The Life Cycle CO_2 Emission Performance of the DOE/NASA Solar Power Satellite System: A Comparison of Alternative Power Generation Systems in Japan

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***Abstract*—Solar power generation and, in particular, space solar power generation seem to be one of the most promising electric power generation technologies for reducing emissions of global warming gases (denoted collectively as CO_2 emissions below). Calculating the precise amount of net reduction in CO_2 emissions of a solar power system over other alternative power systems requires careful life cycle considerations. For example, emissions from a space solar system must include the emissions from consuming rocket fuel during the launching the satellites, and the emissions from the energy consumed while producing the solar panels. In this paper, we calculate the CO_2 emissions observed through the life cycle of a solar power satellite (SPS). This life cycle consists of the production of rocket fuel and solar panels and the construction of a Rectenna (power receiving antenna), satellite, and all other equipment listed in the Department of Energy/NASA reference system. The calculation also includes indirect CO_2 emissions that occur in various stages of production of these materials. Our baseline scenario shows that the life cycle CO_2 emissions for an SPS system per unit of energy generated are almost the same as the emissions for nuclear power systems and are much less than the life cycle emissions for LNG-fired and coal-fired power generation systems. Furthermore, our SPS-Breeder scenario, in which SPSs supply electricity for producing further SPS systems, shows significantly lower CO_2 emissions. As electrical power generation constitutes one fourth of Japan's total CO_2 emissions, reducing emissions from electric power generation is one of the most important issues on Japan's policy agenda for dealing with global warming. Our findings suggest that the SPS is the most effective alternative power generation technology.**

***Index Terms*—Alternative technology, CO_2 emissions, Department of Energy (DOE)/NASA reference system, life cycle assessment (LCA), power generation, solar power satellite (SPS).**

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I. Introduction

In recent years, global warming caused by the greenhouse effect has raised serious policy questions as to what should be done to reduce emissions of global warming gases. Global warming gases (denoted collectively as CO_2 emissions below) are generated when fossil fuels are burnt by consumers and by industry in the intermediate stages of production of goods and services.[1] In particular, CO_2 is generated by electric power generation, industrial production activities, use of automobiles, construction and other human activities. In most countries the economic activity that emits the largest amount of CO_2 is electric power generation. For example, electricity generation accounts for about 25% of Japan's 1.2 billion tons of annual CO_2 emissions. As life cycle assessment (LCA) analyses of CO_2 emissions show [1], [2], many production activities that directly release only small amounts of CO_2 nonetheless use large amounts of electricity. For example, driving electric vehicles does not release CO_2, but they depend on batteries which must be charged. If electricity is generated mainly from coal burning, driving electric cars will indirectly emit large amounts of CO_2. Developing an electric power generation system that uses little fossil fuels and emits small quantities of CO_2 is, therefore, of urgent importance.[2]

In this paper, we estimate the life cycle CO_2 emission performance of a solar power satellite (SPS) system, one possible source of Japan's electric power in the future. These satellites must of course be launched using rockets, and production of their photo-voltaic panels also uses large quantities of energy. In addition,building a rectenna, a microwave power receiving and rectifying antenna on Earth, requires large amounts of cement

[1] We use CO_2 equivalents to measure emissions of global warming gases in this paper. Emissions of global warming gases will be denoted collectively as CO_2 emissions.

[2] One way to encourage energy efficiency and effective use of less polluting equipment globally is to trade emission rights, as is proposed in the Kyoto protocol (e.g., [3]). The Kyoto protocol, of which the U.S. is not a participating member, is expected to become a treaty for most developing and developed countries in the world. It will require developed countries to keep their CO_2 emission levels to the levels below those for 1990. For example, within the Kyoto framework, both Canada and Japan must bring down their CO_2 emission levels over the period of 2008–2012 to levels that are 6% below their 1990 levels. Unlike some other waterborn and airborn pollutants, however, global warming gases cause no immediate health hazard to humans. They are, therefore, not yet receiving much attention as far as implementation of mechanisms to reduce the total amounts of such gases emitted globally is concerned.

