CHAPTER 5

RESULTS

5.1 CO_2 emission from PV manufacture

Table 5. CO_2 emission from PV manufacture

Energy Input (MJ/m^2)	CO_2 emission (kg/m^2)			Net CO_2 emission (kg) (Highest estimation)
	Hydro	Natural Gas	Coal	
6,000	Near 0	649	1,531	61.25×10^6
13,900	Near 0	1,503	3,547	141.90×10^6

Table 5 shows that, for the low and high estimation of energy input for the manufacture of PV panels, CO_2 emission is nearly zero if the source of primary energy is hydropower. If the primary energy is natural gas the emission is equal to 649 kg/m^2 or 0.65 tons and 1,503 kg/m^2 or 1.5 tons and if coal is the primary energy the emission is equal to 1,531 kg/m^2 and 3,547 kg/m^2. As there is 40,000 m^2 of Single Crystalline PV installed in Thailand, that causes the net CO_2 emission equal to 61.25×10^6 kg or 61,250 tons and 141.90×10^6 kg or 141,900 tons, these numbers were estimated by assuming that the primary energy is coal which emits the highest amount of CO_2 in electricity generation for Thailand.

5.2 Comparison between CO_2 emission per kWh from PV and fossil fuels

- **PV**

- For the lowest estimation

CO_2 emission per 1 m^2 or 120 Wp of PV = 1,531 kg

At the first year, the energy produces
from 1 m^2 of PV panel = 0.12 kW x 5 kWh/m^2-day x 365 days x 1 year

= 219 kWh/m^2

$$CO_2 \text{ emission per kWh for the first year} = \frac{1{,}531 \text{ kg}}{219 \text{ kWh/m}^2}$$

= 6.9 kg

- For the highest estimation

CO_2 emission per 1 m^2 or 120 Wp of PV = 3,547 kg

At the first year, the energy produces
from 1 m^2 of PV panel = 0.12 kW x 5 kWh/m^2-day x 365 days x 1 year

= 219 kWh/m^2

CO_2 emission per kWh for the first year $= \frac{3,547 \text{ kg}}{219 \text{ kWh/m}^2}$

= 16.20 kg

- **Fossil Fuels**

Diesel	CO_2 emission per 1 kWh	= 0.99 kg
Natural gas	CO_2 emission per 1 kWh	= 0.39 kg
Lignite	CO_2 emission per 1 kWh	= 0.87 kg
Fuel oil	CO_2 emission per 1 kWh	= 0.59 kg

For the first year, the PV panel had more GHGs produced than any other fossil fuels. However, the PV will not generate additional GHGs in the future whereas the fossil fuels will do so continuously.

Table 6. Comparison of CO_2 emission per kWh between fossil fuels and PV

Year	CO_2 emission (kg/kWh)					
	Fossil fuels				PV	
	Diesel	Natural gas	Fuel oil	Lignite	Low	High
1	0.99	0.39	0.59	0.87	6.99	16.20
2	0.99	0.39	0.59	0.87	3.50	8.10
3	0.99	0.39	0.59	0.87	2.33	5.40
4	0.99	0.39	0.59	0.87	1.75	4.05
5	0.99	0.39	0.59	0.87	1.40	3.24
6	0.99	0.39	0.59	0.87	1.17	2.70
7	0.99	0.39	0.59	0.87	1.00	2.31
8	0.99	0.39	0.59	0.87	0.87	2.02
9	0.99	0.39	0.59	0.87	0.78	1.80
10	0.99	0.39	0.59	0.87	0.70	1.62
11	0.99	0.39	0.59	0.87	0.64	1.47
12	0.99	0.39	0.59	0.87	0.58	1.35
13	0.99	0.39	0.59	0.87	0.54	1.25
14	0.99	0.39	0.59	0.87	0.50	1.16
15	0.99	0.39	0.59	0.87	0.47	1.08
16	0.99	0.39	0.59	0.87	0.44	1.01
17	0.99	0.39	0.59	0.87	0.41	0.95
18	0.99	0.39	0.59	0.87	0.39	0.90
19	0.99	0.39	0.59	0.87	0.37	0.85
20	0.99	0.39	0.59	0.87	0.35	0.81
21	0.99	0.39	0.59	0.87	0.33	0.77
22	0.99	0.39	0.59	0.87	0.32	0.74
23	0.99	0.39	0.59	0.87	0.30	0.70
24	0.99	0.39	0.59	0.87	0.29	0.67
25	0.99	0.39	0.59	0.87	0.28	0.65
26	0.99	0.39	0.59	0.87	0.27	0.62
27	0.99	0.39	0.59	0.87	0.26	0.60
28	0.99	0.39	0.59	0.87	0.25	0.58
29	0.99	0.39	0.59	0.87	0.24	0.56
30	0.99	0.39	0.59	0.87	0.23	0.54

