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Research Article

Environmental impact analysis of solar cell power plant compared with fossil fuel power plants in Thailand

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Abstract

This study was designed to investigate environmental impacts of a solar cell power plant over its entire life cycle. The first solar cell power plant in Thailand with a capacity of 500 kW_p is taken as a model for assessment and two types of the solar cell modules, being multicrystalline silicon (m-Si) solar cells and thin film amorphous silicon (a-Si) solar cells, are considered. Three phases, module manufacturing, transportation from manufacturer to the power plant and the operation of the power plant are considered. The environmental impact results of the solar cell power plant are compared to fossil fuel power plants which are coal-fired, diesel-fired, gas turbine and combined cycle. All of these are analyzed by numerical environmental total standard or LCA-NETS method for the entire life cycle of the plants. It was found that the highest value of environmental impact for the solar cell power plant occurs at the solar module manufacturing phase, wherein the major environmental impacts are natural resource depletion, fossil fuel depletion and air pollution. The CO_2 emissions from the solar cell power plant are much lower than those of the fossil fuel power plants. These results show the potential for a CO_2 reduction project by using renewable energy electricity generation. Finally, the total environmental impacts which are calculated from LCA-NETS method show the obvious results that the solar cell power plants are more environmentally friendly than their fossil fuel counterparts.

Keywords: Life Cycle Assessment, Solar Cell Power Plant, Fossil Fuel Power Plant

Introduction

In the fiscal year 2008, electricity generation in Thailand relied on fossil fuel (natural gas, coal and fuel oil) for more than 90% of power production needs [1], which in turn causes many unfavourable impacts on the environment. Fig. 1 shows CO_2 emissions from the power sector which tend to increase continuously [2] and is one of the main causes of greenhouse effect and global warming. Therefore, the Thai Government has established a policy that electricity generation from renewable energy is targeted to increase the percentage share from 0.5% in 2002 to 8% of final energy production by 2011.

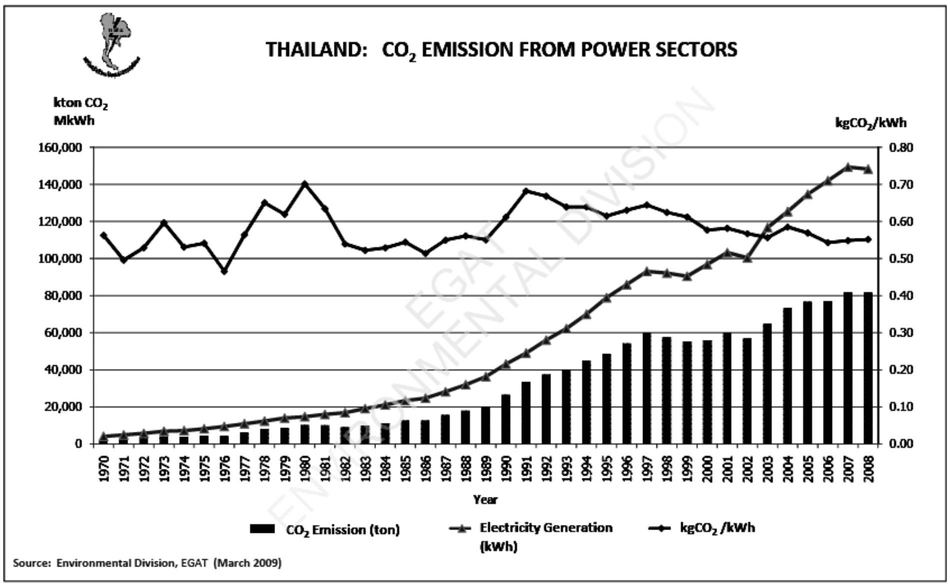

Figure 1. Thailand's CO_2 emissions from power sector [2].

Solar electricity generation is given attention because it is the largest renewable energy resource with abundant reserves and the technology is friendly to the environment when compared with electricity generation by fossil fuels. However, there are some arguments about its disadvantages such as energy conversion efficiency and a question from environmental conservationists that "Is it a genuinely cleaner technology?" To answer these questions, LCA has been widely applied to assess the solar cell power plant system. LCA was applied to assess renewable energy electricity generation in Poland. The electricity from a solar cell system was found to give higher impact value than those of wind turbine and hydro, but lower than those of fossil fuel power plants [3]. LCA results of the solar cell power plant in Switzerland using the new eco-invent database found that important environmental impacts were not directly related to the energy use of the solar energy electricity generation but the impacts occurred at its module production [4] as the assessed results in the Netherlands [5, 6] and the USA [7] also show. In Japan and Thailand, the numerical environmental total standard (NETS) method and LCA technique has been applied to study the environmental impacts of the power plant systems. The results showed that the solar cell power plants gave lower environmental impacts than those of nuclear, waste fuels and fossil-fired power plants [8]. Recently, it was used to assess a multicrystalline silicon (m-Si) solar cell power generation system in Japan. The results showed that the largest impact was at the manufacturing process of the array field due to natural resource (i.e. silicon and aluminum) consumption [9]. For LCA studies of electricity generation in Thailand, grid electricity power plants (excluding renewable energy power plants) were also analyzed by LCA-NETS method for which the inventory data were based on the Japanese database [10]. LCA-NETS were also applied to analyze a gas turbine and a combined cycle power plant. The results found that the major impacts of both power plants to the environment were fossil fuel depletion for electricity generation [11].

In this study, the first solar cell power plant of Thailand in Mae Hong Son province with a capacity of 500 kW_p is taken as a model for assessment. Two types of solar cell for the power plant, multicrystalline silicon (m-Si) solar cell and thin film amorphous silicon (a-Si) solar cell, are considered. The environmental impact results considered by LCA-NETS of the solar cell power plants are compared to the fossil fuel power plants which are coal-fired power plant, diesel-fired power plant, gas turbine power plant and combined cycle power plant [12].

