Title	Input-output table for environmental analysis of Japan: construction and application
Sub Title	
Author	中野, 諭(Nakano, Satoshi) 朝倉, 啓一郎(Asakura, Keiichiro)
Publisher	Keio Economic Observatory Sangyo Kenkyujo
Publication year	2011
Jtitle	KEO discussion paper No.121 (2011. 8)
JaLC DOI	10.14991/004.00000121-0001
Abstract	This paper presents the construction method of the 2000 Input-Output Table for Environmental Analysis of Japan and its application study. The first half of the paper describes the construction of energy inputs and CO2 emissions tables corresponding to the official Input-Output Table by the Ministry of Internal Affairs and Communications, using economic and energy statistics. The second half quantifies the CO2 emission of new power generation technology; Solar Power Satellites (SPS) as one of the application study.
Notes	
Genre	Technical Report
URL	https://koara.lib.keio.ac.jp/xoonips/modules/xoonips/detail.php?koara_id=AA10715861-00000121-0001

Input-Output Table for Environmental Analysis of Japan: Construction and Application

Satoshi NAKANO
Keiichiro ASAKURA

August 2011 (revised)
February 2010
KEO Discussion Paper No. 121

Input-Output Table for Environmental Analysis of Japan: Construction and Application

Satoshi Nakano*
The Japan Institute for Labour Policy and Training
Keio Economic Observatory, Keio University
and
Keiichiro Asakura
Faculty of Economics, Ryutsu Keizai University

August 2011 (revised)
February 2010

Abstract

This paper presents the construction method of the 2000 Input-Output Table for Environmental Analysis of Japan and its application study. The first half of the paper describes the construction of energy inputs and CO_2 emissions tables corresponding to the official Input-Output Table by the Ministry of Internal Affairs and Communications, using economic and energy statistics. The second half quantifies the CO_2 emission of new power generation technology; Solar Power Satellites (SPS) as one of the application study.

Keywords

CO_2 emissions, Input-Output Table, Life Cycle Assessment (LCA), Solar Power Satellites (SPS)

* Author for correspondence. The Japan Institute for Labour Policy and Training, 4-8-23 Kamishakujii, Nerimaku, Tokyo 177-8502, Japan. Tel: +81-3-5903-6223. Fax: +81-3-5903-6118. E-mail: nakano@sanken.keio.ac.jp (or) nakano@jil.go.jp

1. Introduction

Greenhouse gas (GHG) reduction targets of developed countries, including Japan, are provided in the Kyoto Protocol that came into effect in February 2005. Although Japan is required to reduce GHG emissions by 6% from 1990 levels during the first commitment period (2008–2012), domestic emissions have gradually increased instead. Even so, Prime Minister Hatoyama pledged to reduce emissions by 25% from 1990 levels by 2020 at the UN Climate Change Summit in 2009.

After the third UNFCCC Conference of the Parties (COP3) in 1997, international discussion regarding measures against global warming has continued, and COP15 was held in 2009. COP15 introduced the Copenhagen Accord and outlined measures to be implemented after 2013. However, forging an international consensus is a challenging task.

Our research group of environmental issues at Keio Economic Observatory, Keio University, has tried to construct the *Input-Output Table for Environmental Analysis* (*IOTEA*) *1985* and has addressed global warming issues based on the database. We used officially published information as much as possible for constructing the *IOTEA 1995* (Asakura *et al*. 2001) and enhanced the repeatability of constructing the database. The *IOTEA 2000* (Nakano *et al*. 2008) was constructed using the *2000 Input-Output Table* of Japan, and a framework for analyzing CO_2 emission structures by economic activities was prepared.[1]

The IOTEA is not only a basic reference for life cycle assessment (LCA) of technologies but also a database for scenario analysis of recycling processes and multi-sectoral economic models. If other countries construct the IOTEAs using common concepts and classifications and these tables are linked, the environmental impact of technology transfer and carbon leakage can be assessed.

This paper presents the construction method for the *IOTEA 2000* of Japan and its application to case studies. The first half of the paper describes the construction of the table with energy inputs and CO_2 emissions corresponding to the official *2000 Input-Output Table* constructed by the Ministry of Internal Affairs and Communications using economic and energy statistics. The second half quantifies the CO_2 emission of a new power generation technology as an application case study.

---

[1] Nakano (2009) has already constructed the *IOTEA 2005*. However, because studies have still not been conducted using this database, we introduce the estimation method for the *IOTEA 2000* and its application study in this paper.

2. Composition of IOTEA of Japan

The IOTEA of Japan consists of six tables (Figure 1): (1) monetary inputs of raw materials, including the energy goods listed in Table 1; (2) physical inputs of energy goods (original unit); (3) physical inputs of energy goods (calorie basis); (4) physical inputs of energy goods (CO_2 basis); (5) physical inputs of energy goods for non-energy use (CO_2 basis); and (6) CO_2 emissions.

The monetary input table shows the monetary inputs of raw materials by activities valued at producer prices. We used the transaction table (basic sector classification: 405 column sectors, 517 row sectors) of the *2000 Input-Output Table* as the monetary input table of the IOTEA. For analysis using the square table by sector aggregation, the following aggregation method is employed. First, row sectors are aggregated using six digits from the top of the seven-digit row code to reduce the number of row sectors to 401. Next, the square monetary input table (399 × 399) is derived by aggregating both column and row sectors based on Table 2.

The physical input table (original unit) shows the physical inputs of energy goods listed in Table 1 for each activity, by weight or volume. These energy goods include limestone, iron, and steel. Limestone, pig iron, crude steel (converters and electric furnaces), iron scrap, and blast furnace dust are required to calculate the carbon balance. These goods also include substitutable goods such as fly ash, blast furnace slag, converter slag, and electric furnace slag for other inputs that contain carbon.

By using the heating value per weight or volume as listed in Table 1, we can transform the physical input table (original unit) into the physical input table (calorie basis). Because the physical input table (calorie basis) shows the total heating value of energy inputs, we can identify energy-intensive sectors.

We can obtain the physical input table (CO_2 basis) by using the carbon content per weight or calorie as well as the physical input table (calorie basis). The physical input table (CO_2 basis) indicates that carbon in the inputs is fully emitted as CO_2. However, there are energy inputs for non-energy use. Hence, carbon in inputs for non-energy use should be deducted from the physical input table (CO_2 basis). This deduction is described in the physical input table of energy goods for non-energy use (CO_2 basis). The CO_2 emissions table is constructed by deducting the energy inputs for non-energy use from the energy inputs (CO_2 basis).

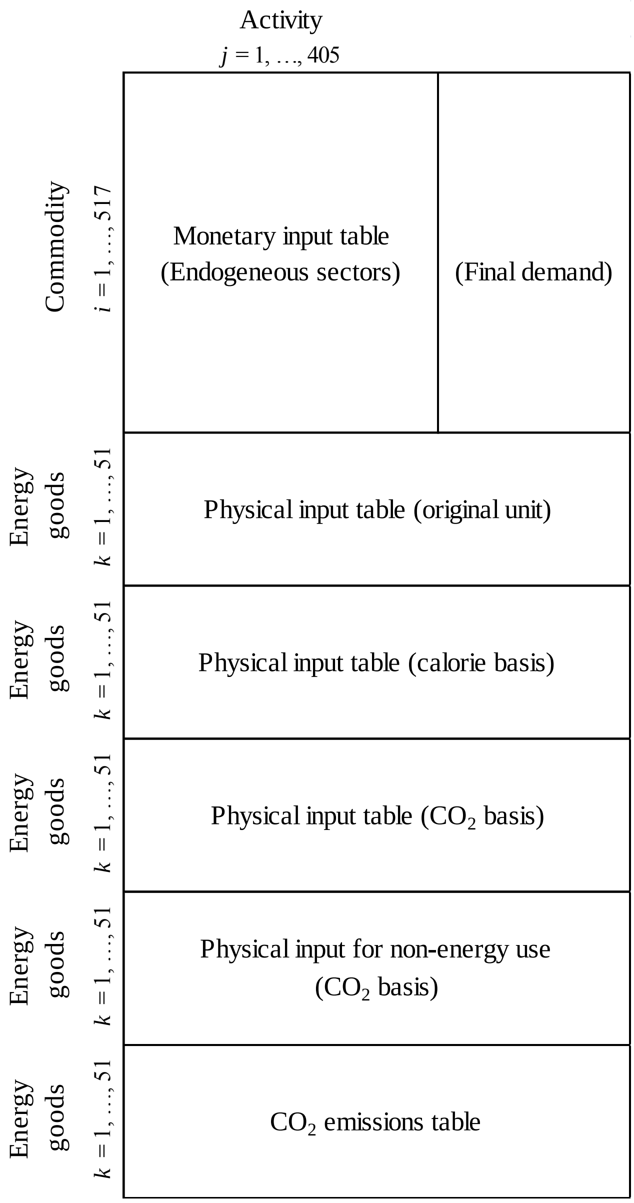


Figure 1: Composition of Input-Output Table for Environmental Analysis (IOTEA)