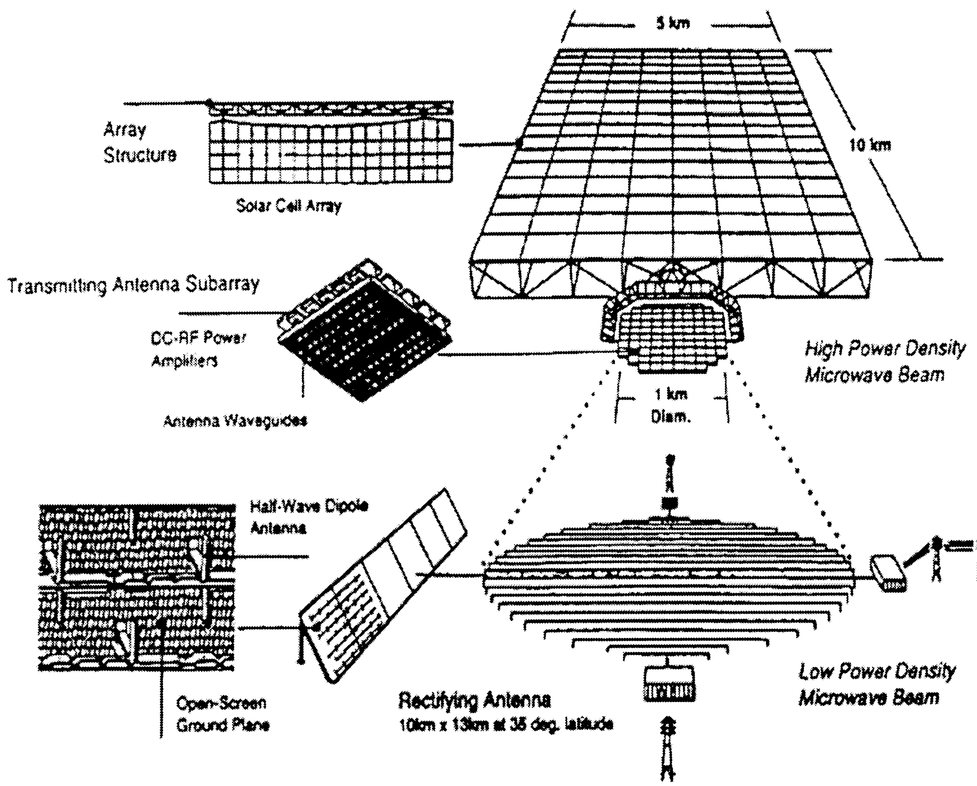

Fig. 1. SPS concept.

and steel. The production of both cement and steel emits large amounts of CO2. The objective of our analysis is to compare the CO_2 emission performance of SPSs with that of liquefied natural gas (LNG) and nuclear power generators. In this paper, we analyze the original "SPS Reference System" published by the U.S. Department of Energy (DOE) and NASA in 1978 [4]. Our analysis of a more recent NASA Reference system [5], [6], which uses a new SPS design and new methods of launching them into space is also under way.

The organization of the rest of this paper is as follows. In the next section (Section II), we describe the DOE/NASA Reference SPS System. In Section III, we briefly describe our input-output (I-O) analysis to estimate the life cycle CO_2 emissions of an electric power generating system. In Section IV, we present our estimation results for the life cycle CO_2 emission performance of various electric power generating systems, including SPSs for Japan. In Section V, we present some simulation results comparing alternative scenarios for implementing SPSs. We conclude in Section VI.

II. Concept of SPS

Solar electricity generation using photo-voltaic cells emits no undesirable gases such as CO_2, NOx, or SOx and is, therefore, more environmentally attractive than other power generating systems that rely on burning fossil fuels. Photo-voltaic cells cause no radiation as nuclear power generators do. Because solar electricity generation is impossible at night and relatively inefficient during cloudy weather, securing a stable supply of electric power from solar electricity generation is often thought to be difficult. However, if solar panels are launched into space, they can produce power continuously, regardless of the weather and the day-and-night cycle. The SPS concept involves a satellite that carries photo-voltaic panels in a geo-stationary orbit (GEO) to generate electric power and transmit this power back to the Earth surface.

The concept of SPS was first published by [7]. The U.S. DOE and NASA published their Reference System in 1978, referred to here as the DOE/NASA Reference System [4]. Although the Reference System was published more than 20 years ago, since no other comparable and equally detailed system has been proposed since then, it remains to be the representative plan of a future SPS system. In this paper, we investigate the CO_2 emission performance of the DOE/NASA SPS Reference System.[3]

The SPS concept is illustrated in Fig. 1. The main assumptions of the SPS system and the components of the SPS system are shown in Tables I and II, respectively. The satellite is shown in the upper part of Fig. 1. It has a rectangular structure 10-km long, 5-km wide, and 300-m deep. It carries photo-voltaic panels over its surface and transmits the power generated using high frequency microwaves from the 1-km diameter antenna shown at the front edge of the satellite in Fig. 1. The lower half of Fig. 1 shows the rectenna on the earth which receives and rectifies the microwave beam from the satellite. The rectenna is elliptical and 13×10-km wide. The DOE/NASA Reference System consists of 60 satellite-rectenna pairs, each with an output of 5 GW. These can generate an annual electricity output of 2628 billion kWh.

III. Estimating the Life Cycle CO_2 Emissions of the SPS

CO_2 emissions from constructing and operating an SPS system for Japan can be calculated using the Extended

[3]See, for example, [8]–[12].

TABLE I
BASIC ASSUMPTIONS UNDERLYING THE DOE/NASA REFERENCE SPS SYSTEM

Power output per satellite	5	GW
Number of satellites	60	units
Number of hours of power supply/day	24	hours
Number of days of power supply/year	365	days
Total energy supplied/year	2,628,000	GWh

TABLE II
COMPONENTS OF THE SPS SYSTEM

Space Transportation
1. Heavy Lift Launch Vehicle (HLLV)
2. Personnel Launch Vehicle (PLV)
3. Cargo Orbital Transfer Vehicle (COTV)
4. Personnel Orbital Transfer Vehicle (POTV)
Space Bases
5. Low Earth Orbit Base (LEO Base)
6. Geostationary Orbit Construction Base (GEO Construction Base)
Solar Power Satellite
7. Satellite
8. Photo-voltaic Cells
Other Components
9. Rectenna (Microwave Power Receiving and Rectifying Antenna)
10. Propellants

Input-Output Tables for environmental analyses, developed by the Research Group for Environmental Issues of the Keio Economic Observatory [13]. Using standard input-output analysis, various commodities directly and indirectly required by a given (1×405) final demand vector f is given by

$$(\mathrm{I}-\mathrm{A})^{-1} f \tag{1}$$

where $(\mathrm{I}-\mathrm{A})^{-1}$ is a 405×405 Leontief inverse matrix. The ith component of f represents the amount of output from the ith sector that is required by the final demand. Using the 405×405 CO_2 emission coefficients matrix C [13], CO_2 emissions observed for 405 sectors and generated by all the production activities required to produce a given final demand f is

$$CO_2 = C(I-A)^{-1} f. \tag{2}$$

In (2), the ith component of the (1×405) vector CO_2 represents the amount of carbon dioxide emitted from the ith sector of the economy during the production activities associated with production of the final demand vector f.