Methodology

LCA of the solar cell power plant

LCA is a concept and a methodology to evaluate the environmental effects of a product or activity holistically by analyzing the entire life cycle of a particular product, process, or activity. Principally, LCA is applied to address input of energy and resources and output of the environmental impacts of product system. There are four steps in LCA procedure and for this particular power plant model they are as follows:

Step 1: Goal and Scope Definitions

The overall goal of this LCA study is to analyze the numerical results of the solar cell power plants in environmental impact issues. The life cycle boundary is demonstrated in Fig. 2. There are three phases, the solar module manufacturing, transportation from manufacturer to the power plant and the operation of the power plant system which covers solar cell modules, inverters, battery storage, power plant building and module support structure as shown in Fig. 3. All of the system components except the solar modules are similar to this power plant. For the solar cell modules, the data are taken from the units fabricated by the local manufacturers in Thailand instead of the imported modules.

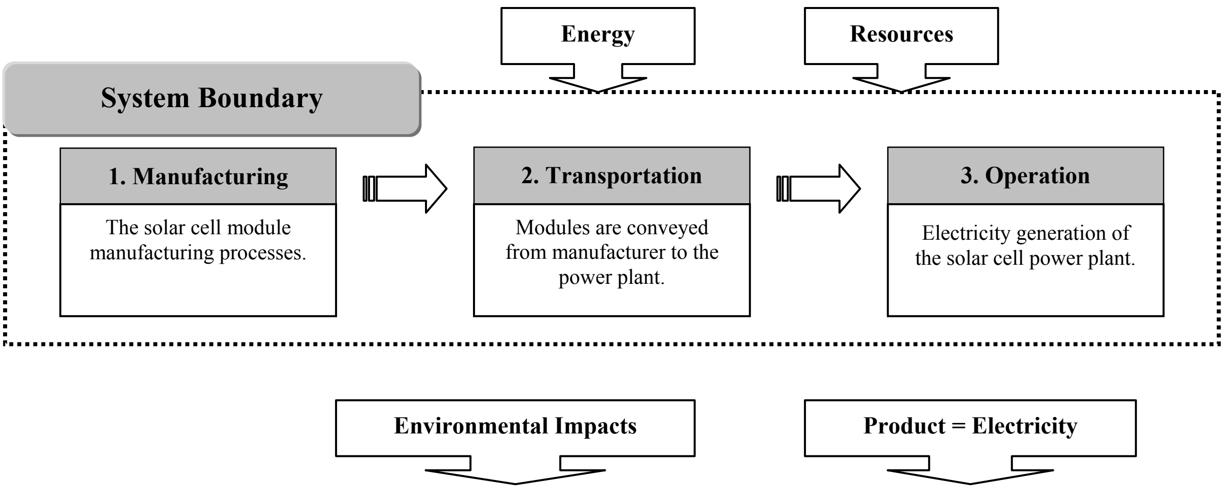

Figure 2. Life cycle boundary of the solar cell power plant study.

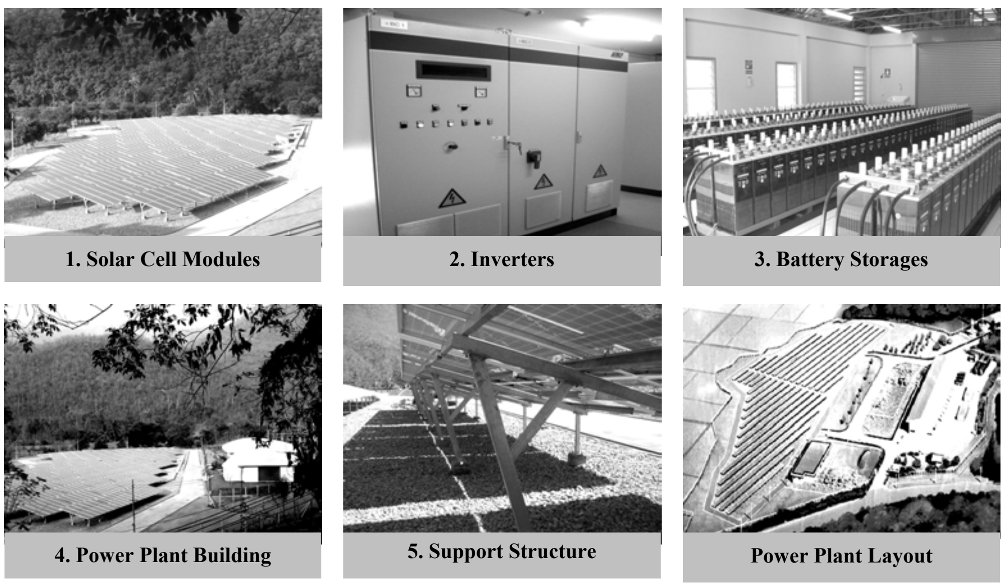

Figure 3. The solar cell power plant system.

- Functional Unit Definition

The functional unit of product, which is necessary for allocating data and calculating the result, is 1 kWh of generated electricity from the solar power plant. Thus, the environmental impact results are calculated in terms of NETS per functional unit of 1 kWh.

- Product Specification

Table 1 shows the details of two types of the solar modules which are the most important component of the solar cell power plant system.

Table 1. Product specification.

