CHAPTER 4

RESULTS AND DISCUSSION

In the chapter, results from the testing of the EPC collector at the Energy Park, validation of the collector's thermal analysis model, and application of the power plant model for performance analysis and simulation, are presented and discussed.

4.1 Characteristic Curve of the Solar Trough Collector

One of the standard ways of defining a solar collector is by means of its characteristic curve [36]. The characteristic curve of the EPC collector was determined by operating the collector during clear sky condition on a sunny day, whereby data regarding the fluid inlet and outlet temperatures were measured at nearly steady conditions. From the fluid temperatures, the instantaneous useful gain can be evaluated and that in turn was used to calculate the collector efficiency for various inlet temperature and insolation conditions. Throughout the test, the fluid mass flux was maintained at 0.15 kg/s. The average wind speed was about 3 m/s and the average solar irradiance during the test was about 750 W/m^2.

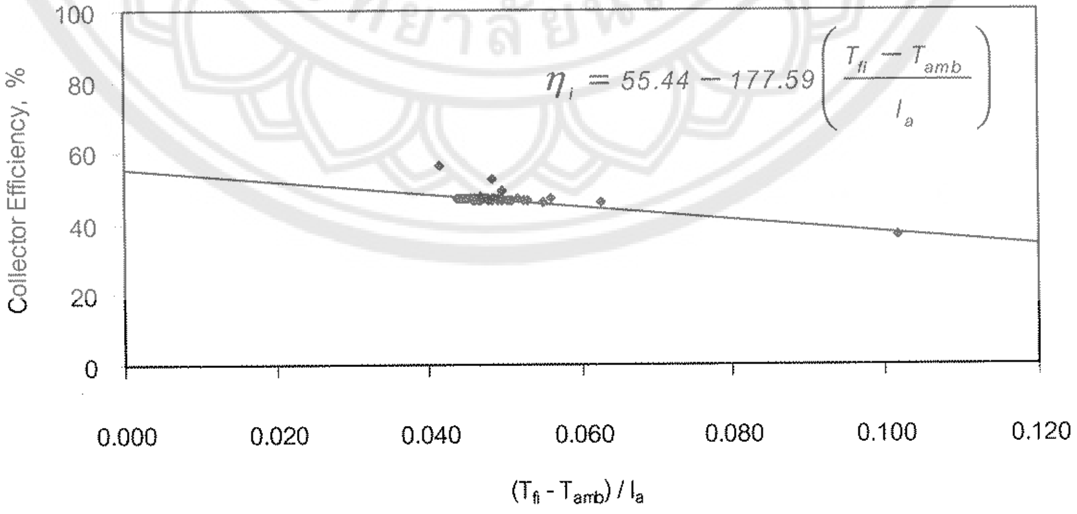

Figure 50 Characteristic curve of EPC collector

By plotting the collector's instantaneous efficiency versus the temperature difference between fluid inlet and ambient divided by solar irradiance, a characteristic curve as shown in Figure 50 was obtained. Due to the fact that the parameters F_R, $\eta_o K_\theta$ and U_L are not constant but are somewhat influenced by temperature, incidence angle and wind effects, the plot of η_i versus $\left(T_{fi}-T_{amb}\right)/I_a$ is not a perfect straight line. However, using linear regression technique, a 'least-square fit' correlation can be obtained for the plot where based on equations (3.27) and (3.31), the y-intercept is given by $F_R\left(\eta_o K_\theta\right)$ and the slope is defined by $-\left(F_R U_L\right)/C_g$. *From the characteristic curve, the peak collector efficiency of the EPC collector is found to be approximately 55.4%.*

4.2 Validation of the Collector System (CS) Model

In Figure 51, the fluid exit temperatures of the EPC collector measured on a sunny day from 10:00 am to 14:00 pm were compared to the simulated results generated by the mathematical model. Figure 52 shows a similar plot but for a partly cloudy day. On both test days, the fluid mass flux was set at 0.15 kg/s and the average wind speed was about 3 m/s. The average direct normal irradiance during the time of testing for the sunny day and partly cloudy day was about 750 W/m^2 and 460 W/m^2 respectively.

