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LIFE CYCLE ANALYSIS OF PHOTOVOLTAIC CELL AND WIND POWER PLANTS

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Abstract

The paper presents life cycle analyses of net energy and CO_2 emissions on photovoltaic cell and wind power generation plants. Energy requirements associated with a plant are estimated for producing materials, manufacturing equipments, constructing facilities, and operating plants. Energy ratio and net supplied energy are calculated by the process energy analysis that examines the entire energy inventory of input and output during life time of a plant. Life cycle CO_2 emission can also be calculated from the energy requirements obtained by the net energy analysis. The emission also includes greenhouse effect equivalent to CO_2 emission of methane gas leakage at a mining as well as CO_2 emissions from fossil fuel combustion during generating electricity, natural gas treatment at an extracting well and cement production in industry. The commercially available and future-commercial technologies are dealt with in the study. Regarding PV technologies, two different kinds of installation are investigated; roof-top typed installation of residential houses and ground installation of electric utilities.

1. INTRODUCTION

Life cycle analysis is a tool that can be used to evaluate the environmental effects of a product, process, or activity. The methodology is similar to the net energy analysis that was popular twenty years ago. Where there are several variations, life cycle analysis is in theory based on entire inventory of all energy and materials associated with a system or process in order to estimate the environmental emissions such as CO_2, NOx, SOx, COD, BOD, etc.

In this study we focus on the life cycle inventory (LCI) of energy and CO_2 for different types of electricity generating technologies. The LCI quantifies the resource use, energy use, and CO_2 releases associated with the system being evaluated. Energy and material requirements are estimated in the process analysis on a 'cradle-to grave' basis for all stages of plant construction and operation & maintenance.

We developed a methodology of life cycle analysis to evaluate energy consumption and GHG emissions from the total electricity supply system including scope ranges from extraction of energy resources through processing, power generation, transmission and distribution, to dismantling of facilities and disposal of waste. We have already reported on net energy analysis and CO_2 emissions of various electricity supply technologies [1],[2],[3]. This paper, based on the above reports, has made further analysis to evaluate the effect of electricity generating technologies of solar and wind energy. Amounts of CO_2 gas indirectly emitted from constructing and operating solar and wind power plants are investigated in order to make the effects of environmental technologies visible.

2.METHODOLOGY

2-1 Net energy analysis and energy payback time

Life cycle inventory analysis is one of the useful methods to analyze greenhouse gas emissions from an energy supply system. The life cycle analysis in this study is the process analysis based on a bottom-up process approach in which each energy system has been subdivided into energy chain processes of fuel extraction, transportation, treatment, conversion and waste disposal. The input energy is the total life cycle energy, i.e. the sum of the construction including materials and equipments production, and the operation energy consumed in all processes of the system. Regarding a renewable energy technology which doesn't need to supply any fossil fuels to generate electricity, a power plant is only a process to be investigated. The output energy is the total amount of electricity produced by the system or supplied to consumers during the plant life.

Energy ratio is defined as the electrical output divided by the equivalent electrical input during a plant life:

$$\text{Energy ratio} = \text{OUT} / (\text{INt} / \alpha + \text{INe})$$

where OUT is the electrical output, INt is the thermal input, INe is the electrical input, and α is the conversion factor of electricity to primary energy(9.42 MJ/kWh).

Net supplied electricity is defined by subtracting the equivalent electrical input from the electrical output during life time:

$$\text{Net supplied electricity} = \text{OUT} - (\text{INt} / \alpha + \text{INe})$$

Energy payback time is also calculated by the results of net energy analysis.
It is defined by the following equation.

$$\text{Energy payback time} = \text{INeq.} / (\text{OUTa} \times \alpha - \text{INa.op.})$$

where INeq. is the initial energy input required for producing raw materials, manufacturing equipments and constructing a plant, OUTa is the annual electrical output, and INa.op. is the annual energy input at operating and maintaining a plant.

