B-14-4.1 Evaluation of important measures in the power generation sector (Final Report)

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Abstract To estimate influence on electric power systems by photovoltaic (PV) generation systems deployed over a wide area, it is important to know the geographical distribution of hourly output from very many PV generation systems, which in turn is due to the geographical distribution of hourly solar irradiation and installation site distribution. A set of formulae are developed based on meteorological observation and satellite images to estimate hourly solar irradiation distribution. Using geographical distribution of hourly output power from very many residential PV generation systems deployed on a nation-wide scale and regional electricity generation characteristics, decrease in annual carbon dioxide (CO_2) emission per installed capacity of PV generation systems was evaluated for the service areas of nine electric utilities in Japan. For the life cycle assessment of PV generation systems, data were collected about the production processes of various types of PV modules with a detailed survey of silicon production. Energy payback and life-cycle carbon dioxide emission of various PV generation systems were estimated with a sensitivity analysis to find the influence by the production rate of PV cells and technological improvement. From these results, life-cycle effect to reduce carbon dioxide emission by the use of residential photovoltaic generation systems on a large scale was evaluated assuming a scenario of introducing PV systems into the generation system in Japan up to the year 2010. Moreover, potential merit of PV module recycling was investigated to mitigate disposal problem expected to arise from the deployment of very many PV systems in the future.

1. Introduction

Technological options are regarded as most practical measures to mitigate global warming from standpoint of cost-effectiveness and potential penetration. It is necessary to evaluate potential effect of promising technological options and to prepare scenarios for their diffusion on a large scale. Since electric power sector is one of major contributors to CO_2 emission, it is important to study the evaluation of important measures in the power generation sector.

2. Research Objective

The objective of this research is to investigate the possible effect of important measures in the power generation sector such as photovoltaic (PV) generation technology to reduce to CO_2 emission originating from electricity generation with emphasis on life cycle assessment.

3. Research Method

Residential photovoltaic (PV) generation system was taken as important measure in the power sector to be investigated in this study. The content of this study falls into three main subjects.

(a) Evaluation of geographical distribution of hourly output power from very many PV generation systems deployed on a nation-wide scale

(b) Life cycle assessment of CO_2 emission from PV generation systems

(c) Evaluation of the effect of wide-spread use of PV generation systems as measures to mitigate global warming.

Potential reduction in CO_2 emission and incremental cost by installing PV generation systems in Japan are estimated using scenarios to increase PV generation systems up to the year 2010.

4. Result

(1) Evaluation of geographical distribution of hourly output power from very many PV generation systems deployed on a nation-wide scale

First, a new method was developed to estimate the geographical distribution of hourly solar irradiation based on meteorological observation and satellite images. The outline of the developed method are described in the following Box. Global solar irradiation during the recent four years at more than eight hundred points, which correspond to part of the AMEDAS observation sites, was simulated hour by hour using this estimation formulae. Correlation factors between estimated and actual values were found to be in the range from 0.96 to 0.98, depending on regions and seasons.

OUTLINE OF THE ESTIMATION METHOD OF HOURLY SOLAR IRRADIATION

(1) The whole nation is divided into nine regions considering their climatic characteristics.

(2) Regression formula of the regression formula has the following form are derived with respect to each region and each month.

$$I_n = Isc*((a_{0,n}*N+a_{1,n})*\cos^2 Z + a_{2,n}*\cos Z + a_{3,n}*r) \quad (1)$$

where

I	: Global irradiation in horizontal planes
Isc	: Extraterrestrial radiation intensity
Z	: Zenith angle
n	: Hourly sunshine hours
N	: Daily average sunshine hour
r	: Reflectivity of clouds
$a_{0,n}$ - $a_{3,n}$	: Coefficients

