CO_2 Emission from Solar Power Satellite through its Life Cycle:

Comparison of Power Generation Systems using Japanese Input-Output Tables*

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Abstract

Solar power generation, especially space solar power, is one of the most promising alternative technologies for reducing CO_2 emissions. However its potential is not obvious, because the launching of satellites consumes rocket fuel, and because solar panel production also involves energy consumption.

For this paper we calculated CO_2 emissions through the life cycle of a Solar Power Satellite (SPS), which comprises production of rocket fuel, solar panels, construction of Rectenna (power receiving antenna), satellite and all equipment listed in the NASA/DOE Reference System. The calculation also includes indirect CO_2 emissions estimated from 1990 Japanese Input-Output Tables broken down into 405 sectors.

The baseline scenario shows that CO_2 emissions from SPS per unit of energy generated, at 20g CO_2 per kWh, is almost the same as from nuclear power systems at 22g CO_2 per kWh, and much less than LNG-fired power generation at 631g CO_2 per kWh, and coal-fired energy at 1,225g CO_2 per kWh. Furthermore, the SPS-Breeder scenario (in which installed Solar Power Satellites supply electricity for producing further SPS units) shows significant improvement in CO_2 emissions at only 11g per kWh.

In spite of Japan's high dependence on nuclear power (which currently provides 32 % of the total electricity supplied), electricity causes one fourth of Japan's total CO_2 emissions. This paper suggests that the SPS is the most effective alternative technology for further CO_2 reduction in electric power generation.

Key words: *Solar Power Satellite (SPS), NASA/DOE Reference System, Life Cycle Assessment (LCA), CO_2 emissions, alternative technology, power generation.*

1 Introduction

The 21st century faces the problems of fossil fuel resource depletion and increasing CO_2 production. In recent years, understanding of the "Greenhouse Effect" has raised questions as to what should be done to reduce CO_2 production, as concerns technological innovation, electricity generation, automobiles, housing and other areas. However, much of this comprises no more than treatment of symptoms, raising the question whether there may not be a more fundamental solution to the problem.

In most countries, among the various domestic and industrial activities, the activity that produces the greatest CO_2 emission is electricity generation. For example, although Japan's use of nuclear power

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is relatively high, electricity generation represents some 25% of the 1.2 billion tons of CO_2 released annually, and the amount is growing. Furthermore, the use of Life Cycle Assessment (LCA) shows that many systems that directly release only small amounts of CO_2 also depend largely on electricity. For example, electric vehicles do not release CO_2 during operation, but they depend on electricity generation and therefore add to the CO_2 emission. Consequently if the electricity is generated mainly from coal burning, electric cars will release large amounts of CO_2. In view of this, an electricity generation system that has a low dependence on fossil fuels, releases small quantities of CO_2 and causes only a small environmental emission is highly desirable for the 21st century.

From this viewpoint we estimate the CO_2 emission of one candidate for electricity generation in the future, Solar Power Satellites (SPS). These satellites must of course be launched using rockets, and the production of their photo-voltaic panels also uses large quantities of energy. In addition the rectenna, the microwave power receiving and rectifying antenna on Earth, contains large amounts of cement and steel, which cause the release of large amounts of CO_2 in their production. Consequently the objective of this analysis is to discover how SPS's CO_2 releases compare with electricity generation from liquefied natural gas (LNG) or nuclear power. In this paper we analyze a rather old system design, the "SPS Reference System" published by the US Department of Energy (DOE) and NASA in 1978[2]. Recently NASA has published new SPS designs and proposed new means of launching it[1]. However, although these seem more advanced, we start by analyzing the basic SPS system represented by the DOE/NASA Reference System. In the following we first of all give a broad overview of the SPS system, and of the method used to calculate its CO_2 emission. In the next section we describe the SPS-Breeder, and in the conclusion we report the main results.

2 Concept of SPS

Electricity generation using photo-voltaic cells is receiving increasing attention as a means of electricity generation that produces neither CO_2, NOx nor SOx pollution as do systems using fossil fuel burning, nor radiation like nuclear power systems. However, because solar energy generation is impossible at night and of poor efficiency during cloudy weather, stable electricity generation is difficult. However, if solar panels are launched into space they can produce power continuously, independent of the weather and of the day-and-night cycle. The Solar Power Satellite (SPS) concept involves a satellite carrying photo-voltaic panels in geo-stationary orbit (GEO) to generate electricity, and transmitting this power to the Earth's surface.

The concept of SPS was first published in 1968 by Peter Glaser, and in 1978 the US Department of Energy (DOE) and NASA published a "Reference System" referred to here as the DOE/NASA Reference System. Although the Reference System was published some 20 years ago, no other equally detailed system has been proposed since then, and so it remains the representative plan of a future SPS system. Consequently, in this paper we investigate the CO_2 emission of the DOE/NASA SPS "Reference System".

Figure 1 shows the SPS concept, Table 1 the main assumptions, and Table 2 the components of the SPS system. The satellite is shown in the upper part of Figure 1 : it has a rectangular structure 10 km long by 5 km wide and 300 meters 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 the Figure. The lower half shows the rectenna on the Earth, which receives and rectifies the microwave beam from a satellite; it is elliptical, 13 km by 10 km. Each satellite-rectenna pair has an output of 5 GW, and the DOE/NASA Reference System comprised 60 such pairs. These would have an annual output of 2,628 billion kWh.

3 Estimating the CO_2 Emission from SPS

The CO_2 emission from constructing and operating the SPS system is estimated using Environmental Input-Output Tables, which have been constructed and published by the 'Research Group for Environmental Issues' in KEO(Keio Economic Observatory)[11]. Environmental Input-Output analysis is given by:

[1] See Science Applications International Corporation et al.[16]