We apply formula (2) to each component of the SPS construction project shown in Table II as follows:

$$CO_2^k = C(I-A)^{-1} f^k, \quad k = 1, 2, \ldots, 10 \tag{3}$$

where

k one of the ten components of an SPS system given in Table II;

CO_2^k 1×405 CO_2 emission vector of the kth SPS component (in production process);

C CO_2 emission coefficient (a 405×405 diagonal matrix);[4]

I (405×405) Identity matrix;

A 405×405 input-output coefficients matrix with 405 sectors;

f^k 1×405 final demand vector of the kth SPS component.

The final demand vector f^k contains, for example, the amount (in monetary terms) of rocket fuel required to produce the kth SPS component. CO_2^k given by (3) provides the direct CO_2 emissions generated by burning the rocket fuel itself as well as the indirect CO_2 emissions generated during all production activities needed to produce the rocket fuel. I-O analysis allows us to calculate, step by step, the indirect CO_2 emissions associated with the production of commodities included in the final demand vector f^k. This step by step process can be seen by writing (3) as follows:

$$CO_2^k = Cf^k + Cx^{k,1} + Cx^{k,2} \cdots \tag{4}$$

or

$$\begin{aligned} CO_2^k &= Cf^k + CAf^k + CA^2 f^k + CA^3 f^k + \cdots \\ &= C(I + A + A^2 + A^3 + \cdots) f^k \\ &= C(I-A)^{-1} f^k. \end{aligned} \tag{5}$$

Cf^k is the direct effect, $Cx^{k,1}$ the first indirect effect, $Cx^{k,2}$ the second indirect effect, $Cx^{k,3}$ the third indirect effect, and so on. Repeating this calculation, the direct and indirect effects converge to $C(I-A)^{-1} f^k$ (it is known, e.g., [14], that the I-O matrix A satisfies the convergence condition).

We first calculated the quantities of all the materials used in the kth component given in [4], [15]. These materials were then re-classified into the 405 sectors of economic activities ac-

[4]Estimation of each element of this matrix requires estimates of the carbon content for all types of energy (fossil fuels) used in each of the intermediate production processes and final consumption. Details are given in [13]

TABLE III
CO_2 RELEASED BY A DOE/NASA SPS REFERENCE SYSTEM CONSISTING OF 60 SPS UNITS (IN 10 000 TONS OF CO_2)

Space Transportation		
1.	HLLV	412
2.	PLV	12
3.	COTV	9,576
4.	POTV	4
Space Bases		
5.	LEO Base	5
6.	GEO Construction Base	19
Solar Power Satellite		
7.	Satellite Structure	1,424
8.	Photo-voltaic Cells	90,393
Other Components		
9.	Rectenna	38,688
10.	Propellants	17,473
	Total	158,007

TABLE IV
CO_2 EMISSIONS FROM AN SPS SYSTEM WITH 18 SATELLITES TO SUPPLY JAPAN'S POWER NEEDS (IN 10 000 TONS)

Space Transportation			Solar Power Satellite		
1.	HLLV	124	7.	Satellite Structure	427
2.	PLV	4	8.	Photo-voltaic Cells	27,118
3.	COTV	2,873	Other Components		
4.	POTV	1	9.	Rectenna	11,606
Space Bases			10.	Propellants	5,242
5.	LEO Base	3			
6.	GEO Construction Base	9	Total		47,407

TABLE V
THREE SPS COMPONENT SECTORS WITH THE LARGEST CO_2 EMISSIONS

	(1) HLLV	t- CO_2	(2) PLV	t- CO_2	(3) COTV	t- CO_2
1st	Electric power	1,184	Electric power	267	Electric power	171
2nd	Aluminum	875	Aluminum	197	Self-Power generation	81
3rd	Self-Power generation	863	Self-Power generation	195	Road freight transport	65
Total		5,498		1,239		732
	(4) POTV	t- CO_2	(5) LEO Base	t- CO_2	(6) GEO Construction Base	t- CO_2
1st	Aluminum	150	Aluminum	2,662	Aluminum	8,720
2nd	Electric power	97	Electric power	2,214	Electric power	7,712
3rd	Self-Power generation	96	Self-Power generation	1,878	Self-Power generation	6,337
Total		521		10,790		37,332
	(7) Satellite structure	t- CO_2	(8) Photo-voltaic cells	1000t - CO_2	(9) Rectenna	1000t - CO_2
1st	Electric power	21,188	Electric power	7,540	Electric power	1,823
2nd	Self-Power generation	11,798	Sheet glass and safety glass	1,634	Pig iron	875
3rd	Pig iron	6,992	Self-Power generation	920	Coal products	584
Total		94,942		14,232		6,448
	(10) Propellants	1000t - CO_2				
1st	Electric power	73,100				
2nd	Self-Power generation	180				
3rd	Coal products	150				
Total		80,430				

Notes: figures presented for component sectors (1) - (9) represent CO_2 emissions per SPS unit; figures for component sector (10) represent CO_2 emissions produced by the fuels for the rockets and other space transport vehicles required for the construction and maintenance of 60 SPS units; the definitions of HLLV, PLV, COTV, POTV, LEO and GEO are given in Table 2; and the aluminum sector includes regenerated aluminum.

cording to the Japanese I-O classification system. The quantities of the materials required for the production of the kth component were then converted into monetary units by using the unit price 10-digit code table of Input-Output tables.[5]

The materials that were given no unit prices in the I-O tables were assigned prices given in Japanese trade statistics. The material inputs in f^k above were first evaluated in terms of their producer prices. However, some materials should be evaluated in terms of purchasers' prices. The reference prices used for calculating certain raw material inputs in the final demand vector are converted by adding the trade margins and domestic transport margins given in the I-O table to producers' prices (Appendix 1).