Table 1: Energy goods in IOTEA 2000

Energy goods	Original unit	Heating value per original unit MJ/Unit	CO_2 emissions per heating value kg-CO_2/GJ	Carbon content (ratio by weight)
1 Limestone	t			0.120
2 Fly ash	t			
3 Blast furnace slag	t			
4 Converter slag	t			
5 Electric furnace slag	t			
6 Coking coal	t	31814	81.61	
7 Steam coal	t	25426	94.75	
8 Crude petroleum	kl	38721	67.64	
9 Natural gas	$1000m^3$	41023	50.81	
10 LNG	t	54418	49.57	
11 Gasoline	kl	35162	66.03	
12 Jet fuel oils	kl	36418	67.62	
13 Kerosene	kl	37255	66.82	
14 Light oils	kl	38511	68.01	
15 Heavy oil A	kl	38930	69.60	
16 Heavy oil B and C	kl	41023	72.68	
17 Naphtha	kl	33488	67.95	
18 LPG (liquefied petroleum gas)	t	50232	59.73	
19 Oil produced by conversion	kl	33488	70.45	
20 Hydrocarbon oil	t	41023	77.09	
21 Hydrocarbon gas	$1000m^3$	39348	59.41	
22 Petroleum coke	t	35581	93.18	
23 Coke	t	30139	107.66	
24 Coke oven gas	$1000m^3$	20093	42.36	
25 Blast furnace gas	$1000m^3$	3349	99.32	
26 Converter furnace gas	$1000m^3$	8372	141.44	
27 Electric furnace gas	$1000m^3$	8372	183.25	
28 Tar	t	32065	89.15	
29 Crude benzene	t			0.923
30 Pig iron	t			0.040
31 Crude steel (converters)	t			0.003
32 Crude steel (electric furnaces)	t			0.003
33 Pig iron scrap	t			0.040
34 Steel scrap	t			0.003
35 Electricity	million kWh	3599960		
36 Private power generation	million kWh	3599960		
37 Gas supply	$1000m^3$	41860	49.68	
38 Steam and hot water supply	GJ	1000		
39 Black liquor	bone-dry t	12558	94.17	
40 General waste	t	6614	84.40	
41 Scrap wood	bone-dry t	16744	76.99	
42 Animal and plant residues	t			
43 Paper scrap	t	18795	90.45	
44 Wood waste	t	17581	96.69	
45 Waste textile	t			
46 Waste oil	t	27000	108.10	
47 Waste plastic	t	32341	79.02	
48 Sludge	t	14651	75.08	
49 Waste tire	t	32341	54.31	
50 Blast furnace dust	t			0.300
51 Used paper	t			

Source) *IOTEA 2000*

Table 2: Sector aggregation for IOTEA 2000

IOTEA		official IO	
Column sector			
011300	Vegetables	011301	Vegetables(outdoor)
		011302	Vegetables(under facilities)
031100	Marine fisheries(domestic)	031101	Coastal fisheries
		031102	Off-shore fisheries
		031103	Distant water fisheries
031200	Inland water fisheries and culture	031201	Inland water fisheries
		031202	Inland water culture
261101	Pig iron	261101	Pig iron
271109	Other non-ferrous metals	271109	Other non-ferrous metals
511100	Electricity	511101	Electricity(nuclear power)
		511102	Electricity(thermal power)
		511103	Electricity(water power, etc.)
Row sector			
011300	Vegetables	011300	Vegetables
031100	Marine fisheries(domestic)	031100	Marine fisheries(domestic)
031200	Inland water fisheries and culture	031200	Inland water fisheries and culture
261101	Pig iron	261101	Pig iron
		261201	Scrap iron
271109	Other non-ferrous metals	271109	Other non-ferrous metals
		271201	Non-ferrous metal scrap
511100	Electricity	511100	Electricity

3. Estimation

First, we construct the table that shows the physical inputs of energy goods (original unit), using economic and energy statistics. Next, the energy input table (original units) is converted into tables that describe the physical inputs of energy goods (calorie basis and CO_2 basis) by per unit heat quantity and carbon content. Third, we estimate the energy inputs for non-energy use (CO_2 basis) from the information on energy consumption by usage. Finally, the CO_2 emissions table is built by deducting the energy inputs for non-energy use from the energy inputs (CO_2 basis).

3.1. Physical input table (original unit)

3.1.1 Physical input table of *2000 Input-Output Table*

The physical inputs of coking coal, steam coal, crude petroleum, gasoline, jet fuel oils, kerosene, light oils, heavy oil A, heavy oil B and C, naphtha, Liquefied petroleum gas (LPG), coke, electricity, gas supply, and steam and hot water supply are based on the physical input table of the *2000 Input-Output Table*. Although the physical inputs of coal are available from the physical input table of the *2000 Input-Output Table*, we cannot divide it into coking and steam coal. Therefore, we divided coal inputs in the *2000 Input-Output Table* using the coking and steam coal shares in the physical input table of the *1995 Input-Output Table*.

3.1.2 Natural gas and liquid natural gas (LNG)

Natural gas and LNG consumption is estimated by the transaction table of the *2000 Input-Output Table* and *Japan Exports & Imports 2000*. The natural gas sector in the transaction table includes natural gas and LNG. The transaction table shows not only the monetary input of domestic natural gas but also the monetary input of imported natural gas. All LNG is imported, while all natural gas is domestically produced. Therefore, the domestic natural gas in the transaction table denotes so-called natural gas, and the imported gas denotes LNG. Natural gas and LNG consumption is estimated by dividing the monetary inputs of domestic and imported gas in the transaction table by the unit prices of natural gas and LNG, respectively. Table 3 shows the unit prices of these energy goods.

Table 3: Unit price of LNG and natural gas in 2000

	Unit	Price
LNG	yen/t	28,199
Natural gas	yen/1000m^3	31,494

Source) *2000 Input-Output Table* and *Japan Exports & Imports 2000*

3.1.3 Byproduct gas and other energy inputs

3.1.3.1 Mining and manufacturing sector

The consumption of oil produced by conversion, hydrocarbon oil, hydrocarbon gas, petroleum coke, coke oven gas, blast furnace gas, converter furnace gas, electric furnace gas, and waste tires in the mining and manufacturing sectors (excluding ten iron and steel sectors and the petroleum refinery products sector) is described in the *Structural Survey of Energy Consumption in Commerce and Manufacturing 2000*.

The industry classification in the *Structural Survey* is based on the classification in the *Census of Manufacturers 2000*. This classification is not consistent with the sector classification of the *2000 Input-Output Table*. Hence, we converted the energy consumption of the former into the latter using a bridge table between the *Census of Manufacturers* and the *Input-Output Table* that was included in the *2000 Input-Output Table*.

The energy consumption in the *Structural Survey* includes the consumption for boilers to obtain heat and electricity. The private power generation of each industry is reported in the private power generation sector of the *Input-Output Table*. Therefore, we divided the energy consumption for boilers into the consumptions for generating electricity and obtaining heat by using the amount of private power generation and the thermal efficiency for power generation (38.1%). The former was allocated to the private power generation sector of the *Input-Output Table*.

3.1.3.2 Ten iron and steel sectors

The consumption of hydrocarbon oil, petroleum coke, coke oven gas, blast furnace gas, converter furnace gas, electric furnace gas, tar, and iron scraps in ten iron and steel sectors, including pig iron, ferroalloys, crude steel (converters and electric furnaces), hot-rolled steel, steel pipes and tubes, cold-finished steel, coated steel, cast and forged steel, and cast and forged materials (iron) was obtained from the *Yearbook of Iron and Steel Statistics 2000*. The byproduct gas yield is also available from this publication. The energy consumption for power generation and boilers in the iron and steel sectors is divided by the steam consumption for power generation and production process. Table 4 shows the corresponding relationship between the *Yearbook* and IOTEA. The energy consumption of ten iron and steel sectors (Table 5) was estimated based in Table 4.

