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PRELIMINARY COMPARATIVE ASSESSMENT OF LAND USE FOR THE SATELLITE POWER SYSTEM (SPS) AND ALTERNATIVE ELECTRIC ENERGY TECHNOLOGIES

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SATELLITE POWER SYSTEM
Concept Development
and
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DEFINITIONS OF UNIT SYMBOLS

°C:	degrees centigrade
J:	joule
km:	kilometer
kWh:	kilowatt-hour
m:	meter
MW:	megawatt
MW-yr:	megawatt-year
m^2-yr:	square meter-year
t:	metric ton (i.e., 1,000 kilograms)

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SUMMARY

A preliminary comparative assessment of land use for the satellite power system (SPS), other solar technologies, and alternative electric energy technologies has been conducted. The alternative technologies are coal-gasiication/combined-cycle, coal fluidized-bed combustion (FBC), light water reactor (LWR), liquid metal fast breeder reactor (LMFBR), terrestrial photovoltaics (TPV), solar thermal electric (STE), and ocean thermal energy conversion (OTEC). Fusion was not included in this preliminary work but will be a part of the final assessment. The objectives of this assessment were to conduct a preliminary evaluation based on available research, to identify a suitable assessment methodology, and to identify data deficiencies.

The major issues of a land use assessment are the quantity, purpose, duration, location, and costs of the required land use. The phased methodology described here treats the first four issues, but not the costs.

The results of the preliminary assessment are summarized in Table 1. Data were typically available in the surveyed research for the land requirements of the plant site proper. However, disparities in the way the data were reported limited their usefulness for comparative assessment. The data from different sources were often normalized differently, with no explicit statement of the information needed to convert from one unit of measure to another. Further, different sources sometimes included different parts of an entire system in their aggregated data. Hence, the data were not directly comparable.

Some general comparisons are possible on the basis of the existing data. Except for OTEC, which is not land based, the coal options have the smallest land requirements for their generating plants. The nuclear options require somewhat more land for their plants, while the solar options have the largest plant-area requirements. The comparison, however, is reversed for land required for the fuel cycle. The solar options need no such land, while the coal and nuclear options require substantial areas for fuel mining and processing. Because it requires less fuel, the LMFBR requires less land per unit of output than the LWR or the coal options.

The lack of explicit data in the construction category renders the possible comparisons questionable. Likewise, comparison is not possible in the waste-disposal category because of the diversity of form of the existing data. In the transmission category, in the absence of better estimates of line lengths for each technology, the data indicate that land requirements for all technologies are roughly comparable.

The survey of available research showed several data deficiencies. For most technologies, explicit data were lacking on the duration and location of land use and on the amount of land required for construction. For the SPS, data were deficient on land required for launch sites and transmission facilities. Some deficiencies in the fuel, disposal, and transmission categories may be eliminated as a result of further system-characterization or scenario-development studies. For example, some data showed the amount of land required for a typical coal mine, but in this preliminary assessment it was not clear what proportion of that land should be allocated to a normalized unit of power or energy production. Such data may be useful to further studies.

For the final assessment, it is recommended that the major effort be devoted to consistent system characterization to fill in the land use matrix. Specific attention should be given to:

- Consistency in the units of measure;
- Explicit statement of the assumptions used in normalizing the data;
- Breaking down the land requirements by purpose of use; and
- Filling in the areas of greatest data deficiency.

Table 1. Summary of Results

Purpose	Construction	Plant	Fuel	Disposal	Transmission
CG/CC					
Quantity	--[a]	smallest	large	5 m^2/MW-yr	300 m^2/MW-yr (480 km)[c]
Duration	--[b]	30 yr	30 yr	--[b]	30 yr
Location	--[b]	--[b]	--[b]	--[b]	--[b]
FBC					
Quantity	--[a]	smallest	large	1.4 m^2/MW-yr	300 m^2/MW-yr
Duration	--[b]	30 yr	--[b]	--[b]	30 yr
Location	--[b]	--[b]	--[b]	--[b]	--[b]
LWR					
Quantity	--[a]	medium	small	4 m^2/MW-yr	225-1000 m^2/MW-yr (480-1600 km)[c]
Duration	--[b]	30-40 yrs	--[b]	10^6 yrs	30-40 yrs
Location	--[b]	--[b]	--[b]	--[b]	--[b]
LMFBR					
Quantity	--[a]	medium	small	--[b]	200 m^2/MW-yr (80 km)[c]
Duration	--[b]	30 yr	--[b]	--[b]	30 yr
Location	--[b]	--[b]	--[b]	--[b]	--[b]
TPV					
Quantity	--[a]	large	negl[d]	negl[d]	300-3000 m^2/MW-yr (480-4800 km)[c]
Duration	--[b]	30 yr	NA[e]	NA[e]	30 yr
Location	--[b]	Southwest	NA	NA	--[b]
STE					
Quantity	--[a]	large	negl	negl	300-3000 m^2/MW-yr (480-4800 km)[c]
Duration	--[b]	30 yr	NA	NA	30 yr
Location	--[b]	Southwest	NA	NA	--[b]
OTEC					
Quantity	--[a]	negl	negl	negl	300 m^2/MW-yr (480 km)[c]
Duration	--[b]	NA	NA	NA	30 yr
Location	--[b]	NA	NA	NA	--[b]
SPS					
Quantity	20-850 km^2 (launch)	large	negl	negl	300-1000 m^2/MW-yr (480-1600 km)[c]
Duration	30 yr	30 yr	NA	NA	30 yr
Location	Florida?	--[b]	NA	NA	--[b]

[a]Approximately the sum of plant and transmission requirements.