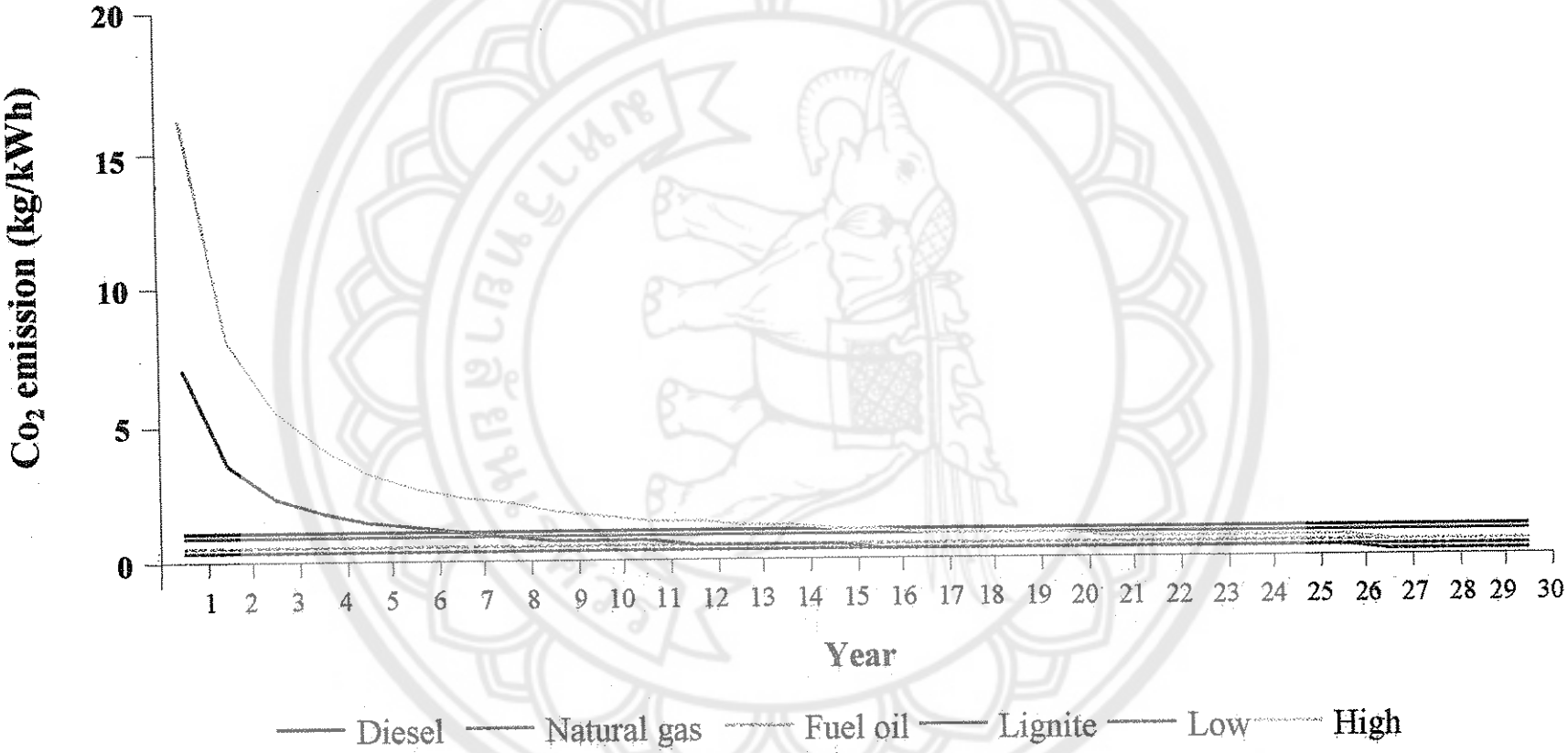

Figure 3. Comparison of CO2 emission per kWh between PV and fossil fuels

Figure 3 shows the comparison of CO_2 emission per kWh between PV and fossil fuels. The CO_2 emission per kWh of electricity produced by PV is decreasing as the time of usage is increased because the kWh is increasing over time but the CO_2 is constant from the time of manufacture. But the emission from fossil fuels remains constant every year because it is being continuously produced as electricity is generated. The year when CO_2 emission from PV is equal to that from fossil fuels is shown in Table 7.

Table 7. The year when CO_2 emission per kWh of PV equal to emission from fossil fuels

Type of Fossil fuels	Number of years	
	Low estimate	High estimate
Diesel	7	16
Natural gas	18	-
Fuel oil	12	27
Lignite	8	18

For diesel the 7th and 16th year are the points at which the CO_2 emission per kWh from a PV system and the emission per kWh from diesel are met for the low and the high PV GHG estimate respectively. After these years, total CO_2 from PV is lower than from diesel; the difference is the CO_2 saved which is a benefit to the environment. The same process holds true for other fossil fuels. For natural gas the number of years for both cases is high, especially for the highest energy required, because natural gas is relatively clean burning. The CO_2 emission per kWh of natural gas is low (lower than the other fossil fuels) and now it is often used to reduce effect on the environment.

5.3 The energy and CO_2 balance of PV manufacture