Table 4: Bridge table between *Yearbook of Iron and Steel Statistics* and IOTEA

Yearbook of Iron and Steel Statistics	IOTEA
For sintering For pellets For iron-making	Pig iron
For ferro-alloys	Ferro alloys
For steel-making(LD converters)	Crude steel (converters)
For steel-making(electric furnaces)	Crude steel (electric furnaces)
For steel forgings For steel castings	Cast and forged steel
For rolled steel, and steel pipes and tubes	Hot rolled steel Steel pipes and tubes Cold-finished steel
Other iron and steel sector	Coated steel
For power generation, boiler and co-generation	Private power generation Ten iron and steel sectors
Coke production sector	Coal products

Table 5: Energy consumption of ten iron and steel sectors in 2000

	Coke oven gas 1000m^3	Balst furnace gas 1000m^3	Converter furnace gas 1000m^3	Electric furnace gas 1000m^3	Hydrocarbon oil kl	Petroleum coke t
Yearbook of Iron and Steel Statistics and Structural Survey of Energy Consumption in Commerce and Manufacturing						
For sintering	157,390	57,197	29,409	0	0	0
For pellets	52,235	0	0	0	0	0
For iron-making	1,533,700	31,657,698	1,097,780	0	0	601,745
For ferro-alloys	3,741	1,455	5,005	6,565	0	6,526
For steel-making(LD converters)	334,090	8,981	19,857	0	0	0
For steel-making(electric furnaces)	27,534	680	2,630	0	0	6,668
For steel forgings	38,447	2,002	7,799	0	0	0
For steel castings	2,654	0	0	0	0	0
For rolled steel, and steel pipes and tubes	4,166,929	1,342,584	1,517,728	0	0	0
For power generation, boiler and co-generation	1,555,768	34,648,421	2,245,809	0	0	0
Other iron and steel sector	380,777	1,559,431	34,686	0	0	54
Coke production sector	1,474,748	16,407,326	206,722	0	142,010	566,474
Cast and forged materials (iron)	53	0	0	0	0	0
Total	9,728,066	85,685,775	5,167,425	6,565	142,010	1,181,467
Input-Output Table for Environmental Analysis						
Pig iron	1,869,002	41,562,807	1,416,568	0	0	601,745
Ferro alloys	4,011	1,907	6,290	6,565	0	6,526
Crude steel (converters)	358,175	11,770	24,955	0	0	0
Crude steel (electric furnaces)	29,519	891	3,305	0	0	6,668
Hot rolled steel	2,597,832	1,023,167	1,109,170	0	0	0
Steel pipes and tubes	412,166	162,333	175,978	0	0	0
Cold-finished steel	1,457,328	573,975	622,220	0	0	0
Coated steel	408,227	2,043,656	43,591	0	0	54
Cast and forged steel	44,064	2,624	9,801	0	0	0
Cast and forged materials (iron)	57	0	0	0	0	0
Private power generation	1,072,937	23,895,320	1,548,825	0	0	0
Coal products	1,474,748	16,407,326	206,722	0	142,010	566,474
Total	9,728,066	85,685,775	5,167,425	6,565	142,010	1,181,467

Source) *Input-Output Table 2000, Yearbook of Iron and Steel Statistics 2000, Structural Survey of Energy Consumption in Commerce and Manufacturing 2000, and IOTEA 2000*

3.1.3.3 Three pulp and paper and petroleum refinery products sectors

The black liquor and scrap wood consumption of the pulp, paper, and paperboard sectors is included in the *Yearbook of the Current Survey of Energy Consumption in Manufacturing 2000*. The consumption of hydrocarbon oil, hydrocarbon gas, and petroleum coke in the petroleum refinery products sector is also included in this publication. The consumption for boilers of these sectors is divided into the consumption for private power generation and the production process by the steam consumption. Tables 6 and 7 show the black liquor and scrap wood consumption of the pulp and paper sectors, respectively. Table 8 shows the energy consumption of the petroleum refinery products sector.

Table 6: Black liquor consumption of three pulp and paper sectors in 2000

(Unit: bone-dry t)

	Consumption incl. private power generation use	Share of private power generation	Consumption for private power generation	Consumption excl. private power generation use
Pulp	5,933,778	0.463	2,750,183	3,183,595
Paper	7,898,600	0.463	3,660,837	4,237,763
Paperboard	762,188	0.463	353,258	408,930

Source) *Yearbook of Current Survey of Energy Consumption in Manufacturing 2000 and IOTEA 2000*

Table 7: Scrap wood consumption of three pulp and paper sectors in 2000

(Unit: bone-dry t)

	Consumption incl. private power generation use	Share of private power generation	Consumption for private power generation	Consumption excl. private power generation use
Pulp	71,347	0.393	28,054	43,293
Paper	224,246	0.393	88,174	136,072
Paperboard	53,071	0.393	20,868	32,203

Source) *Yearbook of Current Survey of Energy Consumption in Manufacturing 2000 and IOTEA 2000*

Table 8: Hydrocarbon oil, petroleum oil, and hydrocarbon gas consumption of petroleum refinery products sector in 2000

	Unit	Consumption incl. private power generation use	Share of private power generation	Consumption for private power generation	Consumption excl. private power generation use
Hydrocarbon oil	kl	203,346	0.289	58,845	144,501
Petroleum coke	t	142,624	0.289	41,273	101,351
Hydrocarbon gas	$1000m^3$	8,848,048	0.043	382,927	8,465,121

Source) *Yearbook of Current Survey of Energy Consumption in Manufacturing 2000 and IOTEA 2000*

3.1.3.4 Electricity (thermal power) sector

The consumption of coke oven, blast furnace, and converter furnace gases in the thermal power electricity sector is described in the *Outline of Electricity Demand and Supply FY 1999 and 2000*. Table 9 shows the energy consumption of the electricity (thermal power) sector.

Table 9: Coke oven gas, blast furnace gas, and converter furnace gas of electricity (thermal) sector in 2000

	Unit	Consumption
Coke oven gas	1000m^3	2,350,952
Blast furnace gas	1000m^3	40,385,092
Converter furnace gas	1000m^3	1,477,861

Source) *Outline of Electricity Demand and Supply 1999 and 2000*

3.1.3.5 Gas supply sector

The consumption of coke oven, hydrocarbon, and methane gases in the gas supply sector is based on the *Yearbook of the Gas Supply 2000*. We related the coal and off gases included in other gases to coke oven and hydrocarbon gases, respectively. Table 10 represents the energy consumption of the gas supply sector.

Table 10: Gas consumption of gas supply sector in 2000

	Unit	Consumption
Coke oven gas	1000m^3	218,209
Hydrocarbon gas	1000m^3	81,626
Methane gas	1000m^3	720
Digestion gas	1000m^3	391

Source) *Yearbook of Gas Supply 2000*

3.1.4 General and industrial waste

The amount of incinerated general waste and industrial waste—including slag, metal scrap, animal excreta, construction and demolition waste, animal and plant residues, dust, paper scrap, glass and pottery waste, waste oil, combustion residue, animal carcass, wood waste, waste plastic, waste acid, waste textile, waste rubber, sludge, and waste alkali—is estimated using the *State of Discharge and Treatment of Industrial Waste* and the *State of Discharge and Treatment of Municipal Solid Waste* for FY 2000.

General waste management is allocated to the waste management service (public) sector in the *Input-Output Table*, and the incineration disposal amount of general waste is available from the report. Industrial waste management is allocated to the waste management services (private) sector. Because industrial waste is incinerated to reduce the volume in the intermediate process, we treat the reduced amount of incinerated waste such as paper scraps and wood waste as the incinerated amount. The incinerated amount of waste oil, waste plastic, and sludge is estimated using the ratio of the incinerated amount to the total amount in the *IOTEA 1990* (Ikeda *et al*. 1996). Table 11 shows the incinerated amount of general and industrial wastes in 2000.

Table 11: Incinerated waste in 2000

		Unit	Incinerated amount	IOTEA
General waste		t	40,304,000	Waste management services (public)
Industrial waste	paper scrap	t	898,413	Waste management services (private)
	wood waste	t	2,901,729	Waste management services (private)
	waste oil	t	921,106	Waste management services (private)
	waste plastic	t	1,005,945	Waste management services (private)
	sludge	t	5,340,089	Waste management services (private)

Source) *State of Discharge and Treatment of Industrial Waste*, *State of Discharge and Treatment of Municipal Solid Waste* and *IOTEA 1990*

3.1.5 Slag of blast furnace, converter and electric furnace, dust of blast furnace and fly ash

The generation and utilization of blast furnace, converter, and electric furnace slag are obtained from the *Statistical Yearbook of Iron and Steel Slag*. The information on fly ash is based on a discussion with the Japan Fly Ash Association. The generation of blast furnace dust is estimated using the dust generation per unit production of pig iron in the *IOTEA 1990*.

3.2 Physical input table (calorie basis)

The physical input table (calorie basis) is converted from the physical input table (original unit) using the heating value per original unit (Table 1). This table shows which sector is energy intensive.

3.3 Physical input table (CO_2 basis), physical input table for non-energy use (CO_2 basis), and CO_2 emission table

The physical input table (CO_2 basis) is calculated by multiplying the physical input table (calorie basis) and CO_2 emissions per heating value listed in Table 1. The physical input table for non-energy use (CO_2 basis) is estimated using the combustion ratio or carbon balance table methods. The CO_2 emissions table is then built by deducting the physical input table for non-energy use (CO_2 basis) from the physical input table (CO_2 basis).

The combustion ratio method for estimating the physical input table for non-energy use (CO_2 basis) calculates the combusted proportion of the total inputs of energy goods and removes the combustion amount from the total inputs. In contrast, the carbon balance table method estimates the carbon content of outputs and uses it as the physical input for non-energy use. We applied the carbon balance table method to five sectors, including the coal products, pig iron, crude steel (converters), crude steel (electric furnaces) and gas supply sectors. The combustion ratio method was applied to the rest of sectors.