IV. EVALUATING LIFE CYCLE CO_2 EMISSION PERFORMANCE

In this section, we present our main estimation results for the overall CO_2 emissions from the construction and operation of an SPS system. The total life cycle CO_2 emissions associated with an SPS system is estimated to be about 1.58 billion tons, which is about 25% more than the 1.2 billion tons of CO_2 released by Japan in 1990 (Table III). We note that CO_2 emissions from launching SPSs by rockets are relatively low. 60% of the total CO_2 emissions is fromproducting photo-voltaic panels, and 30% from production of a rectenna. CO_2 emissions from maintenance of the equipment are not included in our calculations above, because these data are not available. We estimate that if the maintenance ratio of satellites and rectennas is 1% per year, then overall CO_2 emissions would increase by about 30%.

Suppose Japan's electric power were to be entirely supplied by SPSs. As shown in Table I, 60 SPS units would have an annual output of 2,628 billion kWh, or about 3.5 times the electricity produced in Japan in 1995. We see that only 18 such SPSs would be needed to supply Japan's electric power needs in 1995. If Japan's electricity were to be supplied by 18 SPS units, then the required number of rectennas would also be reduced proportionately. The number of LEO and GEO bases needed would be halved to one each, and the associated CO_2 emissions would be reduced to $(18/60)$ times the quantities reported in Table III. These new results are shown in Table IV. The total CO_2 emissions under this scenario would be 470 million tons.

The economic sectors that emit large amounts of CO_2 over the life cycle of their products are electric power, sheet glass and safety glass, self-power generation, and other electricity-consuming sectors. In particular, the electric power and self-power generation sectors together produce about half of the total CO_2 emissions. The production of the SPS itself requires many raw materials and components and, hence, will likely result in large amounts of CO_2 emissions.[6] Table V shows the three SPS component sectors with the largest CO_2 emissions. Even though the production of each SPS component requires different kinds of materials and components, most CO_2 emissions generated are due to electric power used somewhere in the production of these components.

[5]The 10-digit code table includes producer prices of 5000 commodities. See [16]–[18] which report on initial exploratory research of input-output data availability regarding the SPS system.

[6]Complete results are available on request from the authors.

TABLE VI
PRODUCTION OF A DOE/NASA SPS REFERENCE SYSTEM WITH 60 SPS UNITS: 50 LARGEST CO_2 EMISSIONS ECONOMIC SECTORS (100 000 TONS)

Direct CO_2 emissions		Combined direct and indirect CO_2 emissions	
electric power	4549.5	electric power	6900.8
sheet / safety glass	902.6	flat / safety glass	1085.7
LNG combustion	622.1	self power generation	960.0
silica production	399.0	coal products	670.7
hydrogen production	316.4	LNG combustion	622.1
ground freight transport	152.6	iron	622.0
other inorganic products	114.9	silica production	399.0
grinding materials		aluminum	336.5
hot rolled steel		hydrogen (production)	316.4
cast aluminum products	83.8	ground transport	269.7
semiconductor / IC	70.1	petroleum products	225.0
fat / oil intermediate goods	56.5	freighter car transport	188.7
coastal sea transport	44.7	other pottery products	179.5
other glass products	39.8	other inorganic products	160.9
ring compounds	30.3	soda industrial products	156.8
aluminum	29.4	passenger car transport	143.6
plastic products	23.1	fat / oil intermediate goods	130.5
synthetic rubber	22.5	coastal sea transport	127.0
wholesale trade	20.9	basic petrochemical materials	121.4
industrial soda products	12.3	cement	115.0
air transport	11.5	grinding materials	113.2
other metal products	11.4	hot rolled steel	111.6
other non-ferrous metals	11.0	other non-ferrous metals	110.1
carbon / black lead products	10.4	raw steel (rolling mills)	107.1
passenger car transport	9.5	cast aluminum products	88.2
sulfuric acid	9.4	regular / Japanese paper	87.8
freighter car transport	7.2	elastic materials (hot elastic)	79.7
copper	7.1	semiconductor / IC	72.3
cast iron products	6.6	ring compounds	71.3
pottery (china)	5.0	ferro-alloys	71.3
oxygen production	5.0	unclassified materials	68.0
compressed gas and liquefied gas production	3.6	air transport	61.8
unclassified materials	2.7	raw steel (electric furnace)	55.5
electrical circuit breaker	2.6	corporate R&D	54.7
insulation	2.5	other glass products	51.9
natural gas	2.5	industrial waste processing	46.8
self power generation	2.3	petropolycyclic aromatic hydrocarbon products	39.5
other special industrial machinery	2.2	plastic products	38.8
industrial waste processing	2.2	synthetic rubber	38.4
electrical wires / cables	2.0	wholesale trade	38.2
other pottery products	1.7	salt	25.5
retail trade	1.7	sheet paper	23.4
bay water transport	1.4	carbon / black lead products	22.4
building construction (non-wood)	1.3	cold rolled steel	22.2
fresh concrete	1.2	limo / taxi transport	21.2
other metals for pottery	1.1	cast iron products	21.0
other ground transport	0.9	oil	20.2
metals for construction products	0.9	pulp	19.0
cold rolled steel	0.8	other synthetic materials	18.8
Tab(tap?) water	0.8	copper	18.1
all other (combined)	9.0	all other (combined)	451.5
TOTAL (direct CO_2 emissions)	7820.3	TOTAL (direct and indirect CO_2 emissions)	15800.7

Notes: the CO_2 emissions given in the second and fourth columns represent, respectively, direct CO_2 emissions given by the first term, Cf, in (4) and combined direct and indirect CO_2 emissions given by (5), where the final demand vector f contains the amounts (in monetary terms) of all 405 goods and services required in all ten SPS system components for the production and maintenance of 60 SPS units over their life cycle; CO_2 emissions generated during the production of domestic and imported raw materials are included in our calculations. However, CO_2 emissions generated by transport vehicles (e.g. ships, airplanes) to transport the imported materials are not included; the economic sectors listed in the first column produce the 50 largest direct CO_2 emissions; and the economic sectors listed in the third column produce the 50 largest combined direct and indirect CO_2 emissions.