[b]Data lacking; some categories are discussed in text.

[c]Distance to load center.

[d]Negligible.

[e]Not applicable.

PRELIMINARY COMPARATIVE ASSESSMENT OF LAND USE FOR THE SATELLITE POWER SYSTEM AND ALTERNATIVE ELECTRIC ENERGY TECHNOLOGIES

by

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ABSTRACT

The objective of this report is to present a preliminary comparative assessment of land use for satellite power systems and several alternative electric energy technologies. A methodology for performing the assessment is described. Several past efforts at comparative or single-technology assessment are reviewed briefly. The current state of knowledge about land use is described for each technology. Conclusions are drawn regarding deficiencies in the data on comparative land use and needs for further research.

1 INTRODUCTION

One of the important resources required by electric energy technologies is land area. In a satellite power system (SPS), a large amount of land is required for rectenna (receiving and rectifying antenna) sites. Other technologies, too, may have large land requirements. The comparative assessment of an SPS with several alternatives thus includes land as one of the parameters of interest. The major issues of a land-use assessment can be categorized as quantity, purpose, duration, location, and cost.

The most obvious question about land is the amount of land that a given technology will require. The basic unit of measure for this question is simply land area. However, for a fair comparison of the technologies, it is necessary to normalize the measure of land area, such as by the power rating or the energy output of a typical plant. In addition, different amounts of land may be required for varying purposes in a single system. For example, a certain amount may be required during construction, another amount for the plant site during operation, and additional amounts for the fuel source, waste disposal, and power transmission.

Also important to the assessment is the duration of use of the land. The unit of measure for this issue is simply time. Again, for each of the purposes of land use, a different duration of use may be required.

A third important issue is the location of the required land. In concept, the evaluation of this issue could proceed to the detailed evaluation of sites for individual plants. However, a more general representation of location is also possible, for example, region of the country.

The quantity, duration, and location of land use all have impacts upon cost. The direct dollar cost of acquiring or leasing the land is rather obviously affected. There are opportunity costs too, associated with the denial of alternative uses of the land. Though these costs are often difficult to measure, they constitute an important issue concerning the significance of land use. Opportunity costs, however, are not included in this preliminary work or in the final assessment, because evaluating such costs for land use is largely speculative.

The comparative nature of the present assessment raises some additional requirements for treatment of the above issues. For a fair comparison of technologies, a consistent data set is needed. The data must be of similar quality for all of the technologies so that it can be normalized in a consistent manner. The methodology for accomplishing the assessment must also be consistent.

The objectives of the present study were:

- To conduct a preliminary assessment based on research that had already been done;
- To identify a suitable methodology for the land use assessment; and
- To identify available data and deficiencies in it for purposes of the assessment.

In addition to the SPS, this preliminary assessment included two coal technologies (coal-gasification/combined-cycle and fluidized-bed combustion), the light water reactor, the liquid metal fast breeder reactor, terrestrial photovoltaics, solar thermal electric, and ocean thermal energy conversion.

In the next section of this report a systematic methodology is presented for the comparative assessment of land use. In Sec. 3, some pertinent studies relating to this area are reviewed briefly. In Sec. 4 a preliminary assessment of land use is presented for each of the technologies included. Conclusions of this study, including recommendations for further research, are presented in Sec. 5.

2 METHODOLOGY FOR COMPARATIVE ASSESSMENT

One of the objectives of this study was to identify a suitable methodology for the comparative assessment of land use, based on an evaluation of other research already done. The examined research treated land use in various levels of detail. The simplest assessment consisted of giving a single land-use figure aggregated over all purposes of use for the lifetime of a plant. The most detailed assessments broke down the land requirements into fixed land and incremental land for various uses. (Fixed land remains in use for the lifetime of a plant; incremental land is used for only part of the lifetime). Only rarely was any explicit data given as to the duration or location of the land use.

The methodology selected for the comparative assessment needs to present information that is useful for decision making. For this purpose the quality as well as the quantity of land use is important, that is, what criteria the land must satisfy and what impacts the proposed use will have. Therefore, the assessment methodology should include a breakdown of land use by purpose of use. Where possible, data on duration, location, and costs should also be included.

A methodology for comparative assessment of land use is shown in Fig. 1. The present study constitutes a preliminary assessment. The final assessment will include an alternative-futures analysis based on growth scenarios for utilization of the technologies, and will make use of more definitive characterizations of technologies and systems.

As depicted in Fig. 1, the comparative assessment starts with a selection of systems to be compared. This selection is actually outside the land use assessment *per se*, but is shown here for completeness.

Given reference designs for the selected technologies, the systems are characterized as to their land requirements, in terms of quantity, duration, and location. In the preliminary phase, the characterization activity consisted of a literature search. The final assessment will use the results of separate, ongoing characterization activities. Since detailed siting studies are beyond the scope* of this research, locations will be indicated only by general geographic region, such as "Southwest." The assessment will also incorporate the results of ongoing studies to characterize and evaluate possible SPS rectenna sites. These studies are described in more detail later in this report. The result of this step should be a matrix of quantity, duration, and location of land use by technology and purpose of use (Fig. 2).

The side-by-side evaluation resulting from the system-characterization step is as far as this assessment will go. The addition, in the final assessment, of growth scenarios for the alternative technologies will permit the evaluation of total land requirements for the given scenarios.

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*SPS siting studies are to be performed as part of the SPS Societal Assessment.