3.3.1 Combustion ratio method (*Structural Survey of Energy Consumption in Commerce and Manufacturing 2000*)

We applied the combustion ratio method to 400 sectors in the IOTEA. The combustion ratio in nine petrochemical products and chemical fertilizer sectors is based on the *Yearbook of the Current Survey of Energy Consumption in Manufacturing 2000*, while the ratio in the petroleum refinery products sector is estimated from the *Yearbook of Production Supply and Demand of Petroleum, Coal and Coke 2000* and the *Structural Survey of Energy Consumption in Commerce and Manufacturing 2000*. We assumed that all combustion ratios of the primary and tertiary industry sectors in the other 389 sectors are equal to one. The combustion ratio of the secondary industry sector in 389 sectors is based on the *Structural Survey of Energy Consumption in Commerce and Manufacturing 2000*.

However, we have given the combustion rate of certain energy goods. We converted the classification of the *Structural Survey of Energy Consumption in Commerce and Manufacturing* into that of the *Input-Output Table* using only the corresponding relationship between the shipment of the former and production of the latter. Therefore, the converted energy consumption may be not consistent with the classifications of the *Input-Output Table*. We used the following assumptions to tackle the problem. All coke oven gas, blast furnace gas, converter furnace gas, electric converter gas, gasoline, light oils, jet fuel oil, black liquor, scrap wood, general waste, paper scrap, wood waste, waste oil, waste plastic, sludge and waste tire were burned for all cases (i.e., the combustion ratio of these energy goods was equal to one). All coking coal was combusted in the chemical fertilizer and ferroalloy sectors, which do not produce coke, while no coking coal was combusted in the other sectors.

The *Structural Survey of Energy Consumption in Commerce and Manufacturing* reports energy consumption as raw materials. The combustion amount is estimated by deducting the consumption as raw materials from the total consumption, and the combustion ratio is obtained by dividing the combustion amount by the total consumption.

3.3.2 Combustion ratio method (*Yearbook of the Current Survey of Energy Consumption in Manufacturing 2000*)

The combustion ratios in nine petrochemical product sectors and the chemical fertilizer sector are based on the *Yearbook of the Current Survey of Energy Consumption in Manufacturing 2000*. The nine petrochemical product sectors include petrochemical basic products, petrochemical aromatic products, aliphatic intermediates, cyclic intermediates, synthetic rubber, thermo-setting resins, thermoplastics resins, high function resins, and other resins. We assumed the same combustion rate for the nine petrochemical products sectors. Tables 12 and 13 show the combustion ratios of energy goods in the nine petrochemical product sectors and the chemical fertilizer sector, respectively.

Table 12: Combustion share of nine petrochemical products sectors in 2000

	Unit	Consumption incl. non-energy use	Consumption for non-energy use	Combustion share
Kerosene	kl	1,094,258	992,762	0.093
Naphtha	kl	35,639,148	35,639,148	0.000
LPG	t	4,395,741	3,985,356	0.093
Oil produced by conversion	kl	16,823,249	16,823,249	0.000

Source) *Yearbook of Current Survey of Energy Consumption in Manufacturing 2000*

Table 13: Combustion share of chemical fertilizer sector in 2000

	Unit	Consumption incl. non-energy use	Consumption for non-energy use	Combustion share
Natural gas	$1000m^3$	167,873	87,310	0.480
Naphtha	kl	483,224	453,264	0.062
LPG	t	30,309	6,949	0.771
Hydrocarbon gas	$1000m^3$	344,954	228,348	0.338

Source) *Yearbook of Current Survey of Energy Consumption in Manufacturing 2000*

3.3.3 Combustion ratio method (*Yearbook of Production Supply and Demand of Petroleum, Coal and Coke 2000*)

The combustion ratio in the petroleum refinery product sector is calculated using the *Yearbook of Production Supply and Demand of Petroleum, Coal and Coke 2000* and the *Structural Survey of Energy Consumption in Commerce and Manufacturing 2000*. If the ratios obtained from the two sources were different, we selected the lower one. Table 14 represents the combustion ratio of energy goods in the petroleum refinery products sector.

Table 14: Combustion share of petroleum refinery products sector

	Unit	Consumption incl. non-energy use	Consumtion for combustion	Combustion share
Steam coal	t	198,399	195,869	0.98725
Kerosene	kl	92,073	41,455	0.45024
Light oils	kl	2,752	148	0.05378
Naphtha	kl	60,557	0.3	0.00001
Petroleum coke	t	1,965	1,872	0.95303
LPG	t	180,042	37,143	0.20630

Source) *Yearbook of Production Supply and Demand of Petroleum, Coal and Coke 2000*, and *Structural Survey of Energy Consumption in Commerce and Manufacturing 2000*

3.3.4 Combustion ratio of limestone

Limestone initiates a chemical reaction when it is heated or added to acid and the CO_2 is discharged. Most sectors consume limestone through the chemical reaction. However, the materials for ceramics sectors only crush the limestone, and the combustion ratio of limestone is equal to zero in this sector. The combustion ratio of limestone is estimated using information for 1995 from the Central Research Institute of Electric Power Industry (Hondo *et al*. 2002).

3.3.5 Physical input of gas supply

The *Structural Survey of Energy Consumption in Commerce and Manufacturing 2000* reports LNG consumption of the chemical industries, while the *Input-Output Table 2000* reports LNG consumption of only three sectors: gas supply, electricity (thermal), and private power generation. The LNG data of the *Structural Survey* includes the LNG supplied by gas suppliers. On the other hand, the *Input-Output Table* reports the LNG supplied by gas suppliers in the gas supply sector.

The cyclic intermediates, synthetic dyes, and organic pigment manufacturing data of the *Structural Survey* consider LNG as a raw material. Therefore, if the sectors shown in the *Input-Output Table* in relation to these manufacturing sectors burn all of their gas supply, the CO_2 emissions might be overestimated. Hence, when calculating the combustion ratio of the gas supply, the combusted gas supply of the sectors that consume LNG as raw material is estimated by deducting the gas supply as raw material from total gas supply inputs.

3.3.6 Carbon balance table method

We applied the carbon balance table method to the coal product, pig iron, crude steel (converters), crude steel (electric furnaces), and gas supply sectors. The carbon balance table shows the carbon content of inputs and outputs like a balance sheet. CO_2 emissions are calculated by deducting the total carbon content of inputs from the total carbon content of outputs.

We developed a material balance table that shows the physical inputs and outputs (original unit) and then converted the physical quantity (original unit) of the material balance table into carbon using the information listed in Table 1. Tables 15–19 show the material balance table of the pig iron, crude steel (converters), crude steel (electric furnaces), and gas supply sectors. Tables 20–24 show the carbon balance table based on Tables 15–19.

Table 15: Material balance table of coal products sector in 2000

	Unit	Input	Output
Coking coal	t	67,858,120	
Steam coal	t	60,000	
Gasoline	kl	56	
Kerosene	kl	8,069	
Light oils	kl	260	
Heavy oil A	kl	1,670	
Heavy oil B and C	kl	383	
Hydrocarbon oil	t	142,092	
Hydrocarbon gas	$1000m^3$	356	
Petroleum coke	t	566,672	
Coke	t		38,562,016
Coke oven gas	$1000m^3$		13,994,001
Blast furnace gas	$1000m^3$	18,904,221	
Converter furnace gas	$1000m^3$	363,916	
Tar	t		1,561,026
Crude benzene	t		519,867
Gas supply	$1000m^3$	605	

Source) *IOTEA 2000*

Table 16: Material balance table of pig iron sector in 2000

	Unit	Input	Output
Limestone	t	17,753,143	
Coking coal	t	397,518	
Steam coal	t	5,043,956	
Natural gas	$1000m^3$	1,334	
Kerosene	kl	75	
Heavy oil A	kl	1,507	
Heavy oil B and C	kl	33,958	
LPG	t	8,259	
Petroleum coke	t	601,745	
Coke	t	35,960,569	
Coke oven gas	$1000m^3$	2,379,125	
Blast furnace gas	$1000m^3$	41,562,807	132,380,518
Converter furnace gas	$1000m^3$	1,416,568	
Tar	t	52,695	
Pig iron	t		81,105,642
Pig iron scrap	t	2,488	
Gas supply	$1000m^3$	1,532	
Blast furnace dust	t		1,217,351

Source) *IOTEA 2000*

Table 17: Material balance table of crude steel (converters) sector in 2000

	Unit	Input	Output
Limestone	t	17,794,346	
Steam coal	t	730	
Natural gas	$1000m^3$	222	
Kerosene	kl	9,711	
Heavy oil A	kl	18,488	
Heavy oil B and C	kl	2,473	
LPG	t	851	
Coke	t	96,054	
Coke oven gas	$1000m^3$	455,934	
Blast furnace gas	$1000m^3$	11,770	
Converter furnace gas	$1000m^3$	24,955	8,437,446
Pig iron	t	77,145,345	
Crude steel (converters)	t		75,793,461
Pig iron scrap	t	557,251	
Steel scrap	t	6,274,734	
Gas supply	$1000m^3$	15,057	

Source) *IOTEA 2000*

Table 18: Material balance table of crude steel (electric furnaces) sector in 2000

