary side of the steam generator is returned to the core to be reheated to 330°C. Steam produced on the secondary side of the steam generator passes through the turbine generator power-conversion system. The turbine generators, at nominal rated power, produce 1250 MW. The condensate from the

COOLING TOWER

7.66 x 10^9 kJ/h

Gross Generation	1309 MWe
Aux Use	59 MWe
Net Generation	1250 MWe

GENERATOR 1309 MWe (Gross)

3.6 x 10^6 kg/h

CONDENSOR

TANDEM COMPOUND TURBINE

EXTRACTION 3.6 x 10^6 kg/h

FEEDWATER HEATERS

6.7 x 10^6 N/m2

284°C

7.5 x 10^6 kg/h

STEAM GENERATOR

226°C

330°C

75 x 10^6 kg/h

295°C

NUCLEAR STEAM SUPPLY SYSTEM 3750 MWt
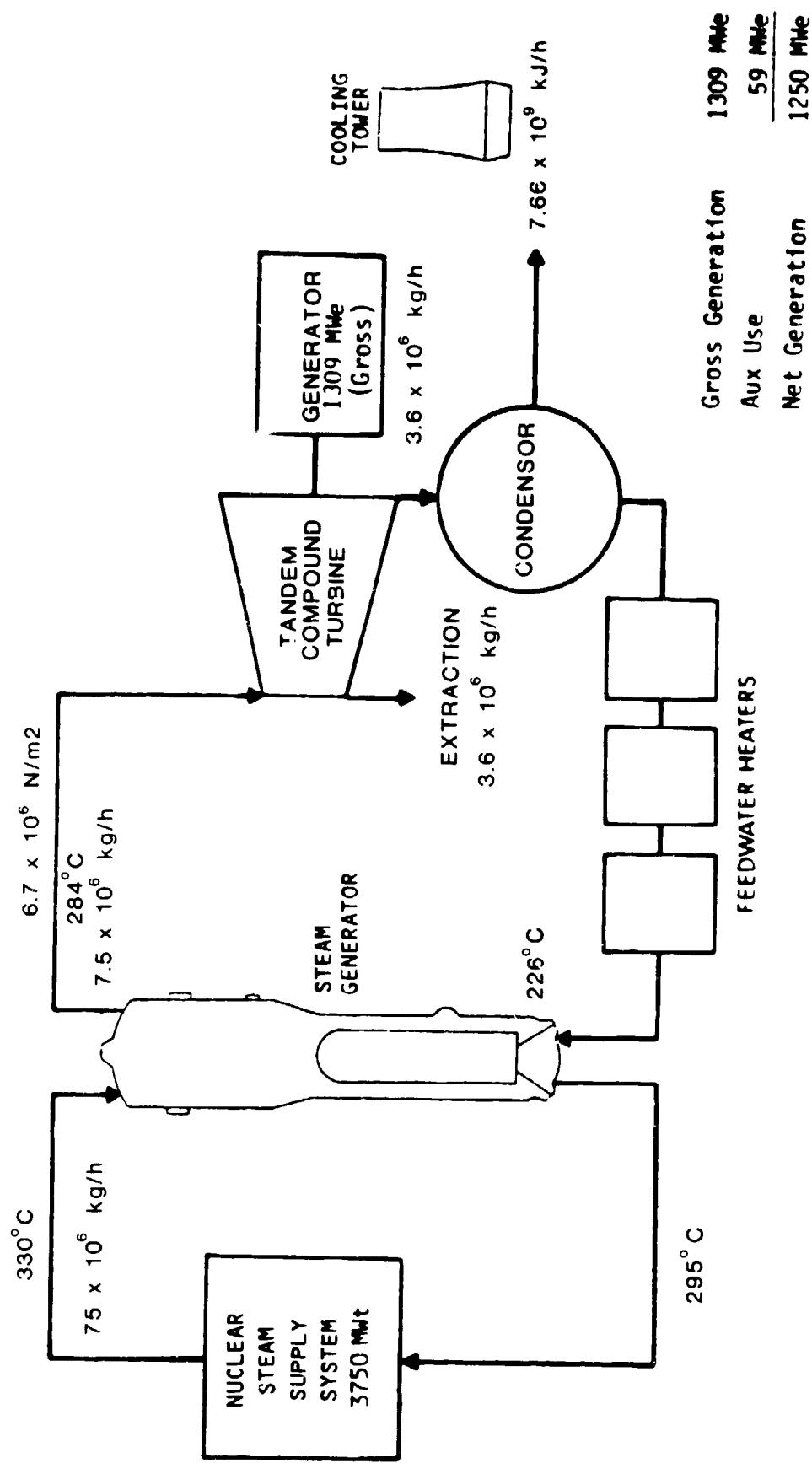
Fig. 3.9 Simplified LWR Flow Diagram

turbine is returned by the steam generator feedwater pumps. The reactor is equipped with residual-heat removal systems. The condensers are designed to condense the outlet steam from the low pressure turbine and the exhaust steam from the auxiliary turbine drive of the feedwater pump at 500 Pa, by dissipating the heat to three mechanical-draft wet cooling towers. The three main mechanical-draft wet cooling towers are each sized for one-third of the requirements. Each tower is designed to cool 13.6 m^3/s of water from 48°C to 33°C when operating at a wet bulb temperature of 23°C. Each tower employs a reinforced concrete-filled structure combined with components for water distribution, fill splash service, support system, drift eliminators, louvers, and fan deck.

Radioactive contaminants can come from the fuel itself or from (1) impurities in the fuel cladding, (2) activated wear products, or (3) other sources. Because several systems are contaminated, normal maintenance, operations, and leaks will lead to release of some of these elements. The mechanisms of release of these radioactive elements are primarily leakage through the building ventilation systems and dissolution in liquid effluents. Areas that have the potential for contamination are ventilated through high efficiency particulate filters, which remove more than 99.9% of the particles larger than 0.3 μm. Potentially contaminated liquid effluents are monitored or processed to remove radioactive elements by filtration and ion exchange. In each case, not all of the radioactive elements can be prevented from entering the biosphere. Consequently, radioactive elements are emitted to the biosphere by the LWR,* within the limits prescribed by the EPA and enforced by the NRC.

Water consumption results primarily from cooling tower evaporative losses and cooling tower blowdown (1.42 m^3/s at full power). The largest consumers of water are the mechanical-draft cooling towers (about 1 m^3/s).

The primary sources of liquid effluents from a LWR facility include the cooling tower blowdown stream and process water effluent. No radioactive wastes are discharged in effluent streams. These waste streams, which are processed to remove radionuclides, are then discharged under controlled conditions.** Cooling tower blowdown does not contain any radionuclide contamination but does contain chemicals added for control of corrosion and biological growth.

3.2.6 Liquid-Metal, Fast-Breeder Reactor

The LMFBR plant reference design[†] is a 3400-MWt loop-type, sodium-cooled fast-breeder reactor plant with a nominal electrical rating of 1250 MW.

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*Airborne radionuclides: total noble gases, 3 x 10^3 Ci/yr; iodine, 13.1 x 10^{-2} Ci/yr; Mn, Fe, Co, Sr, Cs, 4.1 x 10^{-2} Ci/yr.

**Waste-water effluents at 70% capacity factor: total suspended solids, 0.94 t/d; total dissolved solids, 2.35 t/d; organics, 210 kg/d.

[†]The plant design was developed by United Engineers and Constructors for the Department of Energy in the Energy Economic Data Base (EEDB) program as described in Ref. 22. Additional input was derived from Ref. 23.

The plant area will be about 70 acres, including the reactor building, switch-yard, parking lot, access roads, and wet cooling towers. As a minimum, a buffering area of 400 acres is needed. Thus with other physical facilities, a total area of 800 to 1200 acres is needed. The 1000-MWe LMFBR design (about 2500 MWt) was scaled up to 1250 MWe because the cost estimate is also based on this plant and major equipment.

The LMFBR primary system consists of a liquid sodium-cooled nuclear reactor having a reactor core containing low-enriched (about 11-15%) uranium and plutonium oxides in approximately 400 fuel-and-blanket assemblies. The core is refueled by replacing approximately one-third of the assemblies after achieving a 53,000 MW-d/t average burnup. Both the new and spent reactor fuels are intensely radioactive and must be stored in heavily shielded areas.

The reactor produces approximately 3417 MWt at nominal full power. The LMFBR heat transport system removes the heat generated by the reactor core and converts it to the rotational mechanical energy required by the generator to produce electric power. The overall system consists of a radio-active primary coolant (liquid sodium) system, a nonradioactive secondary coolant (also liquid sodium) system, a steam generation system, and a steam plant system, the latter including the turbine that delivers the required mechanical energy to the electrical generator. A simplified system diagram is given in Fig. 3.10.

The primary coolant system consists of several redundant circulating loops that conduct sodium from the core exit plenum of the reactor vessel and circulate it through intermediate heat exchangers. Here, the heat is transferred to the sodium of the secondary coolant system. The primary sodium then returns to the reactor vessel. In the secondary system, secondary sodium is heated in the intermediate heat exchangers and is circulated to the steam generation system. There are four parallel primary loops and four secondary loops, one serving each primary loop.

Two basic arrangements for the primary coolant system have been proposed: the pool-type and the loop-type configurations. These are depicted schematically in Fig. 3.11. In the pool-type configuration, the reactor, intermediate heat exchangers, primary pumps, and interconnecting piping are all immersed in a large primary tank filled with sodium. During operation, sodium is drawn from the bulk content of the tank by the primary pumps and is forced through the reactor. Then, the sodium flows by gravity through the intermediate heat exchangers and discharges back to the bulk sodium in the primary tank. The driving force for the intermediate heat exchanger flow is the difference between the level of sodium over the reactor and that in the remainder of the primary tanks. With this configuration, the primary tank with its cover and the tubes and tube sheets of the intermediate heat exchangers constitute the primary coolant system boundary.

In the loop-type configuration, the primary pumps and the intermediate heat exchangers are located outside the reactor vessel. Either hot-leg or cold-leg pumps could be used in the primary system. The primary loop piping is elevated, and guard vessels are provided around the pump, intermediate heat exchanger, and reactor vessel so that leaks in the primary piping or these components cannot cause the sodium level in the reactor to drop below the minimum safe level. The loop nozzles would be covered, and continuous
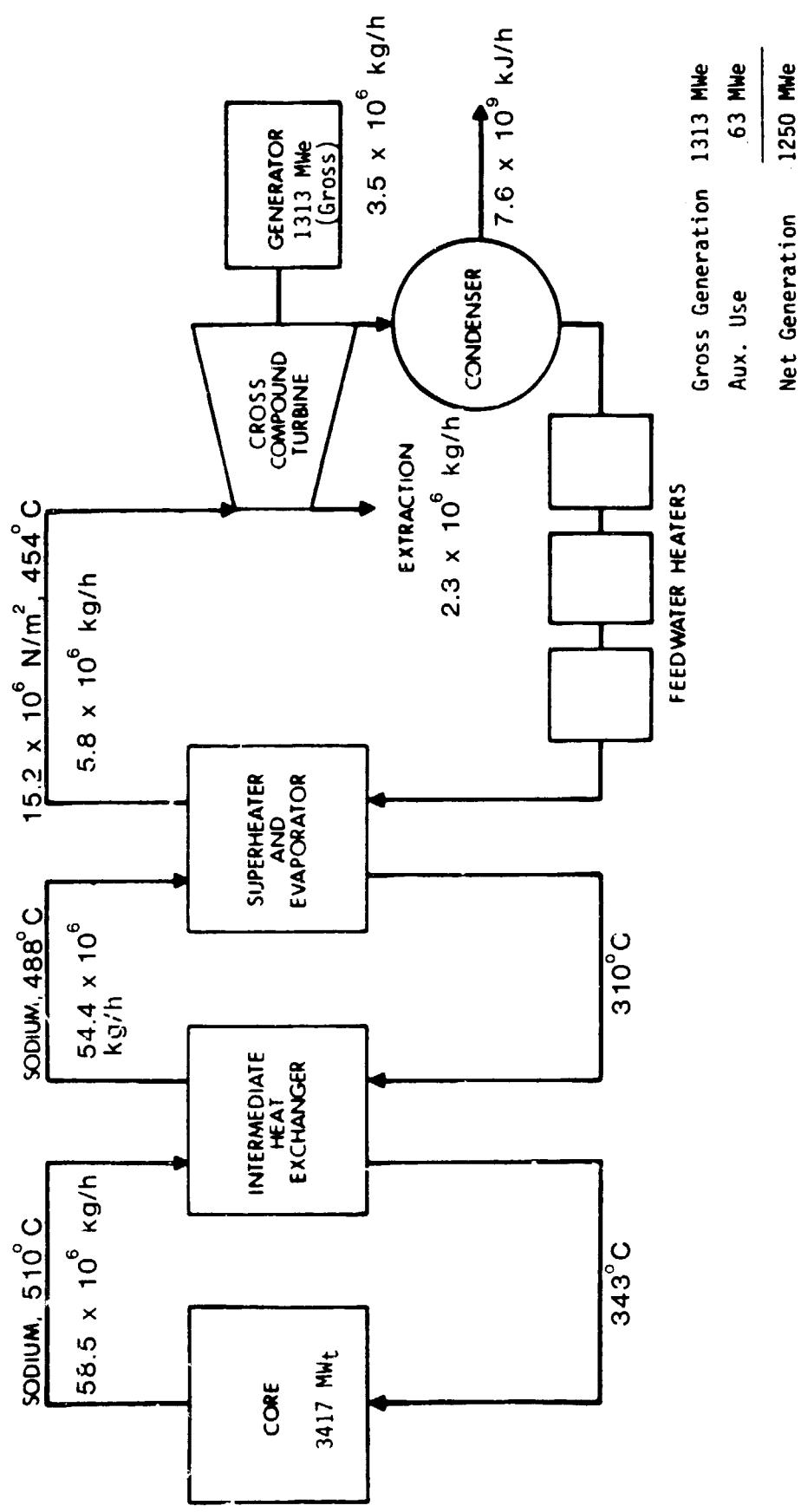
Fig. 3.10   1250 MW Liquid-Metal, Fast-Breeder Reactor
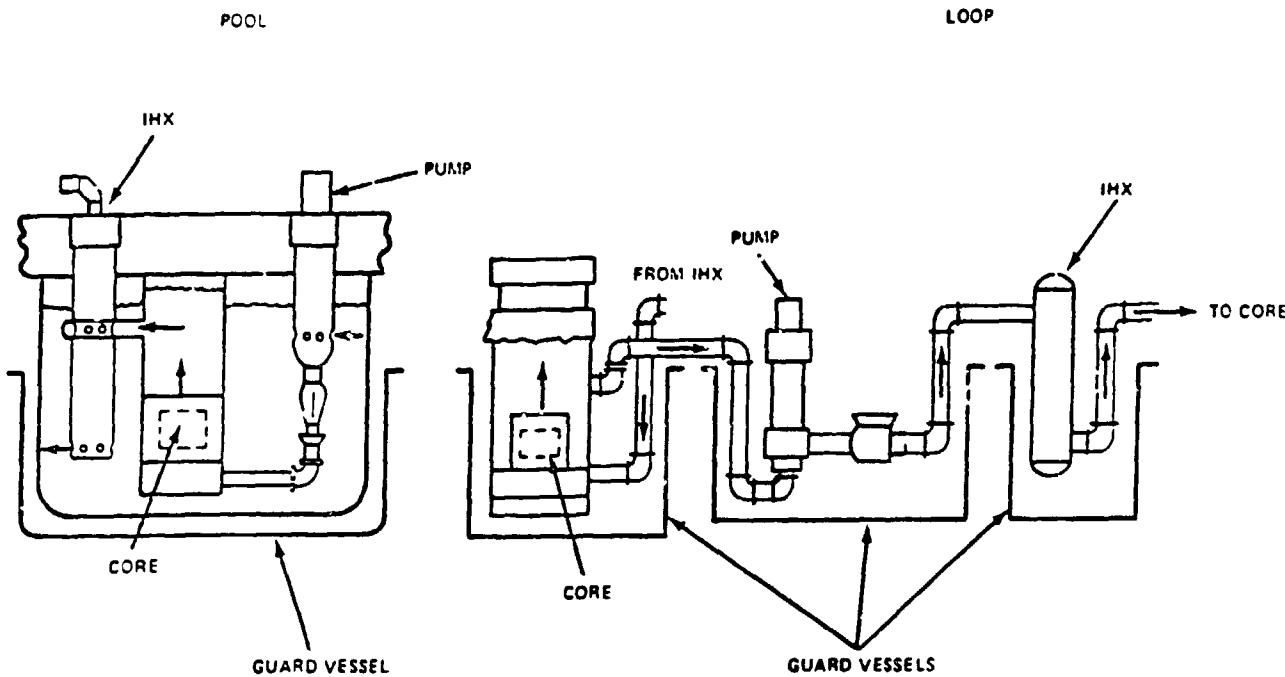
Fig. 3.11   Configurations of Pool- and Loop-type
Primary Coolant Systems

heat removal by sodium circulating through the loops could be permitted.   The
LMFBR characterized in this section is a loop-type plant.

The primary sodium system is designed to operate at a lower pressure
than the secondary system.   Thus, should a leak develop in an intermediate
heat exch ger between these two systems, sodium would flow from the nonradio-
active secondary system into the radioactive primary system.   Finally,
even though such leakage would not result in a radiological problem in the
secondary system, the intermediate heat exchangers are designed to facilitate
removal or replacement of faulty tubes.

The overall steam cycle is expected . be similar to that of modern
fossil-fired, steam-electric power plants.   The turbine design assumed in this
study is a set of tandem compound turbines like those used in fossil-fuel
plants.

Barriers to release of fission products are the fuel element cladding,
the boundary of the primary coolant system, and the outer reactor containment.

The outer containment consists of a leak-tight cylindrical steel
or steel-lined concrete building with a flat bottom and hemispherical or
ellipsoidal dome.   The containment building houses the reactor and entire
primary coolant system, spent fuel handling and storage facilities, and sodium
service systems related to the primary system.

The turbine configuration consists of two half-capacity tandem, com-
pound, four-flow machines with 0.85-m last stages designed to operate at
3600 rpm.   Inlet steam conditions at the high-pressure throttle valves are

15.4×10^6 Pa and 455°C. This reactor plant design provides the superheat so the inlet steam is not saturated; its condition resembles that in a fossil-fired power plant.

The condensers are designed to condense the low-pressure turbine outlet steam and exhaust steam from the auxiliary turbine drive of the feedwater pump by dissipating the heat to three mechanical-draft wet cooling towers. Each tower is designed to cool 12.3 m^3/s of water from 48° to 33°C when operating at a wet bulb temperature of 23°C.

Radioactive contaminants come from the fuel itself, impurities in the fuel cladding, activated wear products, or other sources. Because several systems are contaminated, normal maintenance, operations, and leaks will lead to release of some of these elements. The building ventilation systems and processed liquid effluents are the transport mechanisms for release of these radioactive elements. Areas with the potential for contamination are ventilated through high-efficiency particulate filters, which remove more than 99.9% of the particles greater than 0.3 μm. Potentially contaminated liquid effluents are monitored or processed to remove radioactive elements primarily by filtration and ion exchange. In each case, not all of the radioactive elements can be prevented from entering the biosphere. Table 3.7 shows the estimated airborne radionuclide releases from the reference 1250-MW LMFBR facility. These emissions are within the limits prescribed by the EPA for the LWR.

The aqueous chemical wastes from a nuclear power plant generally enter the environment via the blowdown stream from a closed-cycle cooling system or the circulating cooling water stream from an open-cycle system. The major sources of the waste streams from a nuclear power plant are those originating from the condenser cooling system and the process water system. All other waste streams are minor compared to those. Negligible radioactive effluents will be emitted from an LMFBR plant. A summary of effluents is provided in Table 3.8.

Solid wastes generated at the reactor will consist typically of filters from the heating and ventilation system, deactivated primary coolant sodium cold traps, analytical laboratory and liquid waste treatment residues, contaminated tools and parts, and waste such as plastic bags, footcovers, paper towels, and protective clothing. These wastes will be compacted and packaged in 55-gallon ($0.21 m^3$) sealed drums, then shipped to a low-level waste burial ground. About 0.26 m^3 of tritium waste per year, in the form of $Ca(O^3H)_2$, will be included in these solid wastes.

About 3117 curies of beta-gamma waste and about 30,000 curies of tritium waste will be generated each year.

Table 3.7 Postulated Radionuclide Releases, 1250-MW LMFBR Power Plant at 70% Capacity Factor

Nuclide	Atmospheric Release, Ci/yr
H-3	65.63
Ar-39	87.50
Kr-85m	0.33
Kr-85	0.44
Kr-87	0.44
Kr-88	0.54
Xe-133	0.03

The 1250-MW LMFBR would reject heat at about 7.5×10^6 kJ/h through the cooling towers. In addition, there will be miscellaneous thermal losses to air (called general plant losses) amounting to less than 1%, a value typical of present-day nuclear facilities. Approximately 2.8×10^5 m^2 of land will be required for facilities associated with the LMFBR power plant; namely, the reactor buildings, turbine building, switchyard, parking lot, access roads, and cooling towers. As a minimum, an exclusion area of at least 16×10^6 m^2 is needed, and presently most LWR stations are on even larger sites.

Water consumption results primarily from cooling tower evaporative losses, cooling tower blowdown, and general plant uses, totalling 1.28 m^3/s. By far the largest consumers of water are the mechanical-draft cooling towers, which use approximately 0.88 m^3/s.

3.2.7 Fusion

The reference fusion-power plant is based on the NUWMAK power plant design developed by the University of Wisconsin Fusion Engineering Program of the Nuclear Engineering Department.[24] The NUWMAK power plant produces electricity through a boiling-water reactor power cycle with heat supplied by a Tokamak fusion reactor. One plant produces 660 MW net, and the power facility characterized here consists of two NUWMAK reactors, producing 1320 MW net power.

Table 3.8 LMFBR Wastewater Effluents at Nominal (1250 MW) Operation

Effluent	Amount
Chemical	t/h
BOD	0.000
Chromates	0.000
Phosphates	0.007
Boron	0.051
Acids	0.013
Organics	0.011
Chlorine	0.004
Radiological	Ci/yr
Uranium	negl.
Ra-226	0
Th-230	0
Th-234	0
Co-60	0.774
Sr-90	0.257
I-131	0.01
Cs-134	9.38
Cs-137	7.97
Ce-144	0.030
Pu	0
Tritium	350
Ru-106	0.014
Other activation and fission products	70.32

The NUWMAK discussed here is a newer and more realistic design than the UWMAK series developed by the University of Wisconsin. The objective of the new treatment was to simplify mechanical design and maintainability. The power density in NUWMAK is increased to about 10 W/cm^3 as compared to 0.5 to 2 W/cm^3 in earlier designs. Figure 3.12 is a schematic of this NUWMAK concept. The reference fusion plant uses deuterium-tritium fuel. During the reactor burn cycle the deuterium (D) and tritium (T) in the toroidal reactor chamber are in a plasma state. When a D-T fusion reaction occurs, a helium-4 nucleus (alpha particle) is formed and a 14-MeV neutron is given off. The high-energy neutrons are absorbed by a blanket that surrounds the fusion reaction chamber. The neutrons heat the blanket, and this heat is then removed from the blanket and used to produce electricity. NUWMAK uses boiling water as a coolant and a conventional boiling-water reactor power cycle to produce electricity.

Fig. 3.12   Schematic of NUWMAK Fusion Power Plant

The power flow for one NUWMAK reactor is shown in Fig. 3.12. The gross thermal efficiency is 34.5%. After accounting for auxiliary power requirements of 65 MW, of which 60 MW is needed to cool the magnets, the net power output is 660 MW with a net thermal efficiency of 31.5%. Two reactors would have a net output of 1320 MW.

The NUWMAK reactors differ from those of previous studies (such as UWMAK) in that no diverter is used. Impurity control (which is needed in order to keep the plasma from cooling) is accomplished instead by gas puffing, which, along with partial pellet fueling, permits operation for approximately 225 seconds with adequate plasma cleanliness. During a burn, neutral deuterium gas is puffed into the plasma approximately every 0.5 seconds. Tritium is introduced in solid pellets, which penetrate only the outer plasma mantle. A sharp temperature profile develops at the plasma edge, which is kept cold both by the gas puffing and by introduction of impurities. However, the step temperature profile prevents impurities from diffusing towards the plasma center. The impurities are neutralized and pumped out through vacuum-pump ports.

The plasma requires a magnetic field of 6.05 T (tesla) at a major radius of 5.13 m, which means a maximum field of 12 T at the magnet. To provide the needed access for maintenance and repair, NUWMAK is designed with only eight large superconducting "D"-shaped TF coils and the increased ripple is corrected with 16 saddle-shaped trimming coils. The primary design of the

TF coil uses NbTi superconductor with subcooled superfluid liquid helium at 1.8 K and atmospheric pressure. ... ^ are four cryogenic vertical field coils inside the TF coils and four superconducting coils at the outside of the TF coils to maintain the elongated plasma. The ohmic heating coils are located inside the central core of the reactor system. Since the magnets require a pulsed power supply, each reactor is supplied with a 2-MWh superconductive energy storage unit.

Since ohmic heating is effective only at relatively low plasma temperatures, auxiliary heating is necessary to raise plasma temperatures to ignition conditions (when fusion reactions will sustain themselves without further heat input). The NUWMAK design employs radio-frequency (RF) supplementary heating in the ion cyclotron range of frequencies in order to ignite the plasma. The design entails launching a fast magnetosonic wave into a 50-50 DT plasma and heating the ions at the second harmonic cyclotron frequency of deuterium.

The NUWMAK reactor operates with a cycle length of 245 seconds: 225 seconds of burn followed by 20 seconds of down time. The heat stored in the blanket material provides energy to the coolant during the down time, reducing the cyclic variation from 70% to 30% of the maximum energy to the turbines. Since a 30% variation is still unacceptable, a steam drum is used and the feedwater temperature is adjusted. Figure 3.13 is a schematic of this load-leveling system, with which constant electrical output can be achieved. Simultaneous operation of the two reactors is not necessary for constant electrical output. Two reactors produce 4566 MWt with a net electrical output of 1320 MW. Since the burn time is 92% of the cycle time, the net thermal efficiency is 31.5%.
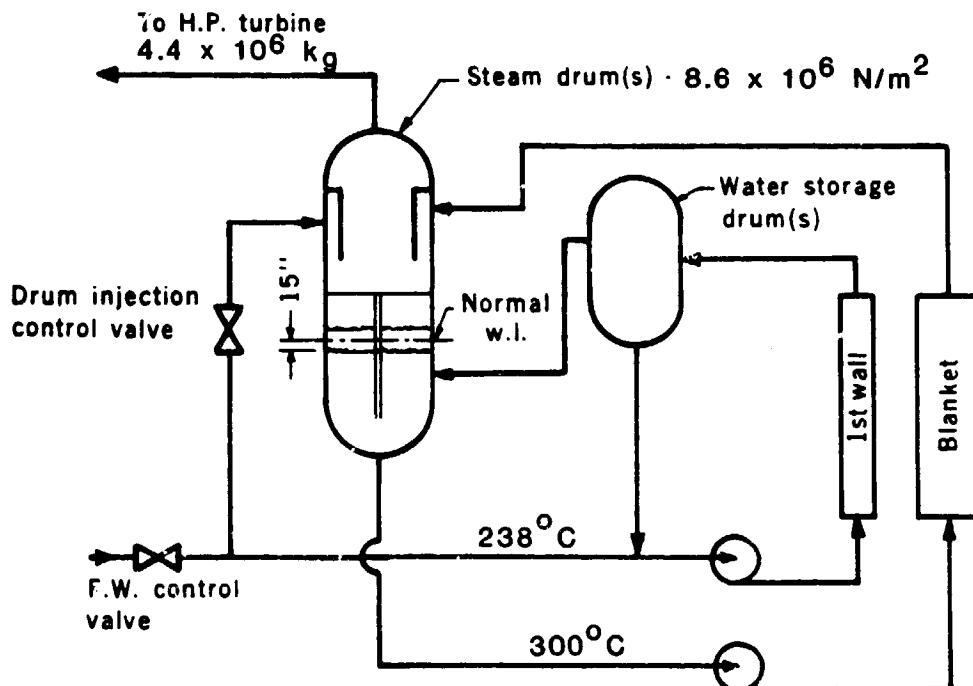
Fig. 3.13   Schematic of NUWMAK Load-Leveling System

The total tritium inventory in NUWMAK may amount to more than 10^{10} Ci. In order to limit tritium releases from NUWMAK to less than 10 Ci per day, tritium losses must be limited to one part in one hundred million on a daily basis. Essentially perfect containment of tritium depends on clearly identifying possible routes of tritium release. During normal operation, potential sources of tritium loss include the plasma fueling and fuel purification components, energy-storage equipment (both normal and emergency), tritium breeding and extraction system components, and the first wall and blanket coolant. Tritium containment associated with each of these systems is examined in the analysis of a multi-layer containment system.

The three-level containment system (Fig. 3.14) is designed to deal with tritium release under both normal and abnormal conditions. Each level prevents the dilution of released tritium, so that it can be recovered before permeating to the next barrier. The primary containment system consists of those pipes and other structural elements that contain tritium or tritium-bearing materials.

The secondary containment system consists mainly of a second physical barrier around the primary system components: for example, primary system piping outside the plasma chamber is contained within larger-diameter piping. A slowly flowing inert gas is passed through the annulus and monitored for tritium leakage. Large pieces of equipment requiring maintenance or adjustment are enclosed in glove boxes.
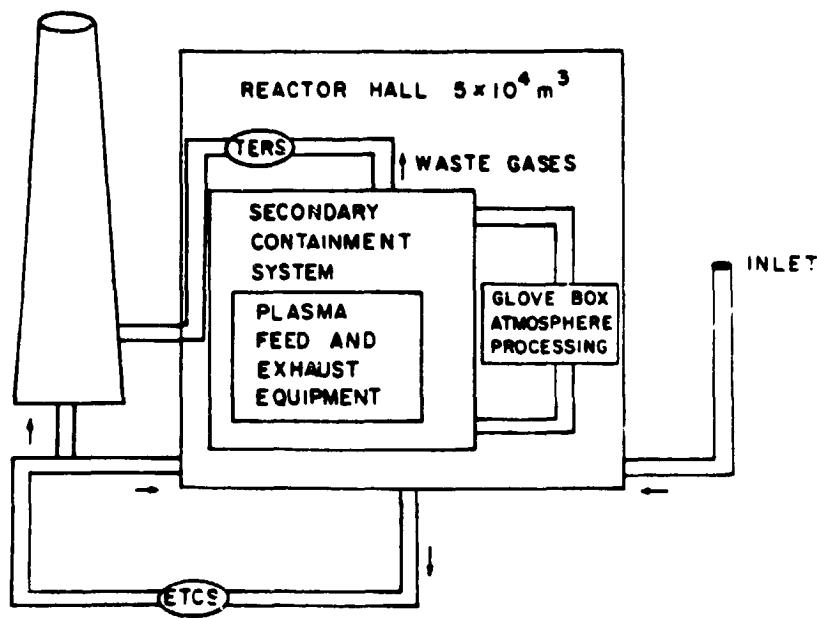
LEGEND:

TERS = TRITIUM EFFLUENT REMOVAL SYSTEM
ETCS = EMERGENCY TRITIUM CONTAINMENT SYSTEM

Fig. 3.14 Tritium Effluent System Design

The tertiary containment system includes the reactor hall, rooms containing tritium processing equipment, the reactor building itself, the tritium effluent removal system (TERS), and the emergency tritium containment system (ETCS). The TERS is designed to operate on routine tritium losses while the ETCS is used only under abnormal conditions.

As with the primary and secondary systems, the reactor building is subdivided to reduce both the extent of loss and the extent of contamination in the event of a leak. Each reactor hall has a volume of 8.7×10^4 m^3 and may be divided radially to provide the least impediment to maintenance operations. The reactor building is maintained at 8.4×10^3 Pa during operation, and the pressure can be reduced to 1.3×10^3 Pa under emergency conditions.

About 20% of the building volume atmosphere would be circulated each day, from areas of smallest to largest radioactive hazard before leaving through a stack of sufficient height to guarantee proper dispersal of the effluent. Under normal operation, this stack effluent would contain about 1 Ci per day.

The emergency tritium containment system (ETCS) consists of a heated catalyst to oxidize HT and T_2 to HTO and T_2O, alumina beds presaturated with water at 100% humidity, and the required air handling equipment. The ETCS is used in the event of a simultaneous breakdown of both the primary and secondary systems to rapidly detritiate air from contaminated areas of the reactor building. During cleanup, the inlet dampers of contaminated areas are closed and only a small fraction of fresh air is allowed to circulate to reduce tritium losses from the stack.

One further source of tritium leakage is the boiling water coolant. It has been calculated that the leak rate of tritium into the cooling water will be limited to a few curies per day. In the event that the leak rate increases, it is possible, without much increase in costs, to add equipment for removing tritium (in the range of 0.001 to 10 Ci/mL) by combined electrolysis-catalysis or by molecular photo-excitation.

The 14-MeV neutrons from the fusion reaction induce radioactivity in the structure surrounding the plasma. Most of the activity originates in the inner region of the blanket. The blanket should be replaced every two years, and the material processed and stored on the plant site.

3.3 COST CHARACTERIZATIONS

A comparative assessment of the electric generation costs for the SPS and alternative technologies requires that the cost components of each system be characterized on a consistent and normalized basis. Unfortunately, technology cost estimates from previous efforts were usually developed under assumptions that differed from study to study, and are inconsistent with the characteristics assumed for the nominal reference systems in this assessment. Thus the remainder of this section quantitatively documents the procedure used to derive a set of consistent capital and operation and maintenance (O&M) costs for the SPS and alternative technologies.

Costs from the original data source are displayed for each technology and it is shown how these costs are adjusted to be consistent with the nominal reference system characteristics such as plant capacity and overall efficiency. Where the original data present estimated costs in other than 1978 dollars, these are normalized to 1978 dollars by application of appropriate escalation factors.

The development presented in this section results in baseline point estimates based on the assumption that each technology is constructed to come on line in 1978 and is financed totally in 1978 dollars. This is the starting point for the analysis presented in the cost and performance comparison, where these 1978 point estimates are adjusted to reflect systems coming on line in the year 2000. These costs are analyzed in the cost and performance comparison in terms of their potential uncertainties in the 2000 time frame by assigning an upper range to the year-2000 base costs. Subsequent analysis is then based on these cost ranges.

As previously mentioned, construction costs for each of the nominal reference systems were developed on a consistent basis by adjusting published data to a common set of rules and assumptions. Thus, all costs make similar assumptions about the owner's costs, contingencies, and allowances for funds used during construction. The primary source of data for the coal and nuclear systems was the Energy Economic Data Base (EEDB)[22] compiled and updated for DOE by United Engineers and Constructors. The General Electric study for EPRI[8] and the SPS concept definition studies[1,7,8] were used for cost data on the terrestrial photovoltaic system and the SPS, respectively.

In several cases the available cost estimates were for plant sizes and heat rates (efficiencies) different from those selected for the reference technologies. These were adjusted by power factors commonly used in electric utility cost estimation. A construction cost that excludes contingencies, owner's costs, and interest during construction was thus derived. Where costs were in a different year's dollars, they were adjusted to 1978 dollars by an appropriate escalation rate; SPS cost estimates[7,8] given in 1977 dollars were escalated to 1978 dollars using an 8.0% escalation factor.

3.3.1 Satellite Power System

Development Costs. Boeing[25] estimated development costs on the basis of the reference system scenario, which predicates a 20-year development schedule and a 30-year deployment schedule (for 60 5-GW satellites). These costs amount to $100-110 billion and are broken down as follows (Fig. 3.15):

- Research costs: mainly ground-based research to address environmental and social issues and alternative systems, resulting in a preferred system;

- Engineering: development and testing of prototype subsystems, resulting in specifications for demonstration units and production facilities;

- Demonstration: flight tests of a 100-200 MW unit integrated with a commercial network;
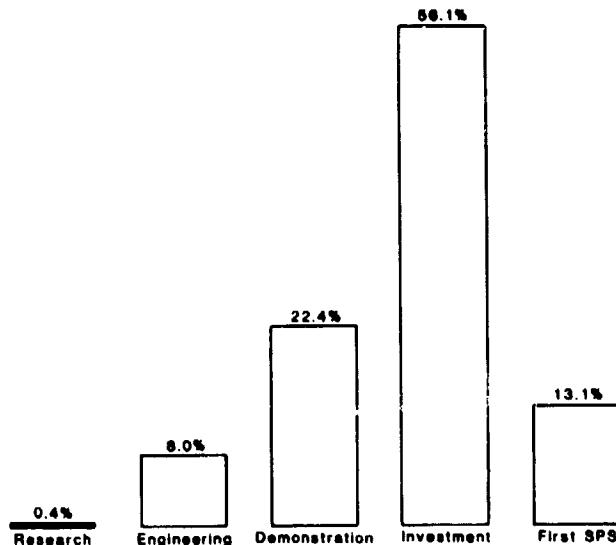
Fig. 3.15 Development Costs of the SPS
(Source: Ref. 26)

- Investment: development of industrial infrastructure,
  e.g., transportation, photovoltaic, and klystron manu-
  facturing facilities.

- Construction and implementation: the first 5-GW SPS
  unit put into place.

It is important to note that these cost estimates assume that all effort is specific to the SPS. The benefits from generic research or from cost sharing (e.g., industry or other federal program support for photovoltaics manufacturing facilities) have not been considered. Such cost modifications could amount to 50-70% of the $102.5 billion.[27]

Since comparable cost data for the other six technologies were not available, side-by-side comparisons of costs or of the benefits or disadvantages of public expenditures were not attempted.

The SPS development program would consist of five phases and include basic research, engineering verification, prototype demonstration, investment requirements, and commercial production of the satellites. A cost estimate compilation based on 1977 dollars was presented on February 20, 1980, by R.J. Harron and R.C. Wadle of NASA.[28]   The estimates were updated to 1978 dollars by a factor of 1.08 and are shown in Table 3.9. The required investment in facilities to produce satellites and related equipment is unique to this program and will enter into the commercial operation costs as an allocated expense, i.e., depreciation of investment for each satellite. In accordance with the reference accounting method, developing and establishing the space fleet for transport of materials, supplies, and personnel are not considered part of the depreciable satellite investment and, accordingly, have been excluded from capital recovery. The cost estimates of the work breakdown structure include provisions for price escalations and for project management and integration, which are included herein, in addition to the applied contingency and owner's costs added for this review.

Table 3.9 Capital Requirements of the SPS (5000 MW), 1978 Dollars x 10^6

Development Phase	Solar Array Satellite Silicon	Solar Array Satellite GaAlAs[a]	Space Construction Bases	Space Transport Silicon	Space Transport GaAlAs	Earth-Based Facilities	Totals Silicon	Totals GaAlAs[b]
Research								
Specific	152.3		27.0	199.8			379.1	
Systems Studies	8.2	–	1.5	10.8	–	–	20.5	–
Total	160.5		28.5	210.6			399.6	
Engineering								
Specific	621.0		3,005.1[c]	4,896.1[d]			8,522.2	
Project Management[a]	4.8	–	23.2	37.9	–	–	65.9	–
Total	625.8		3,023.3	4,934.C			8,588.1	
Demonstration								
Specific	6,119.3		6,580.4	6,977.9		1,897.6	21,575.2	
Operations[e]	852.5		916.7	972.1		264.3	3,005.6	
Project Management	46.6	–	50.1	53.1	–	14.4	164.2	–
Total	7,018.4		7,547.2	8,003.1		2,176.3	24,745.0	
Investment								
Specific	2,322.0		18,571.7	24,361.6		16,246.4	61,501.7	
Project Management	31.0	–	248.2	325.6	–	217.1	821.9	–
Total	2,353.0		18,819.9	24,687.2		16,463.5	62,323.6	
Satellite								
First:								
Specific	4,928.6		1,892.8	4,345.3		2,539.7	13,706.4	
Proj. Mgt.	167.4	–	64.3	147.6	–	86.2	465.5	–
Total	5,096.0		1,957.1	4,492.9		2,625.9	14,171.9	
Avg:								
Specific[f]	5,432.2	5,552.2	945.0	3,062.8	1,900.6	2,421.3	11,861.3	10,819.1
Proj.Mgt.	212.8	212.8	37.0	119.9	119.9	94.7	464.4	464.4
Total	5,645.0	5,765.0	982.0	3,182.7	2,020.5	2,556.0	12,325.7	11,283.5
Project Contingency[g]							2,147.0	1,980.2
Owners Costs at 3%							491.0	455.0
Interest During Construction (IDC), 4%, 3 yr							816.3	755.3
Investment Costs/SPS							1,092.0	1,092.0
Total Capital							16,872.0	11,566.0

[a]Allocated on dollar ratio.

[b]SPS Ref. System Costs – GaAs Option – Memo 3/3/80, D. Taylor to NASA. Used only charges in avg. SPS/space transport. Assumed investment phase unchanged.

[c]Full cost of LEO Lab + 0.5 x cost of LEO shuttle flight.

[d]0.5 x cost of LEO shuttle flight.

[e]Demonstration period expenditure allocated on dollar ratio.

[f]Various segments include "cost growth and escalation" omitted earlier.

[g]16% Total + $1092 x 10^6 Investment per SPS, net of space transport fleets.

Table 3.10 Operation and Maintenance Costs
of the SPS (5000 MW)

Cost Component	10^6 $ (1978)	Mills per kWh
Maintenance		
Satellite		
Klystron	10.8	0.27
DC-RF Converter	15.7	0.40
Balance	15.9	0.40
Total	42.4	1.07
Transportation		
Materials Facility	41.3	1.04
Personnel Facility	87.5	2.22
Total	128.8	3.26
Ground Receiving Station	15.1	0.38
Space Construction Bases	4.2	0.10
Cumulative Total	190.5	4.81
Contingency at 13%	24.8	0.63
Management and Integration at 5%	9.5	0.24
Grand Total O&M Costs	224.8	5.68

Harron and Wadle also estimated annual operating and maintenance (O&M) expenses for the space transport, space construction, and repair of the satellites and the ground receiving station. These were not adjusted in any way except for conversion to 1978 dollars (with a multiplier of 1.08). Total annual expenses (shown in Table 3.10) of $224.8 x 10^6 1978 dollars are equivalent to an annual charge of 5.7 mills per kWh of net electrical output.

3.3.2 Conventional Coal-Fired Power Plant with Advanced Flue Gas Desulfurization (H-S Coal)

The capital costs for the reference system were based on EEDB costs,[22] adjusted to reflect a 5.9% increase in the steam system, insertion of the Wellman-Lord sulfur removal system (and removal of the conventional lime treater), an additional heat exchanger to increase stack gas temperatures, and a larger turbine generator to accomodate higher internal requirements.

Direct and indirect capital costs are estimated at $452.1 million and $90.7 million (1978 dollars), respectively. A contingency allowance of 7% is added to account for the conventional nature of the plant. It is anticipated that the owner will spend approximately 9.2% of the cumulative subtotal on expenses such as consultants, permits, and site selection, and an allowance for funds during construction over the seven-year construction period is

estimated to total approximately $52 million (expressed at "real" rates in January 1978 dollars).

Annual operating and maintenance expenses are estimated to be $23.5 million, representing $5.7 million for the payroll, $4.8 million for disposal of residues, and $5.0 million for acid-gas removal supplies. Other components of O&M are materials, supplies, and interim replacements, which contribute $7.1 million, and administrative and general expenses, estimated at $0.9 million. Based on an annual plant capacity factor of 0.7, the annual cash expenditures amount to 3.06 mills per kilowatt hour.

3.3.3 Combined-Cycle Power Plant with Low-Btu Gasifiers (CG/CC)

Capital costs and annual expenses were based on a 1975 Energy Conversion Alternatives Study (ECAS)[14] reference plant of 579-MW capacity. As a reference system, the unit was updated to 1978 dollars, general facilities were segregated, and processing segments were exponentially scaled to 625 MW with two units on one site making up the total facility. Appropriate adjustments were made to substitute the reference eastern bituminous coal and more rigorous emission standards. Direct capital costs are $537.4 million.

Indirect capital costs, $132.7 million or 24.7%, were derived from data presented on a 630-MW coal gasification facility found in the Energy Economic Data Base (EEDB).[22] A comparison was made summarily to validate this match-up by comparing ECAS with EEDB indirect costs for plants with identical capacity (of a different type). The indirect construction costs for the two units total $132.7 million, with a breakdown of 60% for construction service, 22% for home-office engineering, and 18% for field engineering.

A construction contingency at 9% of the cumulative expenditures was added, resulting in installed facilities amounting to $730.4 million in 1978 dollars. Owners' costs of $66.5 million and an Allowance for Equity Funds Used During Construction (AFUDC) over the seven-year construction period of $65.1 million yield a capital requirement for the 1250-MW CG/CC of $862 million, or $689.60 per installed kilowatt.

Of the estimated operating and maintenance expenses of $20.66 million, materials, supplies, expenses, and interim replacements contribute 47%. The 336-person staff accounts for $7.4 million, and related administrative and general costs are $1.2 million. Environmental control costs are estimated to be $2.3 million/yr, principally for disposal of dry solid wastes. The total contribution of environmental control expenditures to energy cost, at the 70% plant capacity factor, is 2.70 mills per kilowatt hour.

3.3.4 Light Water Reactor (LWR)

A 1139-MW system was changed to the reference 1250-MW design by use of conventional capacity-ratio exponential factors used by the electric industry for various segments of the plant. This method yielded an estimate for installed plant cost, in 1978 dollars, of $485.9 million. Indirect construction costs for the nuclear plant were estimated to be $197.1 million, or some 40.6% of the installed equipment. These indirect construction costs

included construction services ($75.0 million), home-office engineering ($91.2 million), and field engineering ($30.8 million). An allowance for contingent expenditures amounting to 8% of the cumulative subtotal yields a combined plant investment of $737.7 million. Owners' costs of 9.3% and interest during construction (IDC) computed on a 12-year construction cycle result in overall capital requirements of $890.2 million in 1978 dollars.

Annual expenditures for operation and maintenance total $16.9 million, or 2.31 mills per kWh of net production. Materials, supplies, expenses, and interim replacements contribute 57% (1.32 mills) to these costs, with staff costs (including administration and general) at 0.83 mills and the balance accruing to inspection fees, special insurance, and amortized decommissioning expenses.

3.3.5 Liquid-Metal, Fast-Breeder Reactor (LMFBR)

The basic plant cost estimate, in 1978 dollars, for a 1390-MW LMFBR unit, which was prepared by United Engineers and Constructors for the EEDB,[22] was downscaled by the appropriate capacity ratio exponents to the 1250-MW reference size for a total of $702.9 million in direct construction costs. Because of safety and inspection requirements, indirect construction costs amount to $262.6 million, for a total facility cost of $965.5 million. A project contingency at 11% was deemed reasonable for this technology, resulting in a plant investment totalling $1071.7 million in 1979 dollars. Owners' costs over the 12-year construction period are estimated at more than $93 million, and during the lengthy period, IDC will accumulate to 11.3% of the cumulative subtotal, even at the reduced "real" cost of utility capital.

Annual non-fuel operating expenses amount to 2.96 mills per annual kWh of net production, and total $22.7 million. Materials, supplies, expenses, and interim replacements account for 64%; staff, 22%; administrative and general, 9.2%; and the balance (insurance, inspection fees, and allocated decommissioning expenses), approximately 4.8%.

3.3.6 Fusion Reactor (NUWMAK)

The direct capital costs for the magnetically confined fusion facility presented in the NUWMAK report[24] were adjusted to a different average labor rate for consistency with the LWR and LMFBR data. Unlike the procedure in past assessments, in this assessment design allowances for unproven technology appropriate for this system were incorporated in the equipment accounts to eliminate the customary omissions in conceptual design. Direct capital costs for the entire two-unit facility are estimated at $1.5332 billion (in 1979 dollars) over the staged construction period of 10 years, which includes eight years per unit with a two-year lag between construction starts. Indirect costs for the reference system have been adjusted upward from those contained in the NUWMAK report (41% vs. 35%) for consistency with the EEDB boiling water reactor plant, and thus amount to $628.6 million. Reflecting the project uncertainties and status of technology development, a project contingency of 18% is applied to the subtotal for a total plant investment of $2.551 billion. The combination of design allowance, increased indirect costs and higher contingency rate may seem to escalate the final cost more than for the other

technologies, but it is considered prudent for this concept. In any event, the incremental margin would amount to bet·;een 15% and 20% of the total plant investment, well within cost-estimating accuracy of a novel process. Owners' costs of 9% and IDC accruals over the 10-year construction period ($389.2 million) result in a capital requirement of some $3.1395 billion, roughly 2.5 times more expensive than the next most costly terrestrial energy investment, LMFBR.

Annual operating and maintenance expenses for the facility were adjusted, from the basic NUWMAK report, to be $57.9 million/yr, which includes a 2% factor of direct and indirect costs for O&M plus scheduled replacements of other plant facilities. Total O&M costs applied to the energy output amount to 7.29 mills per kWh, adjusted from the reference report to include amortized decommissioning expenses.

3.3.7 Central-Station Terrestrial Photovoltaic (TP·)

Direct construction costs[9] are estimated to be $120.1 million (1978 dollars), and indirect construction amounts to $22.4 million, for a cumulative to 1 construction cost of $142.5 million. Project contingency allowances (12.0%) of $18.5 million yield an installed plant cost of $161.0 million.

Owners' costs for permits, coordination, consultants, and site selection are estimated at 10.2% of the installed plant cost, or $16.4 million in 1978 dollars. The IDC, calculated on a five-year construction period, is $2.0 million in real terms, for a capital requirement of $186.4 million in 1978 dollars, or $863.8 per installed kW.

Operating expenses, in 1978 dollars, are $1.66 million per year, including $561,000 in payroll and $762.000 for the sinking fund accrual of 30% of the basic facility costs for interim replacements. The total, at an assumed 25% plant capacity factor, is calculated at 3.5 mills per kWh.