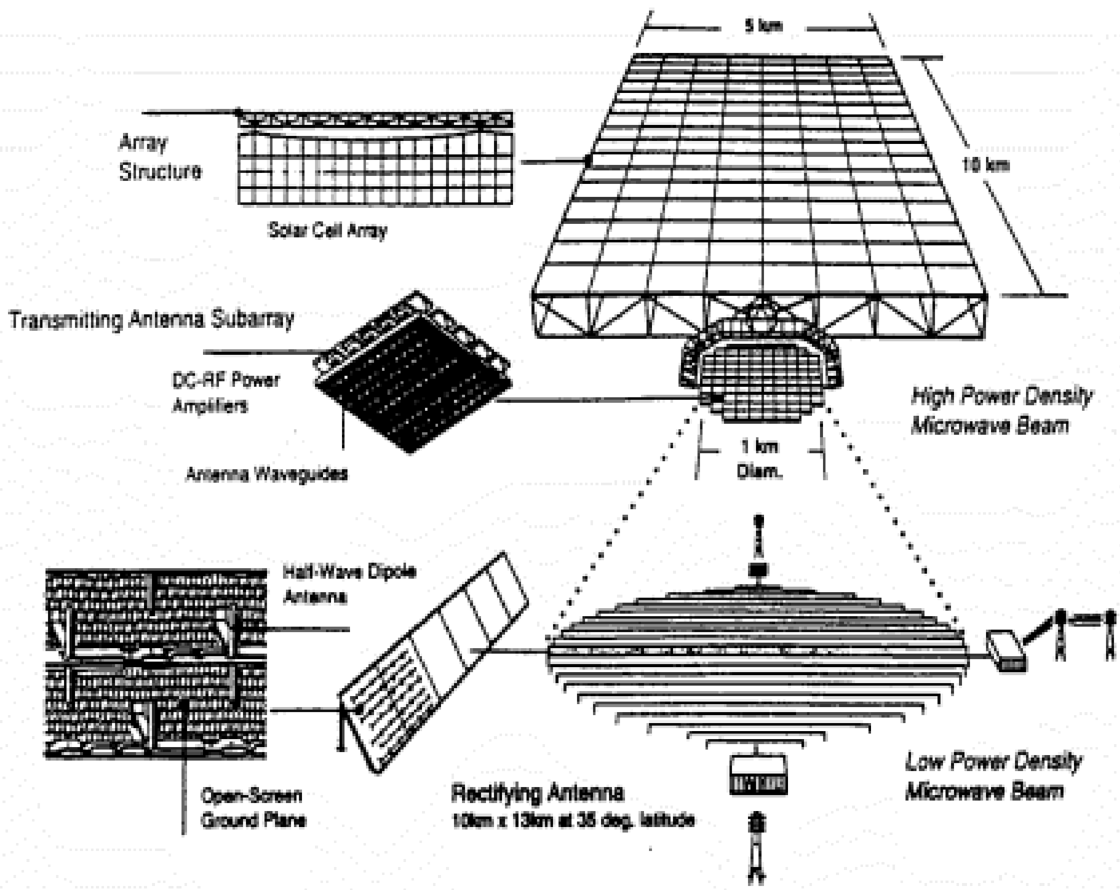

Figure 1: SPS concept

$$\mathbf{CO}_2^k = \mathbf{C}\left(\mathbf{I} - \mathbf{A}\right)^{-1}\mathbf{f}^k$$

where,

$\mathbf{CO}_2^k$	:	CO_2 emission of kth SPS component (in production process)
$\mathbf{C}$	:	CO_2 emission coefficient (diagonal)
$\mathbf{I}$	:	identity matrix
$\mathbf{A}$	:	input coefficients matrix with 405 sectors
$\mathbf{f}^k$	:	final demand vector of kth SPS components

In addition, we need to know the detailed CO_2 repercussion effects, so we calculate the following:

$$\begin{aligned}\mathbf{CO}_2^k &= \mathbf{Cf}^k + \mathbf{Cx}^{k,1} + \mathbf{Cx}^{k,2} + \mathbf{Cx}^{k,3} + \cdots \\ &= \mathbf{Cf}^k + \mathbf{CAf}^k + \mathbf{CA}^2\mathbf{f}^k + \mathbf{CA}^3\mathbf{f}^k + \cdots \\ &= \mathbf{C}\left(\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \cdots\right)\mathbf{f}^k \\ &= \mathbf{C}\left(\mathbf{I} - \mathbf{A}\right)^{-1}\mathbf{f}^k\end{aligned}$$

$\mathbf{Cf}^k$ is called the direct effect, $\mathbf{Cx}^{k,1}$ is the first indirect effect, $\mathbf{Cx}^{k,2}$ is the second indirect effect, and $\mathbf{Cx}^{k,3}$ is the third indirect effect, and so on. Repeating this calculation several times, the direct and indirect effects converge to $(I\text{-}A)^{-1}f^k$. In this way the total CO_2 emission produced by the SPS system can be estimated.

Table 1: Basic assumptions about SPS based DOE/NASA Reference 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	2628000	GWh

Table 2: List of components of 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

As a result, major data problems are how to construct the final demand of the kth SPS component, and we approach this as follows. Initially, the quantities of materials used in the kth component are given by DOE/NASA[2][3] and re-classified to match the Japanese I-O classification. In the next, the materials required for the kth component are converted to monetary units by using unit price in the 10-digit code table of Input-Output tables[2]. For products for which no unit price are given in the I-O tables, figures were taken from trade statistics. Finally, as the materials converted to monetary units are evaluated in producer's price, so they are converted to purchaser's price unit by using the trade margin and domestic transport margin in the I-O table[3].

4 Overview of the CO_2 Emission

In this section we describe the main results of the estimate of the overall CO_2 emission from constructing and operating the SPS system. Table 3 shows that the CO_2 released by the SPS system would be some 1.58 billion tons, which is about 25 % more than the 1.2 billion tons of CO_2 released by Japan during 1990. Notably, the quantity released by the rockets used to launch the SPS satellites is relatively low. The major components are the CO_2 released in producing the photo-voltaic panels, which is some 60 % of the total, and that from the rectenna which is some 30 % of the total. The CO_2 released by maintenance is not included, however, since data is not available:if the maintenance ratio of the satellite and rectenna is 1 % per year, the overall CO_2 emission would increase by some 30 %.

Then, we assume the case that Japan's all electric power are supplied only from SPS system. As showed in Table 1, 60 SPS units would have an annual output of 2,628 billion kWh, or some 3.5 times the electricity produced in Japan in 1995. Consequently only 18 such SPS satellites would be needed to supply Japan. If all Japan's electricity was supplied by 18 SPS units, the number of rectennas would also be reduced proportionately. The number of LEO and GEO bases needed would be halved to one each, and the remaining CO_2 releases would be reduced to 18/60 of the quantities shown in Table 3. The result is shown in Table 4, the total CO_2 emission being reduced to 470 million tons.

[2] 10-digit code table includes prices of 5000 commodities.
[3] See, in addition, Appendix.1.

Table 3: CO_2 released by DOE/NASA SPS "Reference System" of 60 SPS units
units: 10 thousand tons of CO_2)

Space Transportation		
1	HLLV	412
2	PLV	12
3	COTV	9576
4	POTV	4
Space Bases		
5	LEO Base	5
6	GEO Construction Base	19
Solar Power Satellite		
7	Satellite Structure	1424
8	Photo-voltaic Cells	90393
Other Components		
9	Rectenna	38688
10	Propellants	17473
	Total	158007

Table 4: CO_2 released by SPS system of 18 SPS units scaled to supply Japan
(units: 10 thousand tons of CO_2)

Space Transportation		
1	HLLV	124
2	PLV	4
3	COTV	2873
4	POTV	1
Space Bases		
5	LEO Base	3
6	GEO Construction Base	9
Solar Power Satellite		
7	Satellite Structure	427
8	Photo-voltaic Cells	27118
Other Components		
9	Rectenna	11606
10	Propellants	5242
	Total	47407

Table 9 shows a series of repercussion effects of CO_2 emission of the SPS system by sectors. Sectors having a high share of total CO_2 emission of SPS are electric power, sheet glass and safety glass, and self-power generation, and the summed share of electricity-related sectors (electric power sector and self-power generation) represent half the total, although the SPS system requires large amounts of various materials. Then, Table 5 shows the 3 highest ranking sectors of CO_2 emission of SPS components respectively. Each component requires different kinds of materials directly, but CO_2 emission is mainly induced by electrical power generation in almost SPS components.

