

Feasibility Study on the Viability of SORC for Power Generation in Thailand's Six Main Regions

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Abstract

Solar energy is one of the renewable energy resources that proved to be a useful to solve the present energy crisis and achieve sustainable development. In Thailand, Concentrating Solar Power (CSP) technologies are in-appropriate because the annual direct normal solar radiation is much low. In this study, the concept of a small-scale solar Organic Rankine Cycle (SORC) system for power generation with temperature below 100 °C was investigated. The SORC system was analyzed by using 2-capacity ORC units with four system configurations in combination with solar water heating system (SWHS). Flat-plate (FP), Evacuated-tube (ET), and Compound Parabolic Concentrator (CPC) solar collectors were used to generate heat. These four system configurations were mathematically modelled and simulated to evaluate maximum power output, CO₂ emission, and levelized cost of electricity (LCOE). For data simulations, six areas; Chiang Mai, Bangkok, Ratchaburi, Songkhla, Nakhon Ratchasima, and Chon Buri, were selected to represent the main regions of Thailand (i.e.; the northern, central, western, southern, north-eastern and eastern part, respectively). The results showed that a small-scale SORC power plant is appropriate for a heat source producing temperatures below 100 °C and that the ORC system is a good solution for power generation using low-temperature heat. At the simulated highest power outputs, of between 154.19 and 182.89 MWh/Year the reduction of CO₂ emissions from the systems were 71.24 and 84.5 Ton CO₂ eq./Year, respectively. The appropriated number of collectors were between 1710 and 2000 units. Further, LCOE of between 0.931 and 1.110 USD/kWh were achieved. CSP technologies have an LCOE between 0.200 and 0.300 USD/kWh, while solar photovoltaic systems have LCOE between 0.140 and 0.470 USD/kWh. Therefore, without government support or subsidizes for the initial investment cost of the solar collectors and the ORC power generation, the small-scale SORC power plant will not be economically attractive due to higher value of LCOE compared to the other two types of solar energy technologies.

Keywords:

Solar collectors, Solar Organic Rankine Cycle (SORC), Electrical power generation, Levelized Cost of Electricity (LCOE)

1. Introduction

Renewable energy has help solved energy crisis, at the same time providing fuel for sustainable development by reducing fossil fuel consumption and contributing to the conservation of ecosystems and mitigation of climate change. Solar thermal energy is one of the important forms of renewable energy. Solar thermal energy systems are now widely used for satisfying the demand for hot water and steam in large buildings such as hospitals and hotels, and also in industrial processing plants. If solar thermal systems can also be used for power generation, it can substitute for fossil-fueled power plants and help reduced local air pollution and greenhouse gas emissions from the electricity generation sector. These have been proven by the use of Concentrating Solar Power (CSP) plants technologies for large-scale power systems. Such systems require a minimum power input of a few MWe, large plant areas and solar thermal energy or heat at high ranges of temperature ($T > 500$ °C) [1].

The direct normal solar radiation in Thailand is in the range of 1350 – 1400 kW/m²-Year [2]. This makes operation of CSPs requiring radiations of above 1500 kWh/m²-Year inappropriate [3-5]. However, in recent years, there have been increasing interests for solar thermal systems that are small-scale but have high efficiency and flexibility. One of these is the Solar Organic Rankine Cycle (SORC) system, which is similar to a Steam Rankine cycle system that has high energy conversion efficiency, but low working temperature and can have little negative impacts on the environment. ORC systems are increasingly considered as one of the most common and competitive technologies [6].

An ORC system works similarly to a Steam Rankine power plant, but it makes use of organic working fluids which are able to condense and evaporate at an acceptable lower temperature [7]. The working fluid should have low cost, high flash point, good material compatibility and stability limits, low toxicity and freezing point, and low global warming potential (GWP). as well as low ozone depletion potential (ODP) [8].

