Economic, Environmental and Energy Analysis on Future Energy Production Technology: Solar Power Satellite[1]

Keiichiro Asakura
Faculty of Economics , Ryutsu Keizai University
E-mail:asakura@rku.ac.jp

Satoshi Nakano
The Japan Institute for Labour Policy and Training

Abstract

The authors are focusing on the solar power satellite (SPS) as an alternative power generation technology for the future. SPS technology is based on satellites with photovoltaic (PV) panels in geostationary orbit (GEO). The SPS continuously generates electricity regardless of the weather or time of day and transmits this power to the Earth's surface. The SPS does not use fossil fuel for electricity production and can supply large amounts of electric energy.

Therefore, the authors elucidate the multiple aspects of the SPS system through common evaluation methods and an I-O database. In this paper, CO_2 emission and the energy payback time (EPT) and energy profit ratio (EPR) of the SPS system are calculated as environmental-energy indicators. Then the SPS system is compared with various types of power generation from the various viewpoints

The results show that the SPS system is superior in terms of CO_2 emission and energy, however, the cost for electricity production seems to be very high, then we are conducting the further calculation to confirm the economic aspect of SPS.

[1] This paper is confined to CO_2 Emission and energy aspects on the solar power satellite and it includes tentative results. Final result including power production cost of SPS will be presented at the conference. This paper is based on the chapter 5 in Nakano,S. and Asakura,k.(2010.2) "Input-Output Table for Environmental Analysis of Japan: Construction and Application", KEO Discussion Paper,no.121(August 2011,revised).

1 Introduction

The authors are focusing on the solar power satellite (SPS) as an alternative power generation technology for the future. SPS technology is based on satellites with photovoltaic (PV) panels in geostationary orbit (GEO). The SPS continuously generates electricity regardless of the weather or time of day and transmits this power to the Earth's surface. The SPS does not use fossil fuel for electricity production and can supply large amounts of electric energy.

Therefore, the authors elucidate the multiple aspects of the SPS system through common evaluation methods and an I-O database. In this paper, CO_2 emission and the energy payback time (EPT) and energy profit ratio (EPR) of the SPS system are calculated as environmental-energy indicators. Then the SPS system is compared with various types of power generation from the various viewpoints.