4 COMPARATIVE ANALYSIS

4.1 ASSUMPTIONS AND ALTERNATIVE FUTURES SCENARIOS

4.1.1 Assumptions of the Comparative Analysis

Three levels of comparative analysis are described in the assessment framework (Sec. 2) and illustrated in Fig. 2.1. These levels are (1) comparison of characterizations, (2) side-by-side analysis, and (3) alternative futures analysis. In this section, comparisons are made, issue by issue, at each of these levels. Each level of analysis has associated assumptions, and are ordered in a hierachy: therefore, the analysis and assumptions are cumulative as one proceeds from the lowest level (characterization comparison) to the highest level (alternative futures analysis). Before proceeding to the description of these comparative analyses, it is important to delineate the assumptions used here in order to place the comparisons in proper perspective. By assumptions we mean any important information, caveats, or baseline data that affect the analysis.

Many assumptions were made in the course of the comparative analyses, and to describe them all would obscure the comparisons. Therefore, the ones described here are those that most affect the perspective of the analysis. The description of these assumptions is handled sequentially (i.e., as part of the characterization, side-by-side analysis, and alternative futures analysis).

Comparison of Characterizations. These comparisons are made on the basis of the parameters that define a system (e.g., capital cost, O&M cost, resource consumption, and environmental residuals). Therefore, the characterization comparison is solely dependent on the technology description. For currently utilized technologies (i.e., coal and nuclear fission) most of these parameters are fairly well-defined because advanced technologies represent extrapolations of existing systems. In the case of the newer technologies (i.e., TPV, SP, fusion), in which similar technology is not in operation, the parameters represent estimates based on design assumptions.

The technologies selected and characterized for these assessments are intended to represent electrical supply systems that could satisfy energy demand in the 2000-2030 era. Some of the advances in design are in limited operation or have been demonstrated, but for others, only design or conceptual information exists. The characterizations were carefully prepared so that the analysis of each technology is internally consistent. For example, the capital cost information presented for a technology includes the cost of environmental control systems, and the assessment of environmental performance is based on the same environmental control systems. The characterizations were developed according to an integrated procedure; therefore, characterization data reported in this assessment may be different from piecemeal information (e.g., capital cost, environmental performance) reported elsewhere.

Side-By-Side Analysis. The side-by-side analysis uses the characteri-
zation information with impact models to determine the impact of a technology,
and then normalizes this impact to a unit of net energy output. The determin-
ation of impact in most cases requires assumptions about the state of the
world (e   economic conditions, technology penetration, other environmental
pollutants . These assumptions were made in a nonintegrated fashion from
issue to issue. For example, in the health and safety analysis certain
baseline environmental assumptions were necessary, from which incremental
health impacts from the addition of another power plant could be determined.
The results of this type of assessment are generic, not region-specific.
The impact models are based on dose-response data derived from experience with
existing technology, and the pollution levels they indicate do not necessarily
represent projections of what the impact might be from pollution by new
technologies. For example, occupational health and safety information
was developed from the most representative current technology, in an attempt
to predict the levels of occupational health and safety impact of the future
technologies. The important assumptions (e.g., key economic parameters) that
are made in each side-by-side comparative analysis are described in each
section.

Alternative Futures Analysis. Since the objective of this comparative
assessment is to compare technologies projected for the post-2000 era, a great
number of assumptions are required. Most of these assumptions are highly
uncertain and interdependent, so that a single consistent set may not present
the decision maker with an adequate and consistent comparative perspective of
the future. The alternative futures analysis was chosen as a means of
providing a broader perspective of the most important parameters that describe
the future. These alternative futures perspectives represent an integrated
parametric analysis of plausible but unforecastable events, to provide a
broader picture of the comparative issues. The assumptions underlying the
alternative futures analysis constitute a set of energy supply/demand futures
or scenarios.

The alternative futures scenarios describe the level of energy demand
and the mix of energy technologies that are used to meet this demand, given a
set of assumptions about the U.S. economy. The levels of technology deploy-
ment and economic assumptions in each scenario can be used to calculate a
comparative assessment. The scope of this assessment is limited to electrical
energy and does not describe mixes of nonelectrical energy supply.

These scenarios are created from a consistent economic model so that
interdependencies between economic assumptions are preserved. Scenarios were
selected as a means of exploring and analyzing, not predicting, the economic
energy future. The scenarios were selected to represent a plausible future
world, and no probabilities are assigned to any of them. We are not attempt-
ing to eliminate uncertainty in our choice of scenarios; in fact, by choosing
a range of scenarios we hope to explo- the dimensions of uncertainty more
fully. Scenarios were selected to provide a comparative perspective on the
negative and positive aspects of demand and mixes of supply technologies in
the post-2000 era. The remaining part of this section will briefly describe
the procedure and the energy supply-demand scenarios used in the alternative
futures analysi . A more detailed technical description of these scenarios is
found in a separate report.[29]

4.1.2 Alternative Futures Scenarios

At a time when petroleum energy prices have increased nearly tenfold in a decade, and analysts have difficulty understanding events that have already occurred, the notion of making energy/economic forecasts well into the 21st century seems foolhardy.

Given the long-range perspective of the SPS (i.e., not available until year 2000), a 50-year horizon for evaluating alternative major energy technologies (such as the SPS) is necessary. The key problem is how to reduce the vast number of possible "alternative futures" to a few meaningful alternatives that encompass the range of significant policy variables and unknowns without simply creating confusion. The solution is to focus attention mainly on the factors that may cause energy prices and demands to vary under a given set of economic-demographic assumptions. The underlying economic analysis -- a major research effort in itself -- was borrowed from the work of Ridker and Watson.[30]

Most energy/economic analyses begin with some model of the relationship between energy consumption and GNP. The simplest model, found mainly in pre-1973 studies, was based on the observation that GNP and energy demand, E, have tended to move closely in tandem in the U.S. for several decades. A simple E/GNP ratio was sometimes assumed. Deeper study of the data revealed a long-term declining trend in this ratio (see Fig. 4.1). This can be interpreted as a result of the economy's shift from energy-intensive primary agriculture and materials and manufacturing industries toward services, which add greatly to the GNP without consuming much energy.

Until 1973, energy prices were declining, on the average, so that demand for energy presumably would have increased if it were not for the structural changes in the economy mentioned above. After 1973, of course, energy prices rose very sharply. The expected response in a market economy is a further decrease in demand, together with increased supplies. The balancing mechanism is illustrated schematically in Fig. 4.2.

A number of medium- and long-term energy/economic models have an optimizing scheme (usually some mathematical programming algorithm) to project future energy costs for specified levels of demand. This procedure is classified as partial equilibrium insofar as the reverse feedback, i.e., the dependence of GNP on energy prices, is neglected. Examples include the ETA Model,[31] the Nordhaus Model,[32] the Brookhaven BESOM Model,[33] and a dynamic version known as DESOM.[34] All of these models assume that energy prices are bounded by the long-term marginal costs of supply. The independence of GNP and energy-influenced price changes can be a convenient, although rough, approximation if the energy sector is very small (4%) compared to the rest of the GNP.

The ETA-MACRO[35] model is another kind of general equilibrium model with a more detailed energy sector driven by an aggregated macroeconomic model, which includes a link between economic growth and investment. There are several dynamic, multisector, general equilibrium models in the literature, including Hudson-Jorgenson,[36] PIES,[37] and Gulf-SRI,[38] but they are all necessarily very complex and consequently difficult to use and to explicate.
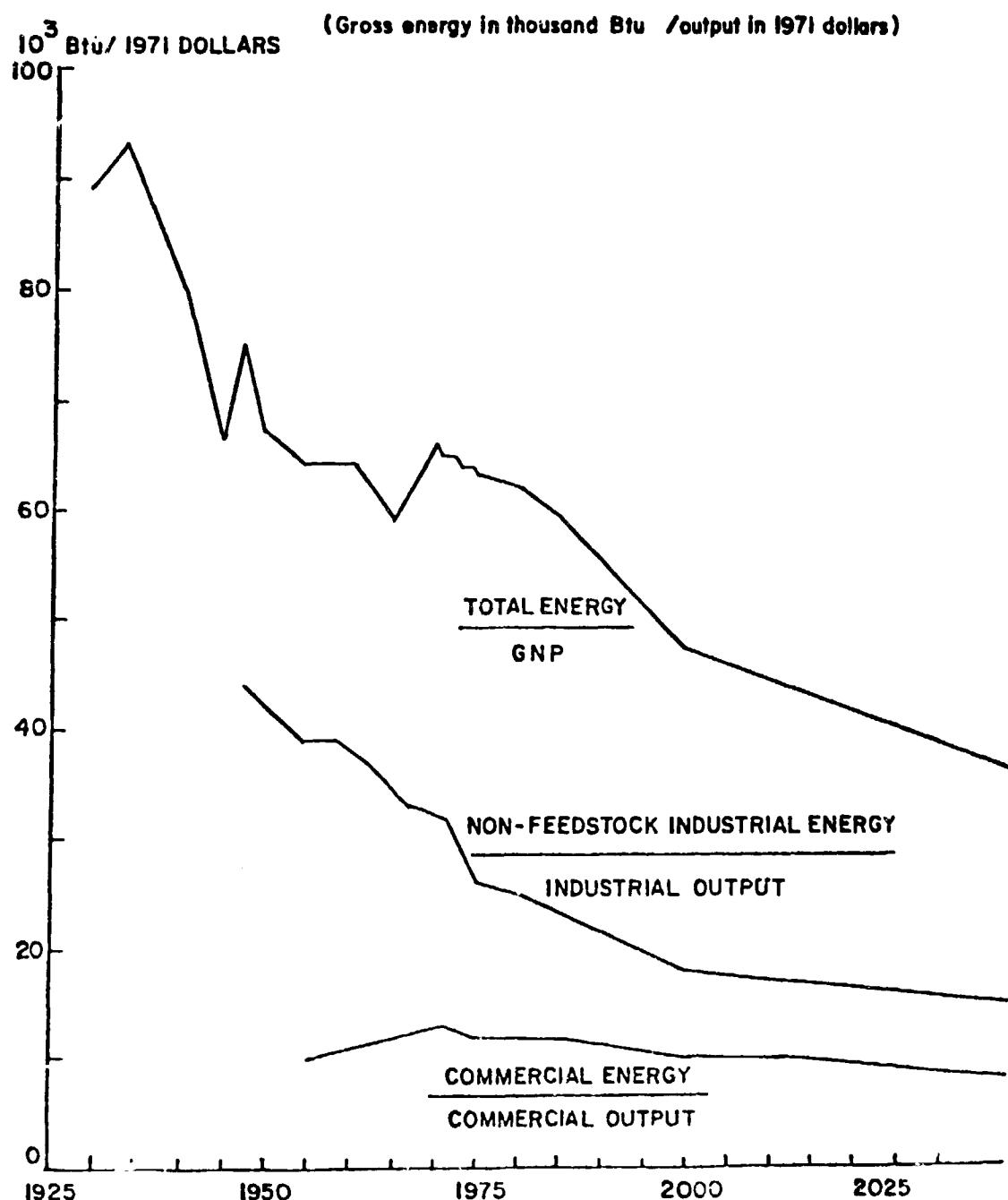
Fig. 4.1   U.S. Energy Output Ratios, 1929-1974,
           and Base Projections to 2025

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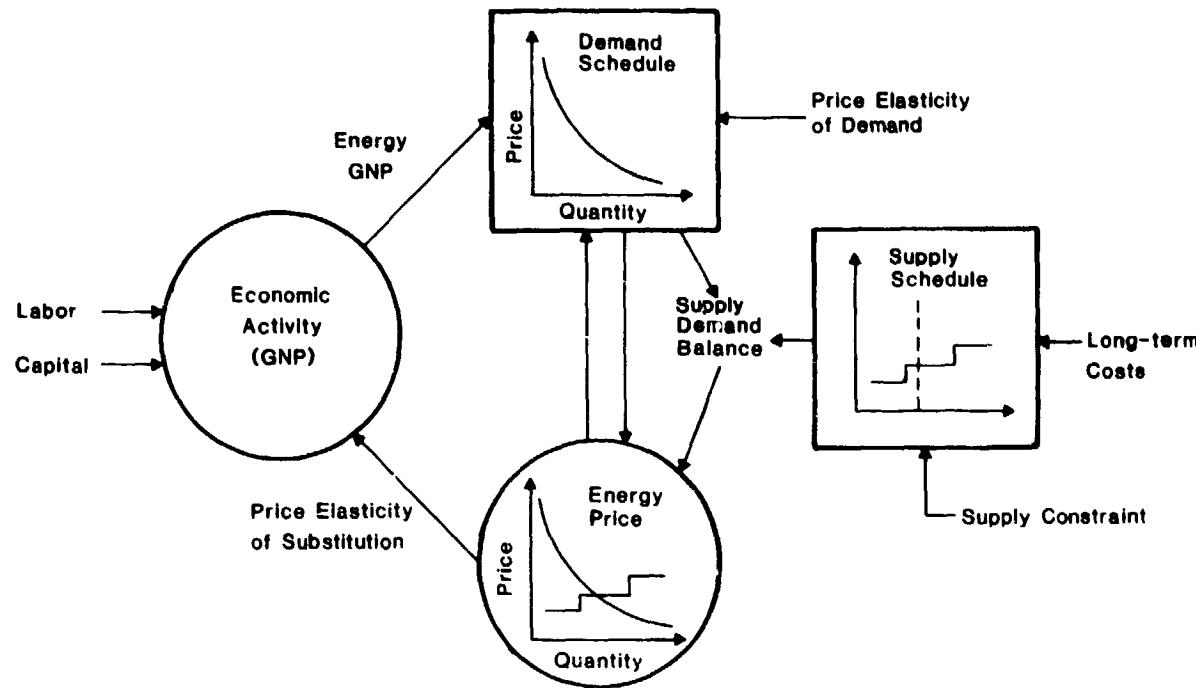
Fig. 4.2   Simplified Macroeconomic Model of the Interaction
           between Energy and the Economy

Probably the long-term model that is most sophisticated in its treat-
ment of interindustry relationships and capital accumulation is the Resources
for the Future (RFF) model, developed by Ridker and Watson,[30] based on a
185-sector dynamic interindustry model.[39]   The RFF model was selected for
this assessment on the basis of several selection criteria -- sectoral detail,
endogenous treatment of both capital investment and final demand, and trans-
ferable experience in the form of existing model runs covering the desired
time frame   -- 2000-2030.

Table 4.1 provides our assumptions about population, labor force, labor
productivity, and GNP in constant (Jan. 1978) dollars.   The population
figures incorporate a replacement fertility rate of 2.1 children per woman.
Although the total fertility rate is currently around 1.9, there is no basis
on which to assume it will remain at this unprecedented level.   Moreover,
immigration -- illegal as well as legal -- will probably remain above the
400,000 per year that is incorporated into these projections.   The labor
numbers, which take into account increased female participation in the labor
force, somewhat earlier retirement age, and other trends, are consistent with
the population figures.   The GNP, derived from projections about the labor
force, participation rates, employment rates, changes in working hours per
year, and   productivity growth rates, increases at an annual rate of 2.8%
between 1980 and 2000 and 2.5% thereafter.   This compares with a rate of 3.1%
per year between 1970 and 1979 and 3.4% between 1950 and 1970.   The decrease
in GNP growth is due in part to declining productivity, attributable to the
need to divert capital into the energy sector and energy conservation.   Clear-
ly, this economic scenario is only one of several self-consistent possibili-
ties.   It probably represents an upper limit to GNP growth.

Table 4.1.   RFF Model Assumptions about Population, Labor Force,
Productivity, and GNP, 1975-2025

Element	1975	1980	1985	2000	2025	2030
Population (millions)	214	225	236	264	304	312
Labor force (millions)	95	107	111	124	139	142
GNP (billions, 1978 $)	1754	2108	2394	3691	6449	7000
Consumption	1131	1350	1451	2351	4226	-
Investment	219	304	435	426	1011	-
Government	383	403	482	742	1154	-
Exports	131	175	196	315	676	-
Imports[a]	-99	-152	-184	-312	-643	--
Inventory change	-14	11	14	17	27	-

[a]Import requirements are computed explicitly in the RFF model, making due
allowance for the cost of imported energy. Exports are then calculated
on the basis of the long-run equilibrium assumption that international
currency exchange rates automatically adjust to permit exports to balance
imports.

But future energy demand and prices depend not only on GNP but also on
other parameters of the economy. The key unknowns are as follows:

- The inherent energy intensiveness of the economy, or
  (equivalently) the price elasticity of demand;

- The degree of effective constraint on production of
  coal and nuclear energy that will be imposed for health,
  safety, and environmental reasons;

- The cost of synthetic fuels from coal and energy from
  other medium- or long-term technological alternatives,
  including wind, biomass, passive solar collectors,
  terrestrial photovoltaic cells, SPS, and fusion.

For simplicity we have considered three alternative price elasticities
of aggregate demand for energy, namely:

H: High energy intensiveness, corresponding to low
     elasticity (-0.25).

I: Intermediate energy intensiveness, corresponding
     to intermediate elasticity (-0.4 for residential
     and housing demand, -0.7 for industry, 0 for
     feedstocks).

L: Low energy intensiveness, corresponding to high
     elasticity (-0.75).

Regarding constraints, we have selected two cases:

U: Unconstrained supply of coal and nuclear power.

C: Constrained supply, due to health, safety, environ-
    mental, and other limitations on the rate of increase
    of supply.

It is important to note that we have assumed domestic production of
petroleum and natural gas, and imports of these fuels, to be strictly limited
by geological factors in the first instance and by international political
factors in the second. The combined effect of all constraints is shown
in Table 4.2.

As regards long-run supply costs, our basic assumptions (Table 4.3)
are taken from a recent comprehensive appraisal by Resources for the Future.[40]

Table 4.2 Constrained Energy Supplies (10^{15} Btu)
for Future Scenarios

Energy Source	1980	1985	2000	2025	2030
Petroleum					
Domestic production	20.2	16.5	11.2	6.1	5.1
Net Imports	18.0	18.0	18.0	18.0	18.0
Total	38.2	34.5	29.2	24.1	23.1
Natural gas					
Domestic gas	19.4	17.6	12.0	5.6	4.3
Net Imports	2.3	3.0	3.0	3.0	3.0
Total	21.7	20.6	15.0	8.6	7.3
Coal					
Direct	14.9	19.2	21.1	22.0	28.2
Converted	0	0	8.5	20.8	23.0
Total	14.9	19.2	29.7[a]	47.8[a]	51.3[a]
Nuclear	3.0	5.0	10.0	14.5	15.4
Hydro	3.2	3.2	3.3	3.5	3.5
Geothermal	0	0	1.0	3.0	3.5
Solar[b]	0	0	1.1	6.4	7.5
Shale	0	0	5.0	18.3	21.0
Total Consumption	81.0	82.5	94.3	126.2	136.6

[a]Or other combinations with the same total.

[b]Passive solar collectors or hot water and seasonal space
heating in suitable applications.

Table 4.3. Assumed Long-Run Costs per
Million Btu (1978 $)

Coal gasification

$3.17 for conversion
+ $0.97 for distribution

Shale oil

$4.67 for extraction
+ $1.90 for refining and distribution

"Alternatives" (e.g., passive solar, wind, etc.)

$9.00 standard case, or
$4.50 "decentralized" case, assuming a cost
breakthrough

Electricity

$7.33 for conversion from coal
$8.96 for conversion from nuclear fuel

Source: Ref. 4

Note that two price cases for "alternative sources" were considered. The higher ($9/10^6 Btu) is consistent with continued dependence on centralized electric or gas utilities. However, the lower-price case ($4.50/10^6 Btu) would presumably lead to more decentralized energy production. Two scenarios of the latter type are considered.

The procedure for quantifying scenarios is outlined briefly as follows. First, from the assumed GNP growth rate and assumed price elasticities of demand, a set of projections of alternative energy (E) to GNP ratios can be derived, as shown in Fig. 4.3. Detailed demands by each of 185 sectors of the economy are computed from an input-output model for this economic scenario, assuming fixed prices.[30] Next, demands for specific fuel types are generated, and a supply-demand balance is computed for each of six scenarios, representing combinations of the levels of price elasticity and constraints, as follows: UH, UI, UL, CH, CI, CL. The supply-demand balances are displayed in Fig. 4.4 (2000) and Fig. 4.5 (2030).

The next step was to calculate the energy prices (for each primary fuel and for electricity) that would match supply and demand in each year. Adjustment lags of unknown length make this calculation approximate. The final steps involve recomputation of total demand, by sector, for the revised energy prices; recomputation of total E and E/GNP; and reiteration of the whole sequence until convergence is achieved.

Our baseline scenario is the constrained case with an intermediate value of price elasticity (designated CI). This choice reflects our belief that constraints on production growth are likely to continue, rather than abate; that the intermediate value of elasticity is more likely than either of the extremes; and that the higher cost level ($9.00/10^6 Btu) is more realistic for "alternative sources" than the lower cost ($4.50/10^6 Btu).
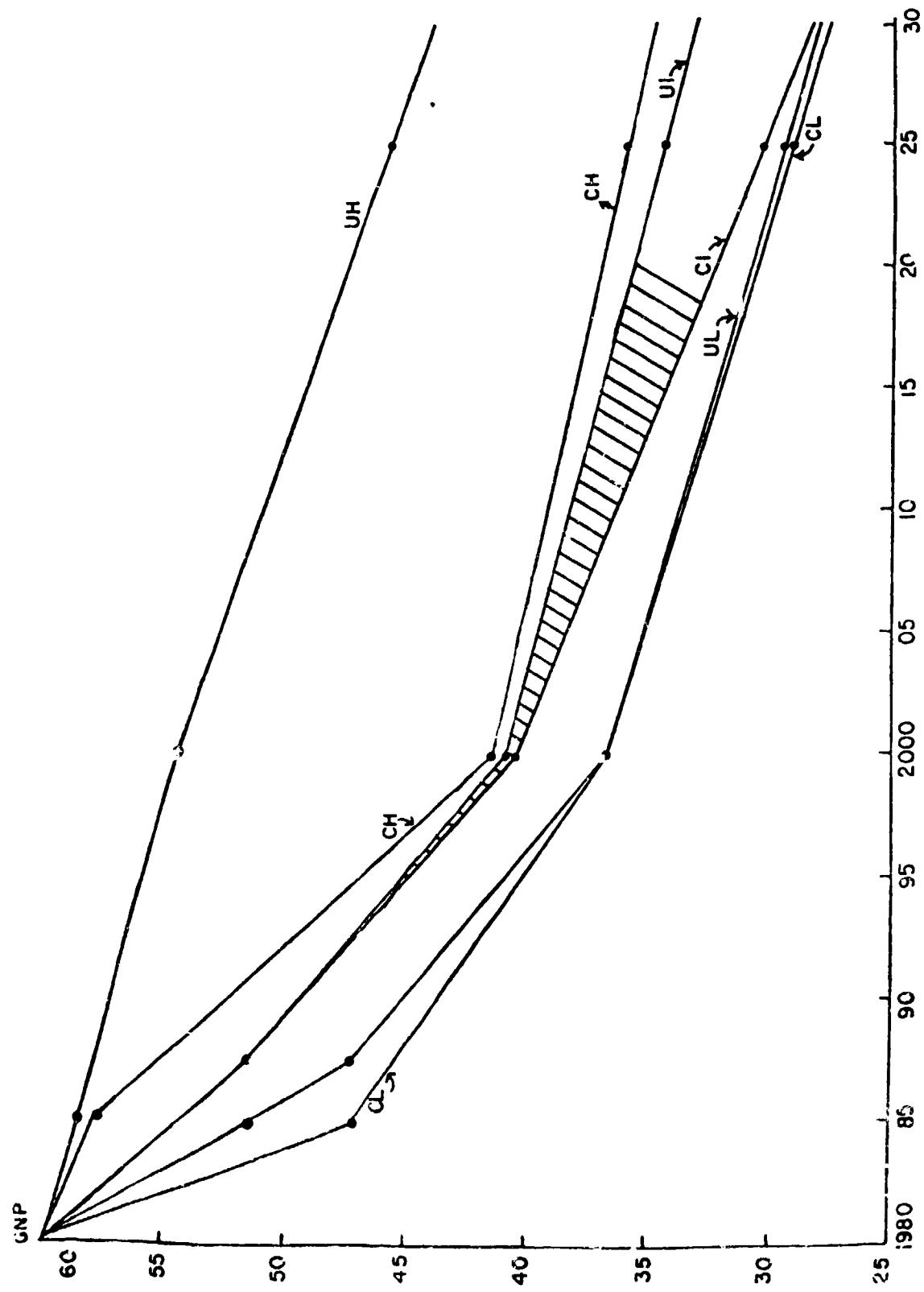
Fig. 4.3 Ratio of Gross Energy/GNP, in 10^3 Btu/1971 $

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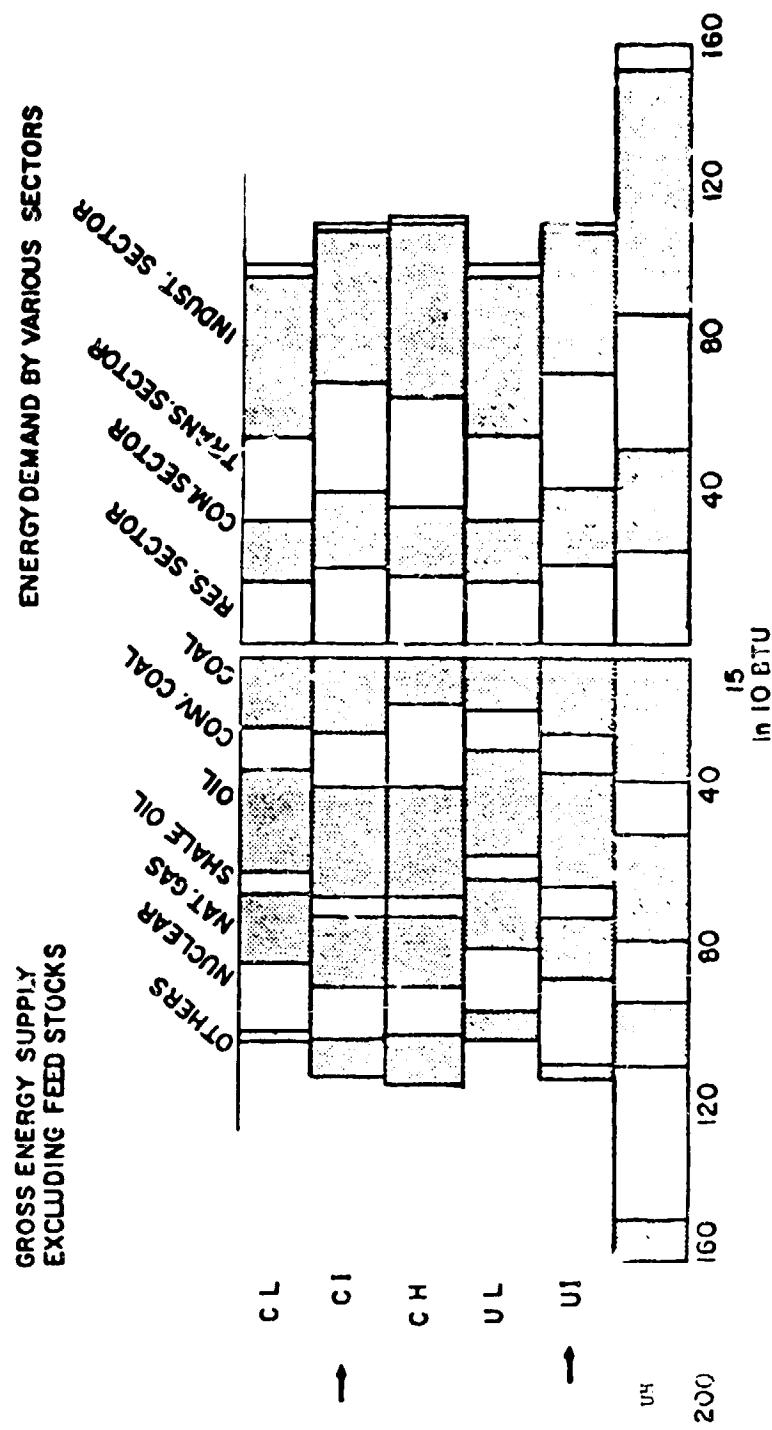
Fig. 4.4 Supply-Demand Patterns for Various Scenarios in the Year 2000
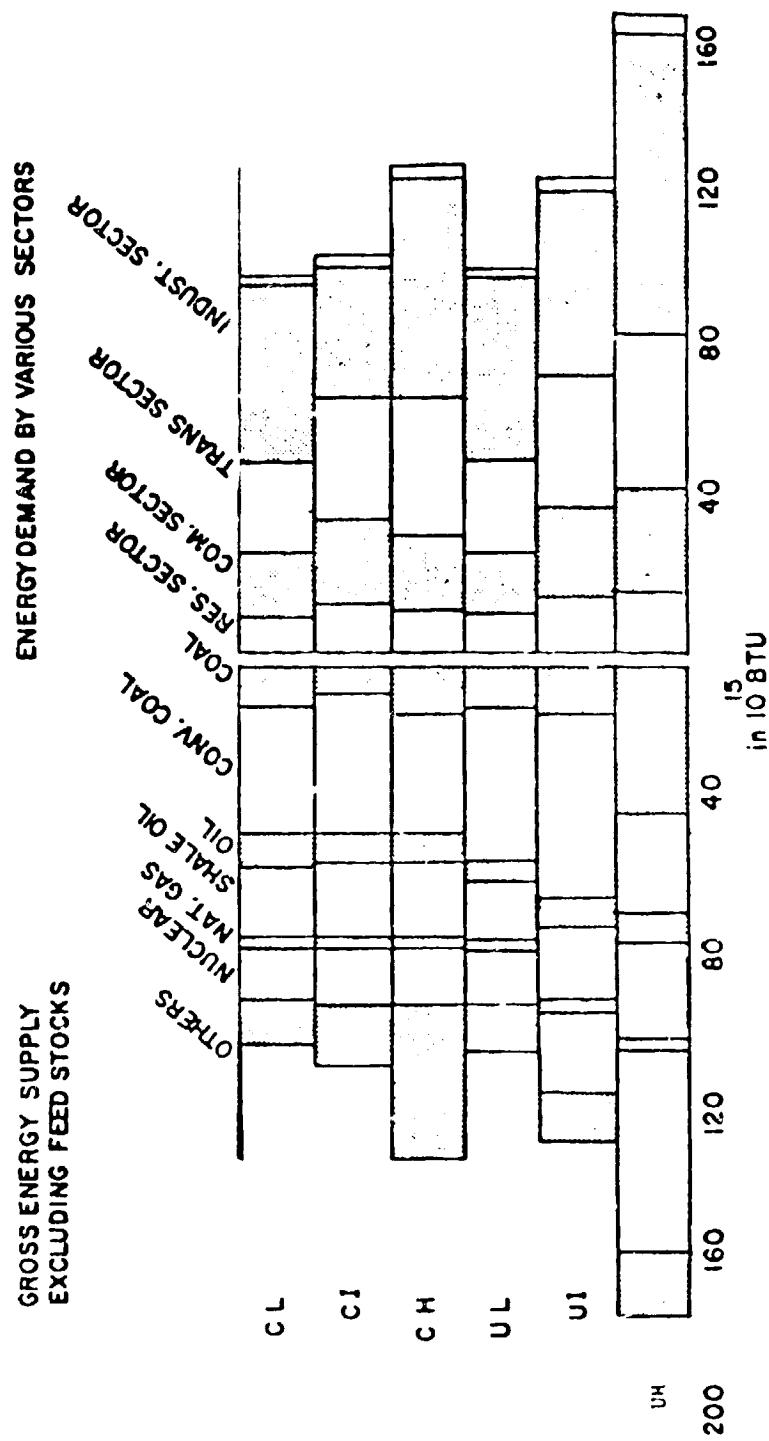
Fig. 4.5 Supply-Demand Patterns for Various Scenarios in the Year 2030

In only one case -- the unconstrained, high-energy-intensiveness scenario (UH) -- does the economy of 2030 depend on electricity more than it does at present.

In all other cases, the use of electricity can be expected to decline in relative importance, at least after the year 2000. In Fig. 4.6 electrification is plotted as a percentage of net energy use in the economy, for three representative scenarios.

It is noteworthy that the foregoing results are qualitatively dependent on most of the detailed supply/demand price projections. The calculated supply-demand balances are shown graphically for all scenarios for the years 2000 and 2030 in Figs. 4.4 and 4.5. Price projections for all scenarios are displayed graphically in Figs. 4.7-4.10 for oil, gas, coal, and electricity, respectively. Nuclear fuel prices for light water reactors and LMFBRs are shown in Table 4.4. As expected, energy prices rise much faster and higher in the 'constrained' scenarios than in the unconstrained cases.

Table 4.5 shows a comparison of the six comparative assessment scenarios and projections updated by the Energy Information Administration.*[41] The
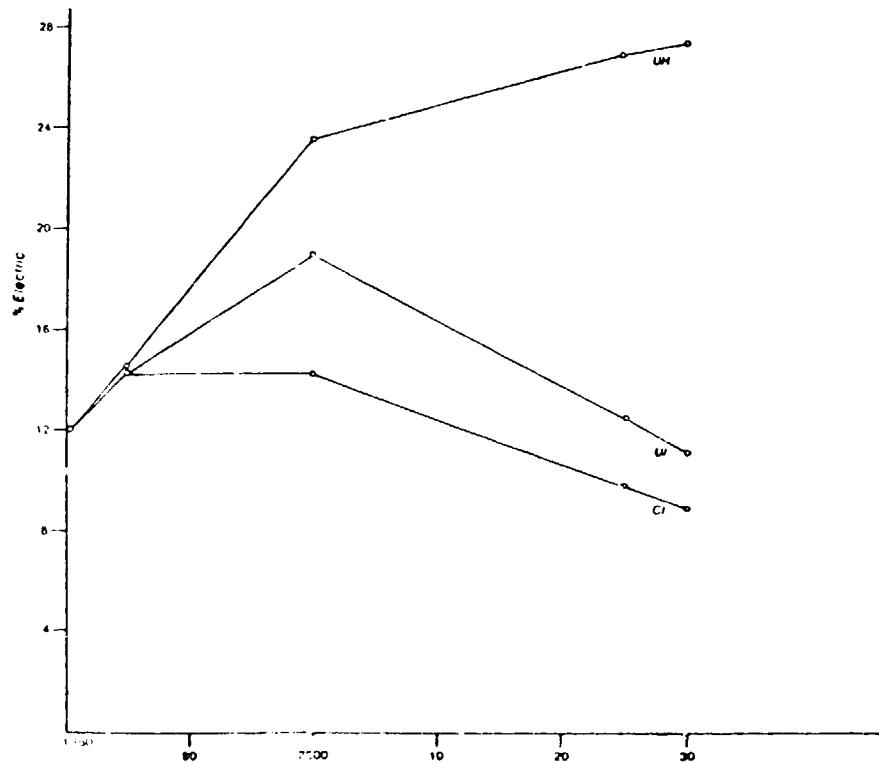
Fig. 4.6. Electrification as a Percentage of Net Energy Use: Three Scenarios

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*Supply assumptions and costs for uranium were developed separately but are consistent with the rest of the calculations.
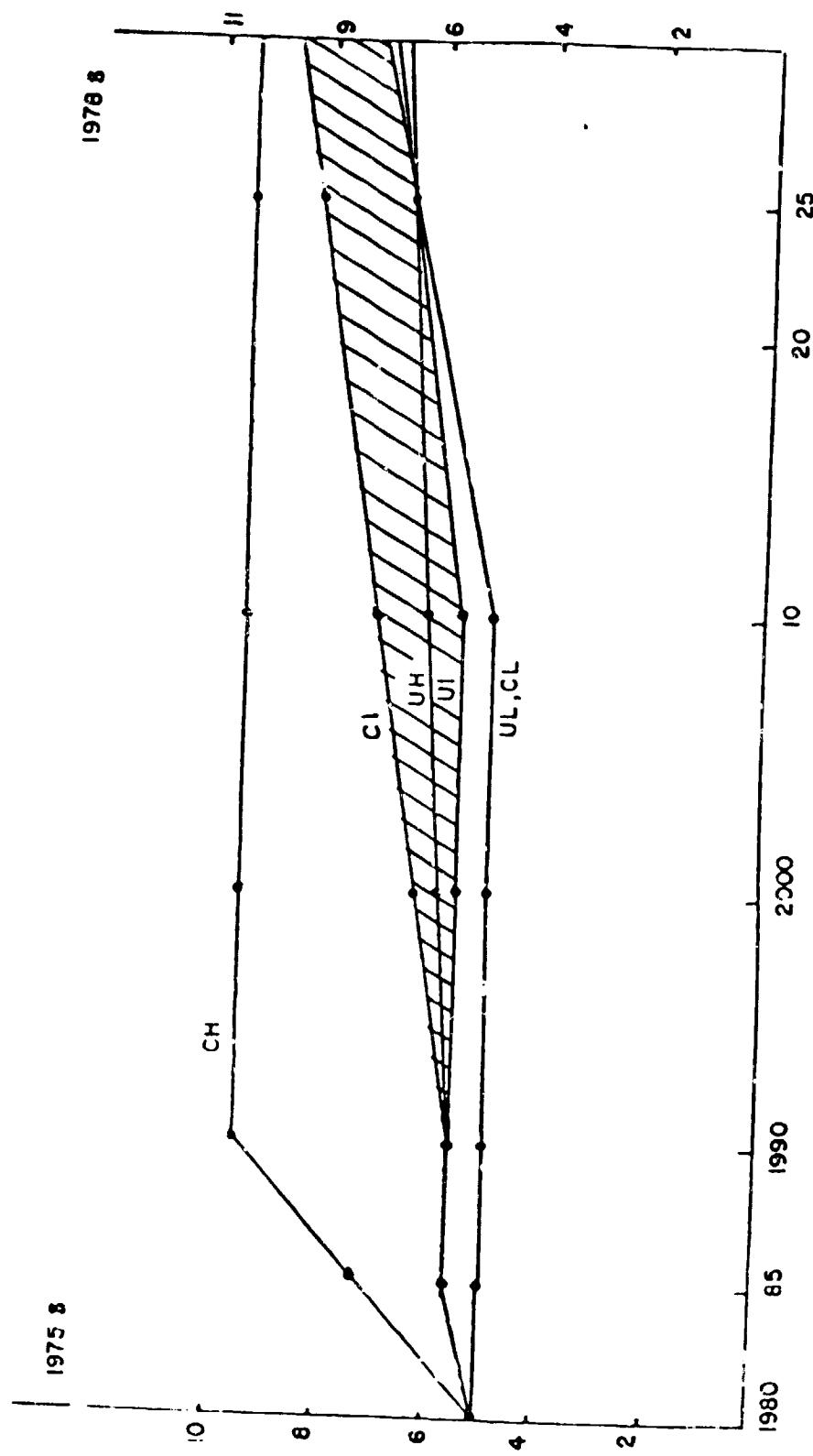
Fig. 4.7 Delivered Oil Prices
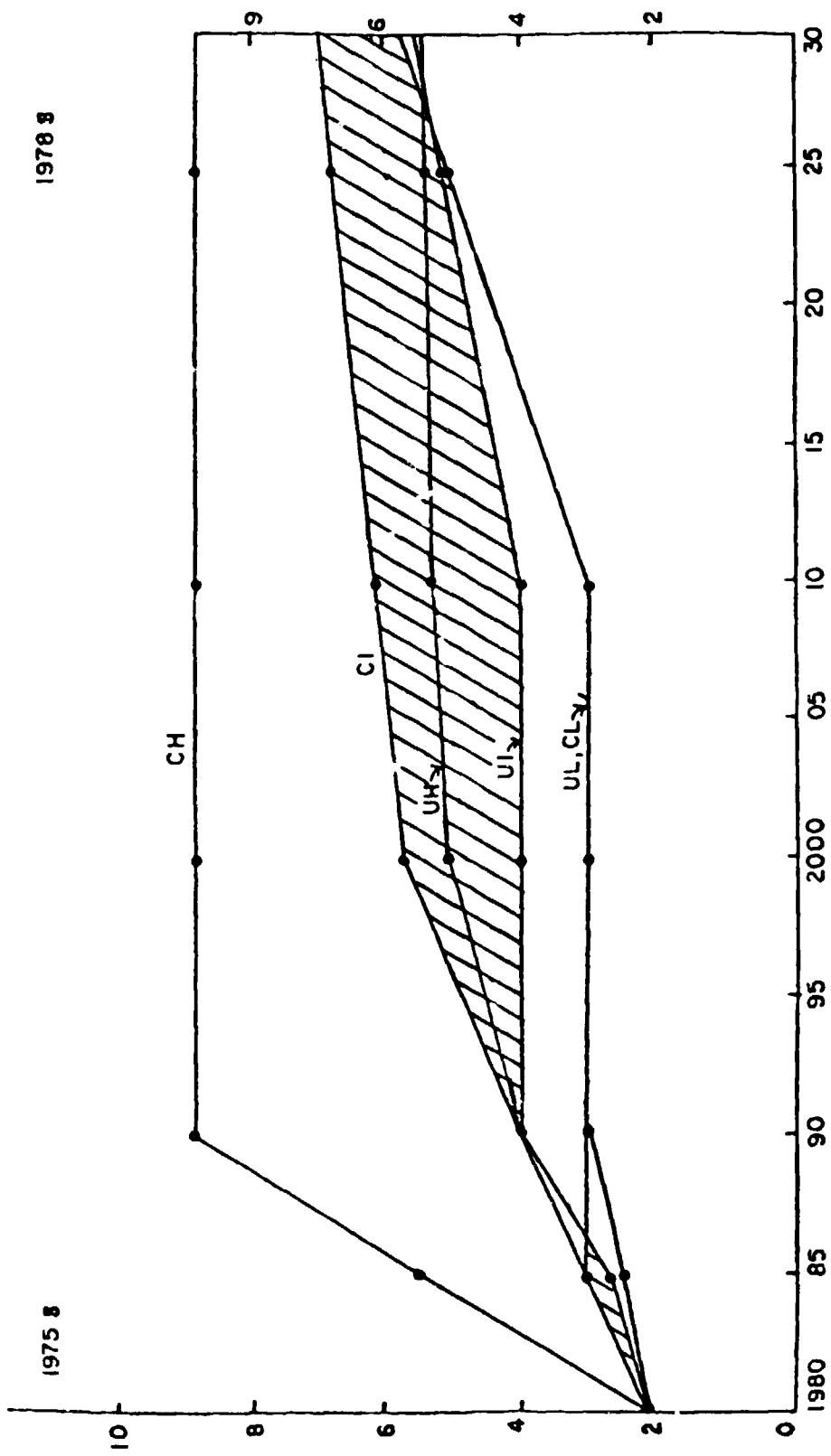
Fig. 4.8 Delivered Natural Gas Prices, $/$10^6$ Btu
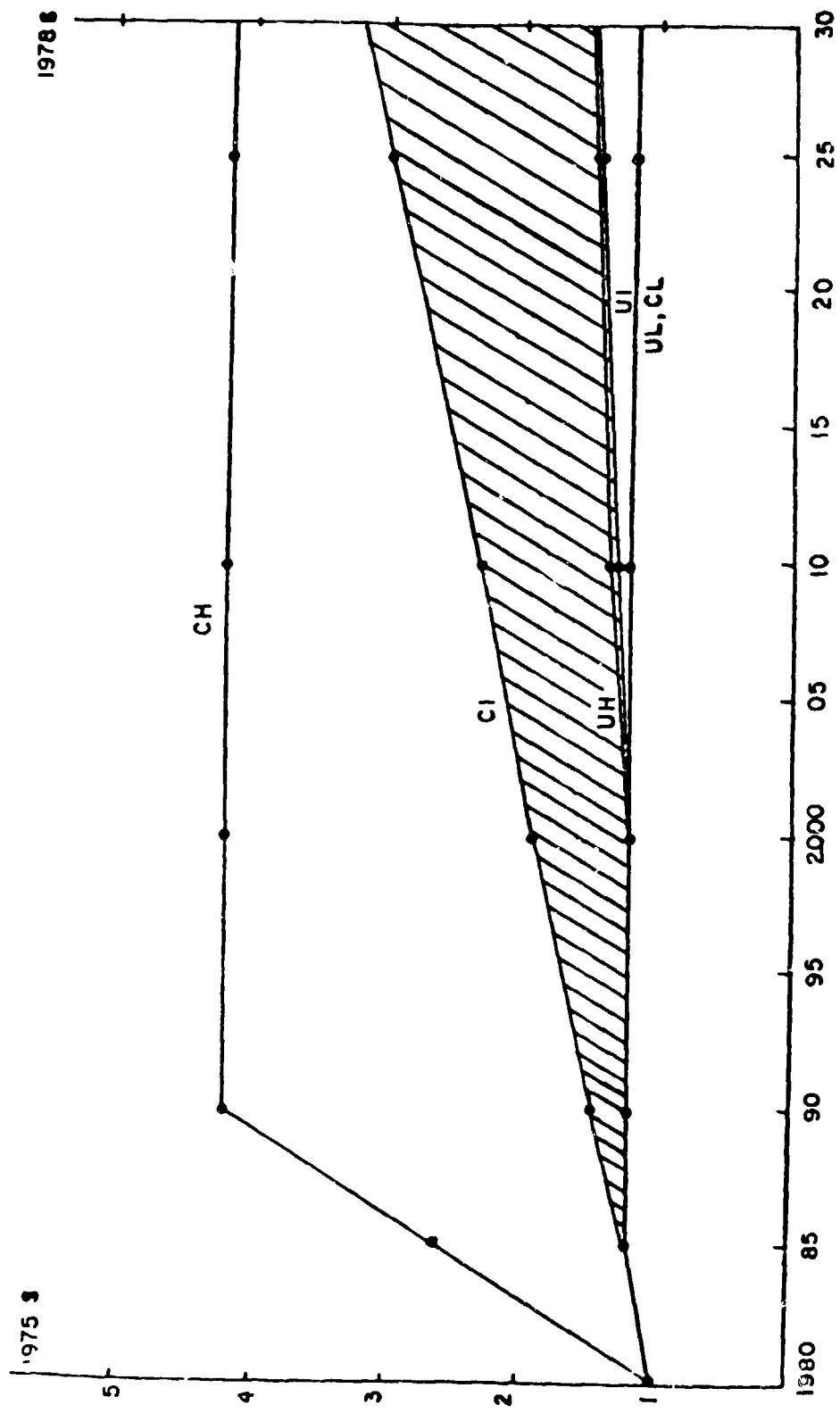
Fig. 4.9 Delivered Coal Prices, $/10^6 Btu
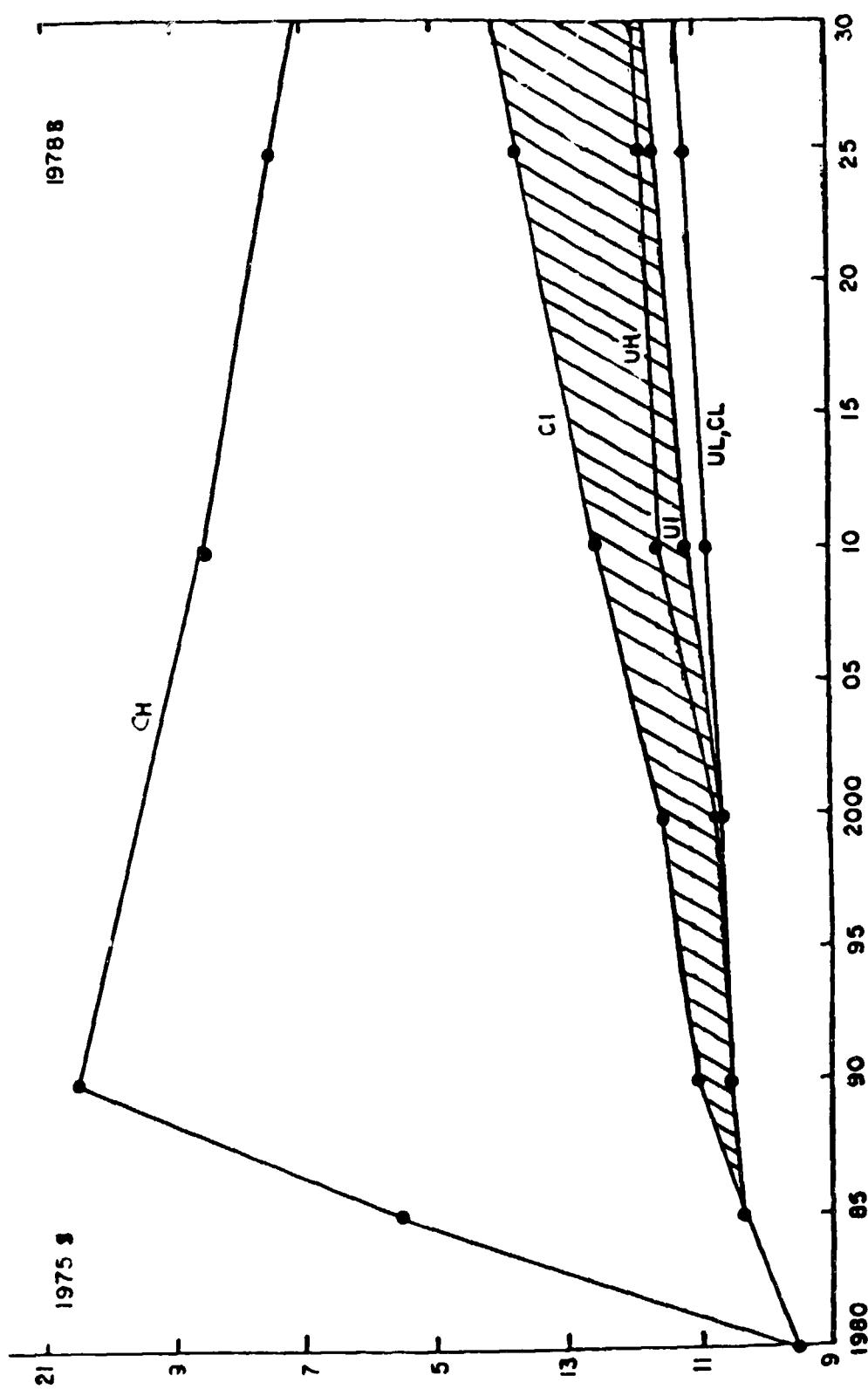
Fig. 4.10 Electricity Prices, $/10^6$ Btu

Table 4.4   Nuclear Fuel Prices (1978 $/$10^6$ Btu)
for Future Scenarios

| Year | Light Water Reactor | | LMFBR |
	UH, UI, UL	CH, CI, CL	All Scenarios
1980	0.62	0.62	a
1985	0.67	0.76	a
1990	0.71	0.81	a
2000	0.72	0.86	0.64
2010	0.79	0.95	0.65
2025	0.89	1.12	0.67
2030	0.93	1.17	0.68

[a]LMFBR introduction assumed between 1990 and 2000.