In Figures 51 and 52, it is observed that the simulated results related closely with the measured data where in both cases, the average % deviation between the simulated and the actual fluid exit temperatures is no higher than 6.0%. This difference can be attributed partly to the collector's conduction heat losses and partly to the effects of solar transient. The lower exit temperatures shown in Figure 52 imply that during non-sunny weather, the thermal output from the collector is comparatively lower and a backup energy source may be required to maintain performance. A summary of the average fluid inlet temperature T_{fi} and exit temperature T_{fo} of the EPC collector for both sunny and partly cloudy weather conditions is given in Table 11. *The exit temperature can be considered as one of the most important parameters of a solar collector. The results from this testing have shown that the collector system (CS) model created in this study is adequate to simulate the fluid exit temperature of a solar trough collector.*

Table 11 Summary of ave fluid temperatures: sunny and partly cloudy conditions

Average wind speed: 3 m/s **Fluid mass flux: 0.15 kg/s** **Average direct irradiance (W/m^2)**	**Weather conditions**			
	Sunny		**Partly cloudy**	
	750		**460**	
	T_{fi}	T_{fo}	T_{fi}	T_{fo}
Simulated ave. temperature (deg. C)	70	198	61	141
Actual ave. temperature (deg. C)	68	188	60	133

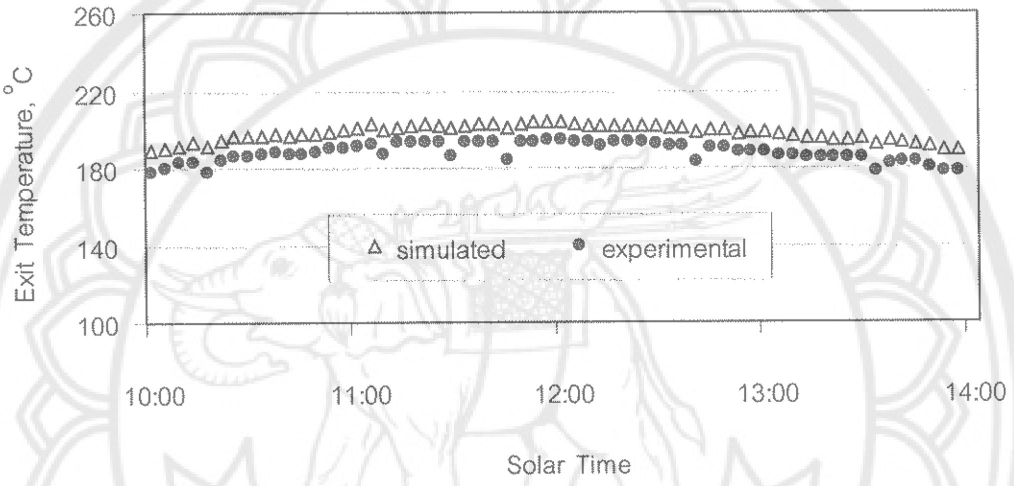

Figure 51 Exit temperature of EPC collector during sunny condition

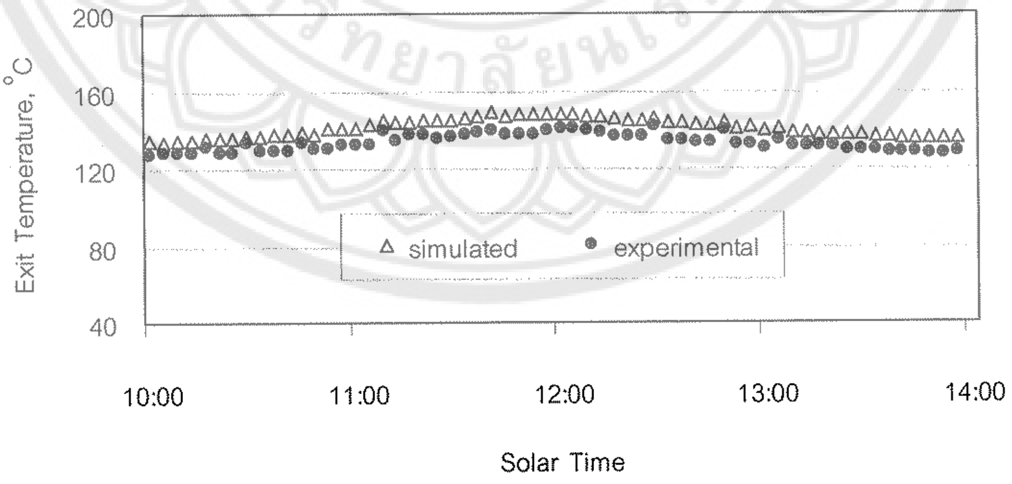

Figure 52 Exit temperature of EPC collector during partly cloudy condition

4.3 Thermal Performance of Collector: Sunny vs. Partly Cloudy

The long term thermal performance of the EPC collector was evaluated with the use of the solar radiation (SR) model of Phitsanulok created by the method described in Chapter 3. When integrated with the collector system (CS) model, it allows for the estimation of the collector's annual thermal output based on two meteorological profiles, i.e. clear sky radiation (or sunny) condition and average radiation (or partly cloudy) condition. Figure 53 shows the monthly useful energy gain of the EPC collector for both sunny and partly cloudy weather conditions. From the analysis, it is found that the annual thermal output of the EPC under average radiation condition is 60,387 MJ and this is about 58% of the maximum possible output of 103,947 MJ if the collector is operated under clear sky radiation throughout the year. When these results are input into the PCU model of the proposed BSPP, the solar fraction S_F to the annual thermal input of the power plant can be evaluated.