For a small-scale SORC power plant, based on Compound Parabolic Concentrating (CPC) solar collectors, a study done by Santos-González I et al. [9] showed that the CPC solar collectors are suitable options due to their lower cost and good thermal performance for low to medium temperature range because they can collect both direct and diffuse solar radiation without a tracking system. Jiangfeng Wang et al. [10] created a model of the CPC solar collectors which combined the ORC power generation and thermal energy storage (TES) unit to achieve continuous operation of the overall system. Also, Pei Gang et al. [11] introduced a configuration of a low-temperature solar thermal electric generation with regenerative ORC. The system mainly consists of CPC solar collectors and a regenerative ORC power generation. The results of these studies indicated that the regenerative cycle has positive effects on the ORC efficiency. With regard to flat-plate solar collectors, Kutlu et al. [12] investigated a medium-temperature SORC system using evacuated flat-plate solar collectors and a pressurized water storage unit. The results revealed that the expander under given conditions produced 47.11 kWh at daytime, 70.97 kWh in the peak period and 31.59 kWh after midnight. Wang et al. [13] carried out a simulation of a solar-driven regenerative ORC based on flat-plate solar collectors using different organic working fluids. The results indicated that when a thermal storage tank is installed, the system can achieve a continuous and stable operation over a longer time. Calise et al. [14] investigated the energy and economic performance of a 6 kW_e ORC power generation coupled with 73.5 m² of innovative flat-plate evacuated solar collectors in different climate conditions. Findings showed that the economic feasibility of such a system is possible with feed-in tariff incentive schemes. Moreover, Delgado-Torres and Garcia-Rodriguez [15] offered a theoretical analysis of a low-temperature SORC power generation. In which they explored the overall efficiency of the SORC and its optimization with different collector types and working fluids and examined the influence of the regeneration process and cycle configuration on its performance. The literature survey done above [10-15] well-established that ORC systems from low-temperature heat source have been extensively applied for power generation. Nevertheless, there are only a few which have been designed with solar collectors to utilize thermal energy with temperature lower than 100 °C. In this paper, the focus is on the application of solar thermal at the temperature range of 70-95 °C.

The design conditions of the power generation system in the present study, i.e. weather condition, three types of non-concentrating solar collectors (Flat-Plate (FP), Evacuated-Tube (ET) and Compound Parabolic Concentrating (CPC) solar collectors), and 2-capacities of ORC power generation (20 and 60 kW_e) were demonstrated in six provinces of Thailand,. Secondary mathematical models were established by employing the MATLAB model. Meanwhile, the performance characteristic of an ORC with capacity of 20 and 60 kW_e was described, and simulation were done for power generation, CO₂ emissions and economic analysis in terms of levelized cost of electricity (LCOE). Ultimately, the different system configurations were compared under different ORC capacity to probe the suitable number of solar collectors and size of the thermal energy storage (TES) for the maximum power output in each province.

2. System simulation and Descriptions

The main components of a small-scale SORC power system as shown in Fig. 1 are solar collectors, an ORC power generation system, a cooling tower, a thermal energy storage (TES), a collectors pump, and an ORC pump. The system operation is shown in Fig. 1 and is described as follows: In the day time or from sunrise, the low-temperature hot water from the TES-I and TES-II ($T_{Coll,i-1}$ and $T_{Coll,i-II}$) is pumped by the collector pump (Collector pump-I and Collector pump-II, respectively), to the solar collector field (Field A and Field B as shown in Fig. 2) to produce a high-temperature hot water. At this step, the hot water flow rate that supplied to the solar collector field (Field A and Field B) is adjusted to achieve a hot water temperature in the range of 70 to 95 °C (This temperature is suitable for small-scale ORC power generation). After that, the high-temperature hot water from the TES-I is supplied to

- The useful heat rate from the collectors (\dot{Q}_{Coll}):

$$\dot{Q}_{Coll} = A_{Coll} [F_R(\tau\alpha)_e I_T - F_R U_L (T_{Coll,i} - T_{Amb})] \quad (2)$$

Where T_{Amb} is the ambient temperature ($^{\circ}\text{C}$), and I_T is the solar radiation (W/m^2).