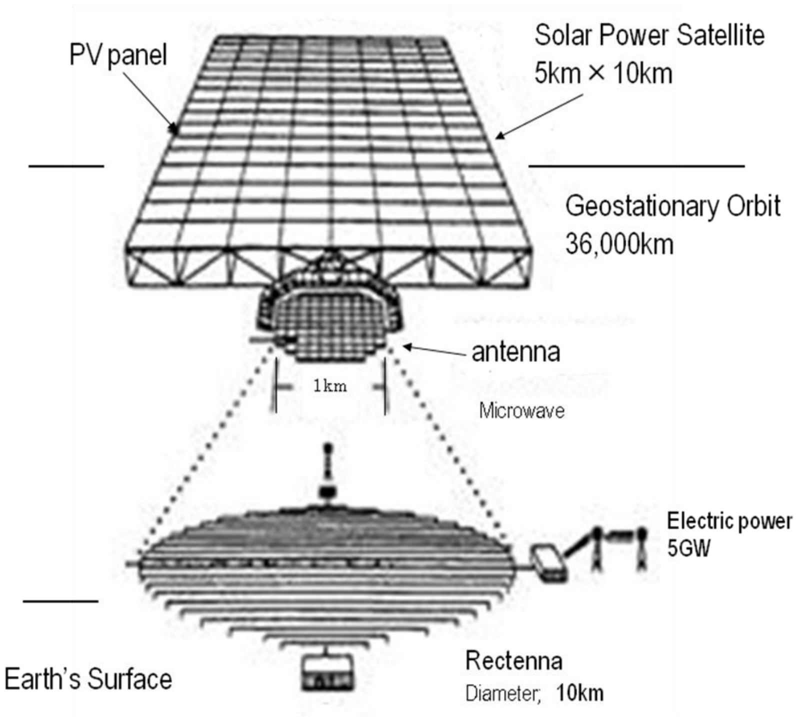
2 Basic Concept of SPS

The PV cells have been receiving increasing attention as a means of electricity generation that produces no CO_2, NOx, or SOx pollution. However, stable electricity generation is difficult because solar energy generation is impossible at night and the poor efficiency during cloudy weather. However, if solar panels are launched into space, they can produce continuous power independent of the weather or the day-and-night cycle. The solar power satellite (SPS) concept is very simple: a satellite carrying PV panels in GEO generates electricity and transmits it to the Earth's surface.

The basic concept of SPS was first published by Glaser (1968); the US Department of Energy (DOE) and NASA published a reference system in 1978, which is referred to as the "DOE/NASA reference system" . Although the reference system was published more than 30 years ago, no other equally detailed system has been proposed since then; therefore, it remains the representative plan for future SPS systems.

Figure 1 shows the concept of the DOE/NASA reference system. The satellite is shown in the upper part: it has a rectangular structure 10 km long by 5 km wide and 300 m deep. It carries PV panels over its surface and transmits the generated power from the 1-km diameter antenna using high-frequency microwaves. The lower half shows the rectenna on the Earth, which receives and rectifies the microwaves from the satellite; it is elliptical in shape and has dimensions of 13 km by 10 km. Each satellite-rectenna pair has an output of 5 GW, and the reference system is comprised of 60 such satellites. The total annual output of electric energy has been estimated to be 2,628 billion kWh.

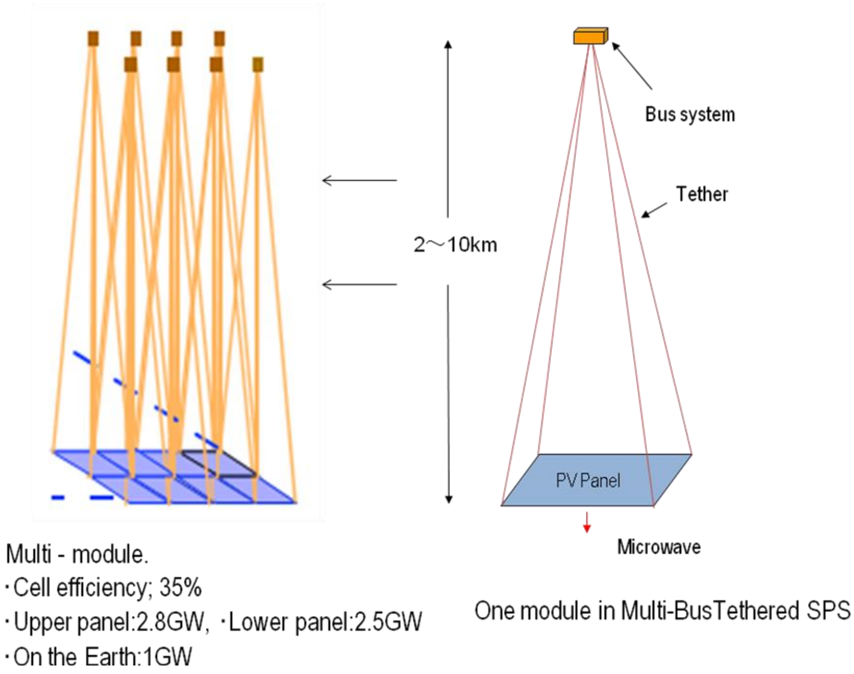
Figure 1 DOE/NASA reference system



*DOE/NASA(1980) 'SPS-FY79 Program Summary'

The SPS concept of the DOE/NASA reference system is very clear, but it may be too large in scale for construction; therefore, smaller types of SPS have been presented by the Institute for Unmanned Space Experiment Free Flyer (USEF), the New Energy and Industrial Technology Development Organization (NEDO) and the Japan Aerospace Exploration Agency (JAXA) that have relatively higher feasibility since 1990's. Fig.2 shows the satellite structure of the latest SPS –Multi Bus Tethered SPS - developed by Sasaki(2006a,2009).

