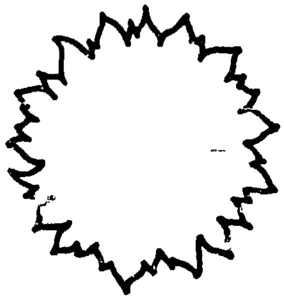
(NASA-CR-152666) AN INITIAL COMPARATIVE ASSESSMENT OF ORBITAL AND TERRESTRIAL CENTRAL POWER SYSTEMS Final Report (Jet Propulsion Lab.) 160 p HC A08/MF A01 CSCL 10A G3/44

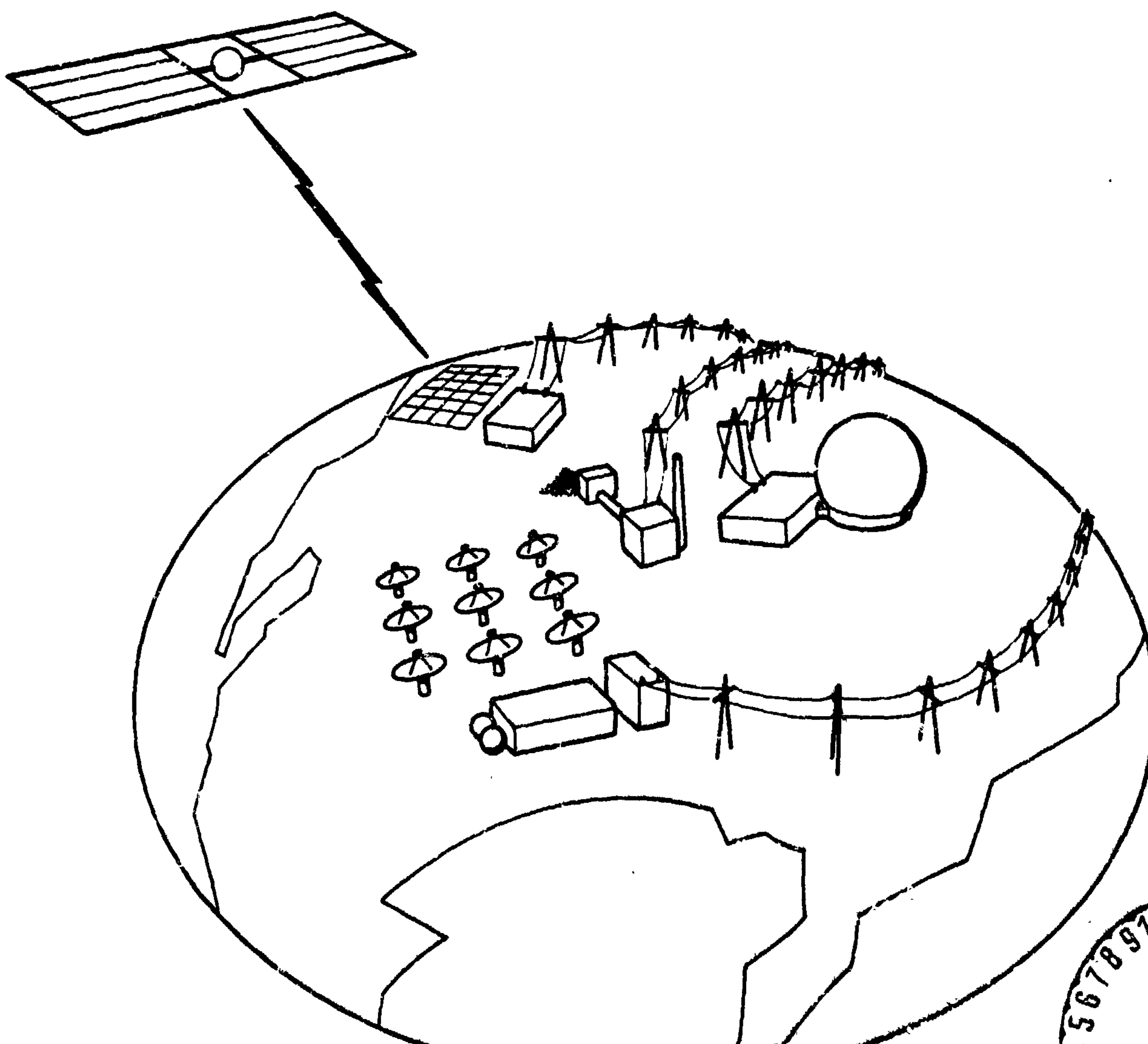
N77-22612

Unclas 26012



AN INITIAL COMPARATIVE ASSESSMENT OF ORBITAL AND TERRESTRIAL CENTRAL POWER SYSTEMS

Final Report



Prepared by The Jet Propulsion Laboratory for the NASA Office of Energy Programs

AN INITIAL COMPARATIVE ASSESSMENT OF ORBITAL AND TERRESTRIAL CENTRAL POWER SYSTEMS

Final Report

900-780
March 1977

Prepared by

Richard Caputo
Project Engineer

Approved by: Vincent Truscello

Vincent C. Truscello,
Project Manager

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

FOREWORD

The concept to use satellite solar power stations as energy sources for earth application was proposed by Dr. Peter Glaser of Arthur D. Little, Incorporated, in 1968. A feasibility study of the concept, with simultaneous identification of key issues, was sponsored by the National Aeronautics and Space Administration (NASA) in 1972. Additional studies are currently in progress under joint sponsorship of NASA and the Energy Research and Development Administration (ERDA).

As part of the concept assessment, NASA in May of 1974 requested the Jet Propulsion Laboratory (JPL) to initiate development of a data base for candidate future terrestrial power systems in order to evaluate the proposed satellite power systems. The terrestrial power plant types included likely fossil and nuclear energy systems and solar energy systems which would be available around the year 2000. Data development included system performance, operations, cost and impact. NASA also requested JPL to conduct an initial comparison of the earth-based and space-based energy configurations, employing the terrestrial power system data developed at JPL and the orbital power system data being developed concurrently by the Marshall Space Flight Center (MSFC) and the Johnson Space Center (JSC).

This report summarizes the work performed by JPL to provide a data base for candidate future terrestrial power systems and presents a preliminary comparison of these systems with a satellite photovoltaic power system.

This study was sponsored by the NASA Office of Energy Programs and was performed under the technical direction of Mr. Simon V. Manson of the Solar Energy Division.

ACKNOWLEDGMENTS

The broad treatment of central energy systems documented in this report is the result of many hours of work by many talented individuals. The work took over 2 years and 24 professionals directly contributed. Very substantial support came from the U.C. Berkeley researchers K. Smith and J. Weyant who developed the data base for conventional power systems under the direction of John Holdren in the Energy and Resources Program. Their maturity of judgment, objectivity and attention to detail was of great value to the project.

The 17 supporting reports to this final report were written by seven individuals. T. Fujita authored five reports, which ranged from energy transmission and distribution, underground storage, electric energy storage to a review of SPS performance and cost. His work went from deep below the earth's surface to geosynchronous orbit. M. K. Selcuk authored or co-authored four reports on solar power plants using various types of collectors. His depth of background in solar equipment gave valuable insights in these early assessments. Ram Manvi contributed in the area of system simulation and utility grid margin analysis. R. Turner reviewed thermal storage, and J. Doane provided support in developing economic methodology. C. Bell analyzed the terrestrial photovoltaic system and provided insights into approaches to technology assessment.

Tom English assisted in extending the impact assessment framework into the material acquisition and construction phases of the energy system and in critically reviewing the conventional energy study. Dr. English also developed the health effects flow diagrams shown in Appendix B. A. Brathenahl evaluated material use, related environmental residues and energy payback questions. F. McLaughlin performed initial studies on solar plant operation and maintenance costs. S. McReynolds developed occupational and public health impacts resulting from material acquisition and plant construction activities for solar plants. L. Smith organized RD&D costs and estimated manpower needs. C. Borden translated RD&D costs into equivalent energy costs. J. Finegold and R. French contributed to the understanding of small heat engine cost and performance. D. Pivirotto and O. Citron helped with early environmental impact assessment. L. Livingston, P. Poon and C. Baker provided support and G. Hill and R. Patton performed computer analysis for solar plants.

Substantial support was received in reviewing this work by T. English, R. O'Toole and R. Phen whose tough minded criticism significantly strengthened this report. I would like to thank the members of the JPL-Caltech review team who helped remove the rough spots from the final report. The chairman, R. Miles, provided a strong guiding hand, assisted by members M. Alper, R. Bourke, K. Dawson, R. Dickinson, R. Forney, M. Goldsmith, A. Hibbs, D. Montogomery and W. Spuck. A special thanks to D. Montgomery who raised significant questions in this review process.

P. Panda and C. Sink provided invaluable service and encouragement over the years by editing and typing all the manuscripts resulting in 17 supporting documents and the rough draft of this final report.

I would like to acknowledge the help and support of the NASA researchers at the Marshall Space Flight Center and Johnson Space Center on the SPS studies and contracted work. Personnel from ECON, Inc. and A. D. Little Company were helpful in various phases of the SPS evaluation.

The work was performed under the supervision of V. Truscello who was the project manager.

CONTENTS

FIGURES

FIGURES (contd)

TABLES

SECTION I

EXECUTIVE SUMMARY

In this report orbital solar power plants, which beam power to earth by microwave, are compared with ground-based solar[1] and conventional baseload power plants. Candidate systems were identified for three types of plants and the selected plant designs were then compared on the basis of economic and social costs. The representative types of plants selected for the comparison are:

1) Conventional
   - Light water nuclear reactor
   - Turbines using low BTU gas from coal
2) Ground Solar
   - Central receiver with steam turbo-electric conversion and thermal storage
   - Silicon photovoltaic power plant without tracking and including solar concentration and redox battery storage
3) Orbital Solar (Satellite Power System)
   - Silicon photovoltaics

Table 1-1 shows the estimates of the capital costs of these plants assuming a year 2000 plant startup, but using 1975 dollars. As may be seen, the capital cost of the orbital photovoltaic plant (estimated at 5600 $/kWe of rated power) is approximately the same as for the ground solar photovoltaic with fossil backup. The costs of both of these systems are about two and one-half to five times the anticipated future costs of conventional plants. The ground solar thermal plant with fossil backup is about one third less capital intensive as the Satellite Power Syutem (SPS).

---

[1]A base load plant is considered to have an annual load factor of at least 0.7. Extra margin is evaluated to maintain grid reliability.

Table 1-1. Summary Data[a]

Type of Power Plant	Coal[1]	Nuclear[2]	Ground Thermal[3]	Solar Photo[4]	Orbital Photovoltaic
Capital, \$/kWe	1150	2280	3600	5700[5]	5600[6]
Energy, mills/kWehr[7]					
• Plant (bus-bar cost)	58[8]	76[8]	89[9]	128[5,9]	118[6,10]
• System[11]	70	91	107	150	137
Federal RD&D, 10^9\$	1.5	1.4[12]	1.1	0.3	60
Energy Surcharge for RD&D, mills/kWehr[13]					
• 10 yr payback	1-15	1-14	0.8-11	0.2-3	42-800
• 30 yr payback	0.2-1	0.2-1	0.1-0.7	0-0.2	8-40
Maximum Health Impacts, PDL/MWeyr					
• Fuel Cycle[15]	200[16]	15.6[17]	0 (3.4)[14]	0 (3.4)[14]	
• Const and Mat'l[15]	1	1.4	6.8 (6.9)	2.9 (5.4)	?[18]
• Total[15]	201	17	6.8 (12.7)	3 (8.8)	?
• Deaths/Plant[19]	530	51	7.7 (35)	3 (30)	?
Land, m^2/MWeyr[11]	3600	800	3600	5400	2800[20]+?[21]
Excess Waste Heat, MWtyr/MWeyr	1.7	2.1	0.25	1.5	0.25[22]
Water, 10^6 liter/MWeyr	0.5-9.2[23]	1-24[23]	0.9-28.4[23,24]	0.6[24]	0.008
Material Total, metric ton/MWeyr[25]	6.1	15	225	65	18.9
Manpower, Total, Man hours/MWeyr	2640	1120	14400	2700+?[26]	6690
Energy Payback, yrs	1.9	1.4	1.7	?	1.4[27]

[a]All cost data for year 2000 plant startup in 1975 dollars. Divide solar capital costs by 1.22 to convert to 1975 startup. Footnotes are on following page.

Table 1-1. Summary Data (contd)

(Footnotes)

1. Coal: Low-Btu gasification with combined cycle.
2. Nuclear: Light-water reactor.
3. Thermal: Central receiver with thermal storage and gasified coal back-up.
4. Photovoltaic: Silicon fixed on tilted surface with concentration of 2:1 using asymetrical "V" trough concentrators rotated twice per year and gasified coal back-up.
5. Average of pumped hydro and redox battery storage.
6. 4 mil thick photovoltaics.
7. Energy costs based on a 30-year plant life.
8. Load factor: Coal = 0.74, nuclear = 0.70 (energy generated/rated energy).
9. Hybrid operation at load factor = 0.864 to meet grid reliability with solar load factor = 0.70.
10. Load factor = 0.864.
11. Includes average transmission and distribution to user in load center.
12. LMFBR RD&D approx 10 billion.
13. Rate of power plant implementation between lower and upper bound shown in Figure 6.4.
14. Solar plant portion of hybrid system, and ( ) includes average effects of 10% coal energy for back-up energy.
15. Accidents $\simeq$ 50 PDL, death $\simeq$ 6000 PDL (person days lost).
16. Does not consider NO_x, CO and other pollutants besides SO_x - particulates.
17. Does not include sabotage, blackmail, material diversion, genetic effects and long-term waste health effects.
18. Effects of making rocket chemicals and effects of combustion products unknown, microwave effects unknown, abort hazards unknown.
19. Based on plant construction and 30 year life.
20. Microwave intensity is 0.1 mw/cm^2 at the outer boundary of the exclusion area. The required land would increase to 7200 m^2/MWeyr if the eastern European standard of 0.01 mw/cm^2 was used.
21. ? Launch complex area.
22. Includes rectenna efficiency and atmospheric absorption of microwave energy.
23. Range indicated is for dry to wet cooling tower and includes fuel cycle water.
24. Photovoltaic collector cleaned every 10 weeks, while heliostat (thermal) cleaned every 5 weeks.
25. Excludes material for fuel (such as coal or uranium) and energy storage material.
26. Partial data. The O&M manpower and material acquisition manpower not included.
27. Primarily due to rectenna.

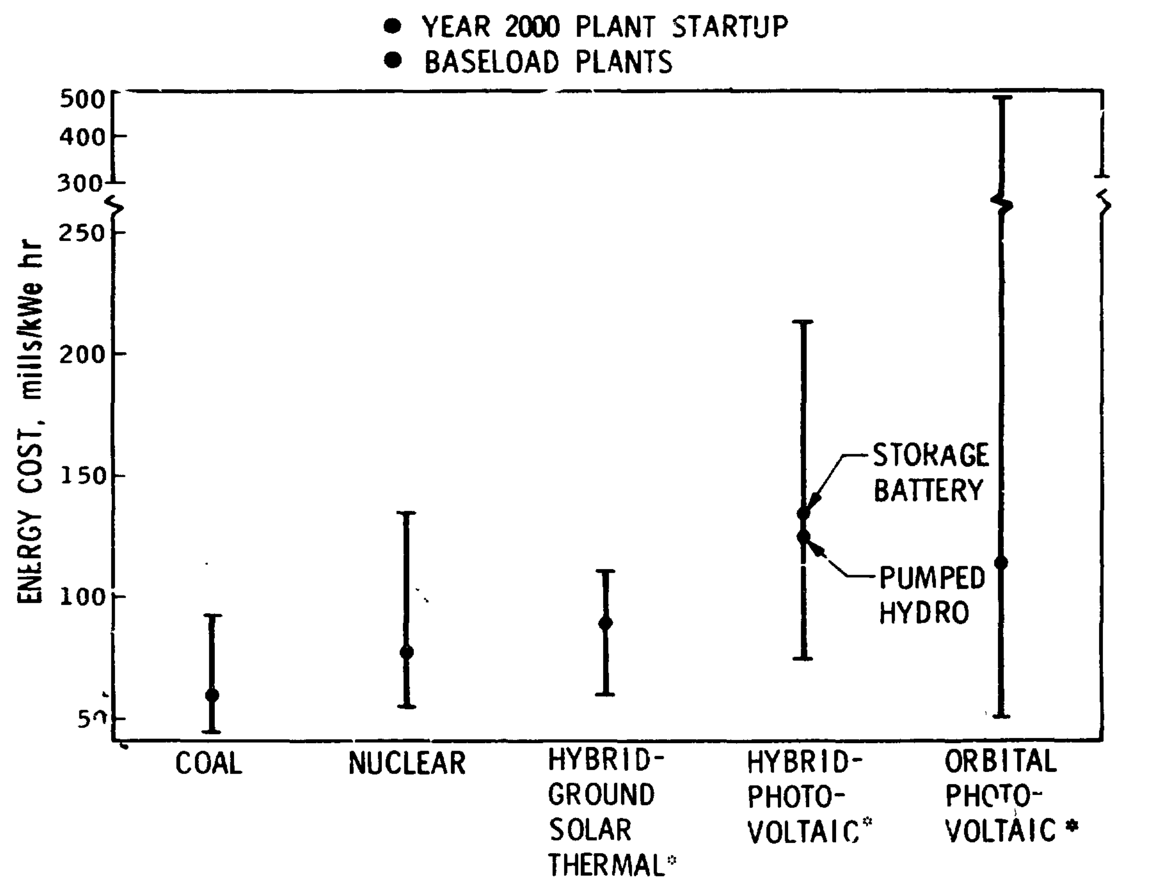
The levelized[2] bus-bar energy cost of the SPS plant (orbital photovoltaic) is estimated to be 118 mills/kWeh. This assumes a 4 mil thick solar cell design, and does not include the cost of the payback of the SPS development cost. The energy cost of the SPS at the reference design point is about the same as the ground solar photovoltaic plant, but is more than 70% greater than that of conventional plants and 30% greater than ground solar thermal with fossil backup.

If all the best and all the worst estimates of performance and cost are combined, the SPS energy cost would vary from about 40 to over 400 mills/kWeh as shown in Figure 1-1. This figure illustrates the wide range of uncertainty associated with an energy system which is at the conceptual stage of development. The ground photovoltaic cost range is from 74 to 210 mills/kWeh. The expected cost ranges of the coal, nuclear and ground solar thermal power plants are similar in the year 2000 time frame although the energy cost of the coal plant has the smallest uncertainty range.

Total energy costs, including the cost of transmission and distribution, were also determined for each approach. The probable transmission distances between the plant and load centers were identified for use some time after the year 2000. Overhead ac lines were assumed for distances up to 300 miles, and overhead dc lines were specified for distances greater than 300 miles. The costs of long distance transmission and distribution within the load center were added to the power plant cost of electricity to achieve the system or total cost of electricity. The total energy costs were only about 20% greater than the power plant bus-bar costs. The relative costs among the various plants remained constant even though the transmission distance varied by a factor of 7 among the different types of plants (300 miles for coal and 2000 miles for ground solar).

Although the plants selected for comparison are all baseload central electric plants, there are great differences among them. These differences result in significant variations in cost uncertainty. The LWR nuclear plant is an existing commercial plant, but faces strong and

[2] Levelized energy cost is approximately the average cost of energy over the life of the plant. It considers fixed (capital payback) and variable (operating) costs and includes cost escalation.



*LOAD FACTOR = 0.864. FOR GROUND PLANTS, THE SOLAR ENERGY CONTRIBUTES 0.70 AND GASIFIED COAL CONTRIBUTES THE REMAINDER. ADDITIONAL CAPACITY IS INCLUDED TO MEET UTILITY GRID RELIABILITY. GROUND PLANTS ARE RATED AT 100 MWe IN A SOUTHWEST U.S.A. LOCATION. SOLAR THERMAL HAS 9 HOURS STORAGE, AND GROUND PHOTOVOLTAIC HAS 12 HOURS STORAGE. STORAGE IS AT 70% RATED POWER

Figure 1-1. Summary of Plant Energy Cost broad social resistance which may require significant, costly changes. There is also resistance to coal plants, although it is not as pronounced at this time. Ground solar thermal plants are in the early stage of development and have large potential cost uncertainties normal to this stage in development. Competitive economics for the ground photovoltaic power plant are based on attaining the 1985 ERDA goal of $0.50/$We_{peak}$ for the photovoltaic modules, and the lower bound is based on $0.20/$We_{peak}$ and improved efficiency. The rest of this system uses state-of-the-art subsystems with the exception of the advanced Redox battery storage subsystem. The orbital photovoltaic system shares the uncertainty of the silicon cell costs with the ground photovoltaic plant, but in addition has many other major subsystem cost and performance uncertainties.

The ground solar-fossil hybrid plant assumes an annual average load factor[3] of 0.70 for the solar part of the plant and 0.864 for the total plant. This is attained by locating the plant in the Southwest USA, having about 9 hours solar storage capacity available at the plant, and providing extra backup capacity (margin) in the form of gassified coal energy to make the ground solar plant as reliable as conventional plants not subject to the sporadic unavailability of sunlight. The backup system increases the capital cost of a ground solar plant by about 8%. However, the energy costs ($/kWh) are lowered by 7% because the added energy capability produced by the backup system is less expensive than the energy produced by a solar stand-alone plant.

Although the SPS is considered to have a high annual load factor (≈ 0.9), it will also require extra backup capacity just due to its large size (5000 MWe). Any plant of this size introduces unreli abilities into a utility grid, but the magnitude of the needed extra margin is unknown at this time.

In addition to capital and energy costs, a number of other areas of concern are compared in this assessment. The other areas considered are Federal Research, Development and Demonstration (RD&D) costs, resource utilization, health costs, environmental costs, and "other" social costs. The utility or consumer costs plus the variety of social costs taken together represent the "true" total cost of the system.

[3]Load factor is the actual energy generated/rated energy.

However, summing these costs is difficult because the data are in different currencies; i.e., consumer dollars, Federal tax dollars, tons of steel, BTUs of excess waste heat, deaths, etc.

The Federal RD&D costs to bring a plant concept to commercialization are shown in Table 1-1. The SPS is estimated to cost $60 B (billion dollars). This cost is significantly greater than that of all the other alternatives which are in the $0.3 to $1.5 B range. The government is presently also developing the liquid-metal fast-breeder reactor (LMFBR). Although it was not selected as the reference nuclear system, it potentially will be a viable candidate after the year 2000. RD&D costs for the LMFBR (not shown in Table 1-1) are estimated to be at least $10 B.

If RD&D costs are spread over the first 30 years of commercial energy generation, the levelized energy cost is from 8 to 40 mills/kWeh[4] for the SPS using a 10% social discount rate. On the same basis the ground solar and conventional plants would have less than 1 mill/kWeh energy charge to pay back the RD&D. Again, the only exception is the LMFBR whose RD&D energy charge would be 1 to 7 mills/kWeh.

The estimates for maximum health impacts for the various types of plants are shown in Table 1-1. These are for the fuel cycle, material acquisition and the construction phases of the plant life. The health impacts of the SPS are presently unknown, but health impacts could come from several sources. Occupational health impacts will occur due to industrial accidents during material acquisition, launch operations, space construction and operation as well as rectenna construction and operation. In addition to typical industrial accidents, there is the potential that several unique occupational hazards exist with the SPS due to launch activities, extra vehicular activity in space, SPS space charge, meteroroid strikes, solar flares and other space phenomena, the natural radiation environment in geosynchronous orbit, the microwave radiation environment near the transmitter, and possibly even at the receiver on the ground.

Public health hazards from launch rocket emissions exist with the SPS. Also the geosynchronous tug and station keeping propellants

[4]The range of equivalent energy cost to payback the RD&D cost is due to the range of new plant installation.

(ionized particles) could cause additional public hazards. The microwave beam could cause indirect public health effects due to atmospheric effects, or direct public health effects near the rectenna. Finally, there is the potential catastrophic public health impact of a launch vehicle or space station items falling on a populated area.

Of the ground power plants, as may be seen in Table 1-1, the "clean" coal plant has the greatest maximum total health effects of about 200 people days lost (PDL) per MWeyr[5] of energy generated. These are derived from a variety of causes such as the occupational health effects due to mining coal, and the public health effects of SO_x emissions at the plant (CO, NO_x and other pollutants are neglected), the public health hazards at railroad crossings due to collisions with coal trains and the waste products from mines and power plants.

Ground solar plants have between 3 and 7 PDL/MWeyr due primarily to occupational accidents during construction, and to a lesser extent to occupational accidents and illness during material acquisition. The public health impact of solar stand-alone plants is almost nil, and what there is, is due to emission from the primary metal fabrication plants which make the steel, aluminum, concrete and glass for the plant. However, the total health impacts increase by about 10% of that of the reference coal plant where the solar plant is operated as a hybrid using coal as the backup energy source, and could be as large as 13 PDL/MWeyr.

The LWR nuclear plant health impacts lie between that of ground solar and that of coal plants with a maximum estimated impact of 17 PDL/MWeyr. The effects of the catastrophic accidents include only direct deaths and does not include person days lost due to illness, injury, genetic effects and property damage as a result of core melt-down. The possibilities of blackmail, sabotage and material diversion to a weapon are neglected, as are health effects of long-term waste disposal and large accidents at other fuel cycle facilities.

As shown in Table 1-1, land use of the SPS is 2800 m^2/MWeyr (for a microwave intensity of 0.1 mw/cm^2 at the outer boundary of the exclusion area). This is somewhat less than a ground solar thermal

---

[5]As a reference point, 100 PDL/MWeyr is equivalent to 2.4 hours of indisposition for each year for the electric energy use by the average person in society.

plant (3600 m^2/MWeyr) and a coal plant (3600 m^2/MWeyr). This total includes land used for transmission right-of-way which is greatest for a ground solar plant based on 1650 mile average transmission link. The LWR is lowest at 800 m^2/MWeyr while the ground photovoltaic plant is highest at 5400 m^2/MWeyr. The LWR land use will increase dramatically toward the end of the century as current high grade ores are depleted. Only the timely introduction of the breeder reactor will prevent this large land consumption for uranium mining. The land used at the plant is almost the same for orbital and ground solar thermal plants (approximately 2200 m^2/MWeyr). However, if the Eastern European microwave standard is used, the SPS plant land use would triple.

The SPS and the ground solar thermal plants have a very favorable excess waste heat balance and only add about 0.25 MWyr thermal energy per MWeyr to the biosphere compared to 1.5 MWtyr/MWeyr for ground photovoltaics, 1.7 MWtyr/MWeyr for coal and 2.0 MWtyr/MWeyr for nuclear.

The SPS will use almost no water except for launch operations and rectenna maintenance (cleaning) which should be quite small. The use of dry cooling techniques with ground solar thermal plants will reduce cooling water requirements to zero, but other plant water requirements will be about 1 million liter/MWeyr. The ground photovoltaic plant will use half this amount of water, mainly for collector surface cleaning. The water use of a LWR is significant at 24 million liter/MWeyr when wet cooling techniques are used, but decreases to 1 to 2% of this value if dry cooling towers were introduced.

As shown in Table 1-1, the material required by the SPS is estimated at 19 MT/MWeyr and manpower is estimated at 6700 MH/MWeyr. The total material and manpower requirements are greatest for the ground solar thermal plant at 225 tons/MWeyr (excluding thermal storage) and 14,400 man hours/MWeyr. Glass production must be increased significantly by the year 2015, and 0.2 million men could be employed in construction if plants were built at the rate of 10 GWe per year. The coal plant has the lowest construction material requirements (6.1 tons/MWeyr), while the LWR plant has the lowest manpower requirements (1120 man hours/MWeyr).

Items which could not be quantified for inclusion in Table 1-1 but which may be of considerable concern have been labeled as "other social costs" and refer to such items having characteristics that are non-quantitative or that are quantitatively known but for which the effects are poorly understood. An example of the first would be the degree of catastrophe associated with a health effect. There apparently is greater perceived social cost (impact) if an energy system's health effects occur all at once in time and location (i.e., nuclear core melt-down or an orbital launch vehicle falling on a population center), versus a more even distribution of health effects (i.e., from coal plants). An example of a poorly understood but quantitatively known effect would be the amount of CO_2 and particulates which are released from a coal fuel cycle. The magnitude is known but the global climatic effects are not well known, nor are the ramifications of these potential climate changes.

A listing of some of these important yet difficult factors to quantify is presented:

1) The social impacts of sabotage or blackmail perpetrated against a power plant.

2) The possibility of material diversion to use as a weapon.

3) The catastrophic nature of accidents.

4) The duration and temporal distribution of an impact.

5) The vulnerability to a military attack either directly or indirectly.

6) The environmental and health effects of:

   a) Excess waste heat.

   b) CO_2 particulates, and Kr-85.

   c) Acid rain.

   d) Long-term toxic wastes.

   e) Microwave beam to earth.

   f) Boost vehicles emission throughout the atmosphere including the magnetosphere.

7) The health impacts of noise.

8) The use of non-renewable rather than renewable or salvageable resources.

9) Conflicting land use.

10) Local disruption due to initial construction and operation over plant life.

11) Communication and radio-astronomy interference due to microwave transmission.

12) Aesthetic impacts.

13) Legal or liability concerns.

In summary, this comparative assessment is an attempt to compile in a consistent framework, the available data describing the economic and social characteristics of a number of central electric base-load power plants. In the final analysis, choosing the mix of technologies for future power production is a social decision and needs broad input from throughout society so that we have some assurances that the system coming on line 15 to 30 years from now will be socially acceptable. This report makes an attempt to provide quantifiable data required to permit these complex decisions to be made.

SECTION II

INTRODUCTION

A comparison is made of the economic and social characteristics of the Satellite Power System (SPS) with those of conventional and solar terrestrial power plants. The study assumes that in making the comparison, the broadest view should be taken of what actually forms the ingredients for social suitability. The concept of total social cost is used as the basis for the evaluation. The total social cost includes utility cost of commercial generation and of electric energy delivery as well as the consideration of social costs involved. These include areas such as the Federal RD&D investment to create a commercial demonstration, the energy payback requirements, the health effects of the entire series of activities required to bring on line and operate a power plant, environment impacts, resource consumption and other impacts.

In conducting this study, no a priori judgment was made regarding the social or economic desirability of the SPS; rather, the study tries to present the economic and social factors of the SPS and alternate systems as well as they are known today.

The SPS and alternative central power plants were compared using a consistent assessment framework. All of the systems were evaluated over the same time period with the same economic ground rules and with a consistent set of resource, environmental and health impact parameters.

The following central electric power systems were selected for comparison since they may be in significant use in the United States toward the end of this century and into early next century:

(1) Fossil Fueled Systems

a) A coal system with low BTU gasification and combined cycle combustion.*

b) A coal fired system with fluidized bed combustion.

*Reference Design.

c) A coal fired system with a line scrubber for flue gas desulfurization.

These three systems remove the sulfur from the coal prior to combustion, during combustion and after combustion, respectively.

d) A residual fuel oil system (RFO) was included in the analysis for the sake of completeness, although the application of this type of system will probably be decreasing in this time frame, due to the price and relative scarcity of oil.

(2) Nuclear Systems

a) The conventional light water reactor (LWR).*

b) The light water reactor with plutonium recycle (LWR-Pu).

c) The liquid metal fast breeder reactor (LMFBR).

d) The high temperature gas cooled reactor (HTGR).

(3) Solar Central Power Plants

a) A "power tower" system (Central Receiver) (2-axis sun tracking).*

b) A parabolic dish collector system with three forms of energy transport (steam, chemical and electrical) (2-axis sun tracking).

c) A parabolic trough system (1-axis sun tracking).

d) A flat plate collector system (non-tracking).

e) A central photovoltaic system (non-tracking).

f) A satellite solar power system using photovoltaic energy conversion.*

Special emphasis has been given to a reference design for each major category of central electric plant. The first plant listed above

---

*Reference Design.

under coal, nuclear and solar is chosen as the reference design, along with the orbital SPS. The gasified coal, combined cycle plant is chosen as a reference since it is based on existing component technology and promises to reduce public health effects at the plant by 2 orders of magnitude compared to uncontrolled current coal plants.

The light water reactor (LWR) was chosen as the nuclear reference design. Although it is the only commercial design available at present, it will be having a fuel (uranium) depletion problem by the year 2000. Even though there is uncertainty, the LWR has the advantage of having the best data base on costs and possible health effects. The LWR with Pu recycle may offer a small economic advantage but introduced the difficulty of moving plutonium (Pu), a nuclear weapon material, through society. The high temperature gas reactor (HTGR) is promising and has several environmental and public health impact advantages over the LWR. However, it has recently been discontinued from commercial development. The breeder reactor (LMFBR) at present has uncertain cost and environmental and public health impacts. The LWR is felt to be representative of nuclear plant cost and hazards, and suitable as the representative nuclear design.

The central receiver solar thermal plant is currently under intensive development as the first generation solar central power plant. Its cost and general characteristics are felt to be representative of several approaches. The terrestrial photovoltaic power plant is also selected as a reference design so there can be a direct comparison with the SPS. Both these approaches are based on achieving the same low cost goal for the photovoltaics, but the SPS assumes further developments to reduce weight and increase efficiency of the photovoltaic modules.

Figure 2-1 gives an overview of the entire assessment program. The conventional power plants, ground solar plants and orbital plants are evaluated on the same basis. For each of the above systems, the economics have been examined in terms of parameters such as capital cost (in dollars per kW electrical rated power), and projected bus-bar cost to the utilities (in mills/kWhr of electrical energy produced). Needless to say, it is quite difficult to precisely estimate what these economic parameters will be near the end of the century. Uncertainties include: the projected performance of the power plants, their eventual

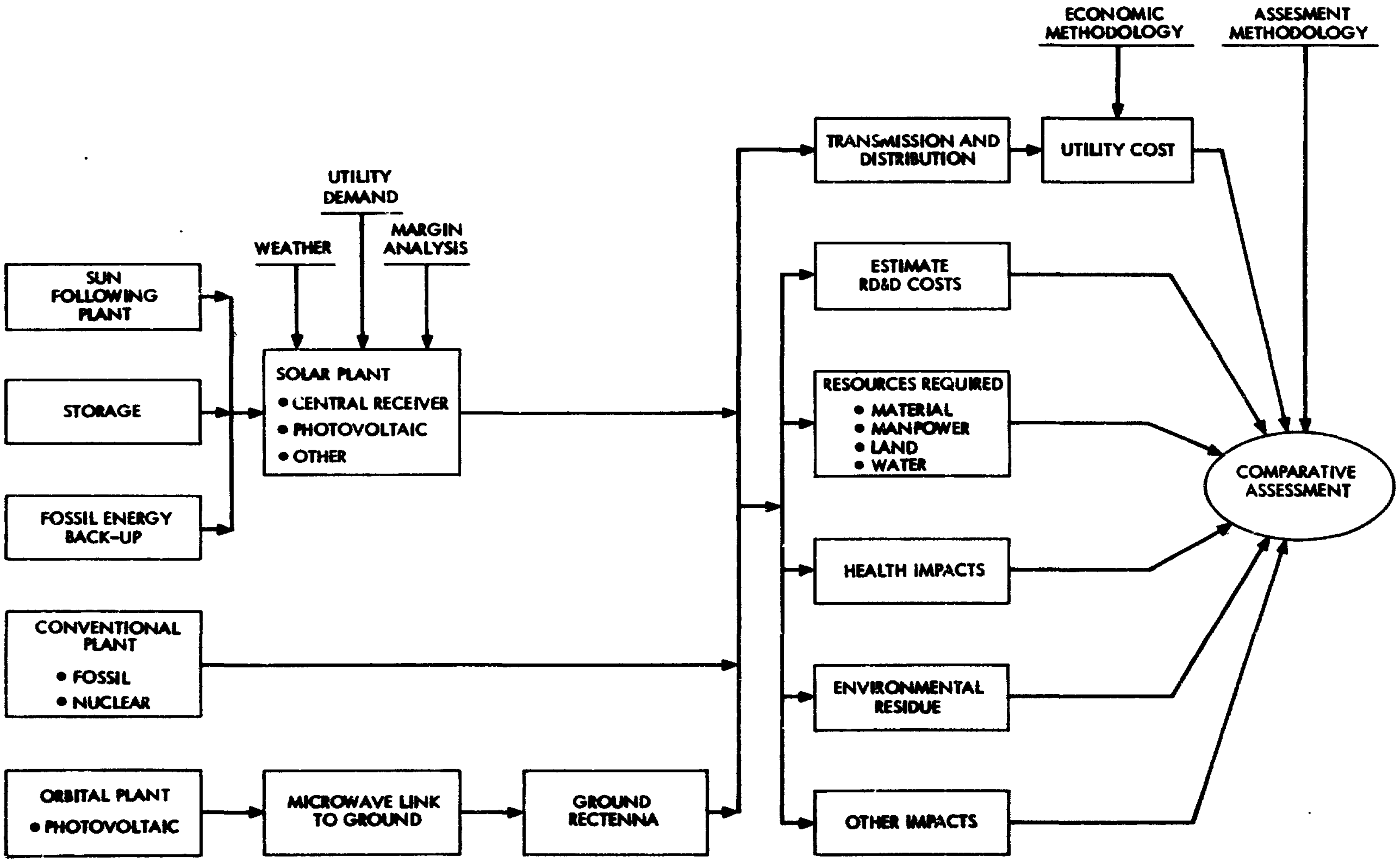


Figure 2-1. Comparative Assessment Overview

commercial costs, and the differential rate of inflation among systems. Plant costs are then combined with transmission and distribution costs to establish the total utility costs to the consumer for each central plant as shown in Figure 2-1.

Each plant type requires RD&D support to reach commercial prototype or to complete work to enhance the safety for minimizing public impact. The Federal RD&D (Research, Development and Demonstration) funds have been estimated for each approach.

The resource requirements were evaluated for each plant and included material, land, water and manpower. In addition, health, environmental and other impact areas were identified for each approach. In a sense, there is double-bookkeeping in this approach to total social cost evaluation. The resources were economically accounted for in the cost of the plant, and the social cost of health and other impacts are also somewhat accounted for in future plant cost increases. Nevertheless, these areas are included as separate areas of concern which should be considered in a plant-to-plant comparison.

The philosophy followed throughout the study was to attempt to evaluate the complete energy cycle for these systems; this cycle is broken down into seven steps. The cycle includes acquisition of materials necessary to build the plant, the construction of the plant, and the complete fuel cycle required to operate and maintain the power plants. The fuel cycle includes extraction of fuel, processing, conversion, transportation, power generation and waste management. This study has employed existing knowledge found in the literature for the fuel cycles of the fossil fuel and nuclear power plants. New data have been developed for the material and equipment acquisition cycle, and for the construction cycle of solar as well as fossil and nuclear power plants.

The scope of the work has been limited to central electric energy systems since this initially is the most appropriate for comparison to the SPS and since the SPS is such a large (5000 MWe) and potentially high load factor (≈ 0.9) plant. The ground solar plants studies convert solar energy to electricity either by thermal or photovoltaic conversion processes. Indirect forms of solar energy, such as wind power, ocean thermal and ocean current power, biomass or geothermal, were not considered in order to limit scope so that sufficient attention could be given to terrestrial uses of direct solar energy. On-site, total energy or community sized solar plants were also not considered, in order to limit scope. Total energy systems would generate electricity as well as waste heat to meet a range of user energy needs. There is no inference that these energy systems which were excluded, due to limited resources, are not as favorable or even more favorable than the solar systems considered.

