CHAPTER 4

METHODOLOGY

The main objective of this thesis was determine the CO_2 emission from PV manufacture. The CO_2 emission from PV manufacture was converted from the amounts of energy required in the manufacture processes which were already estimated. The conversion of the amount of energy required for PV manufacture and primary energy was used the equation and method in the steps below to determining the CO_2 emission.

4.1 Estimation of the energy require for manufacture PV panel

The estimation of energy required for PV modules and systems was estimated based on a review of past energy analysis studies. The researchers explain the main sources of differences and establish the best estimate for key system (Alsema et al., 1998). The energy requirement of PV modules is shown in Table 4.

Table 4. Break-down of the energy requirements for c-Si module production with present-day technology. The low and high variants different approaches with respect to silicon feedstock production.

Process	mc-Si		sc-Si		Unit
	Low	High	Low	High	
Mg silicon production	450	500	500	500	MJ/m^2 module
Silicon purification	1,800	3,800	1,900	4,100	MJ/m^2 module
Crystallization & contouring #1	-	5,350	-	5,700	MJ/m^2 module
Crystallization & contouring #2	750	750	2,400	2,400	MJ/m^2 module
wafering	250	250	250	250	MJ/m^2 module
Cell processing	600	600	600	600	MJ/m^2 module
Module assembly	350	350	350	350	MJ/m^2 module
Total module (frameless)	4,200	11,600	6,000	13,900	MJ/m^2 module
Total module (frameless)	35	96	47	109	MJ/Wp

The numbers of energy requirement in Table 4 are the numbers of primary energy used in the process of PV manufacturing. These numbers can be converted to be the numbers of electrical energy by the formula below:

$$\text{Electrical energy (kWh)} = \frac{\text{Primary energy (MJ)}}{\text{Conversion factor (kJ/kWh)}} \quad (4.1)$$

Where

Conversion factor = 3,600 kJ/kWh

4.2 Calculation of CO_2 emission

The basic formula for the calculation of Annual Carbon Dioxide Emission Impact is:

$$\text{Annual Carbon Dioxide Emission (kg/TJ)} = \text{Carbon dioxide emission factor (kg/TJ)} \times \text{Annual fuel consumption (TJ/year)} \quad (4.2)$$

The formula comes from the 'Environmental Manual For Power Development' (EM model) which is a software developed by Deutsche Gesellschaft fuer Technische Zusammenarbeit (GTZ) with scientific support from Öeko-Institut for Applied Ecology in Germany. It is part of a multilateral project on environmental management, coordinated by the World Bank with contributions from Bundesministerium fuer wirtschaftliche Zusammenarbeit, Germany (BMZ), Bundesamt fuer Aussenwirtschaft, Switzerland (BAWI), Directorate General for International Cooperation, Netherlands (DGIS), GTZ, Overseas Development Administration, UK (ODA). The Emission Factor for some fossil fuels are:

Diesel oil:	Emission Factor $CO_2 = 2.761 \times 10^5$ kg/TJ
Natural gas:	Emission Factor $CO_2 = 1.081 \times 10^5$ kg/TJ
Coal:	Emission Factor $CO_2 = 2.552 \times 10^5$ kg/TJ
Lignite:	Emission Factor $CO_2 = 2.432 \times 10^5$ kg/TJ
Fuel oil:	Emission Factor $CO_2 = 1.627 \times 10^5$ kg/TJ

Example of calculation of CO_2 emission from fossil fuels

Diesel

Emission Factor of CO_2 is equal to 2.761×10^5 kg/TJ
In 1989, the electricity generation from Diesel = 74 MWh

$\therefore$ Primary energy = 74 MWh x 3,600 kJ/kWh
= 266,400 MJ

CO_2 emission from electricity generation from diesel = 266,400 MJ x 2.761×10^5 kg/TJ
= 73.6 Mg

Natural gas

Emission Factor of CO_2 = 1.081 x 10^5 kg/TJ
In 1989, the electricity generation from natural gas = 19,194.80 GWh

$\therefore$ Primary energy = 19,194.8 GWh x 3,600 kJ/kWh
= 69,101.28 TJ

CO_2 emission from electricity generation
from natural gas = 69,101.28 TJ x 1.081 x 10^5 kg/TJ

= 74,698.48 x 10^5 kg
= 7.5 Tg

Fuel oil

Emission Factor of CO_2 = 1.627 x 10^5 kg/TJ
In 1989, the electricity generation from fuel oil = 4,738.8 GWh