Table 4.5   Electrical Generation in Comparative Assessment
Scenarios and Two Other Projections (10^9 kWh)

| Energy Source | EIA[a] (1995) 1978 Annual Report | EPRI[b] (2000) | Comparative Assessment (2000) | | | | | |
			UH	UI	UL	CH	CI	CL
Coal	2549-3163	3396	1922	1300	738	563	91	1010
Oil	130-85	390	126	126	126	126	126	126
Gas	42-17	0	126	126	126	126	126	126
Nuclear	978-1215	2795	3010	1621	1223	893	970	970
Hydro	327-323	395	320	320	320	320	320	320
New	96-76	164	106	106	106	106	106	106
Total	4122-4879	7140	5610	3600	2640	2134	2610	2660

[a]Source: Ref. 41.

[b]Source: Ref. 42.

comparative assessment scenarios fall within the range of those reported by EIA (with the exception of the nuclear/coal distribution) but lower than the EPRI projections. We do not feel that the comparative assessment scenarios are any better or worse than the EIA or EPRI scenarios, just different. However, we feel that the comparative assessment scenarios are plausible, representative, and useful for alternative future comparisons.

Table 4.6 shows the total installed capacity and new baseload construction for the six scenarios. Since the total capacity and additions were not substantially different for several of the scenarios, only the three most representative scenarios (UH, UI, and CI) were selected for comparative analysis. These cases represent the range of energy growth in the six scenarios. Tables 4.7-4.9 report the cumulative capacity for each technology for the three scenarios with and without SPS. These capacity levels will serve as the basis for the comparative analyses reported in subsequent sections of this report.

Table 4.6   Total Installed and New-Construction Baseload Capacity
(1000 MW) for Six Comparative Assessment Scenarios

	UH		UI		UL		CH		CI		CL	
Year	Total	New	Total	New	Total	New	Total	New	Total	New	Total	New
1980	202	63	202	63	202	63	202	63	202	63	202	63
2000	906	231	536	140	364	91	288	47	402	63	364	91
2015	1344	382	570	114	359	58	385	184	398	100	358	58
2030	1772	417	586	173	335	78	503	80	378	110	335	78

Table 4.7   Energy System Deployment (GW
of Capacity) for Scenario UH
with and without SPS

	Year			
Technology	1980	2000	2015	2030
	With SPS			
Coal	155	354	395	460
LWR	47	508	546	534
LMFBR	0	44	175	312
TPV	0	0	36	72
SPS	0	0	150	300
Fusion	0	0	42	94
Total	202	906	1344	1772
	Without SPS			
Coal	155	354	470	584
LWR	47	508	574	628
LMFBR	0	44	210	375
TPV	0	0	36	72
SPS	0	0	0	0
Fusion	0	0	54	113
Total	202	906	1344	1772

Table 4.8   Energy System Deployment (GW of
Capacity) for Scenario UI with
and without SPS

Technology	Year			
	1980	2000	2015	2030
With SPS				
Coal	155	238	166	70
LWR	47	263	208	169
LMFBR	0	34	81	125
TPV	0	0	24	48
SPS	0	0	75	150
Fusion	0	0	16	24
Total	202	5:5	570	586
Without SPS				
Coal	155	238	181	109
LWR	47	263	227	177
LMFBR	0	34	111	195
TPV	0	0	24	48
SPS	0	0	0	0
Fusion	0	0	27	57
Total	202	535	570	586

Table 4.9   Energy System Deployment (GW of
Capacity) for Scenario CI with
and without SPS

Technology	Year			
	1980	2000	2015	2030
With SPS				
Coal	155	224	121	24
LWR	47	157	116	75
LMFBR	0	22	79	124
TPV	0	0	18	36
SPS	0	0	50	100
Fusion	0	0	14	19
Total	202	403	398	378
Without SPS				
Coal	155	224	135	30
LWR	47	157	130	94
LMFBR	0	22	92	169
TPV	0	0	18	36
SPS	0	0	0	0
Fusion	0	0	23	49
Total	202	403	398	378

4.2 COST AND PERFORMANCE

4.2.1 Introduction

The comparison of projected energy costs for alternative technologies is a prime consideration in the selection of programs for further research and development. The basic energy costs of the SPS and other technologies are described in Sec. 3.3. The goal of these cost analyses is to produce an objective comparison using consistent data and assumptions. These comparisons were performed with an internally consistent and traceable data base that was developed for this assessment. In addition, many assumptions were made in performing the cost comparisons reported in this section. Therefore, the absolute numbers reported here are intended only for the present comparison, should not be compared to assessments or energy cost studies reported elsewhere.

Different costing methods, assumptions, or base data could affect the calculations substantially so that comparability to other studies is not possible without a detailed knowledge of technology costing and the differences in assumption and data that exist between studies. However, the goal of this study was not to produce information that is directly comparable in detail to other studies, but rather to be internally consistent, so that this cost comparison would be useful in decision making concerning the relative economic viability of SPS.

The comparative cost analysis conducted in this assessment was a multistep process. These steps were assembled into an evaluation framework so that the numerous analytical steps could be performed in an orderly progression. Figure 4.11 shows the sequence of steps in the evaluation framework.

The results of four of these steps are discussed in other sections of this report: the SPS and the six alternative technologies are characterized in Sec. 3; the cost characterization, which includes capital and operation and maintenance data, is described in Sec. 3.3; and the alternative future energy supply-demand scenarios, which include SPS implementation rates, are described in detail in Sec. 4.1.

The next section of this report (Sec. 4.2.2) will begin with a description of the cost uncertainty that exists in the base data that is reported in Sec. 3.3 for all of the technologies. The uncertainty in fuel price projections that resulted from the alternative futures scenarios will be reported in Sec. 4.2.3. Section 4.2.4 contains comparative cost information standardized to levelized annual costs for all technologies. The comparative cost information described in Sec. 4.2.4 was subjected to sensitivity analyses, which are discussed in Sec. 4.2.5. Finally, an uncertainty analysis of the comparative costing approach was conducted, and this analysis and its implications for any future comparisons are discussed in Sec. 4.2.6. This cost comparison section ends with some summary statements regarding the status and conclusions of the analysis.
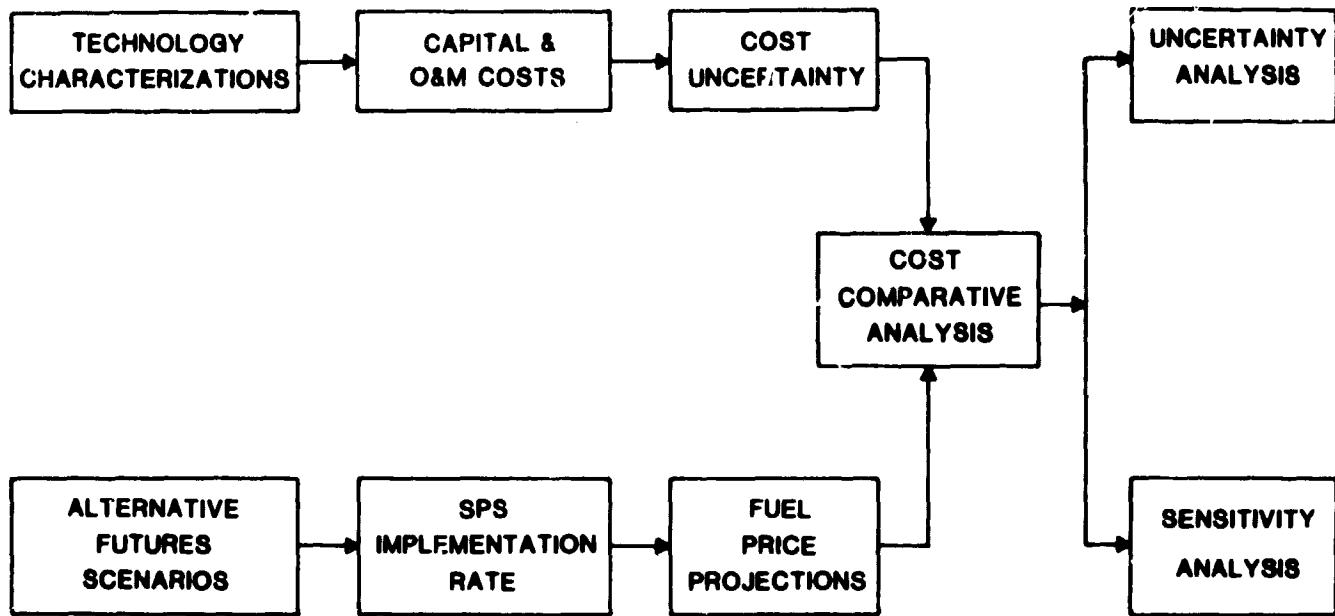
Fig. 4.11   Cost and Performance Evaluation Framework

4.2.2   Uncertair:y in Capital Cost Ranges for SPS and Alternatives

Capital costs of technologies that have not yet been developed are highly uncertain and depend in part on the commitment made to, and the results of, future R&D efforts.   At this time the estimated ranges of capital costs for the SPS and the other advanced technologies are large.   Significant uncertainties also exist in the projected cost of energy from current or conventional technologies.   Capital costs for electric generation technologies to commence operation in the year 2000 are highly uncertain.   Accurate projections of costs in that era, even for technologies that are in commercial operation today, are still difficult.   Consideration of factors that contribute to the range of estimated costs is necessary for a valid pairwise comparison of technologies, and these factors have been included in the following analysis and assessment.

There are many parameters that could be factored into the estimation of capital cost uncertainty, but we have chosen to aggregate the capital cost uncertainty into the following three factors that we feel represent the major uncertainties:

1. Uncertainty about future costs of materials, supplies,
    and labor necessary to construct power plant facilities;

2. Uncertainty about the future requirements and associated
    costs of environmental and safety equipment; and

3. Uncertainty about the capability of technologies to
    perform as conceptualized.

The uncertainty associated with factor 1 was generally accounted for through an analysis of the Handy-Whitman Index[43] of public utility construction costs, which is widely used as a "benchmark" index by the electric

utility industry. It is here referred to as a benchmark since it is derived not from actual project construction costs, but rather from a periodic sampling of a market basket of over 50 standard commodities and components used in conventional utility plant construction. The market basket contents have not been updated significantly in many years, so that the index more closely tracks a lower bound of cost increases. Thus, the Handy-Whitman Index does not appropriately account for technological or regulatory cost increases, as is typified by the added cost of sulfur-removal or nuclear-safety requirements imposed by legislation in recent years.[44]

However, this index does measure the nominal real cost increases in power plant construction. The lack of revision in commodity mix is judged not to be a serious problem, since the mix of added environmental and safety equipment and personnel in post-1970 plants is the same as that of the plants overall.

Over the 30-year period 1948-1978, the Handy-Whitman Index has increased in real terms (relative to the GNP deflator) at an average compound rate of 1.5% per year. For the period 1948-1978, increases were about 1% per year, while for the period 1968-1978 increases averaged over 2% per year relative to the GNP deflator. The analysis of the Handy-Whitman Index indicates that the compound annual real cost increases exhibited over the past 10 years are 1.5% per year for coal and 2.0% per year for nuclear.

Information on factor 2 was derived from construction cost information assembled over the past decade. Although the available data contain the cost estimates of actual construction projects, these estimates are for a mix of plant sizes. However, the data indicate approximately a 10% per year real increase early in the period, with the rate of increase tapering off to about 7% per year more recently. These rates of real escalation are due primarily to added safety regulations and environmental controls that have been imposed over this period; no time-related factors are included. The easing of these rates in more recent years is a result of attempts to consolidate and simplify the existing regulations and of a decrease in the escalation rate due to new regulations. Although these rates may ease even more in the future, it is also possible that they may continue to be quite substantial. Thus, continuing rates of 5% and 6% per year have been assumed as a high range of escalation for the coal and nuclear technologies, respectively.

Factor 3 uncertainties are based on judgments about the technical uncertainty surrounding an advanced technology. Since this is a comparative assessment, these numbers were derived from a range of estimates reported for each technology or from uncertainty in the technology definition.

Low, nominal, and high capital costs were derived for each technology, using the three factors just described. The uncertainties for each technology, at the low, nominal and high cost levels, are summarized in Table 4.10.

A factor of 1.3 was applied to the combined-cycle system and one of 1.35 to the LMFBR system. For the combined-cycle alternative, the gasifier elements make up the major technological uncertainty and also compose 30% of the nominal plant costs. It has been assumed that this component might increase in cost by as much as 100%. For the LMFBR, two recent estimates provided by United Engineers and Constructors show plant costs to vary by 35%.

Table 4.10 Capital Cost Uncertainty Factors for Alternative Technologies
(Low, Nominal, and High Values)

Value	Conventional Coal	LWR	CG/CC	LMFBR	TPV	Fusion	SPS
Low	0.75% per year - 1/2 the historical Hardy-Whitman Index (HWI).	1.0% per year - 1/2 the historical HWI.	Same as conventional coal.	Same as LWR.	No real cost increases assumed in 1978 estimate; a 43% decrease in nominal solar cell costs (to $21.60/m² (1978 $) from $37.80/m².	Assumed to be the same value as originally estimated in the NUWMAK report, which served as the basis for the characterization.	No cost increases assumed; a cost reduction in solar cells to $21.60/m² from $37.80/m². This reduction in costs is an example of the magnitude of cost reduction believed achievable by Westinghouse as a result of a major production technology breakthrough beyond the projections currently being assumed in the reference design.
Nominal	1.5% per year - historical HWI.	2.0% per year - historical HWI.	Same as conventional coal.	Same as LWR.	Cost increases equivalent to 1.0% per year on the total plant cost. Derived from applying the nominal coal plant increase of 1.5% per year to the non-solar array portion of the plant (about 2/3 the total cost).	Cost increases equivalent to 2.0% per year (1978-2000), or the nominal nuclear rate.	Nominal rate of increase of 1.5%/yr, as for coal, applied to the terrestrial, i.e., rectenna, portion of the system, or about 26.7% of the total costs.
High	5.0% per year - continuation of recent high rate of environmental regulatory imposition.	6.0% per year - continuation of recent high rate of safety requirements being imposed for next 22 years.	Same as coal, multiplied by 1.30, which is attributed to a possible doubling of the gasifier vessel costs that make up about 30% of the base plant costs.	Same as LWR, multiplied by 1.35, which is based on the ratio of different esti- ... repre- senting technology uncertainty.	Applies a factor of 4 to the year 2000 nominal cost (mainly cell cost uncertainty).	No estimate of the high endpoint was made because the scientific feasibility of plasma confinement has not been demonstrated.	Technical uncertainty factor of 5.0 applied to 1978-dollar cost estimate.

An uncertainty factor of 5.0 was applied to the 1978-dollar costs of the SPS system. This value is equivalent to a factor of 4.6 applied to the year-2000 base construction cost and was estimated from various cost ranges recently documented in the SPS literature.[45,46] During 1976 and 1977, several independent study teams gave cost estimates that ranged from a low $1400 per kilowatt to a high of $6000 per kilowatt.

A recent ECON report[47] points out the sensitivity of the probability distribution of a cost to a change only in the solar cell assumptions of the Rockwell International design.[8] By a change in assumptions, the spread of a total cost distribution for the first theoretical unit was increased from a high/low ratio of 2 to one of 4. In an article on SPS costs,[48] Glaser discusses the SPS price tag and cost distributions. He states that the cost of producing the second 5-GW SPS may range from $8 to $35 billion, with a median cost of $14 billion.

Little information is available from which a possible range of costs for the terrestrial photovoltaic system can be derived. A reasonable assumption, however, is that this cost range should lie somewhere between the range of the combined cycle or LMFBR and that of the SPS. Since most of the uncertainty results from technical unknowns related to solar cell technology, and in light of ECON's results[47] concerning the possible impact of cell costs on SPS, a factor of 4.0 was assigned.

A combined factor, used to derive the high, year-2000 bounds of capital costs, was thus taken to be the product of the high multiplicative factor and the uncertainty factor for the appropriate technology option. The resultant combined factor was then multiplied by the 1978 base costs to arrive at the upper bound estimate.

An examination of the ratio of high to low year-2000 capital cost estimates resulting from these assumptions shows a reasonable consistency with the level of current knowledge and state of development apparent for each technology. This ratio varies from a value of 2.11 for conventional coal systems to come on line in the year 2000, to 4.58 for the SPS in the same period. Table 4.11 summarizes the year-2000 capital cost ranges used in the analysis.

4.2.3 **Fuel Price Projections**

Background and Methodology. Projections of any type extending far into the future involve many uncertainties that are amplified when that forecast attempts to define energy supply, demand, and costs. Energy sector uncertainties arise in three principal areas: (1) Future energy policy decisions, reflecting actions and reactions between producers and consumers, are not predictable. (2) The ultimately recoverable reserves of energy resources cannot be precisely defined and, similarly, the rate of improvement in production or efficiency for developing technologies such as photovoltaic cells cannot be rigorously determined. (3) The price elasticity of energy substitution in the total economy is not fully known, and therefore assumptions must be made about the adaptability of GNP to varying components of gross energy supply.

Table 4.11   Capital Cost Ranges for Technical
and Regulatory Uncertainty ($/kW)

Costs	Coal	LWR	CC/CC	LMFBR	TPV	Fusion	SPS
1978 Costs (Nominal)	549	712	690	1037	844	2378	3340/3079
2000 Costs							
Low	647	886	813	1291	731	2378	3139/2874
Nominal	762	1100	957	1603	1057	3677	3646/3362
High	1605	2566	2623	5048	4229	?	16,698/ 15,398
Cost Ratios:							
2000 Low/1978 Nominal	1.18	1.24	1.18	1.24	0.87	1.00	0.94/0.94
2000 Nominal/2000 Low	1.18	1.24	1.18	1.25	1.45	1.55	1.16/1.16
2000 High/2000 Nominal	2.11	2.33	2.74	3.14	4.00	?	4.58/4.58

Possible future scenarios (described in Sec. 4.1) were defined by assuming certain values for key unknown parameters and by following an internally consistent computational pathway. Reasonable boundary assumptions were made concerning the key unknowns, which established the range of values within which most plausible futures will fall.

The long-run costs of fuel (primary energy) are, in part, predicated on OPEC maintaining petroleum prices just below the long-run costs of producing substitutes from oil shale or coal. The cost of synthetic natural gas from coal was projected from a non-fuel cost of $3.17/10^6$ Btu plus 1.25 times the cost of coal per 10^6 Btu (to allow for the 80% efficiency estimated for the gasification process) plus an assumed $0.97/10^6$ Btu for transmission and distribution. Similarly, the long-run cost of natural gas was determined to be equivalent to its alternative -- high-Btu gas from coal. Finally, the long-run cost of electricity was based on non-fuel capital costs for the projected coal/nuclear ratios, assuming generation from oil and natural gas phased out and modest improvements in conversion efficiency between now and 2030.

Fuel Price Paths. The long-run costs dictate the price of electricity, but the cost of other energy forms can differ when there are supply con- straints. Oil prices are estimated to increase at a rate that maintains OPEC production more or less at constant levels, and, at a relatively inelastic demand, OPEC could seek increased prices because of constraints on coal and oil shale. However, if the price should reach $9.20 per 10^6 Btu, it is esti- mated that large quantities of low-level solar thermal energy could become economically attractive,[40] free of the environmental constraints affecting the development of other resources. Natural gas prices essentially follow the pattern of oil prices and are set so that remaining resources are produced before higher-cost gas from coal or substitutes such as solar enter the market. In scenarios featuring low elasticities (energy-intensive GNP), the rate of price increases is high, and particularly so when supply constraints affect coal production.

The price of coal is expected to increase from $1.15 to $1.38/10^6$ Btu between 1980 and 1985 because of impacts from the Surface Mine Control and Reclamation Act of 1977 and the possible continuation of decline in

productivity. Beyond 1985, new federal leases of land with high-quality coal will keep prices constant until 2000, with modest increases thereafter to reflect increased long-run costs resulting from rapid production increases when the supply is not constrained. If the supplies are constrained and the price-demand elasticity is moderate or low, prices increase above the long-run costs until demand is dampened to the required level.

Uranium prices, for convenience, are assumed to differ only between the constrained and unconstrained scenarios. The rationale is that future supply-demand conditions of the world-wide market, not local markets, will determine prices.

Projections. Three scenarios were used to measure a range of possible fuel prices and supplies. They are:

UH: An unconstrained scenario wherein energy price elasticities of demand are low (-0.25) and the energy/GNP ratio is therefore relatively constant. The unconstrained scenario is defined as possessing controls at about the level that existed in 1970.

UI: An unconstrained scenario wherein the energy price elasticities of demand are moderate (-0.7 for industrial fuel use, -0.4 for all other fuel uses and 0 for feedstock use).

CI: A constrained scenario wherein the energy price elasticities of demand are moderate, as in UI. The constraints imposed are based on environmental, health, and safety aspects of coal and nuclear fuels and serve to restrict rapid expansion of production. Petroleum and natural gas are constrained only by world market conditions.

The delivered costs of fuels as projected by the RFF model[30] are shown in Table 4.12 and graphically displayed in Fig. 4.12 for the period 1980 to 2030. For comparison, the EPRI Technical Assessment Guide[49] gives coal price estimates of between $2.00 and $2.40/$10^6$ Btu, depending on the consuming and supply regions. Our unconstrained price trajectory for LWR fuel agrees very closely with the EPRI projection until 2000, after which EPRI does not project LWR fuel costs. The corresponding U_3O_8 prices for the unconstrained and constrained scenarios are shown in Fig. 4.13.

4.2.4 Cost Comparisons

The comparative costs reported in this section were calculated by the revenue-requirements (RR) method used by utilities and prescribed by regulatory agencies. Levelized life-cycle costs were calculated by a constant-dollar revenue-requirements method similar to the approach recommended by the Electric Power Research Institute (EPRI) for the analysis of generating costs of alternative technologies.[50] The important assumptions of this method will be briefly described here; a detailed description of the methodology is provided in the EPRI report.[50]

Table 4.12   Fuel Cost Projections (1978 \$/10^6 Btu):   Delivered
Prices for Three Scenarios, 1980 to 2020

Scenario and Energy System	Study Period						
	1980	1985	1990	2000	2010	2025	2030
UH							
Oil	5.75	6.49	6.49	6.79	7.13	7.65	7.82
Natural Gas	2.45	3.11	4.60	5.87	6.10	6.29	6.36
Coal	1.15	1.38	1.38	1.38	1.55	1.73	1.78
LWR Nuclear	0.62	0.67	0.71	0.72	0.79	0.89	0.93
LMFBR	-	-	-	0.64	0.65	0.67	0.68
UI							
Oil	5.75	6.49	6.49	6.49	6.49	7.65	8.04
Natural Gas	2.45	3.53	4.60	4.60	4.60	5.98	6.44
Coal	1.15	1.38	1.38	1.38	1.48	1.66	1.72
LWR Nuclear	0.62	0.67	0.71	0.72	0.79	0.89	0.93
LMFBR	-	-	-	0.64	0.65	0.67	0.68
CI							
Oil	5.75	6.49	6.49	7.33	8.21	9.55	10.00
Natural Gas	2.45	3.53	4.60	6.59	7.10	7.87	8.13
Coal	1.15	1.38	1.66	2.17	2.68	3.45	3.71
LWR Nuclear	0.62	0.76	0.81	0.86	0.95	1.12	1.17
LMFBR	-	-	-	0.64	0.65	0.67	0.68

Annual revenue requirements for an investment will normally vary from year to year over the life of the investment, but as a means of developing a single overall cost metric, the varying annual revenue requirements are converted to an equivalent stream of constant (levelized) annual revenue requirements. Equivalency is established by equating the present worth of the varying annual revenue-requirements stream with the present worth of the constant annual revenue-requirements stream. The revenue requirements are made up of the capital (i.e., return on equity, interest on debt, and depreciation) and operating costs (i.e., income and property taxes, fuel, operation and maintenance, and insurance).

Capital and operating costs usually proceed over the plant life as described in Fig. 4.14. The levelized annual revenue requirement (LARR) is arrived at by the following equation:

$$LARR = \frac{\sum_{n=1}^{B} R_n \left(\frac{1}{1+D}\right)^n}{\sum_{n=1}^{B} \left(\frac{1}{1+D}\right)^n}.$$
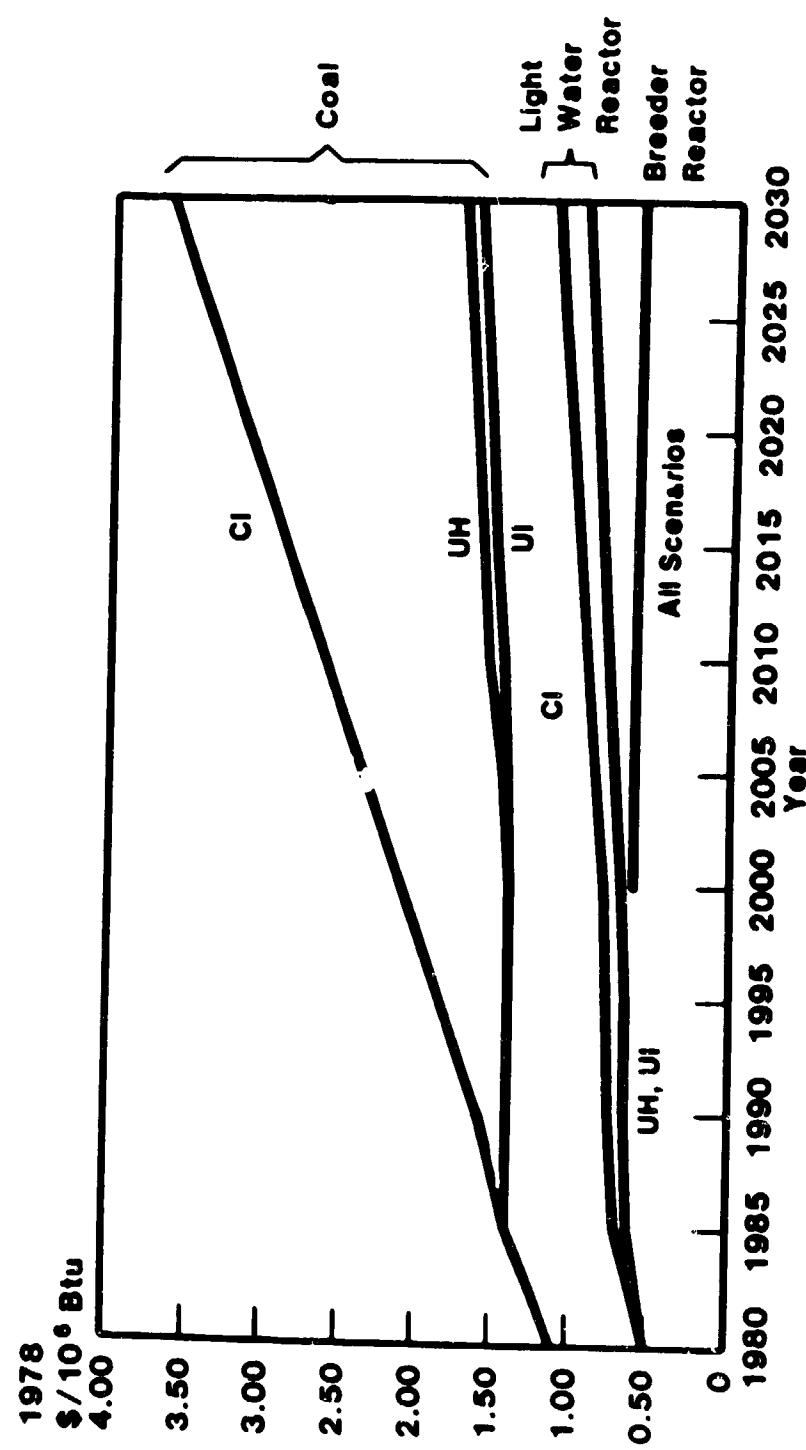
Fig. 4.12 Fuel Price Projections for Different Scenarios
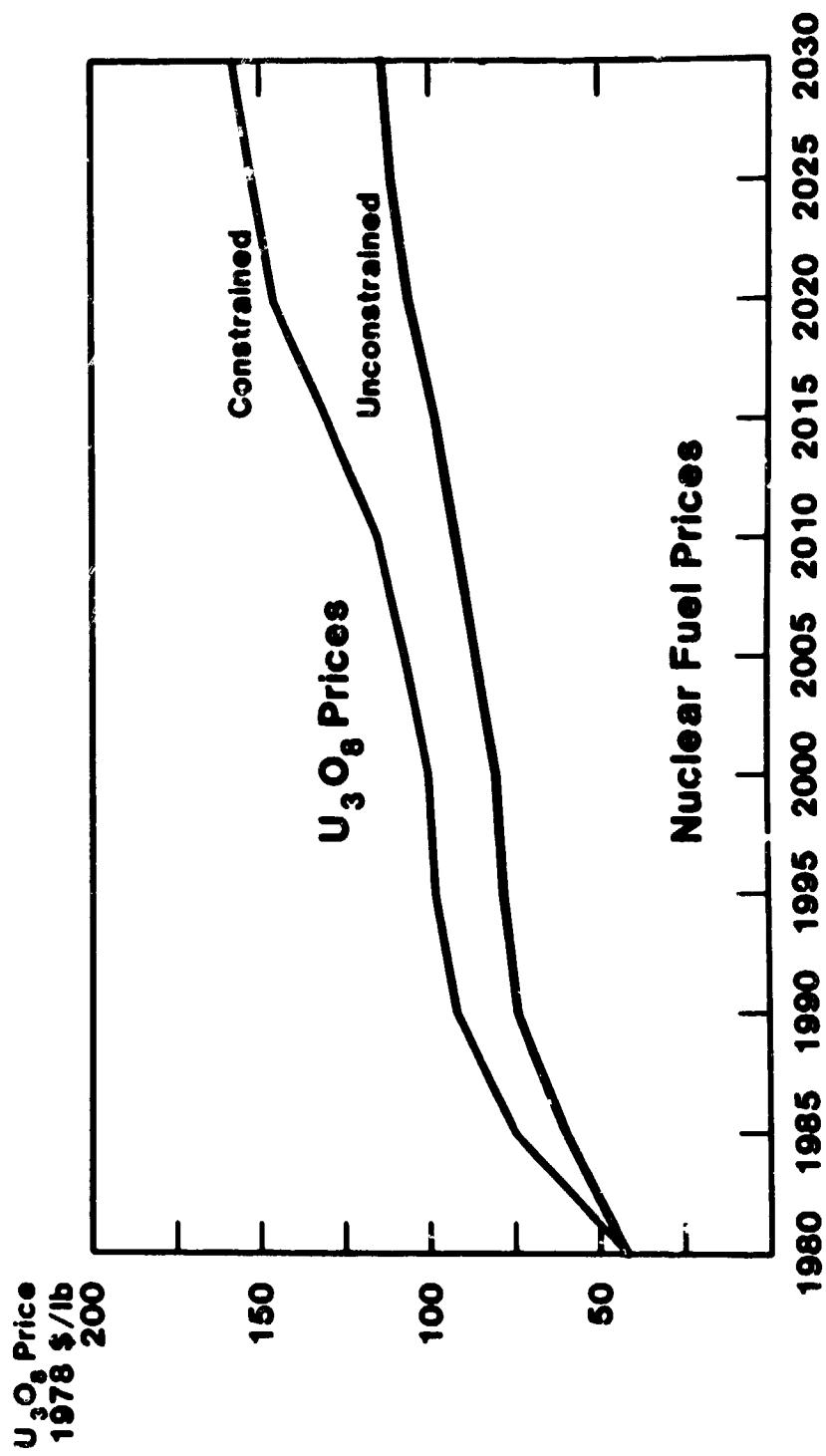
Fig. 4.13 U₃0₈ Prices for Constrained and Unconstrained Scenarios

REVENUE REQUIREMENT (DOLLARS)

LEVELIZED
REVENUE
REQUIREMENT

ANNUAL
REVENUE
REQUIREMENT

OPERATING
COSTS

CAPITAL
COSTS

COMMERCIAL
OPERATION

TIME
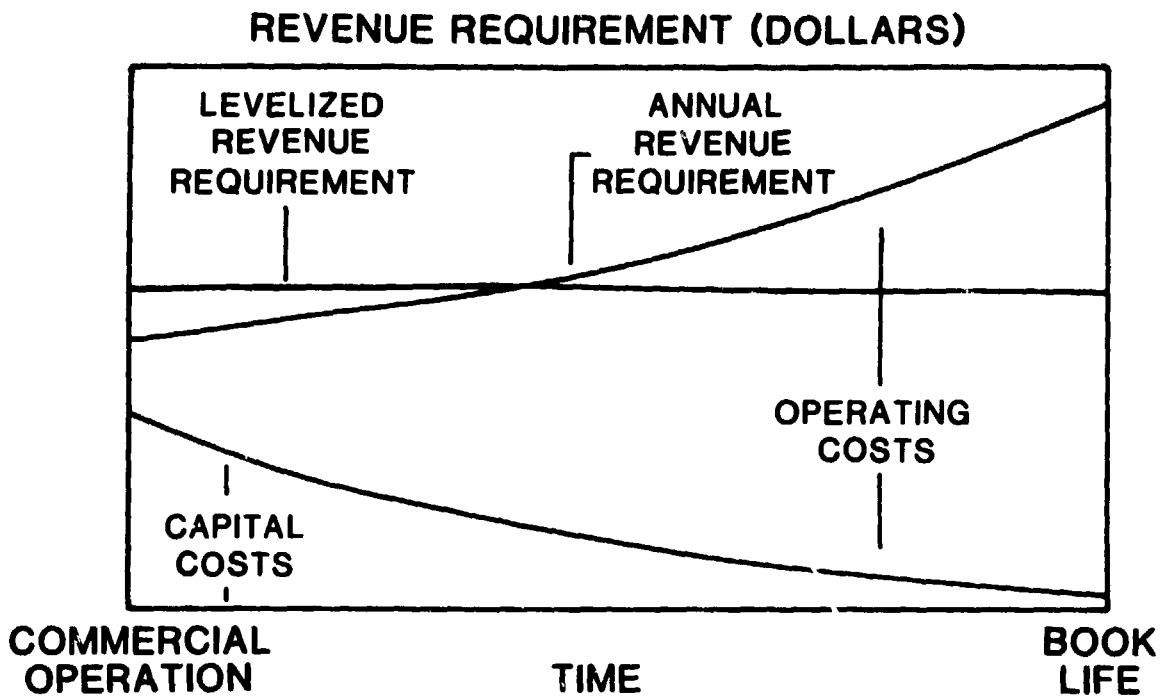
BOOK
LIFE

Fig. 4.14 Typical Patterns of Costs and Revenue Requirements

where:

R_n = revenue requirements in year n,

D = discount rate (weighted average cost of capital), and

B = book life.

A discount rate consistent with financial assumptions is needed for the present worth and levelizing calculations. Most electric utilities use their own weighted average cost of capital as the discount rate for making these calculations. The weighted average cost of capital is composed of the appropriate fractions of preferred stock, common stock, and bonds multiplied by the corresponding rates of return required in the marketplace.

In general, observed market rates of return reflect the investor's expectation of future general inflation plus some premium known as a "real" rate of return. The GNP deflator was used to estimate the historic inflation and to adjust the current-dollar rates of return to obtain real rates of return. In the comparative analyses, annual and levelized revenue requirements were calculated in inflation-free or "constant" dollars. A 1978 dollar value was used as the constant-dollar basis. Hence, only the "real" part of the discount rate should be used. Future prices of goods were expressed in the 1978 values, and increases higher than general inflation were added to these prices.

Base capital structure and economic assumptions typical of privately-owned utilities are used in the analysis and are summarized in Table 4.13.

Table 4.13 Base Capital Structure and
Economic Assumptions

Capital Structure			
Debt	50%	Interest	2.0%
Common Stock	35%	Return	7.5%
Preferred Stock	15%	Return	2.5%
Discount Rate	4%		
Fed. Income Tax Rate	46%		
State Income Tax Rate	4%		
Ad Valorem Taxes	2.5%		
Plant Book Life	30 yr		

Variations in base capital structure and interest rates were examined as part of the analysis. Reasonable variations did not significantly affect the relative ranking or cost differential of technologies.* No investment tax credits were applied in this analysis because these politically determined incentives have had a history of frequent change. Current regulations are considered to be applicable only to the analysis of near-term projects.

Table 4.14 reports the levelized energy cost for the two SPS reference designs and the six alternative central station systems. These energy costs were calculated by using the capital cost ranges reported in Sec. 4.2.2, the fuel prices generated by the alternative futures scenarios, and the cost characterization information reported in Sec. 3.3. Figures 4.15–4.17 display the cost ranges for each of the scenarios for the six technologies and two SPS reference designs. Some sensitivity calculations using these numbers as a basis are described in the next section.

4.2.5 Cost Sensitivity Analysis

Several cost assumptions were made in the comparisons presented in the previous section, and a few of these assumptions were tested to determine their effect on the cost comparisons. The first sensitivity analysis was made on the plant capacity factors. Baseline capacity factors for the technologies were: SPS, 90%; LWR, LMFBR, and coal, 70%; fusion, 70%; and TPV, 25%. The relationship between capacity factor and energy costs is shown in Fig. 4.18, in which energy costs are plotted for the constrained scenario and nominal cost values. Generally speaking, the more capital-intensive the technology, the more sensitive it is to the capacity factor. The TPV curve is steeper than the others, mainly due to the fact that the scaling for this technology is much smaller and therefore the incremental change in capacity factor is much larger.

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*These variations included higher real interest and return rates of 5%, 5.5% and 10.2% for bonds, preferred stock and common stock, respectively. Debt to equity ratio variation was also examined at 70% bonds, 20% common stock, and 10% preferred stock to bracket most utility financial configurations considered reasonable.

Table 4.14   Levelized 2000-2030 Cost of Electricity from SPS and
Alternative Technologies (1978 mills/kWh)

Scenario and Cost Level	SPS		HS Coal	LWR	CG/CC	LMFBR	NUWMAK	TPV
	Silicon	GaAlAs						
			Unconstrained Scenarios					
Nonfuel O&M	5.7	5.7	3.1	2.3	2.7	3.0	7.3	3.6
Capital Related								
Low	39.9	36.6	10.5	14.4	13.2	20.9	38.5	33.0
Nominal	46.4	42.8	12.3	17.8	15.5	26.0	59.6	47.8
High	212.4	196.0	13.8	20.0	20.1	35.1	--	192.1
UH: Fuel Cost	--	--	14.8	8.2	13.7	6.1	7.1	--
Electricity Cost								
Low	45.6	42.3	28.4	24.9	29.6	30.0	52.9	36.6
Nominal	52.1	48.5	30.2	28.3	31.9	35.1	74.0	51.4
High	218.1	201.7	31.7	30.5	36.5	44.2	--	195.7
UI: Fuel Cost	--	--	14.4	8.2	13.3	6.1	7.1	--
Electricity Cost								
Low	45.6	42.3	28.0	24.9	29.2	30.0	52.9	36.6
Nominal	52.1	48.5	29.8	28.3	31.5	35.1	74.0	51.4
High	218.1	201.7	31.3	30.5	36.1	44.2	--	195.7
			Constrained Scenarios					
Nonfuel O&M	5.7	5.7	3.1	2.3	2.7	3.0	7.3	3.6
Capital Related								
Low	39.9	36.6	--	--	--	--	--	33.0
Nominal	46.4	42.8	12.3	17.8	15.5	26.0	59.6	47.8
High	212.4	196.0	26.0	41.6	42.5	81.8	--	192.1
CI: Fuel Cost	--	--	25.7	9.9	23.8	6.1	7.1	--
Electricity Cost								
Low	45.6	42.3	--	--	--	--	--	36.6
Nominal	52.1	48.5	41.1	30.0	42.0	35.1	74.0	51.4
High	218.1	201.7	54.8	53.8	69.0	90.9	--	195.7
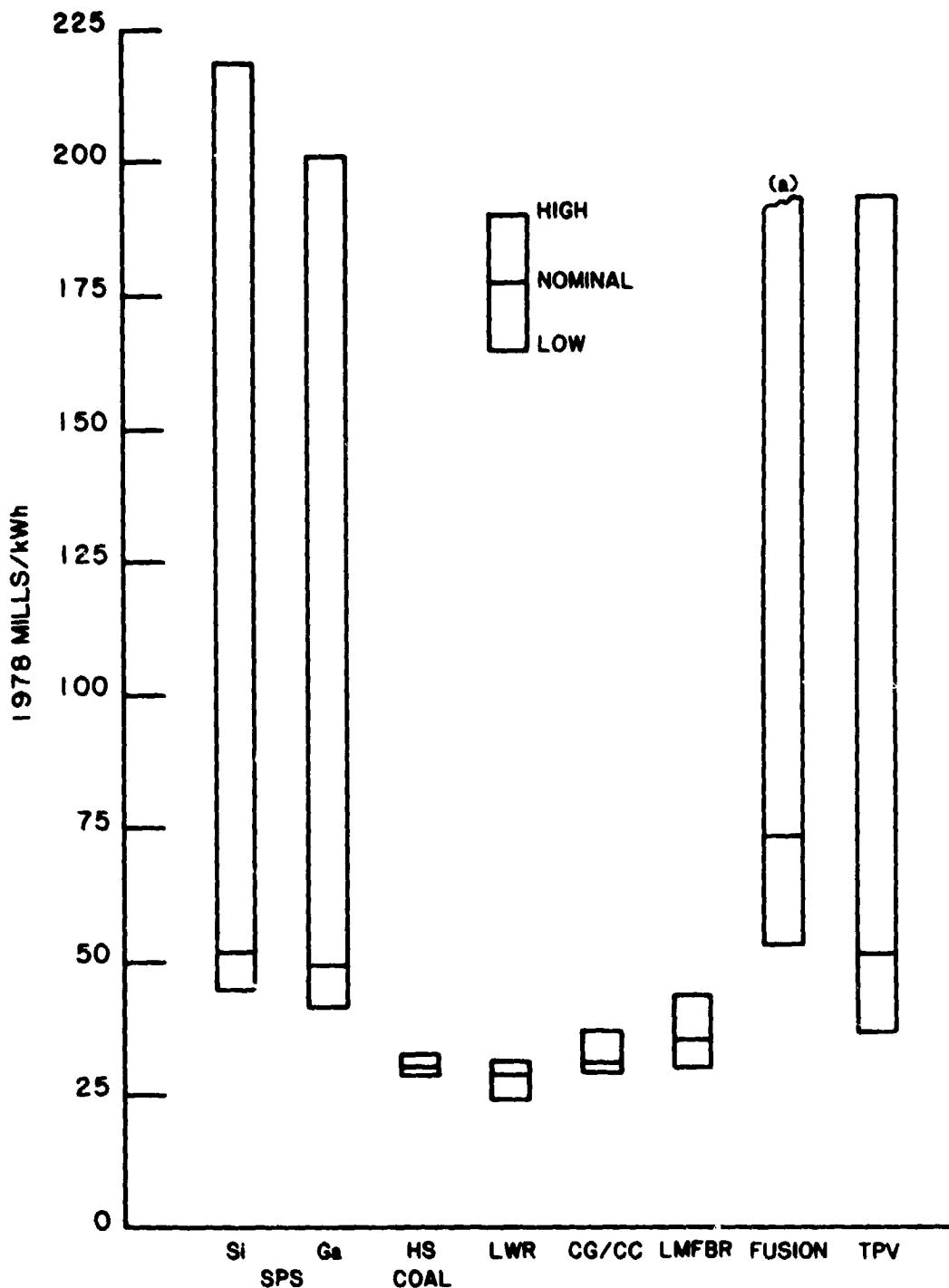
Fig. 4.15 Levelized Energy Cost Ranges for Scenario UH[b]

[a]No upper limit of the range for fusion could be determined.

[b]Unconstrained scenario, no significant restrictions on coal or nuclear power. There are relatively low prices and high energy demand. The price elasticity of demand is -0.25.
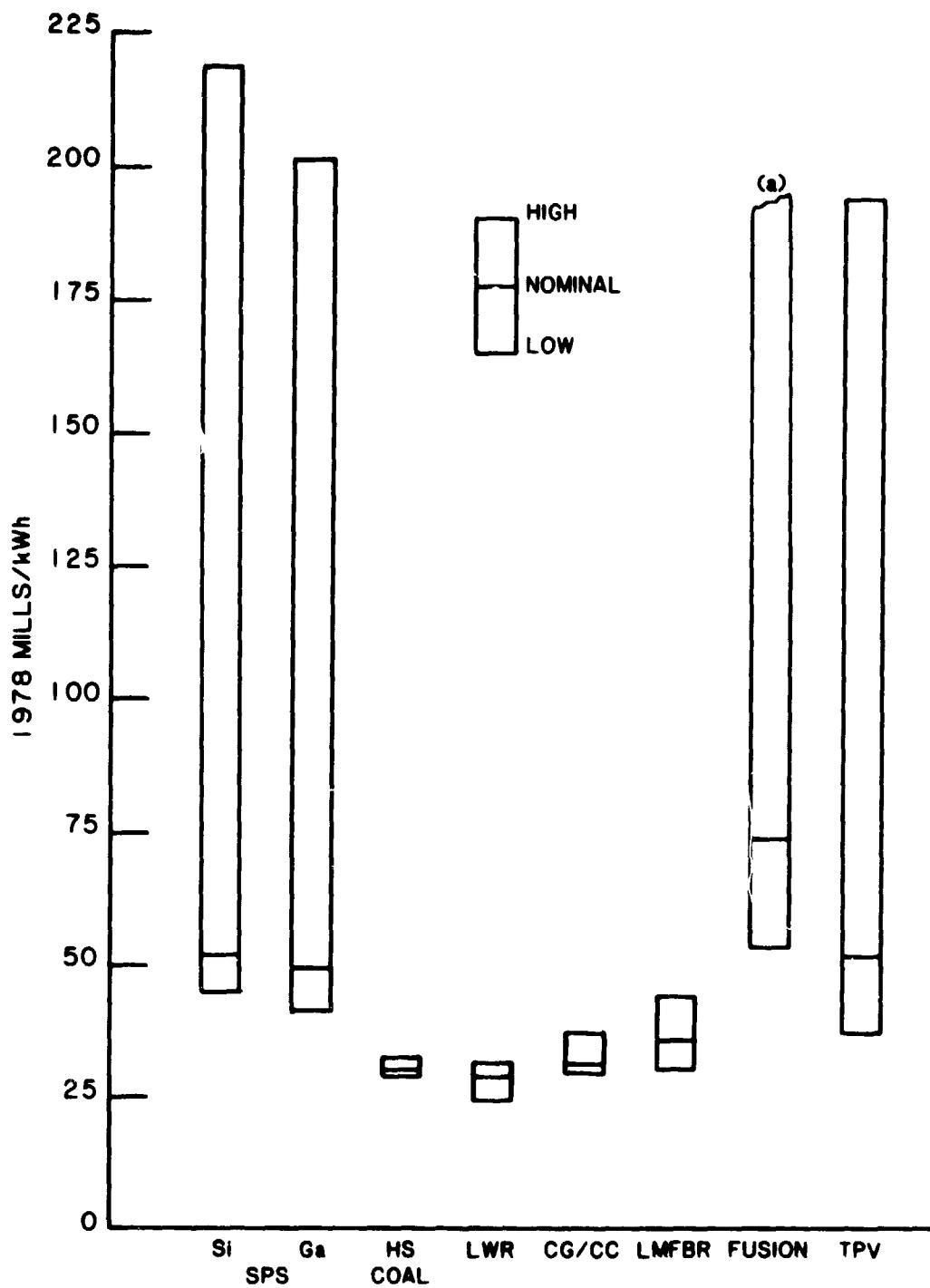
Fig. 4.16 Levelized Energy Cost Ranges for Scenario UI[b]

[a]No upper limit of the range for fusion could be determined.