Item	m-Si solar module	a-Si solar module
Model	120W	40W
Module dimension	662 × 1482 mm	635 × 1245 mm
Overall weight - Frame - Frameless	12.0 kg 7.0 kg	13.8 kg 12.9 kg
Max. power rating: Wp	≥ 120 W	≥ 40 W
Open circuit voltage: Voc	21.5 ± 5% V	62.2 ± 10% V
Rated operating voltage: Vm	16.9 ± 5% V	44.8 ± 10% V
Max. system voltage	600 V	600 V
Rated operating current: Im	7.1 ± 10% A	0.90 ± 10% A
Short circuit current	7.45 ± 10% A	1.16 ± 10% A
Standard test	IEC 61215	IEC 61646

Step 2: Life Cycle Inventory (LCI)

The inventory analysis is to map out the environmental interventions which are general terms for emissions and all other inputs and outputs from and to the environment. The primary and secondary data of the energy and the resources inputs and the emission outputs from each phase are collected. The details of each phase of data collection are as follows:

- Manufacturing Phase

In the manufacturing phase, the input of material and energy in the process and the output due to the discharged pollutants to the environment on the solar module manufacturing are considered. The inventory data can be collected directly and converted to a standard format to provide a description of the physical characteristics. However, there are some unavailable data thus databases from literature surveys are applied.

- Transportation Phase

In the transportation phase, the fabricated solar cell modules are conveyed from the manufacturers to the power plant by truck. Therefore, there is consumption of fossil fuel (diesel oil and motor oil) which generates emissions to the air.

- Operating Phase

Inventory data of the operation phase consists of the power plant equipment data. The considered equipment is battery storage systems, inverters, power plant building and construction and module support structure. Key assumptions of the solar system components are; the solar modules have a lifespan of 25 years, the inverter and the system controllers have a lifespan of 20 years, the building and construction and the module support structure have a lifespan of 25 years, and the battery storage has a lifespan of 10 years.

Step 3: Life Cycle Impact Assessment (LCIA)

In this step, the results of the inventory analysis are translated into scores on a number of environmental issues or themes (e.g. global warming, rain acidification). This study applies the Numerical Environmental Total Standard or NETS method to assess the environmental impacts of the solar cell power plant. NETS has been developed in the Energy System Design Laboratory at Mie University, Japan, which aims to quantitatively describe the total impact to the environment during life cycle, in which the numerical value is calculated according to the maximum tolerable value [13]. All environmental loads are assessed and converted into the single index of NETS. The environmental impacts in NETS method are divided into two categories, global impacts and regional impacts as described in Table 2. The basic idea of NETS is based on the balance between *"Effecter"* that generates the impacts and *"Receiver"* that suffers from these impacts. It is based on tolerant balance theory between the maximum tolerable value of load that the *"Effecter"* could release or consume, and the maximum value that the *"Receiver"* is affected by the load.

Table 2. Environmental impact category in NETS method.

Category	Impact	Abbreviation	Reference
Global Impacts	Fossil Fuel Depletion	FD	Proven reserve
	Natural Resource Depletion	RD	Proven reserve
	Global Warming	GW	World maximum allowable emission
	Ozone Layer Depletion	OD	
	Air Pollution	AP	
	Water Pollution	WP	
Regional Impacts	Rain Acidification	AR	Regional maximum allowable emission
	Solid Waste	SW	

For ISO 14042, which is the framework for life cycle impact assessment (LCIA), the total environmental impact (TEI) is expressed as:

$$TEI = \sum_j \left(y_i \times \frac{1}{MRC^j / MPI^j} \right) \times 100 \quad \textbf{(1)}$$

Where y_i is a category indicator result in the impact category j. MRC^j is maximum release or consumption and MPI^j is maximum permissible impact.

The total environmental impact (*TEI*) in NETS method is correspondence to ISO-LCIA and it is expressed as:

$$TEI[NETS] = \sum_j \sum_i EIM_i^j \times x_i \quad \textbf{(2)}$$

Where x_i is the physical amount of the environmental substance i in the impact category j. EIM_i^j is environmental impact module of an environmental substance i in the impact category j which is calculated from the balancing theory of NETS method. There is a balance between *"Effecter"* generating impacts on environment and *"Receiver"* affecting these impacts as:

$$MPI_i^j[NETS] = MRC_i^j[kg, m^3....] \times EIM_i^j[NETS/(kg, m^3, ...)] \quad \textbf{(3)}$$

From Equation (3), MPI_i^j is maximum permissible impact which is the *Receptor*'s maximum capacity for an environmental substance i in an impact category j. MRC_i^j is maximum release or consumption which is the maximum amount of an environmental substance i that the *Effecter* can release or consume.

The maximum permissible impact, MPI_i^j, in Equation (3) is given by

$$MPI_i^j[NETS] = MPIC[NETSperCapita] \times P_i^j \quad \textbf{(4)}$$

Where *MPIC* is maximum permissible impact per capita. It is a maximum value per capita which is defined as *100[NETS]*. P_j^j is the population in the considering area that is affected by the impact.

An example of the *EIM* calculation of each impact can be expressed in the case of fossil fuel depletion (FD). NETS defines the environmental impact as what causes the "situation" in which "people cannot continue to live unless they change their lifestyle" and treats resource depletion as such an impact. In the case of crude oil, such as a typical fossil fuel, the situation where "people cannot continue to live unless they change their lifestyle" is that the proven reserve of crude oil decreases so much that the oil cannot be extracted further with the present techniques and costs, then people are unable to go on consuming it in the same previous way. This situation affects people all around the world with the world population (P_w) of 6.0×10^9. The people's maximum permissible impact of crude oil in fossil fuel depletion or MPI_i^{FD} is therefore expressed as:

$$
\begin{aligned}
MPI_{crude\ oil}^{FD} &= P_w \times MPIC \\
&= (6.0 \times 10^9) \times 100[\text{NETS}] \\
&= (6.0 \times 10^{11})\ [\text{NETS}]
\end{aligned}
$$

The amount of crude oil consumed until the situation takes place, MRC_i^{FD}, is given by the proven reserve of crude oil which is the amount able to be extracted at the present level of cost and technique. It is found that the present proven reserve of crude oil is 1.05×10^{12} barrels or 1.43×10^{14} kg approximately. Thus, the impact of fossil fuel depletion of crude oil, $\text{EIM}_{\text{crude oil}}^{\text{FD}}$ is therefore calculated as:

$$
\begin{aligned}
EIM_{crude\ oil}^{FD} &= MPI_{crude\ oil}^{FD} / MRC_{crude\ oil}^{FD} \\
&= MPI_{crude\ oil}^{FD} / Proven\ reserve\ of\ crude\ oil \\
&= (6.0 \times 10^{11}\ [\text{NETS}] / 1.43 \times 10^{14}\ [\text{kg}] \\
&= (4.20 \times 10^{-3})\ [\text{NETS/kg}]
\end{aligned}
$$

Table 3 shows the sample of respective EIM_i which are used to identify the total environmental impact.