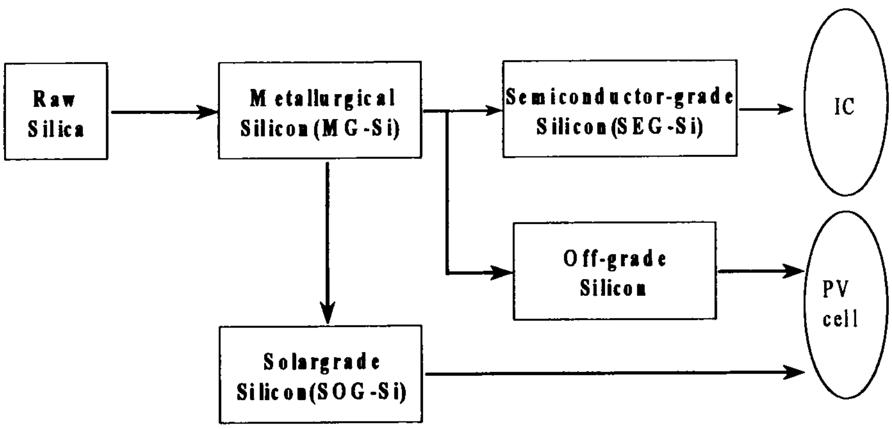
Four coefficients, $a_{0,n}$, $a_{1,n}$, $a_{2,n}$, and $a_{3,n}$, are determined so as to minimize the least square error of estimation by these formula.

(3) Hourly sunshine hour data at each site are available from ground-level measurement. Hourly reflectivity of clouds at each site is derived from cloud images supplied by meteorological satellite "HIMAWARI"

The distribution of sites for residential PV generation systems installation were derived from 1993 housing survey of Japan. Hourly output power from many residential PV generation systems spread in any area can be simulated using the distributions of solar irradiation and PV system installation sites.

(2) Life cycle assessment of CO_2 emission from PV generation systems

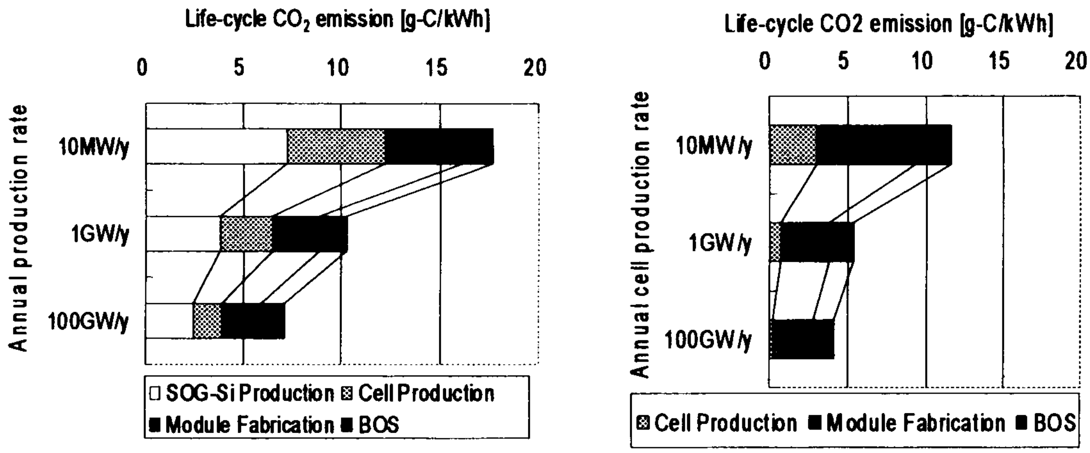
From the viewpoint of life cycle assessment, PV generation systems emit CO_2 in the stage of equipment production and system construction. To conduct life cycle assessment of PV generation systems, necessary data were collected about the production processes of various types of PV modules with a detailed survey of silicon production which is a much energy consuming process. Currently, PV manufacturing industry uses surplus semi conductor grade silicon supplied by semiconductor manufacturers. Use of off-grade silicon from semiconductor industry is rapidly increasing in recent years. Energy requirement and material flows in off-grade silicon production was clarified for the first time in this study. Less energy intensive process to produce solar grade (SOG) silicon is being developed, too. Firstly, life-cycle CO_2 emission of grid connected 3kW residential crystalline silicon (c-Si) PV generation systems using off-grade silicon was evaluated to find the exact life-cycle CO_2 emission of PV generation system in the state of the art and the benefit of SOG silicon production process. The result is shown in Table 1. Secondly, Energy payback and life-cycle CO_2 emission of grid connected 3 kW residential PV generation systems were estimated assuming the use of SOG silicon, with a sensitivity analysis to find the influence by annual PV cell production rate and cell types. Annual cell production rates of 10MW/year, 100MW/year, and 1GW/year were assumed. The result is shown in Figure 1. Finally, potential benefit of PV module recycling was investigated. Recycling of PV modules is expected to lead to decreasing energy and material consumption in PV module production and contribute to the reductionof cost and CO_2 emission in the production of PV generation systems. Figure 2 illustrates possibility to reduce life cycle CO_2 emission