- The temperature of water in the thermal energy storage ($T_S^{t+\Delta t}$) [17]:

$$T_S^{t+\Delta t} = T_S^t + \frac{\Delta t}{M_S C_p} [\dot{Q}_{Coll} - \dot{m}_{ORC} C_p (T_{ORC,i} - T_{ORC,o}) - U_A (T_{TES} - T_{Amb})] \quad (3)$$

Where $T_S^{t+\Delta t}$ is the water temperature in the thermal energy storage at time $t + \Delta t$ and T_S^t is the water temperature at time t . I_T is the total solar radiation. T_{Amb} is the ambient temperature.

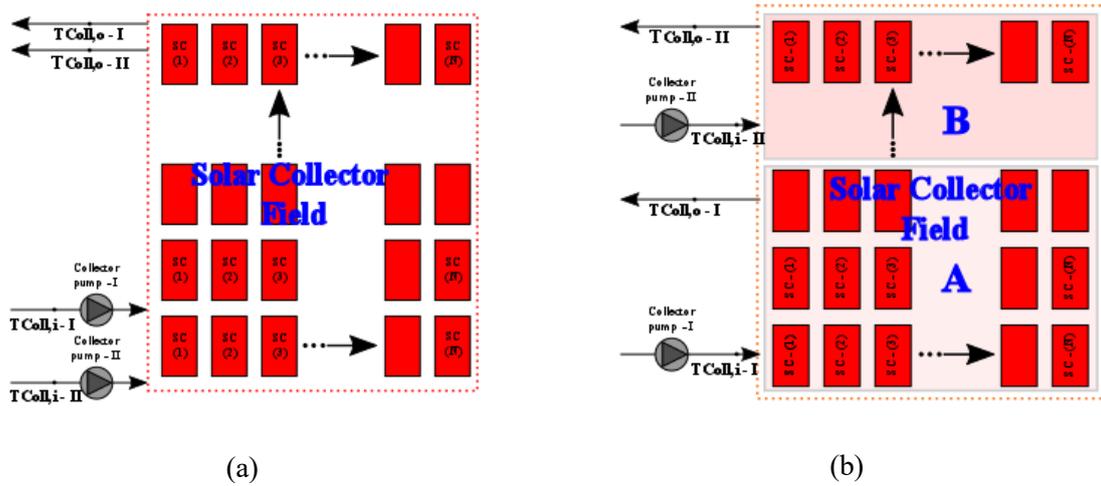


Fig. 2 The solar field operation, (a) total number or maximum number of solar collectors installed in the solar field and (b) Solar collectors field operation (Field A: hot water supply to the thermal energy storage (TES) – I, and Field B: hot water supply to the thermal energy storage (TES) – II).

In this study, 100 to 2000 units (in 10 units increment) of FP, ET, and CPC solar collectors connected in parallel were used for hot water production as shown in Fig. 3, having optical efficiency ($F_R(\tau\alpha)_e$) of 0.74, 0.57, 0.72, overall heat transfer coefficient ($F_R U_L$) of 3.62, 0.75, 0.97 $\text{W}/\text{m}^2\text{-K}$, and with solar collectors (A_{Coll}) of 2.08, 2.37, 2.16 m^2 per unit (Gross area), respectively. Moreover, the TES of 2500 to 50000 liters (in 2500 liters increment) had the overall coefficient of heat loss (U_A) at 5 W/K [17].

2.2. Organic Rankine Cycle (ORC)

The Organic Rankine Cycle (ORC) system is one of the alternative renewable technologies that are widely used in the recovery of low-temperature heat sources [18-20]. In the ORC system, organic fluids are used due to their low boiling points. It means that organic working fluids can be used at lower temperatures and do not require superheating. And it is practical in increasing the efficiency of the cycle with water as a working fluid [21]. Moreover, the ORC can be scaled to smaller unit sizes and has the flexibility to conduct semi attended or unattended operations as compared with the Steam Rankine Cycle [11].