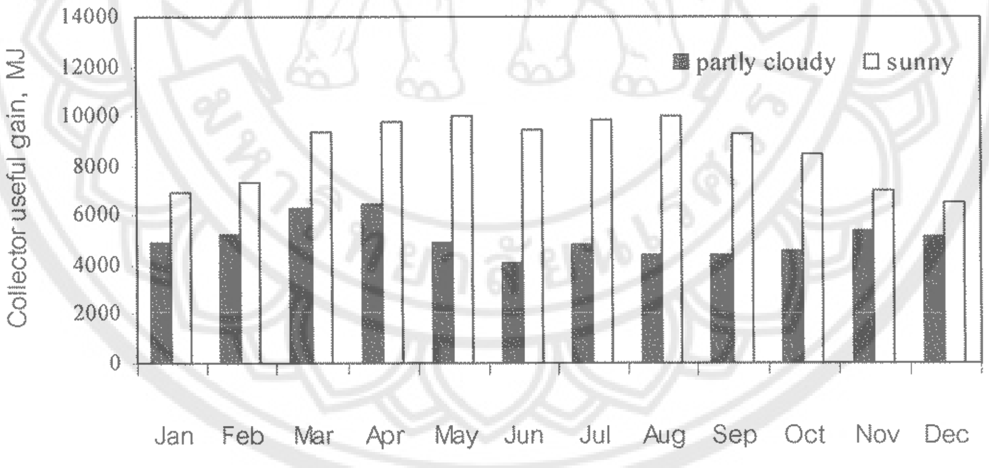

Figure 53 Monthly useful gain of EPC collector: sunny vs. partly cloudy

From the analysis in section 3.4.4, it is known that 307.3 MJ per hour (or about 85.4 kW_{th}) of thermal energy are required by the power block to produce 20 kWh of electricity. Assuming that the annual maximum capacity of the power plant is 58,400 kWh (based on 365 operation-day per year & 8 hours per operation-day), and that the percentage of maximum capacity is assumed to be 50% (Note: Grasse et al. (1991) reported that the annual operating hours and capacity factor of a solar-only thermal power plant is typically between 30-50% of maximum capacity [49]), then the annual aggregate generation time is estimated as 1,460 hours. This means that, on a yearly basis, about 448,658 MJ of thermal energy are needed to generate 29,200 kWh of electricity. Hence from this, the solar contribution (or solar fraction S_F) to the annual thermal input of the power plant for both sunny & partly cloudy conditions are calculated to be 23.2% & 13.5% respectively. The value of these results appears to be relatively low when compared with the commercial SEGS plants in California where the average solar fraction is between 65 – 75%. This difference can be attributed to the higher insolation level at the SEGS locations where the direct radiation is usually greater than 2,000 kWh/m2 per year. *The results from this evaluation indicate that under Phitsanulok climatic conditions (and for Thailand, in general), it is may be inadequate to operate a parabolic trough thermal power plant on solar energy alone and that a backup energy source should be added for effective operation.*

4.4 Thermal Performance of Collector: Water vs. Mineral Oil

Although the direct solar steam (DISS) process has been regarded as state-of-the-art collector technology, so far the main research on DISS has been carried out in Plataforma Solar de Almeria, the European solar test center in Spain, where the beam irradiance is generally high and clear sky condition is the norm. However, the same cannot be said for a location like Thailand where the solar insolation profile is quite different. Therefore, it will be useful to evaluate the performance of the EPC as a DISS collector vis-a-vis its performance as an oil-based collector where thermal oil is used as the heat transfer medium. The type of thermal oil that has been chosen for this comparison analysis is a natural mineral oil known as Therminol XP (available from Solutia Inc.) which has an operating temperature range of -20 °C to 315 °C [47]. Its advantages compared to other HTF are its relatively high flash point, high fire point, high autoignition temperature and low vapor pressure at elevated temperature. Furthermore,

Table 12 Summary of average fluid inlet and exit temperatures: water vs. mineral oil

	Water		Therminol XP	
	T_{fi}	T_{fo}	T_{fi}	T_{fo}
Ave. fluid temperature (deg. C)	68	191	75	241

cost-wise it is considerably lower (by a factor of 10) than the synthetic oil used in the commercial SEGS plants in California.