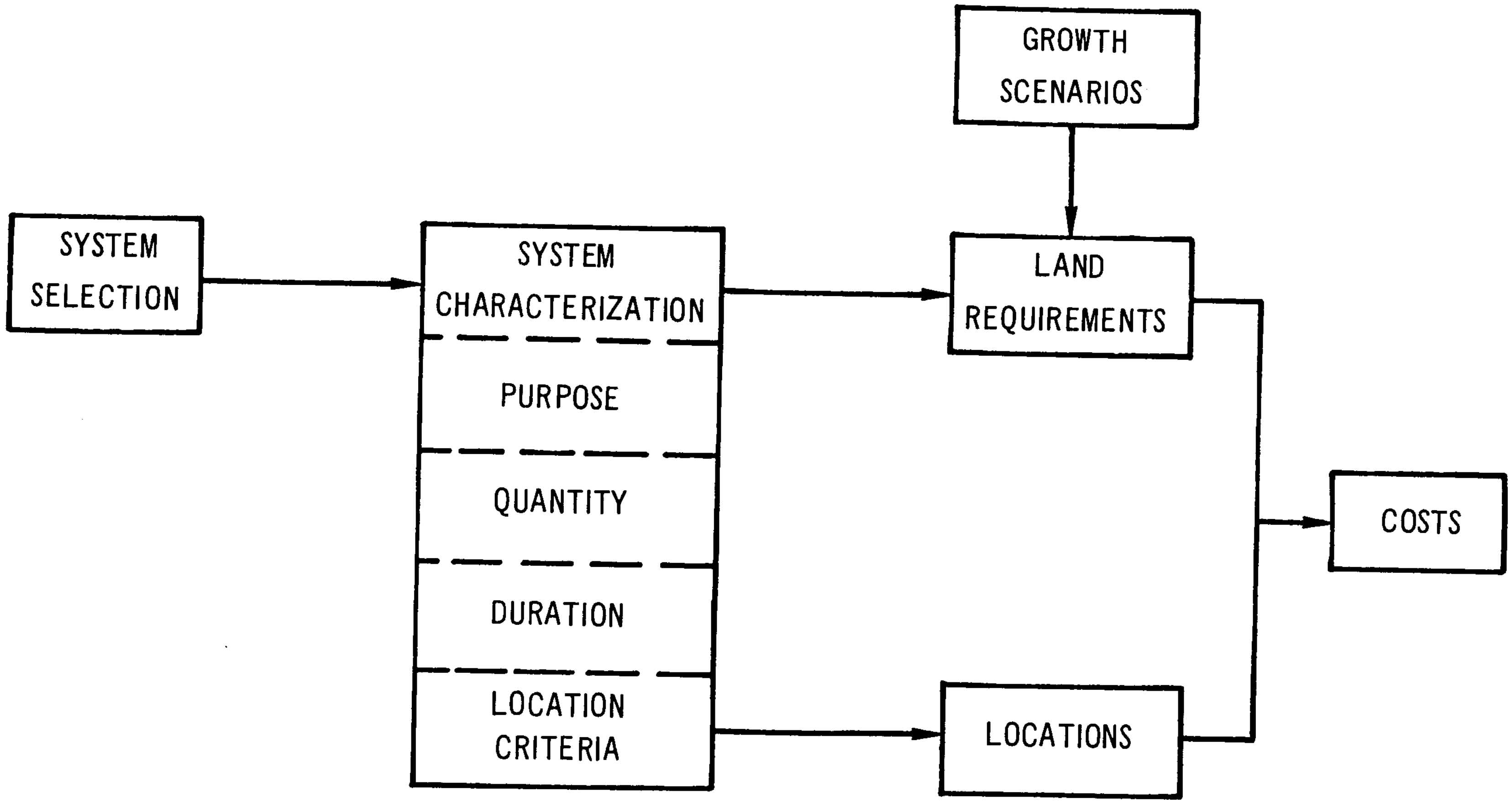

Fig. 1. Methodology for Land Use Comparative Assessment

	PURPOSE:	CONSTRUCTION	PLANT	FUEL	WASTE DISPOSAL	TRANSMISSION
TECHNOLOGY 1	QUANTITY					
	DURATION					
	LOCATION					
TECHNOLOGY 2	QUANTITY					
	DURATION					
	LOCATION					
• • •						

Fig. 2. Matrix of Land Use by Technology and Purpose

The final step shown in Fig. 1 is the evaluation of direct and social costs resulting from the required land usages. As discussed earlier, these costs are important in gauging the significance of land use. In this preliminary assessment, however, the lack of detailed siting studies precludes the detailed assessment of costs. Some generalized statements of impacts can be made where general regional locations of facilities are identified.

Two additional issues require some comment: system boundaries and the treatment of uncertainty. As conceived here, the land required by an energy system will consist only of that required for primary uses, e.g., construction (access roads), the plant site, the fuel cycle, waste disposal, and transmission facilities. Excluded will be secondary uses such as land for the factories that manufacture plant components.

Quantitative uncertainty in the estimates of land use is probably of little importance for decision making, compared to the magnitude of the estimates and the qualitative impacts of land use. The latter are more a function of location than of quantity. Hence, the assessment will not include an explicit quantitative treatment of uncertainty.

3 BRIEF OVERVIEW OF PERTINENT STUDIES

Among data sources that were researched in this assessment are several studies in which side-by-side data are presented for several technologies, as well as many studies of individual technologies. The latter, including studies by Kotin and by Blackburn and Bavinger of SPS land use,[1,2] are discussed in the appropriate parts of Sec. 4. Those studies that in some sense compared several technologies are reviewed here.