Operation of the SPS at geosynchronous orbit (23,000 miles) was the only location considered. Low earth orbit (LEO) locations with microwave beaming to a geosynchronous orbit for microwave relay to earth were not considered.

Only silicon photovoltaics were considered for both the orbital (SPS) and ground photovoltaic plant. Solar thermal conversion and nuclear energy conversion were not considered in this study for the orbital power system.

All materials used in the SPS are brought up from the earth (the moon was not considered as a source for SPS materials).

This report is divided into roughly two parts. The first (Sections III, IV and V) develop the projection of power plant utility and delivered electricity costs by the year 2000 using both terrestrial and orbital central power plants. The second half (Section VI) develops information on other social costs such as federal RD&D, resource requirements, health impacts, environmental and other impacts.

No attempt is made to indicate that there is an "answer" to this study. Once social costs other than economic are introduced into a study, there can be no single best choice for everyone. Each decision maker in society must introduce their own set of values in reviewing this material to determine which energy systems are more (or less) desirable.

The spirit of this study follows along the lines suggested by J. Coates of the congressional Office of Technology Assessment: "To be useful, therefore, a technology assessment must go far beyond conventional engineering and cost studies to look at what else may happen in achieving an immediate goal, to the total range of social costs ..." (Ref. 1).

SECTION III

ECONOMIC GROUND RULES

The comparison of utility cost to generate power at the bus-bar (central plant) or at the consumer in the load center is one of the primary methods used in this study to evaluate alternative power plants. There is a profusion of economic methodologies in use by the utilities, government agencies and research groups studying energy. An attempt was made at JPL, sponsored by the low cost photovoltaics project, to create a methodology which combined several major forces in central power plant economic methodologies. Reference 2 documents this approach and is the result of collaboration of members from ERDA, EPRI, the Aerospace Corporation and the Jet Propulsion Laboratory. Preliminary versions of this economic approach were used in the various analyses during this project, but for this final report all calculations have been redone using the complete and final version.

The economic methodology considers capital, fuel, operation and maintenance (O&M) costs, as well as taxes, insurances, profit and multiple sources for raising capital. The methodology considers escalation from 1975 (the year goods and services are priced) to the year of plant startup in all cost areas (i.e., installed capital, O&M and fuel). Escalation of cost is also considered during the power plant's operational lifetime, especially for recurring costs such as O&M and fuel. These operational costs are collapsed to present values as of the year the plant starts operating and levelized much in the way capital costs are levelized. Such an approach more nearly represents the average cost of energy over the life of the plant rather than the first year cost of energy. This is especially appropriate when comparing different plants that are capital intensive or are fuel cost intensive. The rising costs (in constant dollars) are considered over the plant life.

Several factors are used to go from direct costs to total construction costs. The direct cost is for the manufacture of material and equipment, shipping to the site and labor costs for construction. To this is added an amount for spares and contingency and indirect costs for design, construction management and special construction facilities.

The factors by which the direct costs must be increased are shown below.

	Capital Cost Factors	
	One-of-a-Kind	Repetitive
Spares and Contingency	1.076	1.038
Indirect	1.20 (for 1000 MWe) 1.30 (for 100 MWe)	1.10

The above factors are based on Reference 3; the factor for one-of-a-kind is used for either conventional plants or conventional subsystems of a solar plant. The repetitive factor is for those subsystems that are made up of thousands of similar modules such as collectors, certain types of storage, etc. Capital cost factors should be less for these repetitive subsystems. The total construction cost is the sum of all the direct costs augmented by the proper capital cost factor. For a 100 MWe plant the cost is as follows:

$$\text{TOTAL CONSTRUCTION} = 1.076 \times 1.3 \sum_{i=1}^{n} A_i + 1.038 \times 1.1 \sum_{i=1}^{m} B_i + C$$

where

A_i = direct capital cost of one-of-a kind subsystem

B_i = direct capital cost of repetitive subsystems

C = construction interest

In simplified and approximate terms, the energy cost is given by the expression

$$EC = \frac{R}{PL8,760} (hI + f_1 O + f_2 M + f_3 F) \text{ mills/kWehr}$$

where

R = capital recovery factor which annualizes the initial capital outlay

h = factor which includes taxes and insurance

I = total construction capital cost, dollars

O = annual operating cost, dollars/yr

M = annual maintenance cost, dollars/yr

F = annual fuel cost, dollars/yr

f = factor which creates a present value of the rising cost stream due to inflation

P = plant rated power, MWe

L = annual average load factor (generated energy/8760 P)

Appendix A can be referred to for the development of these relationships and their precise form.

In using this methodology, the year 2000 plant start-up time is generally used; however, 1975 dollars are used throughout and differential escalation to the year 2000 is considered. The time frame near the year 2000 is of interest for this study since this is the estimated time when a small number of SPSs could be operating. The year 1975 plant start-up is also used for conventional plants so that the results of this economic methodology may be compared to today's costs using other approaches.

The specific assumptions used in the economic analysis are shown in Table 3-1. The installed capital escalation rates are for a plant without the presence of social resistance to its installation. The quantities which are the most difficult to evaluate with confidence are the escalation rates for installed capital for the coal, nuclear and solar plants. These rates will be discussed in the following section as each type of power plant is considered.

Table 3-1. Economics Assumptions (Ref. 2)

Factor	Value
System Operating Lifetime, years	30
Annual "Other Taxes" as Fraction of Capital Investment	0.02
Annual Insurance Premiums as Fraction of Capital Investment	0.0025
Effective Income Tax Rate	0.40
Ratio of Debt to Total Capitalization	0.50
Ratio of Common Stock to Total Capitalization	0.40
Ratio of Preferred Stock to Total Capitalization	0.10
Annual Rate of Return on Debt	0.08
Annual Rate of Return on Common Stock	0.12
Annual Rate of Return on Preferred Stock	0.08

	Annual Growth Rates, % (Refs. 4,5)	
	1975-1985	After 1985
General Price Level	5.0	4.2
Labor (Construction)	7.0	6.2
Manufactured Goods	4.3	3.8
O&M (3/4 Labor, 1/4 Goods)	6.3	5.6
Other (Insurance, Taxes, Profit, etc.)	5.0	4.2
Installed Capital	6.2	4.8

SECTION IV

POWER PLANT ECONOMICS

The power plant or bus-bar cost of energy has been determined for the various power plants identified in Section II. Each power plant has peculiarities that make it difficult to project the utility costs to the end of the century. It is almost as difficult to project the future costs of some existing commercial plants as it is to estimate the mature commercial costs for prototype plants or conceptual designs. This difficulty arises because the conventional plants identified as the most likely systems for use as central electric power plants are based on coal and nuclear fuel, and both of these systems have experienced extraordinary cost increases over the past decade. The underlying cause of this inflation seems to be as much a social phenomena as economic. The uncertainty in predicting future costs is more due to the uncertainties of projecting social resistance whether through government bodies or legal processes instituted by citizens, than of understanding labor, material and technical issues (Ref. 6). Consequently, all the estimates which have been made for power plant capital and energy cost have uncertainty bands asso' ' ted with them.

4.1 CONVENTIONAL PLANT ECONOMICS

After reviewing many alternative fossil and nuclear fueled central power plants, eight were identified as potentially feasible systems to provide central electric power by the end of the century (Ref. 7). Three plants were based on coal; these were: 1) a coal fueled steam Rankine plant with lime scrubbed flue gas desulfurization, 2) a coal fueled steam Rankine plant with fluidized-bed combustion, and 3) coal conversion to low BTU gas fueling a combined cycle gas turbine and steam Rankine plant. These three technologies are estimated to remove 90%, 95% and 99.7% of the sulfur in coal either after, during or before coal combustion, respectively. The total construction cost (in 1975 dollars) of a coal plant which comes on-line in the year 1975 is estimated to be 450 $/kWe for the stack scrub, 335 $/kWe for the fluidized bed and 445 $/kWe for the low BTU gasification (Ref. 7). The overall conversion efficiency from coal to electricity with wet cooling towers is estimated to be 37% for each approach (Ref. 7). The plant efficiency of 37% is used but gas turbine technology improvements (2200^{o}F to 3100^{o}F turbine inlet) could increase the combined plant-coal gasification efficiency to 46%.

The residual fuel oil (RFO) plant was considered but this type of plant would be phased out toward the end of this century. Phase out would occur due to oil depletion and the greater social utility of oil for transportation needs.

The coal gasification and combined cycle approach has been chosen as being typical of coal based technologies which will be available by the year 2000 and is used in subsequent comparison studies. It was chosen because it has the minimum public health impacts since it removes almost all of the sulfur oxides (SO_x) pollutant, and has a capital cost within 35% of the least expensive approach. There is currently an unknown amount of pollutants from the gasification stage which may have occupational and possibly some public health effects. This is only one of many uncertainties regarding these power plants.

The four nuclear based technologies selected were: 1) the light-water reactor (LWR) using enriched (2-4% U-235) uranium oxide fuel in metal cladding processed from sandstone ore. Pressurized or boiling water is used to carry the heat from the reactor core, and a steam Rankine plant (with 32% conversion efficiency) is used to generate electricity. The spent fuel is reprocessed but only uranium is recycled; 2) an LWR with plutonium recycle which uses plutonium produced in the uranium-fueled LWR to reduce the need for enriched uranium; 3) a liquid metal fast breeder reactor (LMFBR) which converts U-238 to plutonium and potentially can generate all its fuel from the more plentiful U-238 and be completely independent of U-235. Liquid metals are used to carry the heat from the reactor core to a steam Rankine plant where it is converted to electricity (with 39% conversion efficiency); and 4) a high temperature gas cooled reactor (HTGR) which is an advanced converter reactor which operates on the uranium-thorium fuel cycle (39% conversion efficiency). A graphite matrix core is used with a carbide fuel form, and helium is used to carry the heat from the reactor core. Early versions use a steam Rankine plant, while more advanced versions will use the helium directly in a closed cycle Brayton engine.

Of these options, the one chosen as representative is the LWR since it is the one with the best economic and environmental data base. The LWR is estimated to cost 470 $/kWe total capital cost for a 1975 start-of-operation in 1975 dollars. There are regional differences in nuclear and coal plant costs that could vary by ±25%. The values quoted are national averages. However, the LMFBR or some other breeder will have to be developed if we are to use nuclear power without quickly depleting the uranium resource (Ref. 8). LMFBR economic characteristics are poorly understood and mature cost estimates vary from little more than the LWR system cost to 2000 $/kWe (Ref. 9). The Clinch River demonstration plant is estimated to cost at least 6000 $/kWe ($2 billion for a 350 MWe plant) (Ref. 9). The first full scale commercial LMFBR is expected in the 1990s.

The HTGR program has had a recent setback when the only commercial supplier (Gulf Atomic) decided not to continue introducing this new technology at the present time. Their decision appears to be due to the economic risks that are involved. The Energy Research and Development Administration (ERDA), however, has shown some interest in exploring possible underwriting of early HTGR plants.

The major uncertainty in the economic performance of a nuclear and to a lesser extent, a coal plant, is the future projection of installed capital and fuel costs. The historical (1960 to present) cost escalation for nuclear plants has been about 10% more than general inflation (Ref. 6). Escalations in nuclear capital costs have been in the 16 to 20% per year range since the early 60s while general inflation has averaged 6 to 8% (Ref. 3). The nuclear industry has consistently underestimated the cost when ordering a new plant. Actual costs in constant dollars after construction have been about three times greater than estimated (Ref. 6). The reasons for these trends are varied (Ref. 3); but the major causes apparently are not administrative or technical. The basis for the extraordinary cost increases appears to be social or political in nature. In a broad sense, it represents the internalization of heretofore external social costs and appears to represent a broad social resistance to nuclear and even coal central power plants.

The specific nature of future requirements in coal or nuclear plants that could cause continued differential inflation is not developed in this study. Potential factors in differential inflation for nuclear plants include the possible introduction of underground siting, the use of nuclear parks, the requirements for dry cooling towers, expensive deactivation of obsolete plants, more expensive insurance, redesigned emergency core cooling systems, high waste disposal costs, etc. Coal plants may be required to go to gasification or fluidized bed techniques and the costs of achieving these advances may be greater than expected. Additional pollution controls may be necessary at the gasification step, and coal waste products may have to be dealt with differently than in the past.

Available techniques have erred substantially in the past when attempting to predict current and future costs of nuclear and to a lesser extent coal power plants (Refs. 3 and 6). Rather than predicting specific events that would occur to nuclear and coal plants and establishing a causal relationship between these events and future cost trends, a straightforward approach is taken to bound future costs. The recent past (15 years) is used as a guide to the future. A lower and upper bound of expected nuclear and coal plant capital costs is established to extend past cost increases to the year 2000 in a certain fashion. The upper bound of nuclear capital cost projection is based on assuming the historic rate of 16 to 20% inflation (10% differential inflation) and gradually reducing it to a lower value (nearly 1/2 original rate) by the end of the century (Ref. 7). The lower bound consists of more quickly reducing the differential inflation rate to a socially neutral value by 1990. Socially neutral would represent no social resistance and would have the numerical values shown on Table 3-1 in Section III. A mid (reference) prediction of capital cost differential escalation lies between the upper and lower bound and goes from historic rates to socially neutral rates by the year 2000. These data are shown in Table 4-1.

Table 4-1. Plant Capital Cost Differential Escalation Factors, %*

Type	1975-1980	1980-1985	1985-1990	1990-1995	1995-2000
Nuclear					
Low	10	5.6	1.2	0.6	0.6
Mid	10	8	6	4	2
High	10	8.75	7.5	6.25	5.0
Coal					
Low	4.25	2.4	0.6	0.6	0.6
Mid	4.25	3.3	2.4	1.5	0.6
High	8.5	6.8	6.5	3.4	1.7
General Price Inflation	5	5	4.2	4.2	4.2

*Fuel cost differential escalation from 1975 to 2000:

Coal: Low = 1%, Mid = 2%, High = 3%.

Nuclear: See text.

Note: Total inflation rate equals general price inflation plus differential escalation.

A similar procedure is followed for the bounds of the capital cost of coal plants. We project the use of an advanced and relatively clean operating coal plant (gasification and combined cycle) that eliminates more than 99% of the sulfur from coal and significantly reduces public health effects. Since for such clean coal plants the social resistance will abate more rapidly than would otherwise be the case, we have assumed that the future coal capital costs would decrease more rapidly than was the case with the LWR. Specifically, the coal capital cost upper limit is considered to start at historic rates of differential escalation (8.5%) and decrease to socially neutral by the year 2000. The low bound is considered to go from one-half historic rates to socially neutral by 1985. These rates are shown in Table 4-1.

The effects of this escalation on capital cost are shown graphically in Figure 4-1. The costs for a 1975 plant start-of-operation (less than 500 \$/kWe) escalate to a range of 1400 to 2900 \$/kWe for a nuclear plant and 675 to 1650 \$/kWe for a coal plant for operation by the year 2000 in 1975 dollars. This projection of future costs, due in part to continued internalization of external costs, is in a sense a double accounting of factors that will be considered later in Section VI. The factors to be considered in Section VI deal with resource consumption, energy breakeven, health effects, environmental impacts and other social costs. All these considerations will in some manner contribute to continued cost increases. However, the projection of capital and fuel costs to the time frame of interest is felt to be valuable, as is the evaluation of resource, health, environmental and other impacts of these energy systems.

The fuel costs for coal and uranium ore have undergone rapid increases in recent years. For example, the average coal price to the utility industry doubled from 1973 to 1974. Fuel prices will most certainly continue to escalate due to a combination of union wage demands, increasing attempts to protect the environment, occupational health and the rising cost of alternate fuels such as oil and gas. The long-term differential escalation rate for coal is estimated to be 2% (Ref. 10) while 3% is considered the long-term upper limit (Ref. 7); the lower limit to the escalation of fuel for a coal plant is considered to be 1%. The 2% escalation rate will cause a 64% increase in the average utility industry cost of coal by the year 2000 from the 1975 cost of \$0.89/MBTU (23 \$/ton).

The nuclear fuel cost is made up of five parts as outlined in Reference 7: uranium ore (U_3O_8), uranium floride (UF_6) conversion, U_{235} enrichment, fuel fabrication and reprocessing wastes. In 1975 dollars, the U_3O_8 cost is considered to go from 13 \$/lb for the initial core installation to 45 \$/lb over the last 20 years of the 30 year plant life. The cost of the other components of the LWR fuel are considered to cost as follows averaged over the plant lifetime: UF_6 conversion at 330 \$/kg, enrichment 75 \$/SWU (seperative work unit), fabrication at 70 \$/kg, and reprocessing wastes at 120 \$/kg. The costs are prorated

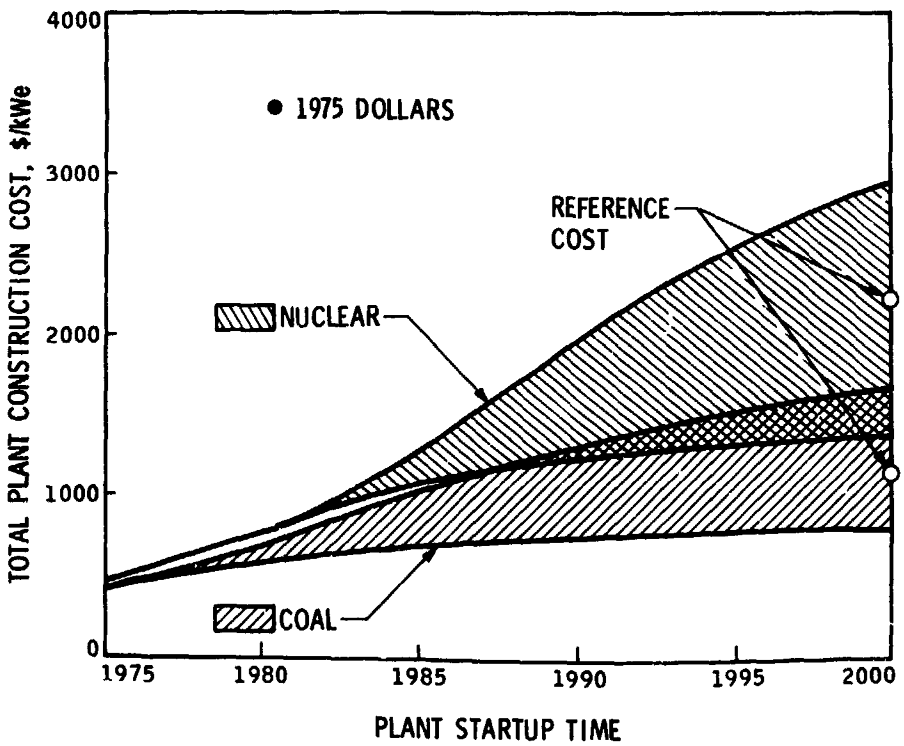


Figure 4-1. Projections of Conventional Plant Capital Cost

per kg of uranium. To be able to evaluate these nuclear fuel costs at future plant start-up dates, a differential escalation factor of 2.2% is used. Thus, a year 2000 start-up would increase the above costs by a factor of 1.72. Fuel reprocessing and the final disposition of nuclear wastes are areas of the LWR fuel cycle that are still in flux; the final outcome will affect both direct and social costs of the nuclear energy cycle.

The historic yearly load factors for baseload nuclear and coal plants have been 0.55 to 0.62 in the recent past (Ref. 7). Load factor is defined as the actual generated energy divided by rated energy generation capacity. This is well below the values used in most costing studies. For this study, the historic load factors have been taken as lower bounds. Improvements in performance are anticipated that should raise the load factor to 0.70 for nuclear plants and 0.74 for coal plants by the year 2000. Factors which would improve the load factor might include maturing of LWR designs including standardization, and a relaxation of present procedures which close all plants of a given design when a problem is found in one plant. For coal plants, the debugging of pollution control equipment would contribute to higher load factors. An upper bound is considered to be about 0.8.

Using the economic methodology and assumptions discussed in Section III, the bus-bar (power plant) energy cost for a LWR nuclear plant has been developed and is shown in Figure 4-2 as a function of load factor. The effect of the upper and lower bound on capital cost escalation rate is shown as well as the assumed year of online operation. The energy cost for 1975 start-up at a 0.7 load factor is 24 mills/kWeh while for year 2000 start-up (the reference point), the cost is 76 mills/kWhr. These costs represent today's cost for energy annualized over the 30 year life of the plant.

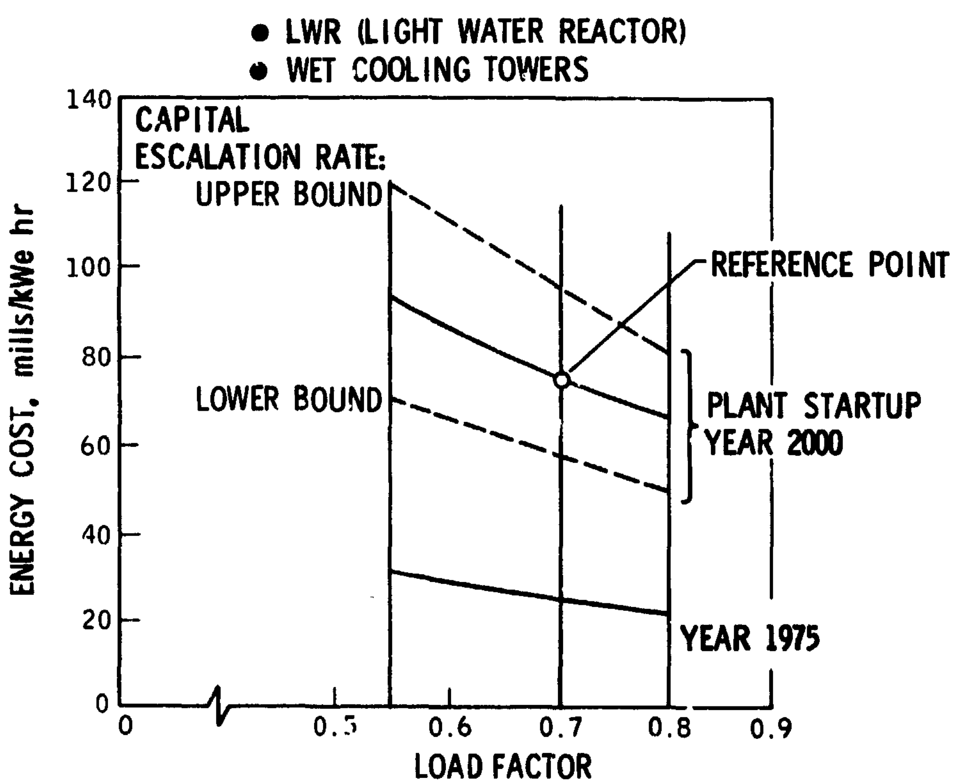


Figure 4-2. Nuclear Plant Economics

Figure 4-3 shows the costs for a low BTU coal gasification power plant at 2% differential coal escalation. The year 2000 start-up energy cost is 58 mills/kWeh at the reference point and 31 mills/kWeh for the 1975 start-up. However, if current technology coal plants are considered with similar differential escalation to current nuclear plants and 3% differential coal escalation, the year 2000 start coal plant is about 84 mills/kWeh.

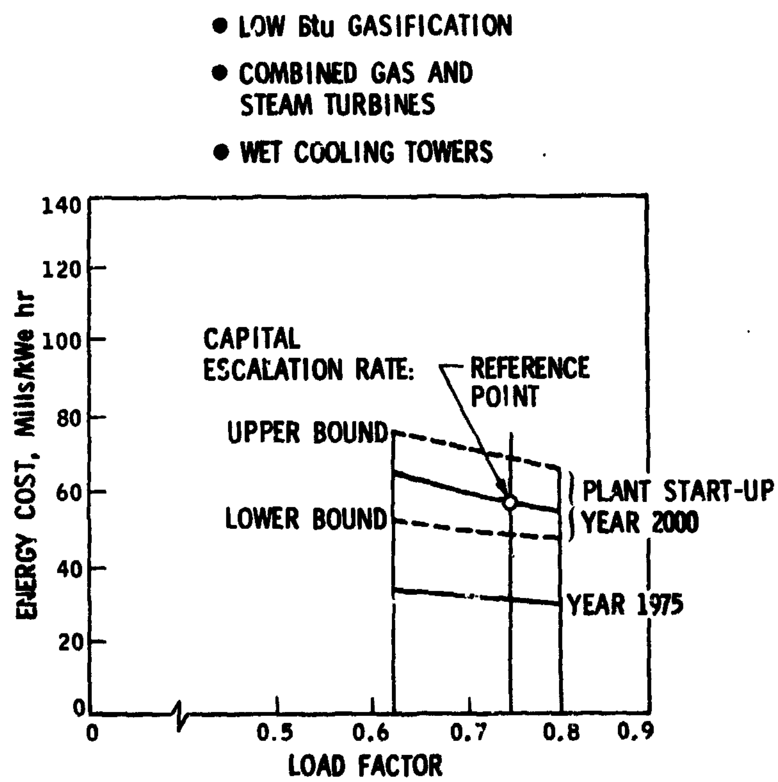


Figure 4-3. Coal Plant Economics

4.2 GROUND SOLAR PLANT ECONOMICS

4.2.1 Introduction

Solar thermal power plants are undergoing limited prototype development by ERDA, and one version of a central receiver 10 MWe pilot plant is expected to be operational in 1980 at Barstow, California. The first version of a full scale commercial feasibility demonstration plant is expected by 1985 and will be rated at 100 MWe. This type of plant uses direct solar energy which is reflected from a field of mirrors and trapped as heat in a central receiver. The heat is used very much like the heat in a fossil boiler or in a reactor core; i.e., it produces steam that is expanded through a turbine, which in turn runs a generator to produce electrical power. The specific approach being pursued by ERDA uses an array of flat or almost flat mirrors (heliostats) and a central receiver at the top of a rather tall (100 to 600 m) tower. Thus, optical collection is used to bring the solar energy to the central receiver. Steam is generated by the collected heat and then transported to the steam power plant at the base of the tower. Of all the different approaches to direct solar thermal electric power plants, this approach is most similar to current central power plants.

A second type of ground solar electric power plant considered in this report uses photovoltaics as the energy conversion device rather than a heat engine. The current Low Cost Silicon Solar Array program sponsored by ERDA may make a wide range of power plants economically feasible.

The JPL study reviewed the above two approaches (Refs. 11, 12 and 13), and also considered several others using thermal conversion to electricity without optical transfer of the sunlight to a central receiver. These studies were based on various types of solar collectors; i.e., ordinary (Ref. 14) and advanced (Ref. 13) flat plate collectors, linear (trough) concentrators using either a continuous parabolic surface or strip mirrors to reflect the energy and concentrate it along a line (Ref. 15), and distributed point concentrators based on a parabolic dish reflecting surface (Refs. 16 and 17). Two major choices exist for collecting and converting thermal energy to electricity with a power plant using parabolic dishes. These choices are (1) the heat can be moved to a central energy conversion plant via a transport fluid or with disassociated chemicals pumped through a piping network, or (2) the heat collected can be converted to electricity in a small heat engine-generator directly coupled to the dish and the electricity produced carried to a central point via wires. Thus, the distributed collectors/

receivers can have either distributed energy conversion (small heat engines at each dish) or central energy conversion (large heat engine).

The decision to implement a central receiver type of solar thermal power plant was made by the government in late 1974 after completion of initial paper studies performed for The National Science Foundation (NSF) by several study groups (Ref. 18). The apparent cost advantage of the central receiver concept over the nearest alternative design approaches, such as the parabolic trough or dish, ranged from 20% to 50%, depending upon the group performing the study.

Results of similar studies at JPL are shown in Table 4-2, which combines the results of References 11, 12, 14, 15, and 16. These results are based on a simplified performance and economic model. There is no storage; it assumes 100% generating efficiency; it does not allow for dirt fouling of reflecting surfaces; and it does not consider operation and maintenance costs. Only direct capital costs (assuming overnight construction) are considered; wet cooling towers are assumed.

In general, this simplified analysis will underestimate costs, but is useful for a first order relative performance comparison. This comparison supported the NSF finding that the central receiver is the least expensive at $900/kWe direct capital cost and 40 mills/kWeh energy when a capital recovery factor of 0.15 was used. The nearest competitor was a parabolic dish collector; it was at least 25% more expensive.

4.2.2 Performance

Based on the above preliminary results, the non-tracking and single axis tracking linear concentrator concepts were dropped by JPL from further consideration for central power plants. Further JPL evaluation effort was limited to the following power plants which appeared to be the most competitive from the initial survey.

(1) Central Receiver

- Thermal storage

Table 4-2. Results of Early JPL Studies of Central Electric Solar Power Plants

Collector Type	Energy Transport	Energy Conversion	Direct[1] Capital Cost, $/kW	Energy[2] Cost, mills/kWh
Flat Heliostat	Optical	Large Central Steam Plant	900	40
Parabolic Dish	Steam	Large Central Steam Plant	1150	50
	Chemicals	Large Central Steam Plant	1150	50
	Electricity	Small Engine on Dish (3)	1450	65
Parabolic Trough	Superheated Steam	Large Central Steam Plant	1750	78
Non-tracking Vee-Trough Flat Plate	Saturated Steam	Large Central Organic Rankine Plant	1450	90
Conventional Flat Plate	Water	Large Central Organic Rankine Plant	2500	150
Silicon (4) Photovoltaic (No Concentration)	Electricity	Photovoltaic	1250	76

(1) Direct costs only with overnight construction, no O&M, no storage, wet cooling towers, no dirt fouling of mirrored collector surface and 100% electric generating efficiency.

(2) Energy Cost ≈ 0.15 ($/kW)/8.76 L where L = 0.383 for tracking systems and L = 0.280 for non-tracking.

(3) Expensive ($400/kW) small Brayton engines considered in this analysis.

(4) The $0.50/W_p$ goal assumed at 10% average module efficiency.

(2) Parabolic Dish Collector

- Chemical transport and underground chemical storage
- Small Stirling engine with electric transport and battery storage or pumped hydro storage

(3) Photovoltaic Conversion with Electric Transport

- Battery storage or pumped hydro storage

As can be seen above, two or more competitive storage options were also selected for each of the three basic concepts. The competitiveness of the various storage options was based on results of studies reported in References 19, 20 and 21. Detailed performance characteristics of the above power plant options were next determined. Unlike the early survey studies, the more detailed analysis included energy storage and its associated inefficiencies as well as many factors not included in the preliminary analysis for the "sun following" plants. One of these factors is the use of dry cooling towers with limited heat rejection on hot days. There is also consideration of auxiliary power for collector aiming and cooling fans, and the introduction of the inefficiency of the electrical generator. A more realistic turbine efficiency was used, and the effects of off-load turbine inefficiency was considered along with the effect of ambient temperature on turbine performance. The solar plant performance methodology developed for ERDA by the Aerospace Corporation was used with a number of modifications as described in Reference 22. This performance methodology is an hour-by-hour calculation that uses weather data, projected user demand and which simulates the plant performance using a specific plant dispatch strategy in a simulation of an entire utility grid. Such a degree of complexity is needed so that major questions of solar plant reliability may be addressed as well as predicting plant energy and cost performance. Extra margin (backup capacity) is required when a solar plant replaces a conventional plant since a solar plant is subject to the vagaries of weather. The Aerospace Corporation margin analysis developed for ERDA was used for this purpose (Ref. 23).

4.2.3 Solar Plant Utilization in a Utility Grid

A utility grid uses a variety of complementary power plants that range from baseload plants, through intermediate to peaking plants. The baseload plants are the cheapest to operate and have load factors greater than 0.4 (Ref. 24). They are usually the newer coal plants and nuclear plants when available. These plants are capital intensive and have relatively low fuel costs. The intermediate plants are operated at intermediate load factors (0.2 to 0.4), and are usually made up of older fossil plants. The peaking plants are operated at low load factor (<0.2), and usually are gas turbines with low capital cost and high fuel costs. Because of their high operating costs they are brought on line only to meet limited peak power demands. A minimum generating cost dispatch strategy is used by the utility to meet the varying daily, weekly and seasonal demand load, while providing adequate spinning reserves.

Note that the definition of what constitutes a baseload plant is a plant that has the lowest operating cost and is run as often as possible due to these operation savings (Ref. 25). With the exception of off-season hydroelectric, any plant now in use can operate 24 hours a day for days or weeks barring maintenance problems. Thus, the ability to operate 24 hours a day does not define a baseload plant since peaking and intermediate plants have this same capability. Rather, annual load factor is used by the utilities to categorize a plant as baseload, intermediate or peaking.

This study will limit itself to baseload power plants because of the need to compare alternative plants to an orbital SPS system which can only be a baseload plant. Thus, this report is basically a direct comparison of various alternative baseload plants.

Historical data on coal and nuclear baseload plants (Ref. 7) indicates that the load factor averaged over the year has been in the 0.55 to 0.62 range. Load factor (L) is defined as the annual energy generated (kWhr), divided by rated power (kW) times 8760 hours*. It is anticipated in this study that the annual load factor of a nuclear and coal plant will improve to 0.70 and 0.74, respectively, by the year 2000. Therefore, a baseload central electric solar power plant is assumed to have an annual-averaged load factor (L_s) of 0.70 including scheduled and unscheduled maintenance factors of 0.90 and 0.96, respectively. Thus, the designed annual capacity factor of a solar plant is 0.81.

The capacity factor (L_c) is the load factor divided by the maintenance factor. It is the fraction of the year the plant could deliver power from direct and stored solar energy. A solar plant with such a large capacity factor would certainly not be recommended (or be needed) for the initial commercial solar plant demonstration. However, no strategy has been developed in this study for choosing the size (annual load factor) of solar plants as solar penetration increases in a utility grid. Obviously, a strategy could be developed, and would certainly involve a mix of solar plant designs that could have an annual load factor of 0.3 to 0.7 as penetration increases.

A ground solar plant would operate somewhat differently than a conventional plant. Depending on the design, it will be down for a few hours a day or operate at partial power over part of the day. Occasionally it will be down for one or more days due to adverse weather. This reduces the reliability of a stand-alone solar plant compared to a conventional plant operating at the same annual load factor. Because of this, it is necessary to install extra margin (backup) capacity and use some form of backup energy to increase the reliability to that of a conventional plant. A valid economic comparison should include these extra margin requirements for a solar plant. The initial analysis given in this section is for the solar plant. In the last part of this section, the extra backup requirements are evaluated and are added to the earlier results.

---

*Number of hours per year.

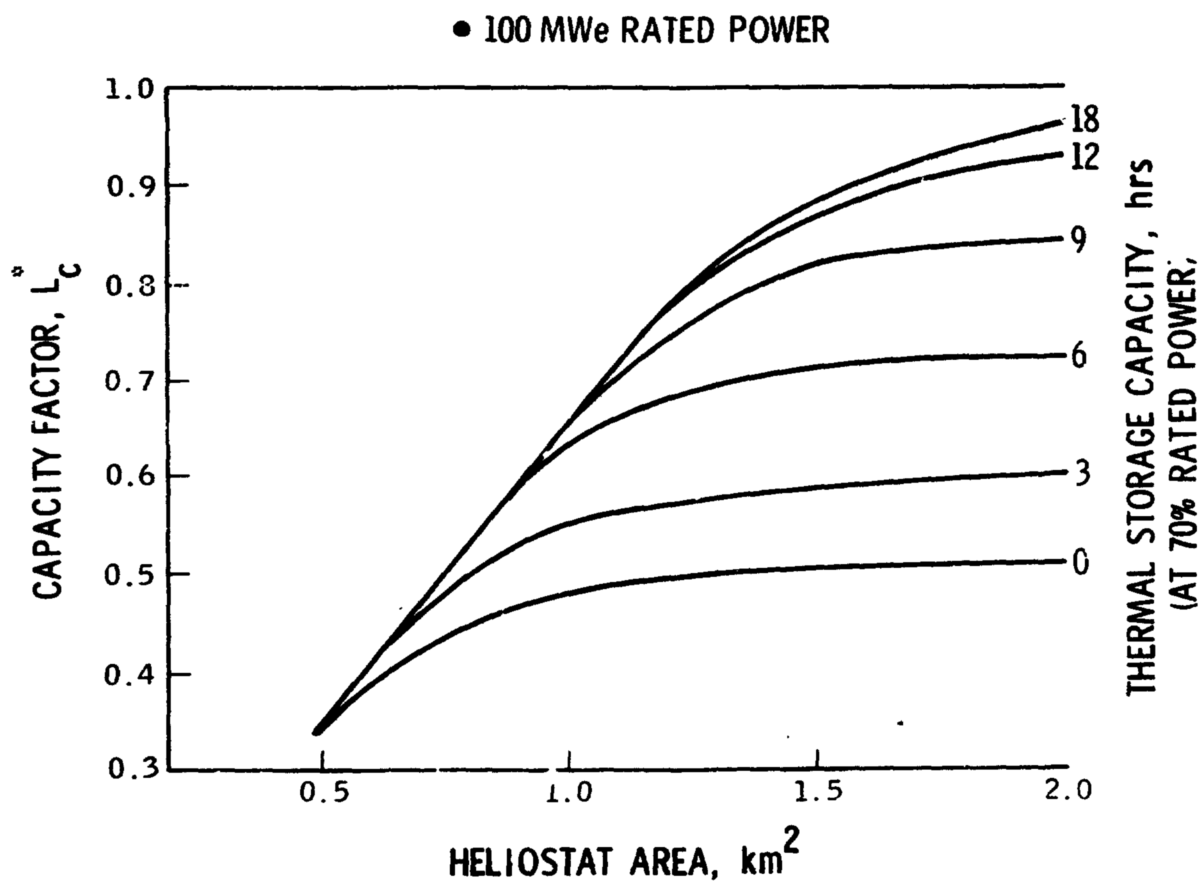
The same analysis should be done for the SPS since it also has outages which occur due to eclipse by the earth, and blockage by an adjacent SPS. However, this has not been done for the SPS in this report.

The approach which has been taken is felt to be conservative; i.e., over estimates solar plant costs. Instead of the approach taken in this study, which is to insert only a baseload ($L_S = 0.7$) solar plants into the grid and then calculate extra margin requirements to meet grid reliability, the following approach is considered more reasonable. Solar plants with a range of design annual load factors (L_S) should be considered with storage capacity varying from 0 to 15 hours. A single design point solar plant as well as a mix of solar plant designs should be introduced into the grid. The other plants in the grid (peaking, intermediate and baseload) should be adjusted; i.e., remove some and add some, to give minimum cost for the entire grid at the same total grid reliability. Then it can be determined what load factor solar plant or mix of load factors is best, as well as the capacity of plants the solar plant replaced. How much energy was replaced would then be known.

This type of analysis would be sensitive to the specific utility being considered, the projection of future demand, the relative economics and reliability of the various types of plants as well as weather and solar plant performance and costs. Early analysis tends to indicate that solar plants will replace a mixture of intermediate and baseload plants with this type of approach (Ref. 26).

4.2.4 Solar Plant Costs

Typical performance results are shown in Figure 4-4 for a steam cycle central receiver solar plant based on a design most similar to that proposed by the Honeywell Corporation (Ref. 12). The annual plant capacity factor is shown as a function of the two major solar plant design variables: The mirrored (heliostat) area and the size of energy storage in hours of operation at 70% rated power. In general, as the area and storage are increased, the capacity factor becomes



* L_c IS THE FRACTION OF ANNUAL ENERGY THAT WOULD BE GENERATED COMPARED TO OPERATION AT RATED POWER CONTINUOSLY IF THERE IS NO DOWN TIME FOR MAINTENANCE.