[b]Unconstrained scenario, no significant restrictions on coal or nuclear power. This is consilered the most likely unconstrained scenario, with moderate price elasticity of demand. Industrial fuels are -0.7, all other fuel uses are -0.4, and chemical feedstock elasticity is 0.0.
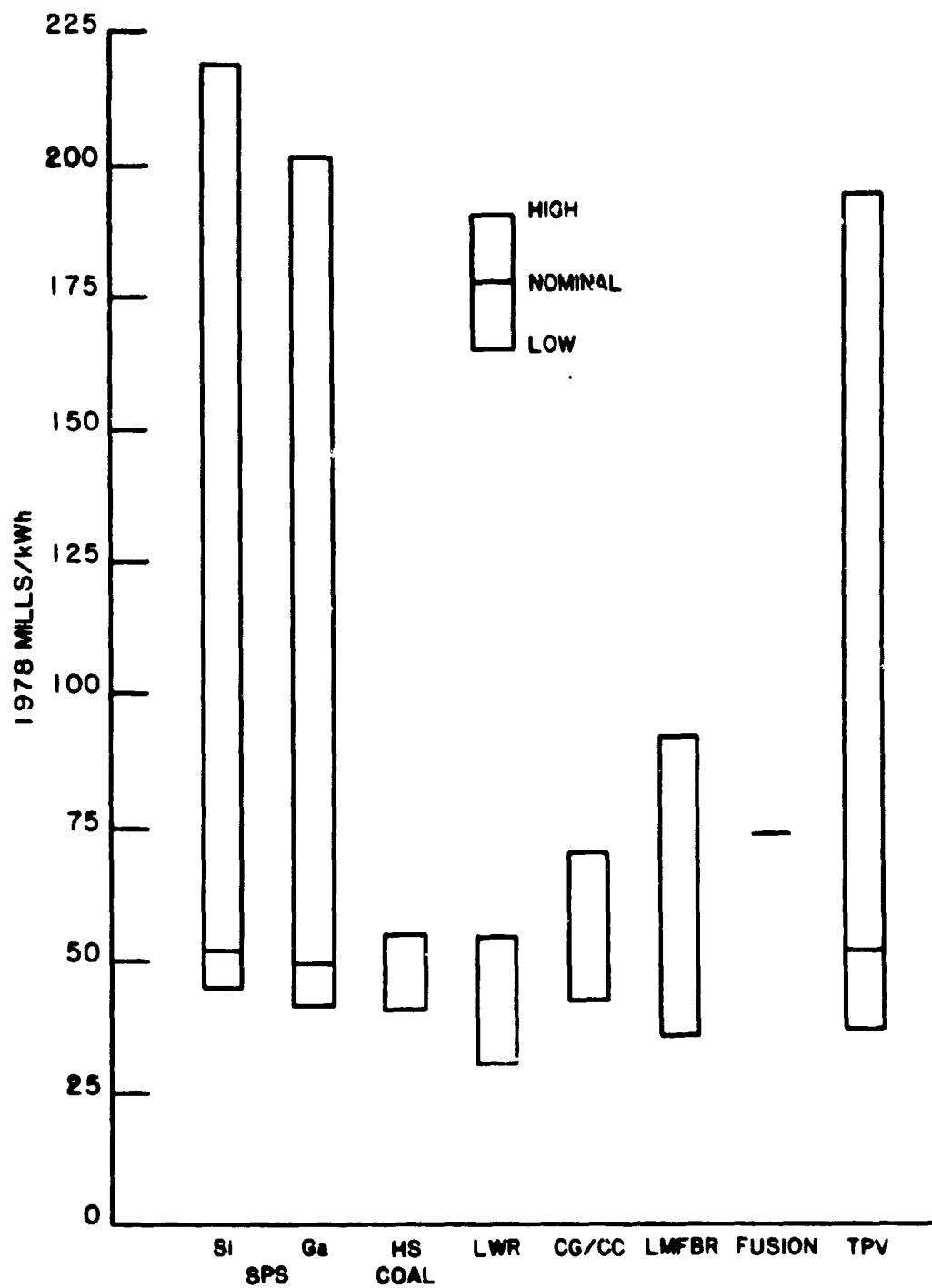
Fig. 4.17 Levelized Energy Cost Ranges for Scenario CI[a]

[a]This constrained scenario represents a continuation and augmentation of current regulatory trends affecting emissions, health, and safety. The energy price elasticities of demand are moderate, and this is considered the most likely situation if constraints are maintained.
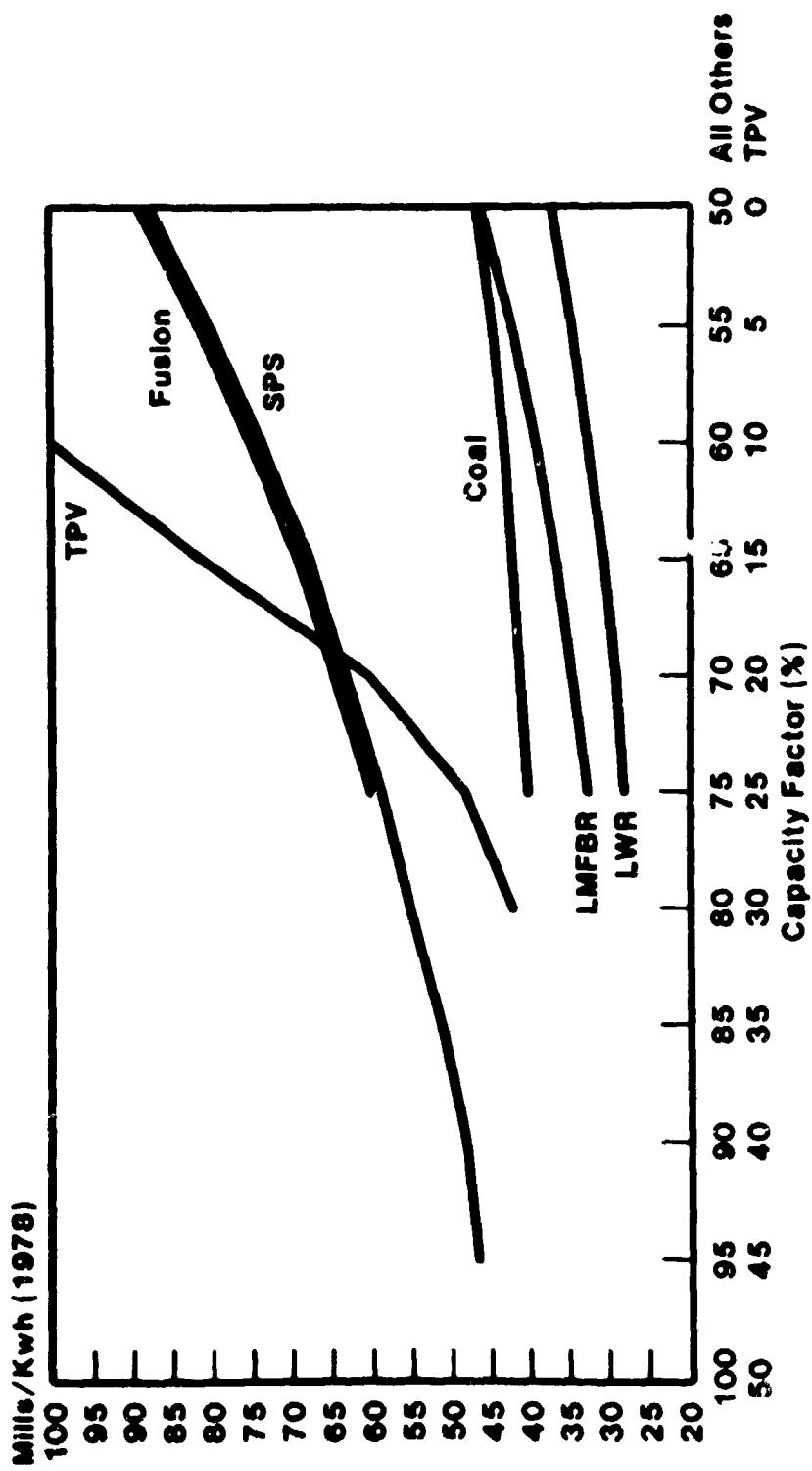
Fig. 4.18 Total Energy Costs as a Function of Capacity

The second parameter th/. was investigated in the sensitivity analysis was the implementation rate for the satellite power system. The reference design scenario for the implementation of the SPS is to build 60 5,000 MW satellites over a 30-year period. As was pointed out in the scenario descrip-ion of this report, this number of satellites may not be feasible if the demand for energy is not adequate (e.g., in the unconstrained intermediate or the constrained intermediate supply/demand scenarios). Table 4.15 shows the change in cost with different building schedules for both the silicon and the gallium aluminum arsenide reference systems. The table shows the total capital cost per unit as a function of three different schedules. The first schedule entails building 60 units over a 30-year period, and the other schedules are 30 and 20 units, respectively, over a 30-year period, a substan-tial reduction in the commitment to SPS. The increase in unit cost is less than 4% as the implementation rate decreases. However, this may be a result of the accounting system, rather than a real estimate, because the SPS base costs were derived under the assumption of a mature industry.

The third cost parameter that was examined for sensitivity to compara-tive costs was the set of economic or financial assumptions that were made in order to calculate energy costs. The baseline economic assumptions were reported in Table 4.13. Figure 4.19 shows the relative technology cost ranges and percentages for bonds, stock, and preferred stock returns on investment for the baseline assumptions and two other sets of assumptions. As shown in the figure, the cost range of each of the technologies varies slightly with different assumptions, but the overall comparative cost position does not change at all.

Table 4.15   Effect of Reduced SPS Implementation Rate on Costs:
Nominal Average Unit Costs (10^6 1978 $)

Unit Cost Component	No. of SPS Units, Silicon Reference System			No. of SPS Units, GaAlAs Reference System		
	60	30	20	60	30	20
Direct	11,073	11,073	11,073	10,035	10,035	10,035
Indirect	464	464	464	464	464	464
Investment	1,093	1,324	1,555	1,093	1,324	1,555
Subtotal	12,630	12,861	13,097	11,592	1,823	12,024
Contingency	2,020	2,058	2,095	1,855	1,892	1,929
Owner's Cost	439	448	455	404	411	420
Interest During Construction	684	745	758	670	685	697
Total	15,773	16,112	16,400	14,521	14,811	15,100
% Increase	Base	2.1	3.8	Base	2.0	4.0

86
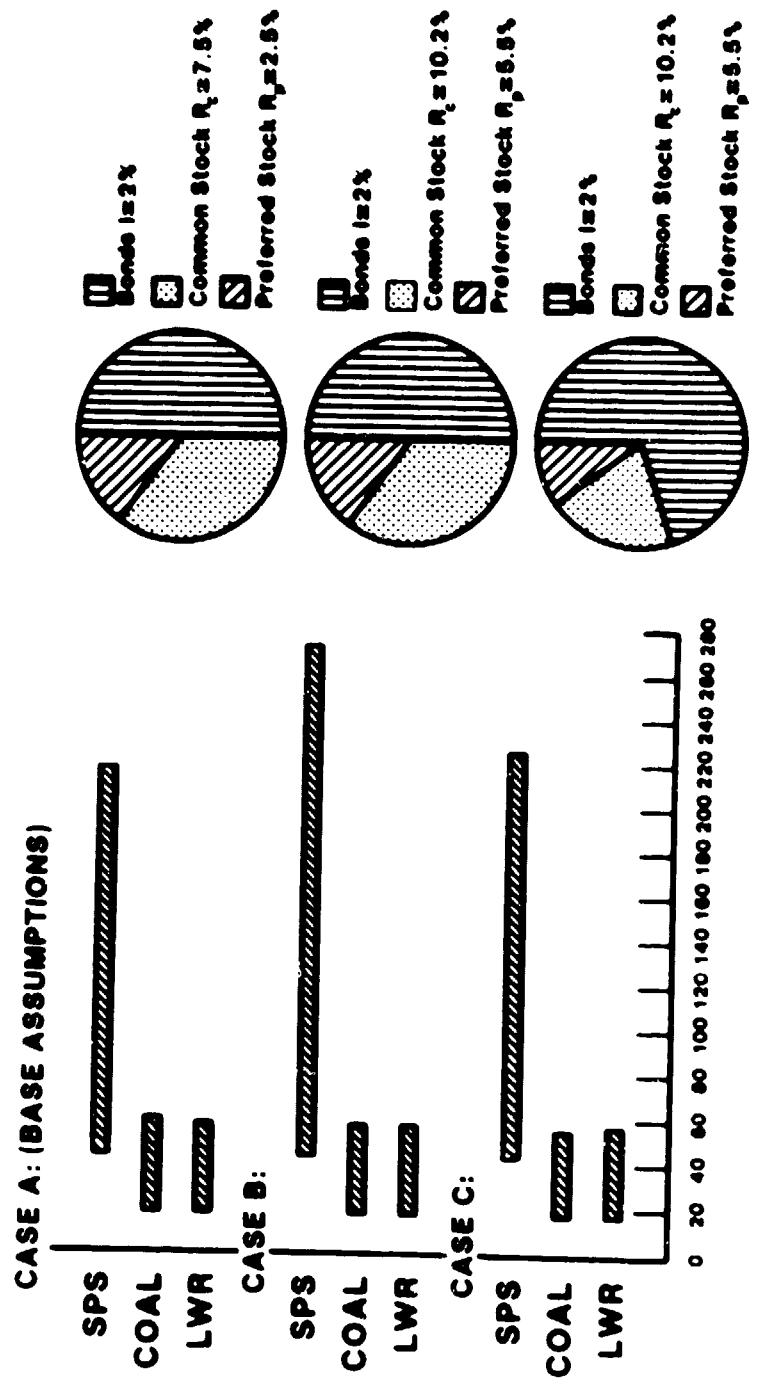
Fig. 4.19 Effect of Changes in Financial Assumptions on Relative Positions of Technologies

4.2.6 Comparative Cost Uncertainty

Previous sections of this report have compared the costs of the SPS and
alternative technologies through an analysis of possible capital and fuel cost
ranges. These ranges of capital and fuel cost uncertainty have resulted
in substantial overlap in total generating costs for all of the energy tech-
nologies. The degree of overlap in these cost comparisons is large because
the comparisons were made from independent data bases and have not taken into
account the correlation between state-of-the-world variables (e.g., the cost
of labor) and these independent estimates. In addition, the cost estimates
for capital and fuel cost were developed deterministically, by including upper
and lower bounds as a means of dealing with uncertainty.

In this section of the report, the question of uncertainty in technolo-
gy cost comparisons is discussed in a probabilistic framework. This approach
to cost comparison is primarily a method using historical data, and informa-
tion used in other sections of the report was prepared to indicate the results
of such an approach to uncertainty. The methodology was applied to a com-
parison between coal and the SPS but is equally relevant to comparisons
between any technologies.

To illustrate the focus of the probabilistic cost comparison between
coal and nuclear, consider the relationship between the cost of energy from
coal technology vs. that of the SPS. Figure 4.20 illustrates the relation-
ships for a fixed set of cost parameters and input assumptions. The typical
levelized cost of electricity from coal is generally shown to increase in
real terms because of increased coal costs. On the other hand, the cost of
electricity from the SPS would not be expected to increase so rapidly, because
it does not stem from a depleting resource base. Conceptually, the levelized
cost of these two technologies should intersect somewhere in the future.
There is no way of telling in what year the intersection will occur. Much
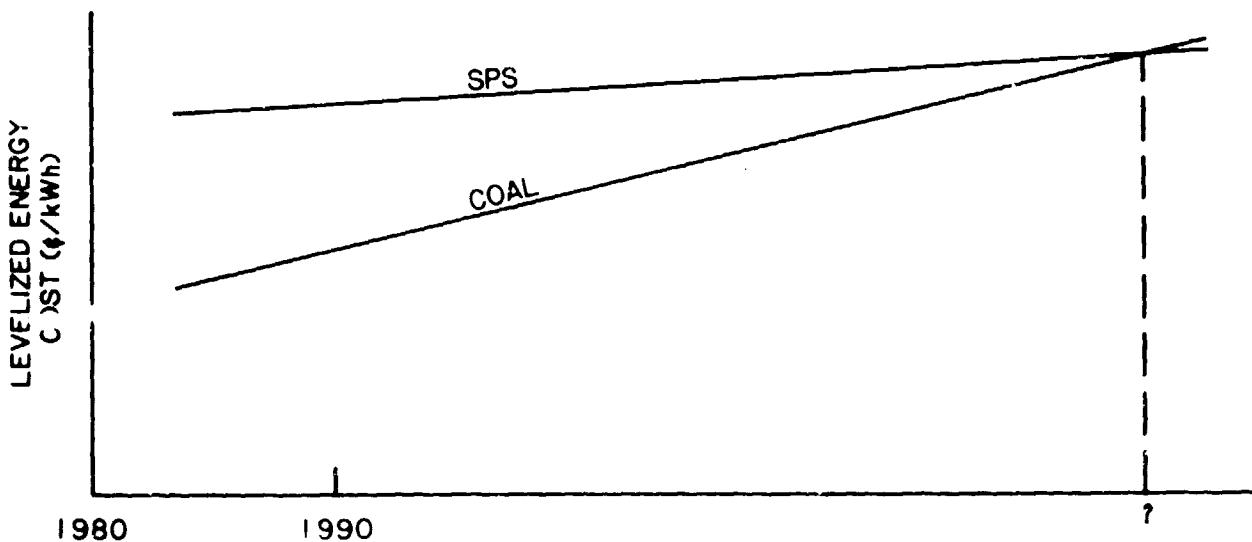
Fig. 4.20 Comparison of Coal and SPS Energy Costs
with Fixed Parameters and Inputs

depends on the supply and use of coal. Figure 4.20 is only a hypothetical
and simplistic illustration of a complex relationship, and <u>it is not expected</u>
<u>that the levelized cost of energy from these technologies would follow such</u>
<u>straight line projections</u>.

The uncertainties in the cost of energy from coal are dominated by
uncertain fuel costs, whereas the uncertainties in the cost of energy from the
SPS are dominated by technologically uncertain fixed costs. The approach in
this probabilistic analysis was to focus only on these two dominant variables
(other uncertainties were ignored in this analysis) and to treat the costs as
random variables; to determine a cost probability distribution for each of
the technologies for any particular year; and to combine them to develop a
probability distribution for the differences in energy cost between the
technologies. First, the coal probability function will be described, along
with its ties to historical data, and then the foundation for SPS cost
uncertainty will be discussed. The resultant combined probability function
will then be shown for a few parameters.

Coal Price Relationships. Figure 4.21 shows a plot of constant-dollar
coal prices from 1950 through 1977. From 1950 to 1968, the real cost of coal
declined by 1.2% per year, mainly due to decreased use because of substitution
by oil and gas. After 1968, the real cost of coal rose sharply (11% per
year), and this could be attributed to the passage of mine safety regulations
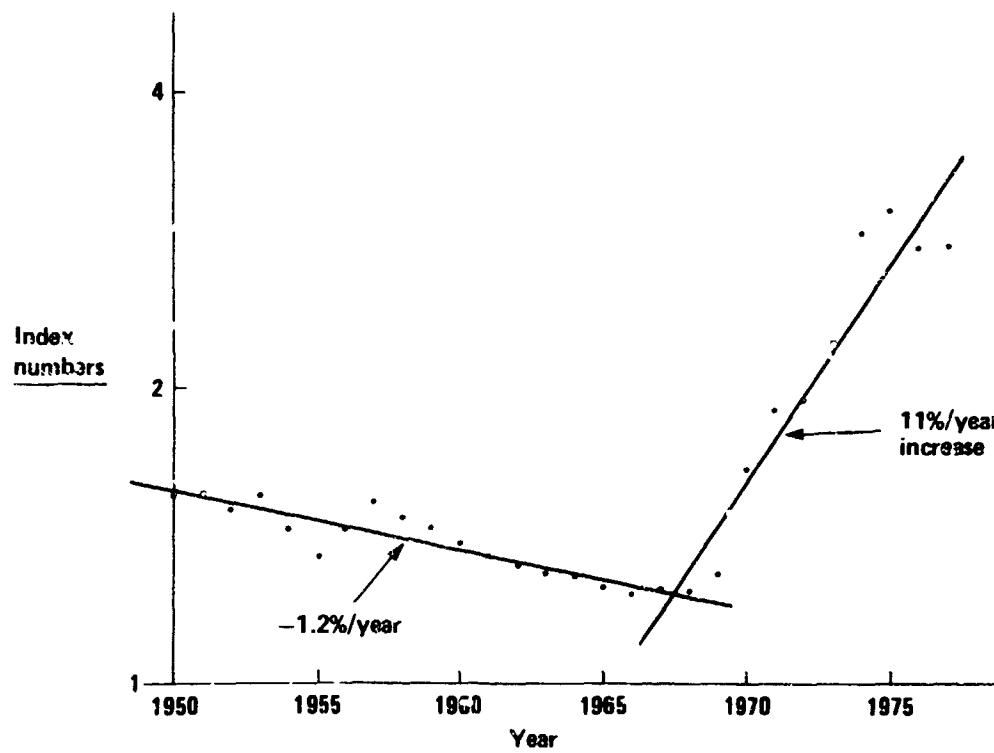
Fig. 4.21 Coal Prices (Constant Dollars)

in 1969 and the increased use of coal. Coal prices fluctuated around these mean increases and decreases, with the average fluctuation between 1950 and 1968 being 3.5% and that between 1968 and 1977 being 14%. The trend and fluctuation in coal prices in the future is uncertain. However, it is unlikely that the trend will be similar to either of the two shown in Fig. 4.21. More probable are some moderate real increases in coal prices (less than in the volatile period from 1968-1977) with fluctuation similar to that in the period from 1950 to 1968 (i.e., 3.5%). The range of average price increases for coal, as described in the supply/demand futures analysis, is shown in Fig. 4.22. The figure shows that the average real increases in coal price ranged from 2.4%/yr to 0.87%/yr for the constrained intermediate case and unconstrained high case, respectively. In approximately the same period of time (i.e., 1964-1977), electrical equipment prices declined 1.5%/yr, with a 1.7% fluctuation. Similarly, construction costs increased 1.9%/yr with 2.6% fluctuation, and transportation and utility labor rose 1.6%/yr with a 3.0% fluctuation.

The price of coal in any particular year (Y_t) can be related to that of another year (Y_0) through a series of factors.

Let:

$$Y_t = Y_0 (1 + \mu + \eta_1) (1 + \mu + \eta_2) \dots (1 + \mu + \eta_t)$$

where:

Y_0 = constant dollar amount, year 0,

Y_t = constant dollar amount, year t,

μ = mean rate of increase,

η = independent random variable with mean 0 and standard deviation σ.

Examples of μ and σ

	μ(%)	σ(%)
Coal prices, 1950-1958	-1.2	3.5
Coal prices, 1968-1977	11	14
Electrical equip. prices 1964-1977	-1.5	1.7
Construction cost 1964-1977	1.9	2.6
Transportation and utility labor 1964-1977	1.6	3.0

This expression gives the price of coal in, say, the year 2000, but in reality, that figure is the levelized cost of coal. Thus the cost of coal for every year over the whole period of operation of the coal plant must be weighted by a discount factor so that the random variable is not just the price of coal in the year 2000 but the levelized cost of coal for the whole period. The equation for the levelized cost of coal, regarded as a random
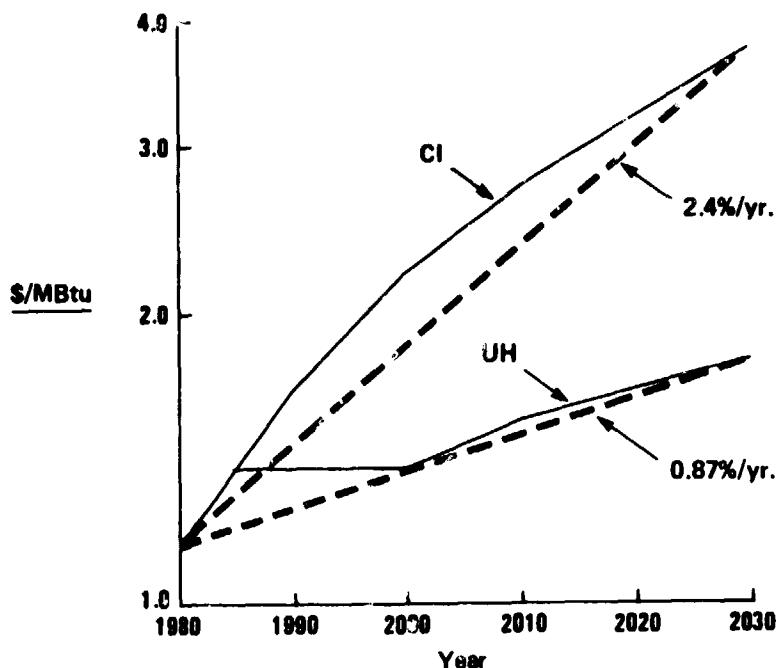
Fig. 4.22 Real Coal Price Increases

variable, for a plant that operates between the year t' and the year t, is as follows:

$$\hat{Y}_{t-t'} = Y_0 \sum_{k=t'+1}^{t} (1 - \alpha)^k \prod_{i=1}^{k} (1 + \mu + \eta_t) \Bigg/ \sum_{k=t'+1}^{t} (1 - \alpha)^k$$

where:

$\hat{Y}$ = the levelized cost of coal over the period $t - t'$,

k = no. of years in the period, and

$1 - \alpha$ = discount factor.

Figure 4.23 shows the distribution for levelized fuel cost and level-ized capital charge for a 2% average growth with 4% fluctuation per year and a real discount rate of 4%. A normal distribution is plotted in dotted lines to show the slight skew of this distribution. The skewed distribution has a long tail on the high side, which is important because the high side of the coal distribution will be important in the comparison to SPS.

SPS Price Relationships. In the case of the SPS, the dominant uncertainty factor is technical uncertainty, since there is no economic experience. The SPS is made up of a number of subsystems that were broken up into six categories: energy conversion, space construction and support, power transmission, transportation, rectenna, and other. A typical probability distribution for the cost that one might expect for each of these subsystems is shown

by the triangular distribution in Fig. 4.24. A skewed distribution was considered representative, because more factors seem to be left out than extra ones included at the early developmental stages of an advanced technology, since a design can never be complete 20 years in advance or before the technical problems have been solved.

What is needed, in reality, is a cost distribution for the SPS. However, to assemble a subsystem cost distribution like that illustrated in Fig. 4.24 requires the consideration of correlation* in the cost components, which means that several subsystems would fall into the high cost range because of the same factors. SPS subsystems are probably highly correlated in some areas and highly uncorrelated in others. For example, energy conversion is heavily dependent on the manufacturing cost for solar cells, which is very dependent on fuel cost. That would
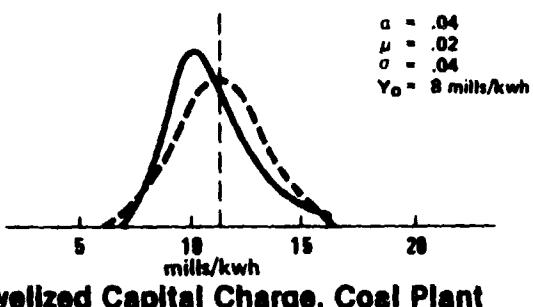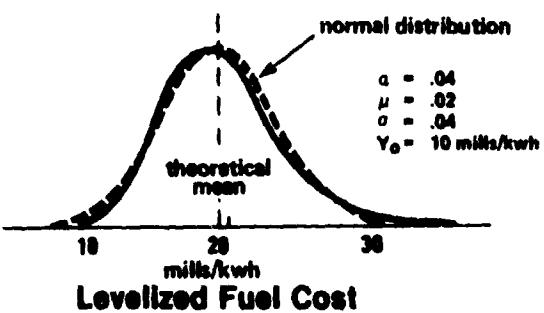
Fig. 4.23 Distributions of Levelized Fuel Cost and Levelized Capital Charge of a Coal Plant
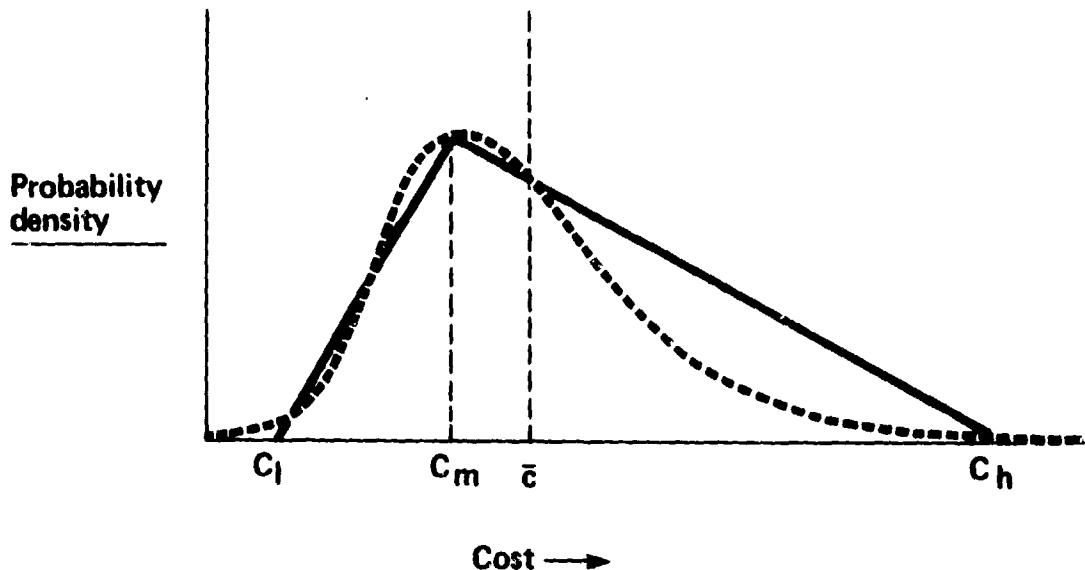
Fig. 4.24 Typical Cost Distribution for Advanced Technologies

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*A more detailed discussion of the correlation effects can be found in Ref. 2, pp. 70-72.

correlate with transportation.   On the other hand, solar cell production depends on the manufacturing sector (not strongly fuel dependent), and this would be uncorrelated with transportation.   If the subsystem cost components were completely correlated, the resulting distribution would look like the triangular figure in Fig. 4.25.   If the components were completely uncorrelated the resulting distribution would look like the normal distribution in that figure.   Since the SPS components are partially correlated, the distribution for the entire system starts out as a triangle and probably ends up something like the smooth distribution shown in Fig. 4.24 (dotted line).   A distribution like this was obtained for the SPS, with 20% of the area to the left of the modal value and 80% to the right.   This assumption was based on the earlier discussion that component projections for advanced technologies err more on the high side than on the low side.   The resulting analysis could be performed using other distributions.   This assumption is consistent with the capital cost range developed in Sec. 4.2.2.

Probabilistic Cost Comparisons Between Coal and the SPS.   The main problem in comparing the coal and SPS cost distributions is to establish the size of the overlap between the two technologies.   Again, developing a cost distribution for the difference between these technologies is dependent on the degree of correlation of cost elements between coal and the SPS.   The correlation was tested and found to be unimportant, because the two technologies stem from such radically different bases.

The goal of this probabilistic analysis is to determine the probability that the cost of electricity from the SPS will equal that from coal, and the time at which this might occur.   Figure 4.26 shows 1%, 10%, and 20% probability curves for the difference in generating cost between coal and the SPS. For example, the slope of the 20% curve indicates that there is a 20% probability that the SPS will cost the same as coal in the year 2018.   Similarly,
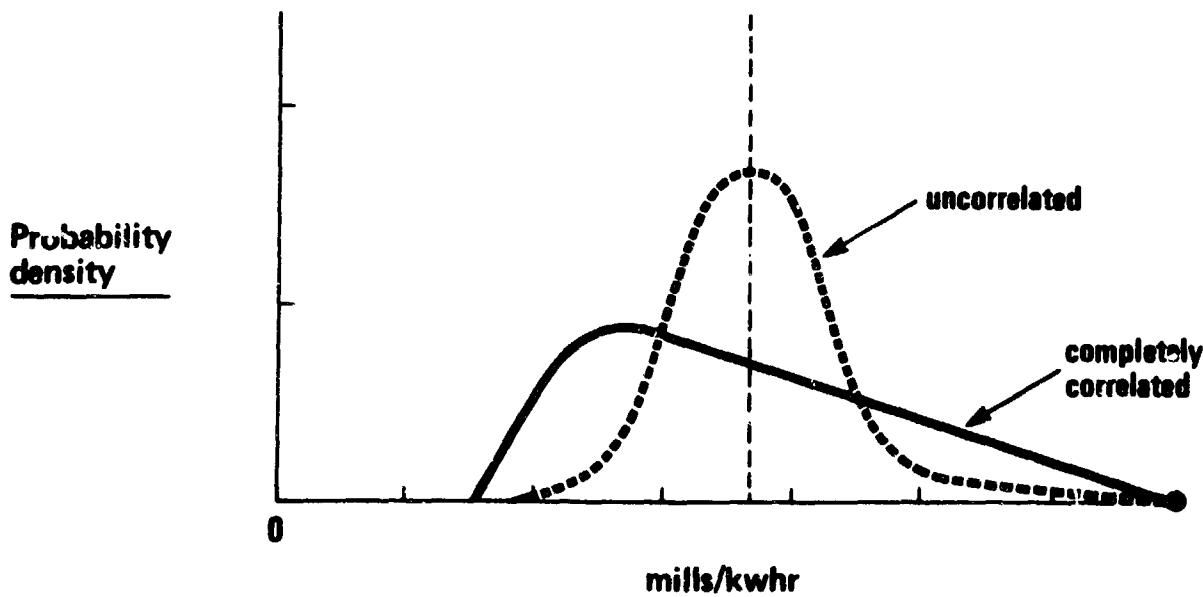
Fig. 4.25 Distributions of the Sum of Cost Elements

there is a 20% probability that the cost differential will be around 16 mills/kWh in the year 1990. This curve was plotted for the constrained intermediate coal price increases (2.4% real per year) and a 3% fluctuation. A real 4% discount rate was used. Curves similar to those in Fig. 4.26 were calculated for other coal price increases and fluctuations, but the results are no more representative than those shown in the figure. It should be pointed out that the probabilistic results were obtained using nominal values for coal and the SPS and only show the conceptual probabilistic differences. The exact numbers plotted in Fig. 4.26 are illustrative and should not be used as hard conclusions, because changing some of the assumptions (e.g., SPS cost distribution, coal price rise and fluctuations) could change the results substantially.
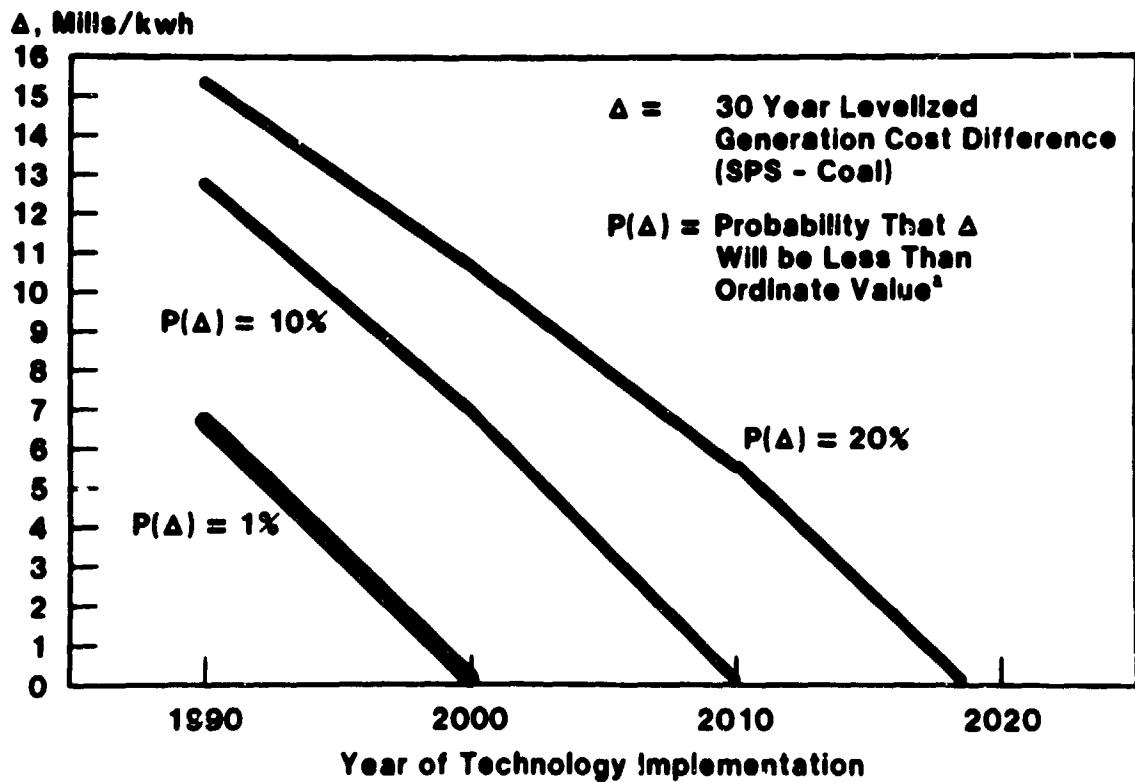
[a]A P(Δ) value of 20% is the highest curve that can be calculated from the SPS cost-uncertainty curve assumed in this study, i.e., with 20% of the probability distribution to the left of the modal cost.

Fig. 4.26 Probability Curves of SPS Costs Equalling Coal Costs

4.3 HEALTH AND SAFETY*

4.3.1 Introduction

The evaluation of health and safety risks is of high priority in the assessment of alternative energy systems because of the increasing U.S. demand for energy as well as societal concern regarding the risks associated with energy technologies. Ideally, health and safety evaluations sum all risks associated with each system under comparison. However, this sort of evaluation is not currently feasible because of uncertainties surrounding system designs and risk estimates. In addition, an evaluation based solely on a summing of impacts would obscure the differences between energy systems that result from different societal perceptions of "acceptable" risks, which are important considerations for the policymaker.

This section describes an assessment taxonomy and results of the comparison of health and safety impacts from six energy systems: the SPS; a light water fission reactor system without fuel reprocessing (LWR); a low-Btu coal gasification system with an open-cycle gas turbine combined with a steam topping cycle (CG/CC); a liquid-metal, fast breeder fission reactor system (LMFBR); a central-station, terrestrial photovoltaic system (TPV); and a first generation fusion system with magnetic confinement.

Two levels of analysis are included in this assessment: the unit health and safety risks associated with 1000-MW average electrical generation for each technology and the cumulative risks of alternative scenarios with different electrical generation technology mixes for the period 2000 to 2030. It must be stressed that the results described in this section are based on highly uncertain factors, and therefore the numbers are subjective; they should not be taken as strictly quantitative, but can provide only a qualitative view of the future.

4.3.2 Methodology

Assessing the health and safety risks of each technology required three major tasks: detailed characterization of each phase of the system as a basis for identifying the major health and safety issues associated with each of those phases; analysis of the magnitude of risk associated with each identified issue; and accumulation of risks by technology, by category of risk, and by generation scenario. Figure 4.27 illustrates this process and identifies the technology system activities and major sources of risk considered.

Detailed descriptions[5,52] of alternative, year-2000 baseload generation systems were compiled on a consistent basis for comparison as part of the larger SPS Concept Development and Evaluation Program. The design for the coal system with low-Btu gasification was based on an SO_2 emission factor of 0.2 lb $SO_2/10^6$ Btu of gas, or 0.326 lb $SO_2/10^6$ Btu of coal. Load factors of

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*The contents of this section are primarily a summary of results in Ref. 51, which includes a more comprehensive list of basic references.
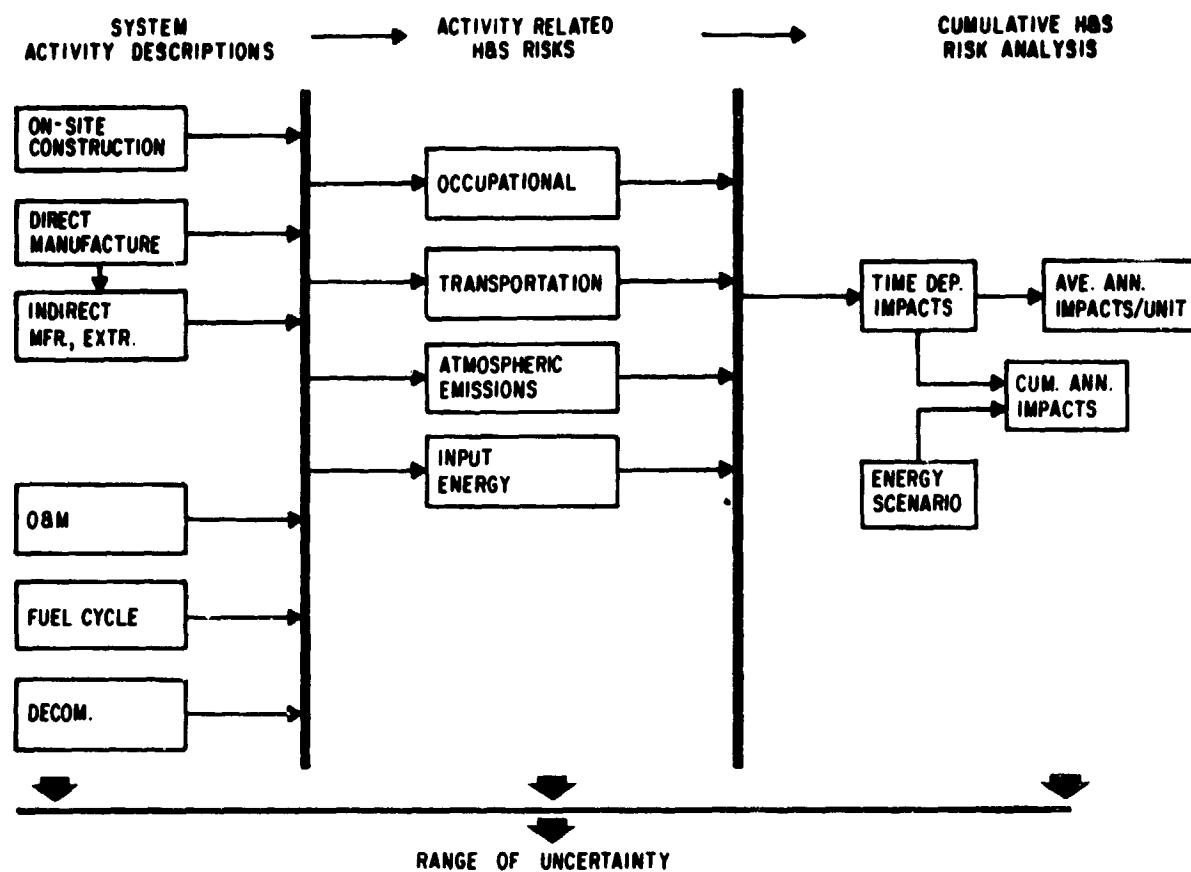
Fig. 4.27   Components of Comprehensive Health
and Safety Impact Analysis

70% were assumed for the coal, fission, and fusion systems, 90% for the SPS systems, and 26% for the centralized terrestrial photovoltaic systems. Silicon photovoltaic cells at an array cost of $35/m^2$ were assigned to the solar energy systems.

From the technology characterizations and other related information, we identified all known, potentially major health and safety issues that could be unambiguously defined and discussed. Each segment of the energy cycle was considered, including component fabrication, plant construction, fuel extraction and processing, operation and maintenance, and waste disposal. The health and safety risks of system storage or utility system back-up were not included for any of the systems.

Compared to the more conventional coal and fission technologies, the advanced solar and fusion technologies present a tradeoff of reduced fuel requirements but higher initial capital and construction requirements. Furthermore, the industries producing the energy system components in turn require certain commodity inputs (e.g., copper mining to produce electrical equipment), and the risks associated with the production of these indirect requirements must be considered in the overall risk analysis, as shown in Fig. 4.28.   Input-output tables based on the 1972 U.S. economic structure[53]

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┌─────────────┐     ┌─────────────┐     ┌─────────────┐
│ SITE DIRECT │     │CONSTRUCTION │     │ SITE DIRECT │
│   LABOR     │────▶│FATALITY & PDL│────▶│OCCUPATIONAL │
│REQUIREMENTS │     │INCIDENCE RATES│    │   RISKS     │
└─────────────┘     └─────────────┘     └─────────────┘

┌─────────────┐     ┌─────────────┐     ┌─────────────┐
│DIRECT COMPONENT│  │INDUSTRY SECTOR│   │DIRECT INDUSTRY│
│ PRODUCTION   │──▶│FATALITY & PDL│──▶│OCCUPATIONAL │
│REQUIREMENTS ($10⁶)│INCIDENCE RATES│  │   RISKS     │
└─────────────┘     └─────────────┘     └─────────────┘

┌─────────────┐  ┌──────────────────┐ ┌─────────────┐ ┌─────────────┐
│  NATIONAL   │  │INDIRECT COMPONENT│ │INDUSTRY SECTOR│INDIRECT INDUSTRY│
│  ECONOMIC   │─▶│   PRODUCTION     │▶│FATALITY & PDL│▶│OCCUPATIONAL │
│ I/O TABLES  │  │REQUIREMENTS ($10⁶)│ │INCIDENCE RATES│ │   RISKS     │
└─────────────┘  └──────────────────┘ └─────────────┘ └─────────────┘
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Fig. 4.28 Procedure for Computation of Occupational Impacts of Direct and Indirect Construction and Component Production

were used to obtain these indirect output requirements for the various categories of industries. The associated occupational fatalities and person-days lost from non-fatal accidents and diseases were then determined from historical data[54] for each of the categories of direct and indirect energy producers.

The analysis of health and safety risks of the remaining phases of the energy cycle was based primarily on adaptation of available literature. (See Ref. 51 for full literature citation.) Whenever possible, a quantitative estimate of fatalities and person days lost was made. Although these measures do not define the total adverse impact of a health and safety issue, they do provide a means for comparison between technologies and categories of energy cycle activities.

A range of impact estimates is included in each quantification, reflecting the uncertainty associated with the magnitude of impact. In addition to the quantitative measure of uncertainty, issues identified for each system were classified according to qualitative uncertainty categories, as indicated in Table 4.16. Included is a category for those identified potential health and safety issues for which it was not possible to provide any meaningful quantification. Lack of information, such as dose-response relationships at low-dose levels, siting patterns, populations exposed, and uncertainties regarding the probability of event occurrence and the characterizations of advanced technologies limited the estimation of risk magnitudes for these issues to qualitative discussion of potential severity or possible mechanisms for occurrence of the event.

For the unquantified or high-uncertainty category 3, the risks were further evaluated as being of potential significance (risk category A, potentially more than 0.01 fatalities/1000 MW-yr) or of low significance (risk category B, potentially fewer than 0.01 fatalities/1000 MW-yr).

Table 4.16 Uncertainty Index for Health
and Safety Issues

Description	Uncertainty Index	Risk Evaluation
Causal relationship and impact levels relatively well established (e.g., coal mining accidents)	1	Quantified Range
Established but poorly quantified causal relationship (e.g., ionizing radiation)	2	Quantified Range
Cause-effect association established but extremely variable impact level estimates (e.g., ground water pollution, catastrophic events)	3	Qualitative Range

The risks resulting from electricity generation differ among the technologies not only in the magnitude but also in the manner in which impacts occur. These distinctions affect societal perceptions of the acceptability of each risk and need to be preserved in the analysis. Catastrophic events constitute a prime example of the need for categorization. Because of the engineered low risk of occurrence for these events, the number of expected deaths per year, averaged over the lifetime of the plant, may be lower than that from more probable low-impact events, but the public perception of the significance of these potential events may critically affect the viability of a technology. The various impact categories utilized in the analysis are listed in Table 4.17.

4.3.3 Discussion of Results

The results of the quantitative risk analysis are summarized in Table 4.18 and Figs. 4.29-4.31. A detailed analysis of each issue considered is provided in Tables 4.19-4.23. The major unquantified issues are listed in Table 4.24. The following is a discussion of major features from those results.

Occupational Risks of the Construction Phase. For each unit value of direct industrial output required to supply components for each of the energy systems, an additional indirect in the range of 0.5-0.9 units from other industries is required. This significant requirement for indirect industrial output results in a significant addition to the average number of occupational fatalities per unit of component production, as illustrated in Fig. 4.29. The combined direct and indirect fatalities per unit of component requirement is within the same range for all the technologies, and, as a result, the total

Table 4.17 Categorization of Health
and Safety Issues

Issue	Category
Affected Population	Public
	Occupational
Impact Period	Intermediate Term (Component Production, Plant Construction)
	Long Term (Plant O&M, Waste Management)
	Short Term (Catastrophic Events)
Impact Cause	Accidents
	Chemical Pollutants (Toxic, Carcinogenic)
	Radiation (Ionizing, Nonionizing)
Impact Severity	Fatalities
	Person Days Lost (Nonfatalities)

component requirement per 1000 MW of generation is the overriding factor in determining risk of component production. The total component production risks, combined with on-site construction risks, are shown in Fig. 4.30 and illustrate the higher construction-phase risk of the terrestrial solar and the fusion technologies, which is due to the more capital-intensive nature of these technologies. The terrestrial photovoltaic system requires nearly 20 units of component production at 200-MW peak capacity and 26% load factor, and the SPS requires extensive ground and space facilities to construct and maintain the orbiting satellites.

Although not shown, similar results are obtained for the number of work days lost. For this parameter, more disaggregated data on risk levels are available for individual industrial categories.

Occupational Risks of the Operation and Maintenance Phase. The total quantified risk of fatality, averaged over an assumed 30-year lifetime, is shown for each technology in Fig. 4.31. Quantified risks of operation and maintenance (O&M) are largest for the coal technology, primarily due to the risks of accidents and illness during coal mining. A major uncertainty in estimates of mining risk derives from uncertainty in the long-term effect of recent regulations for reducing the levels of dust in coal mines. Additional O&M occupational risks of energy production from coal are related to rail transport of the coal, accidents in the coal processing and electrical generation plants, and exposure to potential carcinogenic emissions from the coal gasification process. The estimate for the risk from potential in-plant gasification emissions (0.0-0.2 fatalities/1000 MW-yr) is based on the estimated number of workers in the plant and on historical data from pilot plants with limited control measures.[55] Approximately 70-80% of the O&M risks of the fission systems are related to conventional occupational hazards, and the remaining 20-30% are due to low-level radiation exposure, the impacts

Table 4.18 Summary of Quantified Average Fatalities per Year per
1000 MW Generation, 30-Year Plant Lifetime[a]

Category	LWR	Coal (CG/CC)	LMFBR	TPV	SPS	Fusion
Total	0.28 – 0.88	6.62 – 79.49	0.31 – 0.94	0.43 – 0.73	0.26 – 0.67	0.22 – 0.44
Population Affected						
Public	0.06	5.36 – 76.40	0.07	N[b]	N	0.0001
Occupational	0.22 – 0.82	1.26 – 3.08	0.24 – 0.87	0.43 – 0.73	0.26 – 0.67	0.22 – 0.44
Impact Period						
Manufacture and Construction[c]	0.10 – 0.16	0.11 – 0.18	0.12 – 0.20	0.31 – 0.55	0.19 – 0.55	0.16 – 0.34
Operation and Maintenance	0.18 – 0.72	6.51 – 79.31	0.19 – 0.74	0.12 – 0.18	0.07 – 0.12	0.03 – 0.06
Impact Cause						
Accidents and Non-Radiation Disease	0.21 – 0.67	6.62 – 79.48	0.22 – 0.71	0.43 – 0.73	0.26 – 0.67	0.22 – 0.44
Radiation	0.07 – 0.21	0.0023	0.09 – 0.23	N	N	N

[a]The numbers in this table were calculated on the basis of the rational described in this report and do not necessarily represent past experience nor statistical expectation of future experience. This limitation applies to all figures and tables in Sec. 4.3 of this report.

