Life Cycle Assessment of Amorphous Silicon Solar Cell Power Plant Using Activity-Based Approach

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ABSTRACT

In this study, life cycle assessment or LCA is applied to investigate environmental impacts of an amorphous silicon solar cell power plant over its entire life cycle. The first solar cell power plant of Thailand with a capacity of 500 kW_p is taken as a model for the assessment. The environmental analytical results through the power plant life cycle are shown in term of environmental loads which are calculated from Numerical Environmental Total Standard or NETS method. The functional unit in this study is 1 kWh of electricity generation. The study covers the phases of solar module manufacturing, transportation from manufacturer to the power plant and electricity generation in the power plant. Activity-based approach is applied to collect the relevant data in life cycle inventory step for more accuracy results. The results show that the main environmental impact is at the manufacturing phase which offers about 98% of the total impact and the most violent problem is natural resource depletion due to raw material consumption of aluminum frame. The result which is calculated by the activity-based approach offers higher value than that of the conventional LCA due to expansion of considered boundary.

Keywords: Amorphous Silicon (a-Si) Solar Cell, Life Cycle Assessment (LCA), Activity Based Costing (ABC), Solar Cell Power Plant

1. INTRODUCTION

1.1 Statement of Problems and Backgrounds

In the fiscal year 2008, electricity generation of Thailand relies on fossil fuels which are natural gas, coal and fuel oil more than 90% (Energy Policy and Planning Office, 2008). There is a report that the power sector creates many impacts on environment such as CO_2 emission trends to increase continuously (Electricity Generating Authority of Thailand, 2008) and it is one of the main causes of greenhouse effect and global warming. Therefore, the Thai Government has set a policy on renewable energy using target to increase the percentage share from 0.5% in 2002 to 8% of final energy production by 2011 which renewable energy for electricity generation is one of the main share.

Solar electricity generation is paid attention because it is the largest renewable energy resource with abundant reservation and the technology is friendly to the environment when compared to the electricity generation by fossil fuel. However, there are some arguments about its disadvantages such as energy conversion efficiency and a question from environmental conservator that “Is it a genuinely cleaner technology?” To answer these questions, life cycle assessment, LCA, has been widely applied to assess the solar cell power plant system. 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. In principle, LCA is applied to address input of energy and resources and output of the environmental impacts of product system.

LCA were applied to assess renewable energy electricity generations in Poland. The electricity from 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 (Malgorzata, 2002). LCA result of the solar cell power plant in Switzerland using the new eco-invent database was 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 (Jungbluth, 2004) as the assessed results in the Netherlands (Mariska and Erik, 2005) and the USA (Geoffrey and Gregory, 1997). 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 result showed that the solar cell power plants gave lower environmental impacts than those of nuclear, waste fuels and fossil-fired power plants (Anugerah et al, 2002). Recently, it was used to assess 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 (Nishimura et al, 2009). When focus on LCA studies of electricity generation in Thailand, grid electricity power plants (excluding renewable energy power plants) were also analyzed by LCA-NETS method (Viganda, 2002). LCA-NETS was also applied to analyze a gas turbine and a combined cycle power plants. The result was found that the major impacts of the both power plant to environment were fossil fuel depletion for electricity generation (Theeranuntha et al, 2008). In case of the LCA-NETS database of the solar cell power plant in Thailand, there is no work to be done and published.

1.2 Amorphous Silicon Solar Cell

Amorphous silicon (a-Si) solar cell is a solar cell which is deposited with thin silicon film layer on glass or another substrate material. The layer thickness is less than 1µm (thickness of a human hair: 50-100 µm), so the production cost is lower than the production cost of crystalline silicon. Due to thin film use less than 1% of raw material (silicon or other light absorbers) when compare to the crystalline silicon solar cell, it leads to a significant price drop per kWh. Thin film layers on the a-Si solar module consist of SnO_2 layer, a-Si:H layer, and Al/ZnO layer. The a-Si:H layer has double sub-layers, n-i-p and n-i-p. When solar radiation reaches to the module, photovoltaic reaction will occur in i-layer, the movement of electron (-) and hole (+) bring to electricity generation. While the crystalline silicon solar modules have primary material of silicon wafer or cell, the a-Si solar modules have primary material of silane gas (SiH_4). Processes of the a-Si manufacturing can be described as follows;