Figure 54 shows the simulated fluid exit temperatures of the EPC collector for water and Therminol XP evaluated based on the following conditions: hourly basis from 08:00 am to 16:00 pm, average direct irradiance of about 700 W/m^2, mass flux of 0.15 kg/s and wind speed of 3 m/s. *From the analysis, the average exit temperature of the collector using Therminol XP was about 26% higher compared to water. With all other parameters being equal, the higher exit temperature achievable with oil as HTF is advantageous if thermal energy storage is required.* A summary of the average fluid inlet temperature T_{fi} and exit temperature T_{fo} evaluated for water and mineral oil is given in Table 12.

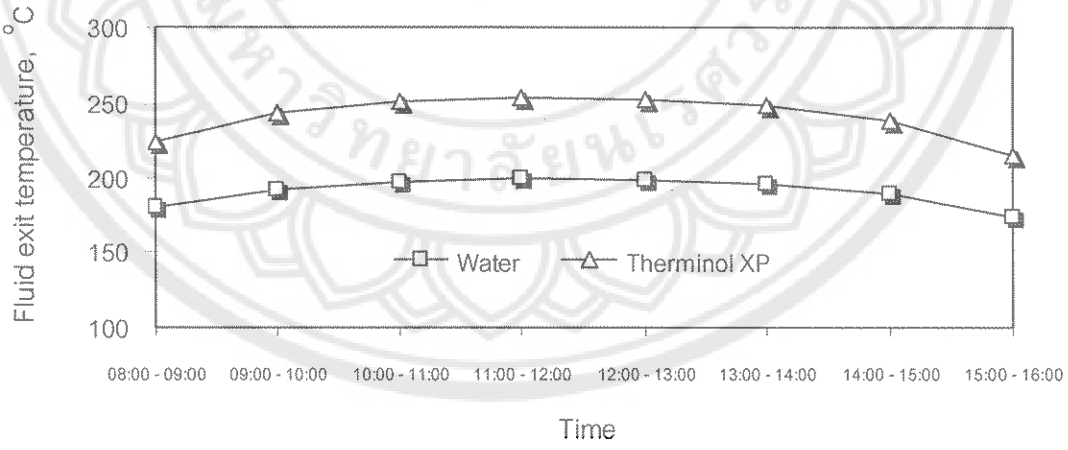

Figure 54 Comparison of exit temperature: water vs. mineral oil

4.5 Analysis and Parametric Study of Proposed Solar Power Plant

In this section, the application of the BSPP mathematical model as a tool for performance analysis and simulation is demonstrated. The model is used to analyzed and evaluate two important parameters of the proposed power plant, namely the HTF mass flow rate and the collector area, for optimal operation under the conditions specified in this study. For the purpose of the simulation exercise, the proposed power plant is assumed to operate with the following design settings:

(i) The HTF used is Therminol XP with a maximum operating temperature of 300 °C.

(ii) All the collector's physical dimensions are similar to that of the EPC collector, a list of which is given in Appendix A.

(iii) The PCU generates electricity at a constant output of 20 kW_e per hour from 08:00 am to 16:00 pm daily. All the electricity produced is fed to the utility grid.

(iv) The boiler of the PCU operates with a saturation temperature of 165 °C at a pressure of 7 bar. This is also the condition of the steam at the inlet of the engine-generator set.

4.5.1 Optimal Collector Area to Meet Electrical Output

In this section, the optimal collector (or aperture) area that is needed to produce a thermal output of 307.3 MJ to enable the PCU to generate at rated power, is evaluated. The equation linking the collector's thermal output (or useful gain) with the aperture area is given by equation (3.76) in Chapter 3, and the equation linking the useful gain with the heat addition to boiler at rated power is given by equation (3.77). When Q_u is set to be equal to Q_A, the collector area A_a is optimized. Thus, using the average hourly direct radiation from the SR model of Phitsanulok (i.e. $I_{std,s}$ & $I_{std,pc}$) and substituting into equation (3.76), the optimal collector areas (that can meet the rated electrical output under sunny & partly cloudy conditions) can be evaluated. A summary of the hourly analysis carried out for both sunny & partly cloudy conditions is given in Tables 12 & 13 respectively.