Figure.2 Features of multi-bus tethered satellite

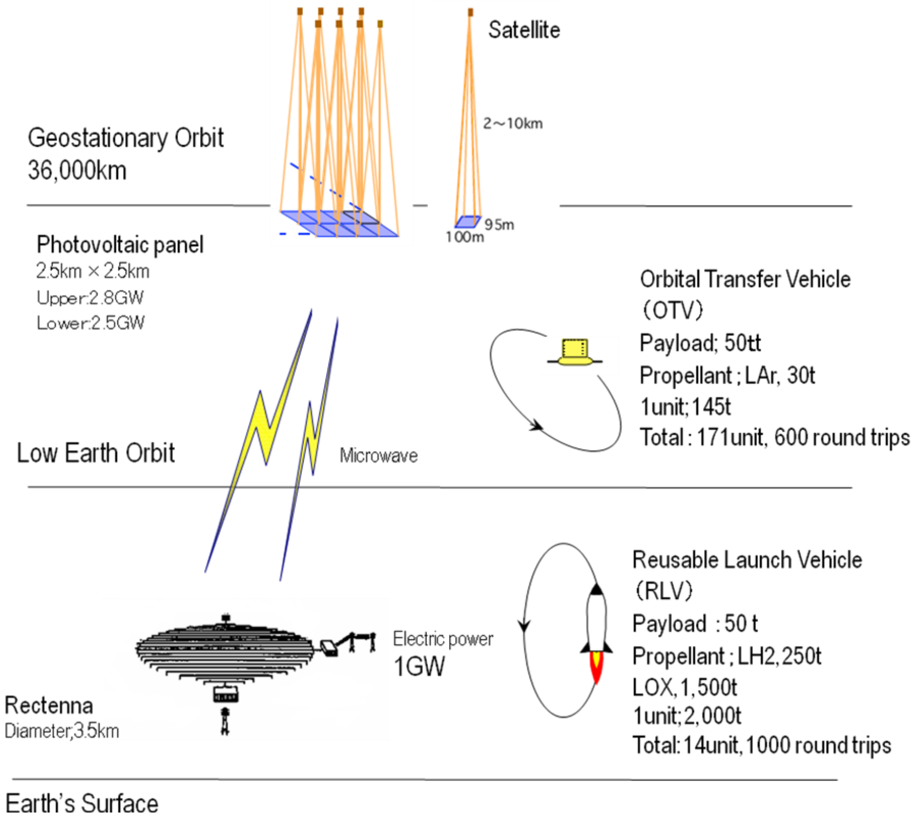


*This technoloby presented by Sasaki (2006a, 2009)

The new SPS system has two features. First, the satellite has a multi-module structure, and the tethers link the bus system with a PV panel in each module. Second, each module itself functions as an electric power generator. The attached PV panel has a high power conversion efficiency of 35%, and the total electric power generated by 625 modules is 2.8 GW in the upper panel and 2.5 GW in the lower one.[2] The generated electricity is charged by a battery, controlled to 1.36 GW and changed to microwave beams; the microwave is then transmitted to the rectenna, which receives and rectifies the microwaves and supplies 1 GW of electricity to industries and households.

[2] The current conversion efficiency of space solar cells has not yet reached 35%.

Figure.3 Construction on multi-bus tethered satellite- Key Items



* This Picture was drowned by authors based on Sasaki (2006a, 2009) and the viewpoint of calculation of CO_2 emissions from SPS.

We then proceed to the SPS construction process in Figure 3 , which is deeply related to the calculation of the CO_2 emissions. First, the Reusable Launch Vehicle (RLV) carries the Orbital Transfer Vehicle (OTV) and satellite to low-earth-orbit; the OTV then carries the satellite to geostationary orbit; finally, the satellite deploys automatically, and the SPS satellite is completed when the 625 modules are connected to each other. We discuss the RLV and OTV structures in more detail here.