In this study, the performance characteristic of an ORC system with the capacity of 20 and 60 kW_e with R-245fa as the working fluid (Model: HR20W [22] for a 20 kW_e ORC power generation, and MB-70H [23] for a 60 kW_e ORC power generation) such as inlet hot water temperature ($T_{ORC,i}$), hot water flow rate (\dot{m}_{ORC}) and cooling water temperature (T_{Amb}) was simulated to find the maximum power output capabilities of the system in four different configurations.



Fig. 3 Three types of solar collectors. (a) FP solar collectors; Model: Superline M-1 FSB PU from Ezince Company [24], (b) ET solar collectors; Model: DF120/6 from EuroSun Solarsystem GmbH [25] and (c) CPC solar collectors; Model: CPC12 from Solar bayer Company [26].

2.3. Simulation conditions

The input data for system simulations utilized the weather data of Chiang Mai (18.80 °N, 09.09 °E), Bangkok (13.75 °N, 100.52 °E), Ratchaburi (13.54 °N, 99.82 °E), Songkhla (7.21 °N, 101.00 °E), Nakhon Ratchasima (13.75 °N, 100.52 °E), and Chon Buri (13.40 °N, 101.00 °E) which represent the northern, central, western, southern, north-eastern and eastern part of Thailand, respectively [16] as shown in Fig. 5. Moreover, Hourly Global Radiation Estimation based on the studies of Duffie JA and Beckman WA [27] and Zhang et al. [28] was taken into account. The system under study was modelled and evaluated for an optimal flow rate of hot water (\dot{m}_{ORC}) in each time of the day, the number of solar collectors, size of the thermal energy storage (TES) for the maximum power output. (In the simulations, the three solar collectors were used at a flow rate other than that of the test conditions. Then, the approximate analytical correction to $F_R(\tau\alpha)_e$ and $F_R U_L$ was obtained from the ratios of values of F_R base on the studies of Duffie JA and Beckman WA [27].

The calculation steps is presented in Fig. 6. The hot water flow rate that was supplied to the solar collector field (Field A and Field B) was adjusted to achieve a hot water temperature and later stored in the TES in the range of 70 to 95 °C. After that, the hot water flow rate (Ton/h) from the performance characteristics of the ORC power generation (A 20 kW_e ORC from IHI Company and A 60 kW ORC from KOBELCO Company) was obtained. In order to attain the optimal hot water flow rate to be supplied to the ORC power generation, the flow rate was varied between the minimum and maximum amount allowed by the ORC system. For the system investigated here, the flow rate was 12 to 28 Ton/h for a 20 kW_e, and 25 to 75 Ton/h for a 60 kW_e ORC (in 1 Ton/h increment).

It is also possible to calculate the heat input to the ORC system. After finding out the power output of the system by interpolation of the data presented in the performance characteristics of the ORC power generation in combination with the hot water flow rate and temperature found in the previous step, and the cooling water temperature (equal to ambient temperature in this study), the system simulation selected the hot water flow rate that would produce the highest power output during the system operation. At this step, the highest power output was also selected. Finally, hot water from the storage tank was supplied to the solar collector field to start the next cycle. During the simulations, the thermodynamic properties of the heat transfer fluid (HTF) were calculated by REFPROP NIST7.0 [29].