	Unit	Input	Output
Limestone	t	1,003,835	
Steam coal	t	558	
Natural gas	1000m^3	1,048	
Kerosene	kl	9,002	
Heavy oil A	kl	10,466	
Heavy oil B and C	kl	2,002	
LPG	t	1,048	
Petroleum coke	t	6,668	
Coke	t	74,084	
Coke oven gas	1000m^3	37,576	
Blast furnace gas	1000m^3	891	
Converter furnace gas	1000m^3	3,305	
Electric furnace gas	1000m^3		98,148
Pig iron	t	1,780,351	
Crude steel (electric furnaces)	t		30,665,213
Pig iron scrap	t	742,014	
Steel scrap	t	30,028,684	
Gas supply	1000m^3	21,245	

Source) *IOTEA 2000*

Table 19: Material balance table of gas supply sector in 2000

	Unit	Input	Output
Coking coal	t	40,298	
Steam coal	t	442	
Natural gas	1000m^3	1,397,788	
LNG	t	15,562,894	
Kerosene	kl	412	
Heavy oil B and C	kl	427	
Naphtha	kl	1,027,075	
LPG	t	1,808,427	
Hydrocarbon gas	1000m^3	408,377	
Coke oven gas	1000m^3	615,287	
Gas supply	1000m^3	305,972	25,734,147
Methane gas	1000m^3	720	

Source) *IOTEA 2000*

Table 20: Carbon balance table of coal products sector in 2000 (Unit: t-C)

	Input	Output
Coking coal	48,046,942	
Steam coal	39,421	
Gasoline	35	
Kerosene	5,478	
Light oils	186	
Heavy oil A	1,234	
Heavy oil B and C	311	
Hydrocarbon oil	122,554	
Hydrocarbon gas	227	
Petroleum coke	512,407	
Coke		34,125,070
Coke oven gas		3,248,008
Blast furnace gas	1,714,726	
Converter furnace gas	117,525	
Tar		1,216,929
Crude benzene		479,837
Gas supply	343	
Total	50,561,390	39,069,844
CO_2		11,491,546

Source) *IOTEA 2000*

Table 21: Carbon balance table of pig iron sector in 2000 (Unit: t-C)

	Input	Output
Limestone	2,130,377	
Coking coal	281,462	
Steam coal	3,313,980	
Natural gas	758	
Kerosene	51	
Heavy oil A	1,114	
Heavy oil B and C	27,613	
LPG	6,758	
Petroleum coke	544,122	
Coke	31,822,946	
Coke oven gas	552,195	
Blast furnace gas	3,769,996	12,007,707
Converter furnace gas	457,472	
Tar	41,079	
Pig iron		3,244,226
Pig iron scrap	100	
Gas supply	869	
Blast furnace dust		365,205
Total	42,950,892	15,617,138
CO_2		27,333,754

Source) *IOTEA 2000*

Table 22: Carbon balance table of crude steel (converters) sector in 2000 (Unit: t-C)

	Input	Output
Limestone	2,135,322	
Steam coal	480	
Natural gas	126	
Kerosene	6,593	
Heavy oil A	13,662	
Heavy oil B and C	2,011	
LPG	696	
Coke	85,002	
Coke oven gas	105,822	
Blast furnace gas	1,068	
Converter furnace gas	8,059	2,724,823
Pig iron	3,085,814	
Crude steel (converters)		227,380
Pig iron scrap	22,290	
Steel scrap	18,824	
Gas supply	8,540	
Total	5,494,310	2,952,203
CO_2		2,542,107

Source) *IOTEA 2000*

Table 23: Carbon balance table of crude steel (electric furnaces) sector in 2000 (Unit: t-C)

	Input	Output
Limestone	120,460	
Steam coal	367	
Natural gas	596	
Kerosene	6,112	
Heavy oil A	7,734	
Heavy oil B and C	1,628	
LPG	858	
Petroleum coke	6,029	
Coke	65,560	
Coke oven gas	8,721	
Blast furnace gas	81	
Converter furnace gas	1,067	
Electric furnace gas		41,067
Pig iron	71,214	
Crude steel (electric converters)		91,996
Pig iron scrap	29,681	
Steel scrap	90,086	
Gas supply	12,050	
Total	422,243	133,063
CO_2		289,181

Source) *IOTEA 2000*

Table 24: Carbon balance table of gas supply sector in 2000 (Unit: t-C)

	Input	Output
Coking coal	28,533	
Steam coal	290	
Natural gas	794,656	
LNG	11,450,399	
Kerosene	280	
Heavy oil B and C	347	
Naphtha	637,423	
LPG	1,479,763	
Hydrocarbon gas	260,373	
Coke oven gas	142,808	
Gas supply	173,541	14,595,893
Methane gas	387	
Total	14,968,802	14,595,893
CO_2		372,909

Source) *IOTEA 2000*

4. Results

Table 25 shows the results obtained by aggregating the sector classifications. Japan's CO_2 emission in 2000 was approximately 1.354 billion tons CO_2, which represents an increase of 3.1% compared with 1995 emission levels.[2] The National Institute for Environmental Studies estimate (Nansai and Moriguchi 2006) was 1.326 billion tons CO_2.

The top three sectors in terms of CO_2 emissions are as follows: the electricity, gas, and heat supply sector (0.393 billion tons CO_2); the transport sector (0.193 billion tons CO_2); and consumption expenditure (private, 0.174 billion tons CO_2), in that order. The emissions in the consumption expenditure (private, 24 million tons CO_2) and the electricity, gas, and heat supply sector (21 million tons CO_2) showed the largest increase.

The emissions for the communication and broadcasting, public administration, and electrical machinery have rapidly been increasing (57.6%, 47.8%, and 39.4%, respectively), while the emissions of textile products, consumption expenditure outside households, and petroleum and coal products have been considerably reduced (－30.7%, －25.5%, and －19.6%, respectively).

Table 26 shows CO_2 emissions by energy goods in 2000. The negative value of the table denotes the carbon content of outputs.

[2] According to *IOTEA 2005*, Japan's CO_2 emission in 2005 was approximately 1.400 billion tons CO_2.

Table 25: CO_2 emissions by sector in 1995 and 2000

	1995		2000		Growth
	Emisssions $t\text{-}CO_2$	Share %	Emissions $t\text{-}CO_2$	Share %	1995-2000 %
Agriculture, forestry and fishery	20,446,520	1.6	16,848,417	1.2	-17.6
Mining	770,861	0.1	763,409	0.1	-1.0
Foods	14,977,620	1.1	14,662,041	1.1	-2.1
Textile products	5,251,253	0.4	3,639,174	0.3	-30.7
Pulp, paper and wooden products	30,497,052	2.3	30,524,256	2.3	0.1
Chemical products	46,361,400	3.5	48,271,757	3.6	4.1
Petroleum and coal products	90,380,493	6.9	72,629,713	5.4	-19.6
Ceramic, stone and clay products	99,611,766	7.6	88,969,799	6.6	-10.7
Iron and steel	96,826,806	7.4	131,702,770	9.7	36.0
Non-ferrous metals	5,271,842	0.4	5,163,190	0.4	-2.1
Metal products	3,799,588	0.3	4,281,744	0.3	12.7
General machinery	3,007,966	0.2	3,734,340	0.3	24.1
Electrical machinery	3,949,852	0.3	5,505,275	0.4	39.4
Transportation equipment	4,896,870	0.4	5,706,417	0.4	16.5
Precision instruments	398,726	0.0	532,365	0.0	33.5
Miscellaneous manufacturing products	6,072,431	0.5	7,682,751	0.6	26.5
Construction	15,508,430	1.2	13,844,529	1.0	-10.7
Electricity, gas and heat supply	372,257,006	28.3	393,005,951	29.0	5.6
Water supply and waste management services	49,270,767	3.8	47,096,719	3.5	-4.4
Commerce	13,882,135	1.1	12,680,898	0.9	-8.7
Financial and insurance	1,109,870	0.1	1,220,418	0.1	10.0
Real estate	3,175,160	0.2	3,214,177	0.2	1.2
Transport	208,086,963	15.8	193,469,233	14.3	-7.0
Communication and broadcasting	1,017,307	0.1	1,602,811	0.1	57.6
Public administration	10,697,508	0.8	15,806,927	1.2	47.8
Education and research	9,951,649	0.8	11,387,279	0.8	14.4
Medical service, health and social security and nursing care	12,330,404	0.9	13,517,487	1.0	9.6
Other public services	1,199,628	0.1	1,196,242	0.1	-0.3
Business services	5,534,919	0.4	6,290,060	0.5	13.6
Personal services	22,118,376	1.7	21,720,041	1.6	-1.8
Office supplies	0	0.0	0	0.0	0.0
Activities not elsewhere classified	3,009,736	0.2	1,679,750	0.1	-44.2
Consumption expenditure outside households (column)	1,872,853	0.1	1,395,770	0.1	-25.5
Consumption expenditure (private)	149,812,625	11.4	174,168,007	12.9	16.3
Total emissions	1,313,356,384	100.0	1,353,913,717	100.0	3.1