Table 13 Calculation of fluid mass flux and temperature in/out of boiler (sunny)

Time	$I_{std,\,s}$ (W/m^2)	Q_u (MJ)	T_{bi} (^oC)	T_{bo} (^oC)	$\dot{m}$ (kg/s)
08:00 – 09:00	636	278	250	105	0.214
09:00 – 10:00	712	308	250	105	0.236
10:00 – 11:00	747	320	250	105	0.245
11:00 – 12:00	761	326	250	105	0.250
12:00 – 13:00	761	326	250	105	0.250
13:00 – 14:00	747	322	250	105	0.246
14:00 – 15:00	712	308	250	105	0.236
15:00 – 16:00	636	276	250	105	0.211
Average	714	307.9			0.236

Table 14 Calculation of fluid mass flux and temperature in/out of boiler (partly cloudy)

Time	$I_{std,\,pc}$ (W/m^2)	Q_u (MJ)	T_{bi} (^oC)	T_{bo} (^oC)	$\dot{m}$ (kg/s)
08:00 – 09:00	367	272	216	100	0.268
09:00 – 10:00	415	302	216	100	0.299
10:00 – 11:00	447	322	216	100	0.318
11:00 – 12:00	463	334	216	100	0.330
12:00 – 13:00	463	335	216	100	0.331
13:00 – 14:00	447	324	216	100	0.321
14:00 – 15:00	415	302	216	100	0.298
15:00 – 16:00	367	267	216	100	0.264
Average	423	307.4			0.304

The analysis is done based on the following assumptions: (a) Heat losses between collector and steam boiler are negligible, (b) Average useful gain per hour Q_u = heat addition Q_A which is equal to 307.3 MJ/hr at rated power, and (c) Saturation temperature in boiler T_{sat} is set at 165 ^oC. The results in Table 13 show that under sunny condition, based on an average $I_{std,s}$ of 714 W/m^2 per hour, a Q_u of 307.9 MJ/hr can be produced at an average hourly mass flux of 0.236 kg/s. Under these conditions, the optimal collector area is determined to be 210 m^2 (i.e. aperture width = 5 m & length =

42 m). Likewise, Table 14 shows that under partly cloudy condition, an average $I_{std,pc}$ of 423 W/m^2 per hour can produce a Q_u of 307.4 MJ/hr at an average hourly mass flux of 0.304 kg/s. In this instance, the optimal collector area is determined to be 355 m^2 (i.e. aperture width = 5 m & length = 71 m). *This means that an additional collector area of 145 m^2 (i.e. 355 m^2 – 210 m^2) is needed during partly cloudy condition to supply the required thermal energy for the power plant to operate at rated power. Alternatively, instead of installing the additional collector area, the deficit energy can be supplied using a backup energy in the form of biomass energy.*

4.5.2 Optimal Mass Flux in terms of the Operating Temperature

Due to the varying nature of the input solar energy, one of the most important parameters of a solar thermal power plant is the mass flux of the heat transfer fluid (HTF). In general, for a given level of radiation, the fluid mass flux $\dot{m}$ tends to vary inversely proportional with the fluid exit temperature T_{fo}, which is another important parameter of the power plant. The fluid exit temperature is itself subjected to two operating limits: it should not be higher than the maximum operating temperature of the HTF but at the same time should be higher than the saturation temperature in the steam boiler of the PCU. In this study, the maximum HTF temperature is 300 °C and the boiler's saturation temperature is set at 165 °C. Therefore, it is necessary to obtain the range of fluid mass flux that will allow the above operating condition to be satisfied. This can be done by using the BSPP model that has been created in this study.

Based on the SR model of Phitsanulok, the collector's fluid exit temperatures corresponding to a range of fluid mass flux can be calculated for both sunny and partly cloudy conditions. Referring to Figure 55, graphs Y1 & Y2 represent the fluid exit temperatures during sunny & partly cloudy conditions respectively. Using a curvilinear regression technique, two polynomial expressions for the graphs can be obtained. By substituting the maximum HTF temperature & saturation temperature into graphs Y1 & Y2 respectively, the optimal range of fluid mass flux can be found. For a 210 m^2 collector, the optimal range of fluid mass flux is evaluated to be 0.154 – 0.368 kg/s. Figure 56 shows a plot similar to Figure 55 but for a 355 m^2 collector. Graphs Y3 & Y4 represent the fluid exit temperatures during sunny & partly cloudy conditions respectively. Likewise, by substituting the maximum HTF temperature & saturation temperature into graphs Y3 & Y4 respectively, the optimal range of fluid mass flux can be obtained. In this instance, the optimal range of fluid mass flux is calculated to be 0.276 – 0.610 kg/s.