2-2 Analysis of greenhouse gas emission

Based on net energy analysis, the life cycle CO_2 emission can be derived from the indirect emissions associated with the energy consumed for construction and O&M of the electricity supply system as well as the direct emissions from combustion of fossil fuel fired power plants. The study also includes the CO_2 equivalent methane gas leakages at coal or natural gas mining and the CO_2 emissions from the cement production. Potential impacts on greenhouse effect from methane gas is 21 times larger than from CO_2 gas as the global warming potential estimated from a time horizon of 100 years. The greenhouse effect of an electricity supply system is expressed in terms of the CO_2 emission factor calculated by the following equation:

The CO_2 emission factor $= (E1 + E2 + E3 + E4)/Out$

where E1 + E2 + E3 + E4 is the total CO_2 emission from an electricity supply system during the plant life, E1 is the direct emission from fossil fuel combustion at a power plant, E2 is the indirect emission from construction and O&M, E3 is the indirect emission from cement production, and E4 is the equivalent CO_2 emission from methane leakage. E1 is eliminated from the analysis of renewable energy technologies.

3. RESULTS OF THE STUDY

3-1 Photovoltaic Cell Technologies

Energy requirements and CO_2 emissions of PV power plant are investigated on advanced technologies expected to commercialize in the future. The process analysis approach is used for analyzing two different PV technologies; polycrystalline silicon(p-Si) and amorphous silicon(a-Si). In the study both technologies would be installed not only as roof materials on residential roof but also as a large scale of power sources of electric utilities setting on the ground.

Total energy required for producing a PV technology includes some process energy consumed by different industrial sectors such as materials production, equipment manufacturing, transportation, and services. It seems that the consumed energy of materials production is dominant among total energy consumed for material intensive products in industry. However the amount of energy consumption in other processes is not ignored for them.

What is evident on comparing direct and indirect CO_2 emissions from products of over 400 different sectors in the Japanese input/output table is that a CO_2 emission ratio of materials production increases for materials intensive products such as food product machine, steel ship, pump, compressor, etc.. In the attached figure A-1 the ratio of CO_2 emission shows a maximum value of 67 percent for a food product machine, 52 percent for a passenger car, and 23 percent for a semiconductor [4]. In general the value tends to increase for products with highly additional value.

The energy requirements and CO_2 emission of PV technologies need to be derived on different processes as shown in the following levels:

- silicon production
- cell foundation
- cell manufacture
- module production

- transportation of equipments and materials
- site materials and construction
- operation and maintenance

The energy requirements for decommissioning of the plant after its lifetime is not considered in the study because of the limited information. Regarding the roof-top installation, energy requirements for transportation, site construction and O&M are not included into the calculation because a PV module is dealt with a part of roof materials.

A PV module consists of aluminum frame and a large number of solar cells which are highly electricity-intensive materials. If advanced technologies to product thinner silicon cell with high efficiency are developed, energy ratio and CO_2 emission factor could be highly improved. Table I gives R&D targets of cell performance in Japan. Solar cell is produced by polycrystal silicon for PV-1 to PV-3 and amorphous silicon for PV-4. The yearly production of cell is assumed to reaches 10 MW for PV-1 and 1 GW for PV-2 to PV-4[5]. Cell efficiency is estimated to 17 percent of the conventional value for PV-1, 20 percent for PV-2 and PV-3 and 12.6 percent for PV-4. Cell thickness of PV-3 is 150 μ m, half of the conventional one. In the table we also show the performance of the conventional PV technology used in the investigation of the previous report[3].

TABLE I EVALUATED PV POWER TECHNOLOGIES

	PV-1	PV-2	PV-3	PV-4	Conventional
Type of cell	polycrystal	polycrystal	polycrystal	amorphous	polycrystal
Cell production[MW/y]	10	1,000	1,000	1,000	5
Cell efficiency[%]	17	20	20	12.6	17
Cell thickness[μ m]	300	300	150	0.3	300
System efficiency[%]	10	13	13	8.6	10

Material loss of silicon from the process of silicon ingot to module production is estimated to 74 percent for polycrystal silicon cell. The entire processes of silicon cell consumes primary energy of 166.0 Gcal/ton for the polycrystal silicon of PV-1 which is produced by the advanced cell production system to reduce the energy consumption of production processes. The energy consumption of PV-1 is less than one third of 562.5 Gcal/ton for the conventional technology of the previous report[3].