The energy input to produce 1 m^2 of PV is equal to 1,666.67 kWh for the lowest estimation and 3,860 kWh for the highest estimation. After production, PV can produce power throughout its lifetime (30 years). Thus, the CO_2 is emitted only when the panel is manufactured. The 1 m^2 of panel produces a continuing amount of energy each year. When the energy produced by the panel equals to the energy used in its manufacture, it is the break-even point between energy and CO_2 emission. From that point on, the energy produced from PV represents CO_2 saved, because no CO_2 is released while it is being used to produce electricity. The internal energy balance of PV manufacture is shown in Table 8.

Table 8. The internal energy balance of a PV panel

Energy input (MJ/m^2)	Year									
	1	2	3	4	5	6	7	8	9	10
1,666.67	219	438	657	876	1,095	1,314	1,533	1,752	1,971	2,190
3,860	219	438	657	876	1,095	1,314	1,533	1,752	1,971	2,190
	11	12	13	14	15	16	17	18	19	20
1,666.67	2,409	2,628	2,847	3,066	3,285	3,504	3,723	3,942	4,161	4,380
3,860	2,409	2628	2,847	3,066	3,285	3,504	3,723	3,942	4,161	4,380
	21	22	23	24	25	26	27	28	29	30
1,666.67	4,599	4,818	5,037	5,256	5,475	5,694	5,913	6,132	6,351	6,570
3,860	4,599	4,818	5,037	5,256	5,475	5,694	5,913	6,132	6,351	6,570

Table 8 the break-even point for energy investment or CO_2 emission for PV production is 7.6 years for the minimum and 17.6 years for the maximum manufacturing energy. This number of year came from the amounts of energy input (MJ/m^2) to manufacture a PV panel for both low and high estimation divided by the amount of power produced from PV in each year.