Caputo[3] has performed a comparative assessment of several central-station technologies, including the issue of land use. The data, however, typically identify only land for transmission and the total land for other purposes for each technology. Some exceptions are noted later in this report. Generally, however, the data do not constitute the detailed breakdown discussed earlier.

One data source that does perform a detailed breakdown of land requirements by purpose is the MERES data base.[4,5] The land-use data are presented as fixed land, incremental land, and a time-averaged total requirement for each of several activities and processes in the fuel cycle. Unfortunately, the data are compiled only for a variety of fossil fuel-based technologies.

Bechtel's Energy Supply Planning Model[6,7] presents data broken down similarly to the MERES data for coal and nuclear facilities. In addition to fixed and incremental land, the Bechtel model also explicitly identifies right-of-way and underground lease requirements. In terms of the breakdown of land requirement by facility, both the MERES and Bechtel data are close to what is envisioned for the comparative assessment methodology. However, in addition to being limited in the scope of their technologies, they also lack data on the duration of land use or its location.

One study that addresses the issue of location is that of MITRE/METREK, applied to solar-related technologies.[8] Generic designs are given for several types of solar plants. The likely locations of each plant type are given in terms of census region, and the major economic and environmental factors causing cost variation between regions are noted. However, only a single figure is given for the total land use of each.

To summarize, all of these studies contain useful data and represent a part of a complete comparative methodology. However, none of them comprises the entire methodology discussed in Chapter 2.

4 LAND USE AND IMPACT ASSESSMENT

This section of the report presents the assessment of land use and impacts for each of the candidate technologies: coal-gasification/combined-cycle, fluidized-bed combustion, light water reactor, liquid metal fast breeder reactor, ground solar photovoltaics, solar thermal electric, ocean thermal energy conversion, and satellite power systems. For each technology the reference design is described briefly and cited. The land use requirements are given, together with discussions of their impacts, to the extent that this information is available from the documents examined.

4.1 COAL-GASIFICATION/COMBINED-CYCLE

The General Electric Company has described a coal-gasification/combined-cycle (CG/CC) system in their energy conversion alternatives study.[9] The system is based on an open-cycle gas turbine, and includes an integrated low-Btu gasifier producing a gaseous fuel from coal on site. The net plant output is 584.8 MW.* The land area requirement is given as 530 m^2/MW. This total is composed of 430 m^2/MW for the main plant and 100 m^2/MW for disposal land (20 m^2/MW-yr and 5 m^2/MW-yr respectively, assuming a 30-yr lifetime and capacity factor of 0.7). No further breakdown or information about land usage is given.

Caputo includes a combined-cycle plant in the comparative assessment of central power systems.[3] The land area disturbed for the plant is given as 150 m^2/MW-yr, with an additional 1800-4520 m^2/MW-yr for fuel-related land use, depending on the region where the coal is mined. An estimated 300 m^2/MW-yr is required for 480 km of transmission lines. Averaging Eastern deep-mined and Western strip-mined coal, a composite figure of 3600 m^2/MW-yr is given.

Strip-mined land may or may not be reclaimable. Depending on such factors as ground slope, annual rainfall, the site specific-ecology, and acid water, the time required for restoration could be under 10 years, or restoration could be impossible. Caputo assumes a restoration time of 30 years, the same as the plant lifetime. No reason for this choice is given.

The Energy Supply Planning Model of Bechtel Corporation[6,7] contains separate data for the land requirements of a combined-cycle power plant, coal mines, and transmission lines. These data explicitly exclude land that is used only in the construction phase. The plant has a gas turbine of 240 MW and a steam turbine of 160 MW, for a total plant output of 400 MW. It requires a fixed amount of land of 60,700 m^2, with no incremental land use. (Fixed land is land that is required during the entire life of a facility. Incremental land is land that is used for only part of the lifetime of a facility.) Assuming a 30-yr plant lifetime and a capacity factor of 0.7, a land requirement of 7.2 m^2/MW-yr is derived. A coal mine, either underground, with a capacity of 2 million metric tons per year (t/yr), or surface, with a capacity of 4×10^6 to 6×10^6 t/yr, would require 40,500-56,700 m^2 of fixed land, and 0.3-0.4 km^2/yr of incremental land. Transmission lines of various voltages and ratings, and of lengths from 800-1300 km, would require 3.1×10^7-6.9×10^7 m^2 of right-of-way.

*See p. iv, "Definition of Unit Symbols."

The Bechtel data, while fitting into the data base needed for the comparative assessment, illustrate a common difficulty encountered with some data. Without further study regarding system characterization and scenario development, the data are not amenable to comparative assessment. For example, it is not clear what proportion of a coal mine should be allocated to one typical generation plant for a normalized comparison. Similar difficulties exist with characterizing the length and type of transmission lines to accompany a typical plant. It should be possible to resolve these difficulties in further phases of the comparative assessment, when the more complete characterization and scenario studies are included.

4.2 FLUIDIZED-BED COMBUSTION

Two fluidized-bed plants are described in GE's energy conversion alternatives study.[9] One is an atmospheric fluidized bed (AFB) plant of 814.3 MW net plant output. The second is a pressurized fluidized-bed (PFB) plant of 903.8 MW net plant output. For the AFB plant, the land requirement is given as 1.53 x 105 m^2/MW; for the PFB plant, 1.05 x 10^5 m^2/MW (8.4 m^2/MW-yr and 5.2 m^2/MW-yr respectively, assuming a 30-yr lifetime and a capacity factor of 0.75). These figures presumably include the land required for the main plant and disposal land. They also include the assumption that friable ash is used as a soil conditioner.