(1) The silane gas (SiH_4) is reacted by Plasma Chemical Vapor Deposition device. The amorphous silicon is made by depositing silicon onto glass or another substrate material from a reactive gas. The layer thickness amounts to less than 1 micron (0.001 millimeter).
(2) When the silane gas reaction the dopants as phosphine and diborane are included to create a p-type, n-type region and p-n junction.
(3) The p-n junction is made up of translucent junction as indium tin oxide.

1.3 Activity-Based Approach

Activity-based approach in this study is applied from the activity-based costing or ABC principle. ABC arose in the mid-to late-1980s for the reason of the increasing lack of relevance of traditional costing system. It is a technique for more accurately allocate the indirect and direct resources of an organization to the activities, which performed based on its consumption. In ABC, activities are identified to four levels, whereas the traditional costing system considers only one level. The four basically levels could be described as follows;

(1) **Unit-Level Activity:** Unit Level drivers are triggered for every unit that is being produced. All activities operate for every product unit will be studied. Main processes of production are usually unit level activities. For example, the main processes of a-Si solar module.

(2) **Batch-Level Activity:** Batch Level drivers are triggered for every batch produced. Activities occur depended on batch, which the number of product units in batch are uncertainty, for example, transportation of materials.
(3) **Product-Level Activity:** Product Level drivers are triggered for every new product changed. Activities occur when change the new product, for example, machine setting, R&D of a new product.
(4) **Facility-Level Activity:** Facility Level drivers are triggered for every supporting system, for example, lighting system, air-conditioning system, waste management.

Generally, LCA focuses on only the main activity of the production. Thus, the improvement is pointed to the main process's problem while the activities in other levels are ignored.

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. In 2004, it was constructed by importing 1,680 multicrystalline silicon (m-Si) solar cell modules from Germany since there was no domestic module manufacturer at that time. A few years later, there is the first domestic module manufacturer who produces thin film amorphous silicon (a-Si) solar cell. As almost of all a-Si module manufacturing processes able to produced in country, they are interested to promote as electricity generation equipments. Thus, the LCA-NETS is applied to assess the environmental impacts from the solar cell power plant when the a-Si solar cell is under taken. And in this study, in the life cycle inventory of LCA, activity-based approach is applied to collect the relevant data.

2. METHODOLOGY

There are four steps in LCA procedure and for our 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 a-Si solar cell power plants in environmental impact issue. The life cycle boundary is demonstrated in Fig. 1. 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 storages, power plant building and module support structure as shown in Fig. 2.

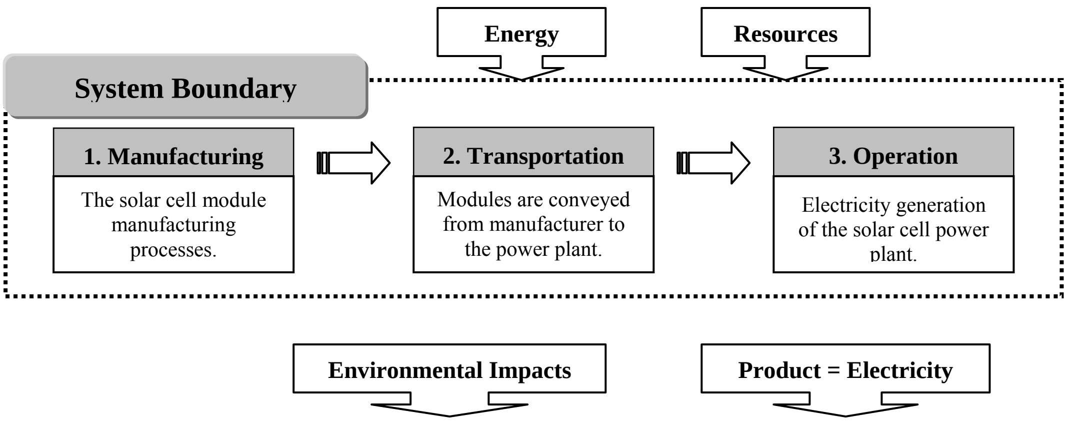

Figure 1. Life cycle boundary of the solar cell power plant study.