Lastly, we compare CO_2 emissions of the SPS system with different electricity generation systems. If we assume a lifetime of 30 years for the SPS Reference System, the annual CO_2 emission then becomes (1580 / 30) = 52.67 million tons/year. SPS produces 2,628 billion kWh/year, consequently the CO_2 output per kWh can be estimated as:

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

Table 6 compares the CO_2 emission per kWh of electrical energy produced by SPS, fossil fuels and nuclear power, based on earlier work of the Reseach Group for Environmental Issues in KEO [11].

The Table shows that the SPS Reference System would release slightly less CO_2 / kWh than nuclear power generation. The CO_2 release from the operations of fossil fuel generation systems is mainly that

Table 5: 3 highest ranking sectors of CO_2 emission of SPS components

	HLLV	t - CO_2	PLV	t - CO_2	COTV	t - CO_2
1st	Electric power	1184	Electric power	267	Electric power	171
2nd	Aluminium	875	Aluminium	197.4	Self-Power generation	81
3rd	Self-Power generation	863	Self-Power generation	194.7	Road freight transport	65
total		5498		1239.4		732

	POTV	t - CO_2	LEO Base	t - CO_2	GEO Construction Base	t - CO_2
1st	Aluminium	150	Aluminium	2662	Electric power	8720
2nd	Electric power	97	Electric power	2214	Self-Power generation	7712
3rd	Self-Power generation	96	Self-Power generation	1878	Coal products	6337
total		521		10790		37332

	Satellite	t - CO_2	Photo-voltaic Cells	1000t- CO_2	Rectenna	1000t- CO_2
1st	Electric power	21188	Electric power	7540	Electric power	1823
2nd	Self-Power generation	11798	Sheet glass and safety glass	1634	Pig iron	875
3rd	Pig iron	6992	Self-Power generation	920	Coal products	584
total		94942		14232		6448

*Aluminium sector include regenerated aluminium.

Table 6: Comparison of relative CO_2 emission of different electricity generation systems
(units: g CO_2 /kWh)

Generating system	Operations	Construction	Total
SPS	0	20	20
Coal	1222	3	1225
Oil	844	2	846
Liquefied Natural Gas (LNG)	629	2	631
Nuclear power	19	3	22

released at the station from burning of fuel, whereas the CO_2 released by nuclear plant operations is mainly from the use of energy to produce nuclear fuel. The CO_2 released in distributing the electricity generated is not included in the SPS figures (since the data is not available) but is included for the other systems. Consequently it is necessary to allow for this in using the results shown in Table 6.

5 Simulation of SPS Construction

In the preceding section, we calculated the CO_2 load of SPS on the basis of the DOE/NASA “Reference System”. It seems reasonable to conclude that the SPS system in construction induces large amounts of CO_2 directly and indirectly, but CO_2 emission per unit of kWh is much less than the other different kinds of electric energy generation system. However, our results assume that 60 SPS units (or 18 SPS units) are constructed at a time, so we don’t take the time span of construction and electricity supply of SPS into account.

In this section we consider the SPS-Breeder scenario in which installed SPS units supply electricity for producing further SPS units, and analyze its CO_2 load. In contrast to this scenario, we call the case in the preceding section the ‘Baseline scenario’.

The concept of SPS-Breeder is shown in Figure 2, and the assumptions of the SPS-Breeder scenario are as follows: [4]

1. A pair of SPS and rectenna is built during one time period, and 18 pairs are built in all (which covers total Japanese electricity supply as of 1995).

[4] For the calculation, see Appendix 2.

2. Space transportation systems, space construction bases, and one SPS-rectenna pair are all built in the 1st period.

3. SPS components constructed in the 1st period use only power from existing electricity generation systems.

4. In the tth period, all $t-1$ SPS units are still operating.($t = 2, 3, ..., N; N = 18$)

5. An SPS unit built during the tth period utilizes electricity from the SPS unit built in the $t-1$th period, and it utilizes electricity from existing electricity supply facilities only if the SPS electricity sup