The total mass of the RLV is 2,000 tons; it is comprised of the payload (50 tons), structure (200 tons), liquid oxygen (LOX) (1,500 tons), and liquid hydrogen (LH_2) (250 tons); the latter two serve as propellants. Fourteen RLVs make 1,000 round trips in total.[3]

The OTV has 2,151 kW of PV panels which ionize liquid argon (LAr) for space propulsion. The total mass of the OTV is 145 tons, which is comprised of the payload (50 tons), structure (54 tons), PV panels (22 tons), and liquid argon (LAr) (30 tons, round trip). One hundred seventy-one OTVs make 600 round trips in total.

[3] Total mass-payload ratio was assumed to be 2.5%, which is very high and a future target. The present ratio is about 1.5%.

3 The model and basic data

The CO_2 emisson that would be produced by constructing and operating the SPS system is estimated using "2000 Input-Output Table for Environmental Analysis (IOTEA)"[4]. Environmental Input-Output analysis based on open input-output model is given by;

$$CO_2^k = C(I - A)^{-1} f^k \quad (1)$$

C: CO_2 emission coefficient (diagonal)

$(I - A)^{-1}$: Leontief inverse matrix

f^k: final demand (FD) vector of kth item of the SPS system

(e.g., $k = 1$, satellite; $k = 2$, OTV; k=3,rectenna;…)

$CO2^k$: CO_2 emission of kth item of SPS system.

C on the right-hand side of equation (1) is derived in the IOTEA, calculated by (CO_2 emission) /(domestic production) in each sector and $(I - A)^{-1}$ can be calculated from the official *2000 Input-Output Table*; therefore, we have to determine the FD vectors for each item such as the satellite, OTV, RLV, rectenna, propellant (LAr, LOX and LH_2), and PV panel, as shown in Fig. 3, to solve for CO_2^k.

Furthermore, the energy payback time (EPT) and energy profit ratio (EPR) of the SPS system are also calculated using 2000 IOTEA. The model is given by;

・EPR= (E_out×n) / (E_in_1+E_in_2×n) (2)

・EPT=E_in_1/ (E_out−E_in_2) (3)

E_out : electricity generated per year

E_in_1 : energy input in construction(by using IOTEA)

E_in_2 : energy input in operation and maintenance per year(by using IOTEA)

n : lifetime of SPS

Here we explain the procedure to set FD vector.

Figure 4 shows the basic procedure for determining an FD vector, using the satellite as an example. First, the unit price and amounts of material inputs are gathered; second, these are linked according to Input-Output Table classification; finally, the trade and transport margins are added.

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[4] See Nakano et al.(2008) and Nakano and Asakura(2010). Although the authors have constructed "2005 IOTEA", there is a limitation for the source data on which 2005 IOTEA is based, so that the authors conduct this calculation throught "2000 IOTEA".

Figure.4 Procedure to determine FD vectors

①Material Input Information(e.g. Satellite)

Resource Requirements	Material Input	Unit Price
silicon transistor	a	p_a
silicon diode	b	p_b
CPU	c	p_c
DRAM	d	p_d
.	.	.
.	.	.
.	.	.

②I-O sector

I-O Classification	Prices
semiconductor devices	a×p_a
semiconductor devices	b×p_b
integrated circuits	c×p_c
integrated circuits	d×p_d
.	.
.	.
.	.

③Add Margin

I-O Classification	Prices
semiconductor devices	a×p_a
semiconductor devices	b×p_b
integrated circuits	c×p_c
integrated circuits	d×p_d
.	.
.	.
.	.
trade and transport margin	m1
	m2
	.
	.

*Main data source of FD vectors estimated are DOE/NASA(1980),Society of Chemical Engineers(1995),Yearbook Machinery Statistics, Unit price information in IO Databases, Naruo et al.(1996) and Sasaki(2006a,2009) etc.

Here, we summarize the basic information to determine the FD vectors of the SPS total system.