[b]N: Not quantified; expected to be small.

[c]Total impacts averaged over 30-year lifetime.
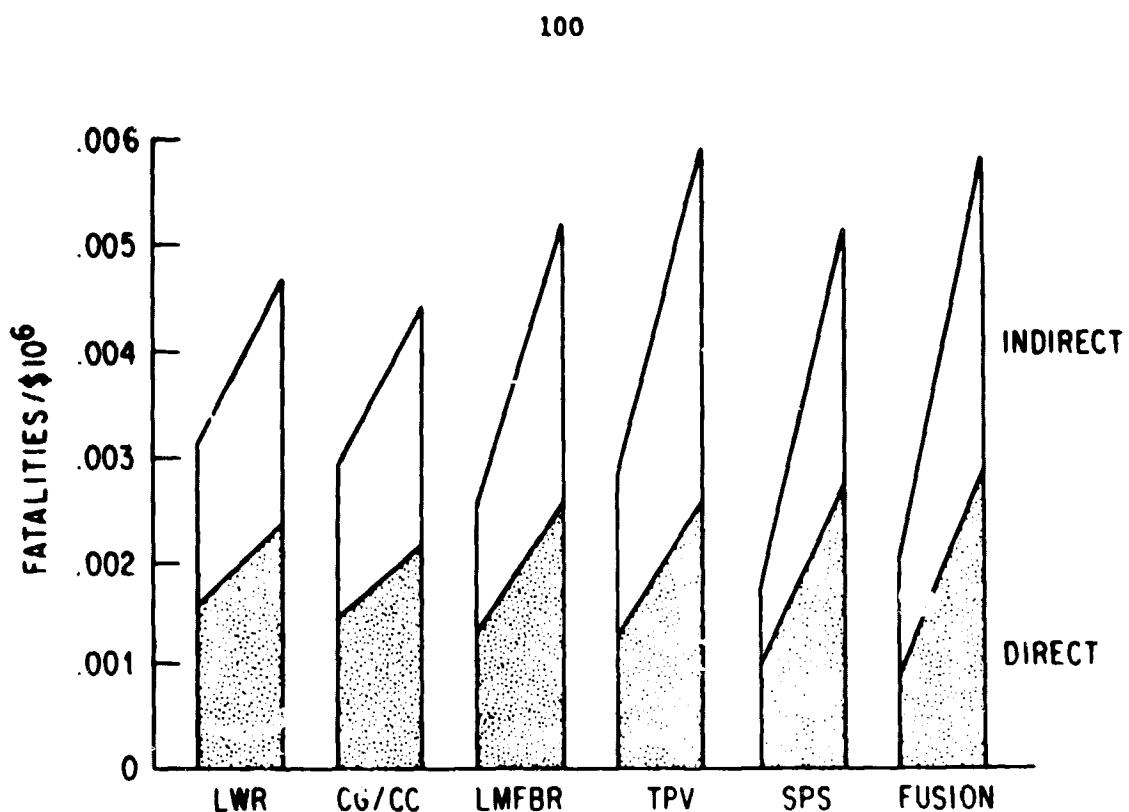
Fig. 4.29 Direct and Indirect Occupational Fatalities from Unit (10^6) Facility Component Production
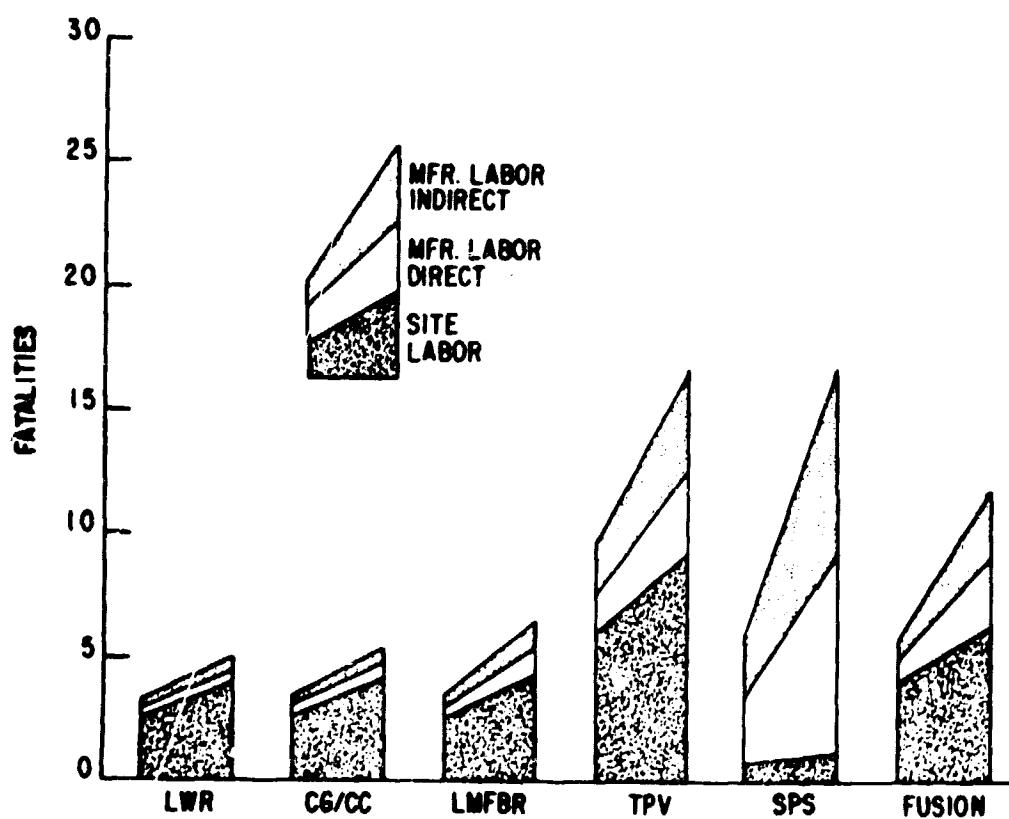
Fig. 4.30 Total Occupational Fatalities in Construction Phase of System with 1000 MW Average Generation

(79)
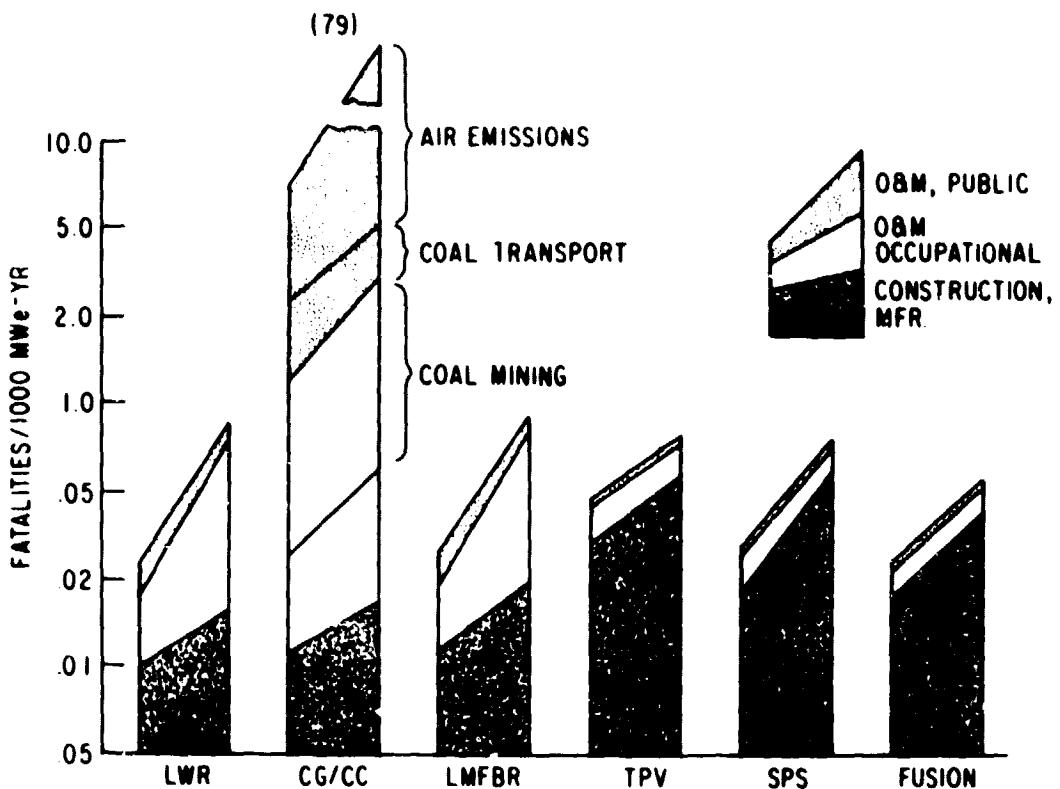
Fig. 4.31 Total Quantified Construction and
O&M Fatalities per 1000 MW-yr

of which are uncertain. The O&M occupational risks of the advanced fusion, SPS, and centralized terrestrial photovoltaic systems have no historical basis and are projected from conventional risk levels for existing similar occupations and estimates of the number of O&M employees required.[5,52]

Public Risks of the Operation and Maintenance Phase. The largest O&M-phase public risks quantified for this study are those related to the coal technologies, and these are almost entirely due to coal transport accidents (0.8-1.9 fatalities/1000 MW-yr) and air pollutants (4.6-75 fatalities/1000 MW-yr). The estimates for air pollutant impacts include long-range transport, and the uncertainty range is based on a 60% confidence level for incidence rates of health effects (adapted from Ref. 56). It should be noted that a similar procedure using 90% confidence levels for air pollutant dose-response gives a range including zero impact. Low levels of public impact (less than 0.1 fatality/1000 MW-yr) can be attributed to normal O&M of the fission and fusion systems, and these impacts are primarily due to low-level radiation, which has a high uncertainty level. The quantified public impacts from O&M for the SPS and the TPV system are negligible.

Unquantified Health and Safety Issues. In contrast to the apparent willingness of the public to accept known limited risks of energy systems, recent experience with light water fission systems indicates that perceived major risks that are less quantifiable or predictable may restrict or completely halt energy system deployment if adequate assurances of very low

Table 4.19 Summary of Health and Safety Issues for Nuclear Fission Reactors (LWR, LMFBR)

Issue	Process	Categories[a]			Estimated Fatalities per 1000 MW of Generation	Uncertainties	Uncertainty Rating
		Affected Group	Phase	Primary Cause			
Accidental injury[b]	Ore extraction and U₃O₈ milling	O	OM	AD	$0.05 - 0.2$/yr	Future use of lower-grade ore will require larger mining and milling operations.	1
Lung cancer as a result of exposure to radon and other decay products of natural uranium[c]	Ore extraction and U₃O₈ milling	O	OM	IR	$0.001 - 0.1$/yr	Exposure levels prior to establishment of standards are not known precisely. Effectiveness of ventilation for the removal of ^{222}Rn.	2
Accidental injury[d]	Fuel fabrication: U₃O₈ conversion, UF₆ enrichment, UO₂ fabrication	O	OM	AD	$0.003 - 0.2$/yr	Occupational accident potential for nuclear fuel preparation	1
Low-level radiation exposure[e]	Fuel fabrication: U₃O₈ conversion, UF₆ enrichment, UO₂ fabrication	O P	OM OM	TR IR	$0.003 - 0.033$/yr 0.0003/yr	Generic to all segments of the fuel cycle; the actual human response to low-level exposures is hypothetical.	2
Exposure to HF, F₂[f]	Fuel fabrication: U₃O₈ conversion, UF₆ enrichment, UO₂, PuO₂ fabrication	O	OM	C	0.005/yr[h]	Possible high level exposure from industrial mishaps. Population response to excess fluorides.	2
Accidental injury possible; radiation hazard and chemical toxicity from UF₆ spill[g]	Transportation	O P	OM OM	AD AD	$0.002 - 0.036$/yr 0.01/yr	Transport distances and modes; trip frequencies.	1

[a] O-Occupational, P-Public, C-Construction, M-Manufacture, OM-Operations and Maintenance, AD-Accidents and Disease, IR-Ionizing Radiation, ER-Electromagnetic Radiation.

[b] Ref. 57; [c] Ref. 58; [d] Ref. 59; [e] Refs. 60, 61; [f] Refs. 57, 62; [g] Refs. 59, 63-65.

[h] From lung damage or osteofluorosis from continuous exposure.

Table 4.19 (Cont'd)

Issue	Process	Categories[a] Affected Group	Phase	Primary Cause	Estimated Fatalities per 1000 MW of Generation	Uncertainties	Uncertainty Rating
Low-level radiation hazard, accidents[i]	Reactor operation	P O O	OM OM OM	IR AD IR	0.05/yr 0.034 – 0.055/yr 0.012 – 0.024/yr	Health impacts of low-level radiation.	2
Acute and delayed effects from catastrophic accidents[j]	Reactor operation	P	OM	IR	p	The operating experience of large power reactors is small. Catastrophic risk estimates are based on this experience.	3-A
Low-level radiation[k]	Reprocessing (LMFBR only)	O P	OM OM	IR IR	0.006/yr 0.003/yr	Extent of exposure.	2
Delayed response to low-level radiation exposure[l]	Radioactive-waste storage	O P	OM OM	IR IR	0.006/yr 0.0003 – 0.001/yr	Ability to contain radioactive wastes over long periods of time.	2
Intentional misuse of nuclear materials resulting in general population injury[m]	Fuel or by-product theft	P	OM	IR,C	q	Accessibility to nuclear materials under future reprocessing requirements, use of non-explosive toxic materials.	3-A
Liquid metal fire[n]	Reactor operations (LMFBR only)	O	OM	AD	Not available.	Initiating events, including intentional	3-A
Accidents and disease[o]	Direct and indirect material extraction and component manufacture	O	C	AD	Total fatalities: (LWR) 0.79 – 1.18 (LMFBR) 1.02 – 2.12	General manufacturing incidence rates.	1
Accidents and disease[o]	Construction on-site	O	C	AD	Total fatalities: (LWR) 2.29 – 3.62 (LMFBR) 2.56 – 4.04	General construction incidence rates	1

[a] C-Occupational, P-Public, C-Construction, M-Manufacture, OM-Operations and Maintenance, AD-Accidents and Disease, IR-Ionizing Radiation, ER-Electromagnetic Radiation.

[i] Refs. 5, 52, 57, 65, 66; [j]Refs. 65, 67; [k]Ref. 68; [l]Ref. 63; [k]Refs. 65, 67; [m]Refs. 60, 69; [n]Refs. 70, 71; [o]Refs. 5, 52, 72.

[p] About 3,500 immediate and 45,000 delayed fatalities per catastrophic incident.

[q] One small dirty terrorist bomb could destroy one city block, producing 50,000 casualties.

Table 4.20 Summary of Health and Safety Issues for Combined-Cycle Coal System

Issue	Process	Categories[a]			Estimated Fatalities per 1000 MW of Generation	Uncertainties	Uncertainty Rating
		Affected Group	Phase	Primary Cause			
Coal dust inhalation[b]	Underground mining (75% of coal)	O	OM	AD	0 - 1.2/yr	Effect of regulations to reduce dust levels.	1
Mining accidents[c]	Surface (25%) and underground (75%) coal mining	O	OM	AD	0.94 - 1.16/yr	Many inexperienced miners, new mining techniques.	1
Railroad crossing accidents[d]	Coal transport	O / P	OM / OM	AD / AD	0.07 - 0.17/yr / 0.78 - 1.9/yr	Transport routes and distances.	1
Inhalation and skin contact with toxic substances and carcinogens[e]	Plant operation and maintenance	O	OM	AD	0 - 0.2/yr	In-plant exposures in commercial facility, impact of low-level exposure.	2
Atmospheric emissions, long-range transport[f]	Plant operation; 0.326 lb SO_2 emitted per 10^6 Btu coal input	P	OM	AD	4.6 - 74.5/yr[l]	Long-range pollutant transport; low-level exposures; impact mechanism and pollutant synergisms.	2
Chemical pollutants in aqueous effluents and solid waste leachates[g]	Coal extraction and processing, plant operation	P	OM	AD	[m]	Health effect of small increments of pollutants; effluent characteristics of gasification facilities.	3-B
Exposure, inhalation, and dietary intake of radioactive coal constituents[h]	Plant air emissions	P	OM	IR	0.0023/yr[n]	Effects of low-level radiation; fate and impact of solid waste radioactive leachates.	2
Occupational health and safety[i]	Direct and indirect material extraction, processing and component fabrication	O	C	AD	0.82 - 1.23/yr	Component needs and associated risks for commercial gasification facilities.	1
Construction accidents[j]	On-site plant construction.	O	C	AD	2.59 - 4.05 (total)	Total and skill-specific labor requirements.	1
Occupational accidents[k]	Coal processing	O	OM	AD	0.073/yr	Year-2000 coal processing practices.	1
Occupational accidents[k]	Plant operation and maintenance	O	OM	AD	0.066 - 0.105/yr	Lack of experience with gasification facilities.	1

[a] O-Occupational, P-Public, C-Construction, M-Manufacture, OM-Operations and Maintenance, AD-Accidents and Disease, IR-Ionizing Radiation, ER-Electromagnetic Radiation.

[b] Refs. 56, 73, 74; [c] Ref. 56; [d] Refs. 56, 72, 75-77; [e] Refs. 55, 78-83; [f] Refs. 56, 84-86; [g] Refs. 56, 78-80, 87; [h] Refs. 61, 88, 89; [i] Refs. 72, 90; [j] Refs. 5, 52, 72; [k] Refs. 5, 52, 56, 72.

[l] 60% confidence interval for dose response.

[m] Many new and exacerbated violations of water-quality standards under scenario of large increase in utility and industrial coal use.

[n] Also 0.002 eventual genetic defects per year within 88.5-km radius of site.

Table 4.21   Summary of Health and Safety Issues for Central-Station
Terrestrial Photovoltaic Power System

Issue	Process	Categories[a]			Estimated Impact per 1000 MW of Generation	Uncertainties	Uncertainty Rating
		Affected Group	Phase	Primary Cause			
Exposure to Si dust, doping agents, process chemicals[b]	Raw material production and manufacture of photovoltaic cells	O,P	C	AD	Potential exposure to Si dust, phosgene, BCl_3, Cd, Ga, As, HF, SnO_x, NH_3, phenols, CdO, $ZnSO_4$, Al_2O_3, and other processing chemicals	Emission levels, bioaccumulation potentials of released wastes, volume of wastes	3-A
Accidents, exposure to toxic process chemicals and environmentally released wastes[c]	Direct and indirect material extraction and component manufacture	O	C	AD	3.45 - 7.18 deaths (total)	Material and manpower requirements	2
Accidents, exposure to toxic chemicals[b]	Construction	O	C	AD	5.92 - 9.30 deaths (total)	Manpower requirements of sectors involved in construction activities	2
Accidents, system malfunction[c]	Operation and maintenance (O&M)	O	OM	AD	0.12 - 0.18 deaths/yr O&M will include risk of electrical and physical trauma and of exposure to off-gases during episodes of array overheating.	Manpower requirements and system malfunction potential	2
Exposure to toxic substances[b]	Disposal of spent photovoltaic cells	O,P		AD	Disposal or recycling of cells will increase worker and public risk of exposure to doping agents including As, Cd, and Ge.	Disposal and recycling techniques	3-A

[a] O-Occupational, P-Public, C-Construction, M-Manufacture, OM-Operations and Maintenance, AD-Accidents and Disease, IR-Ionizing Radiation, ER-Electromagnetic Radiation.

[b] Refs. 91, 92; [c] Refs. 5, 52, 72.

Table 4.22 Summary of Health and Safety Issues for Satellite Power System

Issue	Process	Categories[a] Affected Group	Phase	Primary Cause	Estimated Impact per 1000 MW of Generation	Uncertainties	Uncertainty Rating
Occupational accidents and disease[b]	Direct and indirect material and component fabrication	O	C	AD	5.06 - 15.19 deaths (total)	Changes in SPS components and thus in conventional technology (e.g., materials extraction and processing) may result from SPS demand	2
Construction accidents and disease[c]	O&M of ground launch and recovery areas during construction phase; rectenna construction	O	C	AD	0.72 - 1.11 deaths (total)	Total and skill specific labor requirements	2
Exposure to Si dust, doping agents, process chemicals[d]	Raw material production and manufacture of photovoltaic cells	O,P	C	AD	Potential exposure to Si dust, phosgene, BCl_3, Cd, Ga, As, HF, SnO_x, NH_3, phenols, CdO, $ZnSO_4$, Al_2O_3; and other processing chemicals	Emission levels, bioaccumulation potentials of released wastes, volume of wastes	3-A
Catastrophic Events e.g., HLLV malfunction[e]	Transportation of materials and personnel to low earth orbit (LEO)	P	C,OM	AD	Maximum accident may exceed 1000 fatalities. Approximately 40 flights per 1000 MW capacity during construction	Probability of malfunction during launch and navigation	3-A
Public exposure to fuel emissions, noise from HLLV[f]	Transportation of materials and personnel to LEO	O	C,OM	AD	95 dBa at 6 km during launch. Over-pressure of sonic boom during ascent and descent sufficient to cause nonprimary structural damage at 125 km	Dispersion patterns and concentration of toxic fuel components	3-A
Occupational exposure to noise, fuel emissions, malfunctions during HLLV and PLV launch[g]	Transportation of materials and personnel to LEO and GEO	O	C,OM	AD	Explosion of HLLV could ignite combustibles and cause first degree burns at 300 m. Sound pressure of HLLV launch exceeds pain threshold (130 lb) in launch area.	Potential for exposure to toxic chemicals; probability of system malfunction	3-B

[a] O-Occupational, P-Public, C-Construction, M-Manufacture, OM-Operations and Maintenance, AD-Accidents and Disease, IR-Ionizing Radiation, ER-Electromagnetic Radiation.

[b] Refs. 3, 28, 72, 93, 94; [c]Refs. 28, 72; [d]Refs. 91, 92; [e]Refs. 3, 94-97; [f]Refs. 93-98; [g]Refs. 93, 95, 97, 99.

Table 4.22 (Cont'd)

Issue	Process	Categories[a]			Estimated Impact per 1000 MW of Generation	Uncertainties	Uncertainty Rating
		Affected Group	Phase	Primary Cause			
Stress of life in space, accidents[h]	Construction of photovoltaic array and microwave transmission system	O	C	AD	0.002 - 0.068 deaths (total)[n]	Potential for system malfunction events, radiation exposure, and vehicle collisions with space debris.	2
Electromagnetic radiation exposure, accidents[i]	Operation and maintenance of photovoltaic array and microwave transmission system	O	OM	AD	0 - 0.003 deaths/yr[o]	Effects of high-energy particle exposure. Effects of chronic low-level microwave exposure; potential peak exposure 2500 mW/cm².	2
Electromagnetic radiation exposure, chronic and acute[j]	Operation and maintenance of microwave transmission on system	P	OM	ER	Effects of chronic low-level exposure unquantified	Effects of large-population exposure to low levels of microwave radiation.	3-A
Electromagnetic radiation exposure[k]	Operation and maintenance of ground station rectennas	O	OM	ER	Accidental exposures, power beam reflections could result in exposures of almost 23 mW/cm² under normal operating conditions	Effects of long-term exposure to low levels of microwaves and low-frequency electromagnetic radiation.	3-B
Conventional occupational accidents and disease[l]	Operation and maintenance of ground rectennas, launch and recovery areas	O	OM	AD	0.07 - 0.12 deaths/yr	Limited historical data on space-travel support requirements.	2
Acute exposure to power beam[m]	Operation and maintenance of satellite power system	P	OM	ER	Current reference design has low probability for acute public exposure to peak power beam density of 23 mW/cm²	Accessibility to subversion of beam-aiming controls in final system design; realiability of directional system shutdown controls.	3-B

[a] O-Occupational, P-Public, C-Construction, M-Manufacture, OM-Operations and Maintenance, AD-Accidents and Disease, IR-Ionizing Radiation, ER-Electromagnetic Radiation.

[h] Refs. 28, 60, 72, 100, 101; [i] Refs. 28, 60, 72, 88, 101; [j] Refs. 60, 100, 101; [k] Refs. 60, 101; [l] Refs. 28, 72; [m] Refs. 60, 88, 100.

[n] Based on range of incidence rates in conventional occupations, assuming 640 persons in orbit 0.5 yr to construct 5-GW satellite.

[o] Based on range of incidence rates in conventional occupations, assuming 1400-person maintenance crew in orbit for 300-GW system.

Table 4.23 Summary of Health and Safety Issues for the Fusion Power System

Issue	Process	Categories[a]			Estimated Impact per 1000 MW of Generation	Uncertainties	Uncertainty Rating
		Affected Group	Phase	Primary Cause			
Safety of open pit and brine pumping operations[b]	Lithium ore extraction and processing	O	OM	AD	0.0018 deaths and 0.0068 nonfatal accidents per yr	Injury and disease incidence rates of lithium ore extraction	1
Occupational health and safety[c]	Material extraction and fabrication of structural components, direct and indirect	O	C	AD	1.83 - 5.53 deaths (total)	System design, size; quantity and identity of structural components	2
Exposure to toxic agent (Be)[d]	Component fabrication	O	C	AD	TLV[i] for Be: 0.002 mg/m^3	Satisfactory protection by workplace exposure standards	3-A
Low-level radiological hazards[e]	Fuel (tritium) preparation	O	OM	AD	Tritium required for plant startup only	Size of tritium production facilities and worker exposure levels	3-B
Exposure to toxic agent (H$_2$S)[f]	Fuel preparation	O	OM	AD	TLV[i] for H$_2$S: 15 mg/m^3	H$_2$S exposure specific to the Girdler process for deuterium extraction	3-A
Low-level radiation exposure. Exposure to high-intensity electromagnetic fields[f]	Plant operation	O,P	OM	IR,ER	Maximum tritium dose downwind of plant: 1 rem/yr. Data on electromagnetic field inconclusive	Tritium exposure level inside of plant; health effects of electromagnetic fields	3-B
Occupational accidents and disease, conventional[g]	Plant operation	O	OM	AD	0.034 - 0.055 deaths/yr	Plant O&M requirements	2
Exposure to activation products[h]	Waste disposal, damage repair	O,P	OM	IR	Finite lifetime of first wall and blanket due to radiation damage, nonvolatile components	Potential for migration of wastes	3-B

[a]O-Occupational, P-Public, C-Construction, M-Manufacture, OM-Operations and Maintenance, AD-Accidents and Disease, IR-Ionizing Radiation, ER-Electromagnetic Radiation.
[b]Refs. 102, 103; [c]Refs. 5, 52, 72; [d]Refs. 104-106; [e]Refs. 107, 108; [f]Refs. 103, 109; [g]Refs. 5, 52, 72; [b]Ref. 110.
[i]TLV = threshold limit value.

Table 4.23 (Cont'd)

Issue	Process	Categories[a] Affected Group	Phase	Primary Cause	Estimated Impact per 1000 MW of Generation	Uncertainties	Uncertainty Rating
Highway safety[j]	Transport of materials, fuel, and waste	P	OM	AD	Truck transport: 0.000128 deaths and 0.0011 nonfatal accidents/yr	Amount and mode of required transportation	2
Low-level radiation exposure[k]	Transport of materials, fuel, and waste	O,P	OM	IR	Unknown	Amount and mode of required transportation	3-B
Component failure, plant safety, liquid metal fires and spills, pressure and thermal explosions, missile generation due to magnet or vacuum failure[l]	Operation and maintenance	O	OM	AD	Similar to other industrial experience with high-energy material	System reliability and likelihood of a fire or explosion	3-A
Occupational accidents and disease[m]	On-site plant construction	O	C	AD	3.80 - 5.95 deaths (total)	Personnel requirements for materials and construction	2
Radiation exposure from activation products[n]	Plant deactivation	O,P		IR	Nonvolatile nature of activation products suggests a low level of impact for this issue	Human response to low-level exposure uncertain. Probability of exposure unknown	3-B
High-level radiation exposure[o]	Catastrophic event	O,P		IR	Unknown	Likelihood of exposure during such an event	3-A

[a]O-Occupational, P-Public, C-Construction, M-Manufacture, OM-Operations and Maintenance, AD-Accidents and Disease, IR-Ionizing Radiation, ER-Electromagnetic Radiation.

[j]Refs. 102, 111; [k]Refs. 104, 112; [l]Ref. 103; [m]Refs. 5, 52, 72; [n]Refs. 112-114; [o]Refs. 103, 107-109, 112.

Table 4.24   Summary of Potentially Major but Unquantified Issues

Solar Technologies (TPV, SPS)	Nuclear Technologies (LWR, LMFBR, Fusion)
Exposure to Cell Production Emissions	System Failure with Major Public Exposure to Radiation
Hazardous Waste From Disposal or Recycling of Cell Materials	Occupational Exposure to Chemically Toxic Materials during Fuel Cycle
Chronic Exposure of Large Populations to Low-Level Microwaves (SPS only)	Diversion of Fuel or By-product for Military or Subversive Uses (LWR, LMFBR only)
Space Vehicle Crash into Urban Area (SPS only)	'iquid Metal Fire (LMFBR, Fusion only)
Exposure to Rocket Exhaust Emissions from HLLV (SPS only)	

Coal Technologies

(None Identified)

impact probability cannot be given.   For this reason potentially major, but unquantified, risks should be given prominence comparable to the quantified risks discussed above.   Table 4.2/ is a listing of potentially major (Category A) but unquantified issues identified for the six technologies considered.

Estimates of expected health and safety impact levels have been developed for certain catastrophic events (i.e., events with low probability of occurrence but high impact per event), in particular, for fission reactor systems.[115]   However, these impacts were not included as quantified issues in this study because of inherently high uncertainties associated with pre-dicting occurrence rate and impact per occurrence.   Furthermore, averaging expected catastrophic impacts over plant lifetime does not indicate the full significance of these potential events.   The issues of potential diversion of fission fuel for weapons use and the potential for a crash of a SPS space-transport vehicle into an urban area are also included in the potential catastrophic event category.   Through engineered safeguards, the probability of occurrence of these events can be reduced to very low levels, but essen-tially zero probability is very difficult if not impossible to achieve at reasonable cost.

A further important distinction concerning unquantified issues is whether the potentially affected persons are part of the general public or are workers producing or operating the system.   Issues in the latter category (e.g., emissions from solar cell production, emissions of toxic materials from the fission system fuel cycle, liquid-metal fire hazards in the LMFBR and fusion systems) affect a well-defined group, i.e., occupational workers, and those impacts can be more easily monitored and mitigating actions implemented.   In contrast, impacts from low-level microwave radiation, if they exist, may be difficult to identify because of their potentially small and subtle effects on a large exposed group.

In general, the better-defined technologies (e.g., CG/CC, LWR) have a greater number of quantifiable risks and fewer unquantifiable risks. The opposite is true for the less-defined technologies (e.g., fusion, SPS). Table 4.24 does not attempt to rank the unquantified issues, although, for example, potential radiation release from fission is expected to be greater than that from fusion.[108]

Cumulative Risks From National Energy Scenarios. A further perspective on the significance of relative technology risks is provided by Fig. 4.32, which indicates the range of annual occupational risks for scenarios of energy production in 2000-2020 with and without the SPS system. A nearly constant total electrical energy generation is assumed in this period for the scenarios (Table 4.25). The SPS units were assumed to operate at the design load factor of 90%. However, because of the large SPS unit size (5000 MW), it is assumed that because of reliability requirements, the overall capacity, including conventional technologies, is the same for the SPS scenario as for the non-SPS scenario in which the overall load factor was assumed to be 70%. In the SPS scenario, the non-SPS technologies serve in part as back-up for the SPS and operate at less than 70% load factor.

Because of high construction and manufacturing impacts, the SPS scenario has a higher initial value for the mean occupational health and safety risks. By 2020, in this scenario, these occupational risks have dropped to nearly the same values as those for the non-SPS scenario.
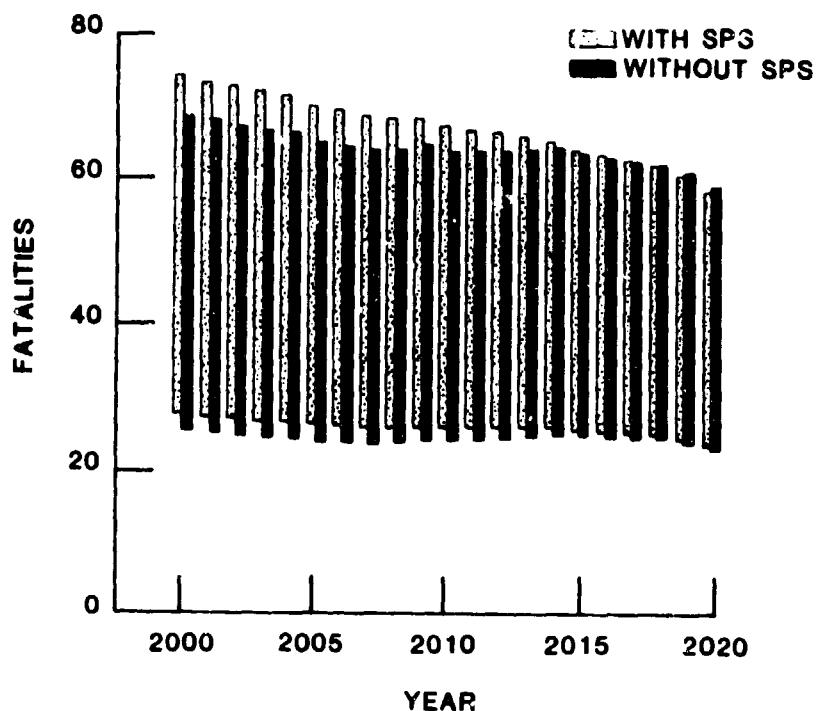
Fig. 4.32 Annual Occupational Fatalities from Construction and O&M in Baseload Scenarios with and without SPS

Table 4.25 Scenario Baseload Capacities and Electrical Generation

| Year | Capacity (GW) | | | | | | | Total Generation (GW-yr) |
	LWR	CG/CC	LMFBR	SPS	TPV	Fusion	Total	
2000	263	238	34	0	0	0	535	375
2020 (SPS)	199	145	96	100	29	19	578	405
2020 (No SPS)	213	159	140	0	29	37	578	405

The addition of quantified public risks to the occupational risks in Fig. 4.32, in particular those from coal, would favor the SPS scenario with reduced conventional generation. However, the unquantified risks to the public in Table 4.24 restrict the delineation of definitive conclusions related to total scenario risks.

Conclusions. Under the assessment taxonomy and the assumptions described in this report, the coal technology appears to have the largest overall quantified risk of the various systems considered, primarily due to coal extraction, processing and transport, and air pollution, although large uncertainties remain in the actual effect of the air pollution. On the other hand, no additional issues were identified for the coal system that are potentially major but remain largely unquantifiable. Quantified risks from the remaining technologies (fission, fusion, SPS, and centralized TPV) are comparable within the range of quantified uncertainty. The occupational risks for component production, both direct and indirect, are a substantial fraction of the total risk, in particular for the advanced, capital-intensive solar and fusion technologies.

Of potential major significance for public acceptance of new energy systems, but not included in the quantification, is the possibility of catastrophic incidents that exist for the fission and fusion systems. Unique, unquantified possibilities of catastrophic incidents also exist for the SPS, in relation to the use of microwave transmission of energy and extensive space travel.

4.4 ENVIRONMENTAL WELFARE EFFECTS

4.4.1 Introduction

Several types of effects from environmental degradation that are not directly related to public or occupational health and safety will be referred to as environmental welfare effects, since they concern the well-being of individuals. For example, deterioration of building materials from SO_2 emissions, reduced crop productivity due to water pollution, and aesthetic impacts such as plumes from stacks and cooling towers are considered. This evaluation of coal (conventional coal and CG/CC), nuclear (LWR, LMFBR, and fusion), and solar (TPV and the GaAlAs version of SPS) systems identifies the

extent and severity of these welfare effects and develops a set of priority effects that require more in-depth analysis. Specifically excluded from this category are effects on health and safety, natural biological systems, resource depletion (including direct land and water use), and social and economic dislocations. Conditions following accidents were also not included in this study.

The sequence[116] for determining the environmental welfare effects of each energy technology begins with an examination of the various activities involved in each fuel cycle, starting with the extraction of the resource and extending to the delivery of electricity to a utility grid. These activities result in environmental impacts such as noise and air and water pollution. In turn, the environmental impacts could result in welfare effects such as property damage, climatic change, interference with other activities, and aesthetic disturbances. This activity-impact-effect chain is illustrated in Fig. 4.33. The structure is used for categorizing the impacts and effects of the various activities in the fuel cycle.

The physical environmental impacts and their effects caused by the various activities associated with selected coal, nuclear, and solar technologies are listed in Tables 4.26-4.32.

4.4.2 Comparative Impacts

The welfare effect of each energy-related activity is examined in the context of the additional burden imposed on a community by that activity. Typical facility sizes -- for a mine, processing plant, or power plant -- are used whenever possible as a basis for determining local welfare effects (the assumed facility sizes represent current opinion regarding the most likely unit sizes to be constructed in the near future). The welfare effects are not scaled to a common metric, such as cost or impact per 1,000 MW of electrical capacity. Use of a common metric tends to obscure information because of the need to introduce various assumptions in converting impacts to a single unit of measure. The approach used in this assessment takes into account the fact that small, dispersed power plants often have smaller local welfare effects than would a large centralized facility, even though the quantity of emissions per megawatt of electricity generated may be smaller for the larger facility and the larger facility could more easily be sited in an isolated area. At the same time, it is recognized that many minor impacts may have a cumulative impact that could equal or exceed a major impact from a single, large facility. Other assumptions that underlie this analysis are that all activities use advanced pollution control technology representative of newer facilities and that facilities operate routinely (that is, without accidents).

The environmental welfare impact of each activity was quantified by the magnitude of some physical effect (e.g., noise level), and its capacity to be mitigated was evaluated. It is thought that this approach provides a qualitative judgment that reflects the more recent trends in emissions and anticipated effects. Direct comparison between technologies tends to obscure the welfare issues associated with each energy technology and was therefore avoided.
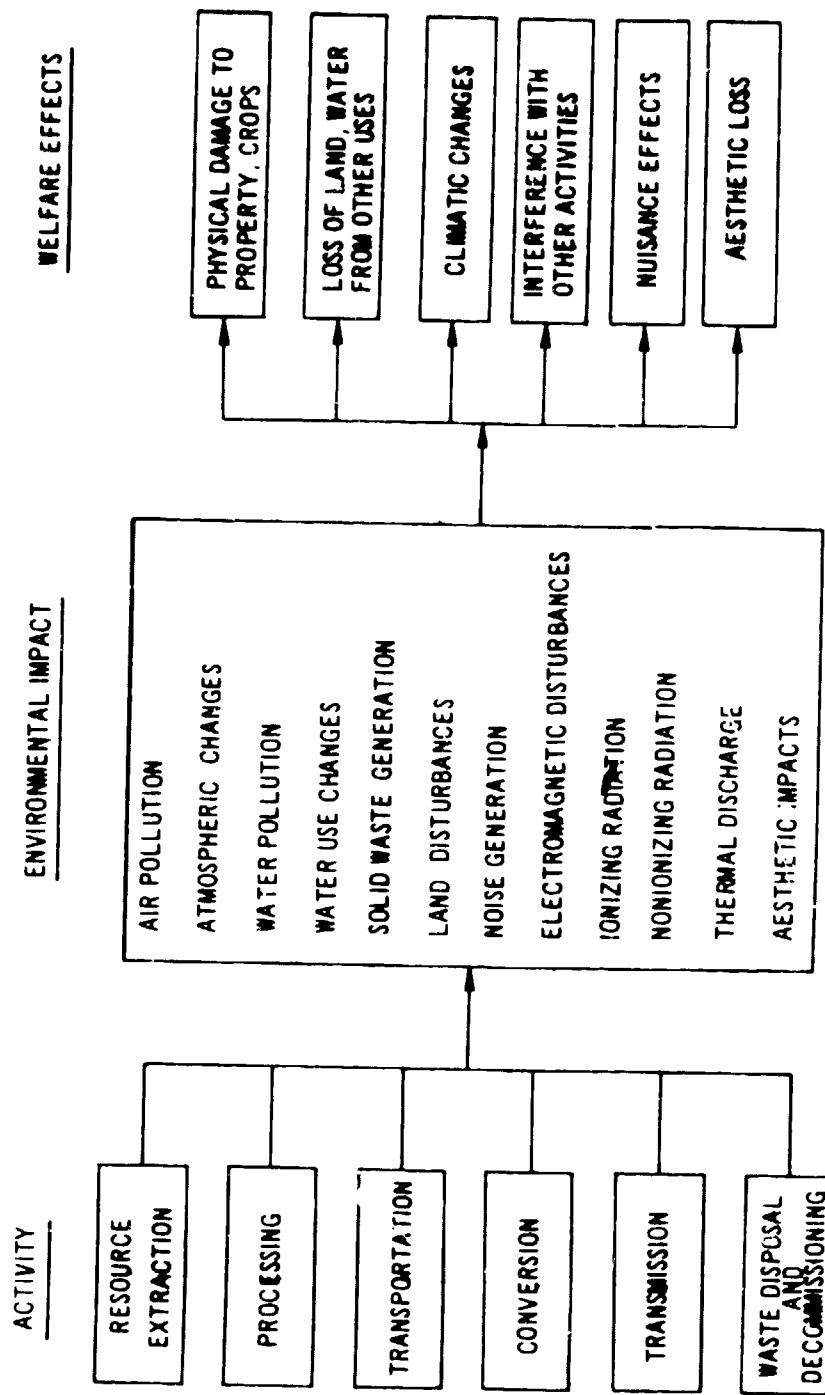
Fig. 4.33 Pathway of Energy Activities, Impacts, and Effects

Table 4.26 Welfare Effects of a Conventional Coal Fuel Cycle[a]

Environmental Impact	Activities Involved	Welfare Effects
Air Pollution	Mining Processing Transportation Power generation	Emissions of SO_2 and NO_x from power generation can lead to acid rainfall, which can reduce crop yield and yield and remove lakes or rivers from commercial or recreational use. Emissions of SO_2 and particulates can cause or augment material damage and reduce crop yields. Secondary particulates can impair visibility. bility.
Atmospheric Changes	Power generation	Injection of large amounts of CO_2 and other green-house gases into the atmosphere may promote global warming, with effects on precipitation, agriculture, and ocean levels. Particulate emissions may also play a minor role in climatic change.
Thermal Discharges	Power generation	Cooling tower operation can increase local fogging and icing, with effects on visibility, traffic, and convenience for nearby residents. Cloud and precipitation augmentation is possible but should be minor, with little effect on crop productivity.
Water Pollution	Mining Processing Power generation	Discharges of acids, dissolved solids, suspended solids, and other chemicals can degrade drinking water supplies, contaminate waterways, lower crop productivity because of acidified irrigation or ground water, and reduce commercial and recreational use of streams and lakes.
Water Use	Mining Processing Power generation	Mining can disrupt water flow patterns. Cooling needs during power production require extensive amounts of water if evaporative systems are used. Both impacts can conflict with downstream and competing uses.
Solid Waste	Mining Processing Power generation	Demand for disposal sites can be increased. Land use, value, and productivity can be reduced by over-burden and refuse from mining and processing, ash and scrubber wastes, and by hazardous trace metals from coal.
Land Use Disturbance	Mining Processing Transportation Power generation Transmission	Surface mining and power generation (waste disposal) remove land from alternate uses; reclaimed land may be less productive agriculturally than before mining. Subsidence of land over underground mines can reduce land values; damage crops, buildings, and livestock; rupture pipes; and disrupt drainage. Coal processing can contaminate and lower value of surrounding land. Transportation and transmission land requirements are significant and limit other uses of the land.
Electromagnetic Disturbances	Transmission	High intensity magnetic fields around transmission lines can cause radio and TV interference in fringe reception areas.
Ionizing Radiation	Power generation	Small quantities of radioactive materials are emitted during coal combustion. Welfare effects of these emissions, which are uncertain, include effects of long-term exposure of crops and livestock to radiation.
Noise	Mining Transportation Power generation Transmission	Welfare impacts of noise generation from most coal-related activities are relatively minor due to the remote locations of the operations. Audible hum from high-voltage transmission lines may occur.
Aesthetic Disturbances	Mining Processing Transportation Power generation Transmission	Visual impacts will occur from mines, tailing piles, power plants, stack plumes, and transmission corridors.

[a]Main sources include Refs. 116-124.

Table 4.27 Welfare Effects of a Light Water Reactor Fuel Cycle[a]

Environmental Impact	Activities Involved	Welfare Effect
Air Pollution	Mining UF_6 production Enrichment Fuel fabrication Transportation Power generation Reprocessing	Fluorine and sulfuric acid emissions could damage live-stock, grazing land, and crops. Other air pollutants are emitted from coal plants, which may be used to supply process power.
Thermal Discharges	Enrichment Power generation	Cooling tower operation can increase local fogging and icing with effects on visibility, traffic, and convenience for nearby residents. Cloud and precipitation augmentation is possible, but should be minor, with little effect on crop productivity. The same effects would be possible from power generation for uranium enrichment facilities. Nuclear power parks would release much more heat than single power plants, with increased welfare effects.
Water Pollution	Mining Milling UF_6 production Enrichment Fuel fabrication Power generation Reprocessing	Process effluents can on occasion degrade drinking water supplies; degrade irrigation water, impairing crop growth; and reduce commercial and recreational use.
Water Use Changes	Mining Power generation Enrichment	Mining operations can disrupt water flow. Cooling needs during power production require extensive amounts of water if evaporative systems are used; uranium enrichment also has significant water requirements. All three impacts can conflict with downstream uses.
Solid Waste	Mining Milling UF_6 production Fuel fabrication	Release of trace elements into terrestrial ecosystems may locally reduce crop productivity. Lateral and upward movement of leachates may contaminate rooting zones of otherwise productive cropland.
Land Use Disturbance	Mining Enrichment Reprocessing Decommissioning	Agricultural use of reclaimed mines may be less productive. Exclusion zones around enrichment and reprocessing plants remove land from other uses, whereas burial of nuclear wastes may remove all further use of land involved.
Electromagnetic Disturbances	Transmission	High intensity magnetic fields around transmission lines can cause radio and TV interference in fringe-reception areas.
Ionizing Radiation	Mining Milling Conversion Enrichment Fuel fabrication Power generation Reprocessing	Low-level radiation emissions could act as an extremely low-level mutating agent for crops and livestock. Knowledge of a threshold level for adverse effects from ionizing radiation is uncertain.
Noise	Mining Power generation Transmission	No major effects. High-voltage transmission lines create a barely audible hum.
Aesthetic Disturbances	Mining Power generation Transmission	Aesthetic degradation due to mines, cooling tower plumes, transmission corridors.

[a]Main sources include Refs. 20, 116, 117, 120, 125-129.

Table 4.28 Welfare Effects of a Coal-Gasification/
Combined-Cycle Fuel Cycle[a]

Environmental Impact	Activities Involved	Welfare Effects
Air Pollution	Mining Processing Transportation Power generation	Emissions of SO_2 and NO_x greatly reduced by CG/CC compared to the conventional coal-fuel cycle. These emissions do contribute to acid rainfall, which can reduce crop yield and remove lakes or rivers from commercial or recreational use. Emissions of SO_2 and particulates can cause or augment material damage and reduce crop yields. Secondary particulates can impair visibility.
Atmospheric Changes	Power generation	Injection of large amounts of CO_2 and other greenhouse gases into the atmosphere may promote global warming, with effects on precipitation, agriculture, and ocean levels. Particulate emissions may also play a minor role in climatic change.
Thermal Discharges	Power generation	Cooling tower operation can increase local fogging and icing, with effects on visibility, traffic, and convenience for nearby residents. Cloud and precipitation augmentation is possible but should be minor, with little effect on crop productivity.
Water Pollution	Mining Processing Power generation	Discharges of acids, dissolved solids, suspended solids, and other chemicals can degrade drinking water supplies, contaminate waterways, lower crop productivity because of acidified irrigation or ground water, and reduce commercial and recreational use of streams and lakes.
Water Use	Mining Processing Power generation	Mining can disrupt water flow patterns. Cooling needs during power production require extensive amounts of water if evaporative systems are used. Both impacts can conflict with downstream and competing uses.
Solid Waste	Mining Processing Power generation	Demand for disposal sites can be increased. Land use, value and productivity can be reduced by overburden and refuse from mining and processing, ash and scrubber wastes, and by hazardous trace metals from coal. Ash wastes are about 25% less than those for the conventional coal fuel cycle.
Land Use Disturbance	Mining Processing Transportation Power generation Transmission	Surface mining and power generation (waste disposal) remove land from alternate uses; reclaimed land may be less productive agriculturally than before mining. Subsidence of land over underground mines can reduce land values; damage crops, buildings, and livestock; rupture pipes; and disrupt drainage. Coal processing can contaminate and lower value of surrounding land. Transportation and transmission land requirements are significant and limit other uses of the land.
Electromagnetic Disturbances	Transmission	High intensity magnetic fields around transmission lines can cause radio and TV interference in fringe reception areas.
Ionizing Radiation	Power generation	Small quantities of radioactive materials are emitted during coal combustion. Welfare effects of these emissions, which are uncertain, include effects of long-term exposure of crops and livestock to radiation.
Noise	Mining Transportation Power generation Transmission	Welfare impacts of noise generation from most coal-related activities are relatively minor due to the remote locations of the operations. Audible hum from high-voltage transmission lines may occur.
Aesthetic Disturbances	Mining Processing Transportation Power generation Transmission	Visual impacts will occur from mines, tailing piles, power plants, stack plumes, and transmission corridors.

[a]Main sources include Refs. 15, 116-124, 130.