In order to evaluate the CO_2 emission performance of the overall SPS system, we need to calculate the aggregate CO_2 emissions from all SPS system components. Table VI shows the 50 economic sectors that produce the largest direct and combined direct and indirect CO_2 emissions, in columns two and four, respectively. The figures in column four represent the total CO_2 emissions generated by the ten SPS system components. As expected, the electric power needed for the production and maintenance of 60 SPS units generates by far the largest amount of CO_2 emissions.

Last, we compare the CO_2 emissions of the SPS system with those of otherelectric power generation systems. Assuming a lifetime of 30 years for the SPS Reference System, annual CO_2 emissions are calculated to be $(1580/30) = 52.67$ million tons/year. The SPS system produces 2,628 billion kWh/year, and CO_2 output per kWh is estimated as

$$52\,670\ (\text{billion g/year})/2,628\ (\text{billion kWh/year}) = 20\ \text{g/year}.$$

Table VII compares the CO_2 emissions per kWh of electrical energy produced by the SPS system with emissions from fossil fuel and nuclear power generation methods.[7]

We see from Table VII that the SPS Reference System would release slightly less CO_2/kWh than nuclear power generation. CO_2 emissions from operating fossil fuel-based electric power generation systems come mainly from burning the fuel itself. CO_2 emissions associated with nuclear plants mostly come from the use of energy to produce nuclear fuel. Possible CO_2 emissions associated with distributing SPS-generated electricity is not included in our SPS figures due to the lack of data. CO_2 emissions associated with distributing electricity is, however, included in our emission figures for the other systems. It is, therefore, important to allow for this difference in using our results reported in Table VII for comparison purposes.[8]

[7]In Table VI, the SPS Reference system being discussed here is labeled "baseline scenario." Another type of SPS system labeled "breeder scenario" is discussed in the next section.

[8]In our kind of policy analysis, the LCA approach is essential in evaluating alternatives. In general, LCA deals with the impact of extended systems (e.g., sequence of industrial operations) on the environment, applied to industrial strategy and product design. The ISO 14040 series of standards provide a set of reusable procedures that can be used in evaluating the impacts of alternative projects within an LCA framework (e.g., [19]). They are: ISO 14 040 on goal and scope (introduced in 1997), ISO 14 041 on life cycle inventory analysis (1998), ISO 14 042 on life cycle impact assessment (2000), and ISO 14 043 on life cycle interpretation (2000). Although our analysis in this paper would allow us to conduct each of these ISO steps, we have chosen not to do so because of space limitations. In general, the ISO LCA standards emphasize the importance of delineating the boundaries of the system under study and also the extent (or the depth) to which upstream activities are included in the analysis. At the firm level, decision criteria are usually clear-cut (e.g., profit maximization, share value maximization) and the boundary for LCA conducted by the firm is often naturally determined by the boundary of the firm operations. The LCA of the SPS system, however, requires considerations at the national level, and, if implemented, will most likely require analysis at the international level. In this paper, we limit our LCA analysis to the economic domain described by the 405 economic sectors of the Japanese I-O classification system. This includes imported materials, services, and products, and we accounted for the CO_2 emissions associated with the production of these goods and services overseas. Nevertheless, our coverage of analysis is not complete. For example, neither CO_2 emissions generated by overseas transport carriers nor by foreign R&D efforts on SPS systems is included, even though their services are used in the present SPS system. Within the economic domain we consider, choosing appropriate depth of coverage of upstream activities is important. For most practical purposes, 405 economic sectors are detailed enough for capturing most CO_2 emissions generated by most types of economic activities. The items listed in Table VI are some of the 405 economic sectors being used in this study.

TABLE VII
CO_2 EMISSIONS FROM ALTERNATIVE ELECTRIC POWER GENERATING SYSTEMS (G CO_2/kWh)

Generating system	Operations	Construction	Total
SPS (baseline scenario)	0	20	20
SPS (breeder scenario)	0	11	11
Coal[b]	1,222	3	1,225
Oil[b]	844	2	846
Liquefied Natural Gas (LNG) [b]	629	2	631
Nuclear power[b]	19	3	22

Notes: the SPS-breeder scenario is discussed in Section V; and estimates for these power generation methods are given in [13].

V. Simulating CO_2 Emissions During the Construction of an SPS

In the preceding section, we calculated the CO_2 load for SPS power using the DOE/NASA Reference System design. We concluded that although constructing an SPS system induces large amounts of CO_2 emissions, the CO_2 emission per unit of kWh is much less for SPS generated power than for alternative electric energy generation systems. One assumption we have made in these calculations of CO_2 emissions for an SPS system is that 60 SPS units (or 18 SPS units) are constructed at a time. We did not, therefore, take into account the time span of the construction project and the electricity needed for established SPS plants.

In this section, we will consider an SPS-Breeder scenario in which installed SPS units supply electricity to produce additional SPS units. In contrast to this scenario, we call the case presented in the preceding section a Baseline scenario. We compute the CO_2 load under the SPS-Breeder scenario as follows.