Table 9. CO_2 emission from fossil fuels replacing PV installed in Thailand

Sources of Energy	CO_2 emission (kg)
1. PV	42.87×10^6 to 61.25×10^6
2. Fossil Fuels	
Diesel	8.7×10^6
Natural gas	3.4×10^6
Fuel oil	5.2×10^6
Lignite	7.6×10^6

Table 9 shows that if PV were not installed in Thailand but the same amount of energy is still needed, fossil fuels will be used as the source of energy and they will emit some CO_2. For the first year, the CO_2 emission from fossil fuels are lower than PV because all the CO_2 that will be caused by the use of PV will already have been produced during its manufacture but the fossil fuel generation will continue to produce CO_2 as long as it is used. That is, PV systems produce CO_2 only once in the beginning but fossil fuels that produce the same amount of energy as the PV continue to emit the same amount of CO_2 every year which will accumulate over time and will eventually be higher than PV. Therefore, if the PV is in service long enough it will eventually have a lower CO_2 production.

5.4 CO_2 emission from fossil fuels

Table 10. CO_2 emission from fossil fuels

Year	CO_2 emission (Million tons)			
	Diesel	Natural Gas	Fuel oil	Lignite
1989	7.3×10^{-5}	7.49	2.80	6.90
1990	7.4×10^{-5}	6.93	5.91	9.68
1991	7.03×10^{-5}	7.72	7.46	11.41
1992	6.70×10^{-5}	8.95	8.81	12.97
1993	5.25×10^{-5}	10.90	10.32	11.82
1994	5.35×10^{-5}	12.25	11.59	12.37
1995	6.30×10^{-5}	13.22	12.81	12.94
1996	7.03×10^{-5}	14.33	12.38	15.33
1997	6.93×10^{-5}	16.84	11.39	16.57
1998	5.94×10^{-5}	18.16	10.39	14.43
Total	6.53×10^{-4}	116.79	93.85	124.42

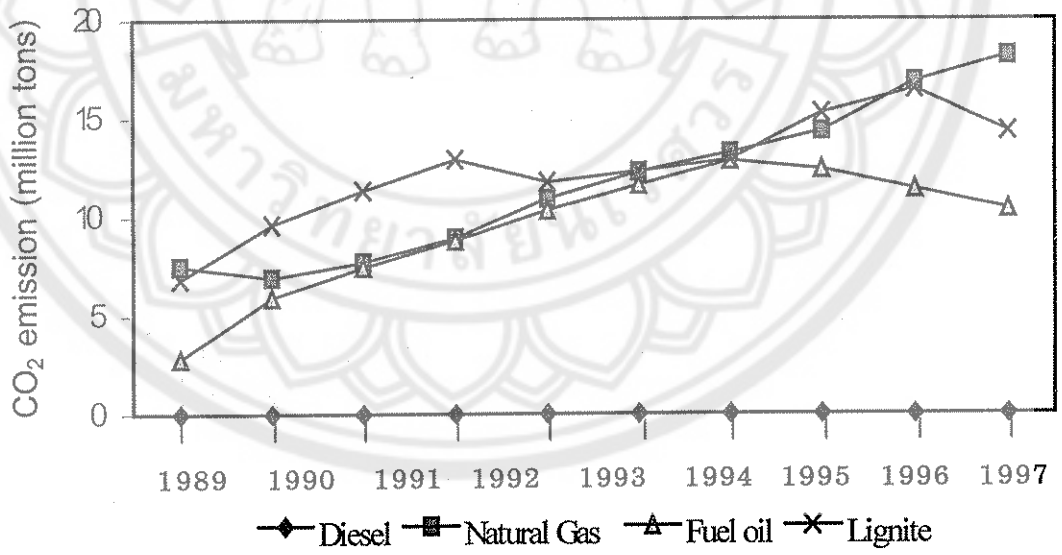

Figure 4. CO_2 emission from fossil fuels from 1989 to 1998

Figure 4 shows that in Thailand from the year 1989 to 1998 for the grid electricity production sector, CO_2 emission from lignite is the highest followed by natural gas, fuel oil and diesel. The trend of emissions from natural gas increases while those from other fossil fuels decrease because the amount of use of natural gas increases while the other fossil fuels decrease in use. Natural gas is used increasingly to generate electricity because it is the cleanest energy. While the amount of use of lignite decreases because its emits high CO_2 and other pollutants.