$\therefore$ Primary energy = 4,738.8 GWh x 3,600 kJ/kWh
= 17,059.68 TJ

CO_2 emission from electricity generation
from fuel oil = 17,059.68 TJ x 1.627 x 10^5 kg/TJ
= 2.78 Tg

Lignite

Emission Factor of CO_2 = 2.432 x 10^5 kg/TJ
In 1989, the electricity generation from coal = 7,878.6 GWh

$\therefore$ Primary energy = 7,878.6 GWh x 3,600 kJ/kWh
= 28,362.96 TJ

CO_2 emission from electricity generation
from coal = 28,362.96 TJ x 2.432 x 10^5 kg/TJ
= 6.89 Tg

4.3 Calculation of CO_2 emission from PV manufacture

The formula for calculate CO_2 emission:

$$CO_2 \text{ emission from PV manufacture (kg)} = \text{Primary energy (kJ)} \times \text{Emission Factor (kg/TJ)} \qquad (4.3)$$

The CO_2 emission is estimated by converting the amount of electricity input to be the amount of primary energy input (Equation 4.1) to the manufacturing processes then by estimating the CO_2 emission from electricity generation because different places generate electricity using different fuel mixtures. Three common sources of electricity production must be compared. These sources are hydropower, natural gas and coal. Because of the different emission characteristics of the different fuels used to generate electricity, the value of CO_2 emissions from PV manufacture cannot be expressed as an exact value but rather as a range of values. Of the three fuels typically used for electricity production in Thailand, the hydropower has almost no greenhouse gas emission value whereas natural gas has moderate amounts and coal has the most.

This thesis was focused on the calculation for emissions from the manufacture of single crystalline PV panels, which are the most popular panels in Thailand and it is assumed that for this kind of PV panel, each 1 m^2 can supply 120 Watts of electrical power. This number of watts was estimated from the average characteristics of PV panels from two companies that are used most in Thailand; that is Siemens Solar and BP Solar.

Siemens Solar

Size of PV panel for 75 Wp; width = 0.527 m
length = 1.2 m
Area = 0.527 m x 1.2 m = 0.6324 m^2

0.6324 m^2 produce 75 Wp
1.000 m^2 produce 75 / 0.6324 = 118.6 Wp

BP Solar

Size of PV panel for 75 Wp; width = 0.530 m
length = 1.165 m
Area = 0.530 m x 1.165 m = 0.6175 m^2

0.6175 m^2 produce 75 Wp
1.0 m^2 produce 75 / 0.6324 = 121.5 Wp

Therefore, the electrical power produced from 1 m^2 of PV panel (under standard conditions of temperature and irradiance) in Thailand is between 118.6 watts and 121.5 watts at standard conditions for panel power rating. The appropriate value used in this thesis is 120 watts per 1 m^2 of PV panel maximum power at 1,000 W/m^2 of solar radiation and 25°C cell temperature.

In Thailand, there are now about 4.8 MWp of single crystalline PV panels used or around 40,000 m^2 (4.8 MWp / 120 Wp) of installed panel surface. (DEDP. 1999 : 35)

The lowest and highest estimation of energy required for completing a squared meter of PV panel is 6,000 MJ and 13,900 MJ, respectively.

CO_2 emission from PV manufacture (kg) = Primary energy (kJ) x Emission Factor (kg/TJ)

- Assume that the source of energy is hydropower.
  CO_2 emission is almost 0 kg.

- Assume that the source of energy is coal.
  Emission Factor $CO_2 = 2.552 \times 10^5$ kg/TJ

  - The amount of energy required: Lowest estimation 6,000 MJ/ m^2

  CO_2 emission = 6,000 MJ / m^2 x 2.552×10^5 kg/TJ

  = 1,531.20 kg / m^2

  There are about 40,000 m^2 of PV installed in Thailand

  $\therefore$ CO_2 emission = 1,531.20 kg x 40,000 m^2

  = 61.25 Gg

  - The amount of energy required: Highest estimation 13,900 MJ/ m^2

  CO_2 emission = 13,900 MJ x 2.552×10^5 kg/TJ

  = 3,547.3 kg / m^2

  There are about 40,000 m^2 of PV installed in Thailand

  $\therefore$ CO_2 emission = 3,547.3 kg / m^2 x 40,000 m^2

  = 141.9 Gg

4.4 Calculation of CO_2 emission per kWh from PV manufacture and fossil fuels

4.4.1 For PV manufacture

The formula for calculate CO_2 emission per kWh from PV:

$$CO_2 \text{ emission / kWh} = \frac{CO_2 \text{ emission per 1 m}^2 \text{ of PV panel (kg)}}{PV_{el} \text{ (kWh)}} \qquad (4.4)$$