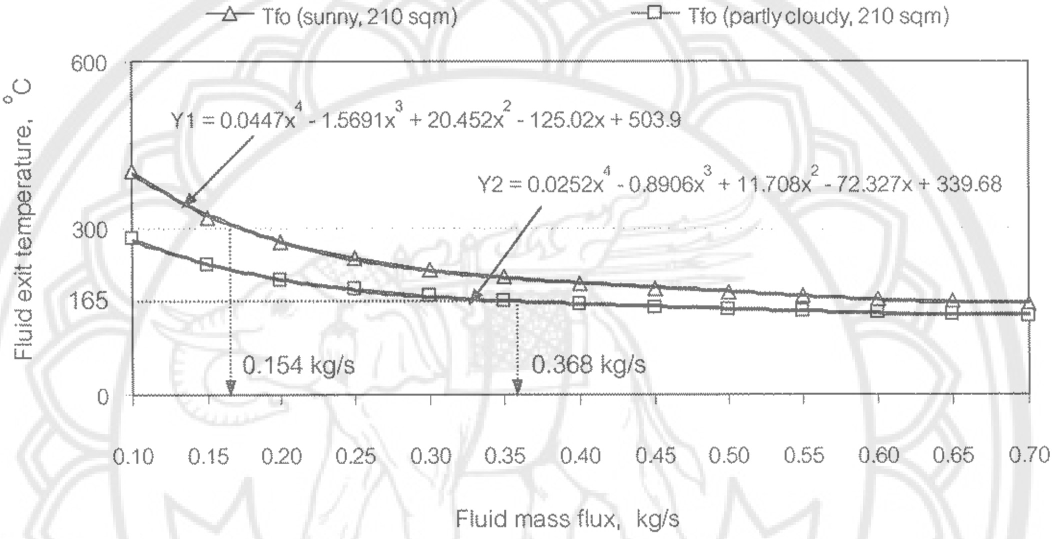

Figure 55 Optimal range of fluid mass flux for a 210 m^2 collector

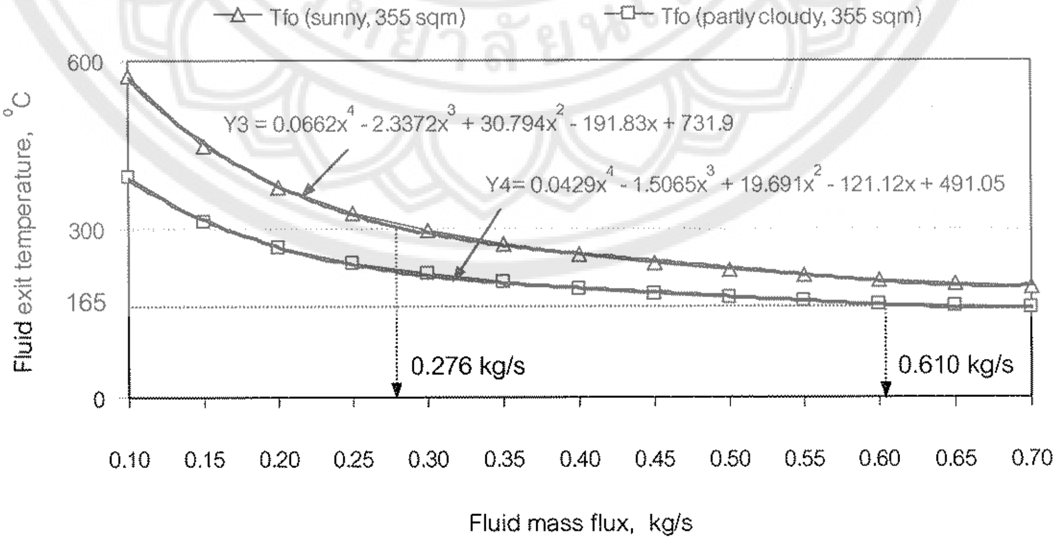

Figure 56 Optimal range of fluid mass flux for a 355 m^2 collector

4.5.3 Biomass Energy Needed for Backup

From equation (3.62), the sum of the collector's useful gain and the gasifier's useful energy multiply by the combustion efficiency is equal to the rated electrical output of the PCU divided by its efficiency. This is also equal to the heat addition to the boiler which in section 3.4.4 is evaluated to be 307.3 MJ. Using this relationship, the amount of biomass backup energy can be calculated on an hourly basis. During sunny condition, where the solar contribution (from 210 m^2 of collector) to the boiler's heat addition is 307.9 MJ, no biomass backup energy is required. During partly cloudy condition, where the solar contribution (from 210 m^2 of collector) is 173.8 MJ, the biomass energy is calculated to be 178.0 MJ, using equation (3.62) and assuming η_{aux} = 75%. During fully cloudy condition, where the solar contribution is zero, the biomass energy needed is 409.7 MJ. This means that the size of the gasifier system would have to be at least 114 kW_{th} in capacity in order that it can deliver a thermal output of 409.7 MJ per hour to enable the power plant to generate at its rated power.