Silicon production technology	CO2 emission	Assumption
Market technology with off grade Si	65 g-C/kWh	All the production energy was considered
	21 g-C/kWh	Off grade Si production energy was ignored
Future technology with SOG-Si	18 g-C/kWh	10MW/y of production scale

Table 1. A silicon material flow and life cycle CO_2 emission of residential PV generation system

from residential PV module with poly-crystalline silicon (poly-Si) cell with respect to energy requirement in recycling process, compared with the case of virgin PV module production. Since no established process exists for PV module recycling, three types of recycling/reuse paths are assumed, Recycling of silicon as raw material, Reuse of silicon wafer, and Reuse of PV cell.



(a) with poly-Silicon PV cells (b) with a-Silicon PV cells

Figure 1. Life cycle CO_2 emission per kWh of residential PV system

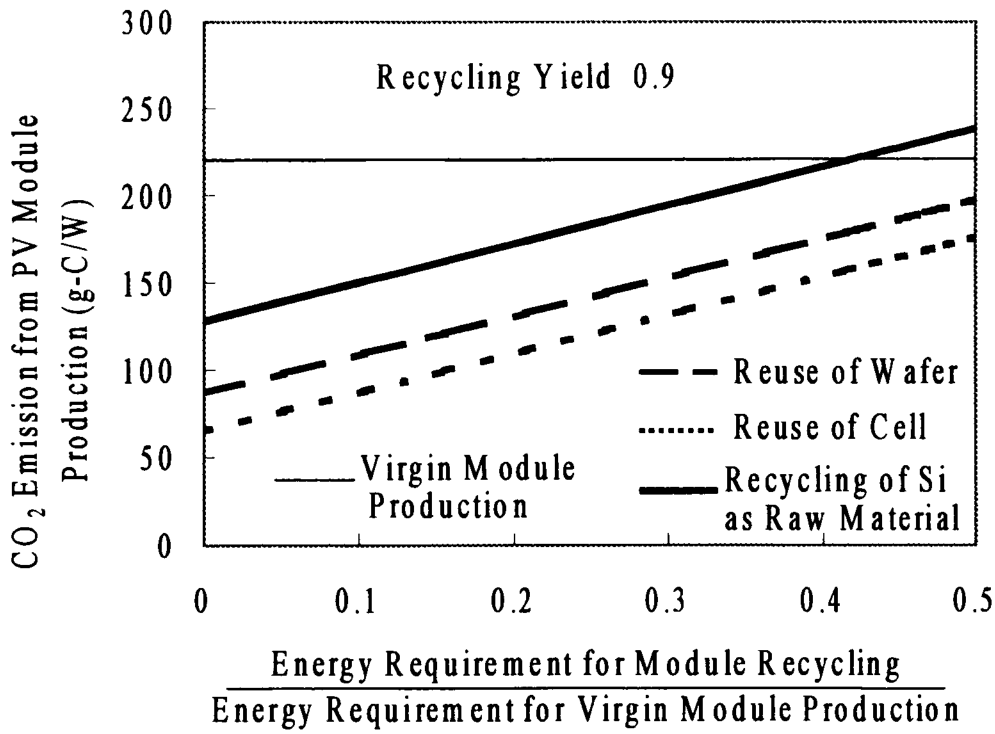


Figure 2. Possibility to reduce life cycle CO_2 emission from p-Silicon PV module by module recycling

(3) Evaluation of the effect of wide-spread use of PV generation systems as measures to mitigate global warming.