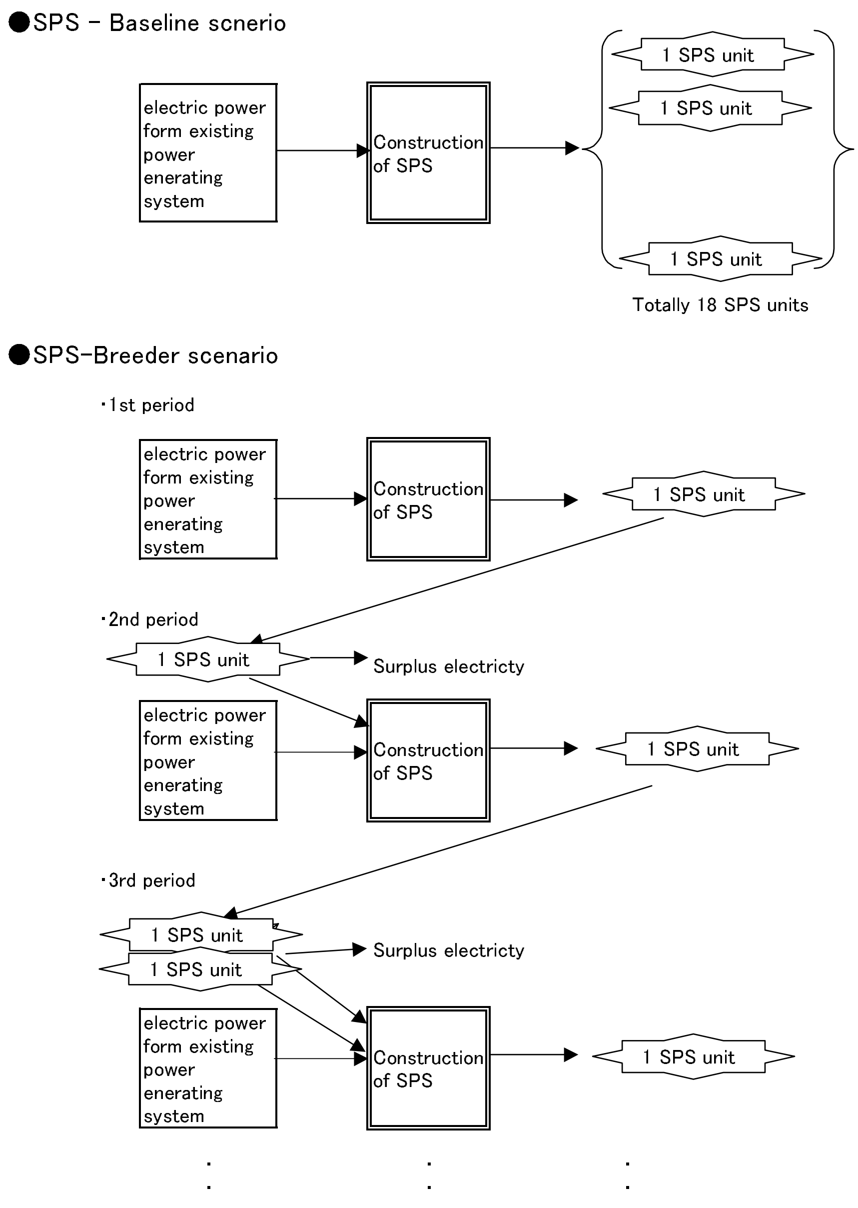

Figure 2: concept of SPS-Breeder scenario

The left part of Table 8 summarizes the CO_2 load calculated based on the SPS-Breeder scenario. In the 1st period the SPS system begins to be constructed and there is no power supply from SPS. So all of the space transportation systems, space bases, and the 1st SPS-rectenna pair are built using only power supply from existing power supply facilities (276.9 hundred million kWh). In the 2nd period, a 2nd SPS is built using electricity from both the 1st SPS unit and existing electricity facilities; however, the result of our simulation shows that a 2nd SPS does not need electricity from existing power supply facilities, and so it is constructed using only electricity from the 1st SPS unit. In the 3rd and later periods, construction of the SPS system does not need electricity from existing generation facilities. As a result, it is clear that the SPS system can be constructed using only power supplied from SPS units after the 2nd period.

Let us now look at "Surplus electricity and imputed CO_2 emission of SPS" in Table 8. In the case of the SPS-Breeder scenario, surplus electricity arises after the 2nd period, which is shown in the third column from the right in the Table. Figures in the second column from the right in the Table (i.e. in (d) column) are CO_2 emissions from surplus electricity evaluated per unit of CO_2 of existing electric generation systems. In other words, 30.2 hundred million CO_2-ton would be released if the same amount of electricity was produced by existing electricity supply facilities. As the SPS system hardly produces any CO_2 at all in operation, we obtain a negative 'net effect' by subtracting (d) from (b). This result is an 'imputation'; however it indicates that the SPS-Breeder has a net -2.8 billion ton effect in total.

We can now compare CO_2 emissions of the SPS-Breeder system with the SPS system in the baseline scenario. We make the same assumption of lifetime as in the baseline scenario. The annual CO_2 emission then becomes (268 / 30) = 8.9 million tons/year. 18 SPS units produce 788 billion kWh totally, consequently the CO_2 output per kWh can be estimated as:

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

As mentioned in the preceding section, CO_2 emissions in g per kWh in the baseline scenario are lower than for other electricity generation systems, but Table 7 indicates that the SPS-Breeder system shows further significant improvement in CO_2 emissions at only 11 g per kWh, which is half that in the baseline scenario.

Table 7: Comparison of relative CO_2 emission of different electricity generation systems

(units: g CO_2 /kWh)

Generating system	Operations	Construction	Total
SPS-Breeder scenario	0	11	11
SPS-baseline scenario	0	20	20

6 Conclusions

In this paper we have analyzed the CO_2 emission likely to be produced by a system of Solar Power Satellites in as much detail as possible, based on the DOE/NASA Reference System. Based on this analysis, in order to satisfy Japan's present electricity supply, some 18 SPSs of 5 GW output would be needed, which we have estimated would release some 470 million tons of CO_2. Japan currently releases some 1.2 billion tons of CO_2 per year, so it is clear that a large amount of CO_2 is released when the SPS system is constructed. However, the overall CO_2 output is of the same order as nuclear power stations at 20 kg per kWh. This is about 1/60 of the output of coal-fired power stations, and 1/30 of the CO_2 output of LNG-fired power stations. Furthermore, the SPS-Breeder scenario shows significant improvement in CO_2 emissions at only 11g per kWh. Of course SPS is a future technological system, and potential problems concerning various parts and components remain to be resolved, but our result suggests that the SPS is one of the most effective alternative technology for further CO_2 reduction in electric power generation.

One of the ways to solve Earth-wide environmental problems is to generate electric power in environmentally clean ways. The SPS system may give us the opportunity to solve this problem and to initiative the escape from a 'closed-Earth' industrial-economic system.

Table 8: CO_2 emission in SPS-Breeder scenario

	electricity reqired SPS construction (100 million kWh)			CO_2 emission	SPS in working		surplus electricity and imputed CO_2 emission of SPS		
period	from SPS (a)	from existing power system	total	10 thousand ton (b)	number	electricity generated 100 million kWh (c)	surplus electricity 100 million kWh (c)-(a)	CO_2 emission 100 million ton (d)	total effect 100 million ton (b)-(d)
1st	0	276.9	276.9	3201	0	0	0	0.0	0.3
2nd	246.8	0	246.8	1388	1	438	191.2	0.1	0.0
3rd	246.8	0	246.8	1388	2	876	629.2	0.3	-0.2
4th	246.8	0	246.8	1388	3	1314	1067.2	0.5	-0.4
5th	246.8	0	246.8	1388	4	1752	1505.2	0.7	-0.6
6th	246.8	0	246.8	1388	5	2190	1943.2	0.9	-0.8
7th	246.8	0	246.8	1388	6	2628	2381.2	1.1	-1.0
8th	246.8	0	246.8	1388	7	3066	2819.2	1.4	-1.2
9th	246.8	0	246.8	1388	8	3504	3257.2	1.6	-1.4
10th	246.8	0	246.8	1388	9	3942	3695.2	1.8	-1.6
11th	246.8	0	246.8	1388	10	4380	4133.2	2.0	-1.8
12th	246.8	0	246.8	1388	11	4818	4571.2	2.2	-2.1
13th	246.8	0	246.8	1388	12	5256	5009.2	2.4	-2.3
14th	246.8	0	246.8	1388	13	5694	5447.2	2.6	-2.5
15th	246.8	0	246.8	1388	14	6132	5885.2	2.8	-2.7
16th	246.8	0	246.8	1388	15	6570	6323.2	3.0	-2.9
17th	246.8	0	246.8	1388	16	7008	6761.2	3.2	-3.1
18th	246.8	0	246.8	1388	17	7446	7199.2	3.5	-3.3
19th	-	-	-	-	18	7884	-	-	-
total	4195.6	276.9	4472.5	26797			62818.4	30.2	-27.5

Table 9: CO_2 emission from 60 SPS units based on NASA/DOE Reference system

(unit : 100,000t-CO_2)