Table 4.29 Welfare Effects of a Liquid-Metal,
Fast-Breeder Reactor Fuel Cycle[a]

Environmental Impact	Activities Involved	Welfare Effect
Air Pollution	Fuel fabrication Transportation Power generation Reprocessing	Air pollutants are emitted from coal plants which may be used to supply process power.
Thermal Discharges	Power generation	Cooling tower operation can increase local fogging and icing with effects on visibility, traffic, and convenience for nearby residents. Cloud and precipitation augmentation is possible, but should be minor, with little effect on crop productivity. Nuclear power parks would release much more heat than single power plants, but such parks would probably be sited in lightly populated areas.
Water Pollution	Fuel fabrication Power generation Reprocessing	Process effluents can on occasion degrade drinking water supplies; degrade irrigation water, impairing crop growth; and reduce commercial and recreational use.
Water Use Changes	Power generation	Cooling needs during power production require extensive amounts of water if evaporative systems are used and can conflict with downstream uses.
Solid Waste	Fuel fabrication	Small releases of trace elements into terrestrial ecosystems may locally reduce crop productivity.
Land Use Disturbance	Reprocessing Decomissioning	Exclusion zones around reprocessing plants remove land from other uses, whereas burial of low-level nuclear wastes may remove all further use of land involved.
Electromagnetic Disturbances	Transmission	High intensity magnetic fields around transmission lines can cause radio and TV interference in fringe-reception areas.
Ionizing Radiation	Fuel fabrication Power generation Reprocessing	Low-level radiation emissions could act as an extremely low-level mutating agent for crops and livestock. Knowledge of a threshold level for adverse effects from ionizing radiation is uncertain.
Noise	Power generation Transmission	No major effects. High-voltage transmission lines create a barely audible hum.
Aesthetic Disturbances	Power generation Transmission	Aesthetic degradation due to cooling tower plumes and transmission corridors.

[a]Main sources include Refs. 23, 110, 116, 120, 131-133.

Table 4.30 Welfare Effects of a Terrestrial
Photovoltaic Fuel Cycle[a]

Environmental Impact	Activities Involved	Welfare Effects
Air Pollution	Mining Manufacturing Construction Transportation	Solar cell manufacturing may produce toxic emissions -- exact emissions and welfare effects are unknown. Environmental probblems from fugitive dust from mining and construction could occur -- welfare effects are not expected to be as severe as those of toxic emissions.
Atmospheric Changes	Solar Collectors	Negligible effects on climate likely.
Water Pollution	Mining Manufacturing	Water pollutants generated by conventional mining and manufacturing activities could degrade drinking water supplies and cause reduced commercial and recreational yield in affected waters.
Water Use	Mining Manufacturing Construction	Mining of materials could disrupt aquifers and bodies of water; impacts unknown.
Solid Waste	Mining Manufacturing	Mine tailings and residuals from photovoltaic cell manufacturing could increase demand for disposal sites. Toxic manufacturing wastes could reduce productivity and usefulness of land to some degree.
Land Use Disturbance	Mining Solar Collectors Transmission	Mining operations and solar collector sites remove large parcels of land from alternate uses. Post-mining agricultural use of reclaimed areas may be less productive. Large solar collector sites could require relocation of homes, roads, and right-of-ways and inconvenience persons having to drive around an area that they formerly could drive through.
Electromagnetic Disturbance	Transmission	Power transmission can effect fringe TV and radio reception.
Noise	Transmission	No major effects. High voltage transmission lines create a barely audible hum.
Aesthetic Disturbances	Mining Transmission	Mining activities and transmission lines would have visual impacts.

[a]Main sources include Refs. 9, 134-140.

Table 4.31 Welfare Effects of a Satellite Power System Fuel Cycle[a]

Environmental Impact	Activities Involved	Welfare Effects
Air Pollution	Launch and recovery Mining Manufacturing Construction Transportation	Solar cell manufacturing and rocket launches may produce toxic emissions -- exact emissions and welfare effects are unknown. Environmental problems from fugitive dust from mining and construction and spills of rocket propellants could occur -- welfare effects are not expected to be as severe as those of toxic emissions.
Atmospheric Changes	Launch and recovery Rectenna	Rocket emissions of CO_2 and H_2O would augment the greenhouse warming effect to a small extent, with slight effects on precipitation, agriculture, and ocean levels.
Thermal Discharges	Launch and recovery Rectenna	Waste heat from the rectenna would raise local temperatures slightly, possibly produce slight changes in local cloudiness, and contribute to heat island effects. Heat from launch ground cloud could modify local weather. Welfare impacts would likely be minor.
Water Pollution	Mining Manufacturing Launch and recovery	Water pollutants generated by conventional mining and manufacturing activities could degrade drinking water supplies and cause reduced commercial and recreational yield in affected waters. (Transportation of propellants could result in accidental spills, with similar welfare effects.)
Water Use	Mining Manufacturing Construction Launch and recovery	Mining of materials could disrupt aquifers and bodies of water; impacts unknown. Local water shortages due to cooling needs of the launch tower would be possible, but should be avoidable.
Solid Waste	Mining Manufacturing Launch and recovery	Mine tailings, residuals from photovoltaic cell manufacturing, and wastes from launch-related activities could increase demand for disposal sites. Toxic manufacturing wastes could reduce productivity and usefulness of land to some degree.
Land Use Disturbance	Mining Launch and recovery Rectenna Transmission	Mining operations, launch and recovery sites, and rectenna sites remove large parcels of land from alternate uses. Post-mining agricultural use of reclaimed areas may be less productive. Large rectenna and launch complex sites could require re'ocation of homes, roads, and right-of-ways and inconvenience persons having to drive around an area that they formerly could drive through.
Electromagnetic Disturbance	Launch and recovery Satellite Microwave power transmission Transmission	Launch vehicle emissions could modify the electron density of the ionosphere and disrupt communications systems. Reflected light and waste heat from the satellite could create EM disturbances; affected systems could include radio astronomy. SPS microwave coupling with electronic systems up to 100 km from the rectenna could occur. Power transmission can effect fringe TV and radio reception.
Microwave Radiation	Rectenna	Rectenna operation would emit low levels of microwave radiation beyond exclusion area. The effects of these emissions are unknown, but possibly could include indirect impacts on beneficial insects and invertebrates. Microwave radiation could also make crops more susceptible to other environmental stresses.
Noise	Launch and recovery Transmission	Noise from HLLV launches could exceed recommended EPA noise standards. Sonic booms would occur during launch and reentry. High voltage transmission lines produce a barely audible hum. High noise levels near residential areas could reduce property values, cause annoyance, and interfere with other activities.
Aesthetic Disturbances	Mining Satellite Transmission	Mining activities and transmission lines would have visual impacts. The satellites would be visible as bright objects in the night sky, affecting optical astronomy.

[a]Main sources include Refs. 3, 90, 97, 116, 141-144.

Table 4.32 Welfare Effects of a Fusion Fuel Cycle[a]

Environmental Impact	Activities Involved	Welfare Effect
Air Pollution	Mining	Impacts of mining lithium are unknown.
Thermal Discharges	Power generation	Cooling tower operation can increase local fogging and icing with effects on visibility, traffic, and convenience for nearby residents. Cloud and precipitation augmentation is possible but should be minor.
Water Pollution	Power generation	Releases of tritium into water supplies would be a health and safety issue.
Water Use Changes	Power generation	Cooling needs during power production could require extensive amounts of water if evaporative systems are used.
Land Use Disturbance	Decommissioning	Burial of nuclear wastes may remove all further use of land involved.
Electromagnetic Disturbances	Transmission	High intensity magnetic fields around transmission lines can can cause radio and TV interference in fringe-reception areas.
Noise	Mining Power generation Transmission	No major effects. High-voltage transmission lines create a barely-audible hum.
Aesthetic Disturbances	Mining Power generation Transmission	Aesthetic degradation due to mines, cooling tower plumes, transmission corridors.

[a]Main sources include Refs. 24, 103-105, 107, 109, 110, 112, 116, 120, 145-152.

Table 4.33 indicates the key areas of impact that have been identified. In the following sections, the principal areas of concern and the rationales for their selection are summarized.

4.4.3 Generation of Air Pollution

Air pollutants consisting of trace and toxic elements could be the major area of concern for coal, TPV, and SPS activities. Such emissions will arise in differing amounts from specific activities within each technology. Insufficient data exist for characterizing the type and quantity of trace

Table 4.33. Potential Severity^a of and Status of Knowledge^b about Key Environmental Welfare Issues

Environmental Impacts with Possible Welfare Effects	Conventional Coal		LWR		CG/CC		LMFBR		TPV		SPS		Fusion		Activities Causing Potentially Severe Welfare Effects
	PS	SK	PS	SK	PS	SK	PS	SK	PS	SK	PS	SK	PS	SK	
Air Pollution	1	B-C	2-3	B	1-2	B-C	2-3	B	1	C	1	C	2	C	Coal-fired power generation (toxic and secondary pollutants). Solar cell materials manufacture and SPS rocket launches.
Atmospheric Changes	1	B-C	4	B	1	B-C	4	B	3	B	3	B	4	B	Coal-fired power generation (CO_2 emissions).
Thermal Discharges	2	B	2	B	2	B	2	B	2	B	2	B	2	B	--
Water Pollution	1	B	1	B	1	B	2-3	B	1	C	1	C	2-3	C	Coal mining (underground). LWR fuel fabrication. Solar cell materials manufacture.
Water Use	2	B	2	B	2	B	2	B	3	B	3	C	2	C	--
Solid Waste	2-3	A	3	B	2-3	A	3	B	2-3	C	2-3	C	3-4	C	--
Land-Use Disturbances	1-2	A	1	B	1-2	A	1	B	1	B	1	B-C	1	C	Coal mining (surface). Nuclear waste disposal. Solar cell materials mining, SPS rocket launch and rectenna sites.
Electromagnetic Disturbances	3	B	3	B	3	B	3	B	3	B	1	B-C	3	B-C	SPS rectenna operation.
Microwave Radiation	4	B	4	B	4	B	4	B	4	B	1	C	4	B	SPS power transmission.
Ionizing Radiation	3	B	3	B	3	B	3	B	4	B	4	B	3	B-C	--
Noise	3	A	3	A	3	A	3	A	3	A	1	A	3	A	SPS rocket launch.
Aesthetic Disturbances	2	A	2	A	2	A	2	A	2	B	2	B	2	C	--

^{a}Potential Severity (PS) ranking is based on the most serious welfare effects of the activities within each fuel cycle. Potential severity is ranked according to the following criteria:

1 - Very significant contribution to welfare effects.   3 - Minor but measurable contribution to welfare effects.
2 - Significant contribution to welfare effects.   4 - Negligible contribution to welfare effects.

^{b}Status-of-knowledge (SK) ranking:
A - Issue thoroughly documented and understood.
B - Parts of issue understood, but gaps in knowledge exist.
C - Very little knowledge of issue exists.

emissions resulting from the solar cell manufacturing process and rocket launch activities. However, the potential exists for atmospheric emissions of gallium, arsenic, hydrogen sulfide, and other compounds during GaAlAs manufacture.[141]

Emissions of potentially hazardous trace metals are discharged into the atmosphere with the waste gases from combustion at coal-fired generating plants. Although the quantities emitted are small, their degree of enrichment in the flyash and their hazardous nature requires that this be considered an area for concern. Other coal-related emissions require attention: coal combustion emits primary SO_2 and NO_x, which are precursors of secondary sulfate and nitrate particles and have been implicated in acid precipitation and impairment of visibility. Lakes with reduced buffering capacity can acidify and deteriorate the aquatic environment, resulting in commercial and recreational losses. Degraded visibility may impair navigation and result in cancelled or delayed airline flights.

Emissions of regulated criteria pollutants from coal combustion (SO_2, NO_x, TSP, HC, CO), releases of cooling tower drift from coal and nuclear generating stations, and fluoride from nuclear fuel-conversion facilities are areas of moderate concern and are likely to be controlled to acceptable levels. However, these pollutants have been implicated in the physical damage to and reduced useful life of metals, building materials, and stone objects such as sculptures. Pollutants at elevated levels have affected the productivity, appearance, and yield of crops, thereby causing economic damage.

4.4.4 Climatic Changes Due to Air Pollution

The impact on global climate that is currently given the most attention is the global warming effect caused by increasing CO_2 levels in the atmosphere and the resulting "greenhouse effect." Atmospheric models predict that doubling of CO_2 levels above pre-industrial levels will produce a global average warming of 1° to 3°C.[153] This could occur as early as 2025, although noticeable warming should not be detected before 2000. Such a temperature increase may significantly affect precipitation patterns, agricultural production, energy use, and ocean levels through melting of polar ice.

Combustion of coal releases substantial amounts of CO_2 into the atmosphere (5×10^6 metric tons annually for a 1,000-MW power plant). Although this is not a local problem, coal combustion contributes significantly to the total man-made input of CO_2 into the atmosphere. Furthermore, coal combustion also releases amounts of other "greenhouse" gases such as SO_2 and H_2O, which appear to be of a less severe nature.

Another area of concern is the increase in global levels of atmospheric particles, which, depending on their location and optical properties, act to change the radiative properties of the earth-atmosphere system and effectively warm or cool the earth's surface. It has not been established whether or not the increase in atmospheric particle concentrations over the past century has produced a net warming or cooling effect. The direct emissions of particles from coal combustion, and emissions of gaseous species such as sulfur and nitrogen oxides which are converted to particles in the atmosphere, do not contribute significantly to global levels of atmospheric particles.[154]

The major emissions into the atmosphere from SPS activities will occur from rocket launches. Rocket effluents include substantial amounts of CO_2, but these emissions are at least 100 times smaller than the CO_2 emissions from coal combustion for an equivalent amount of system capacity.[153] The possibility exists for some upper-level clouds to be formed by H_2O injections into the mesosphere. The impacts of these clouds do not appear to be significant but are not well known at present. A slight depletion of the total ozone column due to emissions of H_2O and NO_x is possible but is not expected to affect global climate to a noticeable extent.[141]

The ability to reliably predict climatic change resulting from air pollution emissions is currently limited by several factors. There is considerable uncertainty concerning the extremely complex nature of the earth-atmosphere system and the interrelations between the various parts of the system. Insufficient knowledge hampers the prediction of how second-order coupled processes or "feedback mechanisms" might enhance or suppress a first-order effect on climate such as a surface warming due to CO_2. There is also uncertainty about the magnitude of the effect of other greenhouse gases and atmospheric particles compared to the CO_2 effect.[155] The role of natural climatic fluctuations in enhancing or masking trends due to man-made emissions further contributes to the uncertainty of predictions. It is expected that the ability to predict climatic change will improve with additional research; however, drastic improvements in forecast reliability are probably not to be expected in the near future because of the complexity of the problem.

4.4.5 Thermal Discharges and Resulting Climatic Change

Production of electrical energy results in the rejection of waste heat to the environment. A nuclear power plant with an efficiency of 32% releases two units of waste heat for each unit of heat used to produce electrical energy, as do coal- and oil-fired plants that operate on the Rankine cycle. However, with nuclear plants all of this waste heat is rejected to cooling towers. The impacts of this waste heat are local and dependent on the type of cooling technology, the amount of heat released, and the local ambient meteorological conditions. Most existing and all planned nuclear power plants employ cooling towers.[141] Most new and planned coal-fired plants also use cooling towers. Mechanical-draft cooling towers can produce an increase in local ground fog a few days per year within a few thousand feet of the towers. Some local icing may occur during the winter when the moist thermal plume contacts the ground. Production or enhancement of cloudiness in the vicinity of large cooling towers has also been observed.[156] In areas where these problems occur, technology is available at a moderate incremental cost to eliminate the adverse effects.

A relatively unlikely, but potentially significant impact could occur in the future if nuclear power plants are clustered into energy "parks." The large release rate of waste heat (e.g., 72,000 MWt from a 36,000 MWe power park) over an area of relatively small radius (10 to 100 km) could produce or enhance severe local weather events such as thunderstorms and hail.[157] Of the three nuclear options characterized here, the LMFBR has the lowest heat rate and fusion has the highest.

A coal-fired power plant is a little more efficient than a nuclear power plant (36% versus 34%). Thus, the local waste heat impacts for coal technologies should be smaller than those of nuclear technologies for a plant of equal size and similar cooling technology. In addition, the waste heat effects from coal-fired power plants are reduced because not all of the waste heat is emitted from the cooling tower. About 25% of the total waste heat of a coal-fired plant is emitted from the stack.

The SPS rectenna will release waste heat with a density of 7.5 W/m^2 over a 100 km^2 area. This is an energy density of about 10% of the average net solar radiation at the earth's surface. In conditions of light winds, temperature perturbations of as much as $1°C$ could occur in the vicinity of the rectenna.[158] Changes in cloudiness near an SPS rectenna or a TPV so`˚ collector area could occur, but an impact on precipitation distribution seems unlikely.

4.4.6 Water Pollution

Insufficient information concerning the solar cell manufacturing process precludes an accurate assessment of the severity of water-polluting emissions from this activity. However, the toxicity of the raw materials and the possibility of accumulation in the environment warrants further attention. With data currently available, it is not possible to identify specific water pollution problems or effects that could occur during normal operation. However, it is possible that water pollution may result from SPS launches, SPS rectenna construction runoff, and TPV construction runoff.

Acid mine drainage from underground coal mining activity is an impact of concern, and in the past such drainage has degraded many eastern waterways. Acid-contaminated waters endanger aquatic populations by altering species type, diversity, and quantity, thereby limiting commercial and recreational opportunities. Various federal and state programs have instituted water quality criteria, effluent limitations, and reclamation requirements to control the problems associated with mining activity. There is controversy over the ability of these laws to achieve the desired effect. LMFBR and fusion technologies require minimal mining activities by comparison, hence significantly smaller environmental welfare effects.

LWR fuel fabrication is also an area of concern although a minor one. Existing plants have occasionally discharged ammonia, nitrates, and fluorides into low-flow streams, thereby reducing the quality of the water.

4.4.7 Water Use Changes

Heavy consumption of water is treated in Sec. 4.5 as a resource issue. However, heavy use of water can decrease the amount of water available downstream for dilution and therefore can be a welfare issue as well. Mining operations can disrupt aquifers, resulting in lowering of the ground water table and alteration of water flow patterns, which could affect crop irrigation. Wet cooling towers at coal or nuclear power stations can consume large quantities of water. Technologies that do not consume water could be utilized in areas where water is scarce. During the LWR fuel cycle, the production of

uranium hexafluoride and enriched uranium (gaseous diffusion process) also requires heavy consumption of water.

4.4.8 Generation of Solid Waste

The impact of solid waste generation cannot be entirely separated from land use issues. However, small amounts of waste can have large impacts on future land use when the nature of the waste affects the disposition of the land into which it is placed. Issues concerned with the quantity of land necessary for the disposal of solid waste are treated in Sec. 4.4 as a land-resource issue.

Manufacture of the GaAlAs solar cell will produce 2×10^7 metric tons of aluminum oxide waste for each 5-GW satellite produced. This quantity of waste could present a disposal problem if al' cells were manufactured at a single facility. Aluminum oxide does have commercial value for other purposes, which could lessen the impact of its disposal. Similar uncertainties exist for the manufacture of silicon cells for the TPV system.

A 1,250 MW conventional coal power plant using Wellman-Lord SO_2 removal will produce about 5×10^5 metric tons of solid waste and sludges annually. CG/CC plants will produce about 20% less solid wastes and sludges. The quantity of waste leaving the power plant site will vary depending on the availability of land for on-site disposal. Procedures for returning these areas to productive use are available but are not mandated. Regulations governing the toxic nature of these wastes are currently being considered.

Modest amounts of solid and liquid waste are generated in support of the LWR power cycle. However, most of these activities generate radioactive waste that must either be sent off site for commercial burial or buried on site. Among these wastes are:

- 500 metric tons per facility per year of uranium hexa-fluoride-process effluents consisting of iron, calcium, magnesium, copper, and nonvolatile f'.uorides (shipped off site).

- 90 metric tons per facility per year of enrichment-cleanup sludge consisting of mostly settleable solids, precipitated metals and soil runoff (retained on site).

- 700 metric tons per facility per year of calcium fluoride from fuel-fabrication activities (generally retained on site).

- Numerous liquid and solid radwastes that are released through fission product leakage, activation of chemical inhibitors, reactor purification procedures and spent reactor parts (shipped off site).

- Spent reactor fuel shipped to the reprocessing center.

Large amounts of mine and mill tailings should not present any specific problem since they are often used as backfill and retained on site. However, inadequate precautionary measures have, on occasion, permitted low-level

radioactive tailings to enter the environment. LMFBR and fusion technologies would have significantly fewer environmental welfare impacts in this area due to minimal mining requirements. LMFBRs could obtain fuel from LWR tailings for many years.

Coal, nuclear, and solar technologies each require the extraction of conventional materials, such as steel and aluminum. These activities will not produce any unique problems with respect to solid waste generation.

4.4.9 Land Use Changes

The quantity of land removed from public use and the permanent isolation of land are not considered here since these are principally resource issues. Additional questions c ncerning changes in land use remain. Mining operations for fuel and materials have the potential of contaminating or eroding other land areas. Reclamation of mined areas may not be entirely effective in returning the land to its formerly productive state. Reclamation of mined areas in arid climates such as the southwestern U.S. is difficult. Proper operation and reclamation techniques should reduce the level of concern.

Electromagnetic interference with communication systems near the SPS rectenna location has the potential for limiting the type and diversity of land use activities around the site; although it is conceptually possible to mitigate these effects, specific measures and cost estimates are currently unavailable. The removal of large land areas from public use, because of the presence of the rectenna, will inconvenience persons having to drive around the site; a similar problem will occur if the rectenna site is near a navigable waterway.

4.4.10 Noise Generation

The major noise disturbances (noise exceeding 60-80 dBa, 24-h weighted average) will be from SPS rocket launch operations,[141] and will likely exceed EPA recommended 24-h, time-averaged noise standards and elevate noise levels in surrounding communities to a distance of 30 km. Launches are projected to occur several times a day. Sonic booms during launch and reentry operation will elevate noise levels to a lesser degree. Elevated noise levels near residential areas could lead to depressed property values. These effects could be mitigated by launching far from populated areas.

Coal and nuclear mining and power generation have a moderate noise impact. Noise from power production arises from cooling tower fans and plant support activities. Blasting and drilling during mining may also elevate noise levels in the immediate vicinity. Noise measurements assessed at the property line in most cases are not expected to be significant, and use of a buffer zone between the noise source and the property line frequently serves as a mitigation technique.

Another source of noise that is common to the energy technologies will occur during rail transport of fuels and materials. Transmission line noise is only barely audible with 345 kV AC lines but increases with the use of higher-voltage lines.

4.4.11 Electromagnetic Disturbances

Significant electromagnetic disturbances from the SPS may occur from microwave coupling with electronic systems at distances of up to 100 km from the rectenna site.[141] Functional degradation can affect military radar, law enforcement, emergency, and utility communications, and other susceptible systems. However, it is anticipated that modifications (currently undefined both technically and from a cost point of view) could be made to these systems to mitigate these effects.

Other electromagnetic disturbances related to SPS activities may be anticipated. Rocket effluents may induce ionospheric alterations that may affect communication systems relying on the ionosphere. Debris clouds consisting of orbiting gaseous and particulate effluents could interfere with radioastronomy and radionavigation. The likelihood and severity of these occurrences is unknown but is currently under investigation in the environmental assessment of the SPS.[141]

High-intensity electromagnetic fields generated around power transmission lines have, in some instances, caused radio and TV disturbances in fringe reception areas. This effect is thought to be of minor concern. However, it is common to all centralized energy technologies and is likely to increase with the higher transmission-line voltages.

4.4.12 Radioactive Emissions

Radiation releases containing trace radioactive materials result from the burning of fossil fuels[123] and all other activities in the nuclear fuel cycle.[20,117] SPS activities do not result in emission of ionizing radiation.

The study of airborne radioactive particles from coal combustion has not been comprehensive. Radioactive effluents originate in coal and are emitted with the stack gases. Uranium, thorium, and radon constitute the radioactive emissions of coal combustion, which may release on the order of 1.2 Ci annually, depending on the nuclide concentration in the coal seam. Radioactive airborne releases from a 1,250-MW coal plant are considerably below the amount resulting from a comparably-sized boiling water reactor. Standards limiting radioactive emissions from fossil-fueled power plants do not currently exist but could be promulgated under the Federal Clean Air Act Amendments of 1977.

Low-level radiation emissions from routine operation of nuclear power facilities are greatest during power generation and milling activities. In addition, fuel reprocessing is required by the LMFBR, and causes the release of larger amounts of radionuclides, primarily krypton, than would be released from an LMFBR power plant. The use of exclusion zones around nuclear facilities reduces the off-site exposure. Radiation emissions are below the levels established by federal Nuclear Regulatory Commission regulations (10 CFR* 20, 10 CFR 50), and are characterized as having low welfare impact. However, the radiation threshold level beneath which an effect will not be observed is uncertain, and therefore these standards are being reexamined.

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*Code of Federal Regulations

4.4.13 Microwave Radiation

Microwave radiation levels will be elevated in the vicinity of the SPS rectenna station. Levels within the exclusion zone will be as high as 23 mW/cm^2. Levels below 0.1 mW/cm^2 will be experienced beyond the exclusion zone.[1]

Limited information exists regarding the direct impact of microwave radiation on biological systems. All of the information that is available relates to high-level microwave exposures.[141] Although the likelihood of occurrence of microwave effects is unknown, the potential severity could be significant. Microwave exposure may alter the mortality, reproduction, and behavior of birds, invertebrates, and beneficial insects. Disturbances of pollinization by bees could affect food supplies and is currently under study.[141] Direct microwave exposure could increase the susceptibility of crops to environmental stress such as drought, resulting in decreased yields. Birds relying on the earth's magnetic field for navigation may show altered migration patterns.[141] Judicious siting may reduce the extent of impact from microwave exposure.

4.4.14 Aesthetic Disturbances

Direct aesthetic impacts are site-specific, and the extent of these disturbances can be moderated by avoiding archaeological, cultural, and historical areas, protected scenic and recreational areas, and habitats of rare and endangered species during the siting process. Other types of aesthetic degradation may arise from unsightly mines; visually disturbed areas, e.g., facilities sited in rural areas; transmission corridors; visible cooling tower and stack plumes and plume shadows; and noise-producing operations.

The aesthetic impacts of satellite operation include the brightness of the satellites visible in the night sky. The diffuse glare from reradiated light may also interfere with optical astronomy.

4.5 RESOURCES

This section summarizes the comparative assessment of five resources -- land, materials, energy, water, and labor. The materials, energy, and labor assessments include only a side-by-side analysis; for land and water, the assessments include an alternative futures perspective using the results of the scenario analysis described earlier in Sec. 4.1.

Seven technologies are compared with regard to the land and water issues, which are considered to be the most important resource issues. Conventional coal with flue gas desulfurization, LWR, CG/CC, LMFBR, TPV, SPS, and fusion were the technologies compared for these issues, and subsets of this group were compared for the other issue areas.

The essential ingredient of the alternative futures analysis for land and water use is energy supply, by technology, through the year 2030. These data (baseload capacities), produced as part of the scenario development, are

listed in Tables 4.7 through 4.9 in Sec. 4.1. Each of the three scenarios CI, UI, and UH is considered under two conditions: (1) excluding the SPS from the energy supply system, and (2) including the SPS after 2000.

Results of the side-by-side analysis are listed qualitatively in Table 4.34. Details of these results, as well as those of the alternative futures analysis, are presented in the following sections.

4.5.1 Land

Overview. Land requirements were developed as part of the energy systems characterizations summarized in Sec. 3. These data were then normalized and compared on a side-by-side basis, by computing the amount of land required to obtain 1,000 MW of installed capacity. Both plant site and annual fuel cycle requirements were considered. Another side-by-side comparison was made on the basis of land per unit energy. This comparison accounted for load factor and, in the case of TPV, average daily insolation. Next, the scenario data were brought into the analysis to determine total land requirements for baseload electrical generation for the period 1980-2030. The 1980 figures provide a frame of reference for the differing results of the three scenarios (CI, UI, and UH) with and without inclusion of the SPS in the energy supply system.

Transmission requirements were not included in any of the calculations because they have been shown to be about the same for all technologies, particularly in view of studies showing that 60 SPS rectennas can be sited within 500 km of a load center.

Side-by-side results show that the solar options (TPV and the SPS) require very large, contiguous land areas. TPV could be deployed in smaller units (with the question of economic effects left unanswered), mitigating the requirement for contiguous land. On the basis of land per unit energy, TPV requires about three times as much land as the SPS, whereas coal requires about half the land of the SPS, and the nuclear options are about a factor of 10 lower than the SPS in this regard.

Scenario results indicate that total land use (excluding transmission) increases 0-500% without SPS and 100-900% with SPS by the year 2030. Over the same period of time, baseload capacity increases 90-800%. SPS land requirements for the year 2030 are about 2-5 times the total land in use today for baseload electrical generation. In all cases, the low figures result from scenario CI and the high figures result from scenario UH; results for scenario UI fall between these values.

Side-by-Side Comparisons. The energy technology characterizations of Sec. 3 provide the plant and fuel cycle requirements. The latter are significant only for coal (conventional coal and CG/CC are very similar and are aggregated for the calculations in this section) and the LWR. Assuming that land disrupted during the fuel cycle is restored in six years, the land use estimates are as listed in Table 4.35.

Table 4.34 Side-by-Side Comparative Assessments: Resources

Resource	Conventional Coal	LWR	CG/CC	LMFBR	TPV	SPS	Fusion
Land	Small plant requirements Mining impacts are the main problem	Small plant requirements Some mining impacts	Small plant requirements Slightly less mining impacts than conventional coal	Smaller impacts than LWR due to smaller mining requirements	Large land areas required for solar collectors	Large, contiguous rectenna sites	Small plant requirements
Materials	Good supply of coal	Uranium supply is limited	Good supply of coal	More efficient use of uranium supply than LWR	Seven potential problem materials identified	Three problem materials identified (mercury, tungsten, gallium)	Lithium supply could be a constraint
Energy	Payback about on year	Payback about one year	Payback about one year	Payback about one year	Payback[a] for Si system about 19 years High energy intensity of cell production	Payback for Si about six years; Ga about one year Less sensitive to energy intensity of cells	Not evaluated
Water	Contamination due to coal mining	Small cooling losses	Mining impacts smaller than those of conventional coal Small cooling losses	Small cooling losses	No impact Negligible water use	No impact Negligible water use	Comparable to LWR
Labor Requirements	Skills available today	Small but highly-skilled operations and maintenance force	Skills available today	Small but highly-skilled operations and maintenance force	Skills readily available	Space construction requires new and highly-skilled work force	Construction requirements similar to LMFBR

aImproved cell efficiency and/or production energy requirements would reduce payback significantly.

Table 4.35 Land Requirements, by Technology, in km^2 per GW of Installed Capacity

Technology	Plant	Fuel Cycle	Total
Coal	2	8	10
LWR	2	1	3
LMFBR	2	0	2
TPV	20	0	20
SPS	30	0	30
Fusion	2	0	2

Fuel cycle figures reflect the fact that LWR activities disrupt about one-eighth the land disrupted for coal technologies. For the remaining technologies, fuel cycle activities result in negligible land disruption. The land area needed for ʲ ʳposal of nuclear waste is negligible (less than 5% of that required for the ᵣₗant). In the case of coal, fuel cycle activities at any point in time will have disrupted about four times as much land as that required for the plant, assuming that a 6-year land reclamation program has been successfully implemented.

To obtain results in terms of land per unit energy output, the operating factor (accounting for availability, load factor, and insolation for TPV) must be specified. These factors, along with the land requirements in km^2/GW-yr, based on a 30-year life for each technology, are listed in Table 4.36. The operating factor for TPV represents an average figure for the two locations (Phoenix and Cleveland) considered in the technology characterizations.

The results of Table 4.36 indicate that only one comparison changes: although SPS requires the most land on an installed-capacity basis, TPV requires the most land on the basis of energy output. One reason for this is the limited number of hours per day that insolation is available.

Alternative Futures Comparison. Demand data have been listed in Tables 4.7 through 4.9 in Sec. 4.1. These data, plus the land requirements data in Table 4.35, can be used to estimate total land requirements. These results are shown for individual scenarios in Figs. 4.34 through 4.39. Figure 4.40 illustrates the overall land requirements for all scenarios.

Table 4.36 Land Requirements per Unit Energy Output

Technology	km^2/GW	Operating Factor	m^2/GW-yr
Coal	10	0.70	450
LWR	3	0.70	130
LMFBR	2	0.70	100
TPV	20	0.22	3000
SPS	30	0.90	1100
Fusion	2	0.70	100
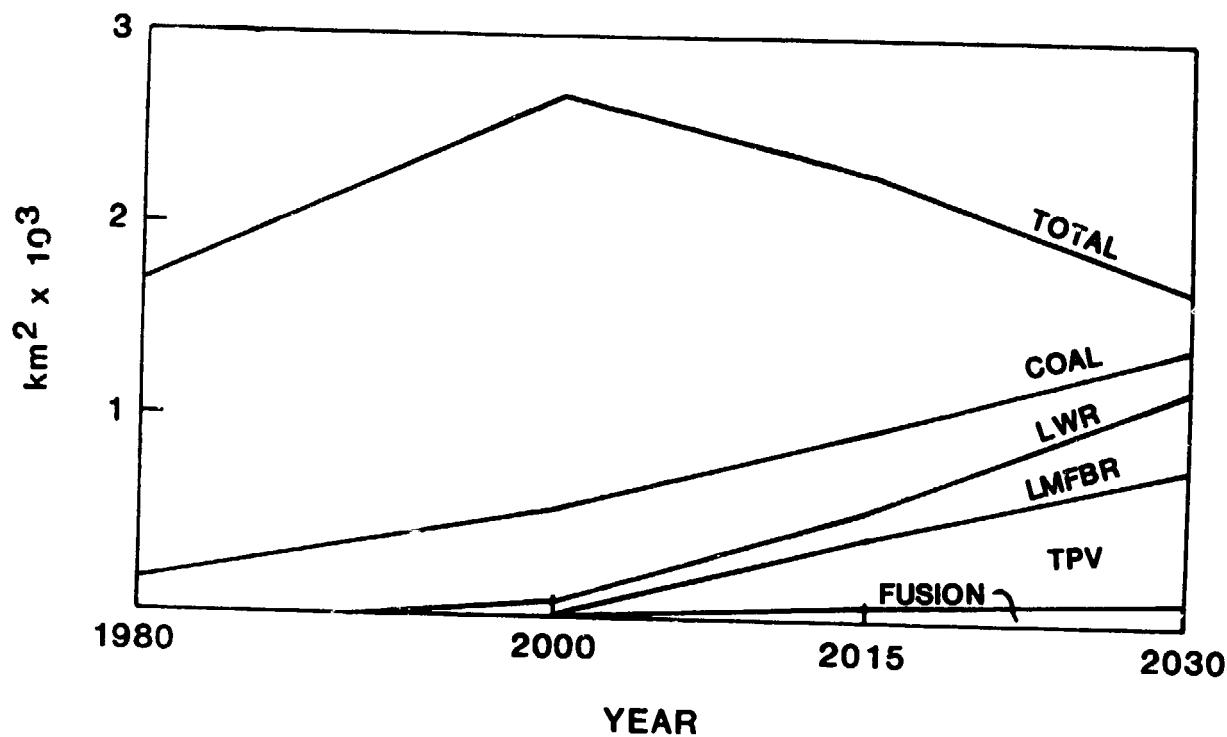
Fig. 4.34   Land Requirements for Scenario CI, without SPS
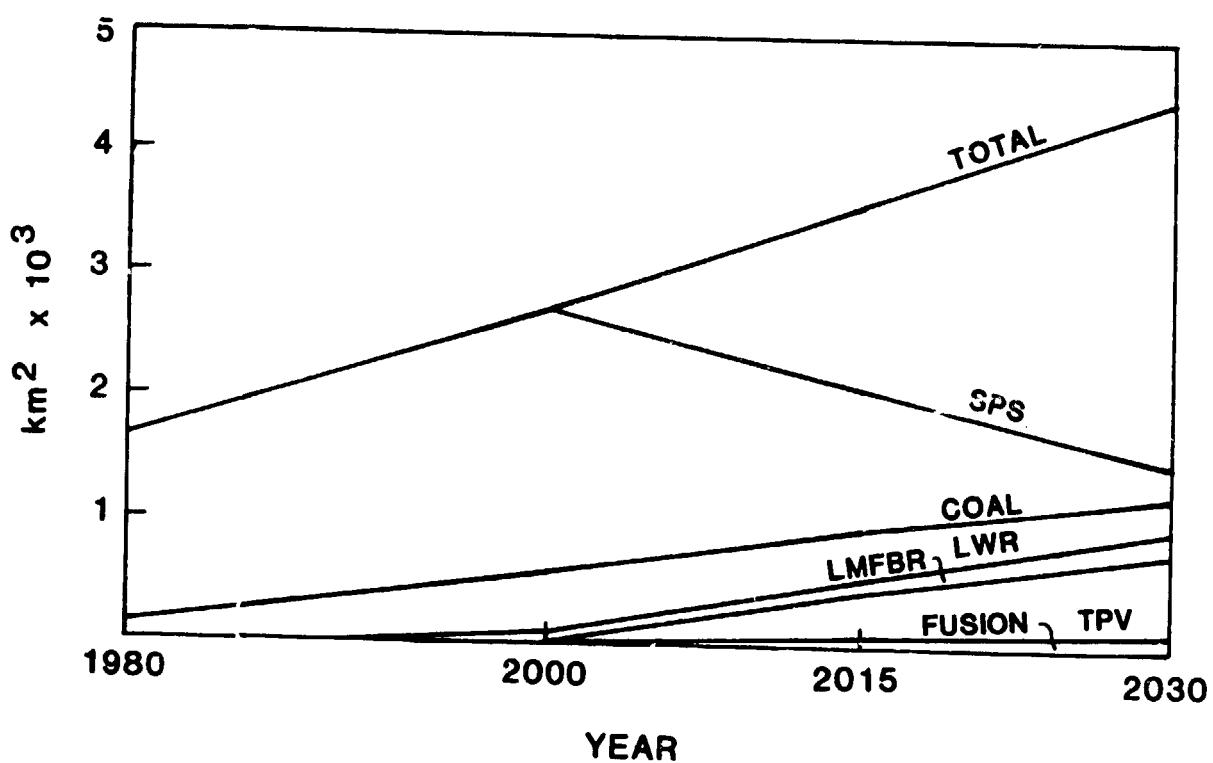
Fig. 4.35   Land Requirements for Scenario CI, with SPS
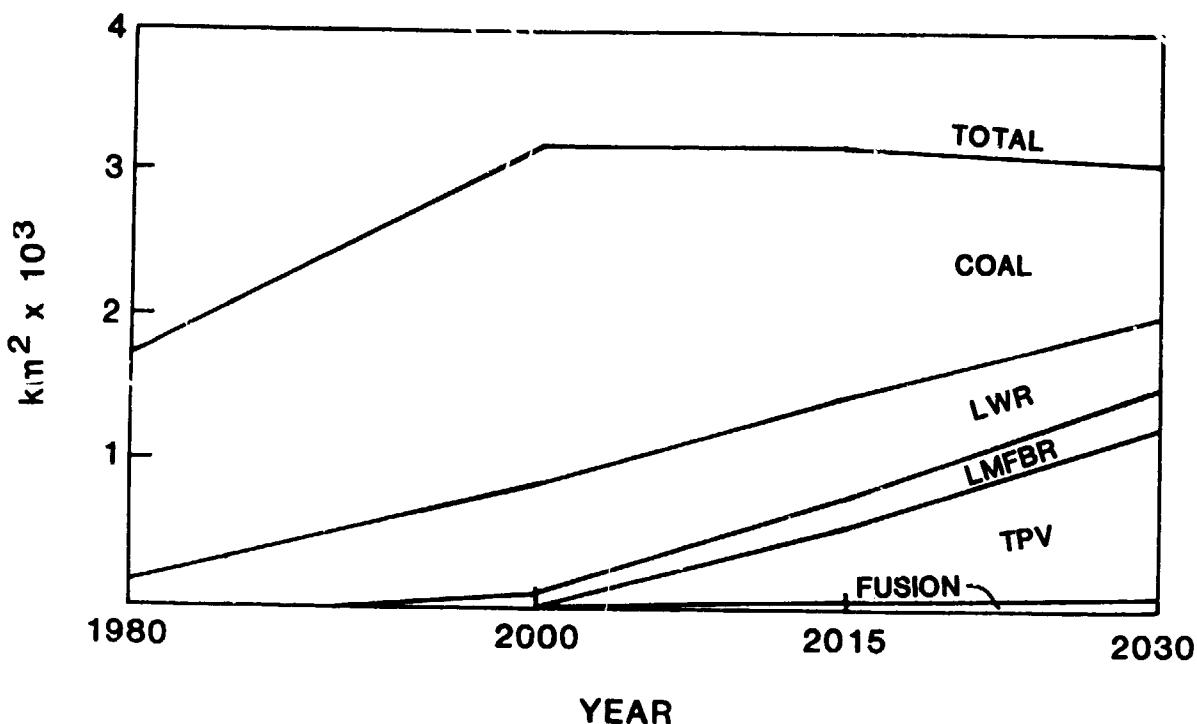
Fig. 4.36 Land Requirements for Scenario UI, without SPS
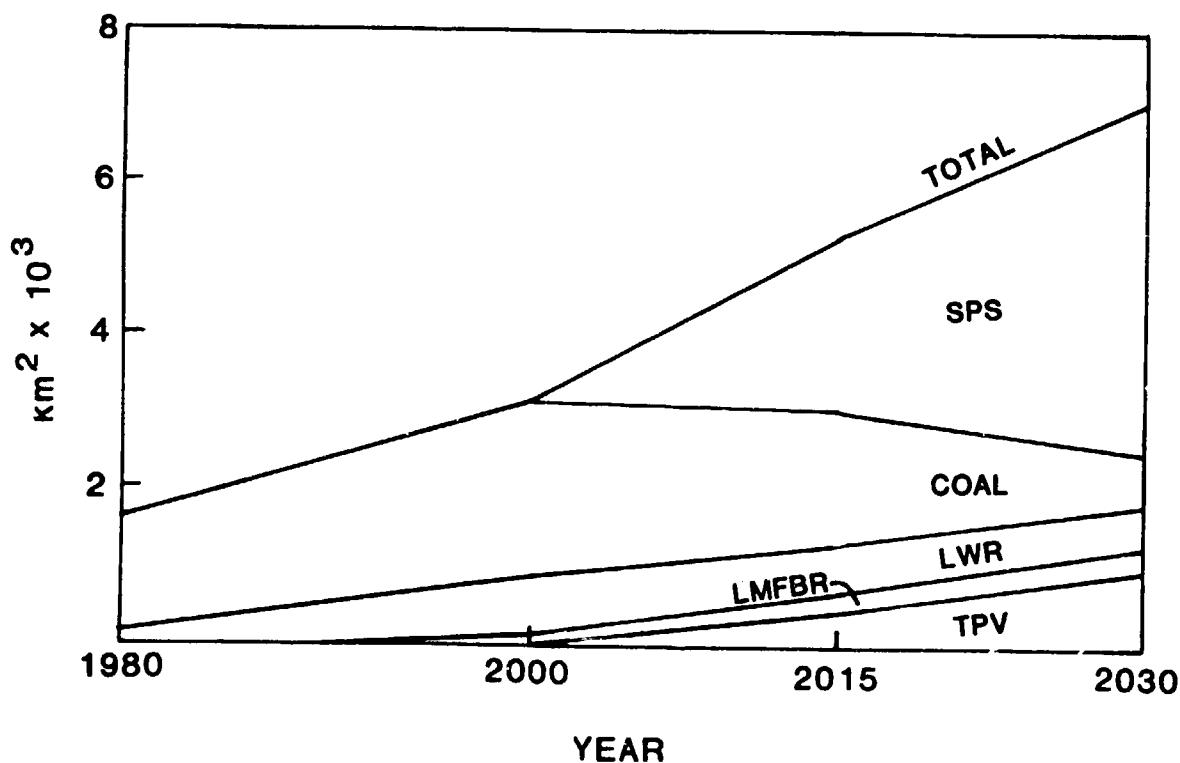
Fig. 4.37 Land Requirements for Scenario UI, with SPS
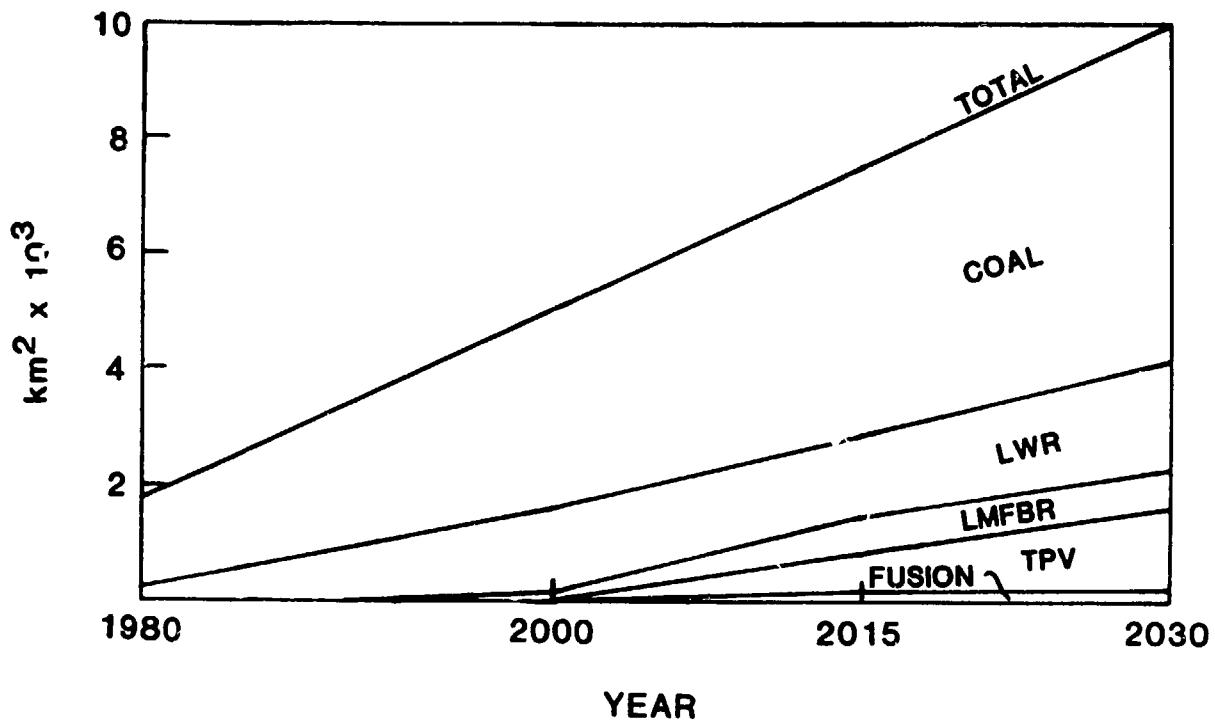
Fig. 4.38   Land Requirements for Scenario UH, without SPS
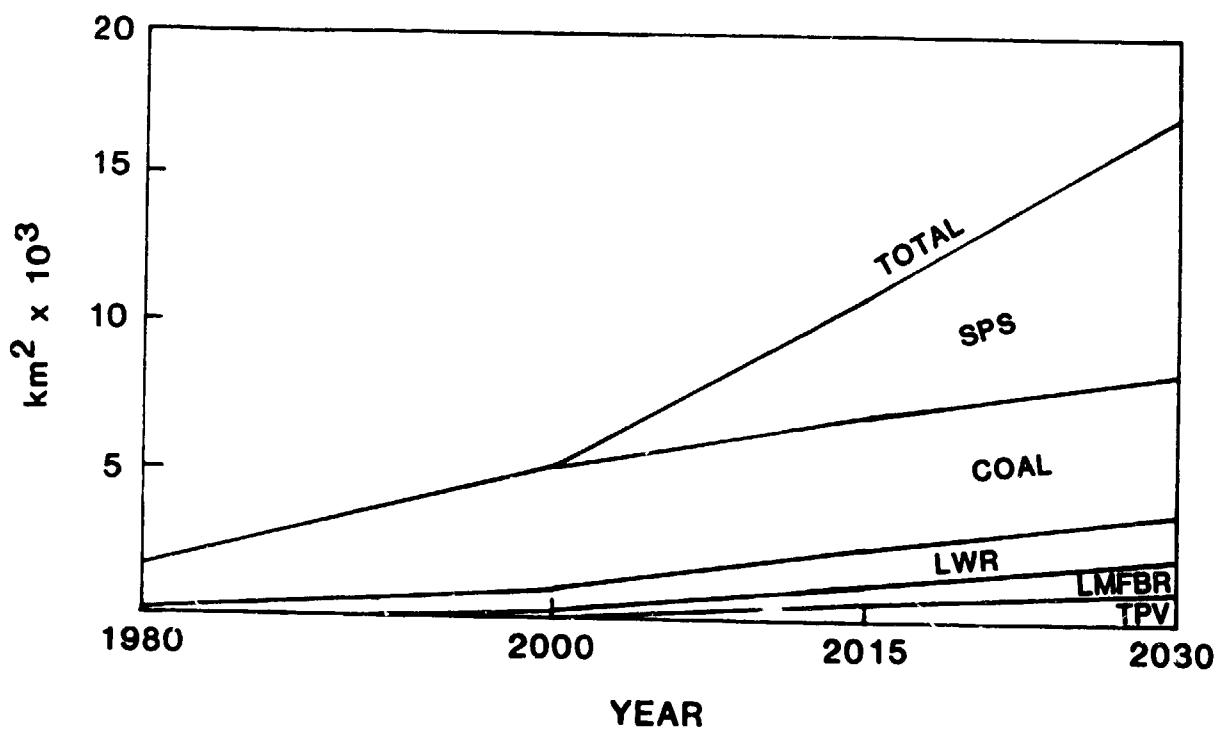
Fig. 4.39   Land Requirements for Scenario UH, with SPS
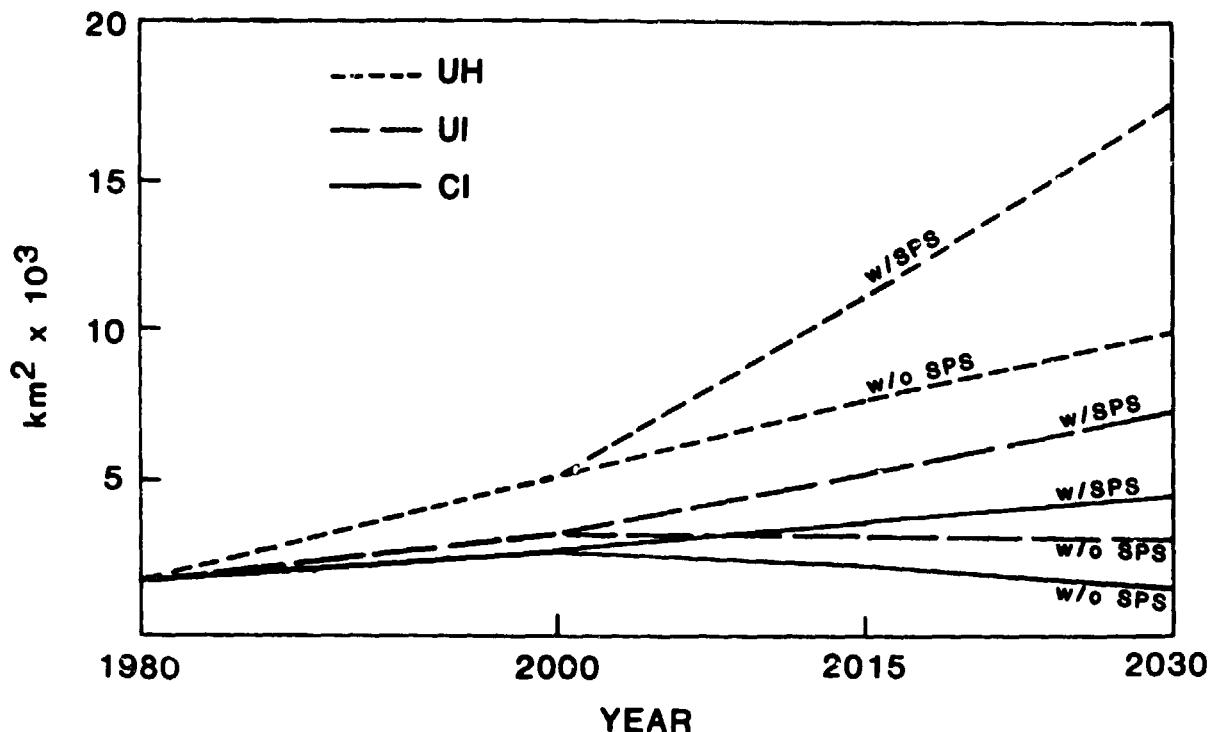
Fig. 4.40 Alternative Futures Analysis of Land Requirements

Observations. An unconstrained energy future with high energy inten-
siveness will likely result in much larger land requirements than used today.
With SPS deployment, land requirements go up even higher. If TPV were to be
deployed at a higher rate, further increases would be required. Without
deploying SPS, it may be possible to keep land requirements for baseload
energy production within a factor of two of today's requirements if lower
energy intensiveness prevails.