Environmental impact per functional unit of 1 kWh is based on electricity generation for the entire solar cell power plant life cycle. In general, the electricity generated from the modules is evaluated from the maximum power output as shown in the module specification which is based on laboratory tests at the standard conditions of 1000 W/m^2 radiation from solar simulator and at 25^oC of controlled surrounding ambient temperature. However, in actual operation, the solar radiation and the ambient temperature are not constant as those set in the laboratory, therefore, the power output from the solar module must deviate from that in the laboratory specification.

Table 3. Example of respective EIM_i in NETS method [13].

Category	Substance	EIM_i [NETS/kg]
1. Energy Resource Depletion	Crude Oil	4.20×10^{-3}
	Natural Gas	5.49×10^{-3}
	Coal	6.12×10^{-4}
	Uranium	1.65×10^{3}
2. Natural Resource Depletion	Bauxite and Alumina	2.41×10^{-2}
	Copper	9.27×10^{-1}
	Iron ore (Crude ore)	2.01×10^{-3}
	Lead	9.41×10^{0}
	Nickel	4.02×10^{0}
	Zinc	1.40×10^{0}
3. Global Warming	CO_2	9.59×10^{-4}
	CH_4	2.21×10^{-2}
	N_2O	2.84×10^{-1}
	SF_6	2.13×10^{1}
4. Ozone Layer Depletion	CFC-11	1.09×10^{1}
	CFC-113	8.73×10^{0}
	HCFC-22	6.00×10^{-1}
5. Water Pollution	Pb	1.69×10^{1}
	As	1.69×10^{1}
	Cr	3.38×10^{0}
	Hg	3.38×10^{2}
6. Air Pollution	SO_2	3.26×10^{-2}
	NO_2	4.08×10^{-2}
	Lead	3.26×10^{0}
7. Rain Acidification	NO_2	1.42×10^{-1}
	SO_2	2.03×10^{-1}
8. Solid Waste	Industrial Waste	2.98×10^{-2}
	General Waste	1.93×10^{-2}

To obtain more accurate results, outdoor module tests have been carried out to record the output module current and the module voltage with the measured data of the solar irradiation, the ambient temperature and the module temperature. A regression model of the power output with the solar radiation level and the ambient temperature is developed [14]. It can be used to calculate and predict the power output when the weather conditions are given. Moreover, the model is used to estimate the power output of the module which is assumed to be located in four selected cities in Thailand as defined in Table 4. The generated electricity per year, $E_{gen/year}$, and the generated electricity throughout the life span, $E_{gen\text{-}lifetime}$, could be estimated by multiplying the power output (P) with the number of days and number of years. To evaluate the power output of the module at different cities, the solar radiation levels and the ambient temperatures could be selected from RETScreen data [15], as given in Table 5. Since the data are global radiation in the horizontal plane, then the values have to be converted to be those on the tilting plane of the solar cell modules which are assumed to be the same as the latitudes of the considered cities. The conversion technique could be taken from many solar energy textbooks.

Table 4. Four selected cities in Thailand.

Location	City	Latitude	Longitude
North	Chiang Mai	18.78 °N	98.98 °E
North-East	Ubon	15.23 °N	105.86 °E
Central	Bangkok	13.69 °N	100.61 °E
South	Songkhla	7.21 °N	100.60 °E

Table 5. Solar radiation and ambient temperature data input into the model [15].

Month	Chiang Mai		Bangkok		Ubon		Songkhla	
	Daily solar radiation on horizontal ($kWh/m^2/day$)	Temp. (°C)	Daily solar radiation on horizontal ($kWh/m^2/day$)	Temp. (°C)	Daily solar radiation on horizontal ($kWh/m^2/day$)	Temp. (°C)	Daily solar radiation on horizontal ($kWh/m^2/day$)	Temp. (°C)
January	5.17	20.0	5.07	25.3	5.18	22.8	4.77	25.6
February	5.92	22.9	5.62	26.4	5.51	24.6	5.49	26.2
March	6.31	25.8	5.99	26.9	5.74	25.7	5.65	26.8
April	6.36	27.6	6.23	27.2	5.88	26.1	5.7	27.3
May	5.36	26.0	5.37	27.0	5.34	26.5	4.98	27.3
June	4.28	24.6	4.93	26.6	4.83	26.1	4.72	27.1
July	3.99	24.1	4.82	26.3	4.66	25.8	4.74	26.9
August	3.91	24.0	4.81	26.2	4.43	25.7	4.63	26.9
September	4.28	23.7	4.73	26.0	4.53	25.4	4.64	26.6
October	4.45	22.6	4.49	25.4	4.82	24.4	4.29	26.3
November	4.48	20.5	4.74	24.4	4.88	22.9	3.59	26.1
December	4.75	18.4	4.86	24.1	4.96	21.7	3.75	25.7
Annual	**4.94**	**23.4**	**5.14**	**26.0**	**5.06**	**24.8**	**4.75**	**26.6**

Step 4: Life Cycle Improvement Analysis
The aim of this step is to identify potential obstructions in the life-cycle and possibly define improvements to overcome these difficulties. The results of the environmental impact assessment can be a decision-making tool and can indicate the method or materials to achieve the best eco-product or eco-process.