Life cycle energy consumption of PV-1 and its distribution ratio of processes are indicated in the table II with comparison of the conventional technology. Energy requirement for producing materials occupies the majority of the life cycle energy. Total energy of PV-1 is highly improved by the advanced technology of cell production. In succession of materials production O&M and equipments manufacturing share 21 and 19 percents of the total energy, respectively.

TABLE II Life Cycle Energy Requirement of 1 MW PV system

	Total Energy	Distribution ratio of Processes [%]				
	[Gcal/y]	Material	Manufacture	Constr.	Transport.	O&M
Conventional	*1,107*	*61.9*	*11.3*	*3.0*	*0.7*	*23.1*
PV-1	572	51.3	18.6	5.9	2.9	21.4

Based on the above performance in Table I, we estimated entire material and energy requirements for different types of PV systems during lifetime of 30 years. The results are indicated in Table III for 1 MW PV plant of electric utility installation, and in Table IV for 3 kW plant of roof-top installation in residential houses. It is shown that the advanced technologies of mass cell production can contribute to reduce the amount of material requirements as well as energy consumption. Although development of amorphous silicon cell is effective to reduce an amount of silicon which is one of the most energy intensive materials, it still requires a large amount of steel, aluminum and cement of frame and base materials because of lower cell efficiency.

TABLE III MATERIALS AND ENERGY REQUIREMENTS FOR MANUFACTURE & CONSTRUCTION OF 1 MW PHOTOVOLTAIC CELL POWER PLANT DURING LIFE OF 30 YEARS (Utility installation)

	PV-1	PV-2	PV-3	PV-4	Conventional
MATERIALS [ton/MW]					
Steel	520	401.1	401.1	603.95	520
Aluminum	19	9.8	9.8	14.86	20
Copper	53.9	42.2	42.2	62.21	56
Cement	250	192.3	192.2	290.75	250
Glass	79.8	38.5	38.5	64.61	60
Insulation	32	25.1	25.1	36.89	47
Silicon	10.6	7.3	3.6		25
SiH4				0.05	
TMT				0.35	
Oxygen gas				1.15	
Nitrogen gas				30.21	
Hydrogen gas				0.01	
EVA				6.33	
Butyl rubber	1.1	0.8	0.8	1.28	
Caulk	10.9	8.4	8.4		
Tedra(PVF)	1.5	1.2	1.2	1.74	

ENERGY (manufacturing, transportation and construction)					
Electricity[MWh]	1,359	1,047	973	925.8	1695
Coal [ton]	33	24	22	31.78	29
Oil [ton]	145	108	96	126.2	100

TABLE IV MATERIALS AND ENERGY REQUIREMENTS FOR MANUFACTURE & CONSTRUCTION OF ROOF-TOP PV POWER PLANT DURING LIFE OF 30 YEARS (Roof-top installation: Scale of 1 MW)

	PV-1	PV-2	PV-3	PV-4
MATERIALS [ton/MW]				
Steel	5.0	5.0	5.0	5.0
Aluminum	19.0	9.8	9.8	14.86
Copper	53.9	42.2	42.2	62.21
Glass	79.8	38.5	38.5	64.61
Insulation	32.0	25.1	25.1	36.89
Silicon	10.6	7.3	3.6	
SiH4				0.05
TMT				0.35
Oxygen gas				1.15
Nitrogen gas				30.21
Hydrogen gas				0.01
EVA				6.33
Butyl rubber	1.1	0.8	0.8	1.28
Caulk	10.9	8.4	8.4	
Tedra(PVF)	1.5	1.2	1.2	1.74
ENERGY (manufacturing, transportation and construction)				
Electricity[MWh]	743	492	418	210.56
Coal [ton]	10	10	9	5.65
Oil [ton]	56	39	27	22.72

Regarding the roof-top installation in which PV modules are used as roof materials, amorphous silicon technologies can contribute highly to reduce amounts of material and energy requirements. Higher cell efficiency of p-silicon can also reduce amounts of material and energy in the processes of material production and plant construction.

Life cycle energy requirements can be calculated from the results of material and energy requirements in the tables. Energy requirements as well as energy ratio, payback time and

CO_2 emission factor are indicated for the utility installation and roof-top installation, in Table V and VI, respectively.