A more detailed accounting of land use for fluidized-bed combustion is given in the MERES data base.[4,5] Figures are again given for both AFB and PFB systems. Summary data are given in Table 2.

The figures in Table 2 include fixed land for coal, ash, and dolomite storage and the plant itself, and incremental land use due to solid waste. Lands for coal extraction and transmission right-of-way are not included. The fixed land is the same for all regions and both systems. Variation in the summary figures is thus due only to variation in incremental land use because of regional differences in the heat content of fuel and in the density of waste. As an example of how the summary figures were arrived at, consider the PFB system in the Central region. The plant is rated at 635 MW, with a 75% load factor, and occupies 2.4 x 10^5 m^2 (16.8 m^2/MW-yr, assuming a 30-yr lifetime). Using a heat rate of 10.2 x 10^6 J/kWh, a contribution to the total of 5.7 m^2-yr/10^{12} J is calculated. Cooling towers, which are stated to occupy 4 x 10^4 m^2 for a 1000-MW plant, add 0.5 m^2-yr/10^{12} J of fixed land. The

Table 2. Land Required for Fluidized Bed Combustion

Region	Land (m^2-yr/10^{12} J) AFB	Land (m^2-yr/10^{12} J) PFB
Central	16.4	16.1
North Appalachia	14.7	14.5
Northwest	11.8	11.8
National Average	14.3	14.1

annual incremental land use due to solid waste is 690 m^2 (1.4 m^2/MW-yr). Averaged over the 30-yr plant lifetime, the incremental land is 9.9 m^2-yr/10^{12} J. The sum of these contributions yields the total of 16.1 m^2-yr/10^{12} J.

Again, the Bechtel data for coal mine and transmission line land requirements are pertinent. However, further system characterization and scenario development studies will be needed if the data are to be used in comparative assessment.

4.3 LIGHT WATER REACTOR

Data concerning the land requirements of a light water reactor (LWR) come from an environmental impact statement (EIS)[10], Caputo's comparative assessment[3], Bechtel's Energy Supply Planning Model,[6,7] and Hub's comparative study.[11]

The EIS is specific to one station, the Black Fox Station in Oklahoma. Hence, some of the specific land uses mentioned for this site would not pertain to a more general description. Likewise the land area figures are more specific than other data in this assessment. However, the figures should give a reasonable idea of the land area required by any LWR plant. The site proper, including two 1220-MW generating units and cooling towers, will require 8.9 x 10^6 m^2 to be displaced from other uses for at least 30-40 years (174 m^2/MW-yr, assuming a capacity factor of 0.7). The central complex will require 1.9 x 10^6 m^2 of the site, only half of which (20 m^2/MW-yr) will be returned to its original condition. Impacts on the land that would pertain to a more general case include exposure of the subsoil to erosion during the construction phase, until revegetation occurs, and deposition of chemicals, mainly salts from the cooling towers. Along the transmission corridors, 11.5 x 10^6 m^2 (225 m^2/MW-yr) of land will be displaced from other uses during construction. Afterwards, less than 0.7 x 10^6 m^2 will be unavailable for other uses during the lifetime of the plant.

Caputo gives a figure of 150 m^2/MW-yr of land required for the plant and fuel cycle.[3] This figure would increase tremendously if depletion of high-grade uranium ore forces the mining of lower-grade ore toward the end of this century. An additional 300-1000 m^2/MW-yr of right-of-way is required for an assumed 480-1600 km of transmission lines. Caputo gives an estimate of 4 m^2/MW-yr of land required for radioactive waste storage. This figure does not include a safety zone around the storage area proper. Assuming that such land would be committed for a million years, a figure of 4 x 10^6 m^2-yr/MW-yr is derived.

Bechtel's Energy Supply Planning Model[6,7] gives the requirements of fixed and incremental land for several phases of the LWR life cycle. Their basic data are summarized in Table 3. Land requirements for transmission lines are as stated in Sec. 4.1. Again, the transmission line and fuel cycle data must await further system characterization and scenario development studies before they can be normalized for use in comparative assessment.

Hub estimates the land required for plant and fuel as 1.2 x 10^6 m^2 and 6.6 x 10^5 m^2, respectively, for 30 years of operation of a 1000-MW LWR.[11] Assuming a capacity factor of 0.7, land requirements for the plant and fuel handling are 57 and 31 m^2/MW-yr, respectively.

Table 3. Land Requirements for LWR

Facility	Fixed Land (m^2)	Incremental Land (m^2/yr)
Surface uranium mine (1200 t/day)	8×10^3	7×10^4
Underground uranium mine (500 t/day)	8×10^3	4×10^4
Uranium mill (1000 t/day)	4×10^4	4×10^4
Uranium conversion (1000 t/day)	2×10^5	--
Uranium enrichment (8750 t/yr)	1.2×10^6	--
Fuel fabrication (600 t/yr w/o Pu recycle; 150 t/yr with recycle)	2×10^5	--
Spent fuel reprocessing (1500 t/yr)	1.2×10^6	--
High-level waste disposal (3000 canisters/yr)	1.0×10^6	--
LWR plant (1100 MW)	2.6×10^6 (113 m^2/MW-yr)	--