LCA of the Fossil Fuel Power Plants
There are four types of the fossil fuel power plants in Thailand which are analyzed and their results compared to the solar cell power plant results. Their LCA descriptions are as follows:

- Coal - Fired Power Plant and Diesel - Fired Power Plant

LCA-NETS is applied to assess the biggest lignite-fired power plant in Thailand and the diesel-fired power plant with their capacity of 2400 MW and 5.4 MW, respectively [10]. Each system boundary is shown in Fig. 4., which covers extraction of raw material, refinery of fuel, transportation, direct fuel consumption for electricity generation and power plant construction.

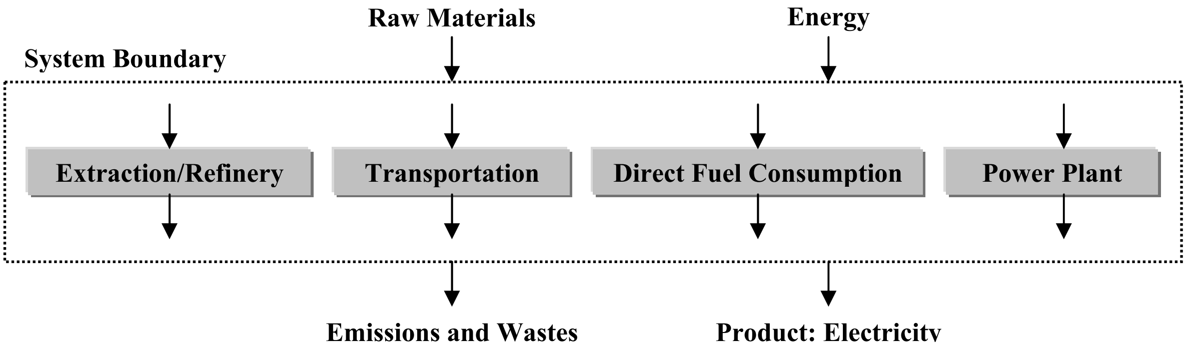

Figure 4. Lignite-fired power plant and diesel-fired power plant system boundary [10].

- Gas Turbine Power Plant and Combined Cycle Power Plant

As natural gas takes up the highest percentage share of fuel for electricity generation in Thailand, gas turbine power plant with a capacity of 366 MW and a combined cycle power plant with a capacity of 1,300 MW which use natural gas as a main fuel are studied [11]. LCA-NETS is also applied to assess their environmental impact per 1 kWh of generated electricity. Their system boundaries are expressed in Fig. 5.

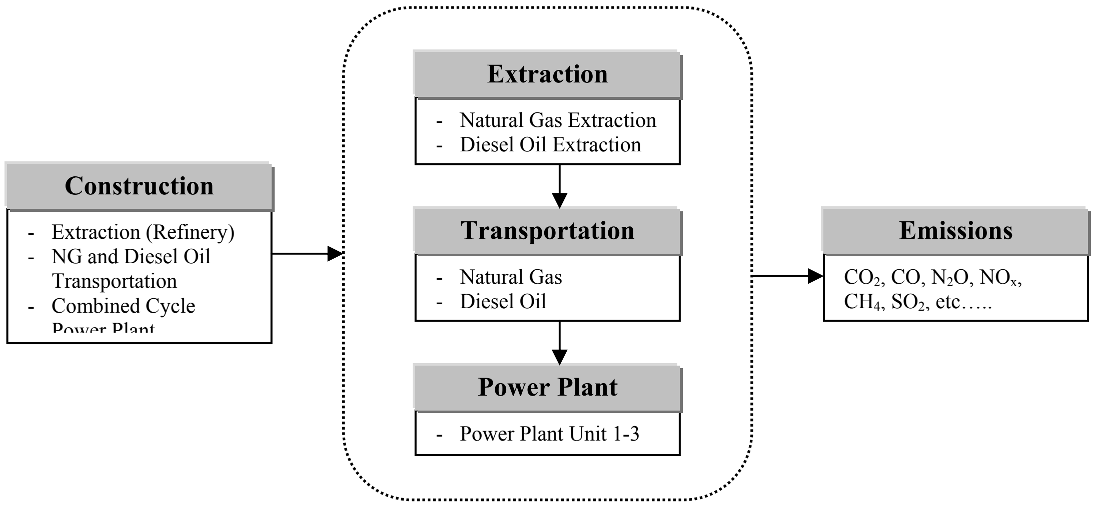

Figure 5. Gas turbine power plant and combined cycle power plant system boundary [11].

Results and Discussion

LCA Results of the Solar Cell Power Plants

- Life Cycle Inventory Results

Table 6 shows material inventory data of the solar cell modules. These primary data can be used to evaluate greenhouse gas (GHG) emissions, such as CO_2 and CH_4. The GHG emission of the solar module can be calculated when emission factors of each material and material consumption per module are given. The result found that the m-Si and the a-Si modules give CO_2 emissions of 0.014 kg per kWh and 0.0067 kg per kWh, respectively. The CH_4 emission results per kWh are insignificant when compared to the CO_2 emission results.

Table 6. Material inventory data of the solar cell manufacturing.