Source) *IOTEA 1995* and *2000*

Table 26: CO_2 emissions by energy goods in 2000

Energy goods	Emissions t-CO_2
Limestone	79,476,080
Fly ash	0
Blast furnace slag	0
Converter slag	0
Electric furnace slag	0
Coking coal	178,048,012
Steam coal	192,810,593
Crude petroleum	22,771,945
Natural gas	6,117,678
LNG	144,953,340
Gasoline	134,497,181
Jet fuel oils	27,166,966
Kerosene	73,053,949
Light oils	114,576,169
Heavy oil A	80,968,073
Heavy oil B and C	133,921,818
Naphtha	2,547,629
LPG (liquefied petroleum gas)	55,564,072
Oil produced by conversion	0
Hydrocarbon oil	7,224,162
Hydrocarbon gas	36,418,264
Petroleum coke	14,176,152
Coke	-579,939
Coke oven gas	0
Blast furnace gas	0
Converter furnace gas	0
Electric furnace gas	0
Tar	-4,311,449
Crude benzene	-1,759,403
Pig iron	-319,725
Crude steel (converters)	-833,728
Crude steel (electric furnaces)	-337,317
Pig iron scrap	190,924
Steel scrap	399,338
Electricity	0
Private power generation	0
Gas supply	15,726
Steam and hot water supply	0
Black liquor	17,259,665
General waste	22,498,257
Scrap wood	449,498
Animal and plant residues	0
Paper scrap	1,527,301
Wood waste	4,932,940
Waste textile	0
Waste oil	2,688,401
Waste plastic	2,570,859
Sludge	5,874,103
Waste tire	693,849
Blast furnace dust	-1,339,086
Used paper	0
Methane gas	1,420
Total	1,353,913,717

Source) *IOTEA 2000*

5. Application

5.1 Introduction

For a case study application of the IOTEA, we focused on Solar Power Satellites (SPS) as a future alternative power generation technology. SPS technology involves a satellite carrying photovoltaic (PV) panels in geostationary orbit (GEO) that continuously generates electricity independent of the weather or time of day and transmits this power to the Earth's surface. This study measured the CO_2 emissions from the latest SPS technology — multi-bus tethered-SPS presented by Sasaki (the Japan Aerospace Exploration Agency, JAXA) — using the IOTEA; several previous types of SPS were included for comparison. The results revealed that the CO_2 emissions from multi-bus tethered SPS per unit of energy generated is a little more than that from a nuclear power system. However, the generated emissions are much less than an LNG-fired power system or a coal-fired energy system. Hence, we concluded that the latest SPS is currently one of the most effective alternative technologies for future CO_2 reduction in electric power generation.

5.2 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, because solar energy generation is impossible at night and the poor efficiency during cloudy weather, stable electricity generation is difficult. 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 the National Aeronautics and Space Administration (NASA) published a reference system in 1978, which is referred to as the "DOE/NASA reference system" in this paper. Although the reference system was published more than 30 years ago, no other equally detailed system including ground facilities and space transportation system has been proposed since then; therefore, it remains the representative plan for future SPS systems.

Figure 2 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.

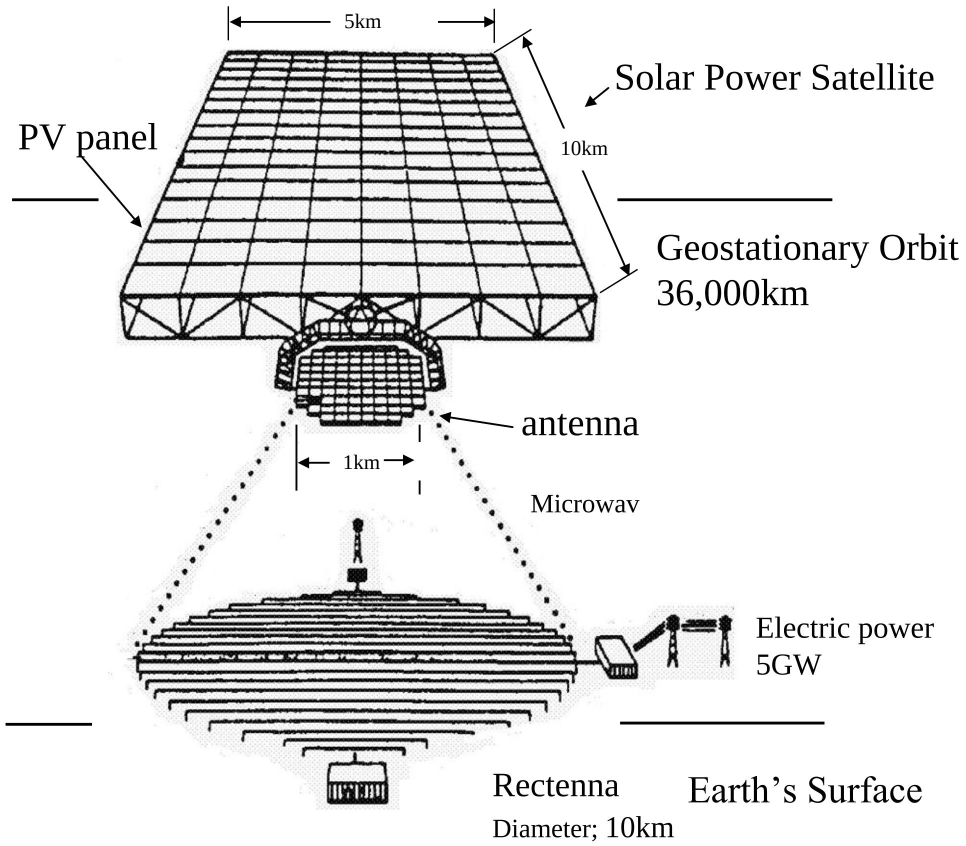


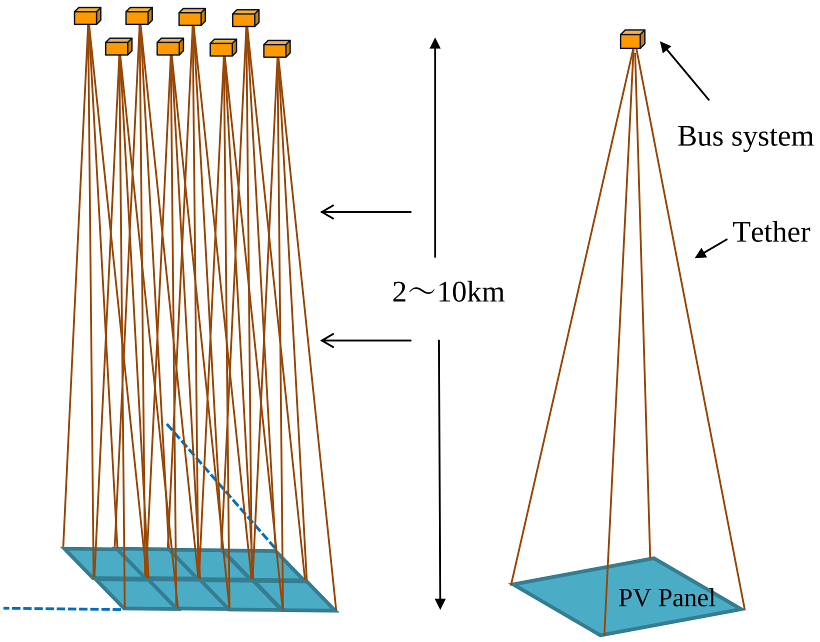
Figure 2: DOE/NASA reference system

Source) 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 JAXA that have relatively higher feasibility.[3] In this study, we focused on the new multi-bus tethered SPS that was developed by Sasaki (2006a, 2009).

---

[3] See the New Energy and Industrial Technology Development Organization (1994), Sasaki *et al.* (2004, 2006a, b).



Multi - module.
・Cell efficiency; 35%
・Upper panel:2.8GW
・Lower panel:2.5GW
・On the Earth:1GW

One module in Multi-BusTethered SPS

Figure 3: Features of multi-bus tethered satellite

Note) This technology presented by Sasaki (2006a, 2009)

Figure 3 shows the satellite structure of the multi-bus tethered SPS; 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.[4] 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.