Direct effect		1st indirect effect		2nd indirect effect	
Electric power	4549.5	Electric power	1102.1	Electric power	597.8
Sheet glass and safety glass	902.6	Self-Power generation	283.9	Pig iron	476.4
LNG burning	622.1	Aluminium(inc.regenerated aluminium)	227.1	Self-Power generation	291.9
silica reduction	399.0	Sheet glass and safety glass	150.9	Coal products	94.1
Hydrogen production	316.4	Coal products	140.7	Aluminium(inc.regenerated aluminium)	57.3
Road freight transport	152.6	Miscellaneous ceramic,stone and clay products	121.3	Petroleum refinery products(inc.grease)	54.8
Other industrial inorganic chemicals	114.9	Petroleum refinery products(inc.grease)	82.4	Ferro alloy	52.2
Abrasive	108.2	Crude steel(converters)	80.4	Self-freight transport by private motor cars	50.0
Hot rolled steel	84.2	Industrial soda chemicals	79.9	Other non-ferrous metals	42.7
Rolled aluminium products	83.8	Cement	69.4	Industrial soda chemicals	38.1
Semi-conductor devices and integrated circuits	70.1	Self-Passenger transport by private motor cars	55.3	Petrochemical basic products	37.3
Aliphatic intermediates	56.5	Road freight transport	54.7	Self-Passenger transport by private motor cars	33.4
Coastal and inland water transport	44.7	Self-freight transport by private motor cars	47.3	Miscellaneous ceramic,stone and clay products	32.1
Other glass and glass products	39.8	Thermoplastics resin	46.1	Road freight transport	29.4
Cyclic intermediates	30.3	Research and development(private,profit)	41.5	Sheet glass and safety glass	25.8
Aluminium(inc.regenerated aluminium)	29.4	Crude steel(electric furnaces)	41.3	Foreign paper and Japanese paper	24.2
Plastic products	23.1	Coastal and inland water transport	35.4	Aliphatic intermediates	21.4
Synthetic rubber	22.5	Other non-ferrous metals	34.7	Coastal and inland water transport	20.5
Wholesale trade	20.9	Petrochemical basic products	31.5	Cyclic intermediates	18.2
Industrial soda chemicals	12.3	Activities not elsewhere classified	28.1	Thermoplastics resin	18.1
Air transport	11.5	Aliphatic intermediates	25.1	Activities not elsewhere classified	17.8
Other metal products	11.4	Other industrial inorganic chemicals	24.7	Air transport	13.5
Other non-ferrous metals	11.1	Air transport	19.1	Cement	12.8
Carbon and graphite products	10.4	Other sanitary services(industrial)	18.1	Salt	11.8
Self-Passenger transport by private motor cars	9.5	Petrochemical aromatic products(except synthetic resin)	12.4	Other sanitary services(industrial)	10.7
Sulfuric acid	9.4	Other weak electrical equipment	11.4	Other industrial inorganic chemicals	10.7
Self-freight transport by private motor cars	7.2	Other industrial organic chemicals	10.3	Hot rolled steel	9.0
Copper	7.1	Other resin	9.8	Petrochemical aromatic products(except synthetic resin)	6.5
Cast and forged materials(iron)	6.7	Foreign paper and Japanese paper	9.6	Research and development(private,profit)	6.4
Oxygen production	5.0	Synthetic rubber	8.9	Crude petroleum	6.2
Pottery,china and earthenware	5.0	Plastic products	8.8	Non-ferrous metal ores	6.1
Compressed gas and liquified gas	3.6	Hired car and taxi transport	8.7	Cold-finished steel	6.0
Activities not elsewhere classified	2.7	Wholesale trade	8.4	Hired car and taxi transport	5.4
Relay switch and switchboard	2.6	Cold-finished steel	8.2	Carbon and graphite products	5.4
Clay refactories	2.5	Other glass and glass products	7.7	Crude steel(converters)	5.2
Natural gas	2.5	Thermo-setting resin	7.6	Paperboard	4.6
Self-Power generation	2.3	Other materials for ceramics	7.5	Other resin	4.6
Other special industrial machinery	2.2	Parts of other electric,communication equipment	7.1	Wholesale trade	4.4
Other sanitary services(industrial)	2.2	Ammonia	6.5	Other industrial organic chemicals	4.0
Electric wires and cables	2.0	Cast and forged materials(iron)	6.5	Plastic products	3.7
Miscellaneous ceramic,stone and clay products	1.7	Methane derivatives	5.9	Zinc(inc.regenerated zinc)	3.6
Retail trade	1.7	Cyclic intermediates	5.4	Synthetic rubber	3.6
Transport service in harbor	1.4	Copper	5.3	Ammonia	2.9
Non-residential construction(non-wooden)	1.3	Hot rolled steel	5.2	Crude steel(electric furnaces)	2.8
Ready mixed concrete	1.2	Lead(inc.regenerated lead)	5.0	Methane derivatives	2.8
Other materials for ceramics	1.1	Abrasive	4.5	Other business services	2.6
Railway forwarding	0.9	Glass fibre and glass products,n.e.c.	4.3	Lead(inc.regenerated lead)	2.6
Metal products for construction	0.9	High functionality resin	4.2	Thermo-setting resin	2.5
Cold-finished steel	0.8	Carbon and graphite products	4.1	Real estate rent	2.4
Water supply	0.8	Gas supply	3.9	Other glass and glass products	2.4
Others	9.0	Others	96.0	Others	77.6
Total	7820.3	Total	3124.1	Total	2275.9
Cummulative total	7820.3	Cummulative total	10944.4	Cummulative total	13220.4

1) sectors showed are high rank 50 sectors and have more than 0.1 ton CO_2 load.

2) 'Others' are sum of quantities excluded above sectors.

Table 9: CO_2 emission from 60 SPS units based on NASA/DOE Reference system (Continued)

(unit : 100,000t-CO_2)