In scenario CI, considered to be the most likely, deployment of SPS
would itself result in the use of about 75% more land than the 1980 estimate
for all technologies. Without SPS, the 1980 and 2030 figures are about equal
in that scenario.

This analysis does not address the issue of acquisition of the needed
land areas. Acquisiton may prove to be a difficult constraint in the case of
the SPS, which requires large amounts of contiguous land in the current
baseline design. A mitigating strategy is to reduce the size of the rectenna,
which would decrease the installed capacity if power densities cannot be
increased appropriately.

Since the question of land use is likely to play an important role in
the siting of future energy technologies, the effects of SPS deployment and/or
highly energy-intensive economies must not be overlooked.

4.5.2 Materials

The objective of the materials analysis was to assess potential materials problems by identifying the types and quantities of materials required by the SPS and alternative technologies. Defining materials problems is not simple; many important factors should be included: resources, reserves, production capacity, import dependence, price, and opportunity costs.

The possibility of resource and/or reserve constraints depends on market penetration scenarios. Domestic production factors include current capacity, normal growth rate, and required growth rate to meet a given demand level. If domestic supplies of a material are inadequate, the balance must come from foreign markets; consequently, the possibility of cartels and the effects on the U.S. balance of trade must be considered. Since price is influenced by supply and demand, the possible effects of large increases in supply or demand must be investigated. If a material is largely used by a single energy technology, opportunity costs result from the limited use of the resource for other purposes. The possibility of substitute materials becomes an important issue for any materials judged to be a potential problem.

This comparative assessment is based on available research. In general, conclusions about materials problems published in the open literature were not based on rigorous considerations of the above-mentioned criteria. Thus there is a lack of uniformity in conclusions from technology to technology because the assessments were done by different researchers. Where possible, an attempt was made to reconcile these differences for this assessment.

Sources include environmental impact statements,[23,159] system designs,[137,160,161] system descriptions,[139,162] federal documents,[163, 165] and comparative studies.[90,166-168]

The present comparison focuses on three screening criteria: Import dependence, availability (resources/reserves), and demand. Table 4.37 summarizes potential materials problems, by technology, for the three screening criteria. There are two materials that raise all three flags: gallium and tungsten. Gallium is used for the SPS, and tungsten is used for both coal and the SPS. A number of materials raise the import dependence flag, probably the most important from a national security point of view. Nine SPS materials are indicated for reasons of import dependence.

Because of the lack of complete and highly reliable materials data, a scenario perspective was not explicitly attempted for materials. Thus, the assessment has proceeded only to a qualitative side-by-side level.

4.5.3 Energy

Objective. The objective of the net energy analysis[169] was to provide a comparison of the net energy requirements of the SPS (silicon and GaAlAs solar cells) and alternative energy supply systems (CG/CC, LWR, and TPV with silicon solar cells). Conventional energy systems provide substantially more energy than was required to put them into operation, and so the concept of net

Table 4.37 Potential Materials Problems, by Technology,
for Three Screening Criteria

	Coal	LWR	LMFBR	TPV	SPS	Fusion
Aluminum					△	
Antimony		△				
Carbon Steel	○	○	○	○	○	○
Chromium	△	△□	△□			△□
Cobalt	△					
Gallium					△□ ○	
GFRTP[a]					○	
Lithium						○
Manganese		△	△		△	△
Mercury					△□	
Molybdenum		□	□			□
Nickel	△□	△□	△□	△□	△□	△□
Silicon				○	○	
Silver					△□	
Titanium					△ ○	△ □
Tungsten	△□ ○				△□ ○	
Zinc			△	△□	△	△

KEY: △ Import Dependence   □ Availability   ○ High Demand
[a]Graphite Fiber Reinforced Thermoplastic.

energy analysis was not important to the decision-making process. Advanced
technologies, however, require more energy investment to recover each unit of
usable energy, and so the net energy assessment becomes a more important
decision parameter.

Approach. This preliminary analysis considers state-of-the-art (circa
1985) capabilities for materials extraction and fabrication in order to
identify critical areas needing improvement. The possibility of technological
improvements was considered in a number of key areas. The energy content of
the fuel is not considered.

The boundary of each energy system was defined as extending from
the primary resource (coal, uranium, and solar radiation) to electricity
transmitted from the generating plant. The boundary includes environmental
control systems and procedures to the extent that they are directly attrib-
utable to the energy system. Materials, fuels, and electricity required for
plant construction and operation are also considered.

A combination of process analysis and input/output analysis was used to compute the energy balance parameters for each supply system. Process analysis involves a detailed balance of energy flows into and out of a system. It is the most accurate and most involved method and can be applied to situations where a great deal of process-specific information exists. Input/output (I/O) analysis uses an analogy to economic input/output analysis to determine the energy "costs" of any energy supply. It involves an identification of the interactions between sectors of the economy required to produce energy and a translation of the flow of goods and services among sectors into energy equivalents.

Each of the systems chosen for evaluation is 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 is described in Fig. 4.41. 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 required to keep the process operating. The gross output is the energy or processed fuel that results from the system element. A portion of this gross output may be used to meet internal energy requirements. 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 the inputs.

Up to this point, a straightforward energy balance can be carried out since all quantities of materials and their energy contents can be directly computed. This is the extent of the process analysis used in this assessment.

The indirect energy requirements of the system are embodied in the capital energy inputs, i.e., the materials, fuels, and electricity required to build the system element, and in the energy required to supply the electricity, fuels, and materials for operating inputs. A simplified analysis was used to compute direct energy requirements during this phase of the analysis.
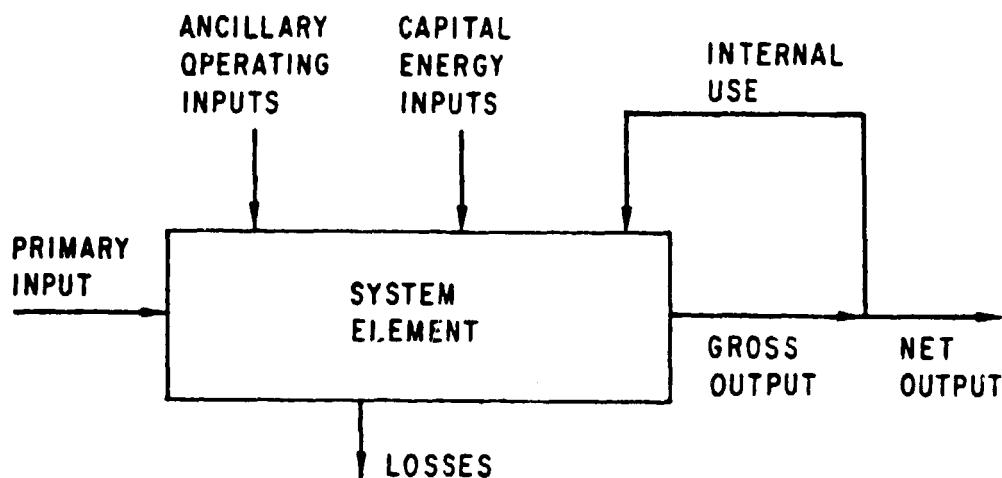

Fig. 4.41 Schematic of Energy Balance

For each system element the quantities of materials, fuels, and electricity required to build and operate the system were compiled with the aid of published data on energy requirements[170-173] expressed either in joules per ton of materials or joules per dollar of material cost. The physical material quantity or material cost is converted into an energy requirement equivalent.

Energy Balance Parameters. A number of energy balance parameters were calculated, including gross efficiency, operating efficiency, operating ratio, lifetime efficiency, lifetime ratio, and payback period. Gross efficiency measures the amount of energy delivered per unit of input energy. Operating efficiency is a more complete measure of how effectively the basic energy resource is being utilized, i.e., how efficiently a given technology extracts useful energy from a primary energy form. The operating ratio eliminates the energy content of the primary resource from the 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 into usable form. The lifetime efficiency and lifetime ratio are analogous to the operating efficiency and operating ratio. They include the capital energy investment in the balance process, which represents the energy required to construct the system. Payback period is the time required for the system to produce enough useful energy to match the energy investment in building and operating it. All of these parameters must be considered because the efficiency and payback calculations tend to be better for the coal and nuclear systems than for the solar energy systems, whereas the operating ratio and lifetime ratio calculations tend to be better for the solar-based systems than for the coal and nuclear systems.

Annual and lifetime net outputs are computed in terms of electrical units. All inputs are computed in thermal units but do not consider the thermal energy content of the fuels or materials involved, only the energy expended on such activities as mining, processing, and transportation. These are the usual conventions for doing a net energy analysis. Thus, this approach represents a short-term view of the use of a nonrenewable resource base; for example, in computing payback, the interest is in determining at what rate an energy system returns electrical energy, given the investments (inputs) required. It does not consider the issue of depletion of a nonrenewable resource base, which must be addressed as a lost opportunity issue for alternative uses of the resource. Furthermore, if the thermal content of a nonrenewable resource were considered, the payback period for systems based on nonrenewable resources would be infinite, by the second law of thermodynamics.

Results. Table 4.38 summarizes the baseline calculations. The coal and nuclear* systems are two to five times more efficient than the solar systems but operate on nonrenewable resources. The calculation of efficiency

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*Of the nuclear systems, only the LWR was studied in detail. The LMFBR, although it has higher capital energy costs, should at least break even due to lower fuel energy costs. LMFBR fuel is produced by chemical separation, which is less energy intensive than the diffusion process needed to enrich fuel for the LWR.

Table 4.38 Summary of Energy Balance Data

Parameter	Nuclear LWR	Coal CG/CC	Terrestrial Solar Photovoltaic Silicon	SPS Silicon	SPS GaAlAs
Gross Efficiency[a] (%)	22	37	6	7	7
Operating Efficiency[b] (%)	20	33	6	7	7
Operating Ratio[c]	3	4	27	17	78
Lifetime Efficiency[d] (%)	20	33	5	7	7
Lifetime Ratio[e]	3	3	1	4	18
Payback Period[f] (yr)	1	1	20	6	1

Source: Ref. 130.

[a]Annual net output/annual primary input.

[b]Annual net output/annual primary, operating, and internal inputs.

[c]Annual net output/annual operating and internal inputs.

[d]Lifetime net output/lifetime primary, operating, and internal inputs.

[e]Lifetime net output/lifetime operating, internal inputs, and capital inputs.

[f]Time at which net output equals operating + capital inputs.

for each system is not sensitive to the gross, operating, or lifetime calculations. The conversion efficiency of the system dominates the result.

The operating ratio calculation shows that the solar energy systems require substantially less operating energy per unit of electrical output. However, the lifetime ratio calculation shows that the intensive capital investment reduces their energy ratios significantly. The payback period for all systems except SPS/Si and terrestrial photovoltaic is less than 1.5 years. In both of these cases, sensitivity analysis shows that long payback is dominated by the energy intensity of silicon production. A number of possibilities, including reduction in the overall energy requirements of cell production, the use of solar-generated electricity in place of conventional electrical power for cell manufacture, increased cell lifetime, and decreased silicon requirements could reduce the SPS/Si payback period to a level comparable to the other systems (i.e., one to two years); the best combination of conditions for the terrestrial photovoltaic system would still result in a payback of about six years.[169]

Comparison to Other Studies. The comparison of these SPS results with those of previous studies is of particular interest. Direct comparison is difficult because each study is based on a different reference design and methodology. Some approximate comparisons can be made however, noting the major sources of difference.

A Planning Research Corporation study[174] used I/O analysis of a GaAlAs SPS. The study assumed higher energy intensiveness and resulted in a 2.5 year payback (vs. 1.3 years calculated here).

Herendeen[172] used I/O analysis and uncertainty to set a range for the lifetime ratio from 0.7 to 6.6, with a mean of 2.1, for a 10-GW SPS. This is surprisingly close to our result of 4.0, considering major differences in the assumption about silicon cell life. Herendeen assumed an exponentially decreasing cell power output over a 30-year lifetime. This analysis assumes maintenance to obtain constant power output and a 30-year life.

A Jet Propulsion Laboratory (JPL) study[171] computed a payback period in the range of 1.2 to 1.6 years for a system of 48 10-GW silicon satellites (vs. 6.4 years here). Three major factors account for the difference in the estimates. JPL assumes a reduction in the requirements for silicon cell production to about one-fourth of the energy requirements assumed here, and only half as much silicon. Most important, JPL converts electrical energy to a thermal equivalent by multiplying by a factor of three. Removing only this last difference results in a payback of 3.6 to 4.8 years for the JPL study.

Summary. The current state of knowledge indicates that energy balance is not a significant factor precluding the development of certain coal, nuclear, and satellite power systems. There are indications that reductions in energy requirements for silicon cell production will be needed, since those requirements constitute a large factor in net energy calculation for silicon systems. In addition, although current data indicate that GaAlAs cells provide a viable alternative, further studies are warranted because information on the energy requirements of these cells is extremely limited.

In conclusion, the net energy analysis has shown that the SPS system with silicon cells is a viable alternative, having a payback period substantially smaller than its lifetime; a TPV system using silicon cells does not look as attractive. However, if the most optimistic projections were realized for silicon cell production, the TPV option would become a viable alternative from an energy-balance perspective.

If development of a gallium photocell proceeds as currently projected, an SPS system with GaAlAs cells will result in a payback period comparable to CG/CC and nuclear. In any event, the SPS is a viable alternative using state-of-the-art technologies, with promise of even better technology in the foreseeable future.

4.5.4 Water

Overview. As for the land assessment, both a side-by-side analysis and an alternative futures analysis were completed for water use. The side-by-side comparison is based on the technology characterization data. Scenario data are coupled with the side-by-side data to provide water use estimates over the 1980-2030 time frame.

Side-by-Side Analysis. All technologies, except for TPV and SPS, require about the same amounts of water. The range is 14-77 x 10^6 $m^3/GW/yr$ (installed). Water use for SPS and TPV is negligible. Table 4.39 summarizes the side-by-side data. The entries are the volumes of water consumed; withdrawal require- ments were not identified in the technology characterizations.

Alternative Futures Analysis. Scenario data do not disaggregate coal use by technology. It is necessary to make an assumption about the ratio of deployment of conventional coal combustion to that of CG/CC. Assuming equal deployment, the average water consumption is about 45 x 10^6 $m^3/GW/yr$ (installed) for coal technology. For non-solar technologies, the range of water consumption is then 32-45 x 10^6 $m^3/GW/yr$ (installed).

Since the real issue here is the impact solar technologies might have on water consumption, the precision gained by considering the individual technologies is of little value. Therefore, a mid-range value of 40 x 10^6 $m^3/GW/yr$ (installed) is used to estimate these effects. Figure 4.42 illustrates these results.

Table 4.39 Water Consumption Data for Energy Systems, 10^6 $m^3/GW/yr$ (installed)

Technology	Consumption
Conventional Coal	77
LWR	37
CG/CC	14
LMFBR	32
TPV	Negligible
SPS	Negligible
Fusion	39
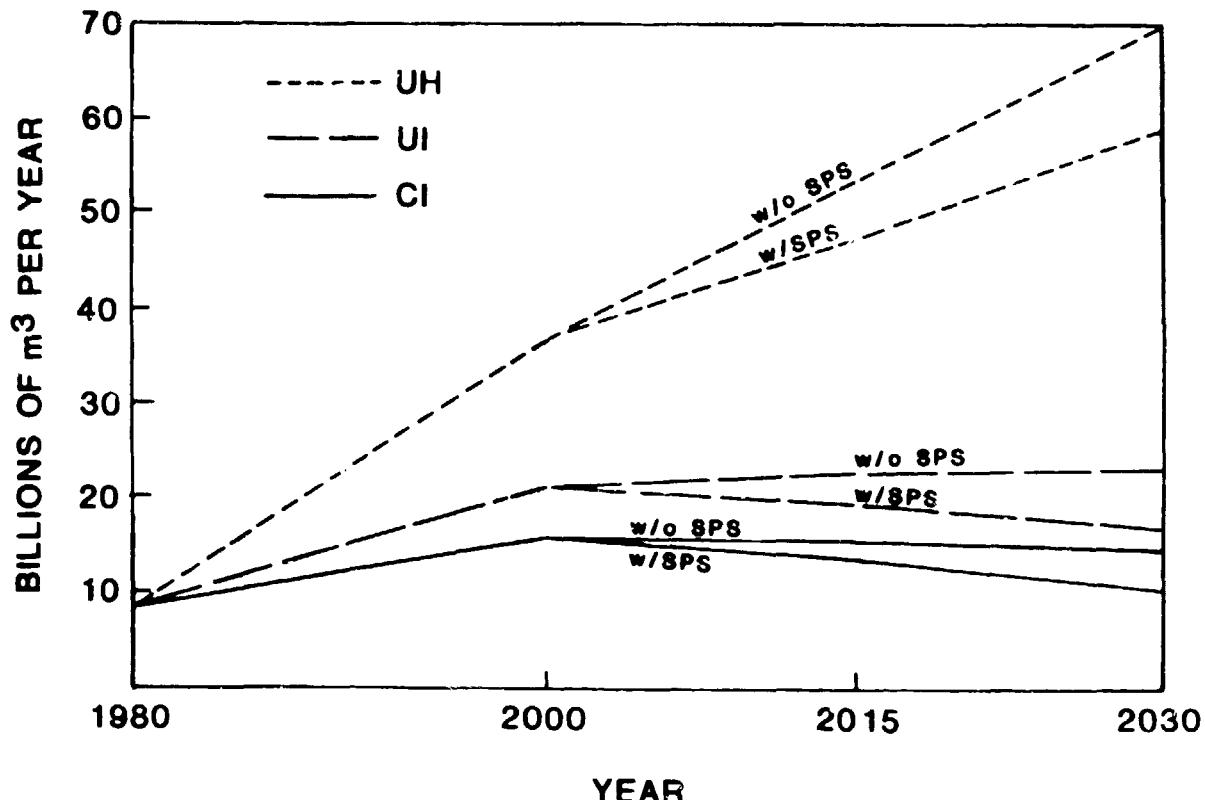
Fig. 4.42 Alternative Futures Analysis of Annual Water Consumption for Baseload Electricity Generation

Deployment of SPS avoids the consumption of 4×10^9, 6×10^9, and 10×10^9 m^3 of water in the year 2030 for scenarios CI, UI, and UH, respectively. These are 30%, 28%, and 19% of the amounts that would otherwise be consumed in the respective scenarios. Another point of reference is the estimated 8.1×10^9 m^3 of water consumed for baseload electricity generation in 1980.

The main factor driving water consumption (and consumption of any other resource) is energy demand. The saving due to SPS deployment in scenario UH is dominated by the issue of supplying roughly 50×10^9 m^3 of water on an annual basis. Clearly, the probability that the water demands of scenario CI or scenario UI will be met has to be much higher than that for scenario UH.

4.5.5 Labor

Overview. The labor assessment estimated the number of workers required for plant construction, operation and maintenance, and fuel cycle for each of the technologies. Again, both side-by-side and alternative futures analyses were performed.

Side-by-Side Analysis. Labor requirements were developed by the technology characterizations activity and are listed in Tables 4.40 and 4.41. Table 4.40 lists requirements for a specific plant design and is useful for considering socioeconomic impacts during the construction phase and the O&M phase. Table 4.41 lists requirements on a per-GW (installed) basis, which is useful for the alternative futures analysis. Labor categories are construction, operation (including maintenance), and fuel cycle.

Except for SPS and TPV, there is little difference in the per-unit labor requirements for construction; SPS requires the largest crew size but also has the largest capacity, while TPV requires the smallest crew size but also has the smallest capacity. These differences are important in considering socioeconomic impacts on localities during construction, discussed in Sec. 4.6.

Annual labor requirements for operation and maintenance (O&M) are significantly different from fuel cycle labor requirements. The approximate numbers of persons required per plant for O&M and the fuel cycle are 900 for coal, 400 for fission and SPS, 200 for fusion, and 26 for TPV. The large coal number is attributable to its fuel cycle (mainly mining) requirements. Operation and maintenance requirements are about the same for all technologies, except for TPV. The ratio of construction force to force is generally about 4 or 5. However, for SPS the difference amounts about 2000 people, which could be a significant factor affecting the magnitude of a boom/bust transition at a rural location.

Alternative Futures Analysis. There is little difference in the construction labor requirements per GW of installed capacity among the technologies. Since SPS requires the smallest labor force, scenarios with higher penetration rates for SPS would result in lower total construction labor requirements.

Table 4.40 Labor Requirements for Specific Plant Designs

	Technologies					
	Coal	LWR	LM BR	TPV	SPS	Fusion
Nominal Capacity (MW)	1250	1250	1250	200	5000	1320
Construction Time (yr)	5	7	7	5	2	8
Labor Requirements						
Plant Construction (persons/yr)	1100	1100	910	170	2500	1100
Plant Operation (persons/yr)	300	215	225	26	450	200[a]
Fuel Cycle (persons/yr)	625	225	150[a]	N/A	N/A	--

NA - Not Applicable

-- - Small or Negligible

[a] Estimate not provided by technology characterization; number assumed to enable comparison.

Table 4.41 Normalized Labor Requirements (per GW)

Activity	Coal	LWR	LMFBR	TPV	SPS	Fusion
Plant Construction (persons/yr)	880	880	730	850	500	830
Plant Operation (persons/yr)	240	170	180	130	9	150
Fuel Cycle (persons/yr)	500	180	120	N/A	N/A	--

NA - Not applicable

-- - Small or Negligible

There are larger differences for the annual O&M and the fuel cycle labor requirements among the technologies. In all scenarios, these requirements are about 15 to 30 times the annual construction requirements for coal and the LWR technologies, which dominate the technology mixes. Replacement of coal and nuclear with solar technologies would reduce these requirements significantly.

Figure 4.43 illustrates these comparisons. The earlier scenario data and the labor data for O&M and the fuel cycle from Table 4.41 form the basis for the figure. The reductions in the year 2030 labor requirements for O&M and the fuel cycle due to SPS deployment are about 20,000, 40,000, and 120,000 persons for scenarios CI, UI, and UH, respectively.
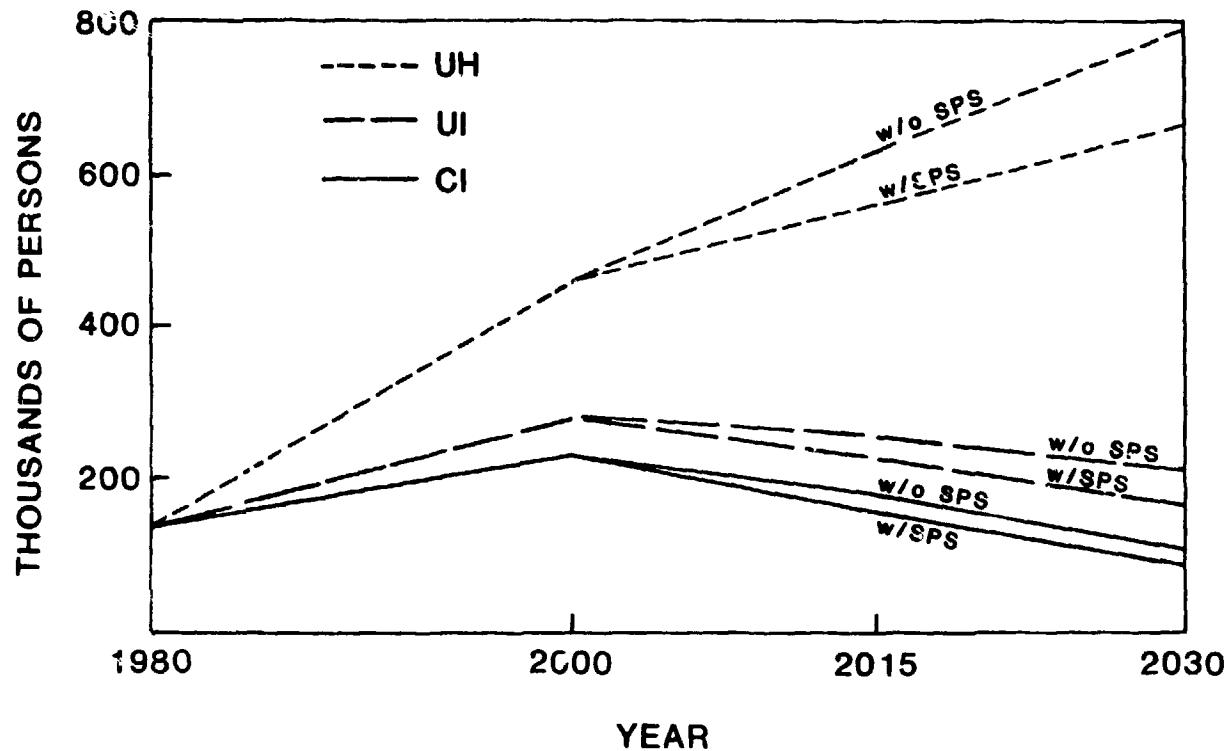
Fig. 4.43 O&M and Fuel Cycle Labor Requirements

The annual construction labor force for SPS has been estimated at 2500 persons per installation. Assuming that construction takes place over two years and that the construction crew must stay at a single site for the entire time period, then the number of crews required (after the first year) would be one or two for scenario CI, two for scenario UI, and four for scenario UH. In scenario CI, the distribution of labor requirements from year to year is uneven due to the deployment rate of two systems every three years.

The skills required are not identified in this analysis. However, they are likely to be much different between technologies (e.g., space constru tion workers for SPS); further treatment of these differences is beyond the scope of this analysis.

4.6 MACROECONOMIC AND SOCIOECONOMIC ISSUES

4.6.1 Introduction

This section uses results from earlier sections on scenarios (Sec. 4.1) and cost and performance (Sec. 4.2).

Results* of the macroeconomic analysis indicate that (1) if uranium and coal supplies are highly constrained, then the costs due to deployment of more

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*All cost figures in this section are in 1978 dollars.

expensive but fuel-saving technologies may be offset by savings in other energy sectors (e.g., deployment of 3.3 GW per year of the SPS priced at 60 mills/kWh could result in a reduction of about $20 billion in energy expenditures for the year 2025, because of savings in nuclear- and coal-based energy technologies); (2) deployment of technologies requiring large capital investments tends to cause a reduction in the GNP growth rate (e.g., deployment of 10 GW per year of SPS could reduce the GNP growth rate by 10-25% in the year 2000 which, if continued and compounded to the year 2030, would result in a $400-1000 x 10^9 reduction in a $7 x 10^{12}-GNP economy); (3) all the constrained scenarios are inflationary, because the prices of scarce fuels are higher than they would be otherwise; and (4) deployment of fuel-saving technologies counteracts to some degree the inflationary aspects of a constrained environment, but quantitative estimates are difficult.

Qualitative macroeconomic assessments on a regional level show that the impacts across technologies are quite different, with different regions having a vested interest in particular technologies. Similarly, income-class macroeconomic assessments show that income groups (low, medium, high) have vested interests in particular technologies during both construction and operation. Public infrastructure costs and social stresses during both construction and operation were considered in a socioeconomic analysis. During construction, these effects may be quite significant for any remotely sited technology; however, due to the large amount of construction involved, this issue is particularly relevant for the SPS and TPV. All technologies should have minimal socioeconomic effects during operation.

One major potential socioeconomic effect, though controversial and unquantifiable, is that successful development of the SPS could provide the technical and industrial infrastructure necessary for further exploration of and industrialization in space.

4.6.2 Macroeconomic Analysis

Calculations performed here are based on data for the years 2000 and 2025 because data for these years are available from the RFF model. Results for other years are largely based on interpolation and extrapolation of these results.

Discussion. The average cost of central-station electricity generation (excluding fuel) in the U.S. is about 25 mills/kWh for coal and 30.5 mills/kWh for nuclear power. These figures may increase somewhat, in constant dollars, as mandated environmental and safety controls are implemented. The added costs will be compensated for, in part, by gradual improvements in technical efficiency. In contrast, the future cost of SPS -- as for other untested technologies -- is quite uncertain. The lower bound of present estimates appears to be at least a factor of two above the present nonfuel cost of nuclear electricity, or around 60 mills/kWh. This translates to $17.50 per million Btu.

The macroeconomic impact of introducing a high-cost alternative technology such as SPS arises from three factors:

- Reduced dependence on imports, with possible associated
  effects on international energy prices, the U.S.
  balance of payments, the international value of the
  dollar, the cost of imports, and the volume of exports;

- Reduced dependence on scarce or constrained domestic
  fuels, resulting in lower domestic prices for most
  forms of energy; and

- Diversion of capital away from the most productive
  forms of investment, with consequent reductions in
  the rate of GNP growth.

The relative importance of the first two factors depends on which fuels
are replaced by the alternative. If SPS were available today, for instance,
it would have its primary impact on the need for oil imports. Assuming the
international oil (spot) market is competitive -- at least at the margin --
the direct consequence of a reduction in U.S. demand (say by 1 quad per year
-- 1 quad = 10^{15} Btu) would be a drop in the international spot price of oil,
depending on short-run elasticities of demand and supply. Indirect further
consequences would include an improved U.S. balance of payments, a stronger
dollar, reduced cost of other imports, a lower domestic inflation rate, and
more dollars spent in the U.S. for domestically produced goods and services.

After the year 2000, however, it seems unlikely that oil from any
source would be used as a boiler fuel. In such circumstances, SPS would
effectively substitute for coal or uranium. A reasonable (perhaps optimal)
strategy in a constrained economy would be to replace all coal used by utili-
ties first, since lower coal prices would then result in lower prices for
syngas manufactured for coal and (because of their direct equivalence) for
natural gas. Lower costs would also be experienced by the steel industry,
which is a major coal user.

Supporting Data. The magnitude of the impact depends on the extent of
the deployment of SPS. Some rough calculations of the effect for three
representative scenarios have been carried out. A set of baseline data for
GNP and energy use is shown in Table 4.42. Table 4.43 disaggregates energy
use by fuel and lists the prices by scenario for the year 2025. Figures 4.44
through 4.46 display supply and demand data for scenarios CI, UI, and UH,
respectively. Table 4.44 summarizes the 2025 baseload generating capacities,
SPS deployment, and percentage SPS for the three scenarios.

Calculating Net Energy Expenditures. In scenario CI, SPS is deployed
at the rate of 3.3 GW per year beginning in the year 2000. At this rate, 83
GW will be in place by the year 2025, about 21% of the total baseload capacity
of 391.4 GW. These 83 GW of installed electrical generation capacity,
operating at a capacity factor of 0.9, could displace the burning of 5.2×10^{15} Btu of coal (at a heat rate of 8125 Btu per kWh). Only 3.3×10^{15} Btu
of coal are burned for electricity in scenario CI; an upper bound of the
economic benefit of 83 GW of SPS capacity (2.2×10^{15} Btu) can be calculated
assuming that no coal is burned for electricity production, with the remaining
SPS generating capacity displacing nuclear electricity production.

Table 4.42   Baseline Energy/Economic Data

Year	GNP $ 10^{12}$ (1978)	Energy (Quads)* CI	UI	UH
1980	2.1	92.4	92.4	92.4
2000	3.7	98.4	99.6	132.3
2015	5.4	117.1	128.8	169.8
2025	6.5	129.6	148.3	194.7
2030	7.0	135.3	158.1	207.1

*1 quad = 10^{15} Btu

Table 4.43   Energy Use and Prices for 2025 Without SPS

Scenario	Electricity Quads*	$/10^6$ Btu	Gas Quads*	$/10^6$ Btu	Coal (Direct) Quads*	$/10^6$ Btu
CI	10.3	15.76	45.6	7.87	7.6	3.45
UI	14.2	13.40	56.2	5.98	9.8	1.66
UH	36.3	13.55	34.7	6.29	15.0	1.73

*1 quad = 10^{15} Btu

To perform these calculations, the change in the price of coal must first be determined. The effect of adding a new source in a constrained economy is to reduce demand for one of the existing fuels (e.g., coal). Consequently, in situations where the market-clearing price lies above the cost, the equilibrium (supply = demand) price level must drop, as illustrated in Fig. 4.44. Demand and supply intersect at point A (from the demand schedule for scenario ¨); the market-clearing price for coal is $1.66 per million Btu. In scenario CI, the supply of coal is restricted and the market clears at a price of $3.45 per million Btu (point B). A straight line through points A and B provides an approximation to the demand schedule.

Under these conditions, there are four impacts of SPS, provided only that output exceeds 3.3 quads:

(1)   SPS displaces 3.3 quads of coal-fired electricity (gross) -- reducing coal-fired electricity to zero -- and thereby shifts the demand curve for coal to the left by 3.3 quads. This, in turn lowers the market clearing price for coal to $3.08 per million Btu (point C in Fig. 4.44).
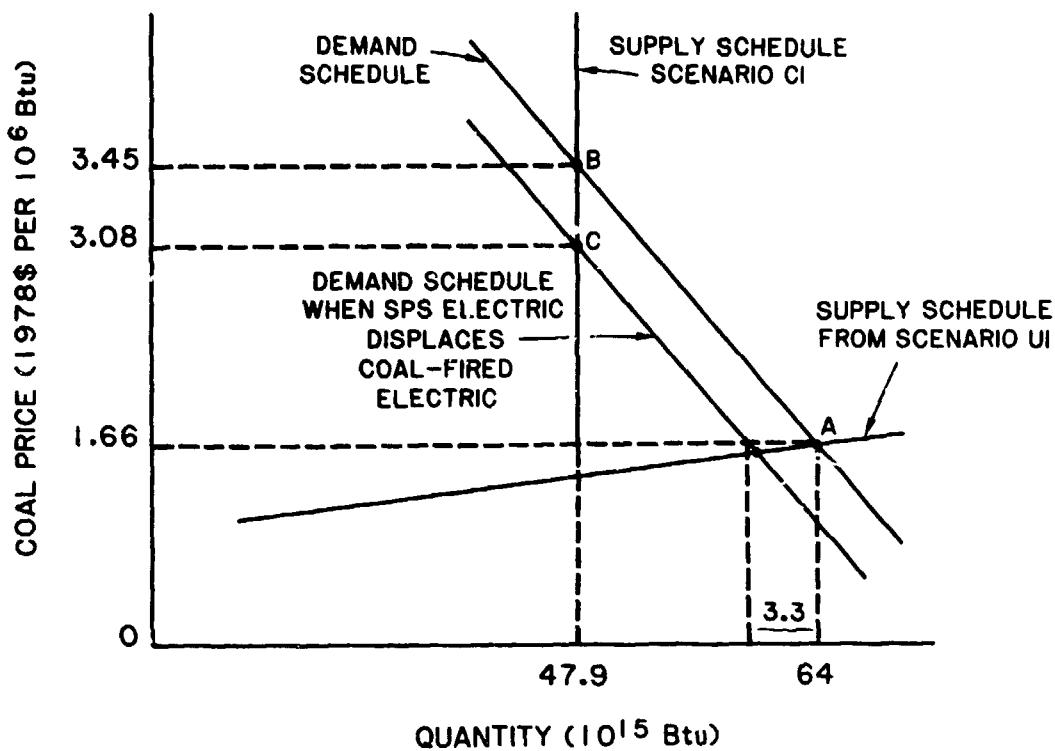
Fig. 4.44   Coal Demand and Supply, Scenario CI (2025)
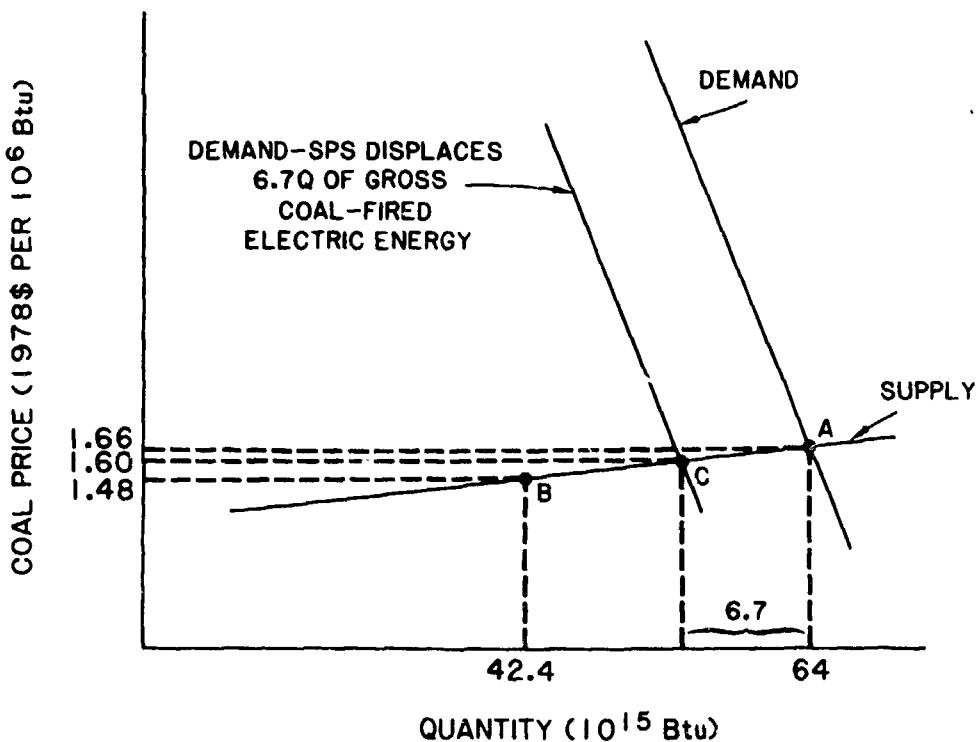
Fig. 4.45   Coal Demand and Supply, Scenario UI (2025)
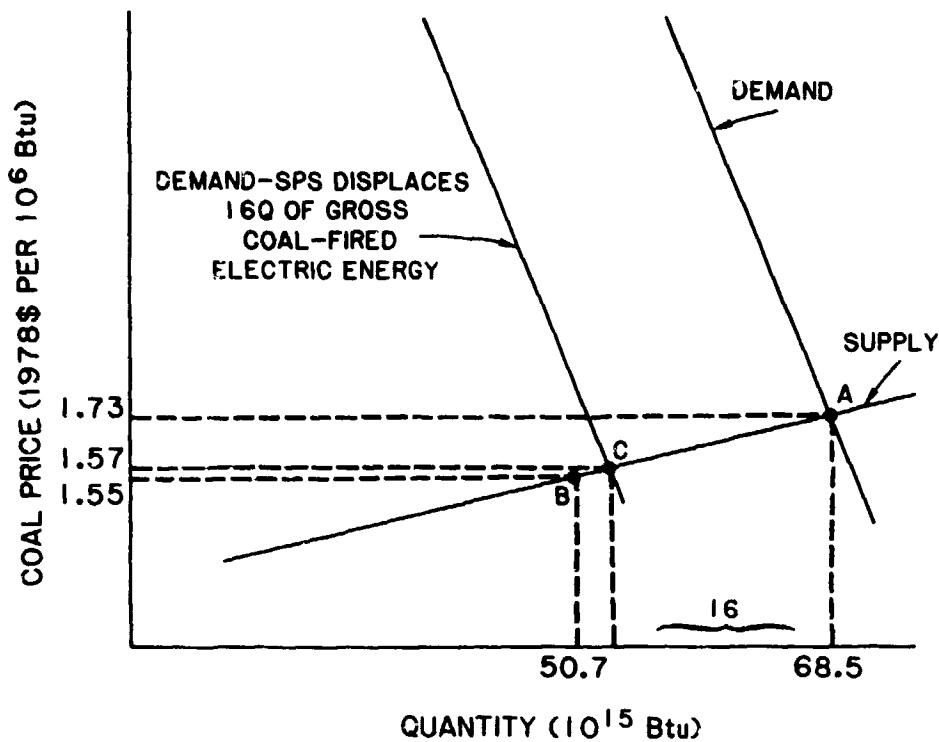
Fig. 4.46. Coal Demand and Supply, Scenario UH (2025)

Table 4.44 Baseload and SPS Deployment Data

Scenario	Baseload (GW)	SPS (GW)	% SPS
CI	391.4	83	21
UI	589.9	125	21
UH	1647.9	250	15

(2) The average direct cost of electricity changes by an amount depending on the cost and deployment of SPS, accompanied by reduced costs of electricity production by other technologies.

(3) The price for gas falls from $7.87 per million Btu to $7.48 per million Btu as a result of the fall in the price of coal.

(4) The fall in the price of coal reduces the direct expenditure for coal to be used as industrial boiler fuel and feedstock.

At a price of 60 mills/kWh ($17.60/10^6 Btu) for SPS electricity, the average direct cost of electricity increases slightly from $15.76/10^6 Btu to

$15.78/10^6 Btu. The price for gas is related to the cost of converting coal to gas at an 80% conversion efficiency; the quantity of gas involved includes both ccal conversion and natural gas sources. Table 4.45 summarizes these data for the three scenarios, with SPS at the appropriate level of deployment. There are two entries for electricity in each scenario, one for SPS electricity, one for non-SPS electricity.

The data in Tables 4.43 through 4.45 provide the basis for the energy expenditures listed in Table 4.46. Net expenditure is the total energy expenditure without SPS, subtracted from the total with SPS. A result greater than zero means that SPS does not trigger enough savings of scarce fuels to offset the increased cost of electricity; a result less than zero indicates the savings are greater than the increased cost of electricity.

The calculation of energy expenditures for different SPS electricity prices is straightforward (approximated by a linear function of the SPS electricity price) given the calculations just described. Figure 4.47 shows year-2025 results for all scenarios over the 30-120 mills/kWh range for SPS electricity.

Table 4.45   Energy Use and Prices for 2025 with SPS
Deployment at 60 mills/kWh (1978 $)

Scenario	Electricity		Gas		Coal (Direct)	
	Quads	$/10^6 Btu	Quads	$/10^6 Btu	Quads	$/10^6 Btu
CI	8.1	15.27	45.6	7.48	7.6	0.08
	2.2	17.60				
UI	10.8	13.33	56.2	5.91	9.8	1.60
	3.4	17.60				
UH	29.6	13.36	34.7	6.13	15.0	1.57
	6.7	17.60				

Table 4.46   Energy Expenditures with SPS at 60 mills/kWh and
without SPS, for the year 2025 ($ 10^9, 1978)

Scenario	SPS	Electricity	Gas	Coal (Direct)	Total	Net Expenditure
CI	No	162.3	358.9	26.2	547.4	-20.4
	Yes	162.5	341.1	23.4	527.0	
UI	No	190.3	336.1	16.3	542.7	9.2
	Yes	204.0	332.1	15.8	551.9	
UH	No	491.9	218.3	26.0	736.2	13.6
	Yes	513.5	212.7	23.6	749.8	
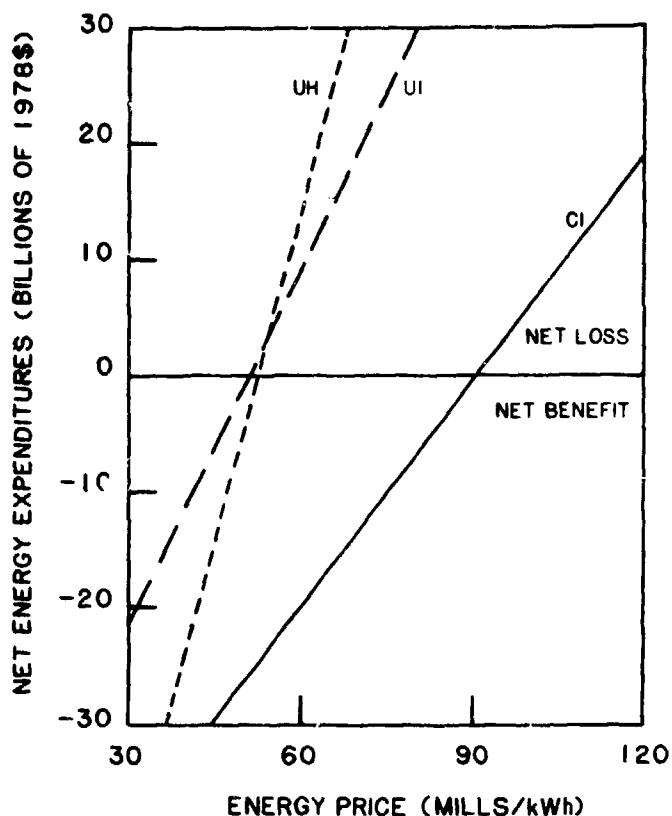
Fig. 4.47 Changes in Annual Energy Expenditures with and without SPS in 2025, as a Function of SPS Energy Price

SPS (or any technology that saves scarce fuel⌐ ⌐ts best advantage, from an energy expenditures point of view, in ⌐ ⌐ined scenario. For scenario CI, there is a net benefit (i.e., reduction in total energy expenditures) when price is below about 90 mills/kWh. In scenarios UI and UH, a net benefit results for prices in the 50-55 mills/kWh range. At 60 mills/kWh, a likely level for ⌐⌐ as indicated in Sec. 4.2, there is a net benefit only in scenario CI. The reason for this is that in an unconstrained economy, the primary effect of introducing a high-cost alternative is to raise the average cost of electricity, with small compensating price advantages elsewhere.

Figure 4.48, derived in a fashion similar to that for Fig. 4.47, depicts the net changes in energy expenditures that would be expected for the various scenarios over the 2000-2030 time frame at 60 and 120 mills/kWh. It also illustrates that net benefits result only in a constrained scenario at sufficiently low prices for SPS energy.

Capital Investments and GNP. To put these expenditure levels in perspective (assuming that SPS is selected over the least costly technology - i.e., coal - for other than economic reasons), the amounts of excess investment per year due to deployment of SPS instead of coal are $7-17 billion in scenario CI, $10-25 billion in scenario UI, and $20-50 billion in scenari⌐ UH.
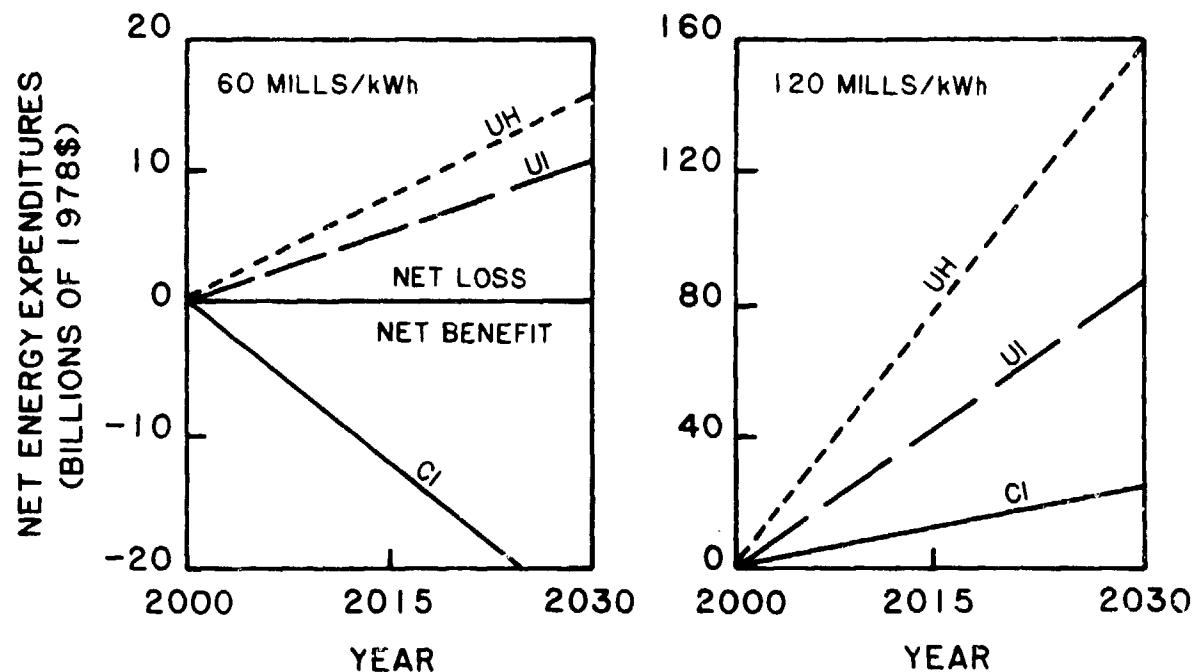
Fig. 4.48   Changes in Energy Expenditures for 2000-2030

Excess energy expenditures at 120 mills/kWh for SPS electricity would soon exceed the upper bound on the extra amount of capital investment needed to deploy SPS in all scenarios.