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

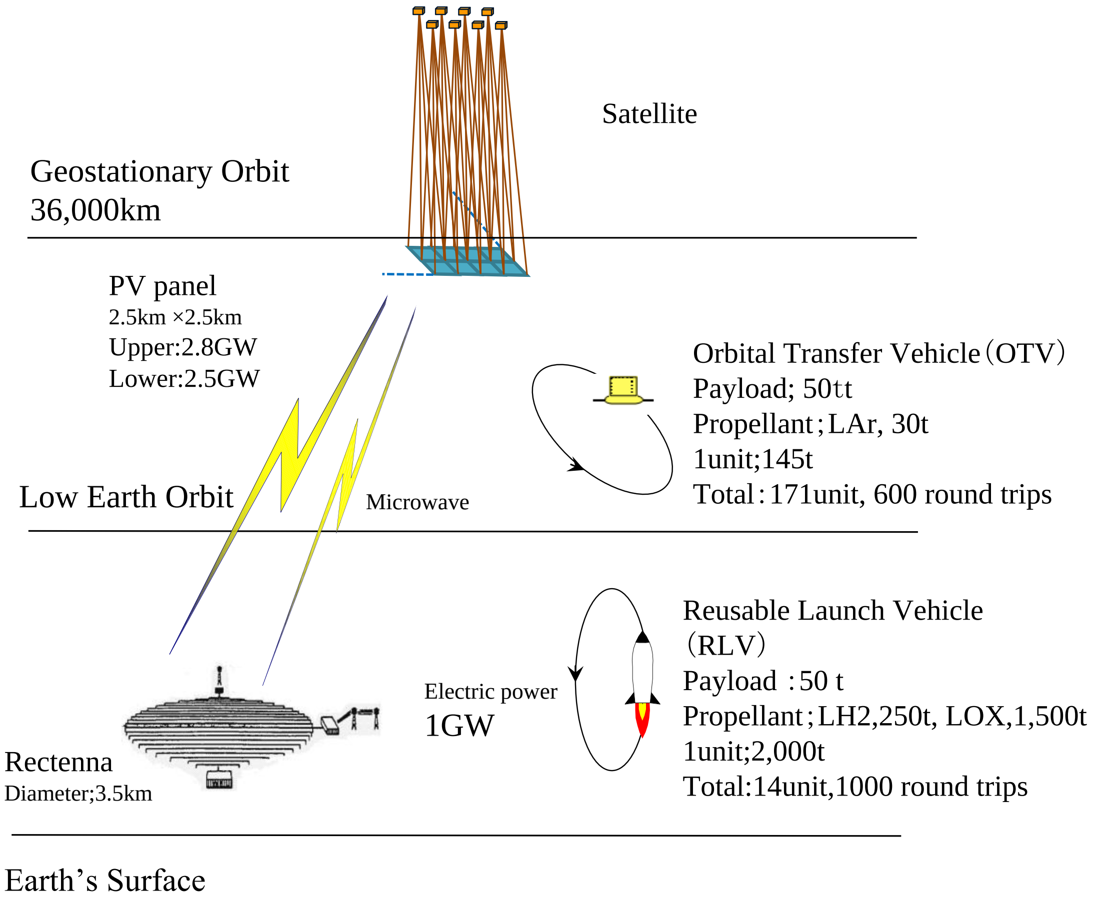


Figure 4: Construction on multi-bus tethered satellite- Key Items

Note) 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 4, 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.[5]

[5] 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%.

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.

5.3 The model

The CO_2 emission that would be produced by constructing and operating the SPS system is estimated using the IOTEA 2000, which was presented in the first part of this paper. The input-output model for environmental analysis based on open input-output model is given by;

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

C: CO_2 emission coefficient matrix (diagonal)

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

$\mathbf{f}^{k}$: final demand (FD) vector of *k*th item of the SPS system

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

$CO_2^{\ k}$: CO_2 emission of *k*th item of SPS system.

C on the right-hand side of equation (1) is derived in the first part of this paper, calculated by (CO_2 emission) /(domestic production) in each sector and $(\mathbf{I} - \mathbf{A})^{-1}$ 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 Figure 4, to solve for CO_2^{k}.

Figure 5 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 the *Input-Output Table* classification; finally, the trade and transport margins are added.

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
	·
	·

Figure 5: Procedure to determine FD vectors

Note) Main data source of FD vectors estimated are DOE/NASA (1980), Society of Chemical Engineers (1995), Yearbook Machinery Statistics, Unit price information in Input output 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 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 in 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 in 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 the *2000 Input-Output 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 PV cells; however, it is difficult to obtain the structural information for this particular type. Therefore, we use recent solar cell activity estimated by Nakano (2006) under the strong assumption that solar cell activity does not change according to the conversion efficiency.

5.4 Overview of CO_2 Emissions

In this section, we describe the main results for estimates of CO_2 emissions from SPS construction. Table 27 shows 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 27: CO_2 emissions from SPS by items

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
	LOX, LH2	6406.9	59.6
Recttna		693.4	6.5
Total		10747.7	100.0

Note) **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).

Table 28 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 27, 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 28 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 28: CO_2 emissions from SPS by sectors

	(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, LOX)	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)

Note) Figures are calculated by eq. (1).

5.5 Comparison of CO_2 Emission.

Lastly, we compare the CO_2 emissions of the multi-bus tethered SPS system with different kinds of electricity generation systems.

First, the annual energy production of SPS can be calculated as:

$$1 \text{ GW} \times 24 \text{ h} \times 365 \text{ day} = 8{,}760 \text{ GWh}.$$

Furthermore, if we assume a 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.

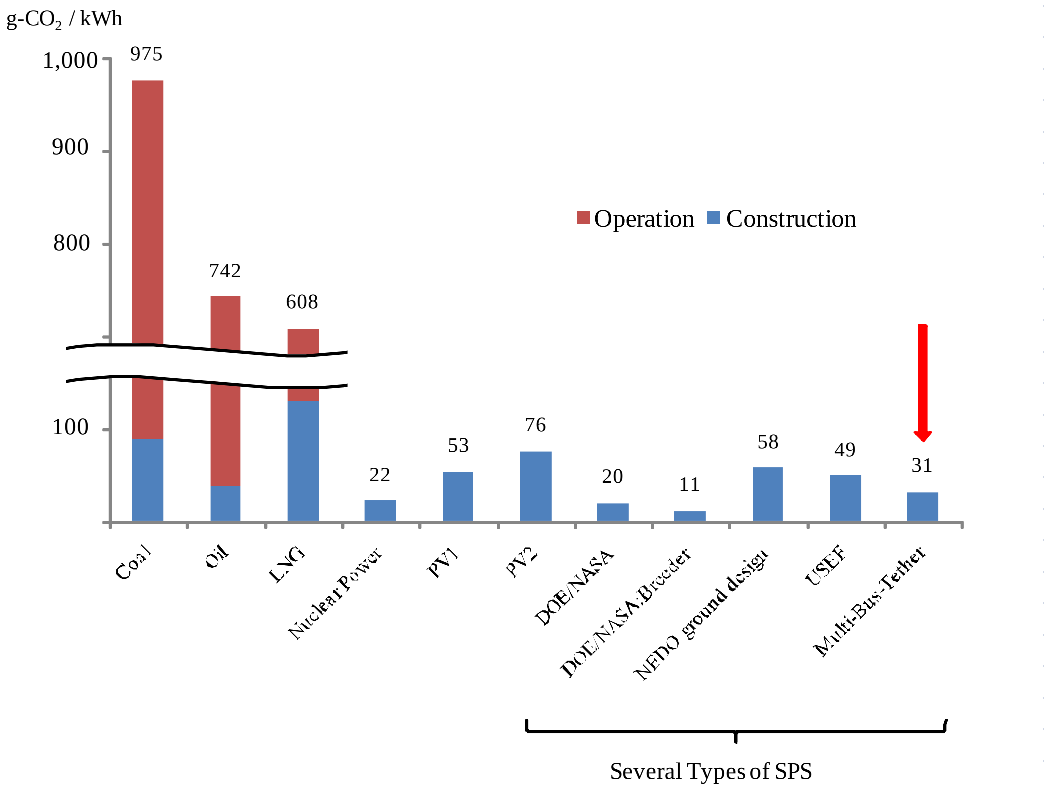


Figure 6: CO_2 emissions per kWh of energy production

Notes) 1) Figures for Coal, Oil, LNG, Nuclear, and PV1 were estimated by Hondo (2000). 2) Figure for PV2 is a recalculation of Nakano (2006) using eq. (1). 3) Figures for several types of SPS are estimated by our group; DOE/NASA and DOE/NASA Breeder are from Asakura *et al.* (2002), NEDO from Ohashi *et al.* (2001), USEF from Asakura *et al.* (2003). 4) Lifetime assumption for multi-tethered satellite system: 40 years.

Figure 6 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, 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 NEDO, 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.

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, NEDO, USEF, and multi-bus tether.

Further investigation is required on how to reduce CO_2 emissions by “solar breeding,” in which installed SPS supplies electricity for producing further SPS or liquid fuel. This is a very challenging research target, and we will try to further develop the next stages.

6. Concluding remarks

This paper is a report on the estimation method for the *IOTEA 2000* and its application study. Energy and economy statistics are considerably developed in Japan compared with other countries. This has led to the detailed estimation of the *Input-Output Table*. The amount of information for energy and environmental analyses is increasing. For instance, we can estimate the energy consumption for co-generation and the recycling sector in the *Input-Output Table*. However, at the same time, the *Structural Survey of Energy Consumption in Commerce and Manufacturing* has already become out of date.

The IOTEA provides information on the detailed structure of CO_2 emissions, which is necessary to assess ecofriendly technologies and to introduce measures against global warming. Hence, ensuring that the necessary statistics are up-to-date and continuously estimating the IOTEA is a major challenge. Effective utilization of the *Survey of Energy Consumption* and *Comprehensive Energy Statistics* should be discussed.