Integrated over an operation-day of 8 hours, the biomass backup requirements for partly & fully cloudy weather conditions are calculated to be 1424.0 MJ and 3277.6 MJ respectively. And using equation (3.60) in Chapter 3, the corresponding mass of solid biomass fuel can be evaluated once the yield & high heating value (HHV) of producer gas and the gasifier efficiency are known. Basing on rice husk as an example, and taking the gas yield as 1.60 m^3/kg & HHV of 11.11 MJ/m^3 [26], and average efficiency of a downdraft gasifier as 50% [31], the amount of rice husk needed to supply the backup energy for one operation-day during partly & fully cloudy conditions are 160.22 kg, and 368.77 kg respectively. And using the average residue-to-product ratio (for rice husk) of 0.267 [48], the corresponding amount of paddy that will produce the above quantities of rice husk are approximately 600.06 kg and 1381.15 kg respectively. For a 114 kW_{th} gasifier that can produce 409.7 MJ of thermal energy per hour, the maximum fuel consumption rate (based on rice husk) is calculated to be about 46.10 kg per hour. A summary of the evaluated results from the above analysis is given in Table 15.

Table 15 Biomass energy needed for backup in partly and fully cloudy conditions

Weather Condition	Mode of Operation	Heat Addition at Rated Power Q_A (MJ/hr)	Useful Gain from Collector Q_u (MJ/hr)	Useful Energy from Gasifier $Q_{u,\,bio}$ (MJ/hr)	Rice Husk Feed Rate (kg/hr)
Sunny	Solar	307.3	307.9	-	-
Partly Cloudy	Hybrid	307.3	173.8	178.0	20.03
Fully Cloudy	Biomass	307.3	-	409.7	46.10

4.5.4 Comparison of Solar & Hybrid Modes by LEC Analysis

From section 4.5.2, it is known that 355 m^2 of collector area is needed for electricity production at rated power based on solar mode operation and from section 4.5.3, a gasifier system with a capacity of 114 kW_{th} (thermal) is required for hybrid and biomass mode operations. In this section, an analysis of the cost effectiveness of using pure solar and a hybrid of solar & biomass energy is carried out, based on the levelized electricity cost (LEC), to determine the suitable mode for optimal operation.

Typically, power plant operations are compared on the basis of their LEC which is defined as the sum of the capital cost (CC) and annual operation & maintenance (O & M) cost, divided by the annual production of electricity. In this analysis, the evaluation of the LEC associated with solar mode and hybrid mode operations is referred to as "Case I & II" respectively. Since the "balance-of-plant" (BOS) is assumed to be the same in both cases, the capital cost in Case I refers only to the costs of the 355 m^2 collector & HTF; while in Case II, the capital cost refers to the costs of the 210 m^2 collector & HTF plus a 114 kW_{th} gasifier system.

In Case I, the LEC can be determined as follow. From the cost data of the commercial SEGS plants in California, it is known that the average cost of collector assemblies is about 200 USD/m^2 [50]. Assuming 1 USD = 40 Baht, this means that the cost is 8,000 Baht/m^2. Thus for installing a 355 m^2 collector, the cost is about 2,840,000 Baht. The HTF cost can be calculated based on the internal volume of the absorber plus an estimated 300% more for the associated piping, multiply by the unit cost of the HTF which is about 30 Baht/liter for Therminol XP [47]. Based on the dimensions of the EPC collector, the HTF cost is calculated to be about 24,090 Baht. Hence the total CC in Case I is estimated to be 2,864,090 Baht. As for the O & M cost, it is estimated to be about 10% of the total CC and is calculated to be 286,409 Baht in this example [50]. The annual electricity production can be evaluated once the maximum possible generation and the percentage of maximum generation, or actual generation are defined. From the analysis in section 4.3, the maximum possible generation is set as 58,400 kWh and assuming an actual generation of 50%, the annual production of electricity at rated power is estimated to be 29,200 kWh. *Hence the LEC in Case I can be calculated by dividing 3,150,499 Baht by 29,200 kWh, giving the result as approximately 107.9 Baht/kWh.*

In Case II, the LEC can be determined as follow. Using the method described above, the costs of a 210 m^2 collector and HTF are calculated to be 1,680,000 Baht & 14,250 Baht respectively, giving a total of 1,694,250 Baht. The O & M cost is estimated to be about 10% of the total CC and is calculated to be 169,425 Baht. In reference [31], the cost of a commercial downdraft gasifier system for the gasification of sugarcane leaf-bagasse was reported to be about USD 59.14/kW_{th}. This experience is used in this analysis where the cost of a similar downdraft gasifier is assumed to be 2,366 Baht/kW_{th}. Thus for a 114 kW_{th} gasifier system, the CC is calculated to be 269,724 Baht. The corresponding O & M cost is estimated as 30% of the CC or 80,917 Baht. Thus the total cost in Case II is evaluated to be 2,214,316 Baht. As for the annual production of electricity, the maximum possible generation is set as 58,400 kWh similar to Case I. But in this instance, the actual generation is assumed to be 80% since electricity production is still possible when no solar energy is available. (Note: Jain (1997) reported that it was possible for a rice husk gasifier to operate for 5,000 hours per annum [51]). *Hence, the LEC in Case II can now be calculated by dividing 2,214,316 Baht by 46,720 kWh, giving the result as approximately 47.4 Baht/kWh.* A summary of the results evaluated for Cases I & II is given in Table 16.