Figure 4-4. Central Receiver Solar Plant Performance

larger. The annual load factor is the plant capacity factor adjusted for scheduled (0.90) and unscheduled (0.96) maintenance. A reasonable design for a 100 MWe rated plant that achieves an annual capacity factor of 0.81 (0.70 load factor) would have about 1.30 km^2 of heliostat area and 12 hours of storage capacity at 70% rated power. This performance is also possible with a 2 km^2 area and about 8 hours storage. The selection of the optimum design is based primarily on economics and is developed below.

For each of the power plants selected for further evaluation, the energy cost, capital cost and extra margin requirements were developed. To do this it was necessary to establish reference costs for each major subsystem. Using the data from earlier JPL survey studies (Refs. 12, 13, 16, 17, and 19 through 21), projections were made of mature commercial costs in each area. "Mature costs" is taken to mean that mass production is assumed where applicable. Our best judgment of what the expected costs are for each major subsystem is shown in Table 4-3 in the "mid" column. The low and high limits of expected costs are also shown; the "low" is intended as a cost at the lower limit of probable cost with low probability of attainment, while the "hi" is a cost that is at the upper limit of probable cost and could be achieved with high confidence. The only exception to this is for the photovoltaic plant where the cost estimates ("mid" column) correspond to the achievement of the ERDA cost goal (Low-Cost Silicon Photovoltaic Program) of $\$0.50/W_p$ at the expected nominal efficiency of 13% at 28^oC in AM (air mass) 1. Land costs are assumed to be $1000/acre and thus are negligible.

The resulting energy cost for each approach (using the "mid" costs for each subsystem) is shown in Figure 4-5 as a function of the annual design solar load factor (L_s) including a factor of 0.864 for scheduled and unscheduled maintenance. L_s is the performance based only on solar equipment. The economics of the reference design are based on a year 2000 plant startup. For a 1975 plant startup, these results should be multiplied by 0.82. The energy cost due to operation and maintenance expenses is obtained by adjusting the first year costs by the first equation in Appendix A to levelize the O&M costs. Thus, this

ORIGINAL PAGE IS OF POOR QUALITY

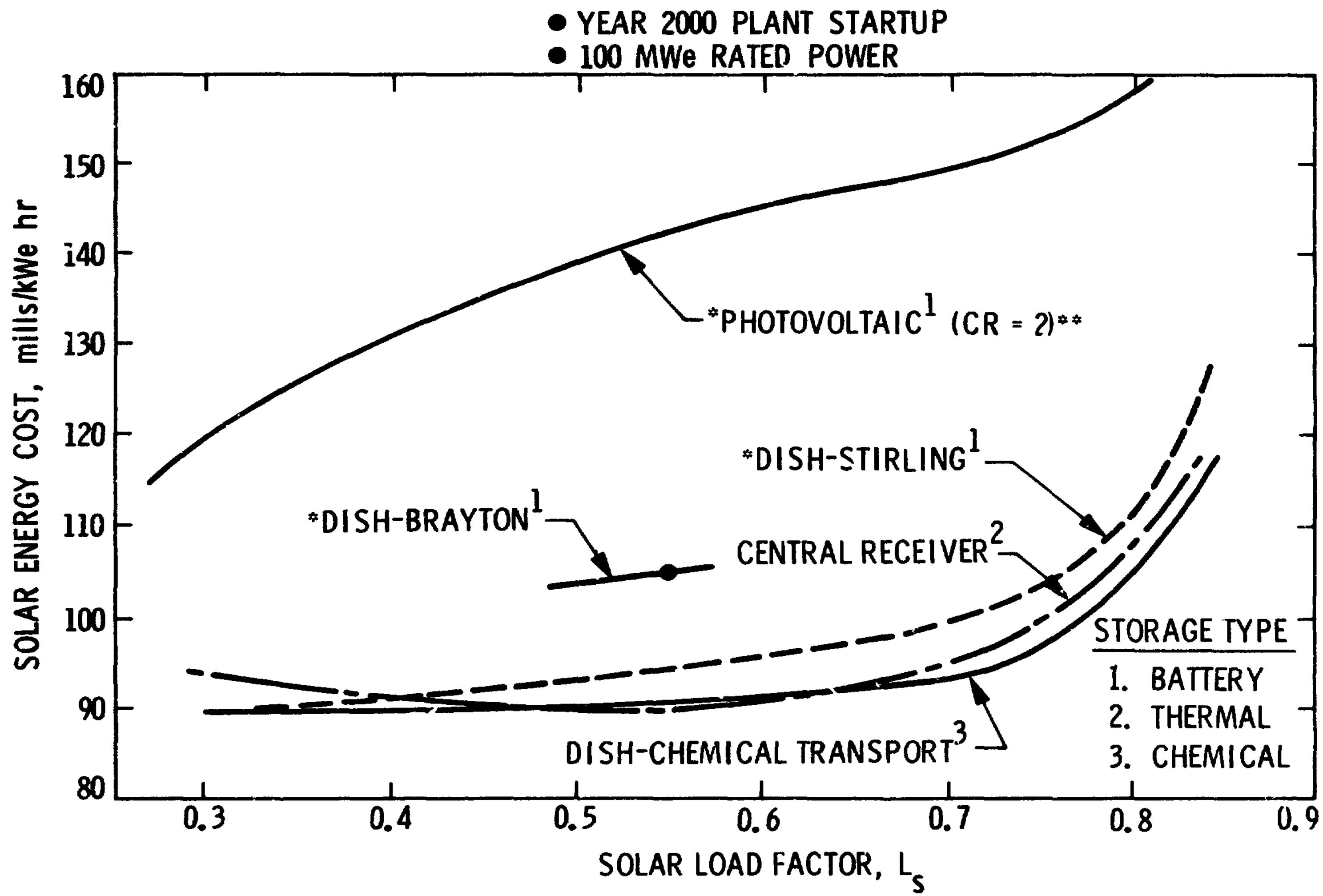
Table 4-3. Solar Plant System Direct Costs

- 100 MWe Plant with Load factor = 0.70*
- with 1975 plant startup (1975 dollars)

Type of Plant	Major Subsystem: Collector[1], \$/m^2 Low	Mid	High	Energy Conversion[2] Low	Mid	High	Energy Transport[3] (\$/kWe) Low	Mid	High	O&M[4] 10^6 \$/yr
Central Receiver	60	91.5	119	170	250	330	162	230	300	3.16
Parabolic Dish										
- Chemical Transport to Central Steam Plant	-	158	-	-	280	-	-	143	-	3.2
- Small Stirling Engine on Dish	-	152	-	-	269[5]	-	-	89[6]	-	5.29
Photovoltaic	45[7]	82.5[8]	125[9]	-	-	-	-	140[6]	-	1.36
Type of Storage		Thermal			Battery			Pumped Hydro		Disassociated Chemicals[11]
Cost, \$/kWehr	26	52[10]	104	15	19.5	26	-	15	-	3.2

(1) Only heliostat cost for central receiver; includes receiver for dish collectors.
(2) Based on 100 MWe rated capacity.
(3) Includes receiver, tower and piping for central receiver.
(4) First year average cost without clearning collectors.
(5) Based on peak power, the engine cost is 106 \$/kWe and includes generator, starter and controls.
(6) Designed for peak power and includes controls and power conditioning.
(7) \$0.20W_{peak} and %15/m^2 structure with no concentration.
(8) Based on 13% module efficiency at \$0.50/W_{peak} which has a module cost of \$65/m^2; structural cost = \$17.5/m^2 without concentration.
(9) \$1.00/W_{peak} and \$25/m^2 structure with no concentration.
(10) 60 \$/kWehr at 6 hrs storage.
(11) Underground storage. Catalysts part of receiver and central plant.

* Southwest location, 9 hours of storage at 70% of rated power, 0.81 capacity factor and 0.86 maintenance factor.



* SELL HALF ENERGY THAT WOULD BE REJECTED WHEN STORAGE FULL.

** CONCENTRATION RATIO = 2, USING ASYMMETRIC VEE-TROUGH REFLECTOR

Figure 4-5. Comparison of Ground Solar Plants includes the effect of inflating recurring costs over the 30 year life of the plant. For the particular values used from Table 3-1, the net effect is to triple the O&M energy cost that would result from the data given in Table 4-3.

The collector area and amount of storage have been optimized for minimum energy cost at each load factor. For example, for the central receiver the optimum designs (minimum energy cost for the solar plant) are shown below for a 100 MWe rated plant operating at Inyokern, California with dry cooling towers.

Annual Solar Load Factor, L_S	Heliostat Area ≈ km^2	Storage Capacity at 70% Rating ≈ Hrs
0.295	0.5	0
0.560	1.0	7.5
0.70	1.3	12
0.753	1.5	12
0.820	2.0	15

On an annual average, there are 10.8 hours of sunlight per day (8.75 kWhrs/m^2 per day) at a good Southwest location. As can be seen in Figure 4-5, there is a bowl shaped curve of energy cost for the plant with thermal (internal) storage. A minimum energy cost is reached at a load factor between 0.35 and 0.65 where there is a balance between: (1) the energy cost of fixed equipment such as the turbine which decreases with increasing load factor, and (2) the cost of storage capacity which increases with higher load factor and also lowers the energy availability and thus lowers the average plant efficiency.

The plant with underground chemical storage levels off in energy cost at high factors since the cost of storage is so inexpensive. Actually, many days of storage could be accommodated and extra non-solar margin (backup) from the grid would not be required.

The plants with external storage (i.e., storage after conversion to electricity), such as the dish-stirling and photovoltaic plant, have an energy conversion device that is designed for peak isolation. Thus, there is no fixed equipment for which the contribution to energy cost can be reduced as load factor increases. The cost increases with load factor (as shown in Figure 4-5) simply because increasingly more energy is put through storage. This reduces the average efficiency of the plant and thus energy cost always increases with increased load factor. It should also be noted that the external storage plants are assumed to sell all electricity generated at rated power. When power is produced at levels greater than the plant rated power the energy is sold at half price. This assumes that energy generated when the power level is greater than rated will only be of value as a fuel saver, not as a capacity displacement as well.

The photovoltaic plant is based on a non-tracking silicon photovoltaic design having an asymmetric vee-trough concentrator that is reversed twice a year (Ref. 13). Concentration ratio (CR) of 2:1 is used, and the cost of maintenance, surface cleaning and reflector rotation in included. The cost for the dish-stirling combination includes maintenance and replacement of the stirling engine every 5 years (Ref. 17). For both systems, an advanced redox battery is used with a 2 mill/kWehr maintenance cost and 20 year life time (Ref. 19). It should be noted that due to these maintenance costs and the use of levelized recurring (operation and maintenance) costs, only 2/3 of the dish-Stirling system energy cost is due to capital. The remaining 1/3 is due to O&M and amounts to nearly 30 mills/kWehr.

Based on these studies, the dish-Stirling engine design, the central receiver, and the dish-chemical approach are all equally attractive from an economic standpoint. The energy cost is estimated to be from 90 to 100 mills/kWeh at an annual average load factor of 0.70 and year 2000 start-up for all three approaches. However, this estimate assumes that the energy conversion engine (Stirling engine) and chemical system are developed commercially, while the central receiver approach uses the existing central energy conversion technology of the steam Rankine plant.

With the $0.50/Wp goal, the photovoltaic plant is 25% to 60% more expensive than the solar thermal plants as the solar load factor goes from 0.3 to 0.70. Lower cost goals may be necessary before the photovoltaic plant is competitive with other ground solar approaches for central electric power.

The total installed capital cost for a year 2000 plant start-up in 1975 dollars is shown in Figure 4-6 as a function of annual average solar load factor for each of the four power plant types. The area and storage capacity increase and the lower thermodynamic availability of the stored energy becomes significant with increasing load factor. This causes the capital cost and to a lessor extent, the energy cost to rise. This characteristic of a solar plant is generically different from conventional (fossil or nuclear) plants. A conventional plant has a capital cost that is more or less fixed and only slightly sensitive to the rated power and indifferent to how much the plant is operated per year (annual load factor). The capital cost of a solar plant, on the other hand, is very sensitive to the designed annual average load factor as shown in Figure 4-6.

The results shown have used the expected subsystem costs ("mid"). The only exception is the use of the 1985 ERDA goal (0.50 $/Wp) for the photovoltaic performance. To show the probable limits of costs, lower and higher boundaries have been established. These are considered to be the combination of all the "low" and of all the "hi" subsystem costs as were shown in Table 4-3. It is unlikely that the cost will be below the lower limit, and unlikely the costs will be above the upper limit when commercially mature. This bounding of costs is shown in Figure 4-7 for two baseload solar electric plants: the central receiver solar thermal plant, and the silicon photovoltaic plant.

4.2.5 Hybrid Solar Plant Costs

The analysis summarized by Figures 4-5 through 4-7 present projections of solar central power plants by themselves. The analysis ignores the unreliabilities of sunlight availability and the need for backup capacity to maintain grid reliability. The results represent

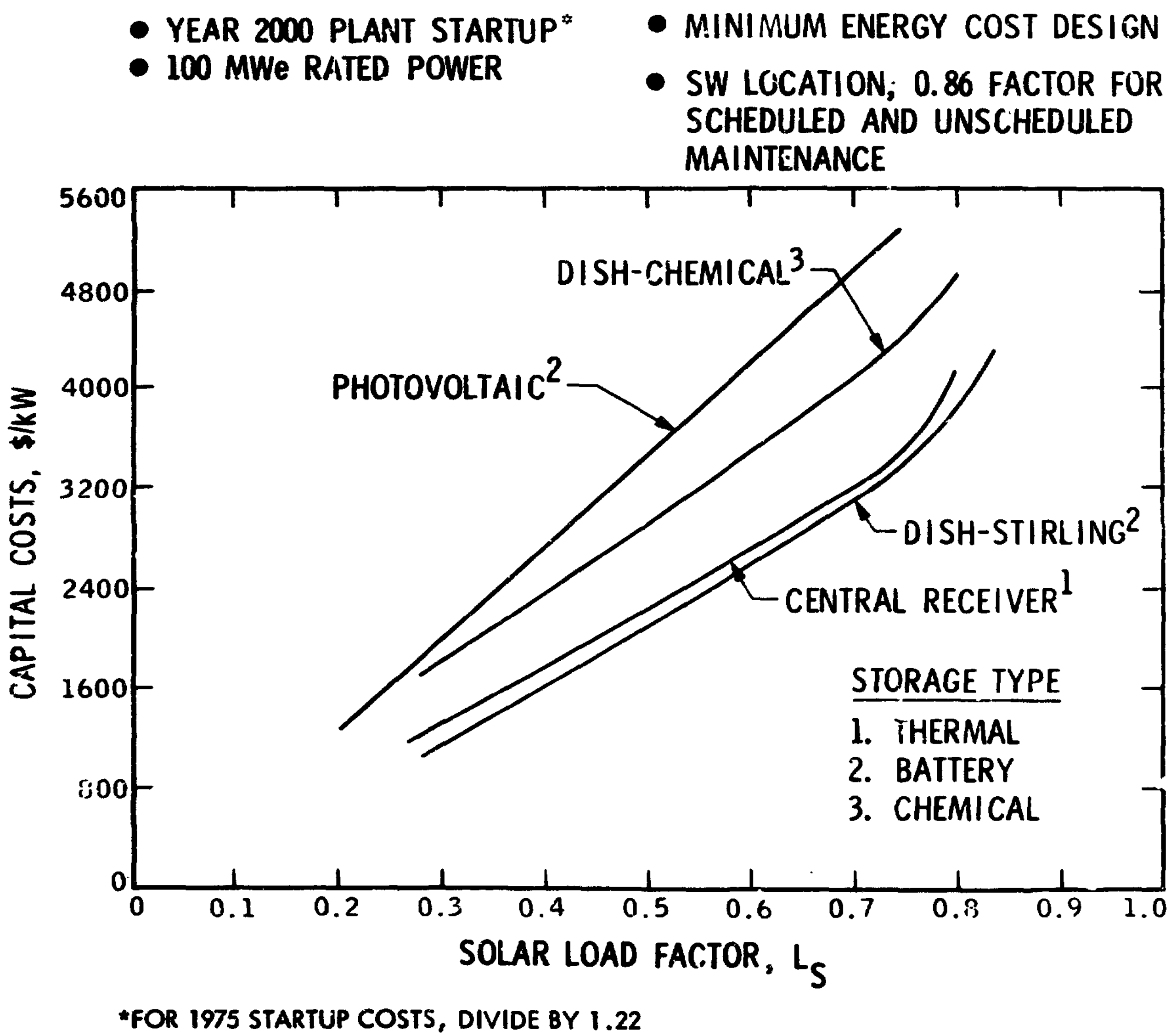
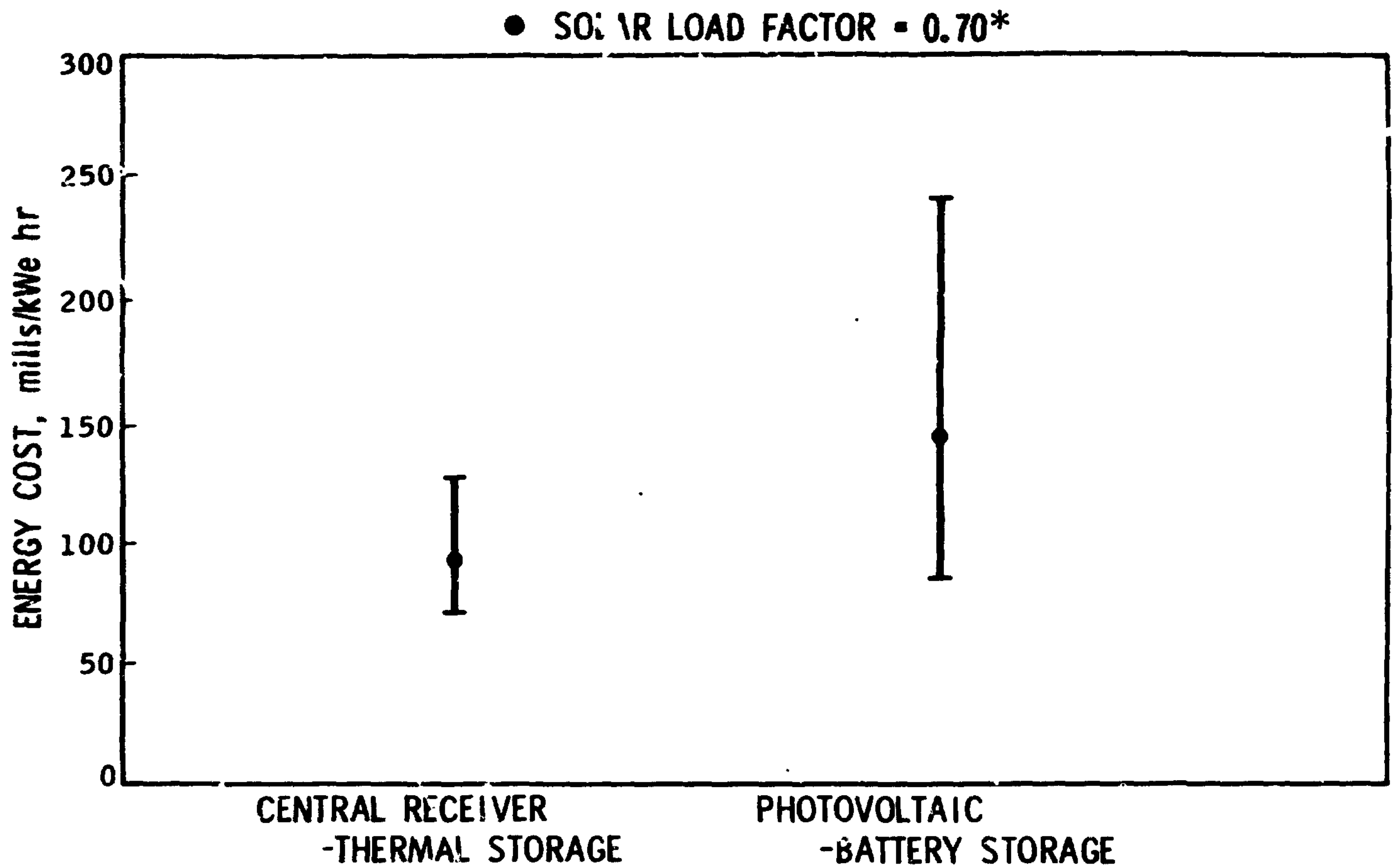


Figure 4-6. Ground Solar Plant Capital Costs



*INCLUDING 0.864 FACTOR FOR MAINTENANCE, SW LOCATION. SOLAR THERMAL HAS 9 HOURS STORAGE, AND PHOTOVOLTAIC HAS 12 HOURS STORAGE. STORAGE AT 70% RATED POWER.

Figure 4-7. Summary of Ground Solar Plant Energy Costs annual average performance; hour by hour simulation was used to determine output power and the status of stored energy. It is possible, however, even in a Southwest location such as Burbank, California, to have nine consecutive days of cloudiness in a particular 4 year period. To build a solar plant to have nine days of thermal storage is prohibitively expensive (≈390 mills/kWehr) except for approaches which use underground gas storage. Underground gas storage costs are potentially so reasonable that many days of storage are possible at a slight cost premium (less than 10%).

All power plants occasionally become unavailable due to scheduled or unscheduled maintenance. It is not the current practice of utilities to have enough storage capacity set aside to cover nuclear plant core refueling or turbine overhaul, etc. What is done is that extra capacity or margin is installed in the utility grid above and beyond peak demand to cover outages. For the operation of ground solar plants, a similar procedure is suggested. That is, it is suggested that additional capacity (extra margin) be installed to maintain grid performance when there are weather related outages of a solar plant.

Using the Aerospace margin analysis code developed for use in mission analysis for ERDA, the extra margin needed to backup solar plants was determined. Extra margin (P_m) is the installed non-solar capacity needed for a utility grid with solar plants that is greater than the installed capacity needed for a utility grid without solar plants.

$$P_m = P_1 - P_2$$

where P_1 is total installed capacity for a utility grid with conventional and solar plants and P_2 is total installed capacity for a utility grid with only conventional plants

$$P_2 = P_{peak} + M$$

where P_{peak} is the annual peak demand and M is the margin needed to have acceptable grid reliability using only conventional plants

Thus $$P_1 = P_{peak} + M + P_m$$

To understand the magnitude of this effect, the ratio of P_m to the rated installed solar capacity P_r is evaluated as a function of several parameters. The parameters of greatest interest are the designed annual load factor of a solar plant (L_s), and the amount of penetration of solar capacity into the grid. The ratio P_m/P_r indicates how many megawatts(e) of extra non-solar capacity should be installed for each megawatt(e) of solar capacity.

For baseload solar plants, the plants are continuously asked to produce energy at the rated power. Since the solar plant does not always meet this expectation, due to weather or being undersized, extra margin must be provided to maintain grid reliability. The amount of extra margin installed capacity (P_m) which should be added for each unit of rated baseload solar capacity (P_r) is shown in Figure 4-8a along with the extra energy needed (E_m) from a non-solar source for an Inyokern site with Southern California Edison demand. The data is shown versus the normalized annual load factor and assumes 20% penetration of baseload solar power into the total grid. The normalized load factor is the design solar load factor (L_s) divided by the expected conventional base-load plant load factor (L_B). As the normalized load factor approaches 1.0, the stand-alone solar plant requires less extra margin and less backup energy. At unity, the needed extra margin (capacity) is 20% of the rated power of the solar plant, and the backup energy is essentially zero. Therefore, for every 1000 MWe of solar capacity, 200 MWe of extra margin must be added to the grid. Also shown in Figure 4-8a is data from analysis by Southern California Edison for 5, 10 and 20% solar penetration. These results compare well to the analysis performed using the Aerospace margin analysis computer code.

Figure 4-8a is plotted versus normalized load factor since there is disagreement as to what load factor constitutes a baseload plant. Values between 0.40 and 0.864 can be suggested as baseload-load

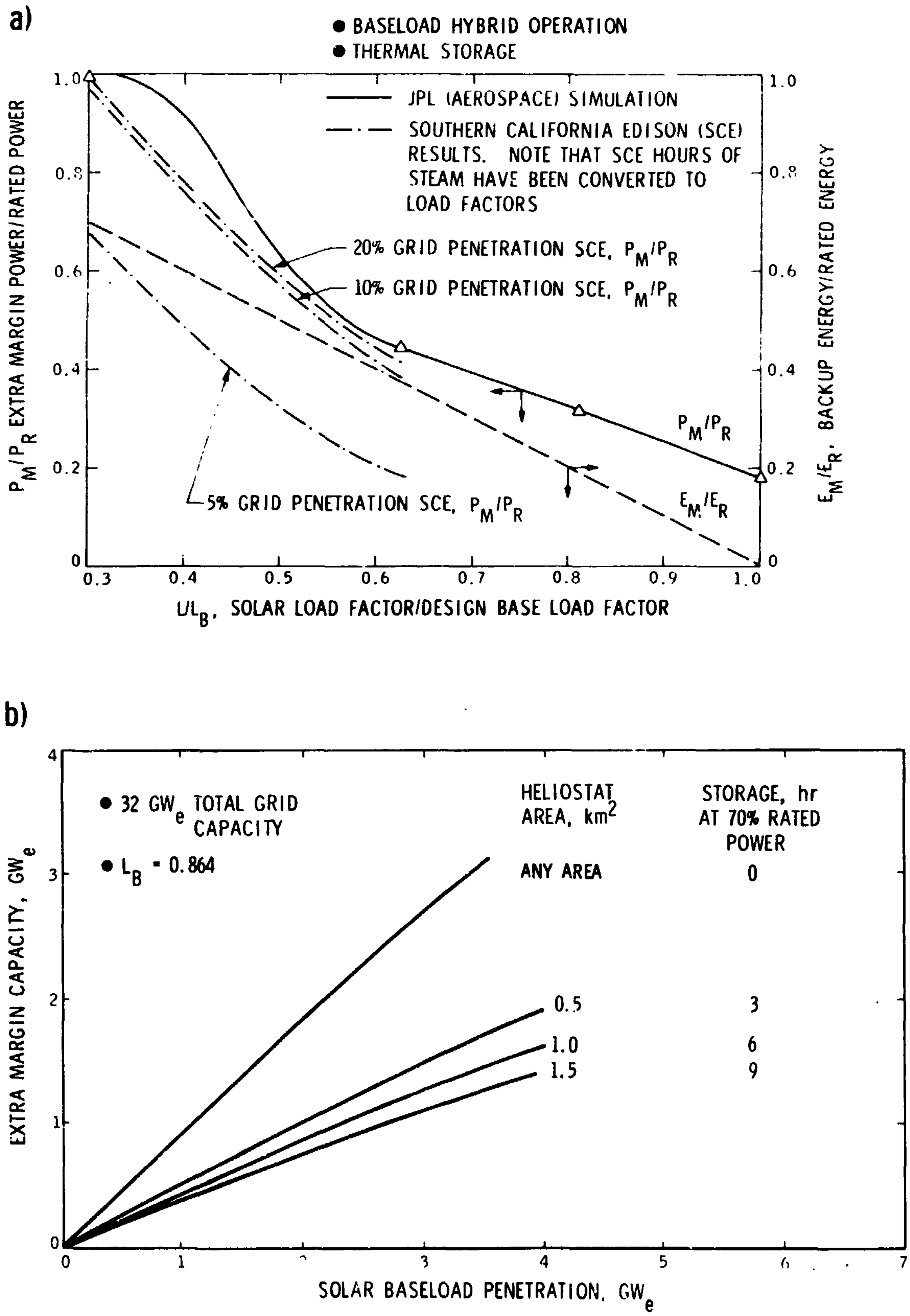


Figure 4-8. Central Receiver Extra Non-Solar Margin

factors. The actual analysis was performed with the designated conventional plant load factor (L_B) equal to 0.864. Figure 4-8a should be used only for baseload plants and is felt to be accurate for $L_B > 0.5$.

Figure 4-8b shows how the extra margin (P_m) increases with solar baseload penetration based on L_B equal to 0.864. The use of multiple sites for solar plants having different weather would reduce the backup margin requirements. Thus, the results shown in Figure 4-8 are conservative since as solar penetration increases, multiple sites would certainly be used.

This extra margin can be obtained in at least two distinct ways. Power plants can be added throughout the utility grid, and some combination of plants can be operated at lower capacity factors to provide this extra margin. A second approach is to add the capacity at the solar plant site itself. Such a solar plant would then be called a hybrid plant. In either case, the extra margin and non-solar energy consumption must be considered in the cost and performance of a solar plant for a proper comparison to power plants that do not depend on the vagaries of weather.

To estimate the cost of the extra margin (back-up capacity) and energy, it is assumed that coal is the source of the energy. As with the reference coal plant discussed earlier, the coal can be gasified to low BTU gas in a gasification plant located in the same region as several solar plants. Using gas pipelines, this low BTU gas can be supplied to inexpensive, once-through auxiliary boilers (coupled to the solar power conversion equipment) to produce high grade steam (such units are being sold commercially to the utility industry by the Rocketdyne Corp. based on rocket nozzle cooling technology). The existing steam Rankine conversion equipment at the solar plant can be used to generate electricity. The cost of this back-up system (i.e., gasification plant, gas pipelines and auxiliary boiler) has been estimated to be 270 $/kWe in 1975 dollars for a 1975 plant start-up (Ref. 7). The coal to be supplied to the gasification plant was assumed to cost $0.89/MBTU ($23/ton) in 1975 dollars. The same capital and fuel cost escalation factors shown earlier for the reference coal plant (Section 4.1) were used to escalate the cost of back-up equipment and fuel to project year 2000 plant start-up costs.

A comparison of the cost characteristics of the hybrid power plant having L_B = 0.864 with the solar plant alone is shown in Figure 4-9 where costs are shown versus solar load factor, L_S. As expected, the capital costs ($/kWe) of the hybrid are greater because of the additional costs of capital for the extra margin. However, the energy costs ($/kWhr) are actually lower for the hybrid plants. The reason for this is that the added energy capability produced by the back-up system is less expensive than the energy produced from solar.

This approach can be used for all solar baseload plants, but the technique of providing the back-up margin may differ. For example, the dish-Stirling solar plant might use the Stirling engine-generator itself as the back-up capacity. Besides adding the low BTU coal gasification plant, the cavity receiver may have to be designed to double as a combustion chamber. The photovoltaic plant will have to have its own gas-turbine or fuel cell generating capacity. Again, the low BTU gas from coal may be the energy form used to drive these electric generators.

The costs shown in Figure 4-9 are felt to be representative of the cost of capacity and energy for this extra margin. At a solar plant load factor of 0.7, the installed capital cost increases by 8%, while the energy cost decreases by 7% when extra margin is included.

Another source of conservatism for the minimum cost plants with external storage such as the dish-Stirling-battery and the photovoltaic-battery is that these plants can have a peak capacity that is much greater than the rated capacity. For example, the dish-Stirling plant with a solar load factor of 0.7 has a peak capacity of over 300 MWe. The storage svstem was sized at over 200 MWe to handle maximum generating capacity greater than the rated capacity. It is possible for this plant to generate over 500 MWe near the midday and over 200 MWe after dark for a short period of time. This is extraordinary for a plant rated at 100 MWe. Such capability for plants with external storage should reduce

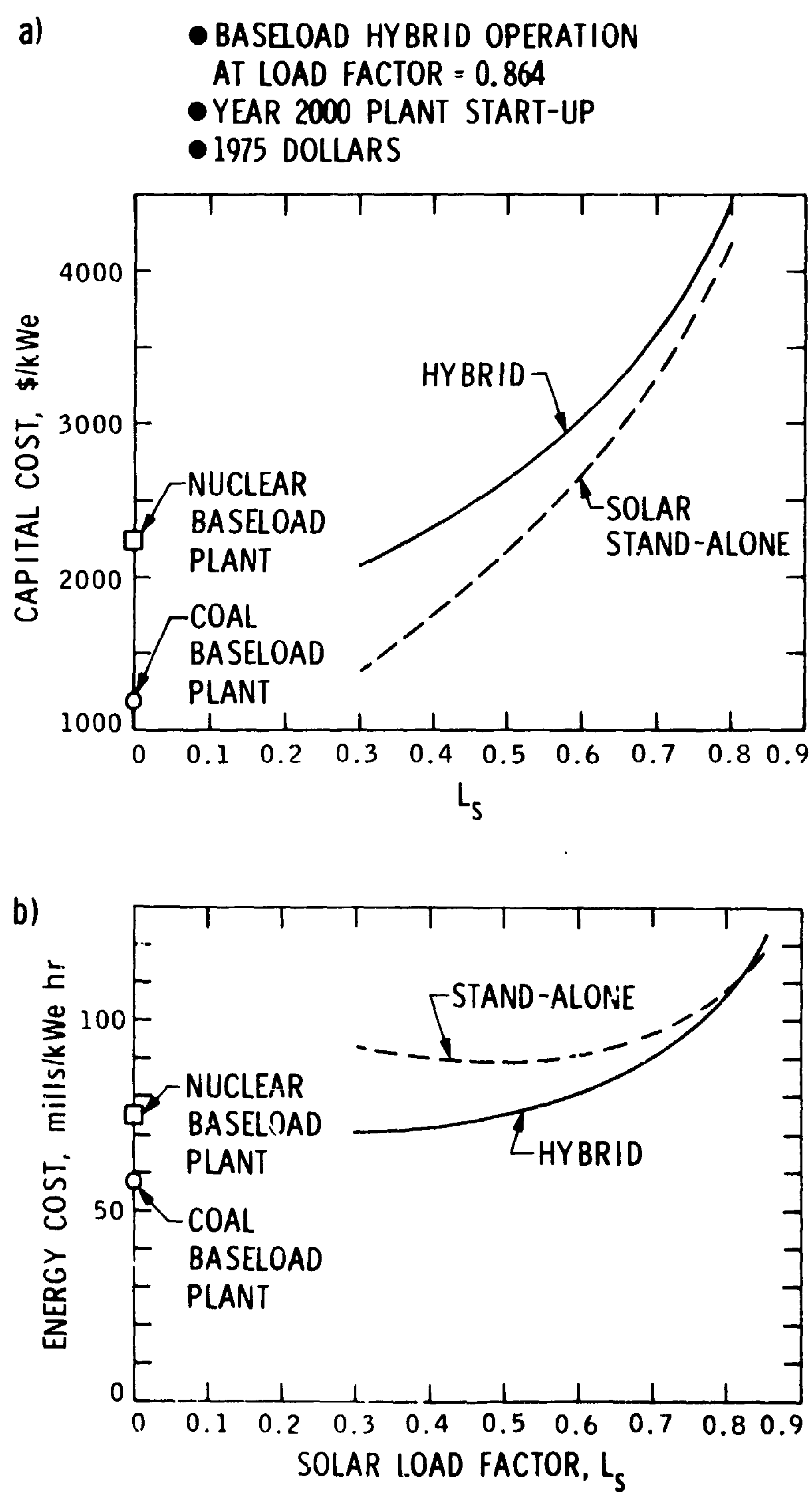


Figure 4-9. Capital Costs For Hybrid and Stand-Alone Solar Power Plant

extra margin requirements and possibly even eliminate its need. Also the back-up fossil source can be used to drive the plant at over 300 MWe whenever the sun is not available and the grid requires this capacity. This added capability may even give this plant a negative extra margin requirement at a capital cost savings. These effects should be evaluated for external storage plants to more accurately determine margin needs.

4.3 SPS PLANT ECONOMICS

The Satellite Power System (SPS) considered in this comparative assessment is based on photovoltaic energy conversion. It is a very large satellite. For the assumptions made in this study, the satellite weighs about 100 x 10^6 kg in geosynchronous orbit for 5 GWe delivered on the ground. About 50 km^2 of photovoltaic blankets are required for 5 GWe of electrical power delivered to the electric utility grid. This system collects solar energy, concentrates it slightly (2:1) onto thin photovoltaics, collects the resulting dc electricity at voltages of about 20 kV and carries it across a rotating joint to a transmitter where the dc is converted to microwave energy. The coherent microwave beam is transmitted 37,000 km to a fixed microwave receiver on the ground in a regional power grid. The microwave energy is converted back to dc, collected and then changed to ac for transmission to the load center using conventional transmission techniques. The SPS power system includes the space power plant, the ground receiving antennas (rectennas) and the dc to ac conversion equipment as well as the orbital support facilities, orbital construction facilities, transport systems from ground to geosynchronous orbit (GSO), ground launch facilities and related ground support facilities.

SPS operation at geosynchronous orbit is considered. Locating the SPS at a lower orbit with microwave beaming to a synchronous orbit relay station is not considered. Only silicon photovoltaics is used as the energy conversion technique. Other types of photovoltaics, solar thermal or nuclear energy conversion are not considered. All materials are brought up from the earth. The moon is not used as a source of materials for the SPS in this study.

A post-shuttle transportation subsystem must be developed (a heavy lift launch vehicle, HLLV) to bring the materials to low earth orbit (LEO). The form of most of the material is bar stock and sheet metal rolls, rather than finished subassemblies, and nearly automated factories must be created to complete the fabrication in either LEO or GSO. Man must develop the capability to be as productive in space as on an automated automobile assembly line in terms of kg of finished products per man-hour worked in order for the SPS costs to be competitive (Ref. 28). LEO to geosynchronous earth orbit (GSO) transport systems must be developed for the satellite (chemical or ion propulsion) and for support personnel (chemical). Maintenance, resupply, station keeping and attitude control, and operational procedures must be developed for LEO and GSO operation. Worker habitats and tele-operators must also be developed. Lightweight structures of enormous area for a single power plant, distributed active control systems and a number of other major subsystems must be developed for a commercial SPS.

Each SPS could be about 5 GW rated capacity and have a ground receiving antenna of 11 km (approximately 4 miles) in diameter (75 km^2 area) with billions of individual half-wave dipole elements. The orbital photovoltaic subsystem must be pointed toward the sun with one degree accuracy, and the microwave transmitter pointed within one arc minute. The land area needed would be at least 300 km^2 (Ref. 29) and possibly as high as 900 km^2. Transportation of one satellite would require of the order of 50-500 flights of a new heavy-lift launch vehicle (HLLV) possibly 3 to 5 times larger than today's Saturn 5. There would be between 1 and 5 flights of the HLLV per day. An illustration of the SPS system is shown in Figure 4-10.

The major economic and technical uncertainties in this system are:

- photovoltaic performance and cost.
- heavy lift launch vehicle, chemical and ion tug boost systems cost.
- microwave link efficiency and cost.