The $20-50 billion range is calculated assuming SPS deployment at 10 GW/yr, SPS capital costs in the range of $3000-6000/kW, and coal capital costs of about $1000/kW. The ranges for scenarios UI and CI are based on reduced deployment rates of 5 GW and 3.3 GW per year, respectively, and assume that there are no increases in SPS costs at the lower deployment rates.

Annual investment for the present $2 trillion-dollar economy (1978 $) i on the order of $300 billion. At the relatively slow growth rates that appear likely for the next twenty years, a scaled-up $3.7 trillion economy with annual investments of the order of $425 billion might be feasible. It can be reasonably assumed that replacement of depreciated capital assets accounts for at least 6% of annual GNP in the year 2000, or $225 billion, leaving no more than $200 billion available to finance economic growth of around 2.1% per annum. The "extra" investment required to build 10 GW of SPS per year (scenario UH) after the year 2000 -- as compared to the cheapest alternative (coal) -- would be in the range of $20-50 billion, or 10-25% of the investment increment dedicated to economic growth. Obviously a less ambitious rate of deployment, such as 3.3 GW/yr, would have a smaller impact on economic growth.

This extra investment could possibly cut potential GNP growth rates below the target level of 2.1% by 0.2-0.5% per annum. This drag effect would not be offset by low coal and gas prices even in a supply-constrained scenario. On the other hand, the drag would be proportionally smaller if SPS

investment were held to a level just sufficient to eliminate the use of coal for electricity production in a constrained economy. In such a case the drag could almost certainly be kept below 0.1% per annum. It would also be less significant as the economy grows larger after the year 2000.

Nevertheless, when the effect of compounding is considered, the economy of 2030 could be lower than the target level ($7 trillion) by anywhere from $400-1000 billion for scenario UH. Results for the other scenarios are: a $300-500 billion reduction for UI, $100-400 billion for CI. (Growth that would likely be created by "spin-offs" from SPS have not been included in these calculations.) These results also illustrate the sensitivity of 30-year projections in GNP growth to small changes in the growth rate.

Inflationary Aspects. It must be acknowledged that calculations of this kind are predicated on so many uncertain factors that limited weight should be placed on them. It is probably enough to say that the capital demands of SPS could possibly hold back real economic growth to some degree, relative to the "cheapest" alternative sources of electric power. Assuming that the rate of capital accumulation through savings and allowable depreciation remains constant -- or declines -- and that capital becomes progressively less productive over time (SPS is itself an example), then economic "growth" for firms tends to be increasingly financed by borrowing, which is inflationary. Thus capital-intensive projects like SPS are also intrinsically inflationary. However, on this score, the counter-inflationary impact of reduced coal and gas prices would probably be more significant than the impact of financing.

Macroeconomic Effects of Other Technologies. The earlier calculations of energy expenditures were accomplished by first determining total energy expenditures without SPS and then substituting a fixed amount of SPS-generated electricity for that from other technologies. This requires an assessment of the economic effects of reduced demand for a particular fuel, resulting generally in reduced electrical generation costs for the technologies that use the fuel. To go the other way, that is, to assess the effects of eliminating part or all of coal (or nuclear) generating capacity, would require extrapolation of the supply/demand relationships for those technologies left in the power generation portfolio. This is necessary to complete the "with vs. without" comparison but is beyond the scope of the present effort. Since the scenarios were developed considering equilibrium conditions, it is probably safe (and enough) to say that the cost of electricity would rise, perhaps even dramatically, if significant amounts of electricity produced by one fuel-consuming technology were unavailable and had to be produced by other fuel-consuming technologies. This would undoubtedly result in an increase in total energy expenditures. Merely eliminating one of several technologies that use the same type of fuel (e.g., the CG/CC system) would probably have little impact on total energy expenditures, assuming that other coal technologies covered the difference.

One exception to the above reasoning is the case of TPV. TPV has been included in the scenarios in much the same fashion as SPS, but at about one-third the rate of deployment of SPS. Thus, while the nominal electricity

prices to the consumer of T.V (60-75 mills/kWh) are about the same as those for SPS (60-70 mills/kWh), penetration considerations indicate that the impact on total energy expenditures (in absolute dollars) would be less than that of SPS with the net impact (with vs. without TPV) unresolved. TPV, like SPS, would probably have to be priced below 60 mills/kWh in order to realize a net benefit, assuming the same linear supply/demand models for electricity as used in the SPS calculations.

Similar arguments would apply to fusion since it would burn an essentially unlimited fuel. In relative terms, the impact of fusion would be about the same as that of TPV, since it is deployed at about the same level as TPV in the scenarios and costs about the same at the low end.

Estimates of the impacts on GNP growth due to technologies other than SPS are difficult for similar reasons. The scenarios were developed assuming a particular GNP and GNP-energy ratio; principles of equilibrium economics were used to determine the technology mix. Thus, estimation of the impact on GNP of a technology that is not the least costly is of questionable accuracy and value.

An order-of-magnitude calculation of impact on GNP can be made by combining capital cost and deployment data, assuming there are no changes in the economics of the other systems. The result can then be compared to SPS results.

Earlier results for SPS were based on the following assumptions: a $1000/kW nominal value for coal, a $3000/kW low value and a $6000/kW high value for SPS in the year 2000 (which should be compared to the $3400/kW nominal and $15,400/kW high values listed in Table 4.11 for the GaAlAs option). Results for SPS at $3000/kW indicate a 10% reduction in the GNP growth rate for scenario UH, 5% for scenario UI, and 3.3% for scenario CI. Nominal capital costs for the LWR and the CG/CC are also about $1000/kW. These, along with conventional coal, form the basis for comparison.

At the nominal $1500/kW for the LMFBR, a 2-1/2% reduction (vs. 10% for SPS) in GNP growth rate for scenario UH would be expected if the breeder is deployed at the same rate as SPS. The deployment rates for SPS and the LMFBR are about the same in scenarios UH and UI, and the breeder deployment rate is about 50% higher in scenario CI. The result is that the drag effect on GNP growth due to the LMFBR would be about one-fourth to one-third that due to SPS. At the high end (about $6000/kW) of capital costs for the LMFBR, the drag effect would be about the same as that for SPS.

For fusion, the nominal capital cost of about $3000/kW (no upper limit of the range is available) is close to that for SPS, but the deployment rate is about one-fifth that of SPS across all scenarios. Thus, fusion would have a nominal drag effect about twice that of SPS for each scenario.

Regional Macroeconomic Effects. The results of the regional analyses are more qualitative than earlier macroeconomic results. Increased coal utilization will provide economic stimulus to the mountain West, the location of much of the low-sulfur coal in the U.S. If the power plants are located near the coal sources, this will provide an additional source of economic growth for

that region. Transporting this coal or transmitting this electrical power to the coastal regions would result in higher charges for electricity consumed in those locations. In contrast, the nuclear options (LWR, LMFBR, and fusion) could be sited in any region, minimizing the differences in macroeconomic effects between regions.

TPV is most economically located in areas of high insolation. These are primarily in the South and Southwest. Deployment at a significant level relative to national electrical energy needs could result in long-haul transmission, as in the case of low-sulfur western coal, and subsequently higher prices to consumers in other areas.

It may be possible to site SPS rectennas in every region in the U.S. This would minimize regional differences just as the nuclear options would. However, if it became necessary to transmit SPS power for long distances due to local siting difficulties (or any other reason), regional differences would result.

4.6.3 Socioeconomic Comparisons

The focus of the socioeconomic analysis is on labor requirements of the various technologies, with some comments on potential "boomtown" effects.

Table 4.47, compiled from technology characterization data in Sec. 3.2, lists the labor requirements of the energy technologies. The average number of people on site during construction and during operation (for operations and maintenance) are given along with construction time. The entries for SPS include only the rectenna site.

The figures given for construction are for the average work force per year over the construction interval. The peak work force would be somewhat higher (by about 30%) than this. Furthermore, families would

Table 4.47 Energy Technology Labor Requirements

Technology	Nominal Capacity (MW)	Construction Average Labor (persons/yr)	Construction Time (years)	O&M Labor (persons/yr)
Conventional				
Coal	1250	900	5	250
LWR	1250	1100	7	220
CG/CC	1250	1300	5	340
LMFBR	1250	900	7	230
TPV	200	200	5	30
SPS[a]	5000	2500	2	450
Fusion	1220	1100	8	b

[a]SPS figures are for the rectenna construction only.

[b]Not estimated.

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be relocating with some of the workers, further adding to the population (by a factor of about three) of the surrounding area. These population increases affect the amounts of services (e.g., water, sewer, food, housing, schools, health care, police, fire protection) required, again adding to the population, although creating permanent jobs for the area in some instances. If the site is fairly distant from a large population center, these impacts can be severe for the affected locality.

On a normalized basis, SPS would require the smallest work force, about 500 persons per year per 1000 MW. All others would be in the range of 700-1000 persons per year per 1000 MW. However, because of the large size (5000 MW) of the SPS, its impact would be much greater when compared to any other single plant of typical size. If plants were located in power parks of comparable size (with regard to capacity) then these differences would decrease, assuming all the plants at a single location were built simultaneously. Another option for any technology is to extend the time period over which construction takes place. This strategy would lessen the peak level of an impact.

4.7 INSTITUTIONAL ISSUES

4.7.1 Introduction

The relative institutional impacts of energy technologies are becoming increasingly important in the assessment of policy priorities for federal research, development, and demonstration expenditures. The environmental impact statement process created by the National Environmental Policy Act of 1969 (NEPA) has been interpreted in many legal opinions to require the consideration of factors beyond air and water pollution. Institutional impacts fall within this spirit, even if they are not covered by the letter of the law.

There is a practical, as well as legal, basis for institutional analysis of new energy technologies. A recent publication of a nuclear industry trade organization, the Atomic Industrial Forum,[175] alleges that government regulation accounted for an increase in nuclear power plant engineering man-hours of nearly 40% in the 1970s alone. Thus, a comparative assessment of the contribution of the Satellite Power System (SPS) to the nation's energy resources should include a discussion of the effects of energy technology deployment on existing and potential regulatory institutions and the effects of these institutions on the deployment of energy technologies.

This section will compare the regulatory issues surrounding electricity systems based on the SPS, coal, light water or breeder reactors, and centralized terrestrial photovoltaics. The comparison is based on the assumption that decision makers who must choose between energy technologies are interested primarily in the significant differences between those technologies, not in a complete catalogue of all of their characteristics. In the case of institutional analysis, this means that the most relevant information is that which highlights the different responses of regulatory institutions to different energy technologies and projects the impact of these institutions on deployment.

To perform this analysis, it is necessary to imagine the regulatory scheme for each technology at the same stage of development. Therefore, this analysis is divided into two parts. Section 4.7.2 will compare the regulations for each technology as they exist at present, without regard to probable future areas of regulatory activity. Section 4.7.3 will attempt to evaluate how national trends are likely to influence technology regulation in the near future.

4.7.2 Comparison of Present Regulatory Schemes

Approach. Analysis of the overall regulatory schemes associated with different technologies will focus on three areas:

- The justifications for government regulation of energy technology.

- The level of government that is primarily responsible for the regulatory task.

- Where possible, the cost of regulation to both the government and the owner of the electricity system.

For the purposes of this section, the term "government regulation" is defined as any conscious and systematic government effort to influence the development and deployment of an energy technology that would otherwise be left to evolve in the private market place.

Justifications for Regulation. A recent article by Stephen Breyer[176] represents one of the most up-to-date efforts at an overview of our regulatory institutions. He organizes regulations into a number of categories, each of which represents a distinct justification for regulation. Justifications, he points out, consist of the best "public interest" arguments of those who have advocated regulatory measures, regardless of whether these reasons actually motivated the governmental action. In effect, these justifications represent the best policy explanation of why government does what it does.

Breyer defines a number of regulatory categories that are not applicable to the issues being considered here. For the purposes of this section, his regulatory justifications can be reduced and adapted to three:

- Control of Monopoly Power. This category includes all of the numerous forms of regulation intended to control the freedom of monopolies or to restrict competition in favor of monopolies.

- Correction for Externalities. This includes any government-imposed requirement intended to prevent the general public from paying for costs that are more properly assumed by the entity that creates them. Environmental control regulations, for example, are included in this category.

- <u>Correction for Inadequate or Improper Information</u>.
  This category covers all regulations intended to promote
  the free flow of information for its own sake or to
  restrict the free flow of information for national
  security purposes.

Regulations effectuated primarily through the tax system are not included
in this discussion, except where specifically noted.

<u>Level of Government</u>.   Each type of regulation for each electricity
system will be classified by the level of government that has primary juris-
diction for enforcing it.   Local, state, federal, and international govern-
mental bodies will be covered.   Hybrid bodies, such as regional agencies or
federal laws that are enforced by state agencies, are classified at the level
of government that has the most direct power over their conduct.   For example,
the clean air laws are considered federal regulations even though State
Implementation Plans guide their use, because the federal government sets the
standards those Plans must meet.

<u>Cost of Regulation</u>.   A rough estimate of the annual cost of each
justification for federal regulation will be included for coal and nuclear
technologies.   The figures listed will cover both the measurable costs to
taxpayers through the operation of the federal government and the compliance
costs to industry.   A fourth category, "hybrid purposes," will include funding
levels for programs that fulfill all three of the justifications for regula-
tions discussed above but which could not be broken down more specifically.

These figures must be read with extreme caution because their sta-
tistics are derived largely from untested sources and thus may be incomplete.
The sole purpose of this overall analysis is to enable comparisons of the
differences between orders of magnitude of the costs of regulating these
energy resources.

<u>Results</u>.   As Tables 4.48-4.51 indicate, substantially different regu-
latory systems are associated with the four different electricity production
systems under consideration.   The regulatory systems differ both in the
overall burden of regulation and in the levels of government that have primary
jurisdiction over different aspects of regulation.   Under the least favorable
circumstances, significant and unprecedented regulatory burdens and conflicts
could accompany the establishment of SPS.

Obvious regulatory difficulties inevitably would accompany SPS deploy-
ment because of its international character.   As Tables 4.48 and 4.50 indi-
cate, neither coal nor centralized terrestrial photovoltaic electricity
production systems are faced with any significant regulation by international
bodies.   Although Table 4.49 reveals that light water and breeder reactors are
subject to certain international restrictions on proliferation and information
disclosure, such basic decisions as reactor location, damage liability in the
event of accident, and permissible emissions are made within the United
States.   Only SPS appears to require an internationally-empowered body or
negotiated treaties to make the types of decisions listed in Table 4.51 --

Table 4.48 Justifications for Regulating Coal Technologies
at Each Level of Government

Justification	Local	State	Federal	International
Control of Monopoly Power	None	Certificate of need, Antitrust, Retail electric rates.	Antitrust, Coal leases on federal land, Wholesale electric rates, Research and development funding.	None
Correction for Externalities	Land Use	Mine and miner health and safety.	Environmental impacts of surface and underground mining, Air and water pollution discharges, Worker safety, Endangered species protection, Research and development funding, Equal employment opportunity.	None
Correction for Inadequate or Improper Information	None	Mining claims.	Corporate securities disclosure, Freedom of information, Patent protection, Research and development funding.	None

Table 4.49 Justifications for Regulating Light Water or Breeder Reactors at Each Level of Government

Justification	Local	State	Federal	International
Control of Monopoly Power	None	Certificate of need, Antitrust, Retail electric rates.	Antitrust, Wholesale electric rates, Research and development funding.	Nuclear non-proliferation treaty.
Correction for Externalities	Land Use, Nuclear materials transport	Nuclear materials transport, Industrial waste discharge, Nuclear waste disposal.	Nuclear materials transport, Siting, Operation, Insurance, Air pollution discharge, Water pollution discharge, Worker safety, Nuclear waste disposal, Power plant decommissioning, Power plant control during emergencies, Endangered species protection, Research and development funding, Equal employment opportunity.	Nuclear non-proliferation treaty.
Correction for Inadequate or Improper Information	None	Emergency evacuation procedures.	Corporate securities disclosure, National security restrictions, Freedom of information, Patent protection, Research and development funding.	International Atomic Energy Agency.

Table 4.50 Justifications for Regulating Terrestrial Photovoltaics at Each Level of Government

Justification	Local	State	Federal	International
Control of Monopoly Power	None	Certificate of need, Antitrust, Retail electric rates.	Antitrust, Utility interconnection for decentralized plants, Wholesale electric rates, Research and development funding.	None
Correction for Externalities	Land Use	Industrial waste discharge from cell production.	Air pollution discharge, Water pollution discharge, Worker safety, Endangered species protection, Research and development funding, Equal employment opportunity.	None
Correction for Inadequate or Improper Information	None	None	Corporate securities disclosure, Freedom of information, Patent protection, Research and development funding.	None

Table 4.51 Justifications for Regulating SPS at Each Level of Government

Justification	Local	State	Federal	International
Control of Monopoly Power	None	Certificate of need, Antitrust, Retail electric rates.	Antitrust, Financial structure and decision-making process of SPS governing entity, Wholesale electric rates, Research and development funding.	Orbit availability, Radio frequency allocation.
Correction for Externalities	Land Use	Rectenna site selection, Industrial waste discharge from cell production.	Land use on federal lands, Air pollution discharge, Water pollution discharge, Aeronautical planning and control, Worker safety, Endangered species protection, Research and development funding, Equal employment opportunity.	U.S. guarantee of damage payment for torts, Possible international microwave emission standards.
Correction for Inadequate or Improper Information	None	None	Corporate securities disclosure, National security restrictions, Freedom of information, Research and development funding.	None

decisions which, like orbit availability, would vest in foreign countries the control over the right to produce and transmit energy. The United States Government would have to be prepared to accept the inevitable extra bureaucratic delay that accompanies such complex decisions.

The international regulation of the SPS is likely to increase the amount of regulation required at the federal level. As Table 4.51 indicates, the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies and the 1972 Convention on International Liability for Damage Caused By Space Objects both guarantee that the United States Government will pay for damages resulting from any SPS activities undertaken with its assistance, regardless of negligence and regardless of the extent of direct government sponsorship. It is logical to assume that the federal government will insist on a powerful voice in the operation of any entity which, like the SPS, could incur substantial liability for which American taxpayers would ultimately be responsible.

Table 4.52 lists the similarities and differences between the costs of regulating coal and regulating nuclear-generated electricity. This comparison has important implications for SPS. Although the costs associated with each justification for regulation make up about the same percentage of the total cost of regulating coal as of the cost of regulating nuclear-derived electricity, the total costs associated with the nuclear option exceed those of the coal option by more than 50%. Moreover, the bulk of the extra money spent on nuclear regulation appears to be concentrated in two areas of justification -- "correction for externalities" and the "hybrid purpose" categories.

The reasons for these differences between costs for coal-electric and nuclear-electric regulation could provide important indications of what would happen if an SPS system were deployed. If the specific programs within the nuclear "correction for externalities" and "hybrid purpose" categories are examined, it becomes apparent that the bulk of spending is on various research and development activities. Programs like back-end fuel-cycle waste management and civilian reactor development account for a large percentage of the total costs in their respective categories. Coal regulatory costs, on the other hand, result from regulations aimed mainly at mitigating adverse impacts that already are relatively well-organized, e.g., protection of miner health and safety and control of surface mining externalities.

The fact that a large portion of the nuclear regulatory spending is on research and development activities intended to improve safety may reflect a more general concern that could also affect the SPS. Nuclear-generated electricity is one example chosen by Talbot Page in a recent article[177] to illustrate the "zero-infinity dilemma," which Page defines as the question of whether a decision to proceed with a technology should ever be made if that technology could result in a virtually infinite catastrophe even though the probability of such an event is virtually zero. It is clear that the United States Government has decided that a nuclear accident that results in a high-level radiation release into the environment would be infinitely costly and therefore intolerable;[176] the substantial spending on research and development illustrated by Table 4.52 testifies to the commitment of the government to reduce the probability of such an accident to zero by effective preventive measures.

Table 4.52 Comparative Cost Estimates (in 1978 dollars) for Federal Regulation of Coal and Light Water Reactor Electricity Production Systems

Justification	Coal-Fired Electricity	Cost of Regulation, 10^6/yr	% of Total Cost of Regulation	Light Water or Breeder Reactor Electricity	Cost of Regulation, 10^6/yr	% of Total Cost of Regulation	Total Cost of Justification, 10^6/yr (% Coal, % Nuclear)
Control of Monopoly Power	Coal Leases on Federal Lands	32.3[a,b]		Uranium Enrichment	220.0[e]		
	Depletion Allowances Revenue Equivalent	443.0[a]		Advanced Isotope Separation	39.2[a,e]		
	Total	475.3	13.8	Total	259.2	4.3	734.5 (64.7, 35.3)
Correction for Externalities	Office of Surface Mining	2,290.6[c]		Waste Management	4,739.0[a,e]		
	Pollution Control (Air, Water)	66.9[d]		Nuclear Materials Transport away from Reactor			
	Miner Health and Safety (CSHA, MESA)	113.5[a,b]		Storage			
	Domestic, Foreign Waterway Subsidy	90.8[a]		Encapsulation Facility			
	Coal Hydrology	13.2[a]		Geologic Repository			
				Overhead			
				Decommissioning	46.2[f]		
				Insurance (potential liability)	(500.0)[g]		
				Site Safety Research	24.7[a,e]		
	Total	2,574.8[h]	75.0	Total	4,809.9	79.0	7384.7(34.9, 65.1)
Correction for Insufficient Information	Data Collection and Analysis	29.0[a,b]		Uranium Resource Assessment	24.7[a]		
	Total	29.0	0.9	Total	24.7	0.4	53.7 (54.0, 46.0)
Hybrid Purpose	Coal Utilization Research and Development	354.5[a,b]		Nuclear Regulatory Commission Regulations	240.0[e]		
				Civilian Reactor Development	684.3[a,e]		
				Nuclear Materials Research	68.4[a,e]		
	Total	354.5	10.3	Total	992.7	16.3	1347.2(26.3, 73.7)
	Total Cost of Regulation	3,433.6	100	Total Cost of Regulation	6,085.5	100	9519.1(36.1, 63.9)

[a]Source: Ref. 179.

[b]Source: Ref. 180. While no specific figures were used from this source because they have not yet been approved, they provided a source of comparison for the future.

[c]Source: Ref. 181; Joe Jewbee, Office of Surface Mining, Office of the Budget, personal communication on revenues received from fees of 35¢/ton for surface-mined coal and 15¢/ton for underground coal, July 13, 1979.

[d]Source: Ref. 182.

[e]Source: Ref. 183.

[f]Source: Average of the various possible methods of decommissioning from Ref. 183.

[g]Source: Ref. 184.

[h]This figure fails to include costs attributable to Equal Employment Opportunity. Although data are available, they were excluded because of their relative insignificance.

If the SPS is perceived to present a zero-infinity dilemma, it is probable that its regulatory costs will look much more like those of nuclear power (Table 4.52) than those of coal-fired electricity. Like nuclear power, the SPS would be faced with continual regulation. Its international character might not provide an "escape route" around United States regulatory requirements -- the rest of the world cannot be expected to be any more willing to permit even a small possibility of a catastrophic SPS accident for the sake of supplying energy to the United States than the United States has been willing to risk a catastrophic nuclear accident within its own borders.

Of course, whether the SPS does present a zero-infinity dilemma as serious as nuclear power is a question on which there is no consensus. How serious an accident must be to become "catastrophic" and how small the probability to be viewed as "impossible" are political decisions that this study is intended to facilitate. It is important to recognize, however, that when a technology has come to be perceived as posing a zero-infinity dilemma, the total costs associated with regulating it could become a determinant of its economic viability.

4.7.3 Regulatory Trends

The comparative evaluation of the regulatory system that is likely to accompany any of the technologies considered here will continue to evolve. The extraordinary public attention that has been focused for a variety of reasons on energy production over the past ten years appears to be having a long-term impact on the ways in which the problem is being perceived and resolved. The purpose of this section is to analyze some of these trends in a qualitative fashion.

In concluding that "the weight and importance of the decentralization trend in America is greater than the 150-year-old trend toward more centralization," John Naisbitt[185] calls attent   to developments that have important implications for the regulatory system ...at would be associated with the SPS, as well as other electricity production technologies. Naisbitt states that if the decentralization trend continues, it is likely to cause intergovernmental conflicts in the regulation of all electricity technologies, but especially the SPS. He further contends that increasing decentralization probably will make uniform regulations more difficult than would otherwise be the case. Of course, it is dangerous to draw too many conclusions from such recent developments. Nonetheless, it is important to understand their implications in the event they become long-term realities.

Intergovernmental Conflicts. As Naisbitt[185] points out, numerous events suggest a growth of power among states and communities at the expense of the federal government. Increasing activity on the part of regions, states, and local governments is leading to greater assertion of decision-making authority by these entities. Naisbitt illustrates this trend with examples of states and localities that have tried recently to gain regulatory control over certain stages of the nuclear fuel cycle, including siting, transportation, and disposal of nuclear materials, and disaster emergency plans.

The present conflict between federal and local governments in the context of nuclear power could be even worse in the case of the SPS. Several studies[186-188] of the SPS have concluded that an international regulatory body probably would be desirable for regulation of the technology. If this move to centralize energy technology regulation comes at a time when the dominant national trend is exactly the opposite, substantial intergovernmental duplication and conflict could result, not only between the federal and local governments, but also between local governments and the international regulatory body. For example, Kotin[189] suggests the possibility that states could attempt to regulate microwave exposure levels to their citizens -- an area ripe for international regulation if the SPS is deployed.

Such disputes, should they arise, could cause unexpected delays, costs, and uncertainties in the deployment of the SPS. While it is true that world-wide commitment to international regulatory bodies such as the Law of the Sea Conference and the International Whaling Commission has grown in recent years, these bodies derive their authority to regulate the United States from the federal government. If the decentralization trend should continue, it is conceivable that state and local interests would reduce the ability of these international regulatory bodies to govern effectively. For example, recent litigation on behalf of Alaskan Eskimos to exempt their whaling activities from regulation by the International Whaling Commission may be decided in their favor, despite vigorous opposition by the federal government.

Non-Uniform Regulation. Regardless of whether the difficulties suggested above materialize, great potential exists for the SPS regulatory system, concurrent with other centralized energy technologies, to become more expensive than is predicted. Naisbitt[185] concluded that governments "have stopped looking for the one best way to accomplish a particular social goal, and are now experimenting with a wide variety of approaches." If the decentralization trend continues, the regulatory system for any of the electricity technologies covered in this section -- at whatever level of government that is vested with primary jurisdiction -- will likely have to be sufficiently flexible to meet this demand for individuality. The cost advantages of the uniform regulatory system that would normally evolve will be reduced as the system becomes unwieldy in the attempt to please widely divergent constituencies. Although the President has proposed a new regulatory body whose explicit purpose is to counteract this tendency, it is unclear whether his objective will be met.

4.7.4 Summary

Institutional (regulatory) considerations are increasingly affecting the viability of new energy technologies. A comparison of regulatory schemes for the SPS, coal, nuclear, and terrestrial photovoltaic technologies suggests that the SPS could be faced with unprecedented regulatory burdens as a result of the number of jurisdictions that might seek to govern it. Moreover, this trend could be exacerbated by the developing tendency of local governmental units to attempt to gain regulatory control from the federal government.

5 ASSESSMENT CONCLUSIONS

5.1 INTRODUCTION

The objective of this assessment is to provide a traceable and consistent comparison of the SPS and selected energy technologies operating after 2000. The approach in this comparative assessment was to analyze each of the technologies issue by issue (side-by-side analysis), on the basis of a preselected set of issues, and then to do an analysis that evaluated the technologies, given different post-2000 economic climates and the economic trajectories that would lead to those climates (alternative futures analysis). The alternative futures analysis was also performed issue by issue, although some issue analyses were qualitative and therefore relatively insensitive to quantitatively defined economic futures.

It is the goal of this section to formulate some conclusions on the basis of the analyses described in earlier sections of this report and the supporting documents. Because the analysis was performed in two ways, two different types of conclusions will be reported. The first type will focus on the issue-by-issue analysis (side by side) and incorporate the key issues for each technology. Conclusions will be made in each major issue category (e.g., health and safety) by looking across the technologies. The second type of conclusion will be concerned with the parameters (e.g., energy demand and fuel prices) of various futures and will include statements about the comparative viability of different supply paths. Conclusions will be formulated in this case for mixes of technologies in different demand scenarios. These two types of concluding analyses will form the basis of this section. No statements regarding the overall viability of the SPS concept will be made. Such a statement is the objective of the overall CDEP program, of which this assessment is only one part.

5.2 SIDE-BY-SIDE CONCLUSIONS

Tables 5.1 through 5.6 summarize the comparison, issue by issue, among the seven technologies. The comparisons in these tables are described in terms of key issues, uncertainties about the understanding of those issues, and a concluding comparative statement that cuts across all technologies for that issue area. Only one or two key issues were identified for each technology unless several were equally important.

Cost and Performance. The SPS is economically competitive with coal and nuclear energy prices if high coal and nuclear fuel prices continue and if further environmental regulations continue to raise the capital costs of these technologies at a rate substantially above inflation. However, if the capital costs of coal and nuclear technology rise because of the increasing regulatory restrictions, the regulatory climate will be such that it may also affect the cost of SPS. If coal prices increase at a rate only moderately above inflation, the probability that the SPS will be competitive with coal energy is relatively small until after the year 2000, although this result is dependent on the amount of coal use.

Table 5.1 Cost and Performance: Key Issues, Uncertainties, and Comparative Conclusions

System	Key Issues	Uncertainties	Comparative Conclusions
Coal (Conventional, CG/CC)	Capital cost expected to escalate only slightly but coal price would raise energy price substantially.	Coal price uncertain but dependent on amount of demand and environmental regulations.	SPS is economically competitive with coal and nuclear if fuel prices rise sharply and environmental regulations raise the capital cost of these technologies. However, if the regulatory climate is severe for coal and nuclear it may also affect SPS. The probability that SPS will be cost competitive with coal is very small until well after 2000.
Nuclear (LWR, LMFBR)	Capital cost will probably escalate due to environmental and safety regulations. Uranium prices expected to increase.	Capital cost increases are uncertain.	
TPV	Costs depend strongly on cell production cost.	Large improvements required in cell cost.	SPS has approximately the same cost range as TPV and fusion, but the range is very large and no judgments can be made regarding any cost advantages. More detailed cost evaluations and design studies would be required to evaluate the relative economic viability of the advanced technologies.
SPS	Capital cost and system efficiency dominate energy cost.	Cell cost; transportation cost, and system performance are all uncertain.	
Fusion	Containment costs cannot be estimated very well.	Plasma containment cost is highly uncertain. System performance and reliability unknown.	

Table 5.2 Health and Safety: Key Issues, Uncertainties, and Comparative Conclusions

System	Key Issues	Uncertainties	Comparative Conclusions
Coal (Conventional, CG/CC)	Coal extraction, transportation and air pollution are the main contributors to impacts. All issues are well-defined.	Data still not accepted for air pollution but more defined than other issues.	SPS has no health advantage over other technologies. Problems are different and less defined. Quantified impacts of coal are highest but this is the most studied technology. The problem of SPS microwave impacts is similar to low-level ionizing radiation and low-level air pollution: it is difficult to quantify the impact, but it will concern many people. This is a potential problem for SPS that does not have a short term solution.
Nuclear (LWR, LMFBR)	Most impacts are occupational. Low-probability catastrophic impacts affect the perception of this technology.	Low-level radiation impacts are uncertain.	
TPV	Extraction of materials for and manufacture of solar cells are the main contributors to impacts. Construction and maintenance of facilities will have large safety impacts.	The production industry may have large impacts.	
SPS	Extraction of raw materials and component manufacture are key problems. Other problems of key concern remain unquantified or undetermined.	Impacts on space worker health are uncertain. Low-level microwave effects are uncertain.	
Fusion	Tritium release.	Tritium pathways are not well-defined.	

Table 5.3 Environmental Welfare: Key Issues, Uncertainties, and Comparative Conclusions

System	Key Issues	Uncertainties	Comparative Conclusions
Coal (Conventional, CG/CC)	CO_2 climate impacts dominate the issues.	CO_2 uncertainty.	Each technology has a different set of environmental welfare problems. The CO_2 problem has the greatest catastrophic potential, but CO_2 from electricity production is only a small part of the overall problem. Microwave problems will not be solved for many years, possibly not until after a system is built and operated.
Nuclear (LWR, LMFBR)	Radiation waste disposal. Safeguards problems.	Waste disposal technology performance is unproven.	
TPV	No significant environmental welfare issues were identified.		
SPS	Electromagnetic interference is a large issue. Microwave radiation may have ecological impacts on agriculture.	Microwave impacts (e.g., communications interference, ecological impacts) are highly uncertain.	
Fusion	No significant issues were identified because the technology is not completely defined.		

Table 5.4 Resources: Key Issues, Uncertainties, and Comparative Conclusions

System	Key Issues	Uncertainties	Comparative Conclusions
Coal (Conventional, CG/CC)	Water contamination is the only issue.	No large uncertainties.	Large contiguous land consumption is the biggest resource issue for SPS. No other resource problem is as important with the possible exception of uranium fuel supplies for the LWRs.
Nuclear (LWR, LMFBR)	Uranium supply could be limited after 2000.	Uranium supply is uncertain for LWR.	
TPV	Large land areas are required. Energy payback is low.	Energy intensity of cell production is uncertain.	
SPS	Large contiguous land use. Some materials problems.	Microwave health and safety regulations may require an even larger buffer zone – even more total land.	
Fusion	No serious problems.		

Table 5.5 Economic/Societal Issues: Key Issues, Uncertainties, and Comparative Conclusions

System	Key Issues	Uncertainties	Comparative Conclusions
Coal (Conventional, CG/CC)	Regional economic impacts are a problem in the West, but have been well-studied.		Because it is a new technology entailing many new industries, SPS would require a large investment in the infrastructure. This, coupled with the capital intensiveness of the technology, would mean that SPS could have the largest effect on the GNP and the economy. Regional impacts of implementing nuclear technology (fission, fusion) are less significant than those of other technologies.
Nuclear (LWR, LMFBR)	Possible opposition to wide deployment of nuclear technology by some sectors of the public.		
TPV	Regional implementation expected. Large capital requirements.	Industrial infrastructure not described.	
SPS	Capital cost and infrastructure investments could affect GNP. Regional effects are likely. Possible public opposition.		
Fusion	No estimates of infrastructure and R&D costs.		

Table 5.6 Institutional Issues: Key Issues, Uncertainties, and Comparative Conclusions

System	Key Issues	Uncertainties	Comparative Conclusions
Coal (Conventional, CG/CC)	Coal is heavily regulated.	Regulations may increase or decrease.	Although reegulations on coal and nuclear technology have been important, SPS faces perhaps the largest challenge because of its far-reaching nature. The international restraints due to orbit ownership, microwave transmission, and space transportation are probably the most serious.
Nuclear (LWR, LMFBR)	Regulations have and will affect designs, deployment, and operation.	How inhibiting future regulations will be is uncertain.	
TPV	Regulatory impacts are undefined, but hazardous materials are sure to fall under strong regulations.		
SPS	Regulations could affect SPS severely because of many areas of impact (e.g., transportation, orbits, microwave transmission).	International regulatory action is highly uncertain.	
Fusion	Not addressed.		

The cost ranges of all the advanced technologies (i.e., SPS, terrestrial photovoltaic, and fusion) appear to be approximately the same, but, given the large uncertainties and judgments about each of these technologies, no conclusion can be made regarding the viability of one relative to another. The cost drivers of each of these technologies have been defined, but it is difficult to come up with uncertainty bounds around each of the cost drivers. More detailed design and cost evaluation studies would be required on each of these advanced technologies to determine relative economic viability.

Health & Safety. The satellite power system offers no overall health and safety advantages over the conventional technologies. The problems are more defined and the status of public knowledge is greater for the conventional technologies, but the problems that are still undefined for these technologies are no closer to solutions than those of the SPS, and uncertainty in such risks can only be quantified by long-term study. The problem of determining the risks associated with low-level human exposure to microwave radiation (specific to SPS) is similar to the problem of determining risk from low-level ionizing radiation (specific to nuclear) or air pollution (specific to coal). The difficult task in studying these areas is to develop impact analyses at low levels, and each will probably take years of careful research to determine the true impact. If the concern with health and safety continues, the effect on SPS can be expected to be similar to that on coal and nuclear technologies.

Terrestrial photovoltaics and fusion may offer fewer public health and safety problems and long-term undefined risks than do the conventional technologies and SPS. With the exception of the tritium problem for fusion, the risks now associated with these two technologies appear to be less than the risks from the low-level radiation or air pollution problems associated with the other technologies. Therefore, terrestrial photovoltaic and fusion may not be as restricted by hazards that cannot be quantified within the period of technology implementation.

Environmental Welfare. Each technology has a different set of environmental welfare problems. Among these, the climatological impacts of increased CO_2 levels have the greatest catastrophic potential, but it must be pointed out that electricity production from coal causes only a small part of the CO_2 problem. The microwave problems resulting from implementation of the SPS system will take many years to solve, and the viability of a solution may not be known until after a system is built and operated.

Resources (Land, Materials, Energy, Water, Labor). The biggest issue in this area is the consumption of large contiguous land areas by the SPS and terrestrial photovoltaic systems. The terrestrial photovoltaic systems are designed in smaller capacity levels, i.e., 200 MW, so that large contiguous blocks of land would not be required for siting. However, the overall land use is approximately the same as that of the SPS. If the SPS is designed in smaller sizes (less than 5 GW), the need for large contiguous land areas may not be as severe a problem, but overall land consumption will probably be a continuing concern.

Fuel supplies, particularly uranium, could be a problem after 2000 if increasing use of electricity continues in the next 20 years. If the demand for electricity continues to fall off as it has in the last several years, then the uranium supplies for use in LWRs could go on for many years beyond the time horizon of study (2000-2030). The introduction of the LMFBR would eliminate uranium resource concerns.

Terrestrial photovoltaic systems, particulary those using silicon cells, have a very poor energy payback because of the energy intensity of silicon cell production. If the energy requirements of silicon cell production are diminished, then energy payback does not appear to be a problem.

Economic/Societal Issues. The SPS, TPV, and fusion are different technologies than those currently producing electricity and will entail many new industries that will require large investments in infrastructure. These large investments, coupled with the capital intensiveness of the technology, could have the largest impact on the GNP compared to the other technologies. The infrastructure and R&D costs for TPV and fusion have not been estimated; however, because the SPS would require many different types of systems (space transportation, space construction), many new types of jobs and training would be created to support it.

Nuclear and fusion technologies would not be as regionally biased as would the other technologies. Terrestrial photovoltaics would probably be the most regionally applied technology because its implementation is determined by climatological factors, and the proper climate is only available in certain areas of the country.

Institutional Issues. The environmental regulatory climate for coal and nuclear technology has increased substantially in the last 10 to 15 years. If this trend continues, the advanced technologies may also feel these institutional restraints at early stages of their development. SPS raises additional institutional questions because of its international nature. Institutional restraints concerning orbital ownership and microwave exposure standards pose the most serious institutional questions for the implementation of an SPS technology. As serious as the regulatory difficulties are within the United States, the international issues will most likely be even more difficult.

5.3 ALTERNATIVE FUTURES CONCLUSIONS OF THE COMPARATIVE ASSESSMENT

The energy supply/demand analyses that were part of this assessment produced several energy-demand and supply trajectories for the future. The two extremes of these scenarios are discussed here to form conclusions about the comparative viability of the SPS in an alternative futures framework. The other scenarios not discussed in this concluding section are intermediate cases and offer no more perspective on SPS and the alternative technologies.

The two scenarios that were chosen were the unconstrained high energy demand scenario and the constrained intermediate demand scenario. These

two scenarios are referred to as UH and CI, respectively. The unconstrained high scenario (UH) is a situation in which the cost of electrical energy from conventional sources does not rise at a rate much greater than inflation and therefore remains relatively cheap. The availability of cheap energy means that the demand for electrical energy from these sources will continue to rise. It also means that conservation and substitutes for these sources of energy would not penetrate to a great degree.

The other energy demand scenario (CI) is the constrained intermediate scenario. In this situation the electrical demand is low because of the increasing cost of energy due to regulatory constraints on the utilization of coal and nuclear energy. Fuel prices would rise, and conservation and other energy substitutes would diminish demand for electrical energy from these sources, thus lowering the overall demand for electrical energy.

Three different mixes of energy supply were examined for each of these scenarios (Table 5.7). These mixes of energy supply were selected to illustrate differences in meeting these radically different demand scenarios.

Supply options 1 through 3 are evaluated for demand scenario UH for each of the comparative issues in Table 5.8. Supply options 4 tnrough 6 are evaluated for demand scenario CI for each of the issue areas in Table 5.9.

Looking across the different supply options for energy demand UH, it appears that the conventional energy systems will bring about the lowest cost of energy for all cases if they remain relatively unconstrained. However, along with this low cost of energy, future health impacts and safety problems with coal would no doubt become more severe. In addition, since coal would be heavily used because of increased electrical production, it would be expected that the western states would continue their very rapid development. The utilization of the SPS, as described in supply option S2, would limit the production of energy from nuclear only to LWRs and then replace this with SPS. Since SPS can be expected to cost more than these unconstrained conventional technologies, the overall cost of energy would rise. However, since the LMFBR would not be implemented, many of the health safeguard issues would not be of concern, but they would be replaced by the SPS health and safety issues. It is not expected that the CO_2 problem would be lessened in the early post-2000 time frame, because the relative change in electrical energy production from coal could be small compared to the overall production of global CO_2. In both supply options S2 and S3, the introduction of a new technology (i.e., SPS or fusion) introduces new industries that would require large investments. In addition, the large coal boom that will exist and will last until fusion or SPS become available would most likely drop very rapidly and produce a boom/bust cycle.

Among the three supply options for the constrained intermediate demand case, supply option S4, the conventional one, would probably have the lowest energy cost. However, because all energy technology would probably be constrained, it is expected that all three of these cases would have higher energy costs than those described in demand scenario UH, unconstrained high. If the electrical energy growth is indeed constrained and substitution does occur in the form of other energy supply or conservation, then the conventional fuel resources (i.e., coal and uranium) will extend further into the 21st Century and therefore require very little in the form of other technologies for replacement. Supply scenarios S4-S6 replace each of these

Table 5.7 Energy Supply Options

Supply Option	Description
S1 Conventional	Conventional coal combustion and combined-cycle plants and nuclecr LWRs with advancement to LMFBRs make up this supply option. Coal and uranium would be continually used in conventional sources until they are replaced by more improved systems, e.g., combined-cycle coal gasification and the LMFBR.
S2 Conventional fuel utilization pl`s SPS	This supply option includes the use of coal, with nuclear only in the form of the LWR replaced by the SPS when fuel prices for uranium either rise too high or the resource is depleted.
S3 Conventional fuel sources plus fusion	This option utilizes coal with nuclear, in the form of both the LWR and LMFBR, and replaces these systems with fusion. If fusion is not available when the LWR fuels are running low, the LMFBR would be utilized until fusion technology is available.
S4 This is the same as Supply Option 1.	
S5 Conventional systems plus SPS.	Same as Supply Option 2.
S6 Conventional systems plus fusion	In this case since the energy demand is expected to be low, only nuclear LWRs would be used until fusion would be available. Since the energy demand is low, it is expected that the uranium fuel would last until fusion technology could be applied.

conventional technologies, coal and LWR, with the LMFBR or SPS or fusion. It would be very difficult to project the energy costs in the constrained, heavily environmentally regulated economy, to compare these latter supply options. However, it is expected that the availability of SPS or fusion might bring down the cost of energy from depleted fuel sources because these resources would no longer be utilized. In all cases, for energy demand scenario CI, the requirement for an advanced technology is diminished for a couple of decades into the 21st Century; therefore, the decision time as to which advanced technology or technologies would replace conventional sources is delayed and would probably have very little effect on the overall future energy supply and demand.

Table 5.8   Evaluation of Energy Supply Options S1-S3 for Demand
Scenario UH - Unconstrained, High Demand

Scenario Definition			
Energy Demand	Energy Supply	Issue	Comparative Analysis
Electrical energy demand is high because coal and nuclear energy remain relatively cheap. Regulation impositions will not get much larger. Conservation and substitution do not penetrate to a great degree.	S1 - Conventional Coal (Conv. and CG/CC) Nuclear (LWR, LMFBR) Continued use of conventional sources with improved systems. LMFBR could provide energy for many years.	Energy Cost	Low because costs of conventional sources remain relatively lowest of all scenarios .
		Health & Safety	Possible impact of further coal use and nuclear safeguard issues.
		Environmental Welfare	Welfare: CO_2 could become a problem after 2000.
		Resource	Nonrenewable fuel supplies continue to be depleted.
		Economic/ Societal	Continued development of coal mining and technology in western states
		Institutional	Minimal impact because role of regulatory bodies will remain relatively constant.
	S2 - Conventional + SPS (Coal, LWR, SPS) Conventional systems will be used until the SPS is implemented.	Energy Cost	Higher energy cost than S1 because of depleting uranium stocks and the introduction of a new technology.
		Health & Safety	Many new health issues associated with SPS, but conventional problems decreased.
		Environmental Welfare	Potential CO_2 impact is not changed because of other uses; several new SPS issues.
		Resources	Increased land consumption, continued uranium depletion.
		Economic/ Societal	New technology will affect the economy because of large investments; western states could go through a boom/bust cycle with cost.
		Institutional	A whole new set of interactions will develop because of SPS.
	S3 - Conventional + Fusion (Coal, LWR, LMFBR, and Fusion) Conventional systems including some form of breeder until fusion technology is available.	Energy Cost	Higher than S1; slightly lower than S2.
		Health & Safety	New radiation problems.
		Environmental Welfare	Same as S1.
		Resource	Same as S1.
		Economic/ Societal	Similar to S2 but probably not as great.
		Institutional	Nuclear fission regulatory bodies will probably handle fusion.

Table 5.9 Evaluation of Energy Supply Options S4-S6 for Demand
Scenario CI - Constrained, Intermediate Demand

Scenario Definition			
Energy Demand	Energy Supply	Issue	Comparative Analysis
Electrical energy demand is low because regulations and fuel prices have driven up the cost of energy. Conservation and other supply substitutions are selected, thereby lessening the demand for electrical energy.	S4 - Conventional (Coal, LWR, LMFBR)	Energy Cost	High because of restrained conventional sources.
	Because of low electrical demand, conventional supply systems could be used for many years (i.e., fuel stretchout). Breeder could be implemented when fuels are depleted (e.g., 2030).	Health & Safety	Better than S1 because of decreased use of conventional technologies.
		Environmental Welfare	Not much different than S1.
		Resource	Depleting fuel supplies but at a low rate.
		Economic/ Societal	Moderate development of western states.
		Institutional	Strong regulation.
	S5 - Conventional + SPS (Coal, LWR, and SPS)	Energy Cost	Lower than S4 because replacement technology will hold down fuel prices somewhat.
	Because of low demand for electricity, SPS would not be required until later (e.g., 2020).	Health & Safety	Same as S2.
		Environmental Welfare	Same as S3.
		Resource	Land consumption, depleting fuels.
		Economic/ Societal	Same as S2 but boom/bust would be less.
		Institutional	Same as S2.
	S6 - Conventional + Fusion (Coal, LWR, LMFBR, and Fusion)	Energy Cost	Lower than S4, maybe less than S5.
	Because of low demand for electricity, fusion would not be needed until later (e.g., 2020).	Health & Safety	New radiation problems.
		Environmental Welfare	Same as S1.
		Resource	Same as S1.
		Economic/ Societal	Similar to S2 but diminished boom/bust.
		Institutional	Same as S3.

5.4 CONCLUDING REMARKS

Within the limits of present knowledge, it is expected that the cost of the SPS would be higher than that of the conventional technologies, its environmental problems different, and its resource consumption (in the form of land instead of fuels) no less important. However, this conclusion probably results in large part from the character of the SPS reference design. Conventional technology and ideas are incorporated into this reference design; they make it the most believable SPS concept but possibly not the most viable. A more advanced SPS concept might compare more favorably to the conventional technologies, but would be difficult to characterize. However, in order to go forward with such a large new venture as SPS, it is important that the payoffs be significant. Therefore a more advanced SPS concept might provide the margins of benefit that are needed to support such a large new technological venture. For example, the introduction of a different, more intense form of microwave transmission could reduce the land requirements, the microwave impacts, and the overall cost of the technology. Each one of these impact areas is a sensitive issue for the current SPS reference design. Therefore, it should be noted that the comparative assessment reported in this document considered only one concept for the SPS design, and that others, although much more advanced, may compare more favorably than the one chosen.

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