TABLE V ENERGY REQUIREMENTS AND CO2 EMISSIONS OF PV POWER TECHNOLOGIES (Utility installation)

	PV-1	PV-2	PV-3	PV-4	Conventional
Energy requirement					
M, M & C [Gcal/y]	450.1	309.7	279.3	342.6	851.3
O & M [Gcal/y]	121.6	82.6	73.5	87.2	255.4
Total [Gcal/y]	571.7	392.3	352.7	429.9	1,106.7
Produced energy[Gcal/y]	2,809	2,809	2,809	2,809	2,809
(MWh/y)	(1,248)	(1,248)	(1,248)	(1,248)	(1,248)
Energy ratio	4.91	7.16	7.96	6.53	2.54
Payback time[year]	5.03	3.41	3.06	3.78	10.0
CO2 emission factor					
M, M & C [g-C/kWh]	27.22	19.25	17.72	23.05	40.64
O & M [g-C/kWh]	7.09	4.95	4.49	5.67	11.78
Total [g-C/kWh]	34.31	24.20	22.21	28.72	52.42

M, M & C: materials, manufacturing and construction

TABLE VI ENERGY REQUIREMENTS AND CO2 EMISSIONS OF PV POWER TECHNOLOGIES (Roof-top installation :Scale of 1 MW)

	PV-1	PV-2	PV-3	PV-4
Energy requirement				
M, M & C [Gcal/y]	257.69	156.19	125.97	110.10
O & M [Gcal/y]	77.31	46.86	37.79	35.73
Total [Gcal/y]	335.00	203.05	163.76	154.82
Produced energy[Gcal/y]	2,956.50	2,956.50	2,956.50	2,956.50
Energy ratio	8.83	14.56	18.05	19.10
Payback time[year]	2.69	1.61	1.29	1.13
CO2 emission factor				
M, M & C [g-C/kWh]	12.32	7.69	6.26	6.17
O & M [g-C/kWh]	3.70	2.31	1.88	1.85
Total [g-C/kWh]	16.02	10.00	8.14	8.02

M, M & C: materials, manufacturing and construction

The energy ratio of a PV system can be improved in case of roof-top typed installation due to eliminating fabrication of PV module frames and site construction. Development of new silicon cell with high performance could also make the energy ratio increase. The value is approximately twice larger than that of the conventional PV system.

Table V and VI also present the results of CO_2 emissions per unit of kWh, including the methane leakages, for conventional electricity generation systems. The CO_2 emission factor of PV system can be improved if higher efficient PV cell may be developed. As shown in the table, advanced PV cell such as thinner silicon cell and amorphous silicon cell with higher efficiency could make the CO_2 emission factor reduced up to half of that of the conventional one in case of roof-top typed installation.

3-2 Wind Power Generation Technology

In the previous study[ref.3] we investigated life cycle analysis of conventional wind power generation plant which was constructed as a demonstration plant in Japan 12 years ago. Recent progress of PV technologies is so rapid that its performance characteristic has been improved year by year. We tried to calculate energy ratio and CO_2 emission factor again for advanced wind technologies installed in recent years. Table VII shows improved performance of Japanese wind machines produced by the Mitubishi Heavy Industry and of Danish one produced by the MICON, and their annual capacity factors when they are installed at the best area of wind flow in Japan.

TABLE VII EVALUATED WIND POWER TECHNOLOGIES

	Mitubishi-1	Mitubishi-2	MICON	Demo. plant[ref.3]
Power output[kW]	300	170/50	400/100	100
Rotor diameter[m]	28	27	31	30
Generator type	Asynchronous (single-speed)	Asynchronous (2-speed)	Asynchronous (2-speed)	Asynchronous (single-speed)
Capacity factor[%]	20	25	20	20

We investigated amounts of material requirements for different types of wind machines based on the above technological performance of the table. Table VIII indicates the results of material requirements for main components and civil work. It is found that recent progress of wind technologies makes total weight of main components reduce by the effort of design improvement. Regarding construction materials required for civil work, amounts of concrete and steel have also large change in material requirements between conventional and advanced technologies; total weight of construction materials for advanced technologies is less by more 20 % than of the conventional one.