Greenhouse Gas	Material	Emission factor (kg/kg-material)[1]	m-Si Module		a-Si Module	
			Amount (kg-material)	Emission (kg-emission)	Amount (kg-material)	Emission (kg-emission)
CO_2	Silicon Cell	3.39	1.20	4.07	low	low
	Glass	0.228	6.50	1.48	12.80	2.92
	Aluminum	9.96	5.00	49.80	0.83	8.27
	EVA	1.78	0.20	0.36	0.23	0.41
	Copper	5.21	0.10	0.52	0.10	0.52
	Total CO_2 emission per module		**56.23**		**12.12**	
	Total CO_2 emission per kWh		**0.014**		**0.0067**	
CH_4	Silicon Cell	3.04×10^{-6}	1.20	3.65×10^{-6}	low	low
	Glass	3.93×10^{-4}	6.50	2.55×10^{-3}	12.80	5.03×10^{-3}
	Aluminum	2.23×10^{-2}	5.00	1.12×10^{-1}	0.83	1.85×10^{-2}
	EVA	5.79×10^{-3}	0.20	1.16×10^{-3}	0.23	1.33×10^{-3}
	Copper	2.80×10^{-7}	0.10	2.80×10^{-8}	0.10	2.80×10^{-8}
	Total CH_4 emission per module		**1.15×10^{-1}**		**2.49×10^{-2}**	
	Total CH_4 emission per kWh		**7.94×10^{-5}**		**1.71×10^{-5}**	

[1] SimaPro 7.1 database

Tables 7 and 8 show energy inventory of the m-Si and the a-Si solar module manufacturing processes, respectively. For the m-Si module, the production from high purity silicon to solar cell is based on European databases from the literature survey due to Thailand only having module assembly wherein the cells are imported from Europe. For the a-Si module, the processes are simpler and link with other industries less than the m-Si process. Thus, energy consumption of the a-Si is much less than that of the m-Si.

Table 7. Energy inventory data of the m-Si solar module.

Process	Energy consumption (kWh/module)	Reference data
1. High purity silicon production	103.17	Mariska and Erik, 2005
2. m-Si wafer production	16.85	Mariska and Erik, 2005
3. Solar cell production	21.24	Mariska and Erik, 2005
4. m-Si module assembly	16.47	Site-specific data, local manufacturer, 2007
5. Aluminum production	78.48	Phylipsen and Erik, 1995
6. Glass production	26.49	Phylipsen and Erik, 1995
7. EVA production	9.81	Phylipsen and Erik, 1995
8. Copper production	0.49	Phylipsen and Erik, 1995
9. Tedlar production	4.12	Phylipsen and Erik, 1995
Total energy consumption	**277.12**	Mixed data

Table 8. Energy inventory data in processes of the a-Si module.

Process	Energy consumption (kWh/module)	Reference data
1. a-Si module production	26.92	Site-specific data, local manufacturer, 2007
2. Aluminum production	14.11	Phylipsen and Erik, 1995
3. Glass production	1.54	Phylipsen and Erik, 1995
4. EVA production	0.98	Phylipsen and Erik, 1995
5. Copper production	0.012	Phylipsen and Erik, 1995
Total energy consumption	**43.56**	Mixed data

Table 9 shows inventory data of the transportation phase which is focused on fuel consumption of vehicles and their environmental emissions.

Table 9. Inventory data of the transportation phase.

Item	Unit	6 - Wheel Truck	10 - Wheel Truck
Fuel consumption rate	Liter/100 km	11.67 – 16.90	21.29 – 31.06
Emission factors			
CO_2	kg/liter diesel	2.6976	3.1924
CO	kg/liter diesel	0.01493	0.03059
CH_4	kg/liter diesel	0.000036	0.000219
NO_x	kg/liter diesel	0.01348	0.03642
N_2O	kg/liter diesel	0.000146	0.000109
NMVOC	kg/liter diesel	0.00401	0.00692

Source: Office of Natural Resources and Environmental Policy and Planning,
Ministry of Natural Resources and Environment, Thailand, 2005

Table 10. Energy analytical results of the solar cell module.

Energy Factors	Unit	Analytical Results			
Regression model for electricity generation estimation	-	$P_{m\text{-}Si} = (9.14 \times 10^{-2})I_T - (4.81 \times 10^{-3})(T_{amb} + 15.41)^2$			
		$P_{a\text{-}Si} = (4.03 \times 10^{-2})I_T - (9.86 \times 10^{-4})(T_{amb} + 11.2)^2$			
Input energy for module manufacturing	kWh/module	m-Si = 277.12			
		a-Si = 43.56			
Selected locations	-	**Chiang Mai**	**Bangkok**	**Ubon**	**Songkhla**
Average solar radiation	$kWh/m^2/yr$	1803	1876	1847	1734
Output energy Electricity generation per year: $E_{gen/yr}$	kWh/module	**m-Si**	**m-Si**	**m-Si**	**m-Si**
		163.65	170.13	167.80	156.78
		a-Si	**a-Si**	**a-Si**	**a-Si**
		72.11	75.03	73.97	69.22
Electricity generation entire life cycle: $E_{gen/lifetime}$	kWh/module	**m-Si**	**m-Si**	**m-Si**	**m-Si**
		4091.25	4253.25	4194.92	3919.50
		a-Si	**a-Si**	**a-Si**	**a-Si**
		1802.75	1875.75	1849.25	1730.50
Average electricity generation entire life cycle (4 cities)	**kWh/module**	**m-Si = 4114.73**			
		a-Si = 1814.56			

Table 10 shows the energy output results of both m-Si and a-Si solar power plants. The regression models of the power output for both solar cell modules with the solar radiation level and the ambient temperature are;

$$Power\ output\ (W) = f(I_T, T_{amb}) \quad \textbf{(5)}$$

Where I_t is the solar radiation (W) incident on the solar cell module and T_{amb} is the ambient temperature (^oC). The regression equations of the m-Si and the a-Si are shown in Table 10.

The solar cell power plants are assumed to be located in the four cities, Chiang Mai, Bangkok, Ubon and Songkla, in different parts of Thailand. The average electricity generation for the entire modules life cycle of the m-Si is 4114.73 kWh per module and the a-Si is 1814.56 kWh per module.

- Life Cycle Impact Assessment Results

Fig. 6. illustrates the environmental impact for entire life cycle of the power plant. The final result obviously shows that the highest value of environmental impact occurs at the manufacturing phase. Manufacturing of the m-Si solar module gives environmental impact values higher than those of the a-Si module due to the crystalline cell having many linked industries.