Satellite: A satellite needs the following electronic components per square meter: 4 silicon transistors, 68 field-effect transistors, 4 diodes, 4 MUPs, 4 DRAMs, 8 chip resistors, 8 tantalum electrolytic capacitors, 1 m^2 multilayer printer boards, and 4 lithium ion batteries. Each satellite is comprised of 4,400 tons of rolled and drawn aluminum products and 45 tons of tether. Each unit price is from the *2000 Yearbook of Machinery Statistics* and the table on domestic products by sector and commodity of the *2000 Input-Output Table*.

OTV: The unit price of LAr in OTV is based on the annual average price in determined by the Economic Research Association (2000). The OTV structure was estimated from Sasaki and Yamagiwa (2000), the cargo orbit transfer vehicle (COTV) developed by DOE/NASA (1980), the table on domestic products by sector and commodity, and the airplane activity vector of the *2000 Input-Output Table*.

RLV: The unit price of LH_2 is based on estimates from Naruo et al. (1996), and the price for LOX is from the *2000 Yearbook of Machinery Statistics*. The RLV structure was estimated from the heavy lift launch vehicle (HLLV) developed by DOE/NASA (1980), the table on domestic products by sector and commodity, and the airplane activity vector of the *2000 Input-Output Table* .

Rectenna: The rectenna cost structure, its installation cost, and the number of diodes and antennas are estimated based on another type of Rectenna from DOE/NASA (1980), large-scale solar power systems on the ground (e.g., Society of Chemical Engineers 1995,Kato et al.1994,Nomura et al. 1995), and the electric power facilities construction activity in I-O Table. Inverters and relay switches are estimated from work done by the Society of Chemical Engineers (1995) , Kato et al.(1994) and Nomura et al. (1995)

PV: PV that are attached to the satellite and OTV are assumed to have high-conversion efficiency, be resistant to radiation, and workable except for the cover glass, which is similar to current copper indium gallium diselenide (CIGS) thin-film photovoltaic cells; however, it is difficult to obtain the structural information for this particular type. Therefore, we use recent solar cell activity estimated by Nakano (2007) under the strong assumption that solar cell activity does not change according to the conversion efficiency.

4 Overview of CO_2 Emissions- Multi-Bus Tethered-SPS

In this section, we describe the results for estimates of CO_2 emissions from the construction of our latest SPS - Multi-Bus Tethered - system. Table 1 show that the released CO_2 would be 11 million tons. The largest amount is released from the production processes of LOX and LH_2 in RLV, which account for 60% of the total CO_2 emissions. The second largest amount comes from the PV attached to the satellite and the OTV in total, which account for 22% of the total emissions.

Table 1 CO_2 emissions from SPS by items;
Multi-Bus Tethered-SPS

Item		kiloton	share(%)
Satellite	Structure	1116.9	10.4
	PV	2194.9	20.4
OTV	Structure	75.3	0.7
	LAr	61.0	0.6
	PV	152.3	1.4
RLV	Structure	47.0	0.4
	LO2,LH2	6406.9	59.6
Recttna		693.4	6.5
Total		10747.7	100.0

***OTV**: Orbital Transfer Vehicle, **RLV**: Reusable Launch Vehicle, **PV**: Photovoltaic cell, **LAr**: Liquid argon, **LH2**: Liquid hydrogen, **LOX**: Liquid oxygen. Figures are calculated by eq. (1). Figures don't include operation and maintenance.

Table 2 shows the four highest-ranking sectors of CO_2 emissions in the SPS system. For LH_2 and LOX in RLV, which induced the largest emissions according to Table 1, the production process of these propellants, such as compression and cooling, require large amounts of electricity; therefore, electricity-related sectors were ranked high as a result. In short, Table 2 shows that each item in the SPS system requires various kinds of materials directly, but direct and indirect CO_2 emissions are mainly induced by electrical power generation.