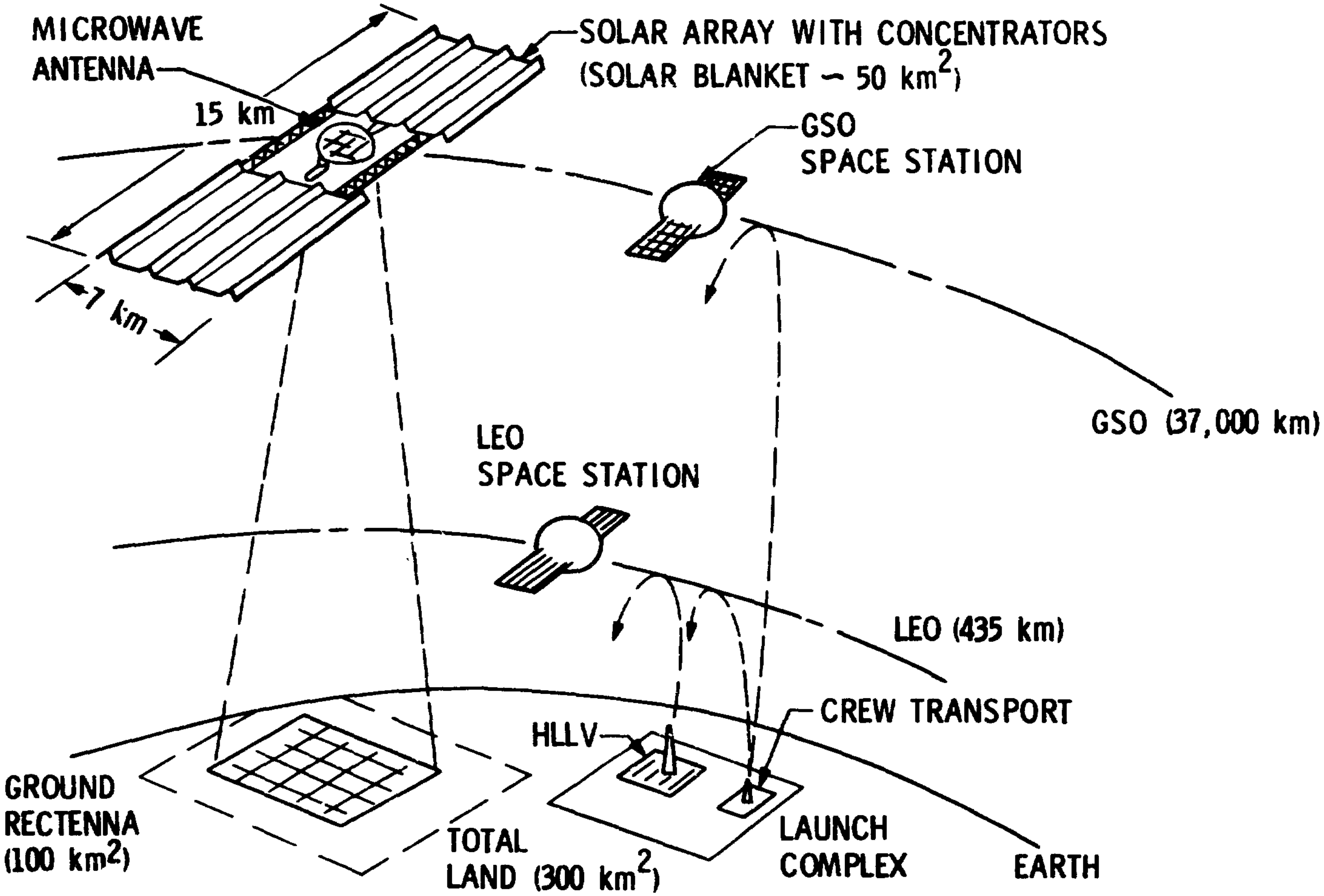


Figure 4-10. Orbital Photovoltaic Space Power Systems — SPS

- economic feasibility of space construction in an orbital factory.
- economic feasibility of constructing lightweight deployable structures.

Possibly the area most sensitive to cost in the above items is the uncertainty of man's productivity in the construction and operational phases (Ref. 30).

The source of most information on the photovoltaic SPS was the study conducted by the ECON team under contract to Marshall Space Flight Center (MSFC) (Ref. 28). Additional information was obtained from study teams at MSFC (Ref. 31) and the Johnson Space Center (JSC) (Ref. 29).

The general approach taken was to use the ECON study definition of subsystem cost and performance (Ref. 28) in all areas except as noted below. Whenever MSFC and JSC data were available, they were combined with the ECON data to form a composite average. These same sources were used to provide a high and low bound. The approach taken in the initial ECON study is to establish a goal in each major area so that when the combination of all these subsystem goals are taken together, the resulting system cost is competitive with competing baseload energy costs. The initial ECON study (Ref. 28) considered the cost goal to be less than 30 mills/kWehr and the SPS capital cost was established at \$7.6 billion dollars for 5 GWe (≈\$1500/kWe). A later report (Ref. 30) doubled this estimate to approximately \$15 billion (≈\$3000/kWe) and represented a departure from the cost-goal approach. It is more an estimate of future cost and performance of the SPS system. Independent studies of SPS cost-performance were performed by MSFC and JSC; their results are discussed later. The major uncertainty is how close it is possible to come to these cost-performance goals.

The amount of RD&D has been estimated by ECON and JSC to be about 60 billion to put up the first 5 GWe SPS plant. It is beyond the scope of this report to attempt to verify that the SPS cost-performance goals can indeed be achieved after this RD&D investment.

The major exception to the above approach, as was indicated earlier, is in the photovoltaic subsystem. Here the same approach used for the ground solar photovoltaic plant was adopted. That is, the 1985 ERDA cost goal of $\$0.50/W_p$ was assumed to be achieved for terrestrial photovoltaics. This was interpreted to be accompanied by an expected module efficiency of 13% air mass 1 (AM1) at a cell temperature of 28°C (Ref. 32). Projections of design modifications and resultant performance of these cells for use in space in the year 2000 were made with the assistance of members of the low cost silicon solar array (LSSA) project at JPL. For example, the 30 to 60 mil cover thickness will be reduced to 1 to 3 mills with a resultant cost savings. Additional processes may be used on the front and back surface to improve performance by approximately 25%, resulting in a net photovoltaic cost increase of about 60%. The cell thickness will be in the range of 2 to 10 mils.

There are several different approaches being considered to achieve the low cost terrestrial solar cell such as refining the current ingot slicing approach or the edge defined film growth (EFG). For the terrestrial application, there is no particular need for a thin cell as an independent design goal. The cost is the main driver. If the ingot slicing technique is used to achieve the cost breakthrough, the resulting cell thickness would be about 10 mils. This would probably be unsuitable for the SPS since a 10 mil cell would cause the system costs to be about 25% greater compared to a similarly performing 4 mil cell.

For the SPS, the reference cell thickness is assumed to be 4 mils, and this assumes that EFG or other growth techniques was used for the terrestrial cell. If this is not the case and ingot slicing techniques are used, the SPS program must perform the additional development to achieve the low cost-thinner cells.

In the analysis, account was made of AMO (no atmosphere) and radiation damage was considered over the 30 year projected life of the plant. Solar flare activity as well as normal radiation was considered in a preliminary analysis, resulting in a reduction factor of 0.89 to account for the average loss of power over 30 years (Ref. 32). More recent and more detailed calculations may increase the radiation related degradation.

A cost and performance model was independently developed to calculate SPS system performance and cost (Ref. 32). The reference costs used to project SPS plant economics along with lower and upper bounds are shown in Table 4-4. The nominal values (Mid) are based on the assumption that a successful program is achieved in each major area. As a guide to understanding these goals, the current cost for silicon photovoltaics is about $\$15.50/W_p$ (Ref. 33) compared to the $\$0.50/W_p$ goal used as a basis for the cost projection shown in Table 4-4. The payload cost to LEO based on a Saturn 5 boost system is about 1100 $/kg (Ref. 28). The goal is 145 $/kg to GSO, and the LEO payload cost would be about 100 $/kg of this total.

Using the Mid values for most subsystems, the total capital cost is shown in Figure 4-11 as a function of payload cost and photovoltaic efficiency. The costs are based on a plant startup in the year 2000 for a 5 GWe plant. The costs shown in Figure 4-11 are the unit cost and exclude RD&D. The reference cost is 5600 $/kWe or 26.5 billion dollars per SPS using the 4 mil cell.

The resulting energy cost as a function of payload cost and photovoltaic efficiency is shown in Figure 4-12. The reference cost is 118 mills/kWeh using the 4 mil thick cell. The original ECON results (Ref. 28) are shown at 7.6 billion (1520 $/kWe) as a point of reference. A more recent study by ECON (Ref. 30) increased the expected capital cost to 14.9 billion dollars or 3000 $/kWe. They estimated that there is a 10% probability to achieving a cost of 2400 $/kWe in 1974 dollars. Other estimates range from 15 billion to 28 billion for a 5 GWe SPS (Refs. 29, 31) using a factor of 1.22 to project to a year 2000 start-up in 1975 dollars.

To establish the upper bounds of costs, all the "high" cost and low efficiency estimates are combined. The lower bound of cost combines all "low" cost and high efficiency estimates. Figure 4-13 shows the energy cost results of this bounding. It is more probable that the high cost estimate can be achieved, than the low cost estimate. There is a difference between these results and the similar figures for ground solar (Figure 4-7), nuclear (Figure 4-2) and coal (Figure 4-3)

Table 4-4. SPS Reference Subsystem Costs — 5 GWe

Major Area	Low	Mid	High
Solar Blanket(1)			
- Cost, $\$/m^2$	48	104	160
- Efficiency in GSO, %	9.7	8.4	6.2
- Thickness, mils	2	4	10
Payload Cost(2) to GSO, \$/kg	71	145	209
Weight of(3) Structural Support, kg/m^2	0.092	0.18	0.37
Microwave(4)			
- Cost, \$/kW	332	520	840
- Efficiency, %	70	60	40
- Spaceborne Wt., kg/kW	1.16	1.33	1.54
Operation and Maintenance(5), 10^6 \$/yr	33	108	150
Construction Time, yrs	3	6	10
Load Factor	0.99	0.864	0.75(6)

(1) Based on same terrestrial cell used in Section 4.2 but modified for orbital use. Terrestrial cell cost was assumed at \$0.50/W_p and had 13% module efficiency in air mass 1 (AM1) at 28°C. Expected range of terrestrial cell efficiency was 10 to 15%. Orbital version of this cell has reduced cover thickness, and improved performance by additional processes to front and back surface at additional cost. AM0 efficiency is 12.5% at 28°C for the 4 mil thick cell.

(2) Nominal from ECON and MSFC; range from JSC.

(3) From ECON and MSFC; weight normalized to solar blanket area.

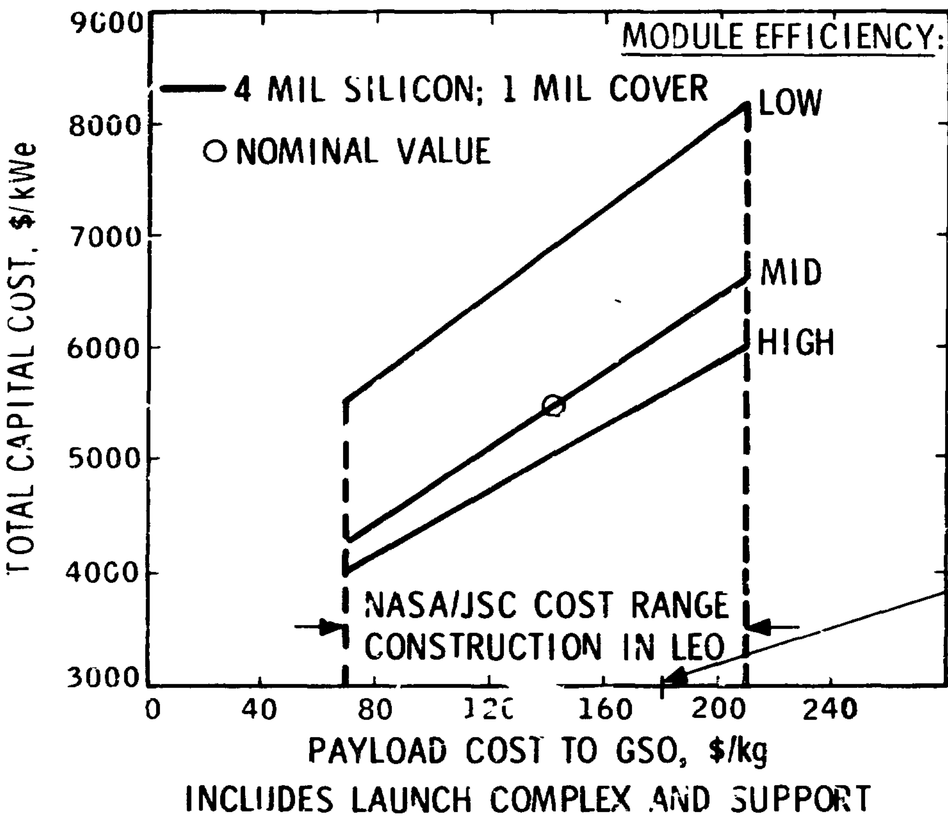
(4) From Raytheon and NASA/LeRC.

(5) From ECON, MSFC and JSC. First year O&M cost.

(6) Based on losing power for 24 hours each time SPS passes in earth's shadow.

EFFECTS OF SOLAR CELL EFFICIENCY AND SPACE TRANSPORTS COSTS

- DELIVERED POWER: 5GWe
- YEAR 2000 PLANT STARTUP*



OPERATIONAL EFFICIENCY AT REFERENCE POINT (%)		NEW MODULE EFFICIENCY IN AMO, 28°C
LOW	6.5	9.7
MED	8.4	12.5
HIGH	9.7	14.4

*DIVIDE BY 1.22 FOR 1975 PLANT STARTUP.

Figure 4-11. Photovoltaic SPS Capital Costs

EFFECTS OF SOLAR CELL EFFICIENCY AND SPACE TRANSPORT COSTS

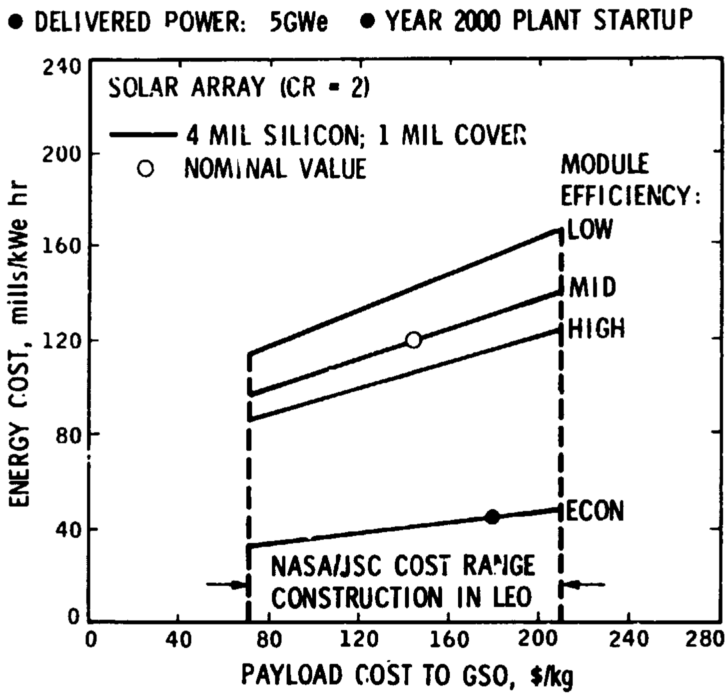
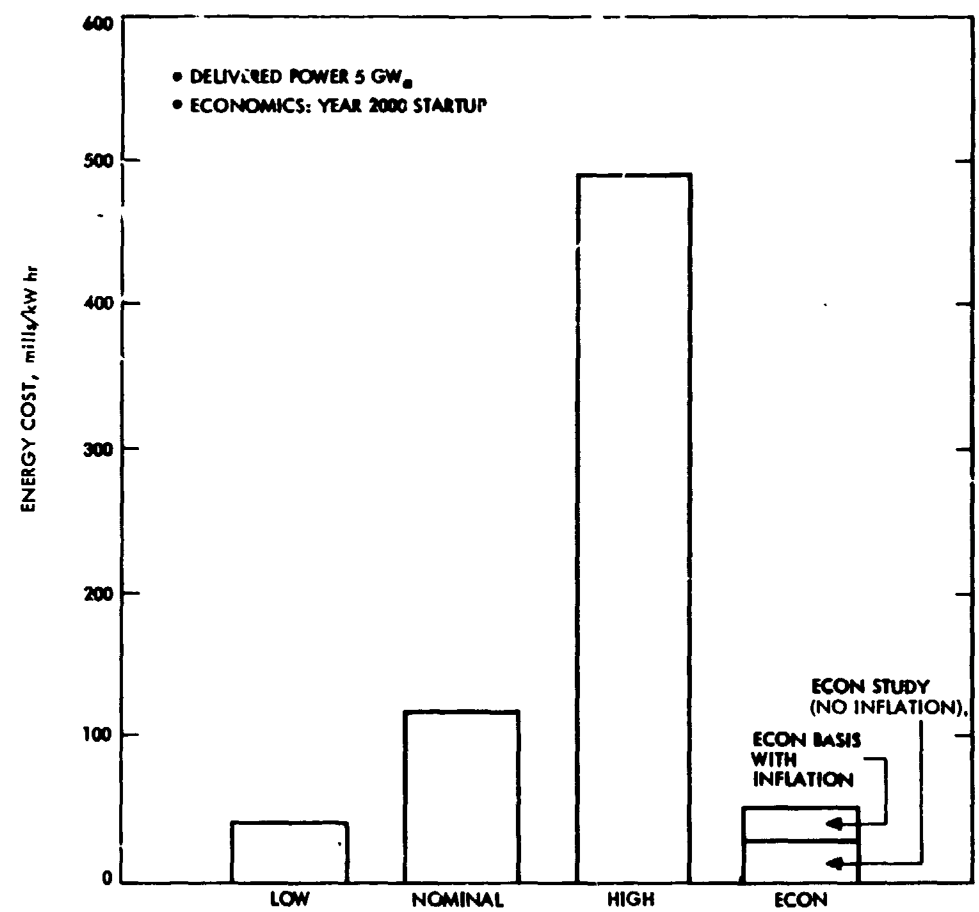


Figure 4-12. Photovoltaic SPS Energy Costs

power plants. A major assumption has been that the RD&D dollars would create successful results in each of many major subsystem areas (e.g., power conversion, low cost structure, heavy lift vehicles, etc.); that is, all goals are achieved. Projecting the orbital photovoltaic SPS cost and performance is much more uncertain than any of the other systems in assessment because of the uncertainty in the successful development of all of the major subsystems in addition to the design changes which may be necessary to avoid or minimize possible social impacts discussed in Section VI.

The SPS size is established at 5 to 10 GWe to keep the system cost down, while the transmitting power is set at 5 GWe to limit the intensity of the microwave beam to 23 w/cm. A power plant of this size even with a high load factor (≈0.9) would introduce reliability problems



		LOW	NOMINAL	HIGH	ECON
PAYLOAD COST TO GSO	- \$/kg	71	145	209	182
SOLAR BLANKET COST	- \$/m^2	48	104	160	54
SOLAR BLANKET EF.	- %	9.7	8.4	6.2	
CELL THICKNESS	- mils	2	4	10	
ARRAY STRUCTURAL WT	- kg/m^2	0.092	0.18	0.37	0.11
MICROWAVE SYSTEM EFF	- %	70	60	40	60
MICROWAVE SYSTEM COST	- \$/kW	332	520	840	368
MICROWAVE SPACEBORNE WT	- kg/kW	1.16	1.33	1.54	1.14
O&M COST	- 10^6 \$/yr	33	108	150	136
CONSTRUCTION TIME	- YR	3	6	10	2
LOAD FACTOR	-	0.99	0.864	0.75	0.95
EFFICIENCY W/O PHOTOVOLTAICS	- %	58	50	33	50

Figure 4-13. Photovoltaic SPS Cost Sensitivity

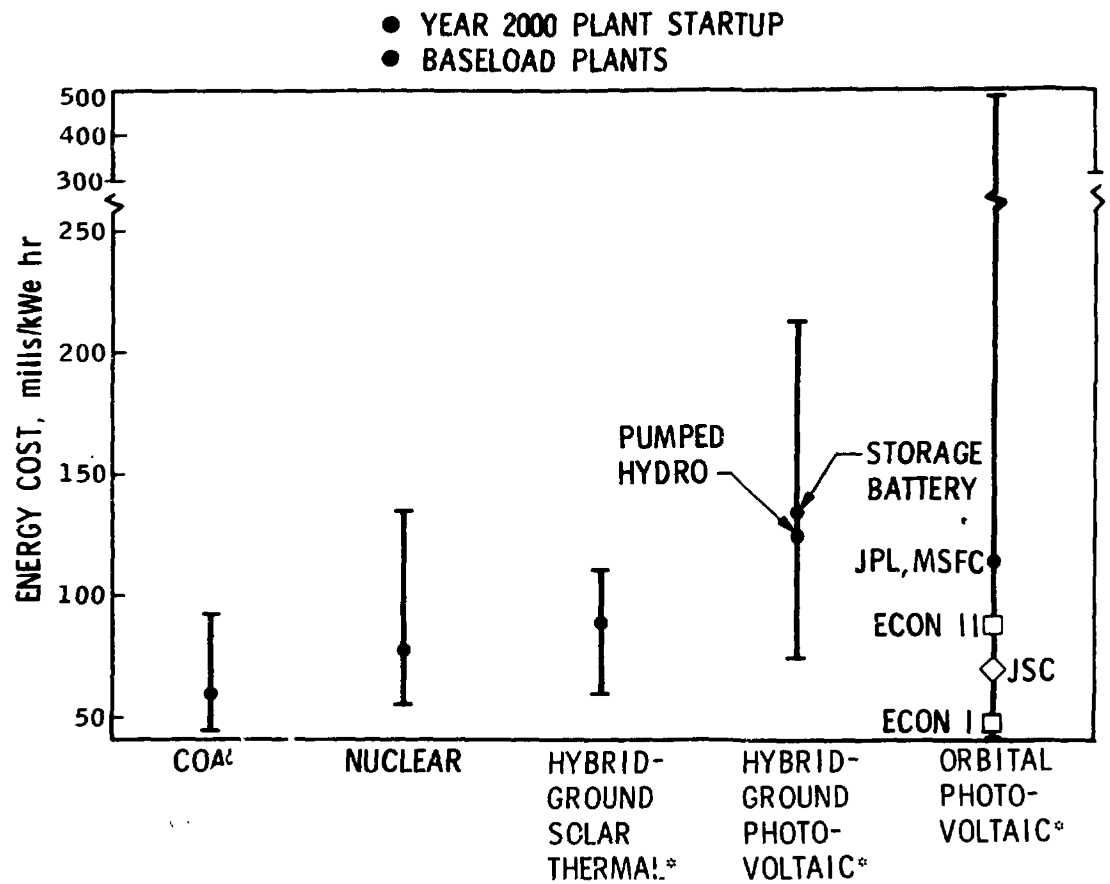
into utility grids. There would be an increased need for margin (extra back-up capacity) just to maintain grid reliability. This effect has not been numerically evaluated in this report but would raise the capital cost of the SPS.

4.4 COMPARISON OF PLANT ECONOMICS

The typical coal, nuclear, ground solar thermal-electric, ground solar photovoltaic and orbital photovoltaic central power plants were identified and a performance estimate was made for each. The time frame of interest was for a year 2000 start of plant operation; 1975 dollars were used. The reference or expected costs were identified and the resulting plant capital and energy costs were calculated. In addition, low and high bounds were estimated for each major subsystem. The combination of all low subsystem cost estimates and performance upper limits were used to establish the lower bound for system cost, while the combination of all high subsystem costs and lower performance limits were used for the upper bound system cost.

These results are shown in Figure 4-14 for the five categories of plants. The conventional systems still appear most attractive economically at the year 2000. In today's dollars, the expected energy costs are from 58 to 76 mills/kWeh. The lower bound could be as low as 39 mills/kWeh and the upper limit to costs as high as 133 mills/kWeh. The ground solar thermal is expected to be under 90 mills/kWeh in the year 2000. The cost uncertainty is similar to coal in that the low-high bound range is about 50 mills/kWeh. The cost goal of the ground photovoltaic plant (128 mils/kWhr) at a solar load factor of 0.70 is about 10 mils/kWhr greater than that of the SPS with 4 mil cells. Also shown is the initial ECON results (ECON I), their more recent estimate (ECON II) and the results from MSFC and JSC adjusted for a year 2000 start-up in 1975 dollars.

The ground photovoltaics has greater uncertainty than the conventional or solar thermal plants due to the nature of development needed to achieve the low cost breakthroughs. The orbital photovoltaic plant has even greater uncertainty in expected costs. The reference



*LOAD FACTOR = 0.864. FOR GROUND PLANTS, THE SOLAR ENERGY CONTRIBUTES 0.70 AND GASIFIED COAL CONTRIBUTES THE REMAINDER. ADDITIONAL CAPACITY IS INCLUDED TO MEET UTILITY GRID RELIABILITY. GROUND PLANTS ARE RATED AT 100 MWe IN A SOUTHWEST U.S.A. LOCATION. SOLAR THERMAL HAS 9 HOURS STORAGE, AND GROUND PHOTOVOLTAIC HAS 12 HOURS STORAGE. STORAGE IS AT 70% RATED POWER.

Figure 4-14. Summary of Plant Energy Cost point for orbital photovoltaics is based on the expectation that not only will low cost photovoltaics be achieved, but that a number of major technological advances will occur in the areas of launch and transport costs, effectiveness of man in space, large structures, controls, microwave, etc.

To a great extent, very different things are being compared. Even though these plants are all baseload central electric plants,* they are at very different stages of development. The basis for the uncertainty in cost, therefore, is quite different from system to system, as is the difficulty in predicting these costs. The nuclear and advanced fossil plant are in a relatively mature state of commercial development. Still, there is great uncertainty in their future capital and fuel costs. This is due primarily to the broad social resistance to these power plants. Thus, the range of costs shown for the conventional plants attempts to quantify this social acceptance uncertainty in terms of economic impacts.

The ground solar plants have future cost uncertainty basically due to their status; these plants are in an earlier part of the development cycle. Prototype subsystems exist now and a pilot plant will come on line in 1980. Cost predictions are not based on sufficient hardware experience to be firm. Yet, the problems can be considered to be engineering problems amenable to detailed design, test and verification. Solar plants are relatively clean with modest social and low public impacts as will be shown in the next section. Social resistance is not felt to be a problem even though it is unlikely that solar thermal plants will be embraced by all Americans as totally acceptable even if it is for just the large land use at the plant site. If any cost escalation due to social resistance should develop, it probably would not develop until significant introduction of solar plants; this would not happen until after the year 2000. Therefore, cost predictions until 2000 should have a minimal social resistance effect for ground solar plants.

---

*The ground solar plants were evaluated as hybrid to achieve the necessary grid reliability.

As discussed at the end of the last section, the orbital photovoltaic plant is earlier in the development phase and greater uncertainty exists. The large cost range in Figure 4-14 indicates this to some extent, and additionally, the reference cost prediction is much more uncertain than for any of the other plants.

SECTION V

ENERGY SYSTEM ECONOMICS

Bus-bar cost of energy at the power plant was estimated in Section IV. The different types of power plants may be located at widely varying distances from the end user in the load center. This difference in transmission distance may introduce additional differential costs among the various central power plant types. To account for transmission differential costs, the complete energy system has been evaluated. The system includes the power plant and transmission and distribution links to the user. Candidate energy systems have been identified for coal, nuclear, ground solar and orbital solar plants, and total system cost has been calculated. The time frame of interest is some time after the year 2000 when solar energy is more than a regional source of electricity.

Many techniques of transmitting energy were reviewed such as: overhead electric using dc and ac; underground electric using dc and ac and superconducting dc; and even hydrogen gas transmission (Ref. 34). Of these techniques, the high voltage (± 800 kV) overhead direct current (dc) is the least expensive for distances greater than 300 to 500 miles. For distances less than this, the high voltage ac used in existing transmission lines is most attractive.

The two main parameters which determine the transmission cost for moving large blocks of electrical energy from the central plant to the city gate is the transmission distance and electricity bus-bar cost. The cost dependency on distance is obvious, but the dependency on bus-bar costs may not be. The electrical losses during transmission amounts to a certain fraction of the input energy. The cost of this loss is a fraction of the input cost of electricity or the bus-bar electricity cost. Thus, the total transmission electricity cost is the sum of the cost of the transmission equipment which is related to distance, and the cost of the transmission inefficiency which is related to bus-bar electricity cost. The resulting costs are shown in Figure 5-1 for overhead ac (756 kV) and dc (± 800 kV) transmission.

The economics used is the same as described in Section III, but uses 10% interest, assumes a 30 year payback life and a year 2000

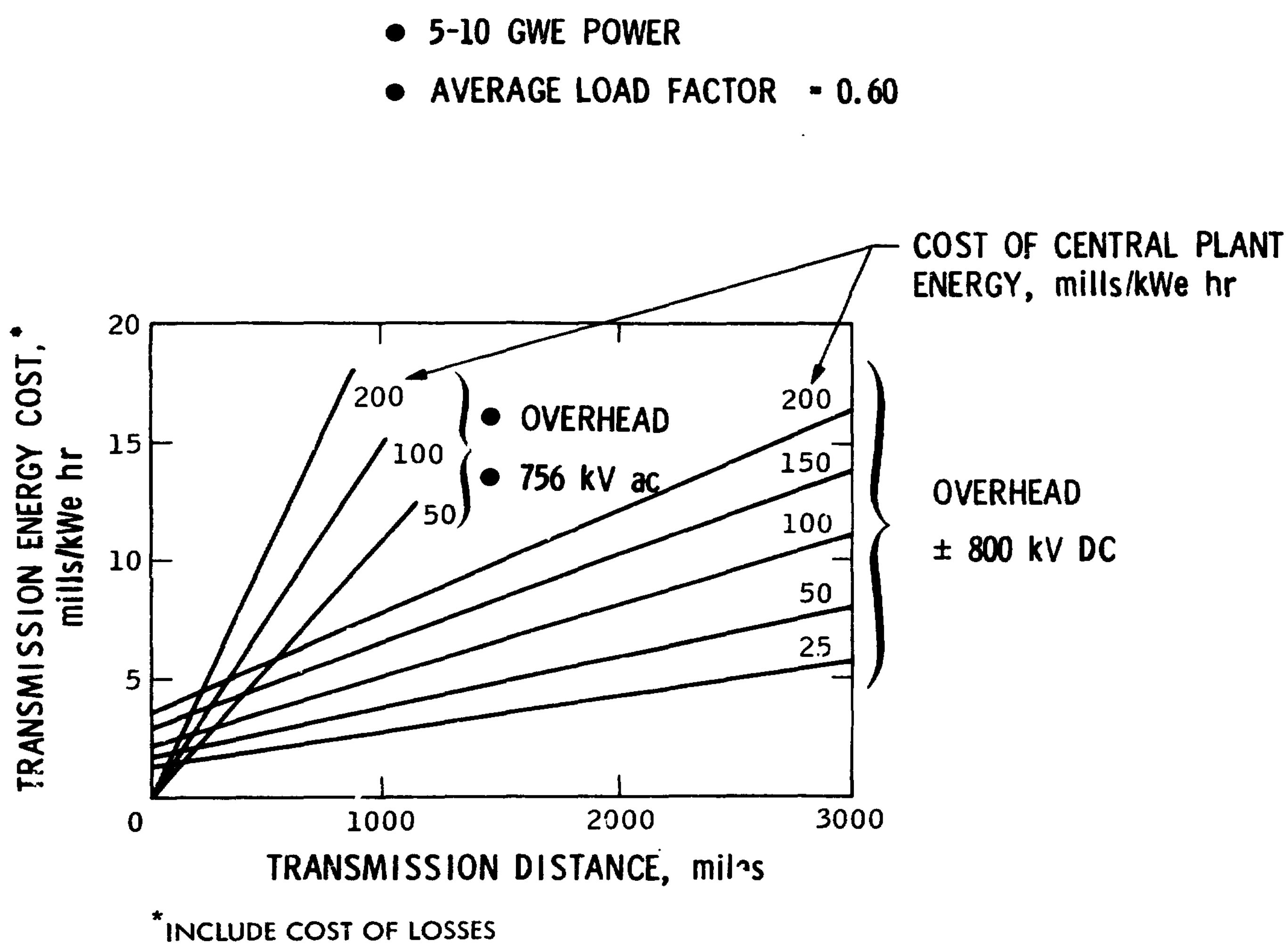


Figure 5-1. Cost of Electric Power Transmission

startup. Land costs are assumed to be $1000/acre. The transmission cost is optimized for each combination of distance and bus-bar energy cost. The cost for 2000 miles of dc transmission (Ref. 35) is about 8 mills/kWeh if the input energy costs 100 mills/kWhe. The transmission efficiency is 0.965 at this condition. High voltage, overhead ac transmission for 300 miles costs about 5 mills/kWhe with 100 mills/kWhe plant energy. If 10% of a 2000 mile transmission link were placed underground to minimize visual and environmental impact, the transmission cost would increase by 20%.

The cost to distribute energy within the load center is 5.5 mills/kWhe (Ref. 35) based on the Southern California electric load center. This includes not only the distribution system construction and maintenance costs but also central office customer services and billing costs. The transmission and distribution costs are added to the reference plant bus-bar energy costs to make up the total system energy cost. The total cost of transmission and distribution is low compared to the projected cost of bus-bar energy. The sensitivity of the total cost of delivered energy may be a weak function of factors which determine the energy transport costs.

The national average electric transmission distance in the U.S. is 300 miles (Ref. 34). For coal based plants, it is assumed that this distance will still be typical even after the year 2000. The cleaner coal plants that are projected for use around the year 2000 should be able to maintain current transmission distances to the load centers.

Nuclear plants are not sited in or near metropolitan areas, but are in the regional utility grid. Thus, 300 mile transmission distance is considered close to typical for nuclear plants. After the year 2000, nuclear plants may be located further from load centers, and the possibility exists that plants will be co-located with reprocessing facilities in order to minimize nuclear fuel cycle hazards and to enhance operational safety. The distance from these regional nuclear centers (nuclear parks) to load centers may be approximately 1000 miles. Therefore, the average distance between a nuclear power plant and load center may be from 300 to 100 miles after the year 2000.

For ground solar electric, the questions raised are: (1) where is the area of high insolation, (2) how much of a resource is it, and (3) can it be used as a national energy source. The combination of high insolation (> 5 kWh/m^2-day) and low cost/low use land is in the Southwest part of the U.S. in an eight state region with a total land area of one million square miles (1/3 total continental land area). The use of solar thermal energy in large central power plants may be confined to just a regional form of energy because of this location of the energy source. To prevent strictly regional use of the solar energy, there must be enough for national uses, and the energy must be transportable outside of the Southwest region. Of the one million square miles of land in the sun bowl, about 2% to 16% is potentially available and suitable for use as a solar power plant (Ref. 36). Today's total national electrical energy use could be met by using only 1/2% (0.005) of this 8 state land area. Thus, this estimate of available land is 4 to 32 times larger than needed to generate the current national electrical requirements.

The other possibility is to use the solar energy available within the regional utility grid. For widely separated locations such as Charleston, SC, Great Falls, Montana, and Blue Hills, Mass., the total normal solar energy is 0.67, 0.69 and 0.65, respectively, of a good Southwest location such as Inyokern, CA in the Mojave Desert. The relative power performance at these sites is 0.84, 0.80 and 0.75 of Inyokern (Ref. 37). The solar energy cost at these locations is thus 16% to 25% higher than that of Inyokern. This represents an upper limit to the acceptable costs for a long distance transmission link.

The second major question of using Southwest lands for national solar power is whether or not there is sufficient cooling water. For all practical purposes, there is no water available in the Southwest region for power plant cooling. The only rivers, with the exception of those in central California, are the Colorado and the Rio Grande which are overcommitted now. Wells are the only other source of cooling water indigenous to the region, but are not sufficient for national power requirements using current cooling techniques. These limited resources can be conserved by switching to dry cooling towers which have a capital cost and operating efficiency penalty of about 10% compared to the use of wet cooling towers. The solar plant costs presented in Section III were based on dry cooling towers to minimize cooling water requirements.

Assuming that the abundant solar energy resource in the Southwest sun bowl is used for national electric power, the required transmission distances would vary from 300 miles for local regional use to as much as 3000 miles. For example, the distance from the middle of this 8 state area to Chicago is about 1800 miles.

Orbital solar power plants can potentially have the receiving antenna near the load center. The land area is similar to ground solar thermal per unit energy, but must all be in one location. A 5 GWe plant needs about 300 km^2 of land which is a circle 12.5 miles in diameter. This large a piece of land, and the possible public perception of health dangers from microwave energy, may require the orbital ground receiver to be placed at large distances from the load center. Therefore, the transmission distance could vary from 300 to 1000 miles. The likely range of transmission distanced for each type of central plant for introduction after the year 2000 are shown below:

COAL	≈300 miles
NUCLEAR	300 - 1000 miles
GROUND SOLAR	300 - 3000 miles
ORBITAL SOLAR	300 - 1000 miles

Table 5-1 displays the results of adding the transmission and distribution energy costs to the bus-bar energy cost. There is a cost increase of about 3 mills/kWe-hr for ground solar relative to other approaches. This is not a strong enough influence to change the economic results of Section IV. The transmission and distribution costs, which are about half the total cost of electric energy today, will drop to less than 20% of the total by the year 2000.

Table 5-1. Comparison of System Energy Cost*

Type of Plant	Energy Cost, mills/kWe hr		
	Plant Bus-Bar	Transmission & Distribution	Total
Orbital Solar			
- Silicon Photovoltaic	118[1]	19[2]	137
Ground Solar[3]			
- Silicon Photovoltaic	128[4][5]	22[6]	150[5]
- Thermal	89[7]	18[6]	107[7]
Coal	58	12[8]	70
Nuclear	76	15[2]	91

(1) 4-mil thick cell.
(2) Transmission distance = 1000 mi.
(3) Terrestrial plants based on hybrid operation at load factor = 0.864 to meet grid reliability with solar load factor = 0.70.
(4) Average of battery and pumped hydro storage.
(5) Stand-alone solar = 145 mills/kWhr bus-bar and 169 mills/kWhr total energy cost.
(6) Transmission distance = 2000 mi.
(7) Stand-alone solar = 96 mills/kWhr bus bar and 115 mills/kWhr total energy cost.
(8) Transmission distance = 300 mi.

*Plant startup in year 2000; reference design.

SECTION VI

SOCIAL COSTS

The methodology developed for the comparison of energy systems is based on a total cost assessment. This is made up of utility or consumer costs (internal costs) (see Sections IV and V) and so-called external costs such as Federal RD&D costs, health effects, resource consumption, environmental residue and impacts and other social costs as shown in Figure 6-1. Although significant RD&D efforts are conducted by EPRI and utility equipment suppliers, only the RD&D costs based on Federal expenditures from general tax revenues are considered. A methodology is developed for calculating the equivalent cost of these RD&D investments using a social discount rate so that it may be added to the direct utility cost of energy.

The health effects associated with the complete energy cycle for the various technologies can be summarized in terms of parameters such as occupational and general public deaths, disease and injury. These non-fatal disease and injuries have been transformed into a common unit of person days lost (PDL) by associating a particular type of injury or disease with the typical PDL resulting from that injury or disease.

Resources required for each energy system are tabulated. These resources such as plant construction material, fuel, construction material used in the rest of the energy system, manpower, land, cooling water and other resources are accounted for in the internal cost of the plant. However, the absolute magnitude of these resources are important in themselves in a world of increasingly limited resources. The amount and type of resources required is one of the many distinguishing characteristics of an energy system.

Environmental impacts, such as excess waste heat, are calculated, and environmental contaminants rejected into the air and water are noted along with solid wastes. The category of "other" social costs involve poorly understood impacts due to environmental, resources, political, etc., effects.