Therefore, the estimation of CO_2 emission from PV manufacture in this thesis indicated that:

1. From the estimation of CO_2 emission from PV manufacture, it was found that to manufacture a 1 m^2 of PV panel, the emitted CO_2 is nearly zero if the energy input is from hydropower. If energy input to manufacture a panel is coming from coal, the CO_2 emission is equal to 1,531 kg to 3,547 kg. And if natural gas is used as the source of energy input, CO_2 emission is equal to 649 kg or 0.65 tons to 1,503 kg or 1.5 tons. Now around 40,000 m^2 of Single Crystalline PV is installed in Thailand making the net maximum CO_2 emission for PV installed in Thailand equal to 61,250 tons to 141,900 tons.

If the PV panels were not installed and the amount of energy were still needed, fossil fuels would become the source of energy and emitted CO_2 for every kWh of energy produced. But for PV, the emission is fixed at the time of the panel manufacture. The panel can be used for over 30 years and during that use, no CO_2 is emitted while the panel generates electrical energy.

2. CO_2 emission per kWh of PV panel is decreased when the time of use is increased. However, for energy from all of fossil fuels, the CO_2 emission remains constant every year for the same energy production. Figure 3 shows the comparison of CO_2 emission per kWh between PV and fossil fuel. The intersection point in the graph is the point at which CO_2 emission per kWh from a PV system and the emission per kWh from fossil fuels are the same for the low and the high PV GHG estimate. After these points, which represent the GHG break even points for the high and low estimates, the CO_2 from PV is lower than that from the fossil per kWh and the difference is the CO_2 saved which is a benefit to the environment.

However, the most important point from a user standpoint is that the PV panel must work more than the number of years needed to balance the CO_2 emission between PV and fossil fuel. For example, after 8 and 17 years PV usage will better than lignite, because the CO_2 emission per kWh will be lower. However, if the PV system does not work for the full 8 or 18 years, it is not a good choice. Most of the PV installed in Thailand is out of order after 4 or 5 years because of a lack of maintenance by the users. These problem causes not only the waste of investment money but also the CO_2 can not be reduced which is one of the most important benefits of using solar energy. So when a PV system is installed it must be used for at least the CO_2 balance year to be of benefit to the GHG balance.

To manufacture 1 m^2 of PV panel, the energy input is equal to 6,000 MJ or 1,666.67 kWh for the lowest estimation and 13,900 MJ or 3,860 kWh for the highest estimation. CO_2 emission per square meter of PV panel is therefore equal to 1,531 kg or 1.5 tons and 3,547 kg or 3.5 tons. The break-even point for energy investment or CO_2 emission between energy required for PV production and energy output from PV is equal to 7.6 years for the minimum and 17.6 years for the maximum manufacturing energy when fossil fuel produced electricity is used in manufacture. It means that when manufacturing 1 m^2 of PV panel some CO_2 is emitted from the process but after using the panel for 7.6 and 17.6 years the CO_2 emission will be balanced and after these years it is the CO_2 saved. In other words, the kWh produced by the panel is equal to the kWh used in its manufacture and the panel is in energy balance.

3. If there is no PV installed and the same amount of energy is still needed, fossil fuels will be used to produce energy and will emit CO_2. The CO_2 emission from all fossil fuels is more than the emission from manufacturing a PV panel when figured over the full lifetime of the panel. However, if the panel is installed in a system that fails before the energy balance year is reached, the panel can not meet its full potential and total CO_2 emission will be higher for the PV than for fossil fuel generation.