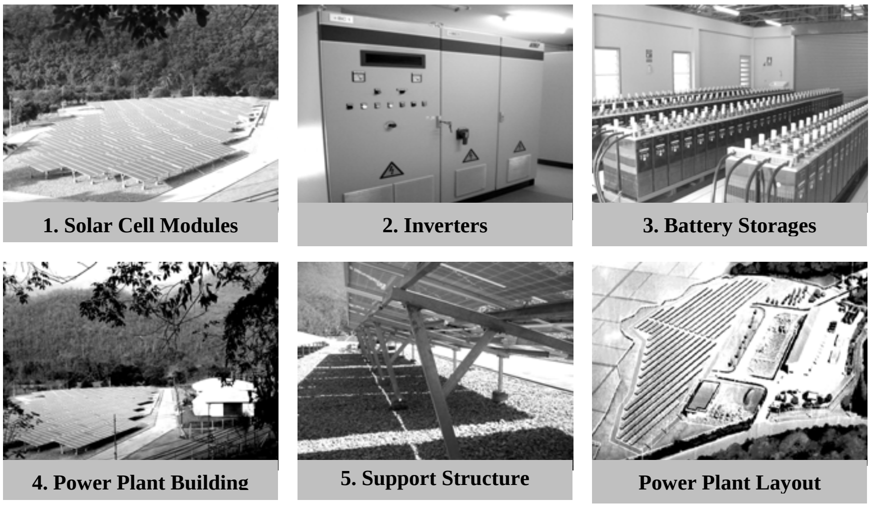

Figure 2. The solar cell power plant system.

- 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 plants. Thus, the environmental impact results are calculated in term of NETS per functional unit of 1 kWh.

- Product Specification

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

Table 1 Product specification.

Item	a-Si solar module
Model	40W
Module dimension	635 × 1245 mm
Overall weight	13.8 kg
Max. power rating: Wp	≥ 40 W
Open circuit voltage: Voc	62.2 ± 10% V
Rated operating voltage: Vm	44.8 ± 10% V
Max. system voltage	600 V
Rated operating current: Im	0.90 ± 10% A
Short circuit current	1.16 ± 10% A
Standard test	IEC 61646

Step 2: Life Cycle Inventory (LCI)

This step is data collection of energy consumption, material used and pollution or emission from each phase in the solar cell power plant system boundary. The inventory is the most important step of LCA because its impact assessment and all results are relevant with the results from the data collection. Thus, activity-based or AB-Data Collection Model has been created to collect all data of the solar module processes for the more accurate data the more accurate results. Fig. 3. explains procedure of the model which consists of 3 steps, (1) pre-data collection, (2) data collection and (3) data analysis. The data collection step is bases on ABC principle which all relevant activities are defined and classified into the activity level. Next, resource drivers and energy drivers are identified and trace them to each activity. Resource driver is a factor used to measure quantity of resource consumption by the activity. Resource driver indicates how much resources an activity requires. An example of the resource driver is quantity of raw material used in production activity. Energy driver is a factor also used to measure quantity of energy consumption by an activity. An example of the energy driver is machine hour per unit of product in process which spends for running the process.

The primary and secondary data of the energy and the resources inputs and the emission outputs from each phase are as follows:

1) Manufacturing Phase

In the manufacturing phase, the input of material and energy in process and the output due to the discharged pollutant to 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. In manufacturing, the most important parameter to indicate energy consumption is standard time of each activity. From the production line survey, it is found that the solar cells in process are moved by human labor. The machine hours and standard times of the process are not certainty contrast with the products in process moved by belting system. The ordinary observed times are not sufficient for being a good energy driver. Thus, motion and time study is necessary to analyze and manage the processes. It is a technique which integrates engineering technique and managerial technique. Its result can be used to manage and improve the processes for better operation. The objectives of this study are to define standard time or machine hour of each activity per a module which used to calculate electricity consumption of the activity. Energy driver of each machine in the unit-level activity is the standard time in unit of hours/module. Fig. 4. expresses the procedure of standard time calculation.