TABLE VIII MATERIALS REQUIREMENTS OF WIND POWER TECHNOLOGIES

unit: ton

	Mitubishi-1	Mitubishi-2	MICON	Demo. plant[ref.3]
Blade	3.15	3.15	3.80	4.2
Nacelle	14.93	14.65	9.21	18.2
Tower	19.60	20.93	21.60	27.0
Generator, etc.	5.93	2.10	5.65	11.6
cement	42	42	41	50
steel	20	20	20	24
stone & sand	289	289	280	345
Total	394.6	388.7	381.3	480.0

Based on the performance characteristics in Table VII and material requirements in Table VIII, life cycle energy requirements, energy ratio and CO_2 emission factor can be calculated as shown in the table IX. The advanced technology is effective to improve energy ratio and CO_2 emission factor of wind power plant. The reduction rate is larger than that of PV plant. Energy payback time of wind technology is less than a year for Mitubishi-1 and MICON machines. Net energy ratio can be improved by advanced technologies with higher performance characteristics. They can also reduce CO_2 emission factor of power generation plants. The emission factors of the advanced technologies are from one third to one fifth of the conventional value of demonstration plant.

TABLE IX ENERGY REQUIREMENTS AND CO2 EMISSIONS OF WIND TECHNOLOGIES

	Mitubishi-1	Mitubishi-2	MICON	Demo. plant
Energy requirement				
M, M & C [Gcal/y]	33.87	33.60	32.47	39.83
O & M [Gcal/y]	14.26	15.60	15.06	22.0
Total [Gcal/y]	48.14	49.20	47.53	61.8
Produced energy[Gcal/y]	1,064	754	1,419	355
Energy ratio	22.1	15.3	29.9	5.7
Payback time[year]	0.98	1.37	0.69	3.59
CO_2 emission factor				
M, M & C [g-C/kWh]	6.99	9.19	4.68	22.63
O & M [g-C/kWh]	2.51	3.73	1.89	11.11
Total [g-C/kWh]	9.51	12.92	6.56	33.74

4. CONCLUSION

The study presents life cycle analysis of net energy, energy payback time and CO_2 emissions from PV and wind power generation technologies in Japan. Materials production, manufacturing of equipments and site construction are evaluated as well as operation and maintenance of plant facilities. Direct and indirect CO_2 emissions from life cycle of a plant are analyzed with the process analysis. Both conventional and advanced generation technologies of PV and wind energy are investigated in the study. The results of the comparative assessment on different generation technologies can be summarized as follows:

(1) It is found that advanced PV technologies make net energy ratio improve by 30 to 40 % for the utility installation and 65 to 110 % for the roof top installation of residential houses. In case of wind power plants, advanced technologies can achieve the large improvement of energy ratio by 170 to 400 % of the demonstration plant.

(2) Energy payback time of PV technologies is 3.06 to 3.78 for the utility installation and 1.13 to 2.69 for the roof top type. Advanced wind technologies can improve energy payback time by 0.69 to 1.37 but cannot achieve the best value of 0.01 for fossil fuel fired and nuclear plants as shown in the attached figure A-2.

(3) The CO_2 emission per unit of kWh of PV and wind technologies is much lower than that of fossil fuel fired power plants. It is clear that PV and wind technologies can contribute to improve CO2 emission factor of average electricity if they are installed into the national electricity grid. The CO_2 emission factor can be reduced by developing advanced PV or wind technologies. The factor of PV is reduced by 18 to 35 % for the utility installation and 35 to 50 % for the roof-top type. Regarding the advanced wind machines higher improvement can be expected ; the factor is improved by 60 to 80 % with comparing the value of the demonstration plant.