Where

PV_{el} = Electricity generating from PV

- Calculate the electricity generating from PV in each year under the conditions: the maximum power per 1 m^2 of PV is 120 Wp, the yearly average daily global solar radiation for Thailand is assumed to be 18.2 MJ/m^2-day or 5 kWh/m^2-day (Janjai. 2542 : 95) and the maximum lifetime of PV is 30 years (Donald E. Osborn. 2000 : 38). The formula for calculate electricity from PV is:

$$PV_{el} = P_{max} \times G_T \times 365 \text{ days} \times n \qquad (4.5)$$

Where

P_{max} = Maximum power from 1 m^2 of PV panel (kWp)
G_T = Yearly average daily global solar radiation (kWh/m^2)
n = Number of years

At the 30th year the electricity generating from PV is:

$$PV_{el} = 0.12 \text{ kW} \times 5 \text{ kWh/m}^2 \times 365 \text{ days} \times 30 \text{ years}$$
$$= 6{,}750 \text{ kWh/m}^2$$

For the lowest estimation, to produce 1 m^2 of PV emit CO_2 = 1,531.2 kg/m^2

$$CO_2 \text{ emission / kWh} = \frac{1{,}531.20 \text{ kg/m}^2}{6{,}750 \text{ kWh/m}^2}$$

$$= 0.23 \text{ kg/kWh}$$

For the lowest energy required of PV manufacture, CO_2 emission/ kWh is equal to 0.23 kg over its 30-years lifetime.

4.4 Calculation of CO_2 emission per kWh from PV manufacture and fossil fuels

4.4.1 For PV manufacture

The formula for calculate CO_2 emission per kWh from PV:

$$CO_2 \text{ emission / kWh} = \frac{CO_2 \text{ emission per 1 } m^2 \text{ of PV panel (kg)}}{PV_{el} \text{ (kWh)}} \tag{4.4}$$

Where

PV_{el} = Electricity generating from PV

- Calculate the electricity generating from PV in each year under the conditions: the maximum power per 1 m^2 of PV is 120 Wp, the yearly average daily global solar radiation for Thailand is assumed to be 18.2 MJ/m^2-day or 5 kWh/m^2-day (Janjai. 2542 : 95) and the maximum lifetime of PV is 30 years (Donald E. Osborn. 2000 : 38). The formula for calculate electricity from PV is:

$$PV_{el} = P_{max} \times G_T \times 365 \text{ days} \times n \tag{4.5}$$

Where

P_{max} = Maximum power from 1 m^2 of PV panel (kWp)
G_T = Yearly average daily global solar radiation (kWh/m^2)
n = Number of years

At the 30^{th} year the electricity generating from PV is:

$$PV_{el} = 0.12 \text{ kW} \times 5 \text{ kWh/m}^2 \times 365 \text{ days} \times 30 \text{ years}$$
$$= 6{,}750 \text{ kWh/m}^2$$

For the lowest estimation, to produce 1 m^2 of PV emit CO_2 = 1,531.2 kg/m^2

$$CO_2 \text{ emission / kWh} = \frac{1{,}531.20 \text{ kg/m}^2}{6{,}750 \text{ kWh/m}^2}$$

$$= 0.23 \text{ kg/kWh}$$

For the lowest energy required of PV manufacture, CO_2 emission/ kWh is equal to 0.23 kg over its 30-years lifetime.

4.4 Calculation of CO_2 emission per kWh from PV manufacture and fossil fuels

4.4.1 For PV manufacture

The formula for calculate CO_2 emission per kWh from PV:

$$CO_2 \text{ emission / kWh} = \frac{CO_2 \text{ emission per 1 m}^2 \text{ of PV panel (kg)}}{PV_{el} \text{ (kWh)}} \quad (4.4)$$