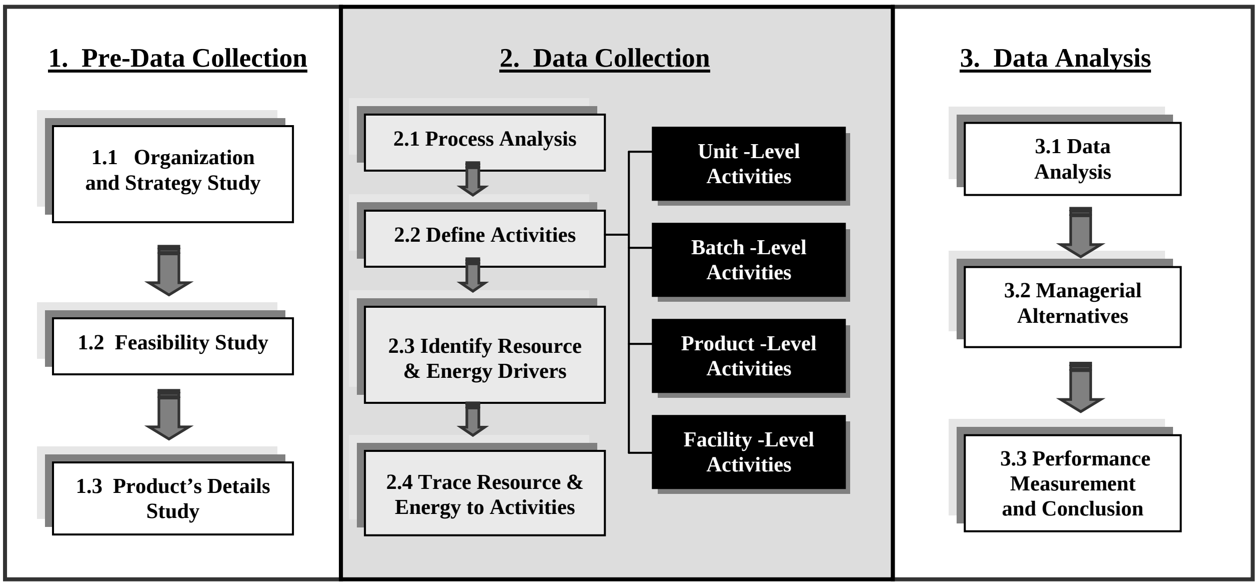

Figure 3. AB-Data Collection Model.

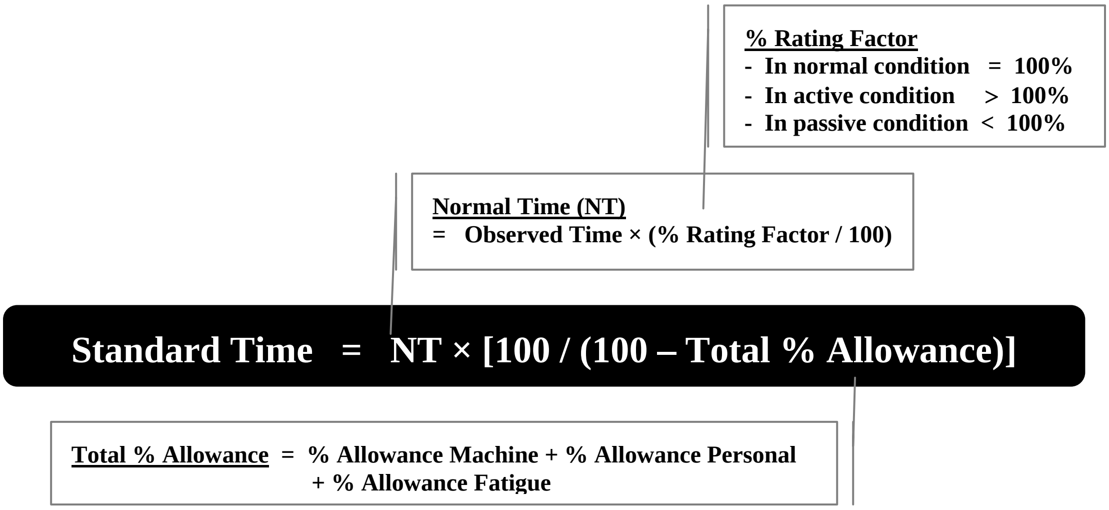

Figure 4. Standard time calculation in motion and time study.