Acknowledgements

We thank Susumu Sasaki (Japan Aerospace Exploration Agency, JAXA) and Yoshihiro Naruo (JAXA) for providing us technical information on the SPS system. Our thanks are also due to Kanji Yoshioka (Keio University) and Hitoshi Hayami (Keio University) for many valuable comments and suggestions on this study. The authors are solely responsible for any errors.

References

Asakura, K., H. Hayami, M. Mizoshita, M. Nakamura, S. Nakano, M. Shinozaki, A. Washizu & K. Yoshioka (2001). *The Input-Output Table for Environmental Analysis*, Keio University Press. (in Japanese)

Asakura, K., Collins, P., Nomura, K., Hayami, H. & Yoshioka, K. (2002). CO_2 Emission from Solar Power Satellite, *KEO Discussion Paper*, No.G-145, Keio Economic Observatory, Keio University.

Asakura, K., Kobayashi, Y. & Yoshioka, K. (2003). CO_2 Emission from a New Solar Power Satellite System of USEF, *proceedings 6^th SPS Symposium* 117-122. (in Japanese)

Department of Energy (DOE) and National Aeronautics and Space Administration (NASA), U.S. (1979). *Satellite Power System*, DOE/ER-0023.

--- (1980). *Preliminary Material Assessment for the Satellite Power System (SPS)*, DOE/ER-0038.

Economic Research Association, Japan (2000). *Price Data for Construction Cost Estimating*, Economic Research Association. (in Japanese)

Electricity and Gas Industry Department, Agency for Natural Resources and Energy (2000). *Outline of Electricity Demand and Supply FY 1999*, Chuwa Printing Co., Ltd. (in Japanese)

-- (2001). *Outline of Electricity Demand and Supply FY 2000*, Chuwa Printing Co., Ltd. (in Japanese)

Gas Market Division, Electricity and Gas Industry Department, Agency for Natural Resources and Energy (2001). *Yearbook of the Gas Supply 2000*, The Japan Gas Association. (in Japanese)

General Policy Division, Director-General's Secretariat, Agency for Natural Resources and Energy (2002). *Comprehensive Energy Statistics FY 2001*, Tsusho Sangyo Kenkyusha. (in Japanese)

Glaser, P. E. (1968). Power from the sun, *Science*, 162, 857-861.

Hondo, H., Uchiyama, Y. & Morizumi, Y. (2000). Evaluation of Power Generation Technologies based on Life Cycle CO_2 Emissions - Re-estimation using the Latest Data and Effects of the Difference of Conditions, *Socio-economic Research Center, Rep*, No.Y99009. (in Japanese)

Hondo, Y., Y. Moriizumi, Y. Tonooka & A. Kannari (2002). Estimation of Greenhouse Gas Emission Factors Using 1995 Japanese Economic Input-Output Table, *Journal of the Japan Institute of Energy*, 81(9), 828-844. (in Japanese)

Ikeda, A., M. Suga, M. Shinozaki, H. Hayami, K. Fujiwara & K. Yoshioka (1996). *The Input-Output Table for Environmental Analysis*, KEO Monograph Series No.7, Keio Economic Observatory, Keio University. (in Japanese)

Kato, K., Yamada, K., Inaba, A., Shimatani, T., Tabata, S., Kawamura, S., Shibuya, H., Iwase, Y., Kakumoto, T., Kojima, T. & H. Komiyama (1994). Cost Evaluation of Photovoltaic Energy System , *The Journal of Chemical Engineering of Japan*, 20(2), 261-267. (in Japanese)

Ministry of Finance (2001). *Japan Exports & Imports 2000*, Japan Tariff Association. (in Japanese) The English version of trade statistics is also available from http://www.customs.go.jp/toukei/info/index_e.htm.

Ministry of Internal Affairs and Communications (2004). *2000 Input-Output Table*, National Federation of Statistics Association. (in Japanese) The English version is also available from http://www.stat.go.jp/english/data/io/io00.htm.

Nakano, S., H. Hayami, M. Nakamura & M. Suzuki (2008). *The Input-Output Table for Environmental Analysis and its Application*, Keio University Press. (in Japanese)

Nakano, S. (2006). CO_2 Reduction Effect and User Cost of Residential Photovoltaic System, *KEO Discussion paper*, No.102, Keio Economic Observatory, Keio University. (in Japanese)

-------------- (2009). The Input-Output Table for Environmental Analysis 2005: Estimation and Results, *KEO Discussion Paper* No.117, Keio Economic Observatory, Keio University. (in Japanese)

Nansai, K. & Y. Moriguchi (2006). Practical determination of sector environmental burdens applied to input-output analysis, *Journal of Life Cycle Assessment, Japan*, 2(1), 22-41. (in Japanese)

Naruo, Y., Inatani, Y. & T. Ota (1996). Regarding the fuel supply system for fully reusable rocket to achieve high-frequency operation, *Proceedings of Space Transportation Symposium*, ISAS, 82-85. (in Japanese)

New Energy and Industrial Technology Development Organization (1994). *New Sunshine Project*, NEDO. (in Japanese)

Nomura, N., Akai, M., Inaba, A., Yamada, K & H. Komiyama (1995). Estimation of Energy Payback Time of Solar Power Station based on Input-Output Analysis, *Energy and Resources*, 16(5) , 57-64. (in Japanese)

Nippon Slag Association (2001). *Statistical Yearbook of Iron and Steel Slag FY2000*, Retrieved from http://www.slg.jp/. (in Japanese)

Ohashi, E., Matsuhashi, R., Ishitani, H., Yoshida, Y., Hikita, K. and K. Yoshioka (2001). CO_2 Emission from Solar Power Satellite-Reference System and New Concept, *KEO Discussion paper*, No.G-127, Keio Economic Observatory, Keio University. (in Japanese)

Research and Statistics Department, Economic and Industrial Policy Bureau, Ministry of Economy, Trade and Industry (2001a). *Structural Survey of Energy Consumption in Commerce and Manufacturing 2000*, Economy, Trade and Industry Statistics Association. (in Japanese)

-- (2001b). *Yearbook of Iron and Steel Statistics 2000*, Research Institute of Economy, Trade and Industry. (in Japanese)

-- (2001c). *Yearbook of Production Supply and Demand of Petroleum, Coal and Coke 2000*, Research Institute of Economy, Trade and Industry. (in Japanese)

-- (2001d). *Yearbook of the Current Survey of Energy Consumption in Manufacturing 2000*, Economy, Trade and Industry Statistics Association. (in Japanese)

-- (2001e). *2000 Yearbook of Machinery Statistics*, Research Institute of Economy, Trade and Industry. (in Japanese and English)

-- (2002). *Census of Manufactures 2000*, Printing Bureau, Ministry of Finance. (in Japanese) The English outline is available from http://www.meti.go.jp/english/statistics/tyo/kougyo/index.html.

Sasaki, S. & Y. Yamagiwa (2000). Transportation by Ion Thruster OTV, mimeo.

Sasaki, S., Tanaka, K, Kawasaki, S., Shinohara, N., Higuchi, K., Okuizumi, N., Senda, K. & the USEF SSPS Study Team (2004). Conceptual Study of SSPS. Demonstration Experiment, *Radio Science Bulletin*, 310, 9-14.

Sasaki, S., Tanaka, K., Higuchi, K., Okuizumi, N., Kawasaki, S., Shinohara, M. & K. Ishimura (2006a). Engineering Research for New Tethered Solar Power Satellite, *Proceedings of 25th ISTS*, 780-785.

--- (2006b). A new concept of solar power satellite: Tetherd-SPS, *Acta Astronautica*, 60, 153-165.

Sasaki, S. (2009). The SPS design and system technology, In Yoshioka, K. Matsuoka, H. & H. Hayami (Eds.), *Essays on the Solar Power Satellite : An Interdisciplinary Study of Space Industry and the Future of Society* (pp. 45-59), Keio University Press. (in Japanese)

Science Applications International Corporation & NASA (1997). *Space Solar Power – A fresh Look at the Feasibility of Generating Solar Power in Space for Use on Earth*, Report Number SAIC-97/1005.

Society of Chemical Engineers, Japan (1995). *Evaluation of Solar Photovoltaic Technology II*. (in Japanese)

Waste Management and Recycling Department, Ministry's Secretariat, Ministry of Environment (2002a). *State of Discharge and Treatment of Industrial Waste FY 2000*, Retrieved from http://www.env.go.jp. (in Japanese)

--- (2002b). *State of Discharge and Treatment of Municipal Solid Waste FY 2000*, Retrieved from http://www.env.go.jp. (in Japanese)

Yoshioka, K., Suga, M., Nomura, K. & K. Asakura (1998). An Application of the Input-Output Table for Environmental Analysis (9) –CO_2 Emission from Solar Power Satellite, *Business Journal PAPAIOS*, Pan Pacific Association of Input-Output Studies, 8(2), 28-44. (in Japanese)