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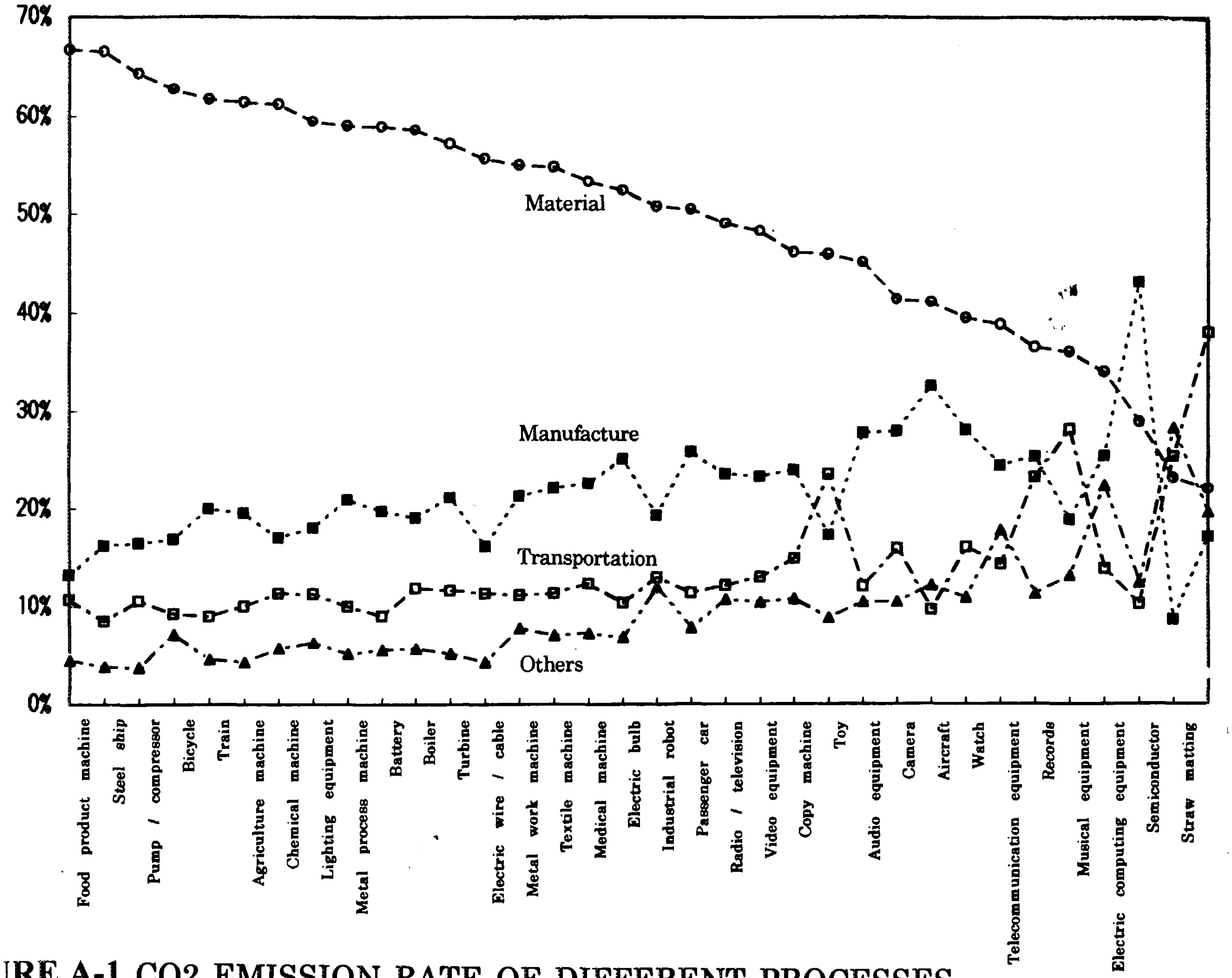

FIGURE A-1 CO2 EMISSION RATE OF DIFFERENT PROCESSES FOR COMMODITIES

FIGURE A-2 ENERGY PAYBACK TIME OF DIFFERENT POWER GENERATION PLANTS

Plant	Payback Time [year]	Plant	Payback time [year]
Oil	0.09	PV (Utility)	
LNG	0.09	Conventional	5.03
Coal	0.15	p.silicon(20%)	3.41
Nuclear(LWR)	0.11	p.silicon(150 μ)	3.06
Hydro	0.59	amorphous	3.78
Geothermal	3.39	PV (Roof-top)	
OTEC	4.58	Conventional	2.69
Solar thermal	5.61	p.silicon(20%)	1.61
Wind		p.silicon(150 μ)	1.29
Conventional	3.59	amorphous	1.13
MHI-1	0.98		
MHI-2	1.37		
MICON	0.69		