TOTAL SOCIAL COST

OTHER	- CONSTRUCTION IMPACTS - LAND USE - NON-RENEWABLE MAT'L USE - ACID RAIN - GENETIC EFFECTS - SABOTAGE, BLACKMAIL - MAT'L DIVERSION TO WEAPONS - LOCAL OR GLOBAL CLIMATE EFFECTS - TIME DISTRIBUTION OF IMPACTS - OTHER
ENVIRONMENTAL	ENVIRONMENTAL RESIDUES SUCH AS: - GASEOUS - LIQUID - SOLID - WASTE HEAT - OTHER
RESOURCES	RESOURCES CONSUMPTION SUCH AS: - MATERIAL - FUEL - MANPOWER - LAND - WATER - CAPITAL - COMMUNICATION FREQUENCY - GEOSYNCHRONOUS SITES, ETC.
HEALTH	COST OF PUBLIC AND OCCUPATIONAL HEALTH IMPACTS DUE TO: - MINING - FUEL UPGRADING AND TRANSPORTING - MAT'L ACQUISITION - CONSTRUCTION - PLANT OPERATION - FINAL WASTE DISPOSAL
RD&D	PUBLIC INVESTMENT FOR RESEARCH, DEVELOPMENT AND COMMERCIAL DEMONSTRATION
UTILITY COST	COST OF MATERIALS, CAPITAL, LABOR, FUEL, TAXES, INSURANCE, ETC. FOR ENERGY SYSETM, i.e.: - CENTRAL PLANT - TRANSMISSION - DISTRIBUTION

Figure 6-1. Total Social Cost Concept

In this report, information is developed for each central electric plant considering the complete energy system; i.e., the acquisition of materials and equipment necessary to build the plant, the construction of the plant and the fuel cycle facilities required to operate and maintain the plant. The seven stages of the energy system are shown in Figure 6-2 along with the social cost matrix. Each major type of central electric baseload power plant is evaluated for each combination of social cost and stage of the energy system.

This information generates a data base for a one-to-one comparison of competing systems as regards total social cost, rather than only the projection of commercial economics for competing baseload electric power systems. These additional areas do not represent a complete listing of energy system characteristics. Nor is the depth of analysis considered definitive in each area. This study is an attempt to organize in one place a number of important characteristics of these plants on a consistent basis so that at least a framework and some data exist for evaluating the SPS against likely competing energy systems. It will be necessary in the final analysis to combine the various currencies (consumer dollars, Federal tax dollars, People Days Lost tons of steel, tons of NO_x, waste heat, catastrophic impact, impacts on life style, political implications, etc.) involved in the different study areas to reach a complete understanding of the impact of each energy system.

6.3 RESEARCH, DEVELOPMENT AND DEMONSTRATION COSTS

Projected RD&D costs and estimated date of commercialization were determined for each of the electric generation systems considered and are summarized in Figure 6-3. The costs are simply the summation of expected costs in constant 1975 dollars. It is not a present value in 1975 dollars using an appropriate discount rate. The data for the conventional fossil and nuclear plants is from Reference 7. The solar thermal RD&D estimate is based on information in References 27, 38 through 43, while that of the terrestrial photovoltaic is taken from References 27, 38, 40, 41, 43 and 44. The orbital photovoltaic RD&D cost estimate is from Reference 28.

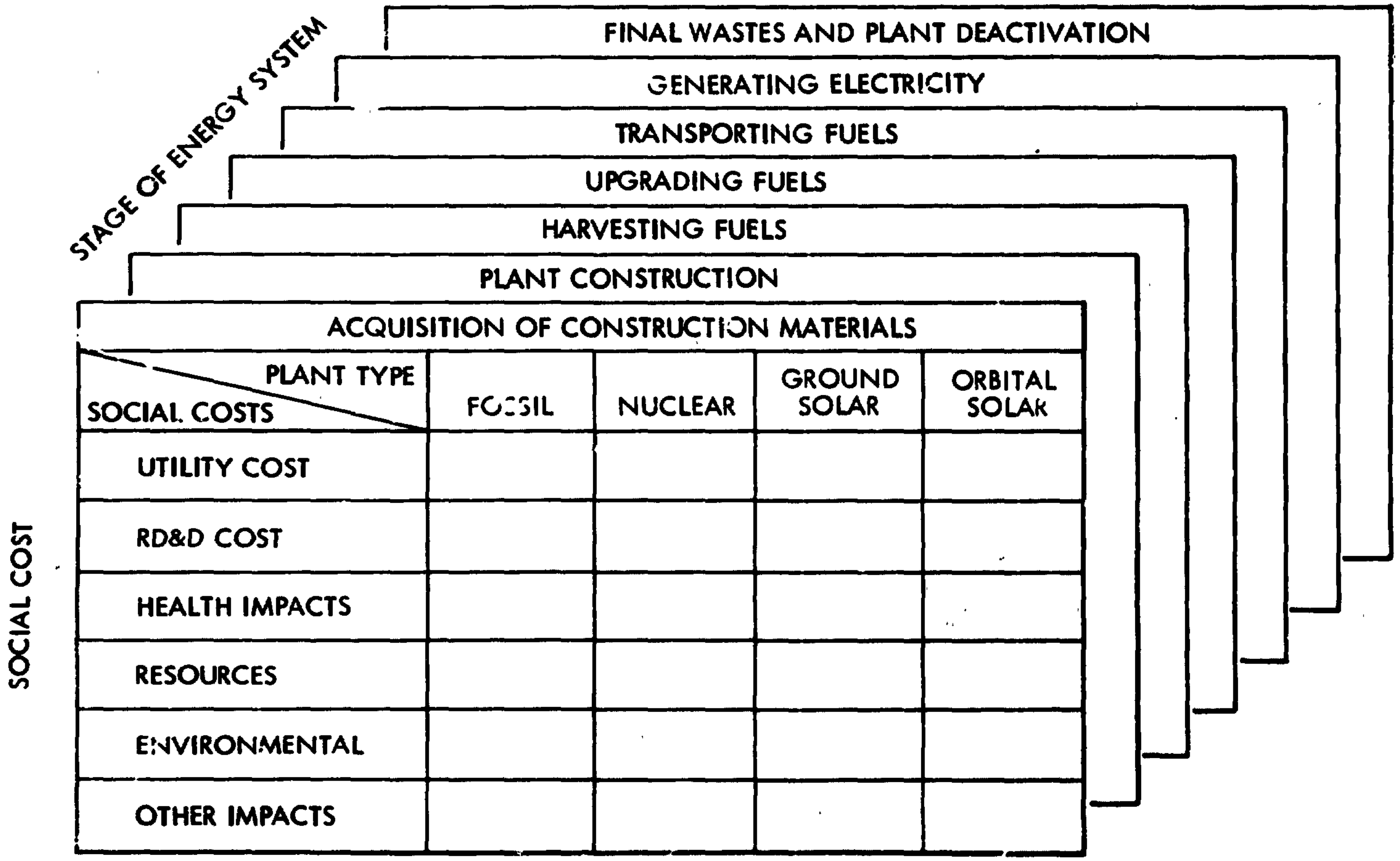
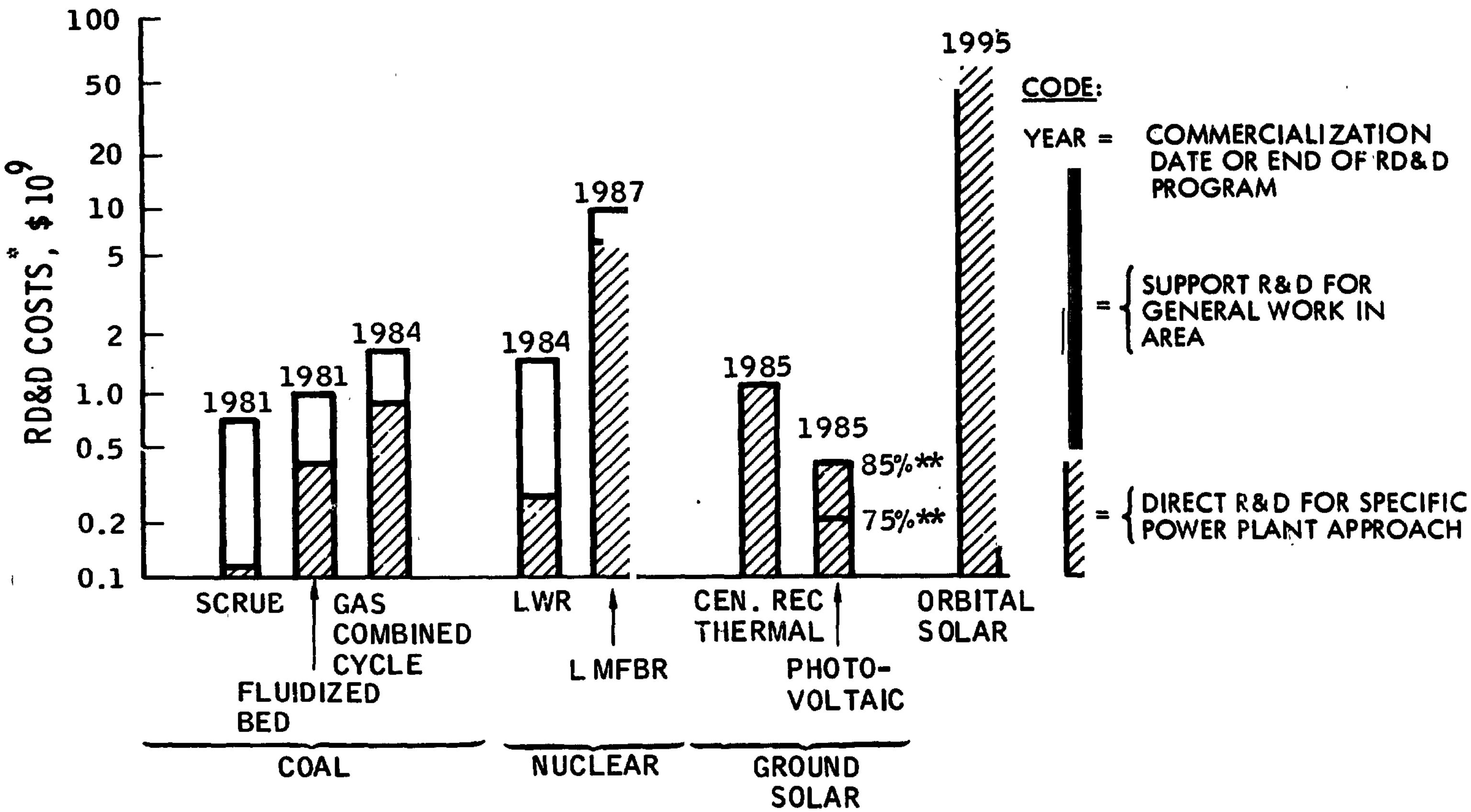


Figure 6-2. Energy System Matrix



*FROM 1975 TO FUTURE, PAST RD&D EXCLUDED

**LEARNING CURVE ASSUMED TO 10 MWe DEMO. PLANT

Figure 6-3. Projected Research, Development and Demonstration (RD&D) Costs*

Figure 6-3 shows estimated program funds that are directly related to a particular type of power plant system as well as the RD&D expenses which generally support these power systems. Where appropriate, these general support funds are equally distributed over all the types of power plants that will benefit from the support work.

In comparing the conventional power plants, it is noted that the total direct and support RD&D is about $1.5 billion for the coal gasification with combined cycle conversion power plant. The other coal approaches are estimated to cost $1 billion or less. The LWR and LWR-Pu (not shown) is estimated to have a total RD&D of $1.6 billion by 1984 in 1975 dollars. The direct RD&D for the LMFBR is estimated to require $7 billion, and the total is at least $10 billion.

The general support RD&D costs for the LMFBR are the largest (3 billion). The LWR and LWR-Pu require about $1.2 billion each for support RD&D for reactor environmental controls, fuel cycle environmental controls, uranium enrichment and waste disposal. The three coal plants require a support RD&D cost of $0.6 billion each for mining health and safety, fuel cycle, environmental controls and plant environmental controls.

The total RD&D for the central receiver solar thermal plant has been estimated to cost $1.1 billion through completion of the 100 MWe commercial demonstration plant in 1985. The ground photovoltaics has been estimated to require from 0.2 billion to 0.4 billion dollars including a 10 MWe commercial demonstration plant in 1985. This figure assumes the equal sharing of the total low cost silicon photovoltaic program between two areas: the central power application and all other applications. The cost range shown in the table is based on a cost learning curve range of 75% to 85% to reach the low cost silicon module cost goal of $\$0.50/W_{peak}$ (1985).

The RD&D cost for orbital solar has been estimated to be about $60 billion leading to the creation of a 5 GWe plant by 1995 (Ref. 28).

The range of RD&D costs of the systems shown in Figure 6-3 vary by a factor of 200 from about $0.3 to $60 billion. To make the magnitudes of these RD&D cost estimates more understandable, a methodology was developed which spreads these costs over the amount of energy that is anticipated to be generated by the new commercial plants. A levelized energy cost has been developed which assumes equal disbursements of RD&D funds each year between now and the year of commercialization. Since these funds are a federal investment in an energy option, the present value of these sums is calculated using a social discount rate rather than market place discount rate. The social discount rate was assumed to be 10%, a rate often used by various government agencies in evaluating potential projects (Ref. 9). More detailed information on the procedure used to levelize the RD&D costs can be obtained in Reference 45. The projection of the rate at which these various types of power plants can be installed is shown in Figure 6-4 and the total national US installed electric generating capacity is taken from Reference 45.

Two bounding rates of successful power plant implementation are shown in Figure 6-4. The lower one is based primarily on the LWR nuclear precedent which achieved 40 GWe in 20 years after the first commercial demonstration. The higher installation rate uses a similar initial rate of power plants introduction, but uses very much larger power plants (≈5 GWe versus 0.1 GWe). The higher rate is considered as an upper bound for SPS sized plants (5 GWe/plant), while the lower rates are more the lower bound for smaller ground solar plants (≈0.1 GWe/plant).

The resulting levelized energy cost for various amounts of RD&D investment are shown in Figure 6-5 for the upper and lower rates of implementation of new ground power plants and orbital power plants. The energy cost is presented as a function of the time after commercial implementation over which the RD&D charges are allowed to be paid back. If one feels that ten years is a reasonable amount of time to repay the RD&D expenditures, the energy cost surcharge that would have to be extracted from the generated energy over the first ten years would be 10 mills/kWe-hr for an energy system costing $1 billion at the lower implementation rate. It would be 42 mills/kWe-hr for an energy system with a total RD&D investment of $60 billion at the higher implementation rate. If one used 30 years for the expected payback, the equivalent

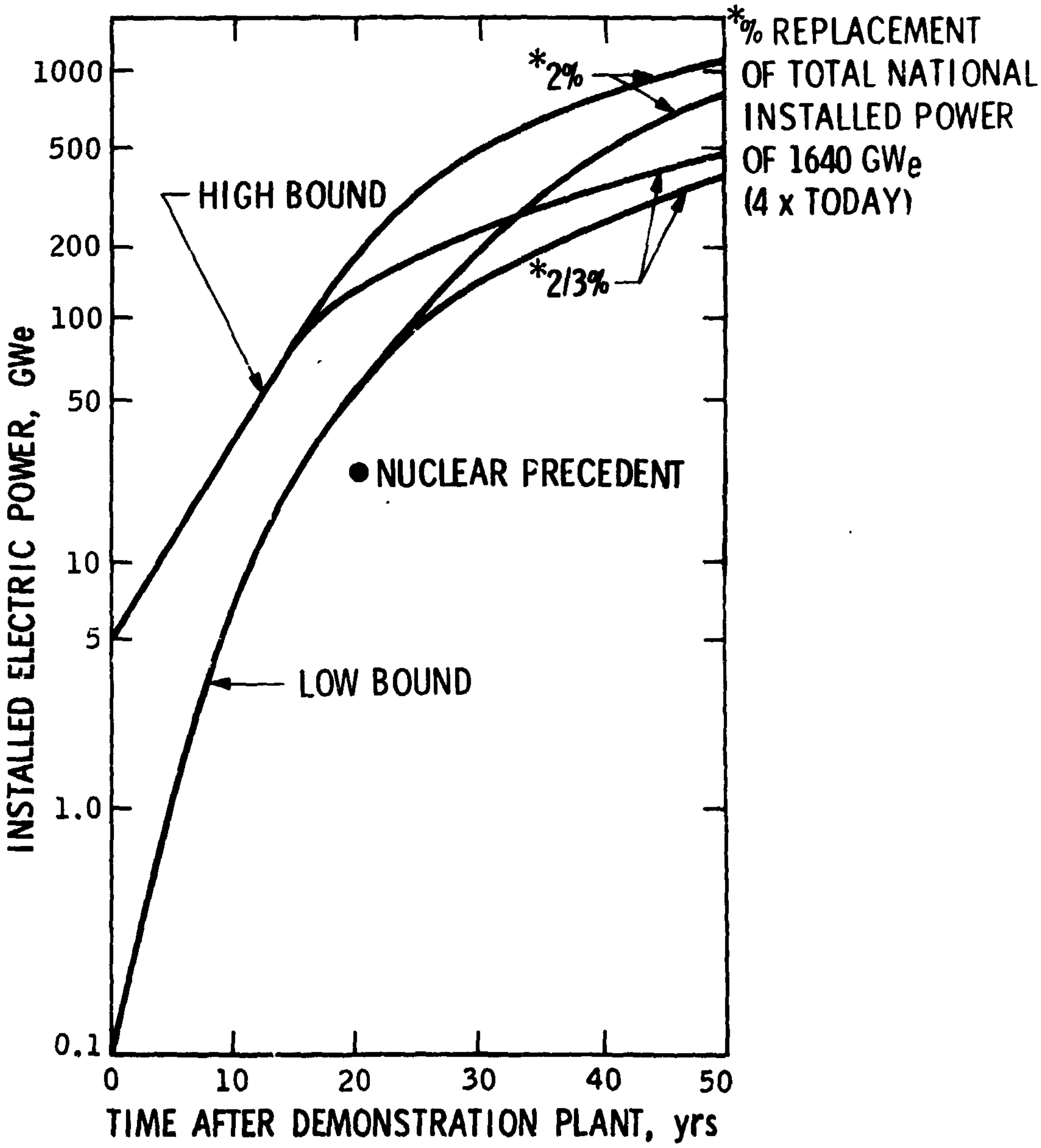


Figure 6-4. Projection of New Plant Installation

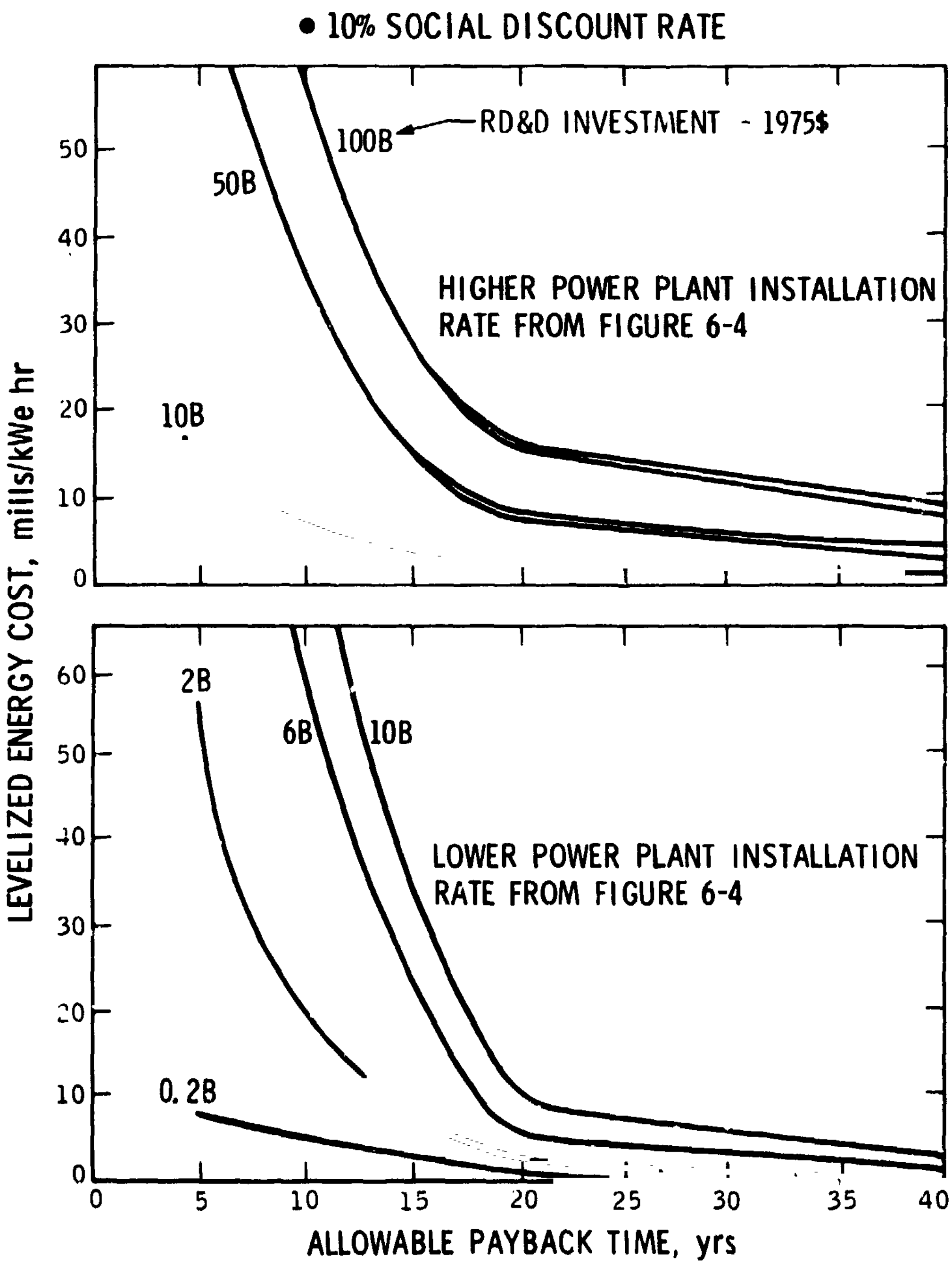


Figure 6-5. Levelized Energy Cost of RD&D

energy cost would be less than 1 mill/kWe-hr and 8 mills/kWe-hr, respectively. A summary of these results is shown in Table 6-1.

At an implementation rate between the upper and lower bounds, the equivalent energy charge for the LMFBR ($10B) would be from 4 to 50 mills/kWehr for a payback time of 10 to 30 years. The SPS ($60B) would have an 8 to 40 mills/kWehr RD&D equivalent energy charge for a 10-30 year payback time. Once the expected payback time is established by the decision maker, the resulting equivalent RD&D energy charge can be directly added to the utility cost of Sections IV and V.

6.2 RESOURCE UTILIZATION

For each electric power production system, estimates have been made of the various resources that the system utilizes. Resource factors estimated include: (1) building materials, such as the concrete, structural metal and pipe needed to construct the plant, (2) fuels required for the operation and maintenance of the plant, (3) human resources such as the number of man-hours required to construct the plant, including skilled and unskilled workers, field supervisors and

Table 6-1. Summary of Equivalent Energy Cost* of RD&D Dollars

Power System Type	RD&D, $B	Equivalent Energy Costs, mills/kWe-hr			
		Payback Time, yrs			
		10		30	
		Rate of Plant Implementation			
		High	Low	High	Low
Coal	1.5	1	15	0	1.0
LWR	1.4	1	14	0.2	0.94
Solar Thermal	1.1	0.8	11	0.1	0.74
Photovoltaic	0.3	0.2	3	0.04	0.20
SPS	60	42	800	8	40

*10% social discount rate.

engineers, (4) water consumption and (5) land utilization, including land for the electrical power plant site, land associated with harvesting the fuels, transporting the fuels, upgrading the fuels, land associated with management of the final waste and land needed for transmission of electric energy to the load center. Some land will be committed to the particular electrical power system only temporarily. Other land, such as that used at a nuclear reactor site, or the land used for the storage of high level radioactive waste, will be essentially permanently committed to these systems. Hence, the type of land use varies vastly from one system to another. Also of interest is the energy payback time for each system. That is, the amount of time that the plant must operate to payback to society the energy it took to form the materials needed for construction and to maintain the supply of fuel. The last resource category of interest is construction capital which was estimated in Section IV. Table 6-2 presents a summary of quantitative data in each of these resource areas.

6.2.1 Material Requirements

Reference 7 presents the material requirement for four types of fossil fuel systems and for four types of nuclear systems. The material requirements are presented for both construction and for operation and maintenance. Reference 45 develops a similar data base for several solar thermal electric power plants such as: 1) the central receiver (power tower), 2) the parabolic dish collector with a small heat engine on each dish, 3) the parabolic dish collector with steam transport to a central Rankine steam plant, and 4) a photovoltaic plant using silicon solar cells.

These data are quite extensive and will not be discussed in detail here. However, in order to make a generic comparison between the materials required to build different electrical power plants, five widely different systems are compared (i.e., a light water reactor, a coal fired system, a "power tower" central receiver, a terrestrial photovoltaic plant and the orbital plant). Table 6-3 shows the number of tons (per megawatt of electrical power output of the plant) of

Table 6-2. Summary of Life Cycle Resources Required*

Resource	Coal[1]	LWR	Ground Solar[2] Thermal	Ground Solar[2] Photovoltaic	Orbital Solar Photovoltaic
Total Land[3], m^2/MWeyr (Transmission Lines)[4]	3600[5] (300)	800[6] (650)	3600[7,8] (1650)	5400 (1650)	2800 + ?[9] (650)
Water, 10^6 liters/MWeyr	0.5 - 9.2[10]	1 - 24[10]	0.9 - 7.4[11,12]	0.6[12]	0.008 + ?[13]
Capital ~ 10^9 \$/GWe 1975 \$, year 2000 startup	1.2[14]	2.3[14]	3.6[15]	5.7[15,16]	5.6[15]
Construction Material, metric Ton/MWeyr[17]					
- Steel[18]	3.1	2.3	39(4.4%)[19]	-	0.17[19,20]
- Concrete	3.0	12.7(2.2%)	174(30%)	4.3	12.6(2%)
- Silver	-	-	3.1×10^{-4}(5%)	-	0.9×10^{-4}
- Silicon	-	-	-	2.5	0.053
- Glass	-	-	6.3 (260%)	2.5 (103%)	0.053(2%)
- Aluminum	-	-	2.2 (7%)	55.7 (178%)	5.02 (16%)
- Total (no storage)	6.1	15	225	65[27]	18.9
- Rock	-	-	71 (1%)	-	
- Heat Transfer Oil	-	-	9.6	-	
- Dolomite[21]	7.9	-	-	-	-
Fuel Ton/MWe yr	3500	≈100	0 to 700[23]	0 to 700[23]	11.8[24]
Manpower ~ Manhour/MWeyr					
- Plant Construction	386	604	1900	808	6680
- Plant O&M	407	250	1900	1900	13.1
- Total[25]	2640	1120	14400	2700 + Mat'l[26]	6690
Energy Payback, yrs[27]	1.9	1.4	1.7	?	1.4[28]

*Footnotes on following page.

Table 6-2. Life Cycle Resources Required (contd)
(Footnotes)

1. Coal gasification with combined cycle.
2. Data for stand-alone solar plant. For hybrid ground solar data should include 10% of effects of backup energy source.
3. Includes fuel cycle, land at plant and transmission lines to load center.
4. Land for 800 kV dc overhead transmission. Average transmission distance: Coal = 300 mi, Nuclear = 650 mi, Ground Solar = 1650 mi, Orbital Solar = 650 mi.
5. Averages Eastern deep-mined coal and Western strip-mined coal. Eastern strip-mined coal would greatly increase this figure.
6. This would increase dramatically toward the end of the century as the average grade of uranium mined decreases.
7. Ground cover ratio = 0.3 and average plant efficiency = 17%, 6 hr storage at 70% of rated power.
8. Installed at 10 GWe/yr, would cover 312 km^2/yr (120 mi^2/yr) which is <1% of minimum available land (0.02×10^6 mi^2) in 8 states in the Southwest.
9. ? launch complex not included. Use of Eastern European microwave standard would increase land to 7200.
10. Range is for dry to wet cooling towers. Costs based on wet cooling.
11. Range is for dry to hybrid (1/4 wet) cooling towers. Cost based on dry cooling.
12. Collector surface cleaned every 5 weeks for solar thermal and every 10 weeks for photovoltaic.
13. Water required for rectenna cleaning not included.
14. Average capital inflation rates.
15. Load factor (L) for energy estimates, Coal = 0.75, Nuclear = 0.75, Solar = 0.864. Ground solar has 0.70 solar load factor with gasified coal providing remainder of energy.
16. Battery storage.
17. Includes material used in fuel cycle facilities as well as for the power plant.
18. Steel includes mechanical equipment.
19. % of 1974 US production if built at rate of 10 GWe per year.
20. Source is Johnson Space Center.
21. Dolomite required for sulfur cleanup of low-btu gas.
22. More recent studies indicate this value may be low.
23. Fuel consumption of solar plants is based on zero to 20% backup energy and it depends on solar plant design.
24. It is assumed that no back-up energy is required to maintain utility grid reliability. Propulsion fuels only.
25. Includes fuel cycle and labor used in material acquisition and fabrication.
26. Manpower for material acquisition not included.
27. Energy payback for construction material energy and operational energy for fuel cycles over 30 yr life of the plant. See Table 6-5.
28. If steel substituted for aluminimum, energy payback is 1.1 yr.

Table 6-3. Plant Construction Material Requirements

Material	Metric Tons per MWe Rating							
	Nuclear[1]		Coal[2]		Ground Solar		Orbital Solar	
	Plant Only	Plant Plus Fuel Cycle [3]	Plant Only	Plant Plus Fuel Cycle[3]	Thermal[4]	Photo Voltaic[5]	SPS	Total[6]
Steel	30.9	32.1	12	27.4	500[7]		0.13	4.8
Mechanical	10.6	18.5	5.8	41.4	136		0.12	0.2
Concrete	279	286	68	68	2820	70.3	-	348
Silver or Silicon	-	-	-	-	0.005	40.8	1.45	1.45
Glass	-	-	-	-	102	40.8	1.45	1.45
Aluminum	-	-	-	-	35	902[8]	2.8	138[8]
Rock	-	-	-	-	1150	-	-	12.9
Heat Transfer Oil	-	-	-	-	155	-[9]	-	-
Other	-	-	-	178[10]	-	?	6.65	11.2

(1) Nuclear - Light Water Reactor (LWR).
(2) Coal - Gasification with combined cycle turbines.
(3) Does not include fuel weight requirements.
(4) Solar - Central Receiver with caloria-rock storage for 6 hours at 70%.
(5) Photovoltaic area sized for 6 hours storage at 70% of rated power but storage subsystem excluded.
(6) Includes rectenna.
(7) Based on heliostat design by Honeywell (1974): venetian blind on circular track.
(8) Other structural members could be substituted for aluminum to reduce energy used to fabricate materials.
(9) No material estimate for external storage system.
(10) Dolomite for sulfur removal in coal gasification.

steel, mechanical parts, concrete, silver (or silicon), glass and aluminum required for these five systems.

The major element in the solar thermal plant is the heliostat (mirror) which reflects and concentrates the insolation onto the boiler. The material estimate is based on an early preliminary design by the Honeywell Corp. (Ref. 46); that design suggested a weight of approximately 10.5 lb/ft^2 excluding concrete in the foundation. More recent designs are lighter (9 lb/ft^2 from Ref. 47) even though they still use glass and metal. A third but more speculative design is based on an aluminized mylar reflector in a clear tedlar dome (Ref. 48). This design is very light (4 lb/ft^2). It is not clear at this time which heliostat design will be selected for commercial applications. The 10.5 lb/ft^2 design has been used for the resource estimates to be conservative; these resources may be reduced by approximately 60% if the lightest design proves acceptable.

The solar thermal power plant requires about a factor of 15 times the construction material than a nuclear plant and its fuel cycle, and approximately 35 times the construction material of the coal fired plant and the facilities for the fuel cycle. (It should be noted that the coal plant with stack scrub requires 2.3 times the material as the reference coal plant.) The photovoltaic plant requires about 1/3 of the material of the solar thermal plant. The SPS energy system requires about the same amount of material as the LWR.

The solar thermal power plants using the distributed dish in various design approaches were very similar in weight to the central receiver. Thus, only the central receiver type plant is displayed since it is typical of all solar thermal plants.

These differences in the amount of materials needed for plant construction have several related impacts. One is the amount of material itself which causes a drain on resources and may cause supply shortages and escalate prices. In addition, there are health effects as a result of mining, transporting, and fabricating the material into components and the eventual construction of the power plant itself.

Since a solar thermal plant uses 15 to 35 times more material than is required for conventional plants, it has greater material related impacts.

By combining the weight of structural steel with mechanical equipment requirements and estimating the total life cycle material demands, the materials required per unit energy (MWe yr) that these plants produce over a 30 year life has been developed and is shown in Table 6-2. To give additional information on the potential impacts of these material requirements, the percentage of current US production (1974) (Ref. 49) is also shown in parenthesis in Table 6-2. The material requirements assume an installation rate of 10 GWe of electrical capacity per year which is slightly over 2% per year based on today's capacity.

As indicated by these results, terrestrial solar plants do consume considerable amounts of resources at the assumed rate of new plant implementation. Glass (260% of current US production) and concrete (30%) for solar thermal, and glass (103%) and aluminum ([illegible]%) for ground solar photovoltaic are the major items. These rates of new plant construction would not take place for at least 20 to 30 years after commercialization and would not occur until after the year 2010. It would probably be possible to develop the glass and concrete production facilities over this long a time period since the basic constituents of these products are plentiful. Aluminum is not as plentiful, and some substitution of steel or other structural material may be needed to keep aluminum from being a restriction on implementation. The material requirements for coal, nuclear and orbital plants are more modest than terrestrial solar and do not require large increases of current production rates.

The above comparisons have focused on the material requirements to build the plant. However, they have not included any consideration of the materials required to run the plant; that is, the fuels for the plant. In the case of the solar plant, the fuel is sunlight and does not require extraction, processing, or transportation in the normal sense. Coal fired plants, on the other hand, require 3500 metric tons per megawatt-year of fuel to be handled (Ref. 50). Over the 30-year life cycle of a coal plant, 105,000 metric tons of coal are required to continuously produce 1 megawatt of electrical power. This weight of fuel is is significantly higher than the 6.1 tons/MWe-yr of material required for coal plant construction or even the 7.9 tons/MWe-yr of dolomite needed for sulfur clean up. The total material requirements for a coal plant, including fuel, is 3514 tons/MWe-yr, which is 35 times the total material requirements for the solar thermal plant (305 tons/MWe-yr). Hence, in terms of tons of material requirement for the coal plant and the solar plant, one sees that the solar plant requires far less material over the life cycle of the plant.

Coal is a non-renewable resource while steel, aluminum, glass, etc., are partially recyclable since they can be reprocessed with a fraction of the original energy required for new mining and processing. This adds another dimension to material consideration since we are depriving future generations of the use of coal as a resource for applications that depend uniquely on fossil materials. The unnecessary consumption of non-renewable resources may appear indefensible to future generations. Balancing the needs of the present versus future generations is a difficult aspect of coal based systems. Uranium also shares this feature with coal and is in much shorter supply when used in a LWR than coal in this country. It may be difficult to commit to current types of LWR toward the end of this century due to potential unavailability of uranium ore (Ref. 51). For nuclear electric power to continue, a switch would have to be made to a thorium fuel cycle such as the high temperature gas reactor (HTGR) or to a breeder system such as the LMFBR.

6.2.2 Land Resource Requirements

The land required for coal plants must include the entire fuel cycle. This land is significantly greater than the actual land used at the power plant site. Based on coal mining averaged over several regions (i.e., half Eastern deep mined and half Western strip mined), the land disturbed for the coal plant is in the range of 1950 to 4670 m^2/MWe-yr. All but 150 m^2/MWe-yr is for fuel related land use (Ref. 7).

It is possible to reclaim strip mined land in the West or East. However, depending on a number of factors such as ground slope, annual rainfall, the site specific ecology, acid water, etc., the time it takes to reestablish the premining ecological balance could vary from somewhat less than 10 years (Ref. 52) to not being possible at all (Ref. 52). The allowable replenishment time assumed in this study is one plant lifetime or 30 years.

The land presently used for the nuclear system is quite small due to the much smaller amount of material mined at current ore grades. However, as the uranium ore is depleted later this century, the amount of land needed could rise substantially and approach the values shown for the coal system. If the current ore grade of 0.25% decreased to 0.01%, the amount of material mined would be approximately equal to that of coal per unit electrical energy generated.

A solar thermal plant uses about 2000 m^2/MWe-yr based on a 100 MWe plant with 1.3 km^2 of mirrored area, a 0.30 ground cover ratio and a 0.70 annual load factor (Ref. 22). The land requirements are 43 km^2 (16.7 mi^2) for ten 100 MWe plants with a total rating of 1 GWe; the land area is all at the plant site.

The terrestrial photovoltaic plant area is 3800 m^2/MWe-yr due to its low energy conversion efficiency, while the orbital solar photovoltaic plant requires 2200 m^2/MWe-yr plus the land area needed at the launch site. The ground rectenna size is 16 times the orbital transmitter size. Such a rectenna size will minimize system cost, keep ionosphere radiation levels to less than 23 mW/m^2, and hold the microwave radiation to levels which are within current US standards at the plant boundary (Ref. 29). Thus the land requirement for a 75 km^2 rectenna (for a 5 GWe plant) is 300 km^2 this will keep the microwave radiation levels down to 0.10 mW/cm^2 at the fence. (This radiation level corresponds to 1/100 of the current US standard for continuous exposure to microwave radiation, but it is 10 times the current Eastern European standard.)

Using the Eastern European standard as the permissible microwave intensity at the boundary, the plant area would triple to 900 km^2. At this power density, side lobe overlap of rectennas in the same region may lead to substantial increases in land area requirements above 900 km^2 per 5 GWe plant.

Another aspect of land use is the amount of time that the land will be used. The nuclear energy system uses some land for a greater time period than the above assumed 30 years. In order to provide perpetual storage of high level waste and other wastes for the nuclear system, a storage area of about 1/1000 of an acre is required per megawatt electrical year (Ref. 9). This figure does not include a safety zone which would be necessary around the perpetual storage area. Assuming that this figure is accurate and that this land will be used in this manner for a period of a million years, this represents a commitment of 1,000 acre-years per megawatt electrical year. This translates to about 4 million square meter-years per megawatt year. The corresponding number for the coal fired system over its lifetime is 0.1 million square meters-year per megawatt electric year. Hence, using this parameter (the land use area times the duration of use), the nuclear system's land utilization becomes approximately 40 times greater than that of the coal fired system and 67 times greater than the land used by the terrestrial solar thermal power plant.

The land required by power transmission from the plant to the load center is approximately 1000 m^2/MWe-yr/1000 mi for overhead ±800 kV dc transmission. Based on the transmission systems suggested in Section V, the additional land area required for each type of plant has been determined and is shown in Table 6-4. These data are also summarized in Table 6-2.