4.4 LIQUID METAL FAST BREEDER REACTOR

A good discussion of the land requirements of the liquid metal fast breeder reactor (LMFBR) is presented in the proposed final environmental statement for the LMFBR program.[12] The plant site would require a minimum of 1.6×10^6 m^2 (76 m^2/MW-yr), including 0.14×10^6-0.20×10^6 m^2 for the plant itself (assumed to be rated at 1000 MW with a 30-yr lifetime and capacity factor of 0.7). The minimum figure assumes once-through cooling at a lake or river. Artificial cooling, if required, would add up to 8×10^6 m^2 more. Typically, about 80 km of transmission lines would be required, using 4.25×10^6 m^2 (200 m^2/MW-yr) of right-of-way. Nearly all of this site and transmission land could be restored to alternative use after plant decommissioning. The environmental statement also comments that these land requirements will not be significantly different for LMFBR, LWR, and coal plants of equivalent size.

Estimates also are given of the land required for several phases of the fuel cycle. The fuel fabrication and fuel reprocessing plants described in the statement each have a capacity of 5 t/day, adequate to serve about 80 power plants of 1000 MW each. The fuel reprocessing and fuel fabrication plants would each require about 4×10^6 m^2 (190 m^2/MW-yr) of land during the lifetime of the facility. This land could revert to other uses after decommissioning. The fuel reprocessing plant would also require 0.4×10^6 m^2 (19 m^2/MW-yr) of permanently committed land, not returnable to other uses. Land requirements for radioactive waste storage would likewise encompass both temporary and permanent commitments. Each burial ground for low-level waste would occupy about 0.4×10^6 m^2 (19 m^2/MW-yr), considered a permanent commitment of land. Facilities for storage of high-level waste, alpha waste, and noble gases would each require a site area of about 6×10^6 m^2 (285 m^2/MW-yr). The facilities themselves would occupy about 0.6×10^6 m^2 (30 m^2/MW-yr) of their sites. These 0.6×10^6-m^2 land commitments would be essentially permanent. The capacity of the waste disposal facilities is not noted in terms of the number of generation plants served by each. Hence, further investigation is needed before the data can be normalized for comparative assessment.

Bechtel's Energy Supply Planning Model[6,7] provides some data that are useful for comparison with the figures above. A fuel fabrication plant with output of 315 t/yr would require a fixed land commitment of 0.4×10^6 m^2. A fuel reprocessing plant with output of 950 t/yr would require 1.2×10^6 m^2 of fixed land. A 1000-MW LMFBR would require 2.8×10^6 m^2 (133 m^2/MW-yr) of fixed land. The duration of these land commitments is not indicated. The land requirements for some other aspects of the fuel cycle and for transmission lines are as stated earlier in Sections 4.1 and 4.3.

4.5 TERRESTRIAL SOLAR PHOTOVOLTAICS

The Solar Program Assessment for photovoltaics[13] gives estimates of the land area required for an assortment of cell types and efficiencies. For an equivalent power output, the most important variable governing land area needed for a terrestrial photovoltaic (TPV) system is the cell efficiency. An array of cadmium sulfide cells at 8% efficiency would require a land area of 11.7×10^6 m^2 to produce a 1000-MW peak output. Silicon cells at 10% efficiency would require 8.8×10^6 m^2; at 16% efficiency, 5.8×10^6 m^2. Gallium aluminum arsenide cells at 17% efficiency would require 5.4×10^6 m^2. Assuming a 30-yr plant lifetime and capacity factor of 0.3, these land requirements are 1300, 980, 660, and 600 m^2/MW-yr, respectively. These simple land area figures do not, however, state well the actual land impact. In the case of the CdS and Si cells, the shadowed areas beneath and between the arrays of cells would be suitable for multiple uses, such as buildings or grazing. Thus, the actual land disturbance could be minimal. In the case of the GaAlAs cells, however, the use of concentrators would require the use of the metallic structural frame for passive cooling. The frame temperature would reach 50-100°C, effectively precluding any other human or animal use of the land beneath the arrays. In any case, the land commitment would be only for the lifetime of the plant.

Caputo[3] also cites somes figures for photovoltaics. Assuming a silicon cell design of unknown efficiency and capacity factor, the land area required by the plant alone is 3800 m^2/MW-yr. The required length of transmission lines is 480-4800 km, requiring 300-3000 m^2/MW-yr of land. The most likely location for the plant would be in the Southwest region, where insolation is high, the cost of land is relatively low, and there are fewer uses of the land that would be difficult to displace.

4.6 TERRESTRIAL SOLAR THERMAL ELECTRIC

The Solar Program Assessment for solar thermal electric (STE) plants[14] presents six estimates of the land area required by a STE central receiver ("power tower"). The estimates range from 2.4 to 6.0 x 10^6 m^2 per 100 MW plant (2660-6650 m^2/MW-yr, assuming a 30-yr lifetime and capacity factor of 0.3). A location in the Southwest region is assumed. A larger area would be required away from the optimal location due to the reduced availability of direct radiation. The land must be flat or only slightly sloped; otherwise, clearing and grading operations would be necessary. In the assumed Southwest region, the major land uses likely to be displaced by this technology include agriculture, grazing, and recreation. Most of the prospective sites are in arid regions, used more for grazing than for agriculture. However, little economic impact is anticipated, due to the abundance of other similar land that may be used for these purposes.