Table 2 CO_2 emissions from SPS by sectors:

Multi-Bus Tethered-SPS

	(a)satellite (structure)	Share(%)	(b)OTV(structure)	Share(%)
1	electricity	35.4	electricity	32.7
2	private power generation	10.4	private power generation	13.0
3	pig iron	6.2	pig iron	6.5
4	coal product	5.5	coal product	5.7
	others	42.5	others	42.1
	total	100.0	total	100.0
		(1,117 kilotons)		(75 kilotons)

	(c)OTV (LAr)	Share(%)	(d)RLV(structure)	Share(%)
1	electricity	73.1	electricity	30.9
2	compressed gas and liquefied gas	7.9	private power generation	15.1
3	private power generation	3.7	coal product	7.8
4	coal product	2.2	pig iron	7.7
	others	13.2	others	38.5
	total	100.0	total	100.0
		(61 kilotons)		(47 kilotons)

	(e)RLV (LH2,LO2)	Share(%)	(g)Rectena	Share(%)
1	electricity	63.9	pig iron	24.0
2	road freight transport	7.5	electricity	23.2
3	compressed gas and liquefied gas	6.7	private power generation	8.7
4	private power generation	3.6	coal product	7.9
	others	18.3	others	36.2
	total	100.0	total	100.0
		(6,407 kilotons)		(693 kilotons)

	(h)PV(satellte and OTV)	Share(%)	(i)SPS total	Share(%)
1	electricity	47.6	electricity	54.4
2	private power generation	10.7	private power generation	6.3
3	coal product	7.5	road freight transport	5.2
4	pig iron	4.7	coal product	4.1
	others	29.5	others	30.0
	total	100.0	total	100.0
		(2,347 kilotons)		(10,748 kilotons)

*figures are calculated by eq.(1).

5 Comparison of CO_2 Emission and Energy indicators

Lastly, we compare the CO_2 emissions and energy indicators of various SPS system with existing electricity generation systems. Taking the case of Multi-Bus Tethered-SPS as a example, first, the annual energy production of SPS can be calculated as:

1 GW × 24 h × 365 day = 8,760 GWh.

Second, as we assume the lifetime is 40 years, and the CO_2 emissions from SPS construction is 10,748 kilotons, the CO_2 emission per kWh can be estimated as:

10,748 kilotons/40 years/8,760 GWh × 1000 =30.7 g CO_2/kWh.

Finally, as we assume the operation and maintenance ratio to total system per year[5] are1.0% or 1.5% based on DOE/NASA or USEF, the CO_2 emission per kWh from the operation and maintenance activity can be also calculated, then the Table.3 show the result of our calculation;.

Table.3 CO_2 emissions per kWh of energy production and operation

(unit: g-CO_2/kWh)

	construction	operation and maintenance	Total
DOE/NASA	15	4	19
USEF	38	26	63
Multi-Bus Tethered[1]	37	15	52
Multi-Bus Tethered[2]	37	22	60
PV on the ground (sillicon type)			
polycrystalline	83	17	100
amorphous	57	11	68
Existing Power Plant(except for PV)			
nuclear power	13	3	16
LNG	460	2	462
oil	769	2	771
coal	1,069	3	1,072

Table Notes;

*Figures for Coal, Oil, LNG, and Nuclear are estimated by updated data based on Nakano et.al(2008)

*Figures for PV are the result of recalculation of Nakano (2007) using eq. (1).

*Figure for DOE/NASA and USEF are result of recalculation of Asakura et al.(2002) and Asakura et al.(2003) under the consistent evaluation methods and database with Multi.-Bus-Tethered.

*Lifetime assumption: DOE/NASA:30 years,USEF:40 years, Multi.-Bus-Tethered : 40 years.

*operation and maitenance ratio per year are estimated from our research based on DOE/NASA and USEF and apply them to Multi.-Bus-Tethered; DOE/NASA:1.0%,USEF:1.5%,Multi-Bus Tethered[1]:1.0% and Multi-Bus Tethered[2]:1.5%

*Each figure doesn't include recycle and scrap process.