6.2.3 Water Requirements

The availability of cooling water is becoming an increasingly difficult problem for all power plants. If once-through cooling is used and the pre-1973 electric use growth rates (6% per year) are assumed to continue, then the entire run-off of all rivers in the continental US will be required to cool power plants by the year 2050. By that

Table 6-4. Energy System Land Requirements

Plant Type	Land Requirements Without Transmission, m^2/MWeyr	Transmission Distance, mi	Land for Transmission, m^2/MWeyr	Total Land*, m^2/MWeyr
Coal	1950-4670	300	300	2250-4970
Nuclear	115	300-1000	300-1000	765
Ground Solar				
- thermal	2000	300-3000	300-3000	3650
- photovoltaic	3800	300-3000	300-3000	5450
Orbital Solar	2200+?**	300-1000	300-1000	2850+?**

*Use transmission distance which is average of range indicated.
?Unknown amount of launch complex land.
**Corresponds to a microwave intensity of 0.1 mw/m^2 at the outer edge of the boundary (10 times the Eastern European limit).

time, most power plants will use wet cooling towers rather than once-through cooling, and in some locations dry cooling will be necessary.

A 1 GW power plant requires from 14 to 22 million m^3/yr (11,000 to 17,000 acre-ft/yr) of water for heat rejection using wet cooling towers based on current coal and nuclear power plants, respectively. Once-through cooling uses an order of magnitude more water, but it actually evaporates about one-half as much as a wet cooling tower. A dry cooling tower does not use any water to carry away heat rejected from the power plant. However, every plant must use some water to account for steam losses from seals and other miscellaneous requirements which amount to only 1 to 2% of the water use of a wet cooling tower (Ref. 53).

The central electric solar power plants will most probably be relegated to the Southwest region of the country where good solar insolation and lower cost, lower use land is available. In this part of the country there are only two major rivers, the Colorado and the Rio Grande. The water of both these rivers are overcommitted now. Wells are the only other source of cooling water indigenous to the region, but will not support sufficient power plants for a national power source using current cooling techniques.

Water availability in the Southwest is relatively low. For example, the maximum capacity of the four major water projects in Southern California is 11.8 billion m^3/yr (9 million acre ft/yr) (Ref. 54). This is currently used for agricultural purposes and human supplies. If 5% of this were made available for power plant cooling using wet cooling towers, only 50 GW could be installed (at 0.70 annual load factor). The 50 GWe would be 10% of the current national installed electric capacity. However, if dry cooling techniques were used, only 1% of Southern California water could supply enough power plants to meet current total national electric needs.

For purposes of this study, wet cooling towers are considered for coal and nuclear plants, while dry towers are considered for solar thermal plants. Costs and system efficiencies used in Section IV were based on dry towers for a solar plant and a wet tower for conventional plants.

Using wet cooling techniques, both the LWR plant and the coal plant would consume 24,000 and 9,200 m^3/MWe-yr of water, respectively, including the fuel cycle (Ref. 7). (One thousand m^3 per year is 0.765 acre ft/yr.) The solar thermal plant with hybrid cooling (assuming 1/4 wet cooling use) would be 7000 m^3/MWe-yr, while dry cooling would reduce this to about 500 m^3/MWe-yr (Ref. 53) exclusive of mirror cleaning requirements. Cleaning the mirrors every 5 weeks would increase the ground solar thermal plant requirements to about 900 m^3/MWe-yr with dry cooling towers.

The ground and orbital photovoltaic plant would use no active cooling and would have relatively small water requirements during operation and maintenance. The ground-photovoltaic would require cleaning (approximately every 10 weeks) which amounts to 620 m^3/MWe-yr water consumption. The orbital system would use water for cooling during the launch operations, and for rectenna cleaning. (The estimated water requirements for solar collector cleaning per m^2 of mirror area is based on 0.75 gal per cleaning) (Ref. 55).

Although techniques are available to reduce water requirements to much lower than current use patterns (dry-cooling towers versus once-through cooling), this is done with a performance penalty (~10% of the efficiency) and capital cost penalty (10-15%). Such penalties would seriously affect the LWR plant since its thermodynamic cycle would have the lower tolerance to increases in the rejection temperature due to dry cooling. Solar thermal and coal systems would be less affected. The ground and orbital photovoltaics power plants have minimum water requirements and are least susceptible to water restrictions.

6.2.4 Manpower Requirements

Manpower requirements can be separated into a number of categories but only plant construction, plant maintenance and total manpower are shown in Table 6-2. The manpower requirements for coal and nuclear are taken from Reference 7, while those for ground solar plants are based on Reference 45. Orbital solar plant O&M manpower requirements are from Reference 28.

The ground solar thermal construction manpower requirement is about 1900 man hr/MWe-yr and is about 4 times greater than that for conventional plants. At a plant installation rate of 10 GWe/yr, solar thermal plants would require 200,000 people for construction, while coal plants would need 43,000 people and nuclear 63,000 people for plant construction. The operation and maintenance of power plants with a total of 100 GWe of capacity would require about 67,000 men for the solar thermal plants including cleaning the mirrors every 5 weeks (cleaning manpower is based on 156 m^2/manhour from Reference 55), while 15,000 and 9,000 men would be needed respectively at coal and nuclear plants.

When fuel cycle related activities of mining, transport and fuel processing are added along with material acquisition activities, the ground solar thermal plant manpower needs are about 5 times the manpower needs of the coal energy system (13 times the LWR energy system).

The ground solar photovoltaic plant uses less construction material, and as a result, has less construction manpower. It is estimated that 808 manhours/MWe-yr is required, a value which is about 1/2 of the solar thermal plant. Material acquisition manpower was not evaluated for the ground photovoltaic system.

In general solar plants require more construction, and operation and maintenance (O&M) personnel. The larger construction manpower requirements would magnify the initial ("boom") impacts of plant construction on the local and regional economy and social services. However, the higher O&M requirements would lessen the post construction ("bust") letdown after construction. In addition, the solar energy system requires more manpower during materials acquisition. Due to these greater manpower needs, solar plants could either cause shortages if manpower was limited, or if unemployment was a persistent problem, it would provide a social benefit in creating additional jobs.

Conventional plants would be more distributed throughout the country near populated load centers, while ground solar central electric power plants would be, for the most part, located in the sparsely populated Southwest. Therefore, solar plants would cause redistribution of population from denser to less dense areas with associated impacts and benefits.

The orbital power system requires 6680 manhours/MWeyr for construction and 13.1 manhours/MWeyr for O&M (Ref. 28 with material acquisition activities added). This is double the manpower the ground solar thermal plants.

6.2.5 Energy Payback Time

Energy requirements like resource requirements, have been included in the internal dollar costs of the energy system; however, it is another characteristic of an energy system that can be helpful in d describing its benefit to society. A long energy payback time means that implementing a new energy source vigorously would cause an energy drain on society for a long period of time before any net energy is available.

There are several possible ways to define energy payback. The first is a static approach where the total energy payback time is the time that a plant must operate to pay back the construction energy and the operational energy needed over the entire plant life.

Another method is a dynamic approach and assumes an implementation rate for new power plants. The time it takes to generate net energy from an increasing host of power plants is calculated; the construction energy is considered a debit as is the operational energy taken from society to maintain the associated fuel cycle. Each plant's net operational energy is applied to paying back the debit energy. This dynamic analysis could be performed for one or more plants.

Apparently, large differences in material energy intensiveness can result depending on where one chooses to set the boundary of the problem. In the analysis performed in this report (based on data from Ref. 7) the operational energy needed to maintain the fuel supply extends back to the extraction process. However, for construction materials, the analysis only includes the energy required at the primary material fabrication plant to convert the ores into finished material stock. The material estimates of Section 6.2.1 are used and combined with the energy intensiveness of the materials based on an energy model described in Reference 56.

Since the technologies employed for solar plants, coal plants, and nuclear plants are vastly different, one would expect to find relatively large differences in their construction energy payback time. The energy required to replace the construction energy is shown in Table 6-5.

In addition, both a coal and nuclear plant require energy from external power sources to maintain the fuel cycle. A coal plant requires energy for mining and transporting coal, while a LWR requires energy to process the uranium ore into an enriched fuel. When the energy required over the 30 year life of these plants is considered as a single quantity, the operational energy payback time is 1.8 years for the coal and 1.2 years for the LWR nuclear plant.

Table 6-5. Energy Payback

Plant Type	Energy Payback Time, yrs		
	Construction	Operation(1)	Total
LWR	0.2	1.2	1.4
Coal	0.1	1.8	1.9
Ground Solar Thermal	1.7	0(2)-(0.18)(3)	1.7-1.9
Orbital SPS	1.36	0.04	1.4

(1) Over the 30 year life of the system.
(2) Stand-alone solar plant.
(3) Hybrid solar baseload plant at load factor = 0.70 and requiring 10% backup energy.

Thus, the total payback energy (construction and operation) is 1.7 years for a solar, 1.9 for a coal and 1.4 for a nuclear energy system as shown in Table 6-5. Thus, these different systems are quite comparable in terms of their energy payback time. The energy payback time for a satellite solar power system has been estimated to be 1.4 year, and is due primarily to the rectenna. The payback time would be 1.1 yr. if steel were substituted for aluminum in the rectenna. The algebraic summing of the payback energy for construction and operation is a useful concept, but it neglects the time distribution difference of these two quantities. The construction energy occurs prior to plant start-up while fuel cycle energy occurs over the plant lifetime.

6.3 HEALTH EFFECTS

The health effects associated with each of the electrical power systems have been considered in terms of both public health effects and occupational health effects. Furthermore, the health impacts have been broken down into two categories: "routine" health impacts and "catastrophic" health impacts. An example of a catastrophic occurrence is a core meltdown of a nuclear power plant. The impacts of more frequent, relatively less severe accidents, such as coal mine disasters, are included under "routine" health effects. "Routine" in this sense merely implies that more definitive health impact statistical data are available.

Health impacts have been examined for the complete energy cycle shown in Figure 6-2. This is especially important in comparing such different technologies as fossil fuel power plants and nuclear power plants with either ground based solar power plants or orbital power plants. Since stand-alone solar power plants do not use any fuel other than sunlight, no mining, processing and transportation of the fuel is required during the operation and maintenance phase. When hybrid solar operation is used to increase grid reliability to that of conventional plants, then it is necessary to charge the solar plant with about 10% of the health impacts of the backup energy source (see Section IV). Thus, the fuel related public health and occupational health impacts of running a solar power plant are relatively small. However, solar power plants require about an order of magnitude more material to construct the plant. Hence, the health impact of the solar power plant during both the materials acquisition cycle and the construction cycle may be larger than that of either the fossil fuel or nuclear power plants. In order to properly understand the relative health impact of a given energy system, it is important to compare the health consequences of the complete energy cycle for one system with the health consequences of other systems. The health effects are measured in terms of person days lost (PDL), and usually stated per unit energy generated; that is, PDL/MWe-yr.

A problem identification matrix is illustrated in Figure 6-6. It shows the following areas of concern: (1) who is impacted (occupational and public), (2) how they are impacted (accident, disease or death), and (3) the stages of fuel cycle at which these impacts occur.

In the case of both accidents and diseases, not only is the incidence of these factors considered, but also the severity is considered in terms of days lost associated with a given category of accident or disease. For example, a scratched finger may account for a few hours of lost time, whereas a severe back injury may account for years. In the case of estimating the impact of air pollution on public health, an asthma attack is counted as a one day loss while a chronic respiratory disease symptom is counted as a five-day loss. The total number of person days lost due to diseases and accidents that are associated with a given energy cycle can be used as a measure of the health impact.

In the case of death, a 30-year occupational loss is assumed; i.e., one death is associated with 6000 PDL (30 years x 200 working days per year). This simplifying transformation is used even though it can be convincingly argued that deaths and PDL are incommensurable parameters. Certainly, there is no broad societal consensus on this matter. Therefore, deaths resulting from an energy system are also totalled separately from PDL.

Some deaths are due to air pollution from the use of coal and are thought to be "premature" deaths. That is, deaths occurring to older people with poor respiratory systems who die several days, weeks or even months before they normally would. An accident such as a

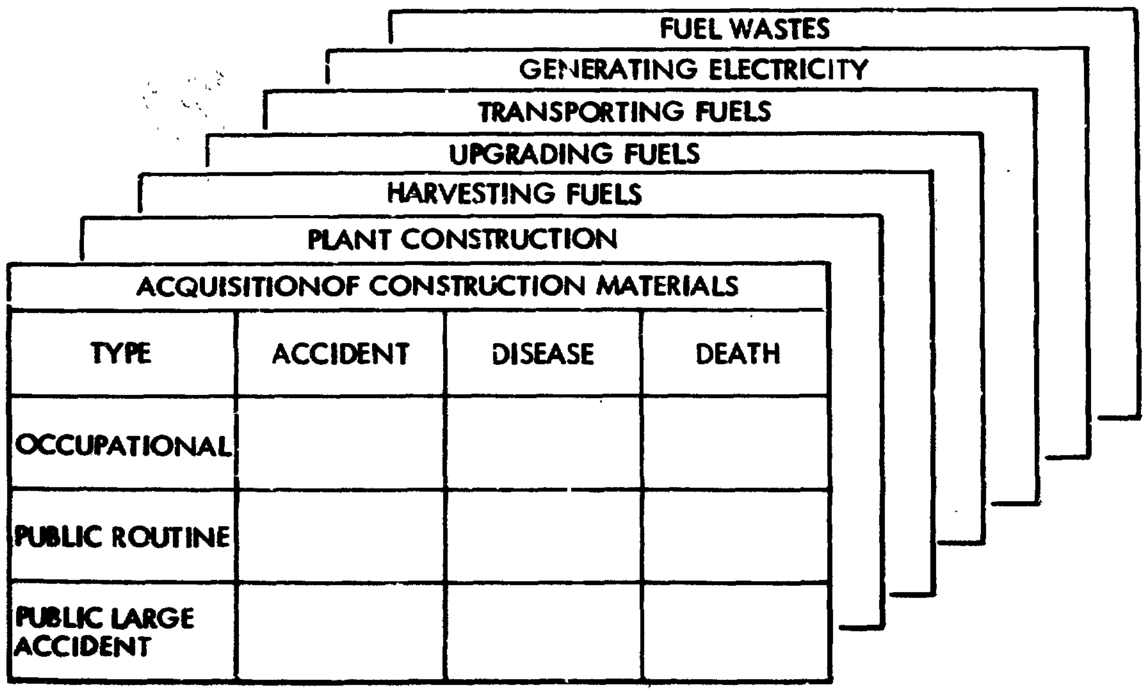


Figure 6-6. Power Plant Health Impact Matrix

nuclear core meltdown would cause deaths to people more likely to be of average age and health. Thus, if one considers the different circumstances of age and health of the likely victims of these two public health hazards, all deaths are not the same in some sense. However, this difference in types of deaths has not been considered in this study. The death of a 60-year old person is treated here as fully equivalent to that of a 20-year old person.

In estimating the health impacts, both routine and catastrophic, there is a wide variation in the data and the level of uncertainty in the analysis is quite high. The time scale over which the effects take place is also quite different. For example, the impacts associated with the oxides of sulfur emitted from a fossil fuel power system take place over the scale of weeks whereas the potential impacts associated with the storage of high level radioactive waste could take place over the scale of hundreds of thousands of years.

Similar vast differences among the electrical power systems exist with respect to the impacts of possible sabotage. For example, diversion of many coal cars would have very little impact on our society as a whole; however, the diversion of nuclear fuel and possible later conversion into weapons could have enormous impact.

Reference 7 modified by more recent information has been relied upon heavily for the health effects of the conventional power systems, while JPL studies have developed additional data on the material acquisition cycle and plant construction for all types of plants except the SPS (Ref. 45).

6.3.1 Fuel Cycle Health Effects

Five of the seven stages in the life of the plant are related to the fuel cycle. These specific stages are those which track the fuel cycle (i.e., harvesting, upgrading, transporting, generating electricity and waste disposal). As an example of the results of this study, the occupational, routine public and large accident health impacts are shown in Figure 6-7 for the reference fossil and nuclear plants. The range of values for accidents and disease are estimated

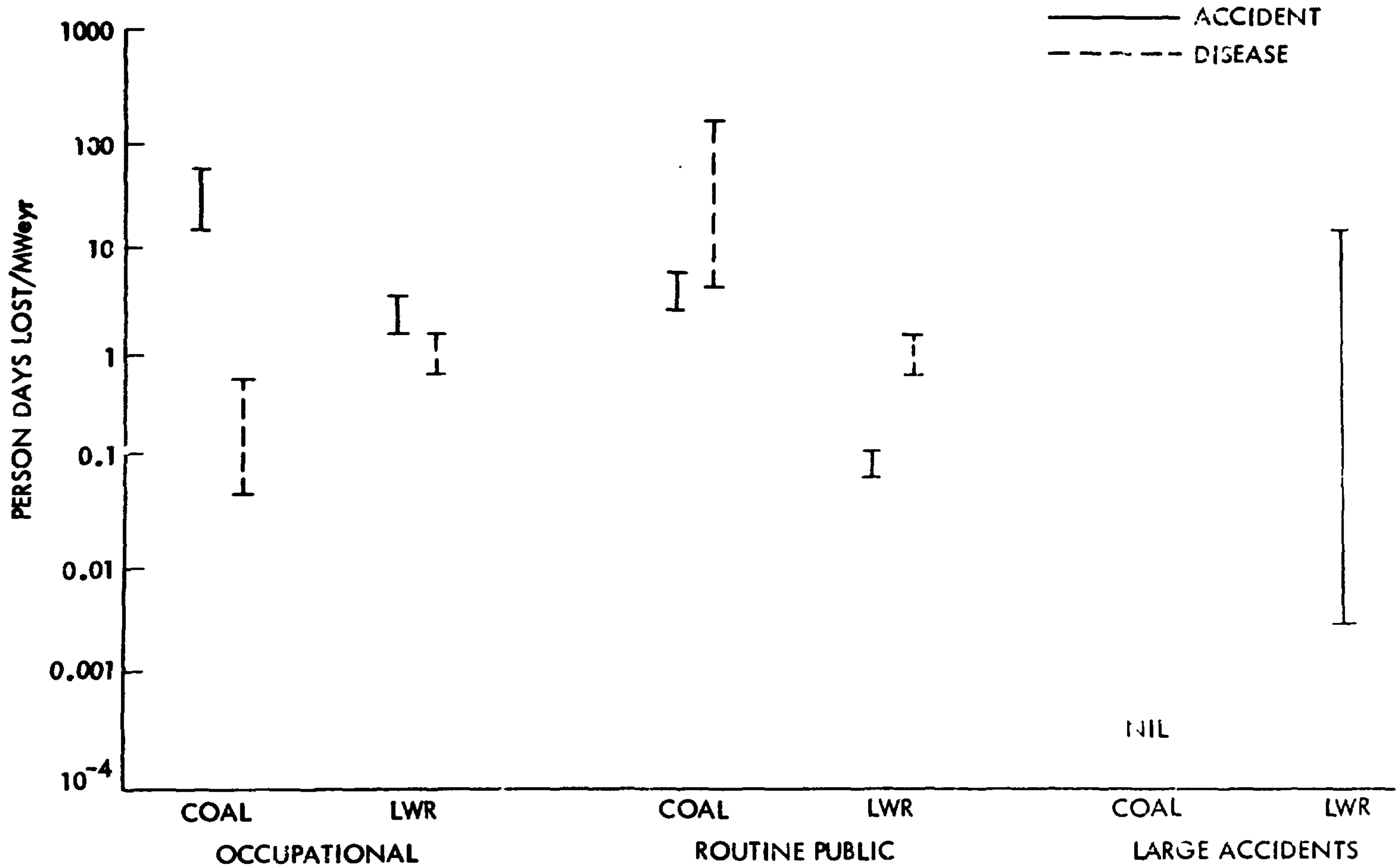


Figure 6-7. Conventional Power Plant Fuel Cycle Health Impacts

for these two plants; coal is the low BTU gasification with combined gas and steam turbines, and the nuclear is the light water reactor (LWR). Deaths are included in the accident or disease category using 6000 PDL/death as a conversion factor in Figure 6-7. The time frame is a projection to the year 2000. The estimates are based on historic data and assume new developments in these industries which could affect health and safety such as the new mine dust standards. The LWR system estimates, however, are based on current high ore grades, and no allowance is made for decreasing ore quality and the increased mining activities which will be necessary.

The routine occupational and public health effects indicate that coal plants have much greater routine impacts than nuclear plants. The greater bulk of fuel that is mined for the coal plant compared to the nuclear plant is clearly evident in Figure 6-7 as occupational accidents. The disease rates due to mining activities are expected to be lower than current rates due to anticipated implementation of coal mine dust standards. This will gradually reduce pneumoconiosis (black lung disease). Routine public impacts are much greater for coal plants than for the LWR. However, the reference coal plant which gasifies the coal and burns clean low BTU gas in a combined cycle gas and steam turbine is considered to remove 99+% of the SO_x from the coal. This is more than a factor of 10 better than the equivalent value for a coal plant with stack scrubbers (being implemented today). It is about a factor of 100 better than the value for uncontrolled coal plants. Since the public health impacts are proportional to SO_x emissions, the reference coal plant is considered to have 1/10 and 1/100 the public health effects (at the power plant) of the stack scrub and uncontrolled coal plant, respectively.

The nuclear public impacts are evident in the large accident category. This is based primarily on the Rasmussen report (Ref. 57) modified slightly by recent criticisms (see note 6 in Table 6-6). The range of uncertainty is quite large (3 orders of magnitude). In addition, many effects have not been taken into account including non-fatal diseases, genetic effects of radiation, accidents due to sabotage or diversion of nuclear materials, and accidents at other parts of the

Table 6-6. Comparison of Coal, Nuclear and Solar Fuel Cycle Health Impacts

Impact Area	Person Days Lost/MWe-yr			
	Coal[1]	LWR	Solar	
			Stand-alone	Hybrid
Occupational				
- Accidents[2]	18-57	1.2-2.7	?	3.2[3]
- Disease	0.03-0.4	0.2-1.0	-	0.01
Public Routine				
- Accidents[2]	4.5	0.08	-	0.45
- Disease[4,5]	0.2-138	0.5-1.1	-	0.5
Public Large Accidents[2,6]	-	0.003-10.8[7]	-	-
Total	23-200	2-15.6	?	4.4
Total Deaths/MWeyr x 10^2	0.34-2.5	0.03-0.23	-	0.09

? Small, but unknown at this time.

1 Low BTU gasification with combined cycle.
2 6000 PDL/death, 50 PDL/injury, and 100 PDL/cancer, except for uranium miners and accidents, whole body exposure only is considered.
3 Based on requiring 10% coal energy for extra backup margin to meet baseload plant reliability. Geometric average of coal range used.
4 Coal derived public disease from SO_x and particulates only at power plant. Nuclear and coal long-term wastes ignored.
5 Coal system produces mainly air pollution effects (premature deaths and aggravation of heart and lung conditions). If remote siting and/or very strict controls are implemented, coal train accidents become dominant. Nuclear system effects are mainly cancers which would occur after a decade or more.
6 Nuclear deaths based on NRC's WASH-1400 (Rasmussen report). Modifications as follows: Latent cancers included along with early fatalities. Factor of 23 times per year for 30 yrs. Dose response risk is twice that used and applies to latent cancers (BEIR report of National Academy of Science). Variation of 1/2 to 2x for impact at different sites. Uncertainty in WASH 1400 is from 1/30 to 15. These modifications to the WASH 1400 report increase the range from 1/35 to 42000. See EPA (1976), Yellin (1976), Von Hippel (1976), and Biological Effects of Ionizing Radiation, National Academy of Sciences, 1972.
7 Does not include genetic effects, non-fatal illness, sabotage, material diversion, and other reactor accidents.

fuel cycle. These factors must be considered t. ther with the unquantified but important differences in the publi s perception of different kinds of risk, and they will affect the marg. between clean coal and LWRs. These results are summed up for the 5 fue related stages and shown in the first two columns of Table 6-6.

The public health impacts of the operation and maintenance phase for both the stand-alone ground solar thermal power system and the ground solar photovoltaic power system will be quite small compared to any of the conventional electrical power systems. These systems are not characterized by air emissions other than those that come from the evaporative cooling towers if they are used. Liquid wastes will be associated with these systems; however, the health effects of these wastes are thought to be very small compared to the health impacts associated with the air pollutants of coal systems. In addition, the occupational health impacts during operation and maintenance are felt to be negligible and are not quantitatively evaluated.

Major fuel cycle related health impacts of a fossil hybrid solar plant do not come from the solar plant itself. Rather, they derive from the extra utility grid backup margin that is required to increase the solar plant reliability to that of non-weather dependent power plants. The magnitude of this extra backup margin energy for a baseload solar plant (0.7 load factor) was shown in Figure 4-8a to be 10% of the rated energy requirement. If the extra backup margin is based on coal, then the solar baseload plant will produce about 10% of the health impacts of a coal system. It is unlikely that a nuclear plant will be used for a solar plant backup since a nuclear plant is unsuitable for this use. It is more likely that oil or gas would be used for peaking backup. These fuels will tend to be unavailable toward the end of the century. Therefore, the extra backup margin is based on using coal in a manner similar to the reference coal plant. The coal is gasified to low BTU gas and burned in an auxiliary boiler using the existing solar plant turbine-generator equipment for energy conversion. The solar plant fuel cycle health effects are compared to those of the reference coal and nuclear plants in Table 6-6.

This data for the health impacts of the eight conventional energy systems can be more easily visualized by using the health effects flow diagram. Appendix B displays this graphic representation of the five stages in the fuel cycle showing disease, deaths and accidents.

A broad interpretation of these results could be than even a relatively clean coal plant has fuel cycle health effects that cuase roughly 100 PDL/MWe-yr, while the effects calculated for a LWR nuclear plant would on the average cause about 10 PDL/MWe-yr. The solar plant as a stand-alone plant has almost no fuel cycle health hazard. However, when the extra backup margin is considered, then the solar plant has some fuel cycle health effects. Using coal as the backup system, the health effects of the solar plant are estimated to be approximately 5 PDL/MWe-yr and could vary from zero to 9 PDL/MWe-yr, this is similar to the average health effects of nuclear systems, but is essentially one order of magnitude less than the coal plant.

6.3.2 Material Acquisition and Construction Health Impacts

The two remaining stages of possible health impacts shown in Figure 6-6 are the acquisition of construction materials and plant construction. Due to the much greater material consumption of ground solar plants, consideration should be given to public and occupational health effects which are a result of these activities. The public health effects are derived primarily from the pollutants which are generated when the basic material is formed in the steel, aluminum, glass, etc., plants. However, the majority of the health impacts are occupational and occur mainly in two stages: (1) the material acquisition stage which combines the construction material ore mining and the primary material forming plant, and (2) the actual construction of the power plant.

6.3.2.1 Public Health Impacts. In a manner similar to that used to estimate coal plant public health effects (Ref. 7), only the SO_x-particulate effluent is used to calculate values for public disease and death. Using the material requirements displayed in Section 6.2, the SO_x emissions are calculated from the production of steel, aluminum, concrete, glass and mechanical components (Ref. 45).

Two cases were considered. In the first, the primary material production plants were assumed to be in remote sites; the second case assumes that the production plants are in an urban area with a population of 11.5 million people. The results of these two cases are 0.5 to 1.5 PDL/MWe-yr for thermal power plants and 0.02 PDL/MWe-yr for the photovoltaic power plant (Ref. 45). These types of public health impacts for conventional plants are negligible since so much less material is involved. The data for the orbital solar plant is not available at this time.

6.3.2.2 Occupational Health Effects. These effects are computed for the acquisition of materials (mining and primary material fabrication), and power plant construction. Federal and California occupational accident, illness and death statistics were used for 15 different industries that would contribute to a power plant. Coal mining needed for steel production (Ref. 45) was also included.

The results are shown in Table 6-7 where death, illness and accidents are shown for the material acquisition and construction phases for four power plants. The conventional coal and nuclear plants have a relatively small contribution to their health impacts in these two stages (1 to 2 PDL/MWe-yr). Ground photovoltaic has nearly 3 PDL/MWe-yr due to greater material requirements than conventional plants. The ground solar thermal has nearly 6 PDL/MWe-yr due to its larger material requirements. Thus, the greater material content of the solar thermal plant has translated itself into a several times greater health impact during the material acquisition and construction stages.

The health impacts of all seven stages shown in Figure 6-6 have been combined and the results are presented in Table 6-8.

Table 6-7. Material Acquisition and Construction Health Effects

Type	Material Acquisition			Construction			Total		
	Death[1]	Illness[2]	Accident[2]	Death[1]	Illness[2]	Accident[2]	Death[1]	Illness & Accident[2]	All Effects[2,3]
Ground Solar									
Thermal	2.35	0.03	1.1	5.37	0.03	1.8	7.7	3	5.8
Photovoltaic	1.85	0.06	1.4	1.11	0.004	0.31	3	1.8	2.9
Coal	0.53	0.006	0.19	1.26	0.0017	0.20	1.8	0.39	1.1
Nuclear[4]	0.63	0.008	0.26	1.7	0.0035	0.29	2.3	0.55	1.4

1 Per 1000 MWe piant.
2. PDL/MWeyr.
3. Death ≈ 6000 PDL.
4. Average of LWR-Pu and LMFBR.

Table 6-8. Summary Health Effects

Type	Occupational, PDL/MWe-yr[1]		Public[1] PDL/MWe-yr	Total	
	Const. & Mat'l Acq.	Fuel Cycle & Oper.		PDL/MWe-yr[1]	Death per Plant
Ground Solar					
Thermal	5.8	0[2] (3.4)[3]	1.0[4] (3.5)[3]	6.8[2] (12.7)[3]	7.7[2] (35)[3]
Photovoltaic	2.9	0 (3.4)	0.02 (2.5)	3 (8.8)	3 (30)
Coal[5,6,7]	1.1	18 - 57	4.7 - 138	2.4 - 201	71 - 530
Nuclear[7,8,9]	1.4	1.4 - 3.7	0.6 - 12	3.4 - 17	8.6 - 51

1 6000 PDL/death, 50 PDL/injury, and 100 PDL/cancer, except for uranium miners and accidents, whole body exposure only is considered.
2 Stand-alone solar plant without backup energy.
3 Based on requiring 10% coal energy for extra backup margin to meet baseload plant reliability. Geometric average of coal range used.
4 No air pollution controls at primary material plant.
5 Low BTU gasification with combined cycle.
6 Coal derived public disease from SO_x and particulates only at power plant. Nuclear and coal long-term wastes ignored.
7 Coal system produces mainly air pollution effects (premature deaths and aggravation of heart and lung conditions). If remote siting and/or very strict controls are implemented, coal train accidents become dominant. Nuclear system effects are mainly cancers which would occur after a decade or more.
8 Nuclear deaths based on NRC's WASH-1400 (Rasmussen report). Modifications as follows: Latent cancers included along with early fatalities. Factor of 23 times per year for 30 yrs. Dose response risk is twice that used and applies to latent cancers (BEIR report of National Academy of Science). Variation of 1/2 to 2x for impact at different sites. Uncertairty in WASH 1400 is from 1/30 to 15. These modifications to the WASH 1400 report increase the range from 1/35 to 42000. See EPA (1976), Yellin (1976), Von Hippel (1976), and Biological Effects of Ionizing Radiation, National Academy of Sciences, 1972.
9 Does not include genetic effects, non-fatal illness, sabotage, material diversion, and other reactor accidents.

6.3.3 Limitations of the Health Impacts Data

The solar plant health effects can be determined with the most certainty since they are based on industrial statistics of accidents, illness and death primarily. However, the attempt to use data from many related industries may or may not prove to be an accurate estimate of solar plant occupational health impacts. There may be differences between a solar plant construction and other industries that are not apparent in this initial analysis. The solar thermal material and health effects may be as little as 1/4 those quoted due to variations in the design of the heliostat.

The new mine dust standards (Ref. 58) should essentially eliminate health hazards due to mining related disease; in addition, the reference coal plant will have reduced public hazard at the plant so that it is on a par with other stages in the fuel cycle. However, the data base for public health effects due to SO_x-particulate is controversial and may prove to be in error by factors. In addition, there is the currently unknown effects of other effluents such as CO, NO_x, etc.

The LWR health effects are due to the public impacts of nuclear power plant accidents, public radiation exposure from fuel cycle operation, and occupational impacts from mining and plant construction (Ref. 7). Power plant accidents are low probability-high damage events that could result in more than 100,000 people dead (Ref. 7). This has been converted to an average impact using the Rasmussen probability study with some modification (see note 8 of Table 6-8). In addition, the Rasmussen report does not consider a number of possibilities which are very real such as sabotage, terrorism or blackmail related activities at the plant or with diverted material in the form of a nuclear device. In this event genetic effects and non-fatal illness are not considered.

The quantity PDL/MWe-yr has an ellusive quality to it and an attempt has been made to translate it to a personal health impact basis. The magnitude of this parameter varies from 3 to 200 PDL/MWe-yr for the plants considered. Using the average national per capita consumption of energy, the number of hours per year someone is indisposed (sick, recovering from an accident, etc.) for each year's worth of electricity consumed was determined. This quantity is called person hours lost per person year of electricity use (PHL/person-year). Although 12 kW (thermal) is consumed on a continuous per capita basis for all energy uses in society (US), the continuous electrical consumption is only 1 kWe. This translates to 0.001 MWe-yr of electric energy each year for each person (MWe-yr/person-yr). The range of health impacts which is 3 to 200 PDL/MWe-yr thus becomes 0.08 to 5.2 PHL/person-yr. Thus, up to 5.2 hours of being indisposed by one or more people can be caused by one year's worth of electricity for the average person in the United States, based on a clean coal plant operating in the year 2000. This 5.2 hrs is spread over several persons in both the occupational and public section, and there is certainly no uniform distribution of these health effects.

6.3.4 SPS Health Effects

Since the health effects of orbital photovoltaic power plants were not evaluated in the SPS source references (Ref. 28,30), there is no quantitative data available at this time. It is possible to identify several potential problem areas for the SPS. Occupational health effects will exist due to industrial accidents during material acquisition, launch operations, space construction and operation as well as rectenna construction and operation. In addition to typical industrial accidents, there is the potential that several unique occupational hazards exist with the SPS due to extra vehicular activity in space, SPS space charge,* the natural radiation environment in geosynchronous orbit, the microwave radiation environment near the transmitter, and possibly even near the receiver on the ground.

SPS impacts on public health may occur through: (a) effects on the atmosphere, magnetosphere, and space plasma environment due to emissions by SPS launch vehicles, orbit transfer vehicles and on-orbit mobility elements; (b) biological/ecological effects at the rectenna site, nationally and globally due to microwave radiation; (c) noise and vibration effects of heavy-lift vehicle launch and recovery and (d) possible effects of a launch abort. Basic data on these effects are

*Large voltage differences (≈20 kv) will exist between the SPS and the magnetosphere at certain times of the day.

required. Data on public health impacts due to such effects must then be developed so that the SPS energy system can be understood as well as the terrestrial systems to which it is compared.

A number of these potential health impacts are presently being evaluated at JPL and preliminary results should be available by the fall of 1977.

6.4 ENVIRONMENTAL IMPACTS

Each of the electric power generating systems is characterized by a variety of different land uses and water requirements (both total water requirements and consumptive water requirements). These data have been compiled and were presented in Section 6.2 on resource utilization. Each system is also characterized by environmental residuals such as air emissions, water pollutant effluents, and solid wastes for each step of the complete energy cycle. These environmental residuals can have a variety of impacts on human, plant and animal life, in addition to strong aesthetic impacts on the land, rivers and seas, and the atmosphere. Data for these environmental residuals are tabulated (Ref. 7) for the conventional fossil and nuclear plants for each stage in the fuel cycle. However, the operation and fuel cycle of a stand-alone solar plant has relatively low environmental impacts. This is especially true if dry cooling towers are used which is most likely after the year 2000. The environmental impacts due to air, water and solid wastes come from the materials used to make a solar plant. Impacts would include contributions from the mining, transportation of material, manufacturing and final construction of the solar plant (Ref. 45).

Table 6-9 lists the water, air and solid pollution data for the candidate terrestrial power systems. For the most part, these are expressed in metric tons/MWe-yr. The solar plants have almost no environmental pollutants with the exception of a modest amount of particulates from aluminum and concrete production.

The coal system produces large quantities of pollutants; the most significant are the acid, solids, particulates, NO_x and SO_x.

Table 6-9. Environmental Impacts of Central Power Plants[1] (tons/MWe yr)[2]

Type of Pollutant	Ground Solar		Coal Stack Scrub	Nuclear LWR-Pu
	Thermal	Photovoltaic		
Water Pollutants				
COD (Chemical Oxygen Demand)	-	1.2	N.D.[3]	N.D.
Other Dissolved Solids	-	0.5	N.D.	N.D.
Organic Substances	-	0.2	N.D.	N.D.
Acid	-	-	660-55,000	-
Suspended Coal	-	-	0-8	-
Sludge	-	-	1.6-5.4	-
Non-radioactive	-	-	-	260-4230
Radioactive (curies/MWeyr)	-	-	-	0.1-4.5
Air Pollutants				
Particulates	5.7	11.2	4.8-44.9	-
NO_x	1.0	-	14.3-28.4	0.45
SO_x	-	-	12.1-41.9	1.2
Hydrocarbons	-	-	0.8	-
CO	0.2	-	0.6-2.4	-
Aldehydes	-	0.2	-	-
Toxic Metals	-	-	0.02	-
Radioactive (curies/MWeyr)	-	-	-	4.7-600
Solid Pollutants				
Non-radioactive	-	-	1875-2316	105,000
Radioactive	-	-	-	-
High Level (liters/MWeyr)	-	-	-	43-48
Low Level (liters/MWeyr)	-	-	-	1530
Intermediate Level (liters/MWeyr)	-	-	-	30.7
Buried Solids (m^3/MWeyr)	-	-	-	0.24
Tailings (curies/MWeyr)	-	-	-	0.01-0.02

(1) No data available on SPS.

(2) No entry if less than 0.1 ton/MWeyr.

(3) N.D. = no data.

The coal gasification type plant would reduce the SO_x by an order of magnitude compared to the stack scrub system shown in Table 6-9. The nuclear plant (LWR-Pu) has modest water pollutants, and modest low level radioactive solid wastes (1530 liters/MWe-yr).

The hybrid solar thermal power plant should be charged for the pollution caused by the extra backup margin from a non-solar source. For baseload operation, at 0.7 annual average load factor, the solar plant is estimated to require about 10% backup energy (see Section 6.3 for a more complete discussion). Assuming that either coal or a coal derived liquid or gas fuel will supply the backup energy source, then the solar plant should be charged with 10% of the environmental impact of the coal system shown in Table 6-9. Thus, a hybrid solar plant incurs only one tenth of the environmental impacts of a coal system.

In addition to air pollutants, water pollutants and solid wastes, waste heat is another environmental impact characteristic of all power plants. Rather than just calculating the waste heat from a plant, it is more appropriate to identify the excess waste heat. The excess waste heat is that heat released at the plant that is in excess of what would have been released if the plant were not there. For coal and nuclear, all the heat rejected at the plant is excess waste heat as it is for the SPS at the ground rectenna and in the atmosphere due to the microwave beam losses. However, the ground solar thermal and photovoltaics plants are using solar energy that normally would strike the ground and heat the area to a certain extent. Some of the sunlight is "bounced" (reflected) off the ground and sent back up into the sky, while the remainder is absorbed by the ground. Part of this absorbed energy heats the ground and surrounding air, while the rest radiates to the surrounding environment at a longer wavelength than sunlight. Under certain conditions, it is possible for a ground solar plant to produce no excess waste heat. For instance, if the collector field has the appropriate efficiency and surface properties, it can act in a similar manner to the undisturbed ground before the plant was built. That is, it can reflect solar energy and also remove energy via electricity in an amount that is equal to the solar energy that was originally "bounced" off the undisturbed ground before the building of the solar plant. Under these conditions, the amount of energy remaining due to the various inefficiencies of the power plant would be the same magnitude as that originally absorbed by the incoming solar energy. Also, it is possible to control the surface properties of the collector structure or rectenna structure to minimize or even eliminate excess waste heat on the biosphere.