From the results described in the previous sections, life-cycle effect to reduce CO_2 emission by the use of residential photovoltaic power systems on a large scale was evaluated. Using simulated geographical distribution of hourly output power from very many residential PV generation systems and regional electricity generation characteristics in a recent year, decrease in annual CO_2 emission per installed capacity of PV generation systems was evaluated for the service areas of nine electric power companies in Japan. Potential reduction in CO_2 emission and incremental cost by installing PV generation systems in Japan are estimated using scenarios to increase PV generation systems in Japan up to the year 2010. Incremental cost to introduce PV generation systems is defined as (discounted) investment cost of installed PV generation systems minus fuel cost saving in fossil power generation substituted by PV generation. Again, reduction in CO_2 emission is defined as decrease due to cut down in fuel use by substituted fossil power generation minus life cycle CO_2 emission from installed PV generation systems. SOG silicon production process are assumed to be utilized and 18g-C/kWh

Potential reduction	Assumption: Suppose 0.4GW grid connected residential PV system installation is capable by year of 2000 and 4.6GW by 2010. Annual production of PV cell is 1GW and life time of the PV system is 20 years. Emission reduction: If 4.6GW PV would be installed by 2010, life cycle emission reduction of those PV facility will be 12MT-C(13MT-C reduced by fossil power substitution, and 1MT-C emitted from equipment production).
Annual CO_2 emission reduction per installed PV Capacity	Annual CO_2 emission reduction per installed capacity: Nation average is 130-140t-C/ year/ MW grid connected residential PV system capacity. * Fossil power substitution will reduce 140-150t-C/ MW/ yr and equipment will emit 10t-C/ MW/ yr. Annual emission reduction per installed capacity will be influenced by total installed PV capacity. Annual emission reduction per installed capacity ranges from 110t-C/ MW/ yr to 240t-C/ MW/ yr by region where PV systems are deployed.
Incremental Cost	Assumption: Suppose 0.4GW of grid connected residential PV system is installed by 2000 and 4.6GW by 2010. 5% discount rate is used to convert to 1995 YEN. Fossil fuel cost is assured to rise at 3%/year. Incremental Cost: (Case1) Up to 2000, PV system price is ¥1,150,000/ kW(equivalent to market price in '96.8) and from 2000 and later cost reduction to ¥330,000/ kW. 1995-2010 total PV system cost ¥1.35billion Cut down expenses of fossil power fuel ¥ 0.4billion Net incremental cost ¥ 0.95billion (Case 2) Up to 2010, PV system price is ¥1,150,000/ kW(equivalent to market price in '96.8). 1995-2010 total PV system cost ¥ 3.7billion Cut down expenses of fossil power fuel ¥ 0.4billion Net incremental cost ¥ 3.3billion

Table 2. Life Cycle CO_2 Emission Reduction by Residential PV Generation System

was used as life cycle CO_2 emission of residential PV generation system for the estimation. The result is shown in Table 2.

5. Discussion

It is necessary to consider geographical distributions of hourly output power to estimate total power generated by very many PV systems wide-spread in a wide area because solar irradiation is likely to be correlated within a certain distance. Detailed geographical distributions of hourly output power from residential PV generation systems deployed on a nation-wide scale in Japan were used for the first time to estimate potential reduction in annual CO_2 from the power generation sector. It was found that decrease in annual CO_2 emission per installed capacity of PV generation systems may differ by a factor of two from area to area. Energy requirement and material flows in off-grade silicon production was clarified and applied to the evaluation of energy payback and life cycle CO_2 emission of residential PV generation system with crystalline silicon PV cell. It was found that the life cycle CO_2 emission of residential PV generation system equipped with crystalline silicon PV cell made from off grade silicon is well below the CO_2 emission intensity of conventional coal fired power generation, though it is much larger than the life cycle CO_2 emission of residential PV system with crystalline silicon PV cell made from SOG silicon if all the silicon production energy is considered as shown in Table 1. Possibility of recycling PV modules were investigated systematically in the Japanese context for the first time in this study.

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