Where

PV_{el} = Electricity generating from PV

- Calculate the electricity generating from PV in each year under the conditions: the maximum power per 1 m^2 of PV is 120 Wp, the yearly average daily global solar radiation for Thailand is assumed to be 18.2 MJ/m^2-day or 5 kWh/m^2-day (Janjai. 2542 : 95) and the maximum lifetime of PV is 30 years (Donald E. Osborn. 2000 : 38). The formula for calculate electricity from PV is:

$$PV_{el} = P_{max} \times G_T \times 365 \text{ days} \times n \quad (4.5)$$

Where

P_{max} = Maximum power from 1 m^2 of PV panel (kWp)
G_T = Yearly average daily global solar radiation (kWh/m^2)
n = Number of years

At the 30th year the electricity generating from PV is:

$$PV_{el} = 0.12 \text{ kW} \times 5 \text{ kWh/m}^2 \times 365 \text{ days} \times 30 \text{ years}$$
$$= 6{,}750 \text{ kWh/m}^2$$

For the lowest estimation, to produce 1 m^2 of PV emit CO_2 = 1,531.2 kg/m^2

$$CO_2 \text{ emission / kWh} = \frac{1{,}531.20 \text{ kg/m}^2}{6{,}750 \text{ kWh/m}^2}$$

$$= 0.23 \text{ kg/kWh}$$

For the lowest energy required of PV manufacture, CO_2 emission/ kWh is equal to 0.23 kg over its 30-years lifetime.

For the highest estimation, to produce 1 m^2 of PV emit CO_2 = 3,547.3 kg/m^2

$$CO_2 \text{ emission / kWh} = \frac{3{,}547.3 \text{ kg/m}^2}{6{,}750 \text{ kWh/m}^2}$$

$$= 0.54 \text{ kg/kWh}$$

For the highest energy required of PV manufacture, CO_2 emission/ kWh is equal to 0.54 kg over its 30-years lifetime.

4.4.2 For the other fossil fuels

The formula for calculate CO_2 emission per kWh from fossil fuels:

$$CO_2 \text{ emission / kWh} = \frac{\text{Emission Factor of } CO_2 \text{ (kg/TJ)}}{\text{Conversion Factor}} \quad (4.6)$$

Where

Conversion Factor = 2.78×10^5 kWh

Calculation of CO_2 emission/kWh from fossil fuels

- **Diesel Oil:** **Emission Factor CO_2 = 2.761×10^5 kg/TJ**

$$CO_2 \text{ emission/kWh} = \frac{2.761 \times 10^5 \text{ kg}}{2.78 \times 10^5 \text{ kWh}}$$

$$= 0.99 \text{ kg/kWh}$$

1 kWh of electricity from diesel emits CO_2 = 0.99 kg

- **Natural Gas:** **Emission Factor CO_2 = 1.081×10^5 kg/TJ**

$$CO_2 \text{ emission/kWh} = \frac{1.081 \times 10^5 \text{ kg}}{2.78 \times 10^5 \text{ kWh}}$$

$$= 0.39 \text{ kg/kWh}$$

1 kWh of electricity from natural gas emit CO_2 = 0.39 kg

- **Lignite:** **Emission Factor $CO_2 = 2.432 \times 10^5$ kg/TJ**

$$CO_2 \text{ emission/kWh} = \frac{2.432 \times 10^5 \text{ kg}}{2.78 \times 10^5 \text{ kWh}}$$

$$= 0.87 \text{ kg/kWh}$$

1 kWh of electricity from coal emit CO_2 = 0.87 kg

- **Fuel oil:** **Emission Factor $CO_2 = 1.627 \times 10^5$ kg/TJ**

$$CO_2 \text{ emission/kWh} = \frac{1.627 \times 10^5 \text{ kg}}{2.78 \times 10^5 \text{ kWh}}$$

$$= 0.59 \text{ kg/kWh}$$

1 kWh of electricity from fuel oil emit CO_2 = 0.59 kg

4.5 Analysis and interpretation results

The results of calculation showed the CO_2 emission from PV manufacture, small diesel generator and grid electricity in order to compare which sources of energy emitted the lowest CO_2. In the case of PV manufacture, the CO_2 emission was based on per m^2 of PV panel and per kWh of electricity produced over 30 years of lifetime. Then, the CO_2 emission per kWh of PV was used to compare with the emission per kWh from other types of fossil fuels. At the point where the CO_2 emission per kWh from PV is less than that from fossil fuels, it means that using PV is better than using fossil fuels because the former emits no CO_2 while still generating electricity. The results of CO_2 emission from PV manufacture showed the total effect from all the Single Crystalline Silicon PV modules installed in Thailand.