If it is assumed (1) that the albedo (energy reflected from a surface compared to the incident energy) of soils typical to the Southwest is 0.30, (2) that the solar thermal plant has an average efficiency of 0.20, and (3) that the collector mirrors use front surface glass with a reflectivity of 92%, then the solar thermal plant rejects only somewhat more energy than the undisturbed ground. The amount of excess waste heat rejected per unit electrical energy generated for various power plants is shown below:

Type Plant	MWt-yr/MWe-yr
Coal (Gasification)	1.7
Nuclear (LWR)	2.1
Solar	
Thermal	0.25
Ground Photovoltaic	1.5
Orbital Photovoltaic	0.25

The LWR is considered to have 32% plant efficiency, while the coal plant has a 37% efficiency (coal to electricity). Potentially, the low BTU gasification and combined cycle plant could have efficiencies as high as 45% if technologies for gasification and high temperature turbines improve as planned. The ground photovoltaic plant is considered to have a 13% module efficiency and has a cover glass over the photovoltaics. The orbital photovoltaics rejects energy to the environment at the receiving antenna (rectenna), from the ground around the rectenna due to microwave energy that m' sed, and some energy is absorbed from the microwave beam in the atmosphere above the ground.

As can be seen in the table above, the solar thermal and orbital photovoltaics reduce the excess heat burden in the biosphere by nearly an order of magnitude compared to conventional nuclear or fossil power plants.

Besides waste heat, the exact SPS environmental impacts are unknown at this time. Several areas require investigation. These are: vehicle emissions; interaction of the microwave beam with the magnetosphere, ionosphere and atmosphere; biological/ecological effects of the microwave beam; and noise from vehicle launch and recovery operations.

A number of other environmental issues are considered in the next section.

6.5 OTHER SOCIAL IMPACTS

Throughout Section VI, the social costs for various central power plants has been quantitatively evaluated in the areas of RD&D expenses, resource utilization, and health and environmental residuals. There are aspects of these parameters that cause social impacts that do not lend themselves to quantitative evaluation, or if they do, the meaning of the numbers is very difficult to determine. These impacts are called "other" social impacts. For example, it is difficult to know the social cost of an event which presents a low average health impact because of its low probability of occurring, but has catastrophic effects if it does occur (e.g., core meltdown of a nuclear plant).

Society's acceptance of catastrophic events where it has little or no control over the event is lower than its tolerance of more frequent but low impact events that it may have some direct control over. The question is, how great is the difference in public perceptions and how will this difference be translated into social cost. It may be that a large nuclear incident would be unacceptable to the public and would shut down the nuclear industry for months and possibly years. Such an impact would have the characteristics of temporarily disrupting the supply of a domestic source of energy.

Characteristics such as discussed above do not lend themselves easily to quantitative evaluation and thus have been included in this section on "other" social impacts. Other examples are CO_2, waste heat, and particulate generation. In these cases, reasonably precise numbers can be generated for the quantity of pollutants, yet it is difficult at this time to interpret the effect these pollutants would have on climate which could have environmental and human health impacts sometime in the future.

To deal to some extent with these types of characteristics of electric power systems, a rather simple comparative evaluation is proposed. Social cost areas of this type were identified and a rating of low (L), medium (M), high (H) and very high (V) was given for each type of central electric power system. Such ratings are only an indication of the relative magnitude of the social impact of a particular impact area. The ratings are shown in Table 6-10, and a definition of each impact is given below.

(1) Sabotage, Blackmail, Terrorism. Sabotage is an act which destroys property or causes equipment to destroy itself. Blackmail is using sabotage or threats of sabotage, exposure, disclosure of confidential information, etc. to obtain money, other property, political favors, etc. Terrorism could be the motivation for acts of destruction for political or other ideological purposes, anarchy or madness.

(2) Material Diversion to Weapons. The act of using material, such as Pu-239, to make weapons by either governments or terrorist groups.

(3) Catastrophic Impact of an Accident. Catastrophic impact is a great calamity or destructive event, whether it is measured in enormous loss of life, disease or bodily injury, property damage, environmental damage, etc.

Table 6-10. Summary of Relative Potential of "Other" Social Costs

Area	Fossil		Nuclear				Solar		
							Ground		Orbital Photo
	Coal	Oil	LWR	LWR-Pu	LMFBR	HTGR	Thermal	Photo	
Sabotage, Blackmail	-	L	H	V	V	H	-	-	M
Material Diversion to weapon	-	-	H	V	V	H	-	-	?
Catastrophic impact of above or accident	L	L	H	V	V	H	-	-	?
Duration of impact	-	L	V	V	V	V	-	-	L
Military Vulnerability	-	V	-	-	-	-	-	-	H
CO_2 and particulate emissions	H	H	-	-	-	-	-	-	-
Acid rain	H	H	-	-	-	-	-	-	-
Net thermal emission	H	H	V	V	H	H	L	H	L
Long Term Toxic Waste	-	-	V	V	V	V	-	-	-
Microwave	-	-	-	-	-	-	-	-	?
Magnetospheric, Ionospheric and Stratospheric	-	-	-	-	-	-	-	-	?
Noise	-	-	-	-	-	-	-	-	H
Life Cycle Mass Utilization	V	V	L	L	L	L	M	M	?
Non-Renewable Resource Use	V	V	V	H	L	M	L	L	L
Land Use									
● Area	H	M	L	L	L	L	H	H	H
● Area x Time	L	L	V	V	V	V	L	L	L
Local Disruption									
● Construction	M	M	M	M	M	M	H	H	H
● Operation	H	M	L	L	L	L	M	M	M
Interference									
● Communications	-	-	-	-	-	-	-	-	?
● Radio Astronomy	-	-	-	-	-	-	-	-	?
Aesthetic Impact	H	L	-	-	-	-	M	H	?
Legal, Liability	-	-	H	H	H	H	-	-	H

Key: L = Low, M = Medium, H = High, V = Very High, - = Nil or Little

(4) Duration of Impact. Duration of impact is the length of time the effects will last. Each type of problem is different, in the case of fossil fuel it could be only months or a few years but with nuclear power plants, it could be a matter of thousands of years.

(5) Military Vulnerability. Susceptibility of a power plant to destruction or curtailment of its operation by a foreign nation or subgroup. Examples would be a) oil embargoes, b) aggressive action against a power station or action against enrichment plants, or c) potential for giving the appearance of accidental destruction of an orbital power plant by an orbital collision.

(6) CO_2-Particulate Emissions. These are expected emissions from any fossil fuel power plants; both of these could have profound effects on global climates.

(7) Acid Rain. Acid rain comes mainly from the SO_2 emissions of a power plant when the SO_2 contacts water vapor and changes into sulfuric acid (H_2SO_4) and sulfurous acid (H_2SO_3). This acid will then rain onto the property downwind from the plant and cause environmental and crop damage (Ref. 59).

(8) Excess Thermal Energy Emitted. Because the power plant is a heat source, the excess thermal energy is that heat that the power plant emits greater than what would normally be rejected to the atmosphere if the plant were not there. This has the potential of long-term climate change.

(9) Long-Term Toxic Waste. Wastes that can produce human health or environmental impacts for long-term time period; e.g., radioactive wastes.

(10) Microwave Radiation. A comparatively short electromagnetic wave which has the potential to cause human

impacts, terrestrial and atmospheric environmental impacts.

(11) Magretosphere, Ionosphere and Stratosphere Impacts. The magnetosphere is a region of the upper atmosphere that surrounds the earth, extends out for thousands of miles, and is influenced by the earth's magnetic field so that charged particles are trapped in it. The ionosphere is a section of the atmosphere that contains a large number of free electrons extending from about 80 km to about 300 km. The stratosphere is a region of the atmosphere of nearly constant temperature about the lowest region of atmosphere, between the surface and 20 km. Due to pollutants or microwaves, environmental impacts may be caused in these regions.

(12) Noise. Undesirable sound that can have human health effects. This sound can be from turbines, boilers and cooling towers and from SPS vehicle launch and recovery.

(13) Life Cycle Mass Utilization. This is the amount of material used over all the phases in the life of the plant.

(14) Non-Renewable Resource Use. This is the use of a resource that cannot be replaced; e.g., a fuel such as coal or uranium.

(15) Land Use. Area: land used by an electrical power generating system over its entire fuel cycle and construction material acquisition cycle. Area x Time: the product of the area and the time this land will be used.

(16) Local Disruption. Boom-bust cycle disruption on local and regional social fabric during construction, and has impact on economic, social services, crime and quality of life in general.

(17) Operation. The impact during the plant operation phase over a much longer time period (≲30 years) which will create permanent jobs and economic stimulation and increased development. Adverse impacts could include over-developments, increased population, overuse of limited recreation.

(18) Interference. Communication confusion of received radio signals due to noise created by microwave beam from power stations, or from transmission lines.

(19) Radio Astronomy Interference. Limiting or destroying ability to do earth based radio astronomy.

(20) Aesthetic Impact. This is an indication of how much the power plant, mines, transmission lines, etc., change the natural appearance of the land area or sky view.

(21) Legal-Liability. There could be legal difficulties due to regulation, international law, etc., or liability difficulties when there is the potential for damage and insurance coverage is a problem.

Table 6-10 indicates the rating given each plant in each of these areas. The first four areas, which have to do with sabotage, material diversion to weapons, catastrophic impacts and duration of impacts, mainly affect nuclear power plants. The ratings are either high or very high. For nuclear plants, much speculation on these dangers is available publicly.

The only other entries of note in these categories of Table 6-10 are those associated with the orbital power satellite and are based on its unique characteristics. It has sabotage and blackmail potential which could result in plant destruction with economic and power shortage effects. The SPS also has military vulnerability and military potential that could result in possible retaliation by the owner nation or nations. This possibility may necessitate international cooperation in designing, building and operating and owning an SPS.

The SPS also has a potential for major impact due to launch aborts where a large vehicle (perhaps 3 times the Saturn V) unintentionally impacts a populated area. Further study would have to examine these SPS related areas.

The oil system is very susceptable to interruption militarily and will be increasingly so until the resource depletes early next century.

The next category of other impacts is CO_2-particulate emissions and acid rain which are residuals of fossil plants. The particulates and acid rain can be controlled to some extent. They will be reduced in the reference coal plant since about 99% of the sulfur is removed, and a gas is burned in the power plant. The effect of CO_2 and particulates on global climate is difficult to asses, as is the effect of acid rain on human health and vegetation.

Thermal emission effects are a characteristic of all energy systems and the magnitude of excess waste heat was indicated in Section 6.4. Even the generated electrical energy should be included along with the excess waste heat, since it eventually becomes heat. Power plant heat islands, or increased moisture if wet cooling towers are used, will have some impact on local climate. The magnitude and nature of the impact are very site specific. In general, power plants used to sustain human activities contribute to the global heat burden. With continued growth, this heat burden could reach a significant fraction of global solar input in several centuries with profound global effects. Approximately 0.01 of global solar input could be reached by 2070 at 5% growth of energy use (Ref. 60). The LWR system produces the most net thermal emission since it is least efficient. Fossil, advanced reactors (LMFBR, HTGR) and ground photovoltaics have less excess heat emissions which are an order of magnitude less than the LWR system. Although the relative magnitudes were shown earlier the long-term climate effects are unknown.

Long term toxic waste is a problem of nuclear systems; some waste products have to be confined outside the biosphere for more than 100,000 years if they are not transmutated to substances with shorter half lives. The length of time and the toxicity of the wastes in certain forms contribute to the social impacts.

The effects of microwave radiation on the upper atmosphere are limited solely to the orbital power system (SPS); these effects and their impacts on the environment, flora and fauna, and public attitudes toward SPS are currently unknown and require investigation.

The transportation system for the SPS will introduce pollutants at every level in the atmosphere, ionisphere and even the magnetosphere. The nature and magnitude of these effects are unknown at this time and require investigation.

Noise potential is associated with launch and recovery of SPS heavy lift launch vehicles (HLLV). Noise levels, launch frequency and types of vehicles and the number and location of sites for launch and recovery are currently unknown. Study is required to provide a basis for design to minimize the noise potential.

Table 6-10 also indicates that life cycle mass utilization, including fuel and construction materials, are greatest for fossil systems. It has medium impact for ground solar systems while nuclear systems have low impacts.

The use of nonrenewable resources is greatest for fossil and LWR systems. The breeder reactor would have low impacts at high breeding ratios as would solar plants since most of the materials can be recycled. Depriving future generations of nonrenewable fuels is a difficult impact to assess. Another nonrenewable resource is geosynchronous orbit locations. Many satellites now and many more in the future will use this very attractive location for communications, earth survey and other possible applications. This is a limited resource and there would be competition for varied uses. This space is presently controlled by international bodies and their permission would be necessary for SPS use. Communications frequency is also a limited commodity. The SPS will use only one frequency but may spill over into a host of other frequencies and produce radio frequency interference (RFI).

The product of time multiplied by the land area used results in a reversal of the land use impacts of all the systems. This factor introduces the difficulty of considering the time distribution of impacts.

The next category of "other" social costs in Table 6-10 is local disruption during the construction phase; it is potentially large for ground solar systems due to the greater material and land requirements. There are similar potential impacts for SPS system due to rectenna and launch complex construction. The local disruption of the coal and nuclear plant construction is probably lower than the solar systems due to lower material and land requirements. Continued coal mining would sustain high impacts during operation.

The communications and ratio astronomy interference by the microwave subsystem of the SPS is unknown at this time. There would also be some optical astronomy interference from an SPS since it would be in a stationary orbit in relation to the ground.

The aesthetic impact of coal mining is high while there may be mixed response to the night visibility of the SPS against the background star field. The large area ground solar plants would change the appearance of large sections of the Southwest areas. Nuclear plants are compact and clean looking and should have little adverse visual impact.

The last category in Table 6-10 is the legal-liability area. For the SPS commercial rights in space, as well as use of the limited resource of a synchronous orbit position will require resolution. Communications frequencies, and perhaps international agreements on weapon systems in space will have to be addressed. There are legal and regulatory aspects of a power system that is multi-state in nature since the SPS could transmit to different rectennas.

The liability area may become an increasing difficulty for nuclear systems due to the large potential damage from LWR core meltdown or LMFBR nuclear explosions which are not contained. For public acceptance and low liability, radio frequency interference (RFI) due to the SPS microwave beam will have to be demonstrated to be within acceptable limits. Launch accidents with large potential loss of life may cause problems for the SPS similar to the nuclear plants and require study.

This preliminary compilation of "other" social costs is useful only in identifying some issues which could have a very strong bearing on the social acceptability of these power systems. A more careful development of these and other social costs is necessary and should be the subject of future work.

APPENDIX A

ECONOMIC METHODOLOGY

The equation used to calculate the present value (PV) is:

$$PV_x = (1 + g_x)^p X_o \left(\frac{1 + g_x}{k - g_x}\right)\left[1 - \left(\frac{1 + g_x}{1 + k}\right)^N\right]$$

if $k \neq g_x$

$$PV_x = (1 + g_x)^p X_o N$$

if $k = g_x$

where

g_x = escalation rate for a particular recurring cost area

$p = y_{co} - y_p$

y_{co} = first year of commercial operation

y_p = year that goods are priced

X_o = cash flow in y_{co} year in y_p dollars

k = average after tax cost of capital

N = plant lifetime

This lumped present value is then annualized[(1)] the same way the initial capital outlay is annualized by using a capital recovery factor (CRF). This is a function only of the discount rate and years of operation as shown below:

$$CRF = \frac{k}{1 - (1 + k)^{-N}}$$

[1] Annualized Cost - The annuity or uniform stream of annual payments over the system lifetime, which has the same present value as the totality of all system resultant costs.

Thus, this is not a first year of operation energy cost calculation. Rather, it is the weighted average cost of energy over the life of the plant. This is important when comparing different plants especially one that is capital intensive (such as a solar or nuclear plant) to one that is much less so (such as coal or oil). The escalations that occur over the plant life are considered, and a more accurate assessment is made of the real cost of energy from the plant.

The constant annual payment (reassessed in base year dollars) due to borrowed capital, taxes, "other taxes" and insurance is

$$\overline{AC}_{capital} = (1 + g)^{-d}\ \overline{FCR} \cdot CI$$

where

g = rate of inflation

$d = y_{co} - y_b$

y_b = the base year for constant dollars

CI = present value of capital expenditures

$\overline{FCR}$ is the annualized fixed charge rate and

$$FCR = \frac{1}{1 - \tau}\left(CRF - \frac{\tau}{N}\right) + \beta_1 + \beta_2$$

where

τ = effective income tax rate

β_1 = annual "other taxes" as fraction of CI

β_2 = annual insurance premiums as fraction of CI

The cost of capital k, is computed as

$$k = (1 - \tau)k_d \frac{D}{V} + K_c \frac{C}{V} + k_p \frac{P}{V}$$

where

k_d = annual rate of return on debt

k_c = annual rate of return on common stock

k_p = annual rate of return on preferred stock

D/V = ratio of debt to total capitalization

C/V = ratio of common stock to total capitalization

P/V = ratio of preferred stock to total capitalization

Therefore, the total annual payment is

$$\overline{AC} = (1 + g)^{-d}\ \overline{FCR} \cdot CI + CRF\ (PV_o + PV_m + PV_f)$$

where

PV_o = present value of recurrent operational recurring costs

PV_m = present value of recurrent maintenance recurring costs

PV_f = present value of recurrent fuel recurring costs

The energy cost is

$$\overline{EC} = \frac{\overline{AC}}{PL\ 8760},\ \text{mills/kWehr}$$

where

P = rated power, MWe

L = average annual load factor (actual generated energy/ 8760 x rated power)

Refer to Reference 2 for a full treatment of this economic methodology.

APPENDIX B

HEALTH EFFECTS FLOW DIAGRAMS

In order to increase the ease with which one can acquire an understanding of both the overall health impacts of a given fuel cycle, and also the relative contributions of each component of the fuel cycle, a new "Health Effects Flow Diagram" was designed. This diagram depicts the health impact parameters (death, accident or disease) of a particular fuel cycle stage as a set of tubes coming from that stage. The stages are fuel harvesting, upgrading, transporting, conversion to electricity and final wastes and is based on the data in Reference 7. The width of a given tube is proportional to the impact of that stage. In Figure B-1, the accident tubes are cross batched, and the death tubes are simply left unmarked. In subsequent figures, the tubes representing disease impact are speckled.

The health impact of a given fuel cycle step, for example harvesting, will vary considerably depending on the particular technology used to extract the fuel, the relative degree of safety consciousness of the corporation, the training of the miners, etc. Two "tubes" are shown for the health impact of each step of the fuel cycle; the inner tube indicates a numerical estimate of the "reasonable" lower limits for a given health impact parameter. The outer tube is a numerical estimate of the "reasonable" upper limit of health impact for a particular fuel cycle step. An illustration of the annual death and accident impact of the transportation phase of the fuel cycle for a 1,000 megawatt electrical coal fired electrical power system is shown in Figure B-1. This figure indicates a lower estimate of 2.3 deaths per year due to the transport of fuel and an upper estimate of 5.7 deaths per year due to the transport of fuel. Also shown is an upper estimate of 5,120 person days lost (PDL) per year due to accidents during transport of the coal. A lower estimate of 520 person days lost due to accidents during transport is also shown. This approach provides a highly visible display of the area health impacts of a given phase of the fuel cycle.

In order to understand the health impacts of a complete fuel cycle, it is important not only to understand the impact of each phase of the fuel cycle as shown in Figure B-1, but also to understand the

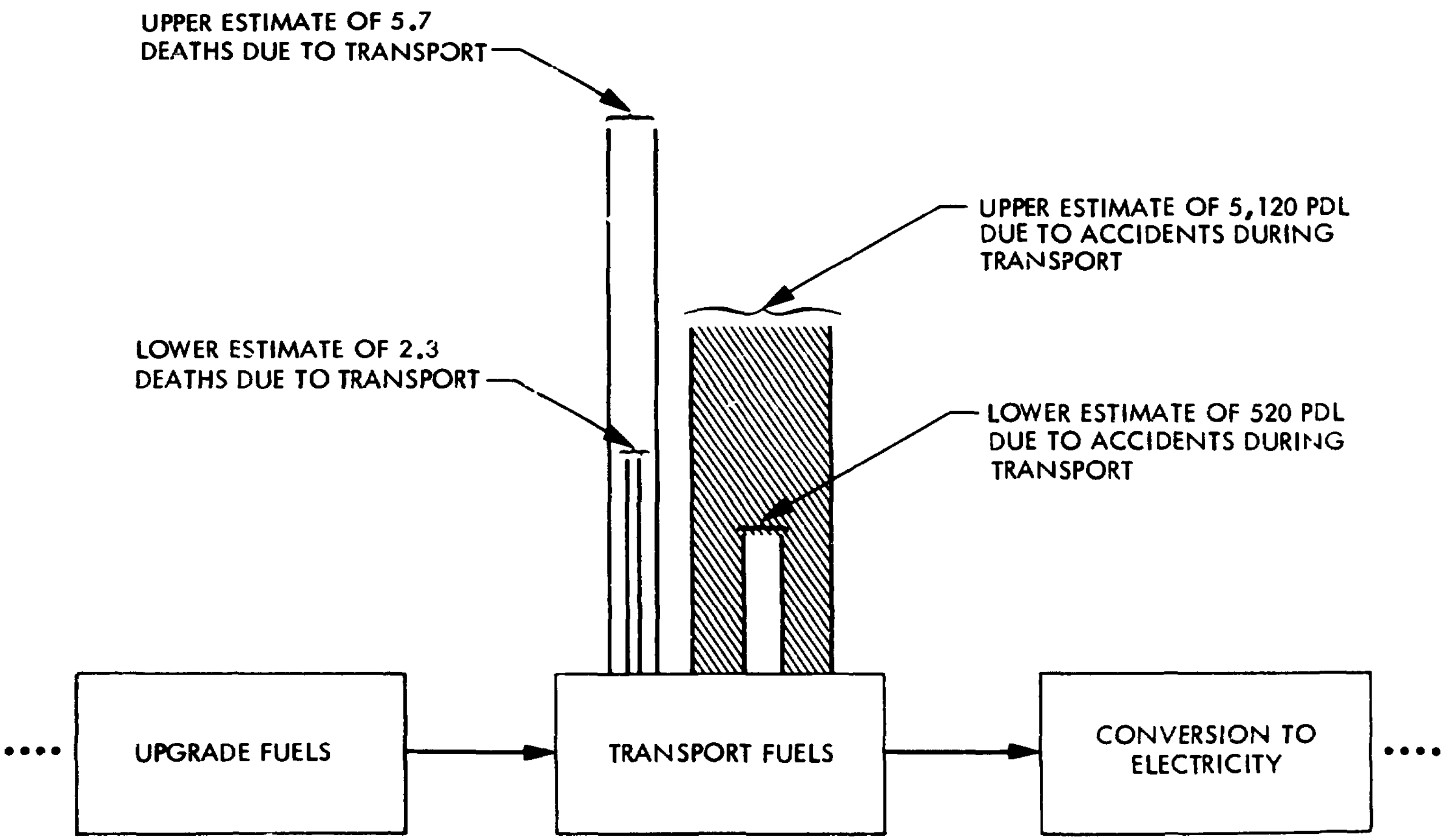


Figure B-1. Illustration of Annual Death and Accident Impact of Transport Phase of Fuel Cycle for 1,000 MWe Coal-Fired Electrical Power System overall impacts of a given fuel cycle. In order to do this, the tubes for a given health parameter from each process phase are combined to display the cumulative impact of the process steps. This is analogous to the width of a river increasing as tributaries flow into it. As an example of this technique, the annual deaths associated with a single 1,000 megawatt coal fired electrical power system with lime flue-gas desulphurization are shown in Figure B-2. The harvesting step shows 0.8 deaths per year as the lower limit, and 2.3 deaths per year as the upper limit. These deaths include the impacts of mine cave-ins, explosions, and other catastrophic mine accidents, as well as the deaths due to black lung disease; i.e., pneumoconiosis. The death impact of the upgrading of the coal (that is, the crushing and cleaning of the coal) varies from 0.02 deaths per year to 0.04 deaths per year. Its impact is considerable smaller than that of the harvesting step.

In transporting the coal to the power plants, deaths occur due to accidents and involve not only workers but also the public. Collisions at rail-crossings between autos and coal trains are included in this category.

The deaths associated with the conversion to electricity step (i.e., burning of coal to produce electrical power) varies from a lower estimates of two deaths per year to an upper estimate of thirty-six deaths per year. The lower limits are obtained by assumming that the power plant is located at a remote site that is more than 50 miles away from an urban center, that the flue gas scrubber removes 90% of the SO_2, and that the least case estimates of the health effects of SO_x are used. The upper limits combined the assumptions that the power plant is located in an urban site which has a regional population of approximately 50 million people, such as the New York, New Jersey, Connecticut area, that the flue gas scrubber removes 80% of the SO_2 and that the worst case limits of the health effects of SO_x are used. Similarly, the impact of the air pollution from the final waste (burning coal mine tailing banks) is estimated to range from 0 deaths per year to 13 deaths per year. The death streams from each phase of the fuel cycle flow into the upper horizontal stream which shows the cumulative death impact of this system for each stage in the process. The upper limits are obtained by adding the upper limits of each phase of the fuel cycle.

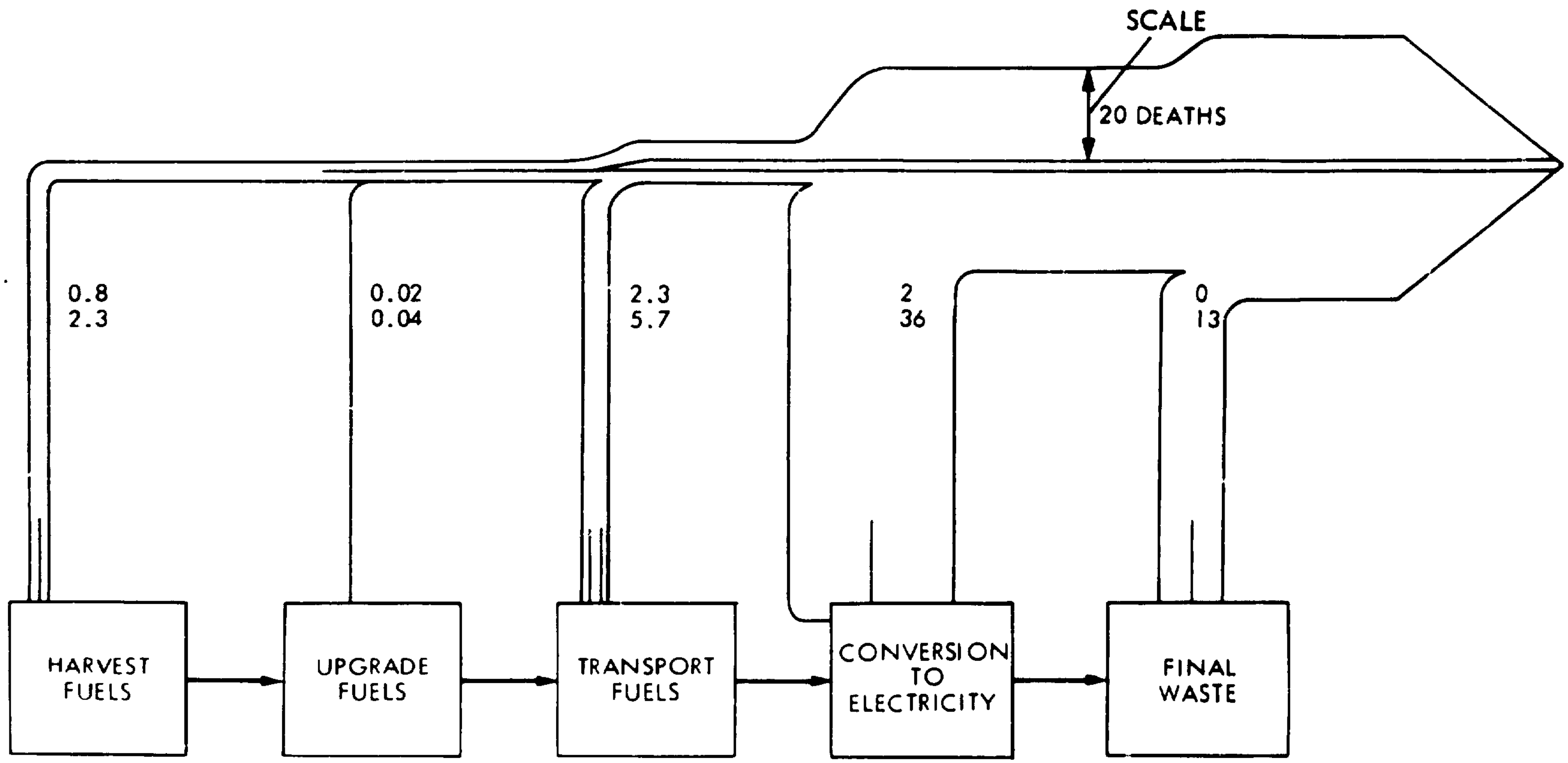


Figure B-2. Annual Deaths Associated with 1,000 MW_e Coal Fired Electrical Power System with Lime Flue Gas Desulfurization

Diagrams similar to Figure B-2, can be drawn for the number of person days lost due to accidents, and also for the number of person days lost due to disease. In order to provide a comprehensive overview of the health impacts of the fuel cycle, flow diagrams for deaths, accidents and diseases are superimposed in Figure B-3. Hence, this figure provides an overview of the "Routine" annual health effects associated with a 1,000 megawatt coal fired electrical power system with lime flue gas desulphurization.

It should be pointed out that the assumption has been made that the lime flue gas desulphurization scrubber removes between 80 and 90% of the sulphur in the flue gas, this performance is considerably better than that of the typical power plant today. Since the typical power plant does not have a scrubber to remove the sulphur oxides. It should further be noted that the calculations of deaths and diseases from the conversion to electricity phase of the fuel cycle includes only the health impacts of oxides of sulphur. Other pollutants such as oxides of nitrogen, ozone and carbon monoxides also have an effect but are not included in this analyses. In calculating the person days lost due to disease the following assumptions have been made:

- an aggravation of chronic respiratory disease, results in 5 days lost.
- an asthma attack, results in an average of 1 day lost.
- respiratory disease in children, result in a lost of 1 day.
- aggravation of cardiolpulmonary disease results in 1 day lost.

The routine annual health effects associated with a 1,000 megawatt coal fired electrical power system with fluidized bed combustion are shown in Figure B-4. A quick comparison of Figure B-4 and Figure B-3 reveals that the number of accidents for the two systems is identical, since same amount of coal must be harvested, upgraded, transported, converted to electricity, and disposed of as final waste. The deaths estimates are also identical with the exception of the deaths due to conversion to electricity are decreased since the fluidized bed system

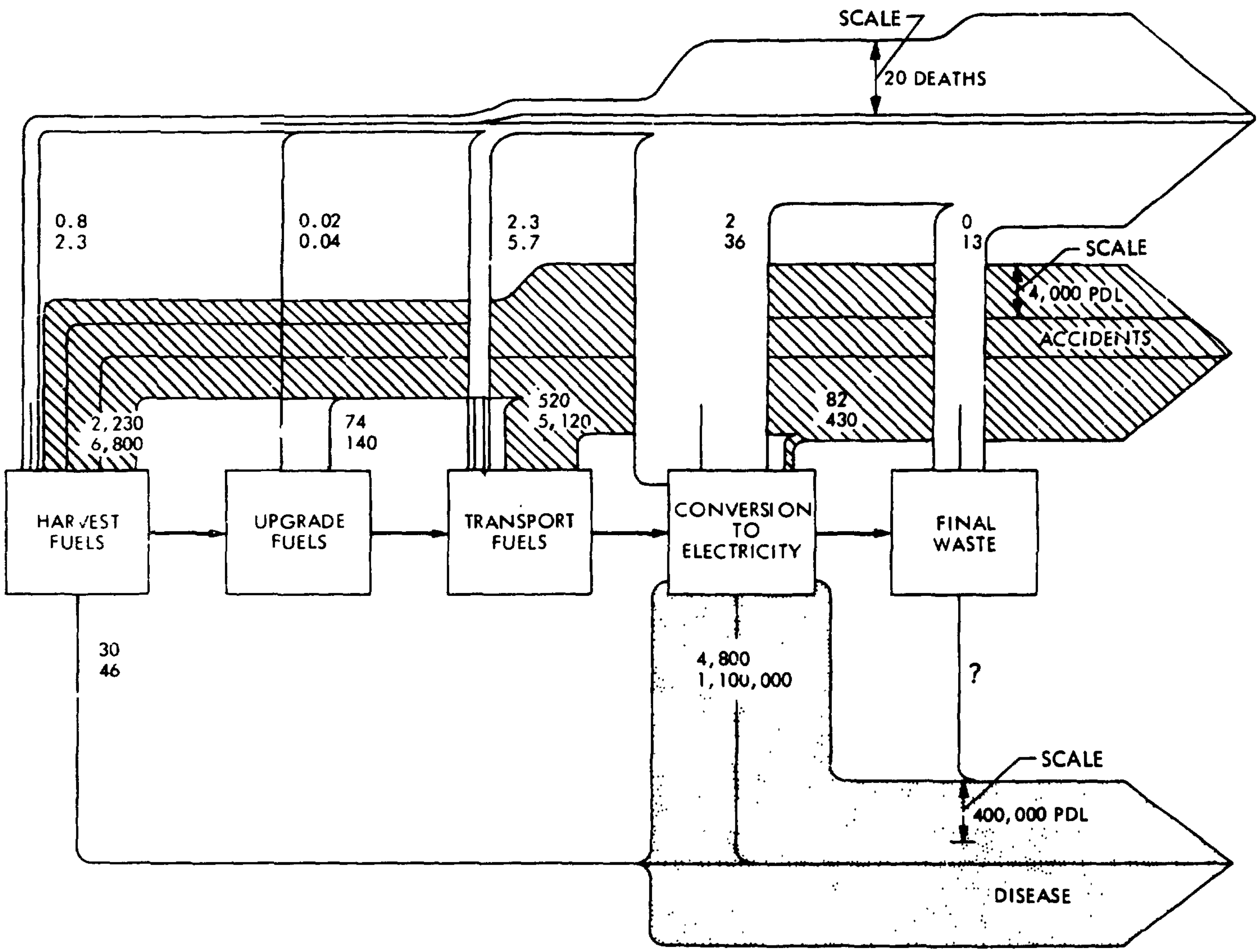


Figure B-3. "Routine" Annual Health Effects of 1,000 MW_e Coal Fired Electrical Power System With Lime Flue Gas Desulfurization

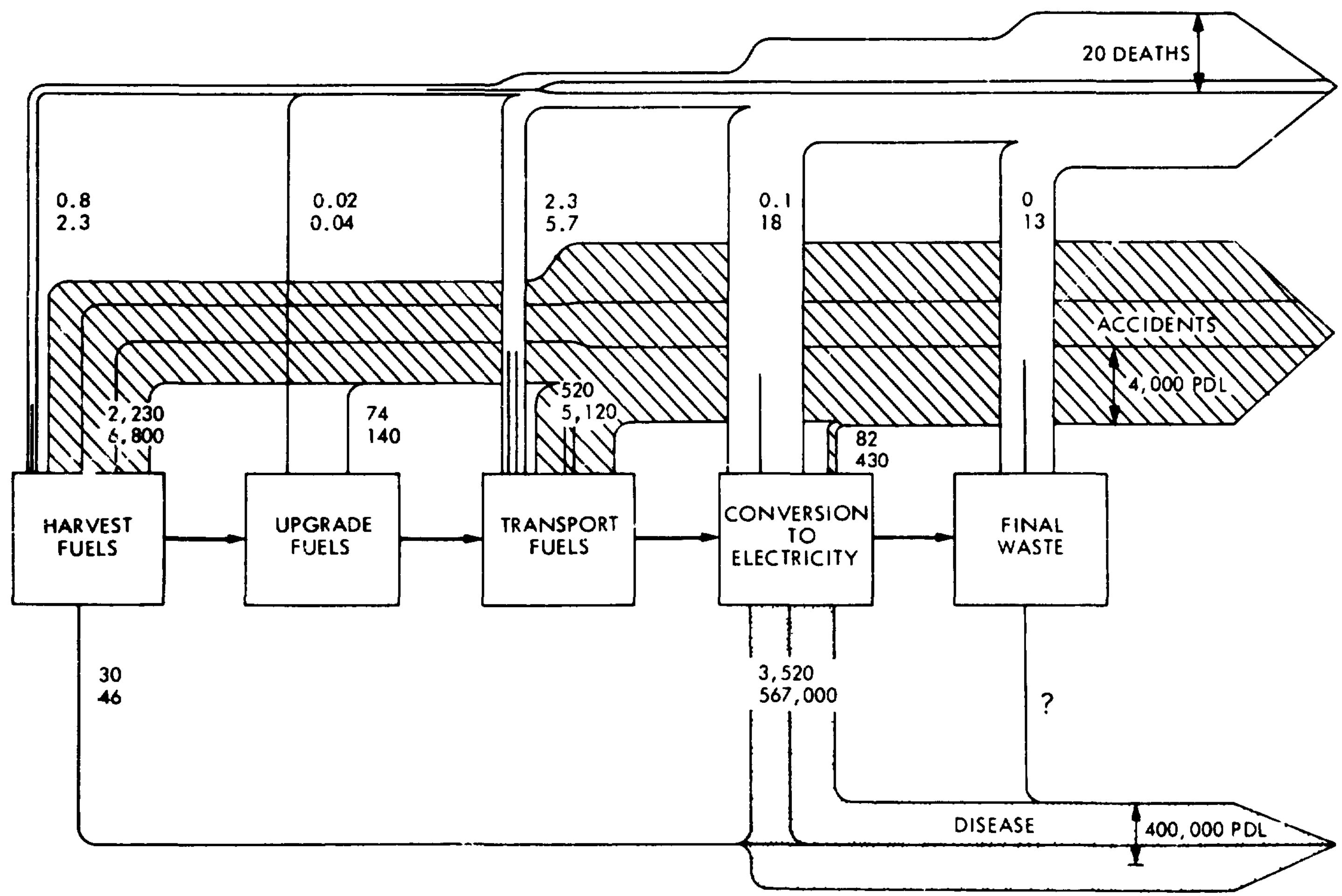


Figure B-4. "Routine" Annual Health Effects of 1,000 MW_e Coal Fired Electrical Power System With Fluidized-Bed Combustion is more efficient in removing sulphur. The assumption has been made that between 90% and 95% of the sulphur is removed by the fluidized bed desulphurization system. This also causes a significant decrease in the person days lost due to disease associated with conversion to electricity. Hence, the coal fired system with fluidized bed combustion is superior to that of the coal fired system with lime flue gas desulphurization from a health point-of-view.