The concept of the SPS-Breeder is shown in Fig. 2, and the assumptions for the SPS-Breeder scenario are as follows (see Appendix 2 for the calculation methodology).

1) A pair of SPS and rectenna is to be built in time period 1. A total of 18 pairs will be built. Output from these pairs will equal the total Japanese electricity supply in 1995.
2) Space transportation systems, space construction bases, and one SPS-rectenna pair will also be built in the first time period.
3) Constructing SPS components in period 1 will use power from the existing electricity generation systems.
4) In the tth period, all t-1 SPS units will be already operating $(\mathrm{t} = 2, 3, \ldots, \mathrm{N}; \mathrm{N} = 18)$.
5) Construction of the SPS unit to be built in period t will utilize electricity generated by the SPS unit built in period (t-1) and utilizes electricity from other existing electricity supply facilities only if the SPS electricity supply from the (t-1)st period SPS is insufficient.

The left panel of Table VIII summarizes the CO_2 load calculated from the SPS-Breeder scenario. In period 1, an SPS system begins to be constructed and there is no power supply from SPS sources. All the space transportation systems, space bases, and the first SPS-rectenna pair are to be, therefore, built using power supply from existing power supply facilities (276.9 hundred million kWh). In period 2, a second SPS system is to be built using electricity from the first SPS unit and, if necessary, from existing

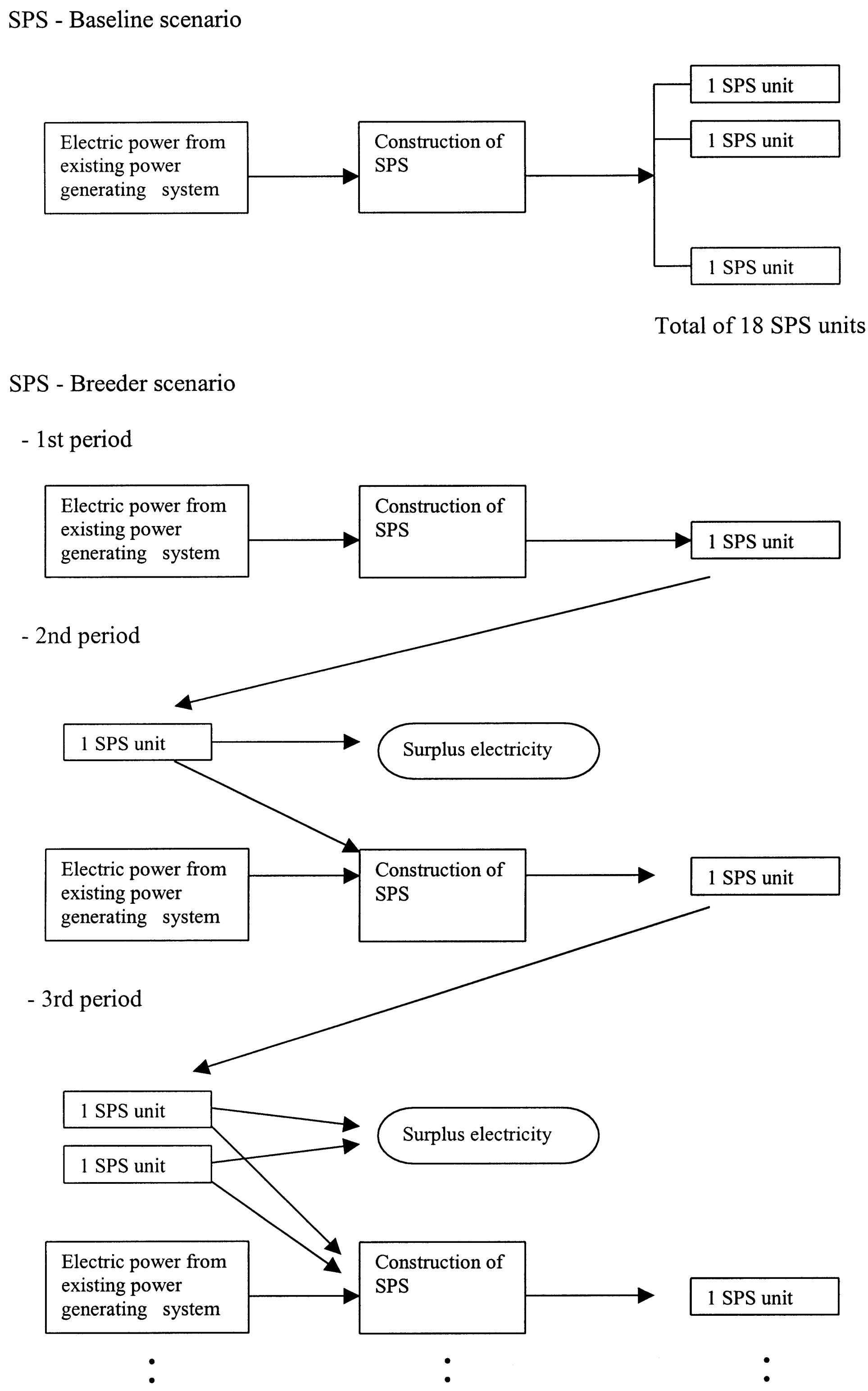

Fig. 2. SPS-breeder scenario.

electricity facilities. Our simulation results show, however, that construction of a second SPS system does not need electricity from the existing power supply facilities (other than the SPS system built in period 1). Similarly, construction of subsequent SPS systems from period 3 on will not need electricity from the existing generation facilities.