2) Transportation Phase

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

3) Operating Phase

Inventory data of the operation phase consist of the power plant equipments data. The first solar cell power plant of Thailand with a capacity of 500 kW_p is taken as a model for the assessment. The considered equipments are battery storage system, inverter, power plant building and construction and module support structure. Key assumptions of the solar system components are as; the solar modules have lifespan of 25 years, the inverter and the system controllers have lifespan of 20 years, the building and construction and the module support structure have lifespan of 25 years, and the battery storages have 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 of environment during life cycle, in which the numerical value is calculated according to the maximum tolerable value (Yucho, 2006). 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"* who generates the impacts and *"Receiver"* who 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 frameworks for life cycle impact assessment (LCIA), the total environmental impact (TEI) is expressed as:

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

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:

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

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:

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

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

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

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 who is affected by the impact.

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

Table 3 Example of respective EIM_i in NETS method (Yucho, 2006).

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}

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 indicate the method or materials to achieve the best eco-product or eco-process.

3. RESULTS AND DISCUSSIONS

Fig. 5 shows the environmental impact score of the a-Si solar cell power plant. It is found that the enormous environmental impact occurs at the manufacturing phase which is about 98%.

Figure 5 The a-Si solar cell power plant environmental impacts, calculated by NETS method.

When focus on the manufacturing of the a-Si solar module, the inventory data of the thin film a-Si layer deposition processes and the module fabrication processes are site-specific data from local manufacturer. However, there are unavailable data of the module component materials. Thus, input and output data of each material inventory is based on the eco-invent database in inventory databases of SimaPro software. Finally, all inventory data are classified to environmental impact categories of NETS method and computed environmental impact in unit of NETS. Table 4 shows material inventory data of the a-Si solar module components. Table 5 shows gross energy consumption of the main processes.

Table 4 Material inventory data of the a-Si solar module.

Material	Weight (kg/module)[1]	Input/Output Inventory[2]	
		Type	Example
Chemical Gases		Resource Consumption	N.A.
- SiH_4	1.13×10^{-6}	Emission to Air	N.A.
- H_2	1.69×10^{-8}		
- CH_4	1.54×10^{-7}	Emission to Water	N.A.
- Ar	2.33×10^{-6}		
- PH_3	2.87×10^{-7}	Emission to Soil	N.A.
- TMB	2.70×10^{-7}		
- N_2	3.39×10^{-4}		
Tempered Glass	12.80	Resource Consumption	Sand, Aluminum, Water, Oil
		Emission to Air	CO_2, CO, CH_4, NO
		Emission to Water	Aluminum, Calcium, Sulfate
		Emission to Soil	Aluminum, Chloride, Oil
Aluminum	0.83	Resource Consumption	Bauxite, Lead, Copper, Water
		Emission to Air	CO_2, CO, CH_4, NMVOC
		Emission to Water	Aluminum, Barium, Calcium
		Emission to Soil	Aluminum, Arsenic, Carbon
EVA Film	0.23	Resource Consumption	Crude oil, Clay, Zinc
		Emission to Air	Acetic acid, CO_2, CO, CH_4
		Emission to Water	Aluminum, Arsenic, Lead
		Emission to Soil	Calcium, Chloride
Copper	0.10	Resource Consumption	Copper, Gravel, Iron, Sand
		Emission to Air	CO_2, CO, CH_4, Dioxin
		Emission to Water	Aluminum, Barite, Chloride
		Emission to Soil	Carbon, Calcium, Iron

[1] **Site-specific data, local manufacturer**
[2] **SimaPro 7.1 database**

Table 5 Energy inventory in processes of the a-Si solar module.