The "routine" annual health effects associated with a 1,000 megawatt electrical power system fired with low BTU gas with combined cycle combustion are shown in Figure B-5. Once again, the person days lost due to accidents for the low BTU gas system appears to be very similar to the results presented for both the fluidized bed system and the flue gas desulphurization system. The reason for this similarity is that the accidents due to mining and transporting coal contribute significantly more person days lost than accident assoicated with either coal gasification, or conversion to electricity. In the example shown in Figure B-5 the assumption has been made that the coal must be transported to a coal gasification plant which is co-located with the electrical conversion plant. If the mine, gasification plant, and the electrical power generation plant were co-located, then the public accident impact could be decreased to approximately zero. However, this type of co-location may not always be possible due to such factors as shortages of water which may be required for the coal gasification process, economic and environmental considerations. The coal gasification process is assumed to be quite efficient in removing sulphur. The sulphur removal efficiency is thought to vary between 98% and 99.7%! Hence, the deaths associated with conversion to electricity are now estimated to range between 0.1 to 3.7 deaths per 1,000 megawatt-year. These death estimates are significantly smaller than those estimated for either the scrubber or the fluidized bed systems. Similar large reductions are also shown in Figure B-5 for the person days lost due to disease. These numbers are now estimated to range between 170 and 113,000 person days lost per 1,000 megawatt-year. We currently do not have sufficiently accurate data available to estimate the occupational health impact associated with coal gasification. The National Institute of Occupational Safety and Health, "NIOSH", is in the process of funding two programs in this

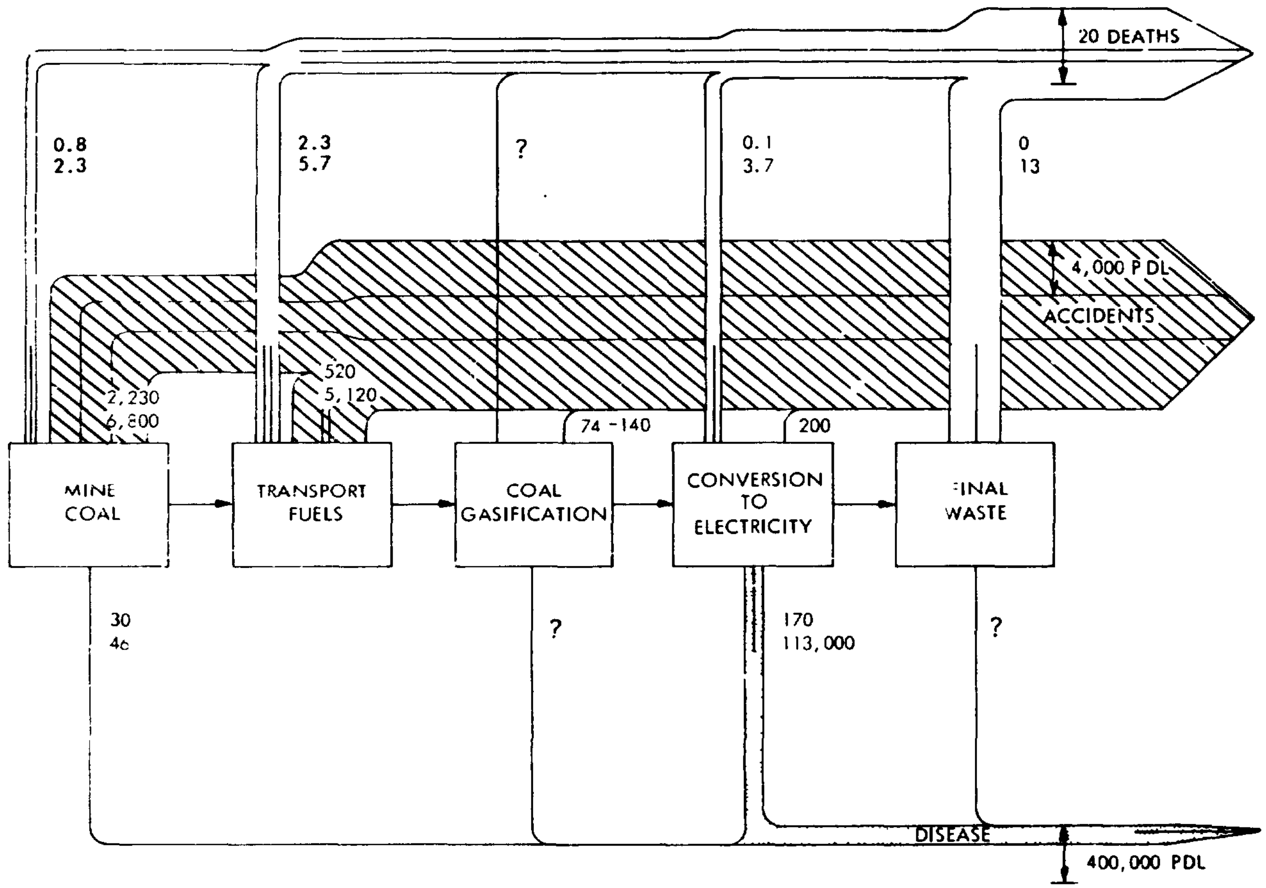


Figure B-5. "Routine" Annual Health Effects of 1,000 MW_e Low Btu Gas Fired Electrical Power System With Combined Cycle Combustion area. Based on the health information available, the low BTU system is preferable to both the fluidized bed system, and the lime flue gas desulphurization system.

The "routine" annual health effects associated with a 1,000 megawatt residual fuel oil fired electrical power system with lime flue gas desulphurization are shown in Figure B-6. This system is included in the report for the sake of completeness; however, it is expected that due to problems of scarcity and price of oil near the end of this century that the use of oil for generating electrical power will be decreasing. Figure B-6 shows that the residual fuel oil fired system is characterized by a dramatic decrease in the number of person days lost due to accidents. A residual fuel oil system indicates a total of approximately 700 person days lost per year due to accidents. This compares to approximately 12,000 person days lost per year due to accident for any of the coal fired systems. However, this advantage is accompanied by the disadvantage that the fuel is assumed to have between 0.6 and 1% sulphur by weight and the plant sulphur removal efficiency varying from 0 to 90%. These two factors caused the total deaths and person days lost due to disease for the residual fuel oil system to be quite similar to the values shown in Figure B-3 for a coal-fired system with lime flue gas desulphurization.

Nuclear Systems "Routine" Health Impacts

We shall now contrast the "routine" health impacts of the previous fossil fuel systems with those impacts associated with nuclear electric power systems. The nuclear systems considered will be the following:

- Light water reactor with uranium recycle.
- Light water reactor with plutonium recycle.
- Liquid metal fast breeder reactor.
- High temperature gas reactor.

To compare the contributions of each step in the nuclear fuel cycle to the "routine" health effects, the scales used for deaths,

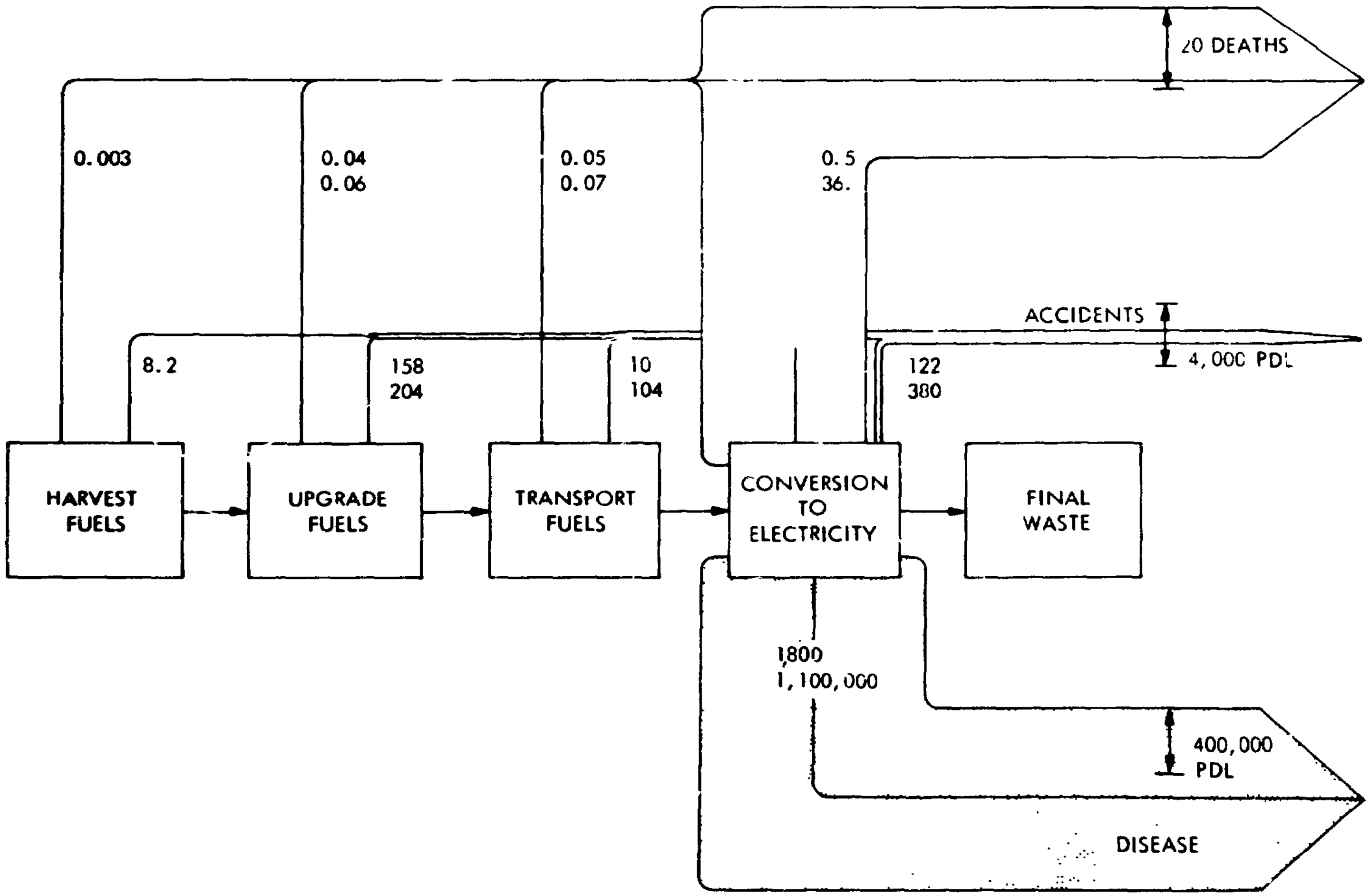


Figure B-6. "Routine" Annual Health Effects of 1,000 MW_e Residual Fuel Oil Fired Electrical Power System With Lime Flue Gas Desulfurization accidents, and diseases had to be reduced considerably from those used in the fossil fuel examples. The death scale is reduced by a factor of 60. The accident scale is reduced by a factor of 17, and the disease scale is reduced by a factor of 62,000. These reductions were required in order to be able to display the relative contribution of various phases of the fuel cycle for the nuclear power system.

It should be pointed out that these "routine" annual health effects do not include any impact at all due to possible catastrophic accidents at the Isotope separation plant, at the nuclear power generation plant, during transportation, or during either interim or perpetual storage of the high level radioactive wastes. Very little data is availalbe in many of these areas. The Rasmusen Report, Ref. 57, treats only the impact of the nuclear power plant itself in terms of a probabilistic analyses of the likelihood of given events taking place, and the severity associated with such events. This report is currently the center of considerable controversy. Hence it is once again emphasized that the diagrams to be shown only include "routine" annual health effects, and do not include effects of a catastrophic nature or effects associated with perpetual storage of radioactive wastes.

In this nuclear fuel cycle the upgrade duel phase includes conversion of U_3O_8 to UF_6, Isotope separation, conversion and fabrication of fuel rods. The final waste phase includes: 1) 150 day storage of the spent fuel rods, 2) shipment of the spent fuel rods to a reprocessing plant where the U^{235} and possible plutonium are removed from the spent fuel rods to be sent back into isotope separation, 3) interim 5 year storage of high level waste and 4) shipment to a Federal repository for perpetual storage of high level and other wastes. It should be pointed out that this definition of final waste does not include any radioactive waste that is associated with deactivation of any of these nuclear electrical power systems.

The "routine" annual health effects associated with a 1,000 megawatt light water reactor (LWR) electrical power system are shown in Figure B-7. The principle contributions to person days lost due to accidents occurs during the mining operation. These losses are quite comparable to those shown previously for the residual fuel oil system.

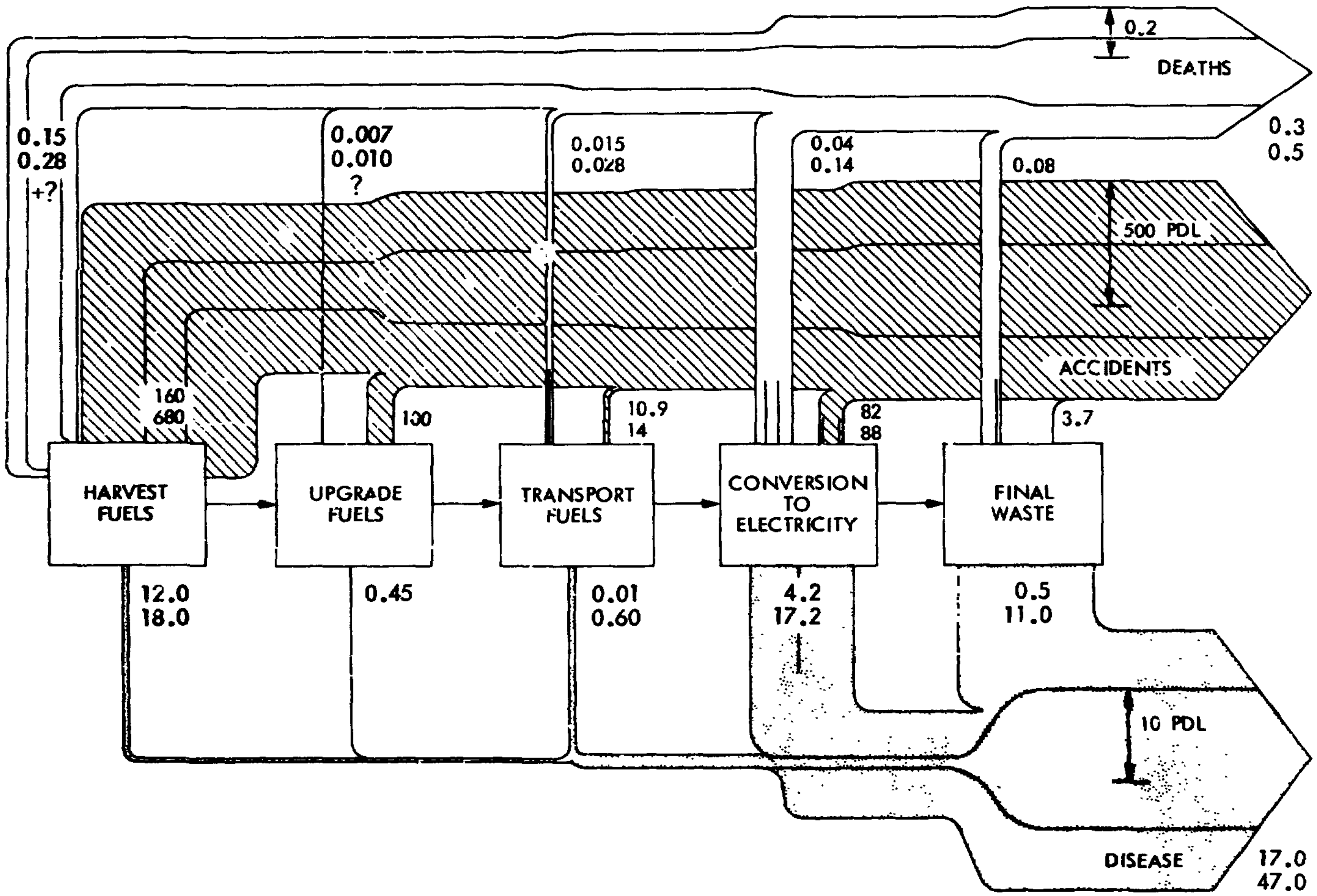


Figure B-7. "Routine" Annual Health Effects of 1,000 MW_e Light Water Reactor Electrical Power System With Uranium Recycle

Figure B-7 indicates a maximum of about 0.50 deaths per year for the light water reactor system. This is a factor of six less than the minimum estimate for the low BTU gas fossil fuel system. The person days lost due to accidents for the light water reactor system are also significantly less than those associated with the fossil fuel system. However, this is based on the assumption that Uranium ores remain at today's high concentrations. In the future, lower grade ores will be mined. Since the number of accidents is a function of the amount of material mined, there will be an increase in the accident person days lost.

An examination of Figure B-7 indicates that the upper limit of annual person days lost due to disease associated with the light water reactor is approximately 31. This upper limit contrasts with the lower limit estimated for the coal fired electrical power system with lime flue gas desulfurization of about 5000. Hence the "routine" disease impact of the coal system is at least 100 times worse than the "routine" disease impact of the light water reactor system.

If Plutonium is recycled from the reprocessing plant back into the fuel rods, the estimated health impacts might decrease slightly. For example, the person days lost due to disease is decreased to approximately 11 compared to 42 for the light water reactor. The "routine" annual health effects associated with a 1000 megawatts light water reactor electrical power system with plutonium recycle are shown in Figure B-8. The number of total deaths for this system is about 0.3 deaths annually which represents an improvement over the light water reactor. The accident rate, in terms of person days lost per year, is approximately the same for both systems. Hence the light water reactor with plutonium recycle represents a slight improvement over the plain light water reactor from a "routine" health point-of-view. This system may be not be an unmixed blessing however, due to potential problems associated with sabotage and diversions of the plutonium.

A Health Effects Flow Diagram for the "routine" annual health effects associated with 1000 megawatts electrical liquid metal fast breeder reactor electrical power system are shown in Figure B-9. In the liquid metal fast breeder reactor LMFBR system, U^{238} is converted to

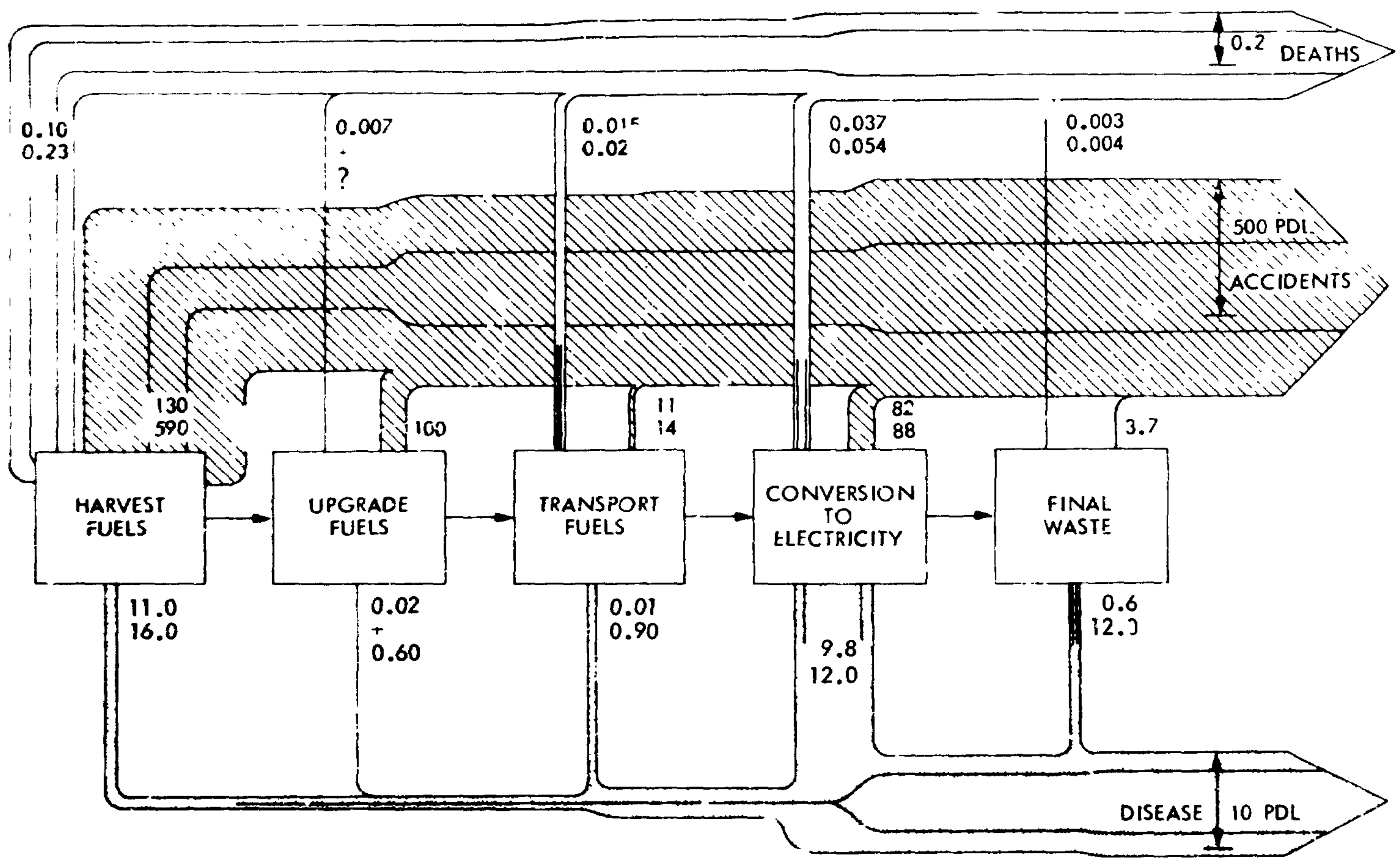


Figure B-8. "Routine" Annual Health Effects of 1,000 MW_e Light Water Reactor Electrical Power System With Uranium and Plutonium Recycle

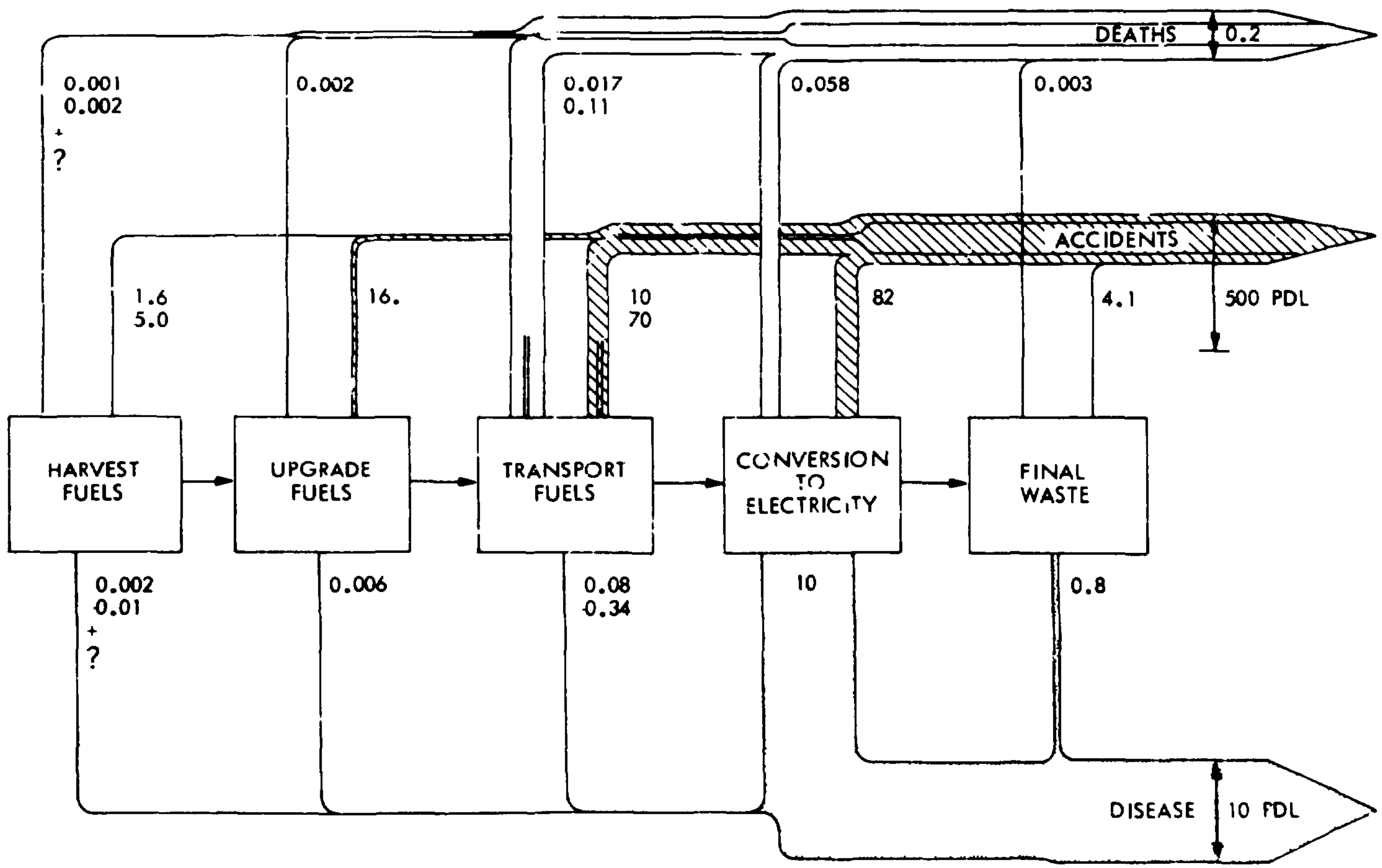


Figure B-9. "Routine" Annual Health Effects of 1,000 MW_e Liquid Metal Fast Breeder Reactor Electrical Power System

P_u^{239}. This plutonium acts as a fuel similar to the U^{235} used in the light water reactor. Hence the liquid metal fast breeder reactor system has the virtue of greatly increasing the energy utilization obtainable from uranium ore. This causes a large decrease in the amount of material that needs to be harvested. For example, the accidents associated with harvesting fuel for the LMFBR system range between 1.6 and 5.0 person days lost per year. These numbers are two orders of magnitude smaller than those shown in Figure B-7 for the light water reactor system. Another reduction in accidents takes place during the upgrading of fuel step for the LMFBR. This step is characterized by a 100 person days lost annually. The complete fuel cycle for the liquid metal fast breeder reactor estimates an upper limit of approximately 180 person days lost per year annually. This is in contrast to approximately 800 person days lost annually with the light water reactor system. Hence the LMFBR represents a considerable improvement in "routine" accident rate over that available with the light water reactor.

The disease rates of both systems are essentially identical. It should be noted that the impact of catastrophic accidents with the liquid metal fast breeder reactor may be considerable more severe than that associated with the light water reactor.

The routine annual health effects associated with a 1000 megawatt electrical high temperature gas reactor electrical power system are shown in Figure B-10. The overall fuel cycle person days lost per year due to disease for the system is similar to that of the light water reactor shown in Figure B-7. However, the overall death and accidents associated with the high temperature gas reactor are decreased somewhat with respect to those associated with the light water reactor. The person days lost due to accidents have been decreased from approximately 900 to approximately 550. The deaths have been decreased from a maximum of 0.5 deaths per year to a value of approximately 0.3 deaths per year. The estimates of effects from the HTGR and LMFBR systems are more speculative than for LWRs since there is less operating experience.

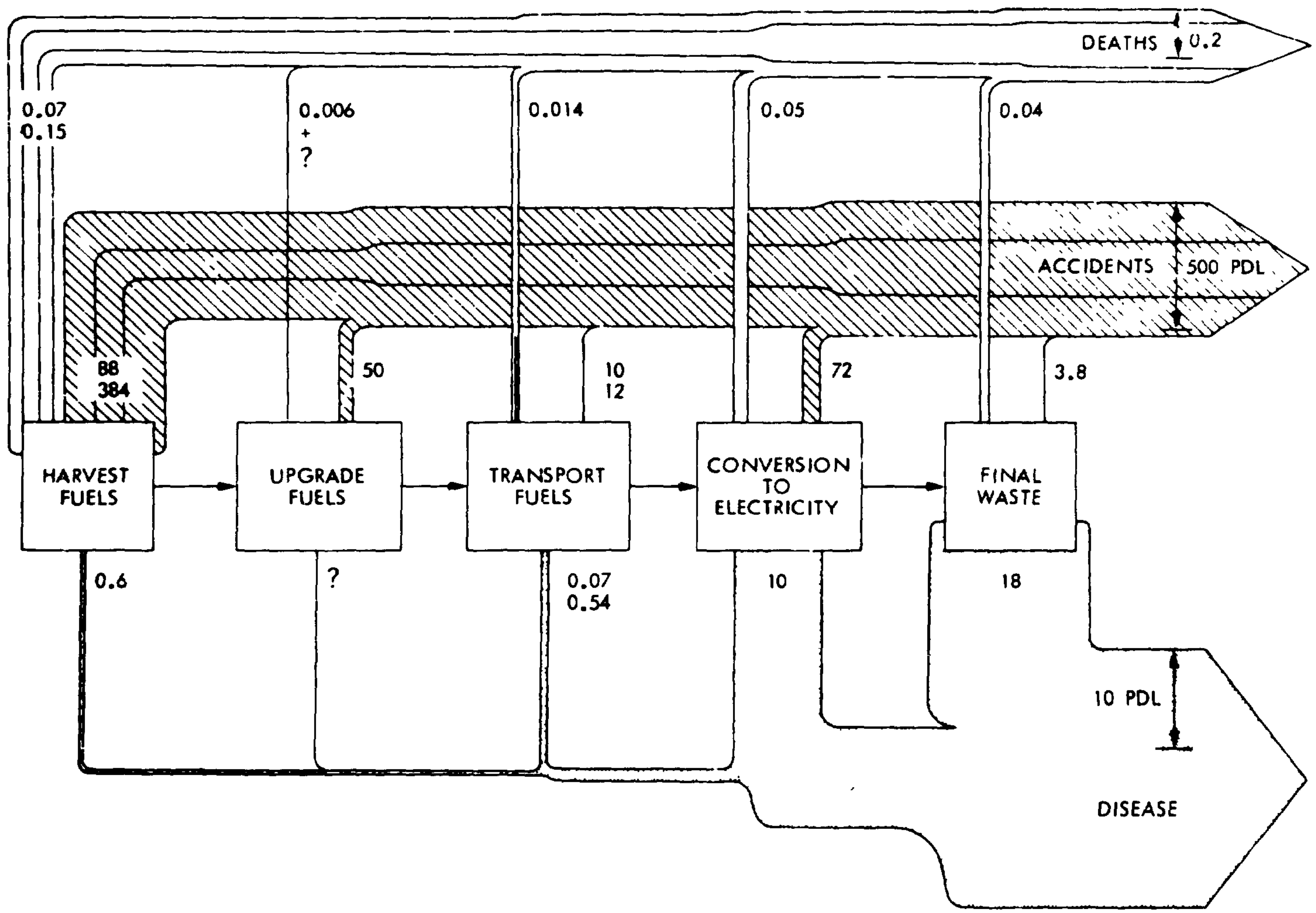


Figure B-10. "Routine" Annual Health Effects of 1,000 MW_e High Temperature Gas Reactor Electrical Power System

REFERENCES

1. Coates J.F., "Technology Assessment", McGraw-Hill Year Book of Science and Technology, 1974.

2. Doane, J. W., et al, "The Cost of Energy from Utility-Owned Solar Electric Systems," JPL Internal Report 5040-29, ERDA/JPL-1-12-76/3, June 1976.

3. "Power Plant Capital Costs: Current Trends and Sensitivity to Economic Parameters," AEC, WASH-1345, October 1974.

4. "A Time to Choose," Final Report of the Energy Policy Project of the Ford Foundation, Ballinger Publishing Company, 1974.

5. In-house studies by G. E. Tempo, Santa Barbara, Ca., 1974, provided by W. Hausz.

6. Bupp, I. C., et al, "Trends in Light Water Reactor Capital Costs in the United States: Costs and Consequences," MIT Center for Policy Alternatives, December 1974.

7. Smith, K. R., Weyant, J. and J. Holdren, "Evaluation of Conventional Power Systems," ERG 75-5, U. C. Berkeley, July 1975.

8. Hogerton, R. F., Uranium Supply U.S., A Current Assessment, Vol. 19, Nuclear News, p. 73, June 1976.

9. "Liquid Metal Fast Breeder Reactor Program", Vol. I: Summary and Background, Wash 1535, March 1974.

10. 1976 National Energy Outlook, Federal Energy Agency, FEA-N-75/713, Feb. 1976.

11. Bell, C. R., "Assessment of a Solar Photovoltaic Power Conversion System for Central Station Applications", JPL Internal Report 900-702, Jet Propulsion Laboratory, June 1975.

12. Selcuk, M. K., "Survey of Several Central Receiver Solar Thermal Power Plant Design Concepts", JPL Internal Report 900-714, August 1975.

13. Caputo, R. S., "An Assessment of Utilizing a Reversible Vee-Trough Concentrator with a Fixed Collector for Thermal-Electric and Photovoltaic Central Power Plant", JPL Internal Report 900-783, October 1976.

14. Selcuk, M. K., "Preliminary Assessment of Flat Plate Collector Solar Thermal Power Plants", JPL Internal Report 900-692, March 1975.

15. Selcuk, M. K., "A Preliminary Technical and Economic Assessment of Solar Power Plants Using Line Concentrators", JPL Internal Report 900-704, July 1975.

16. Caputo, R.S., "An Initial Study of Solar Power Plants Using a Distributed Network of Point Focusing Collectors", JPL Internal Report 900-724, July 1975.

17. Selcuk, M. K., Caputo, R. S., French, R., and Finegold, J., "Preliminary Evaluation of a Parabolic Dish-Small Heat Engine Central Solar Plant", JPL Internal Report 900-749, July 1976.

18. "Solar Thermal Conversion Mission Analysis", Summary Report, Southwest U.S., ATR-74 (7417-16)-2, Vol. I, Aerospace Corp., January 1975.

19. Fujita, T., "Preliminary Data on Electric Energy Storage Systems for Utility Applications", JPL Internal Report 900-738, April 1976.

20. Fujita, T., "Underground Energy Storage for Electric Utilities Employing Hydrogen Energy Systems", JPL Internal Report 900-744, June 1976.

21. Turner, R. H., "Thermal Energy Storage for Solar Power Plants", JPL Internal Report 900-754, July 1976.

22. Manvi, R., "Performance and Economics of Terrestrial Solar Electric Central Power Plants", JPL Internal Report 900-781, October 1976.

23. "Solar Thermal Conversion Mission Analysis", Mid-Term Report, ATR-76 (7506-05)-1, Aerospace Corp., September 1975.

24. "Central Receiver Solar Thermal Power Plant Design Summary", Report No. ATR-76 (7523-14)-2, Aerospace Corp., November 1976.

25. Personal Communications, Jerry Braun, Southern California Edison, November-December 1976.

26. Braun, G. W., et al., Integration of Solar Thermal Power Plants into Electric Utility Systems, Southern California Edison, 76-RD-63, Sept. 1976.

27. "An Assessment of Solar Energy as a National Energy Resource", NSF/NASA Solar Energy Panel, December 1972.

28. "Space-Based Solar Power Conversion and Delivery System Study", Interim Summary Report, 76-145-IB, ECON, Inc., March 31, 1976.

29. "Initial Technical, Environmental and Economic Evaluation of Space Solar Power Concepts", Lyndon B. Johnson Space Center, August 1976.

30. "Space-Based Solar Power Conversion and Delivery Systems Study", Second Interim Report, ECON, Inc., June 30, 1976.

31. "Satellite Power Systems: An Engineering and Economic Analysis Summary", NASA TM-X-73344, MSFC, November 1976.

32. Fujita, T., "Preliminary Parametric Data for Satellite Power Stations, Based on Published Systems Studies", JPL Internal Report 900-785, January 1977.

33. "Low-Cost Silicon Solar Array Project", Quarterly Report, ERDA/JPL 5101-7, October 1976.

34. Fujita, T., "Preliminary Assessment of Electrical and Hydrogen Pipeline Transmission Systems", JPL Internal Report 900-703, March 1975.

35. Fujita, T., "Preliminary Studies of Electrical and Hydrogen Distribution and Cost Optimization of Electrical Transmission Lines", JPL Internal Report 900-734, March 1976.

36. "Solar Thermal Conversion Mission Analysis", Midterm Report, Aerospace Corporation, September 1975.

37. "Solar Thermal Conversion Mission Analysis", Semiannual Review, Aerospace Corporation, April 1975.

38. "Creating Energy Choices for the Future", ERDA-48, Volume 2, 1975.

39. "Definition Report, National Solar Energy Research, Development and Demonstration Program", ERDA-49, June 1975.

40. "Solar Energy Research Program Alternatives", NSF/RANN-73-111B, December 1973.

41. "Solar Energy Intelligence Report", Business Publications, Inc., December 15, 1975.

42. "FEA Project Independence Blueprint, Final Task Force Report Solar Energy," NSF, November 1974.

43. U. S. Administrative Budget for 1977.

44. Maycock, D., and Wakefield, F., "Business Analysis of Solar Photovoltaic Energy Conversion", Proceedings of the 11th IEEE Photovoltaic Specialists Conference (1975), pp. 252-255, 1975.

45. "Assessment of RD&D, Resources, Health and Environmental Effects, O&M Costs and Other Social Costs for Conventional and Terrestrial Solar Electric Plants", Edited by G. Herrera, JPL Internal Report 900-782, January 1977.

46. Powell, J.C., et al., Dynamic Conversion of Solar Generated Heat to Electricity, Honeywell Corp.. NASA CR-134724, August 1974.

47. The Central Receiver Solar Thermal Power System Phase 1, ERDA Semi-Annual Review, McDonald Douglas Corp., December 1976.

48. "Central Receiver Solar Thermal Power System", ERDA Semi-Annual Review, Boeing Engineering and Construction Co., December 1976.

49. Commodity Data Summaries, Dept. of Interior, 1975.

50. "Comprehensive Standards: The Power Generation Case," EPA No. 68-01-0561, Teknekron, Inc., Berkeley, CA, March 1975.

51. 1976 National Energy Outlook, FEA-N-75/713, Federal Energy Agency, February 1976.

52. Rehabilitation Potential of Western Coal Lands, Report to Energy Policy Project Ford Foundation, National Academy of Science, Ballinger Publishing Co., Cambridge, Mass., 1974.

53. Personal Communication with W. Lang of Sterns and Rogers based on performance of the Neil Simpson Station Plant (20.2 MW_e) of Black Hills Power and Lighting which uses dry cooling, September 1976.

54. Solar Thermal Conversion Mission Analysis, Semi-Annual Review, Aerospace Corp., April 1975.

55. "Central Receiver Solar Thermal Power System, Phase I", Martin Marietta Corp., April 1976.

56. "Energy Model Data Base", Brookhaven National Laboratory, BNL 19200.

57. "Reactor Safety Study: An Assessment of Accidental Risks In U.S. Commercial Nuclear Power Plants, Draft" AEC, Wash-1400 (The Rasmussen Report), Volumes 1-10, August 1976.

58. Paul, S., "Parolbeck, Effect of 2.0 mg/cm^3 Coal Mine Dust Standard on Underground Environmental Dust Levels", American Industrial Hygiene Association, p. 604, August 1975.

59. Energy and Human Welfare - A critical Analysis., Vol. 1, The Social Costs of Power Production, Edited by B. Commoner, et al., MacMillan Publishing, New York, N.Y., 1975.

60. Ehrlich, P., "The Heat Barrier", Saturday Review, April 3, 1971.