3rd indirect effect		4th indirect effect		5th indirect effect	
Electric power	313.2	Electric power	170.2	Electric power	80.6
Coal products	261.9	Self-Power generation	90.9	Self-Power generation	59.2
Self-Power generation	174.7	Coal products	70.9	Coal products	43.8
Self-freight transport by private motor cars	39.6	Pig iron	50.7	Pig iron	32.7
Petroleum refinery products(inc.grease)	36.8	Self-freight transport by private motor cars	24.7	Petroleum refinery products(inc.grease)	13.1
Pig iron	28.3	Petroleum refinery products(inc.grease)	23.7	Self-freight transport by private motor cars	10.8
Foreign paper and Japanese paper	24.2	Petrochemical basic products	13.8	Foreign paper and Japanese paper	7.5
Petrochemical basic products	24.2	Foreign paper and Japanese paper	13.6	Petrochemical basic products	7.2
Self-Passenger transport by private motor cars	20.4	Self-Passenger transport by private motor cars	11.7	Self-Passenger transport by private motor cars	6.3
Road freight transport	15.2	Cement	9.1	Cement	4.6
Aluminium(inc.regenerated aluminium)	15.1	Road freight transport	8.3	Road freight transport	4.4
Cement	14.8	Aliphatic intermediates	7.1	Ferro alloy	3.8
Other non-ferrous metals	14.7	Coastal and inland water transport	6.9	Aliphatic intermediates	3.7
Industrial soda chemicals	14.2	Industrial soda chemicals	6.1	Coastal and inland water transport	3.6
Aliphatic intermediates	12.9	Ferro alloy	5.8	Crude steel(converters)	3.1
Miscellaneous ceramic,stone and clay products	12.4	Petrochemical aromatic products(except synthetic resin)	5.6	Pulp	3.1
Coastal and inland water transport	11.9	Pulp	5.6	Industrial soda chemicals	3.0
Activities not elsewhere classified	9.4	Crude steel(converters)	5.5	Miscellaneous ceramic,stone and clay products	3.0
Petrochemical aromatic products(except synthetic resin)	9.2	Miscellaneous ceramic,stone and clay products	5.4	Petrochemical aromatic products(except synthetic resin)	2.9
Paperboard	9.1	Paperboard	4.9	Activities not elsewhere classified	2.5
Cyclic intermediates	9.0	Activities not elsewhere classified	4.7	Air transport	2.4
Crude steel(converters)	8.7	Air transport	4.6	Paperboard	2.3
Thermoplastics resin	8.4	Aluminium(inc.regenerated aluminium)	4.6	Other sanitary services(industrial)	2.2
Air transport	8.0	Other non-ferrous metals	4.3	Cyclic intermediates	2.0
Iron and ore mining	7.7	Cyclic intermediates	4.3	Hot rolled steel	1.9
Other sanitary services(industrial)	7.0	Other sanitary services(industrial)	4.2	Thermoplastics resin	1.7
Salt	6.0	Thermoplastics resin	3.6	Crude petroleum	1.7
Hot rolled steel	5.8	Hot rolled steel	3.2	Aluminium(inc.regenerated aluminium)	1.7
Pulp	5.0	Crude steel(electric furnaces)	2.9	Crude steel(electric furnaces)	1.6
Other industrial inorganic chemicals	4.9	Crude petroleum	2.7	Other non-ferrous metals	1.5
Sheet glass and safety glass	4.8	Other industrial inorganic chemicals	2.6	Other industrial inorganic chemicals	1.4
Crude steel(electric furnaces)	4.5	Salt	2.3	Cold-finished steel	1.0
Ferro alloy	4.5	Cold-finished steel	1.8	Salt	1.0
Non-ferrous metal ores	4.3	Hired car and taxi transport	1.8	Hired car and taxi transport	0.9
Crude petroleum	4.0	Research and development(private,profit)	1.6	Cast and forged materials(iron)	0.9
Research and development(private,profit)	3.2	Non-ferrous metal ores	1.6	Research and development(private,profit)	0.8
Cold-finished steel	3.1	Cast and forged materials(iron)	1.4	Iron and ore mining	0.8
Hired car and taxi transport	3.1	Coal mining	1.4	Zinc(inc.regenerated zinc)	0.6
Copper	2.5	Zinc(inc.regenerated zinc)	1.2	Wholesale trade	0.6
Zinc(inc.regenerated zinc)	2.5	Other resin	1.1	Ammonia	0.6
Ammonia	2.4	Wholesale trade	1.1	Other resin	0.6
Wholesale trade	2.2	Ammonia	1.1	Synthetic rubber	0.5
Other resin	2.2	Sheet glass and safety glass	1.1	Other business services	0.5
Cast and forged materials(iron)	2.1	Other industrial organic chemicals	0.9	Non-ferrous metal ores	0.5
Other industrial organic chemicals	1.8	Other business services	0.9	Other industrial organic chemicals	0.4
Transport service in harbor	1.7	Synthetic rubber	0.9	Coal mining	0.4
Plastic products	1.6	Plastic products	0.8	Yarn and fabric dyeing and finishing(entrusted processing only)	0.4
Other business services	1.6	Transport service in harbor	0.7	Real estate rent	0.4
Carbon and graphite products	1.5	Yarn and fabric dyeing and finishing(entrusted processing only)	0.7	Plastic products	0.4
Lead(inc.regenerated lead)	1.4	Copper	0.7	Other final chemical products	0.3
Others	45.0	Others	24.0	Others	12.4
Total	1232.8	Total	629.2	Total	343.3
Cummulative total	14453.2	Cummulative total	15082.3	Cummulative total	15425.7

Table 9: CO_2 emission from 60 SPS units based on NASA/DOE Reference system (Continued)

(unit：100,000t-CO_2)