Process	Energy Consumption (kWh/module)	Data source
- Primary a-Si processes	17.78	Site-specific data
- Secondary materials processes:		P. Frankl, et. al., 1998.
1) Aluminum Production	14.11	
2) Float Glass Production	1.54	
3) EVA Film Production	0.98	
4) Copper Production	0.012	
Gross energy of module manufacturing	**34.42 kWh/module**	

When specify to the process data as in Fig. 6., it is clearly shown that the activities in facility-level consume much more electricity than the activities in unit-level activities. Air conditioning system is main cause of electricity consumption while the major processes of the a-Si module production are not the main cause as understanding in the conventional LCA.

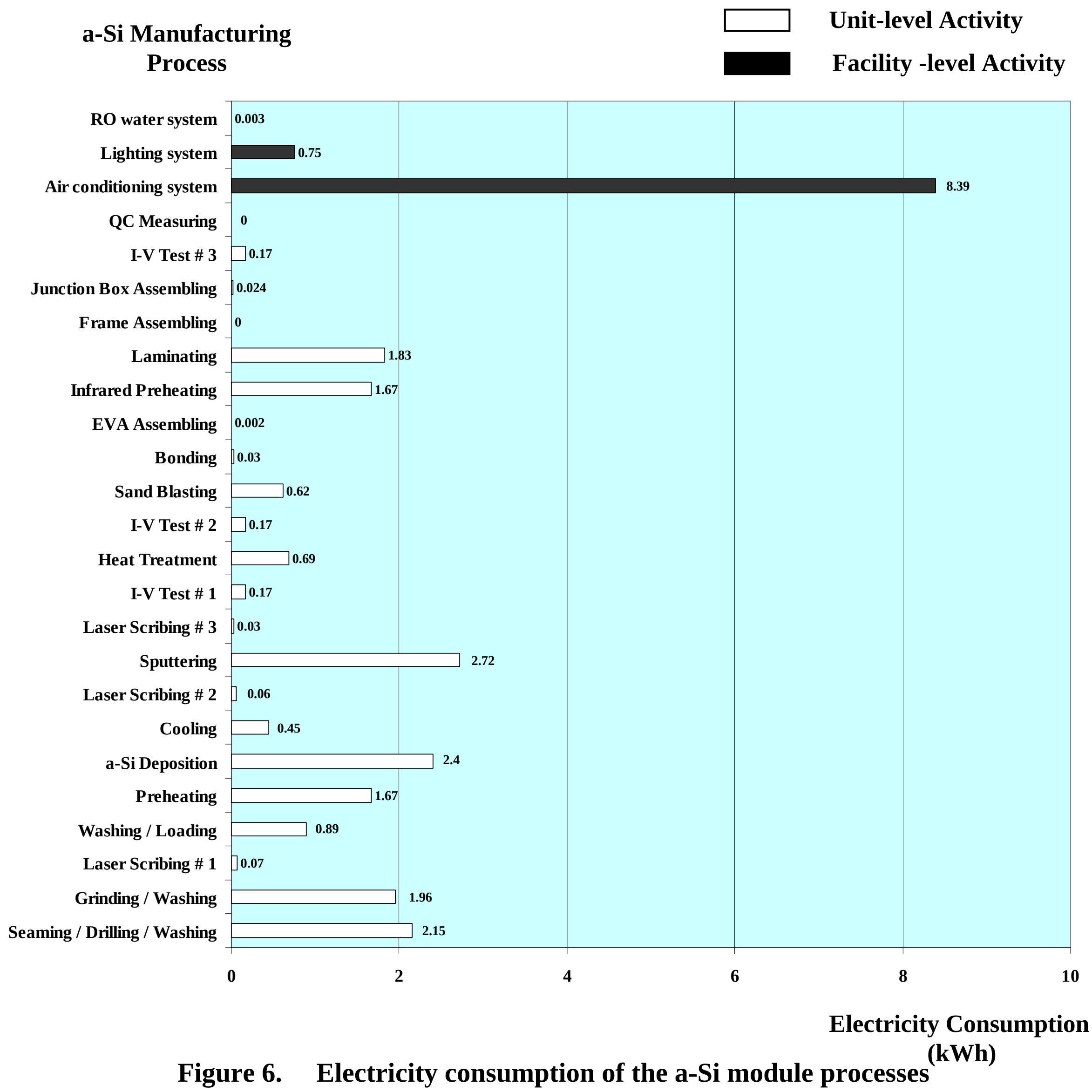

Figure 6. Electricity consumption of the a-Si module processes

Fig. 7 shows the environmental impact in the manufacturing phase. It is a comparison result between the conventional LCIA which is considered only the unit-level activities and the AB-LCIA which is considered covers the unit-level activities and the facility-level activities. The result shows that impact assessment by AB-LCIA offer higher value than that of the conventional LCIA due to expansion of considered boundary. The most violent impact is natural resource depletion due to raw material consumption of aluminum frame.