When focusing on the manufacturing phase, it was found that the major environmental impacts are natural resource depletion, fossil fuel depletion and air pollution (Fig. 7). The most significant problem is natural resource depletion due to aluminum usage for the module frame structure.

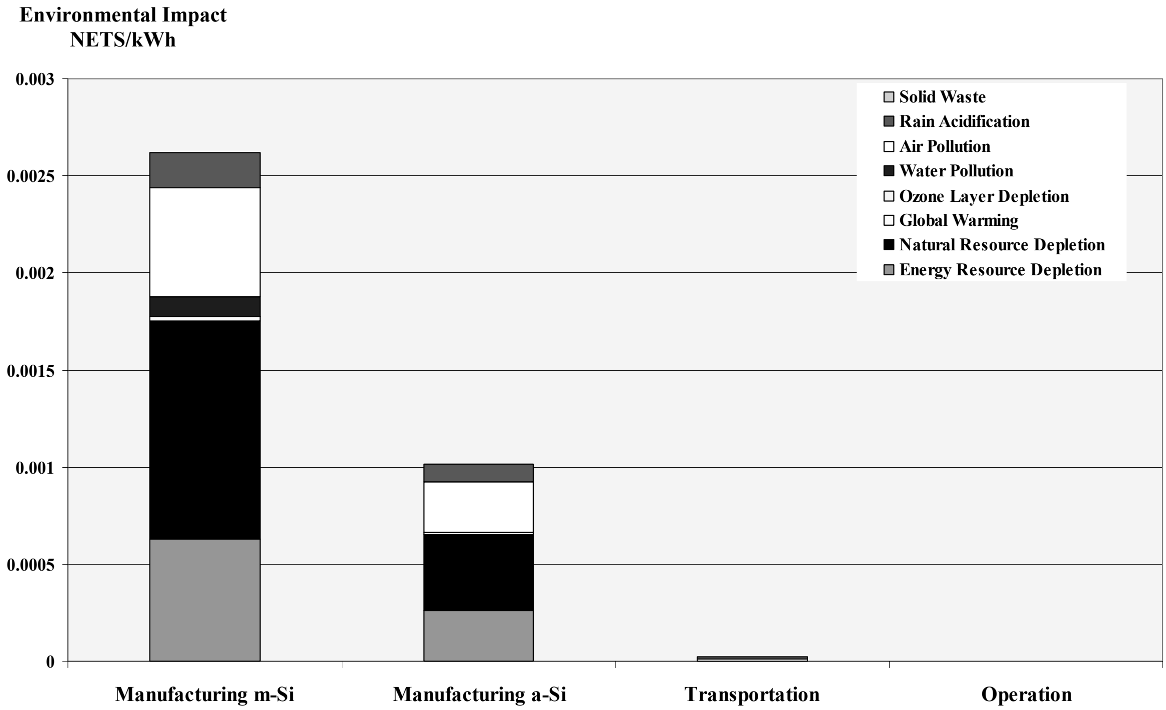

Figure 6. Life cycle impact assessment result of the solar cell power plant, calculated by NETS method.

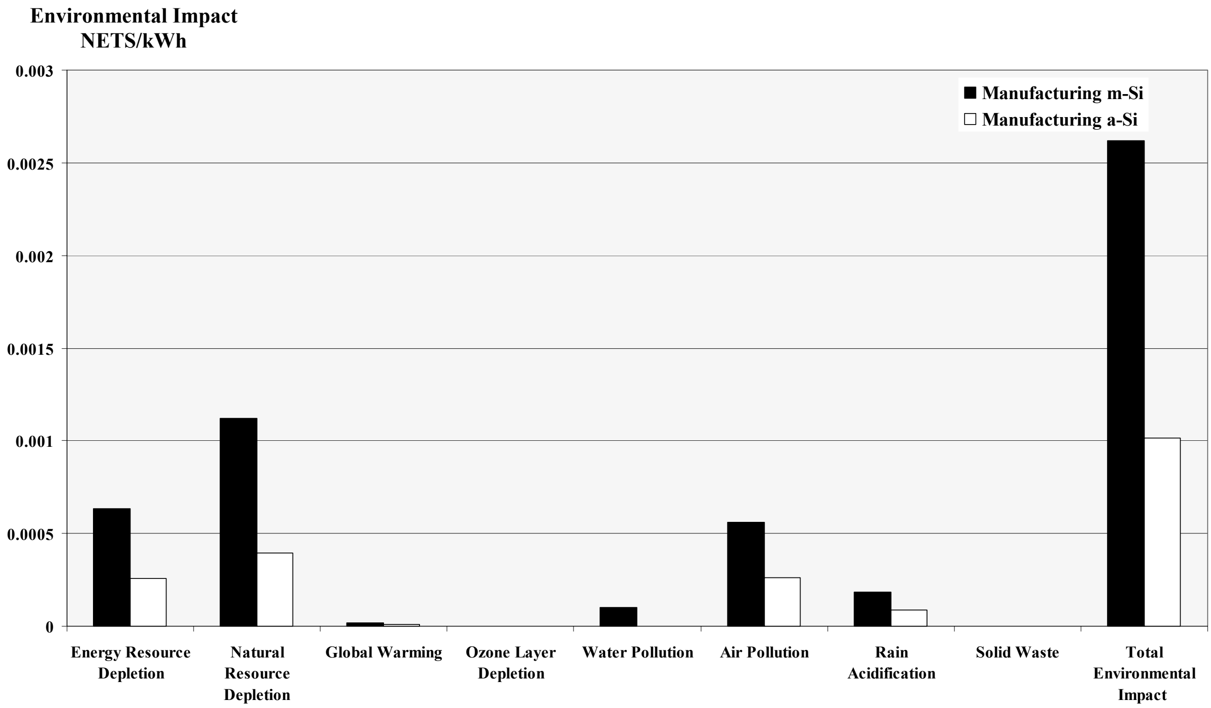

Figure 7. Environmental impact comparison between the m-Si and the a-Si solar module in manufacturing phase.