We show in Table VIII the surplus SPS generated electricity net of the electricity used for the construction of SPS units and imputed CO_2 emissions for SPS systems. We have surplus electricity starting from period 2 (see third column from the right in Table VIII). Figures in column (d) of Table VIII are potential CO_2 emissions due to the surplus electricity that becomes

TABLE VIII
CO_2 EMISSIONS: SPS-BREEDER SCENARIO

	SPS construction				Electricity Supply from SPS				
	Electricity supply (100GWh) for the SPS constriction								
	SPS (a)	Conventional Power Station	Total	CO_2 emission (10,000 tons) (b)	Number	Electricity (100GWh) (c)	Net Power Generation (100GWh) (c)-(a)	CO_2 equivalent of the Net Power Generation (million tons) (d)	(million tons) (b)-(d)
1st	0.0	276.9	276.9	3,201	0	0	0	0	32
2nd	246.8	0.0	246.8	1,388	1	438	191	10	4
3rd	246.8	0.0	246.8	1,388	2	876	629	30	-16
4th	246.8	0.0	246.8	1,388	3	1,314	1,067	50	-36
5th	246.8	0.0	246.8	1,388	4	1,752	1,505	70	-56
6th	246.8	0.0	246.8	1,388	5	2,190	1,943	90	-76
7th	246.8	0.0	246.8	1,388	6	2,628	2,381	110	-96
8th	246.8	0.0	246.8	1,388	7	3,066	2,819	140	-126
9th	246.8	0.0	246.8	1,388	8	3,504	3,257	160	-146
10th	246.8	0.0	246.8	1,388	9	3,942	3,695	180	-166
11th	246.8	0.0	246.8	1,388	10	4,380	4,133	200	-186
12th	246.8	0.0	246.8	1,388	11	4,818	4,571	220	-206
13th	246.8	0.0	246.8	1,388	12	5,256	5,009	240	-226
14th	246.8	0.0	246.8	1,388	13	5,694	5,447	260	-246
15th	246.8	0.0	246.8	1,388	14	6,132	5,885	280	-266
16th	246.8	0.0	246.8	1,388	15	6,570	6,323	300	-286
17th	246.8	0.0	246.8	1,388	16	7,008	6,761	320	-306
18th	246.8	0.0	246.8	1,388	17	7,446	7,199	350	-336
19th	-	-	-	-	18	7,884	-	-	
Total	4,195.6	276.9	4,472.5	26,797			62,818	3,020	-2,752

available (evaluated per unit of CO_2 emissions generated by existing electric generation systems). For example, 30.2 hundred million tons of CO_2 would be released if the same amount of electricity were produced by existing electricity supply facilities. Since the SPS system produces very little CO_2 while operating, its net CO_2 emission [given by (b)–(d)] is estimated to be negative (-2.8 billion tons).

We now compare CO_2 emissions under the SPS-Breeder and baseline scenarios, and assume the same lifetime for both scenarios. Under the SPS-Breeder scenario, annual CO_2 emission becomes $(268/30) = 8.9$ million tons/year. 18 SPS units produce a total of 788 billion kWh and CO_2 emissions per kWh are estimated to be

$$89, 32(\text{billion g/year})/788(\text{billion kWh}) = 11 \text{ g/kWh}.$$

This is presented in Table VII under the "breeder scenario."

We have shown that CO_2 emissions per kWh under the baseline scenario are lower than those for other electricity generation systems. We show in Table VII that an SPS-Breeder system performs much better than the baseline system, with CO_2 emissions of only 11 g per kWh, half the emission under the baseline scenario.[9]

[9]We do not consider the potential implications of the dynamic allocation decision problem of how many SPS units to assign to produce additional SPS units. For example, how many SPS units to use as breeders may have significant implications for the existing power supply and also other parts of the economy. We also do not consider general resource constraints explicitly in the present SPS-Breeder analysis, even though maintaining the level of total electric power supply at some constant level (except in period 1) is explicitly taken into account. The cost and other economic implications of the dynamic allocation problem of SPS units are important future research topics.

VI. CONCLUDING REMARKS

In this paper, we have analyzed CO_2 emissions associated with the SPS system using detailed sector-specific CO_2 emission data. Our results show that Japan's present electricity needs would be met by 18 SPSs, each of 5 GW output. Construction of these 18 SPSs would release 470 million tons of CO_2. This is a relatively large amount of emission given Japan's current release of 1.2 billion tons of CO_2 per year. However, the SPS systems' CO_2 emissions (20 kg per kWh), which are of the same magnitude as the emissions from nuclear power stations, are about one 60th of the CO_2 emissions from coal-fired power stations and one 30th of the CO_2 emissions from LNG-fired power stations. Furthermore, the SPS-Breeder scenario shows a significant improvement in CO_2 emissions over the baseline NASA/DEA system. At present, complete development of SPS systems is not possible because certain remaining technological problems have yet to be solved.[10] Nevertheless, our results suggest that the SPS is one of the most effective alternative technologies for achieving massive reductions in emissions generated by electric power generation.