Table 16 Comparison of solar and hybrid modes by LEC analysis

Mode			Size of System	Capital Cost (Baht) [a]	O & M Cost (Baht) [b]	Total Cost (Baht) [a+b = c]	Annual Electricity Production (kWh) [d]	LEC (Baht/ kWh) [c / d]
Case I	Solar only	Collector	355 m^2	2,864,090	286,409	3,150,499	29,200	107.9
Case II	Hybrid	Collector	210 m^2	1,694,250	169,425	2,214,316	46,720	47.4
		Gasifier	114 kW_{th}	269,724	80,917			

From the above analysis, it is found that the LEC of operating with solar energy by itself is about 2.3 times the LEC of operating with a combination of solar & biomass energy. *The implication of this result is that it would be more cost effective to operate the proposed 20 kW_e power plant in hybrid mode with a 210 m^2 solar trough collector and a 114 kW_{th} gasifier, rather than operating the plant with a 355 m^2 collector in pure solar mode with no energy backup.*

4.6 Sensitivity Analysis of Parameter Change on Power Plant Performance

A sensitivity analysis is carried out in order to have an indication of the effect of parameter change on the performance of the power plant in terms of its power output. There are many parameters in a power plant; however in this study, four important parameters (considered to have the main impact) are selected as examples for the analysis. The four parameters are collector area, concentration ratio, direct irradiance and fluid mass flux; the first two are design parameters and the last two are operating parameters. The analysis is carried out according to the following conditions. The reference situation of the analysis is based on the optimal condition of the power plant where the four evaluated parameters assumed the nominal values as follow: collector area = 210 m^2, concentration ratio = 22.4, direct irradiance = 714 W/m^2, and fluid mass flux = 0.240 kg/s. It is also assumed that all the input thermal energy to the power plant is supplied by the solar collector such that $Q_u = Q_A$.

Table 17 Effect of parameter change on power output

Parameter	**Degree of Change**	**Value**	**Q_u (MJ/hr)**	**Q_A (MJ/hr)**	**Q_{output} (MJ/hr)**	**P_{output} (kW)**	**% Effect**
Direct Irradiance, I_a (W/m^2)	- 10%	643	274.4	274.4	64.29	17.86	- 10.9%
	nominal	714	307.9	307.9	72.14	20.04	
	+ 10%	785	341.7	341.7	80.06	22.24	+11.0%
Collector Area, A_a (m^2)	- 10%	189	279.2	279.2	65.42	18.17	- 9.3%
	nominal	210	307.9	307.9	72.14	20.04	
	+ 10%	231	337.1	337.1	78.98	21.94	+ 9.5%
Fluid Mass Flux, $\dot{m}$ (kg/s)	- 10%	0.216	306.1	306.1	71.72	19.92	- 0.6%
	nominal	0.240	307.9	307.9	72.14	20.04	
	+ 10%	0.264	309.6	309.6	72.54	20.15	+ 0.6%
Concentration Ratio, C_g	- 10%	20.2	307.3	307.3	72.00	20.00	- 0.2%
	nominal	22.4	307.9	307.9	72.14	20.04	
	+ 10%	24.6	308.4	308.4	72.26	20.07	+ 0.2%

The value of each parameter is then increased or decreased by 10%, and the corresponding % change in power output is calculated using the BSPP model created in this study. While each parameter is being varied, the other three parameters remain at their nominal values. In this manner, the effect of parameter change on the performance of the power plant in terms of its average hourly power output can be evaluated.

Table 17 summarizes the results of the analysis. From the results, it can be observed that of the four major parameters considered, the variation of direct irradiance has the greatest effect on the performance of the power plant. A 10% increase in direct radiation causes an 11.0% increase in power output while a 10% decrease in direct radiation leads to a corresponding 10.9% decrease in power output. The parameter that has the next highest effect is the size of the solar collector. A 10% increase in collector area increases the power output by 9.5% while a 10% decrease in collector area reduces the power output by 9.3%. In third place is the fluid mass flux, where a +/- 10% change leads to a +/- 0.6% change in power output. Finally, the parameter with the least effect is the concentration ratio where the % power change is only +/- 0.2%.