Comparison results

- Greenhouse Gases (GHGs) Emission Comparison

The CO_2 emission of the solar cell power plants can be compared to the emission from the fossil fuel power plants [16], as shown in Fig. 8. It is clearly shown that the solar cell power plant emits much less CO_2 to the environment than those of the fossil fuel power plants.

- Total Environmental Impact Comparison

Fig. 9. shows the total environmental impact comparison of the solar cell power plants and the fossil fuel power plants in Thailand. It is shown that the solar cell power plants have lower environmental impact than that of the fossil fuel power plants. The most significant impact from the fossil fuel power plant is fossil fuel depletion due to use of fossil fuels to generate electricity.

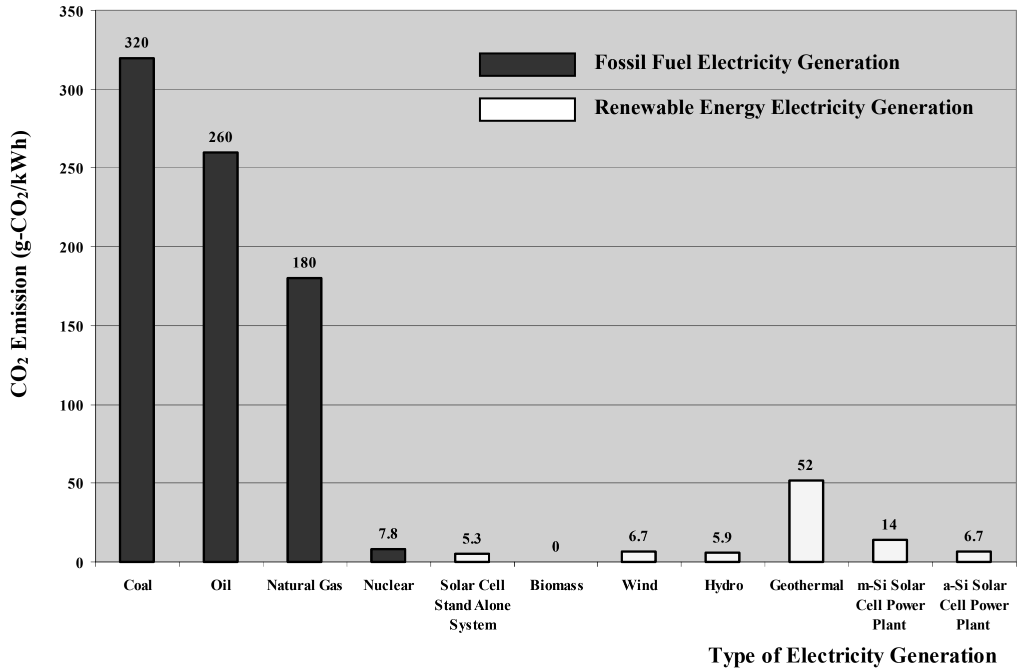

Figure 8. CO_2 emission from the power plants in Thailand.

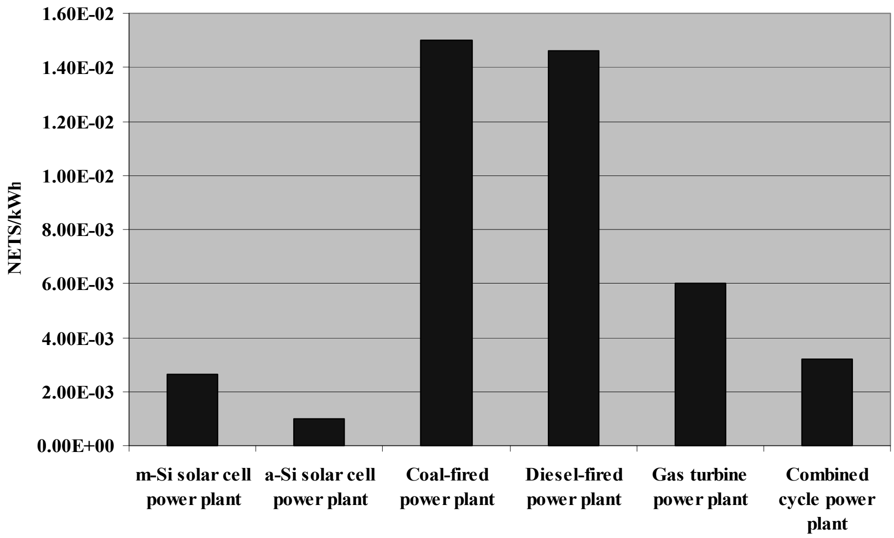

Figure 9. Total environmental impact comparison of the power plants, calculated by LCA-NETS method.

Conclusions

This study attempts to evaluate the numerical results on the environmental aspect of the solar cell power plant located in Thailand. The life cycle consideration covers the phases of solar module manufacturing, transportation from manufacturer to the power plant and the operation for electricity generation in the power plant. The results show that the main environmental impact is at the manufacturing phase and the most significant problem is natural resource depletion for module component materials. To obtain better environmental impact, some material such as aluminum should be replaced or not used since its consumption gives a high environmental impact. When comparing the solar cell power plant results to the fossil fuel power plant results, the CO_2 emissions from the solar cell power plants are much lower than those of the fossil fuel power plants. These results show that there is high potential for a CO_2 reduction strategy by using renewable energy for electricity generation. Finally, the total environmental impacts which are calculated from LCA-NETS method show that that the solar cell power plants are more friendly to the environment than fossil fuel power plants. Although the manufacturing of the solar cell module has some environmental impact, it is easier to control or manage these problems.

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