[5] The author calculated operation and maintenance ratio based on DOE/MASA(1978,1980c),Franz and Cambel(1981),Shibata and Matsuoka(1997) and USEF(2003).

Table.4 EPR and EPT of SPS

	EPR	EPT
DOE/NASA	9.1	2.6
USEF	2.4	12.5
Multi-Bus Tethered1	2.7	11.8
Multi-Bus Tethered2	2.4	12.5
PV on the ground (sillicon type)		
polycrystalline	1.8	10.4
amorphous	2.9	6.0

	EPR	EPT
Existing Power Plant, exclude operation fuel		
LNG	9.1	0.3
COAL	8.7	0.5
OIL	9.1	0.3
nucler power	11.4	0.4
Existing Power Plant, include operation fuel		
LNG	0.3	129.8
COAL	0.2	170.2
OIL	0.2	149.0
nucler power	0.3	107.4

*Table Notes; see Notes under Table.2.
*Each figure is calculated from eq.(2) and (3).
*Figures for existing power plant are calculated as a reference.

Table.3 compares the CO_2 emissions per kWh of electrical energy produced by several types of existing electric power generation systems and the SPS systems. When comparing SPS systems one another, the DOE/NASA reference system has the lowest CO_2 emissions per kWh, as it has a very efficient transport system; i.e., the total mass-payload ratio is relatively higher than those for USEF, and multi-bus tether, which means relatively less propellant is needed.

When the CO_2 emissions of the multi-bus tethered SPS is compared with existing electric power generation systems, the SPS CO_2 emission is a little higher than that of nuclear power; however, it is much lower than that of fossil fuel electric power generation, 1/30 of coal, 1/24 of oil, and 1/20 of natural gas.

Table.4 indicates the energy feature of the SPS, and DOE/NASA has high efficiency here too. Although other SPS System have longer EPT than PV on the ground, the length of time doesn't exceed each lifetime.

5 Brief Concluding Remarks with calculation in progress

This study clearly shows that construction of the SPS system releases large amounts of CO_2; however, the CO_2 emissions per kWh for SPS are much lower than that of existing power plants. In addition, our recent calculations show that the CO_2 per kWh of SPS is in double digits even when the structures are different, such as DOE/NASA,USEF, and Multi-Bus Tether. Furthermore, the energy indicators show the SPS system seems to be a superior electricity generating system. However, the cost for electricity production seems to be very high, then we are conducting the further calculation to confirm the economic aspect of SPS[6].

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[6]The basic formula of calculation of power production cost is as follows and its results will be presented at the conference.

Unit Price of Electricity ＝ （Capital Cost＋Fuel＋O&M）/ Electricity ・・・ (4)

items		Calculating Formula
Capital Cost	Depreciation	Σ[Remaining Book Value ×Depreciation Rate×κ_i]
	Fixed Asset tax	Σ[Remaining Book Value× Fixed Asset Tax Rate ×κ_i]
	Operating Surplus	Σ[Remaining Book Value× Operating Surplus rate(＝q) ×κ_i]
O&E	Maintenance	Σ[Cf × P × Maintenance rate×κ_i]
	Wage and salaries	Σ[average wage and salaries × Employee × κ_i]
	Other Expenses	Σ[Cf × P × rate of Other Expenses × κ_i]
	Business Tax	Σ[Capital Cost＋Maintenance＋Wage and salaries ＋ Other Expenses) × tax rate/ (1－rate) × κ_i]
Electricity at Generation End		ΣG
Electricity at Transmission End		Σ[G×（1-Ls）]

Note;

・Cf : Unit price of Construction、P:Electricity（kw）、α : facility usage rate(%)、q : discount rate、Ls : electricity consumption rate within the station (%)、κ_i : discount factor: $(1+q)^{-I}$, G_i: P×24(hour)×365(day)×α×κ_i

・The items are arranged from OECD/NEA(2010) and The Federation of Electric Power Companies of Japan(2004) to calculate the power generation cost of SPS.

・'Fuel' is omitted in the case of SPS.

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