6th indirect effect		7th indirect effect		Total effect	
Electric power	41.4	Electric power	21.6	Electric power	6900.8
Self-Power generation	26.8	Coal products	14.5	Sheet glass and safety glass	1085.7
Coal products	26.3	Self-Power generation	14.2	Self-Power generation	960.0
Pig iron	18.4	Pig iron	10.9	Coal products	670.7
Petroleum refinery products(inc.grease)	6.8	Petroleum refinery products(inc.grease)	3.4	LNG burning	622.1
Self-freight transport by private motor cars	4.5	Self-freight transport by private motor cars	2.2	Pig iron	622.0
Foreign paper and Japanese paper	4.1	Foreign paper and Japanese paper	2.2	Silica reduction	399.0
Petrochemical basic products	3.6	Petrochemical basic products	1.9	Aluminium(inc.regenerated aluminium)	336.5
Self-Passenger transport by private motor cars	3.3	Self-Passenger transport by private motor cars	1.8	Hydrogen production	316.4
Road freight transport	2.4	Road freight transport	1.3	Road freight transport	269.7
Cement	2.1	Ferro alloy	1.3	Petroleum refinery products(inc.grease)	225.1
Ferro alloy	2.1	Cement	1.1	Self-freight transport by private motor cars	188.7
Aliphatic intermediates	1.9	Crude steel(converters)	1.0	Miscellaneous ceramic,stone and clay products	179.5
Coastal and inland water transport	1.9	Aliphatic intermediates	1.0	Other industrial inorganic chemicals	160.9
Crude steel(converters)	1.9	Coastal and inland water transport	1.0	Industrial soda chemicals	156.8
Miscellaneous ceramic,stone and clay products	1.7	Miscellaneous ceramic,stone and clay products	0.9	Self-Passenger transport by private motor cars	143.6
Pulp	1.6	Pulp	0.9	Aliphatic intermediates	130.5
Industrial soda chemicals	1.5	Industrial soda chemicals	0.8	Coastal and inland water transport	127.0
Petrochemical aromatic products(except synthetic resin)	1.4	Petrochemical aromatic products(except synthetic resin)	0.7	Petrochemical basic products	121.4
Activities not elsewhere classified	1.3	Activities not elsewhere classified	0.7	Cement	115.0
Air transport	1.3	Air transport	0.7	Abrasive	113.2
Other sanitary services(industrial)	1.2	Other sanitary services(industrial)	0.6	Hot rolled steel	111.6
Paperboard	1.1	Hot rolled steel	0.6	Other non-ferrous metals	110.1
Hot rolled steel	1.1	Paperboard	0.6	Crude steel(converters)	107.1
Cyclic intermediates	1.0	Crude steel(electric furnaces)	0.6	Rolled aluminium products	88.2
Crude steel(electric furnaces)	1.0	Cyclic intermediates	0.5	Foreign paper and Japanese paper	87.8
Crude petroleum	0.9	Crude petroleum	0.5	Thermoplastics resin	79.7
Thermoplastics resin	0.8	Thermoplastics resin	0.4	Semi-conductor devices and integrated circuits	72.3
Other industrial inorganic chemicals	0.8	Other industrial inorganic chemicals	0.4	Cyclic intermediates	71.3
Aluminium(inc.regenerated aluminium)	0.7	Aluminium(inc.regenerated aluminium)	0.3	Ferro alloy	71.3
Other non-ferrous metals	0.6	Cold-finished steel	0.3	Activities not elsewhere classified	68.0
Cold-finished steel	0.6	Cast and forged materials(iron)	0.3	Air transport	61.8
Iron and ore mining	0.5	Iron and ore mining	0.3	Crude steel(electric furnaces)	55.5
Cast and forged materials(iron)	0.5	Other non-ferrous metals	0.3	Research and development(private,profit)	54.7
Salt	0.5	Hired car and taxi transport	0.3	Other glass and glass products	51.9
Hired car and taxi transport	0.5	Salt	0.3	Other sanitary services(industrial)	46.8
Research and development(private,profit)	0.4	Research and development(private,profit)	0.2	Petrochemical aromatic products(except synthetic resin)	39.5
Zinc(inc.regenerated zinc)	0.3	Zinc(inc.regenerated zinc)	0.2	Plastic products	38.8
Synthetic rubber	0.3	Synthetic rubber	0.2	Synthetic rubber	38.4
Ammonia	0.3	Wholesale trade	0.1	Wholesale trade	38.2
Wholesale trade	0.3	Other resin	0.1	Salt	25.5
Other resin	0.3	Ammonia	0.1	Paperboard	23.4
Other business services	0.3	Coal mining	0.1	Carbon and graphite products	22.4
Coal mining	0.3	Other business services	0.1	Cold-finished steel	22.2
Other industrial organic chemicals	0.2	Other industrial organic chemicals	0.1	Hired car and taxi transport	21.1
Yarn and fabric dyeing and finishing(entrusted processing only)	0.2	Yarn and fabric dyeing and finishing(entrusted processing only)	0.1	Cast and forged materials(iron)	21.0
Real estate rent	0.2			Crude petroleum	20.2
Plastic products	0.2			Pulp	19.1
Other final chemical products	0.2			Other resin	18.8
Non-ferrous metal ores	0.2			Copper	18.1
Others	6.4	Others	3.6	Others	451.5
Total	177.9	Total	95.1	Total	15800.7
Cummulative total	15603.6	Cummulative total	15698.7	Cummulative total	15800.7

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A Appendix.1

The production of each SPS component involves both production and assembly of commodities, both of which use electrical energy. The problem was to calculate the CO_2 released in processing the required materials, production of commodities, and goods and services used in the assembly of the SPS components. This information was not included in the DOE/NASA SPS Reference System study, and so other sources were necessary.

Fortunately, a detailed activity of photo-voltaic Cells is reported in Uchiyama[18], we calculate its CO_2 emission based on the paper.

As to Space Transportation vehicles, taking HLLV as a example we calculate the CO_2 emission in the following procedure;

One way to estimate CO_2 emission from processing is to use the the "aerospace vehicle" sector of Input-Output tables. This sector of the I-O tables includes various vehicles, including passenger aircraft, military aircraft, rockets and components, and so it is not identical to the HLLV. However the assumption was made that the ratio between the CO_2 released in the production of aerospace vehicles and the CO_2 released in the production of the materials used in them is the same ratio as for the HLLV. A detailed description of this calculation is as follows; we assume input vector of aerospace sector is $\mathbf{f}_1$. Induced production $\mathbf{x}_1$ and induced CO_2 emission C_1 by the sector are calculated by following;

$$\mathbf{x}_1 = [\mathbf{I} - \mathbf{A}]^{-1} \cdot \mathbf{f}_1$$

$$C_1 = \mathbf{e}' \cdot \mathbf{x}_1$$

where,

$\mathbf{I}$:	identity matrix
$\mathbf{A}$:	input coefficients matrix
$\mathbf{e}$:	CO_2 emission coefficient
$\mathbf{f}_1$:	input vector of aerospace sector
$\mathbf{x}_1$:	production vector induced by aerospace sector
C_1:	CO_2 emission induced by aerospace sector

In the elements of $\mathbf{x}_1$, figures of 6 sectors such as Plastic products sector, Sheet glass and safety glass sector, Clay refactories sector, Hot rolled steel, Aluminiuim sector, and Other non-ferrous metals sector listed in NASA/DOE Reference system remain, the other sectors are made to be zero. We call this vector $\mathbf{f}_2$ and calculate again using $\mathbf{f}_2$;

$$C_2 = \mathbf{e}' \cdot [\mathbf{I} - \mathbf{A}]^{-1} \cdot \mathbf{f}_2$$

The term " Raw Material Ratio " is defined by;

$$\frac{C_1}{C_2} = \frac{\text{CO}_2 \text{ emission from total process}}{\text{CO}_2 \text{ emission form production of raw materials}} = \text{“}\textit{Raw Material Ratio}\text{”}$$

The " Raw Material Ratio "calculated for aerospace vehicles in the I-O tables is 2.5, and so this figure can be also used for the HLLV. The CO_2 emission from producing the raw materials for a single HLLV was estimated as 5498.3 tons based DOE/NASA Reference report. Consequently the total CO_2 released in the production of the HLLV is (5498.3 x 2.5) = 13745.75 tons, or some 14,000 tons per vehicle.

The same calculation was used for the other space transportation vehicles.

B Appendix.2

In the simulation of SPS-Breeder scenario we divide the Electric power sector into existing electric power sector and SPS in the environmental I-O Table. Figure 3 shows new Environmental I-O Tabulation[5].