Caputo[3] gives figures that may be compared with those above. For a 100-MW plant, the mirrored area is given as 1.3 x 10^6 m^2. Assuming a ground cover ratio of 30% and an annual load factor of 70%, Caputo computes a land requirement of 2000 m^2/MW-yr for the central plant. The total site area for a 100-MW plant would be 4.3 x 10^6 m^2, about in the middle of the range of estimates noted earlier. The land area required for transmission lines would be comparable to that required by solar photovoltaic plants, 300-3000 m^2/MW-yr.

4.7 OCEAN THERMAL ENERGY CONVERSION

Given the system boundaries as defined earlier (plant, fuel cycle, and transmission), excluding secondary effects, the only portion of an ocean thermal energy conversion (OTEC) system that has an impact on land use is the conventional land-based transmission system. In only one reference was an estimate given for the length of transmission lines attributable to an OTEC system. In performing a net energy analysis on OTEC[15], the authors assumed overland transmission to be by AC lines for about 480 km. By comparison with the figures noted in other sections for lines of this length, a land requirement of 300 m^2/MW-yr is assumed.

4.8 SATELLITE POWER SYSTEM

The two most important land uses of concern in a satellite power system (SPS) are areas for launching cargo and personnel from earth to low earth orbit and sites for the rectennas. To date, comparatively little attention has been paid to launch areas. Much more work has gone into the evaluation of rectenna sites.

The launch area required for SPS construction is affected by both the frequency of the launches and the design of the launch vehicles. Although the construction scenario is at best hypothetical at this early stage of analysis, it will apparently require many more frequent launches than the space program has handled so far. A larger number of simultaneously usable launch sites will thus be required. The heavy lift launch vehicle will be much larger than vehicles launched so far, hence will require a larger launch site. One source has estimated the land area required for this purpose at 20×10^6-850×10^6 m^2 depending on the vehicle design.[16] It has been assumed so far that the launch area requirement could be met by expansion of the Kennedy Space Flight Center facilities, but it may become necessary to develop an additional launch location. Resolution of these questions must await further system characterization.

The greatest requirement for land in an SPS is for rectenna sites. In the current reference concept, 60 rectenna sites are needed. Each rectenna would be in the shape of an ellipse, about 10 x 13 km.[17] The analyses in Refs. 1 and 2 are based on a 9 x 13-km ellipse. A 2-km buffer zone surrounding the rectenna proper would expand the ellipse to 13 x 17 km. Each site would require about 2×10^8 m^2 (1480 m^2/MW-yr, assuming a 30-yr lifetime and capacity factor of 0.9); the 60 sites would thus require about 1.2×10^{10} m^2 of land. Each site is sized for 5 GW of power output. Transmission facilities and access roads outside the rectenna sites would add some land area to this figure. Caputo[3] has estimated a transmission land requirement of 300-1000 m^2/MW-yr for 480-1600 km of line length; however, this characterization is very tentative. The most important determinant of this extra land area is the rectenna location. Remote locations will require longer transmission lines, hence more land area than locations nearer to load centers.

Given the land requirement for the rectennas, a major question is where such a requirement can be fulfilled. What characteristics should the land have or not have? Where is such land located? A joint effort by Blackburn and Bavinger,[2] of Rice University, and Allan D. Kotin[1] has explored these questions. Their study attempted to identify eligible areas for rectenna sites. The first step in their methodology was the identification of "exclusion variables," criteria that would definitely or potentially exclude an area of land from consideration. Data for the exclusion variables were collected and mapped for the continental U.S. By overlaying the maps for several exclusion variables, the eligible areas remaining, given that combination of variables, could be identified. The study explicitly involved only large-scale mapping. Hence, to actually qualify a rectenna site in an eligible area would require the more detailed application of local siting criteria. Refs. 1 and 2 present the exclusion criteria that were established in the initial effort and the results of several map exercises. It is hoped that further work will be possible in refining the list of exclusion criteria and the mapping of data, thus producing somewhat more certainty in the conclusions regarding eligible areas. To the extent that this work continues, it will provide valuable input to future phases of the comparative assessment.

5 CONCLUSIONS AND RECOMMENDATIONS

In order to assess the land use of an SPS in comparison to other technologies, a consistent methodology for the assessment and a complete and consistent data base for all of the technologies are needed. This paper presents a methodology for performing the assessment, investigates the availability of data, and performs a preliminary assessment of what is known on the basis of readily available data.

A summary of the land requirements for the eight technologies studied here is given in Table 4. The table is arranged as a matrix of land requirement by technology and purpose of use, identifying also the duration and location of use where known. For most technologies and purposes, explicit data on the duration and location of land use are missing in this preliminary assessment. In some cases these deficiencies may be remedied by reasonable assumptions that would not be explicitly cited in the documents studied. For example, one may often assume a plant lifetime of 30-40 years. In some studies, such an assumption was explicitly stated, and is so represented in Table 4. Other data deficiencies, categorized by purpose of use, include:

- <u>Construction</u> - for most technologies;
- <u>Fuel</u> - for LWR;
- <u>Waste Disposal</u> - for CG/CC and LMFBR;
- <u>Transmission</u> - for SPS.

Some of these deficiencies may be remedied by extrapolation from other data. For example, land for construction is probably approximately the sum of plant and transmission requirements. For transmission lines, the land required during construction can probably be correlated with the length and voltage of the lines. Further system characterization studies should thus help to remedy these deficiencies.

Similar studies should also help to fill in many of the indicated location deficiencies, for the problem is not that it is not known where the facilities could be built, but in choosing suitably characteristic locations to enable a fair comparative assessment to be done.