The SPS system generates electric power in environmentally clean ways and may give us an opportunity to solve the global warming problem by escaping from a closed-Earth industrial-economic system. Our results are based on Japanese data. However, we do not expect that our basic results would fundamentally change if data from other developed countries were used,

[10]See, for example, [9]–[11] and [20].

provided their economies depend largely on fossil fuels for electric power generation.[11]

APPENDIX

Production of each of the SPS components involves both the production of materials and their assembly. We can calculate direct and indirect CO_2 emissions associated with the production of materials using the method described in the text. We discuss here how to calculate direct and indirect emissions associated with the assembly processes of these components. The DOE/NASA SPS Reference System Study does not report materials, electric power and other energy, and various other services required in assembling rockets and other components. Our calculations for assembly-generated CO_2 emissions are based on the following. 1) Photo-voltaic cells: We follow the detailed assembly processes of these cells given in [22] Uchiyama (1994).[12] 2) Space transportation vehicles: We assume that the input coefficients for assembling HLLVs are the same as the input coefficients for aerospace vehicles in our I-O table. The aerospace vehicle sector of the I-O table, in fact, includes passenger aircrafts, military aircrafts, rockets and their components. Under this assumption, we can obtain CO_2 emissions for assembling HLLVs as follows. Suppose the input vector for the aerospace sector in the I-O table is f_1, the CO_2 emission coefficients matrix (diagonal) C, and the resulting total CO_2 emissions CO_2^1. We obtain CO_2^1, as follows:

$$\begin{aligned}CO_2^1 &= C(I-A)^{-1}f_1\\ CO_2^1 &= \sum_j CO_{2j}^1.\end{aligned}$$

The six sectors listed in the DOE/NASA Reference system are raw materials, plastic products, sheet glass and safety glass, clay refectories, hot rolled steel, aluminum, and other nonferrous metals. We have already obtained CO_2 emissions from the production of these materials in Section III. Let f_2, another final demand vector, consist of elements for raw materials in f_1 and zeros for other inputs. The CO_2 emissions for aerospace vehicles including consumption of the required raw materials is given as follows:

$$\begin{aligned}CO_2^2 &= C(I-A)^{-1}f_2\\ CO_2^2 &= \sum_j CO_{2\mathrm{j}}^2.\end{aligned}$$

We assume here that the whole production process for HHLV vehicles is divided into two processes; raw materials and assembly. This implies that the ratio of the CO_2 emissions from the raw materials production to the CO_2 emissions from the future production process is the same for aerospace vehicle production and HLLV production. The raw material ratio defined by CO_2^1/CO_2^2 is calculated to be 2.5 for aerospace vehicles in the I-O table.

CO_2 emissions for the raw materials used in the production of a single HLLV vehicle are 5 498.3 tons. We apply the raw material ratio to HLLV production and find the total CO_2 emissions from production of HLLVs to be 13 745.75 tons $(=5\,498.3 \times 2.5)$ per vehicle. The same calculation method has been used for all other space transportation vehicles.

APPENDIX

To simulate the SPS-Breeder scenario, we divide the electric power sector into the existing electric power sector in the I-O Table and the SPS sector. At first, all the SPS components must be constructed using existing (conventional) electric power generation systems. We denote by X_1 production of goods and services other than electric power generation induced by production of an SPS system and by x_2 production of electric power. We denote the final demand vector for SPS construction by $f(f^R, f^S, f^O)$, where f^R denotes the rectenna, f^S the SPS photo-voltaic cells, and f^O the commodity vector consisting of other SPS components that must be first constructed at the same time. f^R and f^S can be constructed sequentially, because they involve 18 independent rectenna and satellite pairs. The input-output balance for the above system can be expressed as follows:

$$\begin{aligned}&A_{11}X_1 + A_{12}z + \frac{1}{N}(f^R + f^S) + f^O = X_1\\ &A_{21}X_1 + A_{22}z = x_2\\ &z = \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = \begin{pmatrix} \alpha \\ 1-\alpha \end{pmatrix} x_2.\end{aligned}$$

A_{11} denotes the input coefficients for SPS construction but its components do not include electric power. A_{12} denotes the inputs coefficients for electric power generation including both conventional power generation and SPS. A_{21} denotes electricity input of the sectors other than electric power generation, and A_{22} denotes electricity input of the electric power generations. z_1 denotes electricity from the conventional power generation, and z_2 denotes electricity from the SPS. α is the ratio of conventional power generation to total power generation. At first, α is set equal to 1, i.e., all the electricity is generated by conventional power stations, and $1/N$ pair of the total SPS is constructed with f^O.

In period 2, suppose electric power generated from SPS is z_2 kWh/year and f is given by $(1/\mathrm{N})(f^R + f^{SO})$. Then X_1, x_2, and CO_2 are calculated by

$$\begin{aligned}&A_{11}X_1 + A_{12}z + \frac{1}{N}(f^R + f^S) = X_1\\ &A_{21}X_1 + A_{22}z = x_2\\ &x_2 = z_1 + z_2\\ &z = \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = \begin{pmatrix} \alpha \\ 1-\alpha \end{pmatrix} x_2\\ &CO_2 = \begin{pmatrix} C & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} X_1 \\ z_1 \\ z_2 \end{pmatrix}.\end{aligned}$$

[11]To implement the type of SPS system presented in this paper would require a large amount of resources (e.g., raw materials and R&D resources). Some form of international cooperation might be essential in such a project (see, for example, [21] for some of the joint activities in space power being conducted by JUSTSAP). We have not considered the cost aspect of implementation because of the difficulty in estimating the impact of a project as large as this on the Japanese or perhaps global economy. For example, while expenditures on R&D (in the forms of personnel and equipment costs) are expected to be large, it is difficult to predict the positive effects (and price effects) of such expenditures on the economy. Another possible benefit of this project from the global perspective comes from significant reductions in energy use and CO_2 emissions. In our cost calculations, we would have to estimate monetary value for these reductions. We thank a reviewer for pointing out this and other cost issues associated with the SPS system.

[12]See also [23]

We note that the CO_2 emission coefficient for electricity is zero. The same procedure has been applied for the following SPS construction up to N pairs of rectenna and satellite. The value of z_2 will increase as the number of operating SPSs increases.

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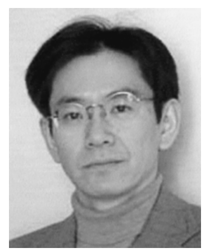

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