$\boldsymbol{A_{11}}, \boldsymbol{A_{12}}, \boldsymbol{A_{21}}, \boldsymbol{A_{22}}$	:	input coefficient matrix divided as indicated in Figure 3
$\boldsymbol{f^R}, \boldsymbol{f^S}$	:	commodity vectors of rectenna(R) and SPS Photo − voltaic Cells(S) constructed step by step during N period
$\boldsymbol{f^0}$	:	commodity vector of SPS component constructed at a time (ex. Spase Base)
$\boldsymbol{X_1}$	:	vector of induced production excluded electric power generation
x_2	:	induced production in electric sector
z_1, z_2	:	productions induced by existing electric power generationg system, and by SPS respectively
$\boldsymbol{e}$	:	CO_2 emission coefficient (CO_2 emission per production)
$\boldsymbol{\alpha}$	:	vector of share of elctric power supply

[5]For detailed arguments for tabulation, see Yoshioka and Suga[19]

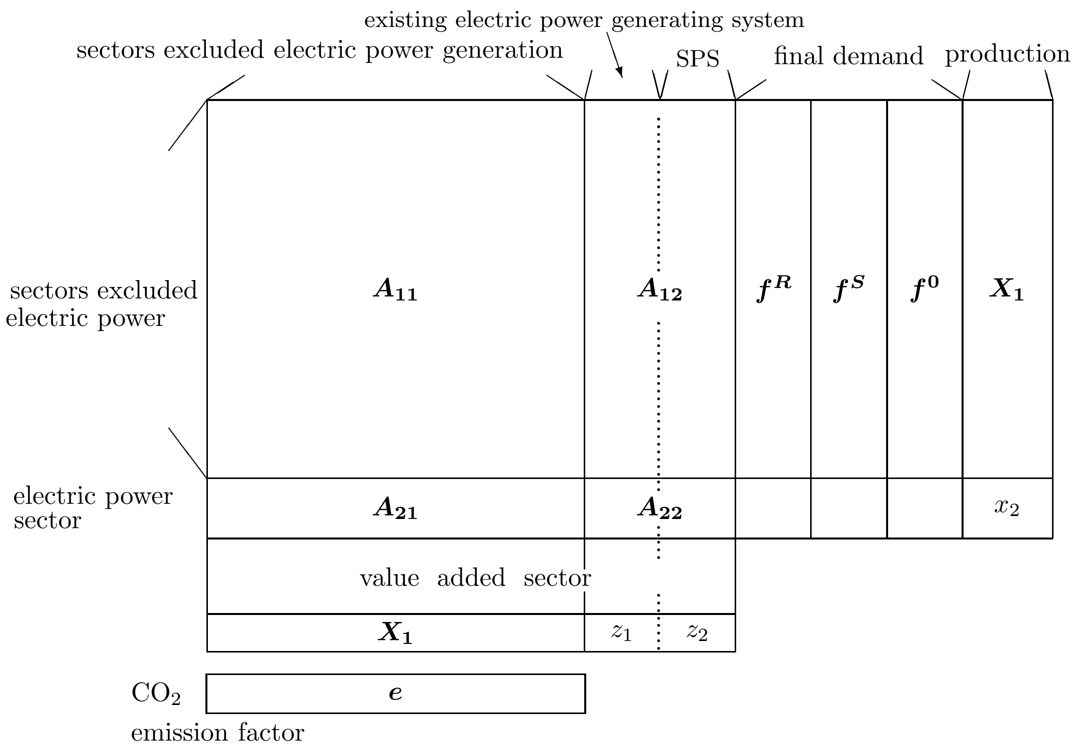

Figure 3: Outline of environmental I-O table for the SPS-Breeder scenario

Let us now explain the a method of calculation. If SPS components are constructed by using only electric power from existing electric power generation system, $\boldsymbol{X_1}$ and x_2 induced by $\boldsymbol{f(f^R, f^S, f^0)}$ are obtained by solving following vector-valued function:

$$\left\{ \begin{array}{rcl} \boldsymbol{A_{11}X_1 + A_{12}z + f} &=& \boldsymbol{X_1} \\ \boldsymbol{A_{21}X_1 + A_{22}z} &=& x_2 \\ \begin{pmatrix} \boldsymbol{z_1} \\ \boldsymbol{z_2} \end{pmatrix} &=& \boldsymbol{\alpha} x_2 \quad \textbf{where,}\boldsymbol{\alpha} = \begin{pmatrix} \mathbf{1} \\ \mathbf{0} \end{pmatrix} \end{array} \right. \tag{1}$$

And $CO_{\mathbf{2}}$ emission are calculated by:

$$CO_2 = \left(\quad \boldsymbol{e} \quad \right) \begin{pmatrix} \boldsymbol{X_1} \\ z_1 \\ z_2 \end{pmatrix}$$

In the next step SPS activity is divided by N. In the 1st period, space transportation systems, space construction bases and $1/N$ pair of SPS Photo-voltaic Cells and Rectenna begin to be constructed. In this case $\boldsymbol{f}=\frac{\mathbf{1}}{\boldsymbol{N}}\boldsymbol{(f^R + f^S) + f^0}$ and a vector of share of electric pawer $\boldsymbol{\alpha}$ are $\boldsymbol{\alpha}=(1 \;\; 0)'$.

In the 2nd period, if total electric energy from SPS system is SkWh/year and $\boldsymbol{f}$ is given by $\frac{\mathbf{1}}{\boldsymbol{N}}\boldsymbol{(f^R + f^S)}$, $\boldsymbol{X_1}$, x_2, and CO_2 are calculated by:

$$\left\{ \begin{array}{rcl} z_2 &=& \mathrm{S}/N \\ z_1 + z_2 &=& x_2 \\ \boldsymbol{A_{11}X_1 + A_{12}z + f} &=& \boldsymbol{X_1} \\ \boldsymbol{A_{21}X_1 + A_{22}z} &=& x_2 \\ CO_2 &=& \left(\quad \boldsymbol{e} \quad \right) \begin{pmatrix} \boldsymbol{X_1} \\ z_1 \\ z_2 \end{pmatrix} \end{array} \right. \tag{2}$$

As the same way, in the tth($t = 3, ..., N$) period, $\boldsymbol{X_1}$, x_2, and CO_2 emission induced by $\boldsymbol{f}=\frac{\mathbf{1}}{\boldsymbol{N}}\boldsymbol{(f^R + f^S)}$ are calculated by:

$$\left\{\begin{array}{rcl} z_2 & = & (t-1)\mathrm{S}/N \\ z_1+z_2 & = & x_2 \\ \boldsymbol{A_{11}X_1}+\boldsymbol{A_{12}z}+\boldsymbol{f} & = & \boldsymbol{X_1} \\ \boldsymbol{A_{21}X_1}+\boldsymbol{A_{22}z} & = & x_2 \\ \mathrm{CO}_{\mathbf{2}} & = & \left(\quad \boldsymbol{e} \quad\right)\left(\begin{array}{c} \boldsymbol{X_1} \\ z_1 \\ z_2 \end{array}\right) \end{array}\right. \tag{3}$$

By calculating equation (3) from $t = 3$ to N continuously and summing up the CO_2 emission step by step, we obtain the total CO_2 emission in SPS-Breeder scenario.