For this study, no attempt was made to prorate such facilities as fuel processing and waste disposal where such allocation was not made in the literature. Thus, for some of the indicated deficiencies for the coal and nuclear technologies, information is available, but some work is still required to convert it to a comparative form.

Another problem with the available data is the disparity in the way units of measure are normalized by plant size. As seen in the previous discussions, the surveyed literature presented land requirements in various units, for example, m^2/MW, m^2/MW-yr, and m^2-yr/10^{12} J. Mutually consistent units could be calculated from the published data if such numbers as plant lifetime, capacity factor, and fuel heat rate were known. Often, though, there is no explicit statement of these values. Thus, it is not possible to get behind the published final numbers to the basic numbers used, or to compute different units of measure with certainty. Some normalization has

Table 4. Summary of Land Requirements

Purpose	Construction	Plant	Fuel	Disposal	Transmission
CG/CC					
Quantity	--[a]	7.2-150 m^2/MW-yr	1800-4520 m^2/MW-yr	5 m^2/MW-yr	300 m^2/MW-yr (480 km)[b]
Duration	--[c]	30 yr	30 yr	--[c]	30 yr
Location	--[c]	--[c]	--[c]	--[c]	--[c]
FBC					
Quantity	--[a]	5.2-16.8 m^2/MW-yr	--[c]	1.4 m^2/MW-yr	300 m^2/MW-yr (assume same as combined cycle)
Duration	--[c]	30 yr	--[c]	--[c]	30 yr
Location	--[c]	--[c]	--[c]	--[c]	--[c]
LWR					
Quantity	--[a]	57-174 m^2/MW-yr	31 m^2/MW-yr	4m^2/MW-yr	225-1000 m^2/MW-yr (480-1600 km)[b]
Duration	--[c]	30-40 yrs (20 m^2/MW-yr "permanent")	30 yr	10^6 years	30-40 yrs
Location	--[c]	--[c]	--[c]	--[c]	--[c]
LMFBR					
Quantity	--[a]	76-133 m^2/MW-yr	5 m^2/MW-yr (plant lifetime) and .25 m^2/MW-yr (permanent)	--[c]	200 m^2/MW-yr (80 km)[b]
Duration	--[c]	30 yr	--[c]	--[c]	30 yr
Location	--[c]	--[c]	--[c]	--[c]	--[c]
TPV					
Quantity	--[a]	600-3800 m^2/MW-yr (depending on cell efficiency and capacity factor)	negl[d]	negl[d]	300-3000 m^2/MW-yr (480-4800 km)[b]
Duration	--[c]	30 yr	NA[e]	NA[e]	30 yr
Location	--[c]	Southwest	NA	NA	--[c]
STE					
Quantity	--[a]	2260-6650 m^2/MW-yr	negl[d]	negl[d]	300-3000 m^2/MW-yr 480-4800 km)[b]
Duration	--[c]	30 yr	NA	NA	30 yr
Location	--[c]	Southwest	NA	NA	--[c]
OTEC					
Quantity	--[a]	negl	negl[d]	negl[d]	300 m^2/MW-yr (480 km)[b]
Duration	--[c]	NA[e]	NA[e]	NA[e]	30 yr
Location	--[c]	NA[e]	NA	NA	--[c]
SPS					
Quantity	20-850 km^2 (launch)	1480 m^2/MW-yr (rectenna)[f]	negl[d]	negl[d]	300-1000 m^2/MW-yr (480-1600 km)[b]
Duration	30 yr	30 yr	NA[e]	NA[e]	30 yr
Location	Florida?	--[c]	NA	NA	--[c]

[a]Approximately the sum of plant and transmission requirements.

[b]Distance to load center.

[c]Data lacking; some categories are discussed in text.

[d]Negligible.

[e]NA - Not applicable.

[f]Includes buffer zone; rectenna proper occupies about 50% of total.

been done in Table 4 by assuming values for plant lifetimes and capacity factors. These assumptions should not, however, be taken as conclusive determinations.

Some preliminary comparisons of the technologies may be made from the data in Table 4. The solar technologies require much more land area for their central plants (for the rectennas in the case of an SPS) than do the coal or nuclear technologies. The smallest plant area is required by the coal options. However, unlike the solar options, the coal and nuclear options require substantial amounts of land for fuel mining, fuel processing, and waste disposal. The land required for transmission depends strongly on the assumed line length, hence on the assumed location of the plant relative to load centers. Lacking more detailed system characterizations, the preliminary data indicate that the transmission requirements could be roughly comparable for all technologies.

Though the quantities in Table 4 are normalized to the same units (m^2/MW-yr), it would be misleading to use the sum of each row for comparison as a "total" land requirement. For example, land for construction largely duplicates land for the plant and transmission lines, hence should not be added. For another example, the land required for nuclear waste disposal is of much greater importance than its small numerical value (4 m^2/MW-yr) would signify, because of the extremely long duration of use of this land. More meaningful quantitative comparisons will be possible after further studies based on scenarios.

Further, not just the quantity and duration of land use, but also its geometry and location, are important in comparative assessment. For example, a quantity of land required for an SPS rectenna differs in importance from the same quantity distributed along the length of a transmission line.

For the final comparative assessment of land use, it is recommended that the major effort be devoted to consistent system characterization to fill in the land-use matrix for the technologies to be included. Such a set of consistent numbers is a prerequisite for a fair comparison of impacts. Specific attention should be given to:

- Consistency in the units of measure;
- Explicit statement of the assumptions used in arriving at normalized figures;
- Breaking down the land requirements by purpose of use; and
- Filling in the areas of greatest data deficiency.

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