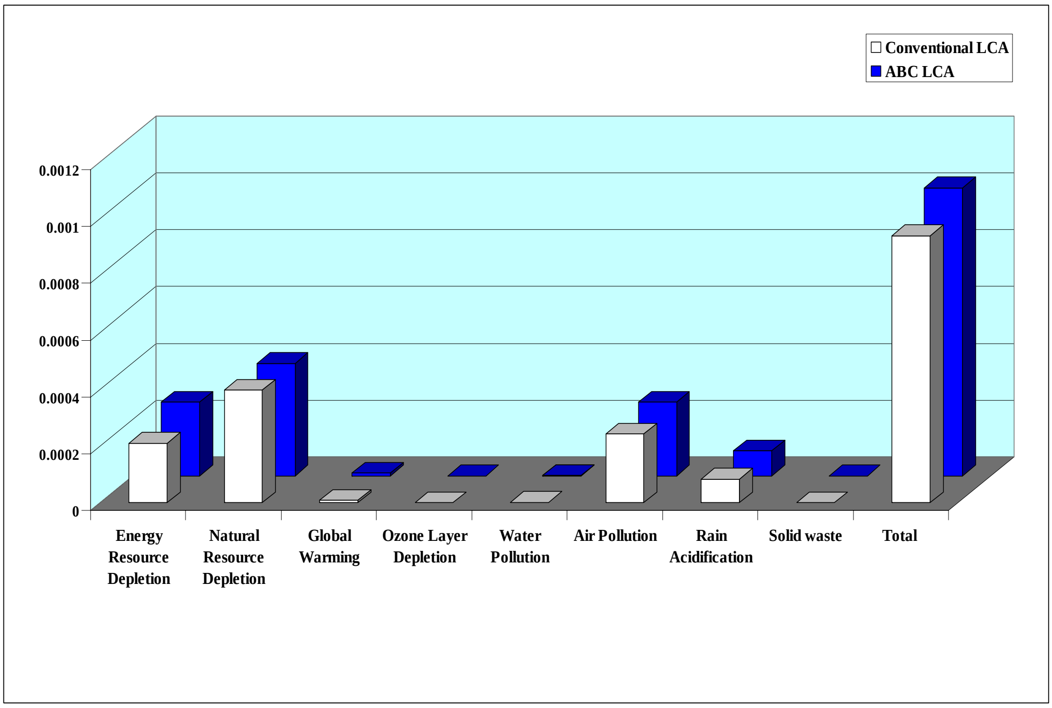

Figure 7. The environmental impact of the manufacturing phase.

4. CONCLUSIONS AND RECOMMENDATIONS

This study attempts to evaluate the numerical results on the environmental impacts of the a-Si solar cell power plant located in Thailand. The life cycle consideration covers the phases of solar module manufacturing, transportation from manufactures 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 violent problem is natural resource depletion due to aluminum frame. To get better environmental impact, some material such as aluminum should be replaced or not used since its consumption gives a high environmental impact. In this case study, activity-based approach is suitable for collecting the data of a-Si solar module manufacturing. The result is clearly shown that, the facility-level activities offer more energy consumption than the main processes in the unit-level activities, while the conventional LCA inventory did not consider the activities in this level.

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