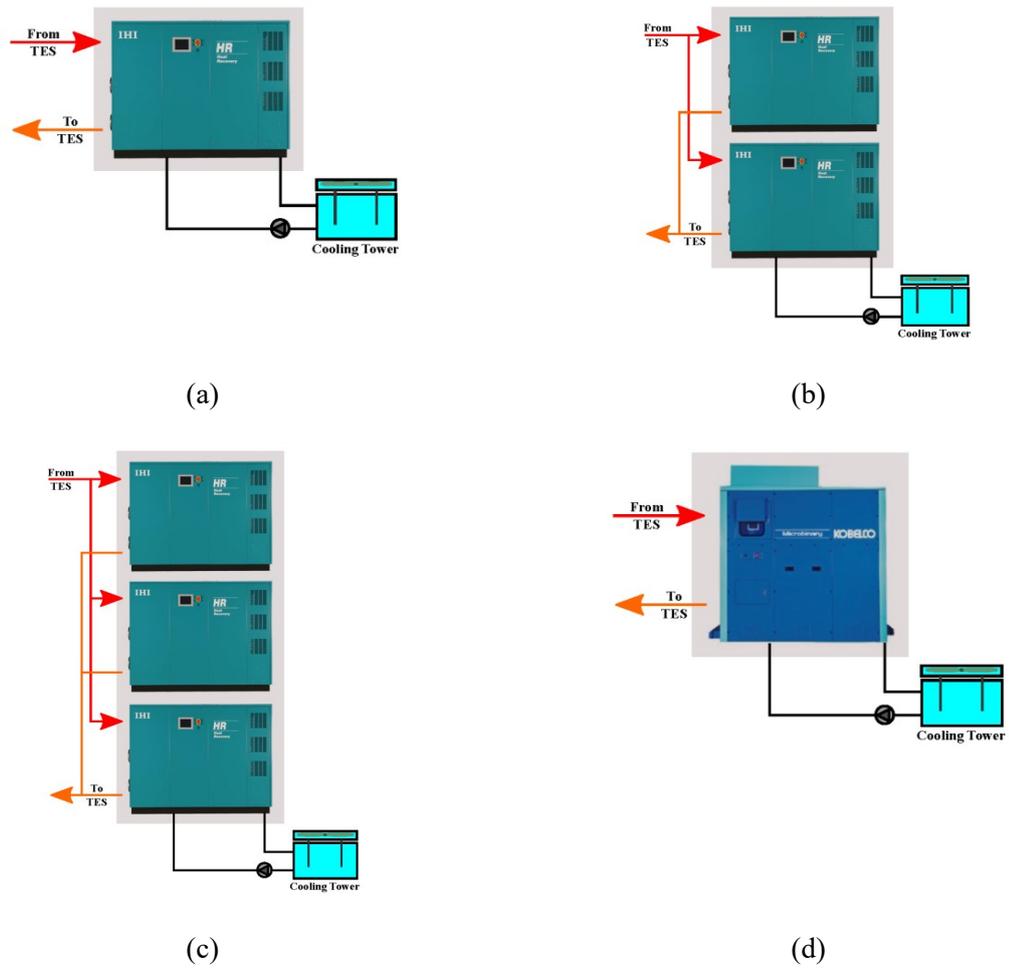


Fig. 4 Four different models of the SORC system. (a) Solar collectors integrated with one unit of a 20 kW_e (SORC-I), (b) Solar collectors integrated with two units of a 20 kW_e (SORC-II), (c) Solar collectors integrated with three units of 20 kW_e (SORC-III) and (d) Solar collectors integrated with one unit of a 60 kW_e (SORC-IV).

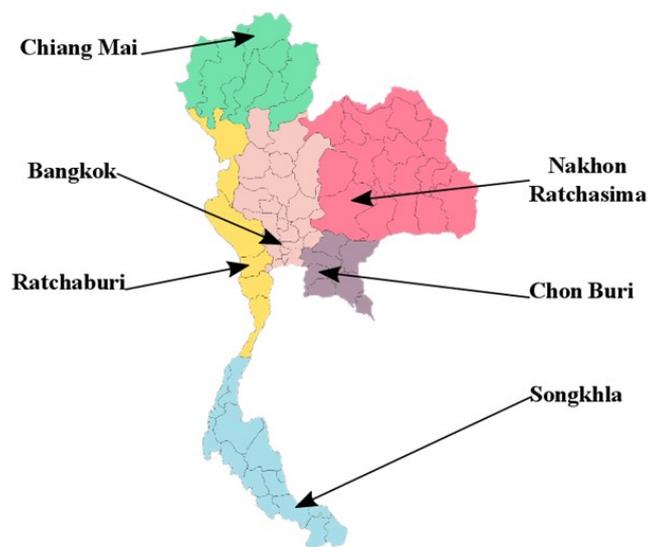


Fig. 5 The location of Chiang Mai, Bangkok, Ratchaburi, Songkhla, Nakhon Ratchasima, and Chon Buri [16].

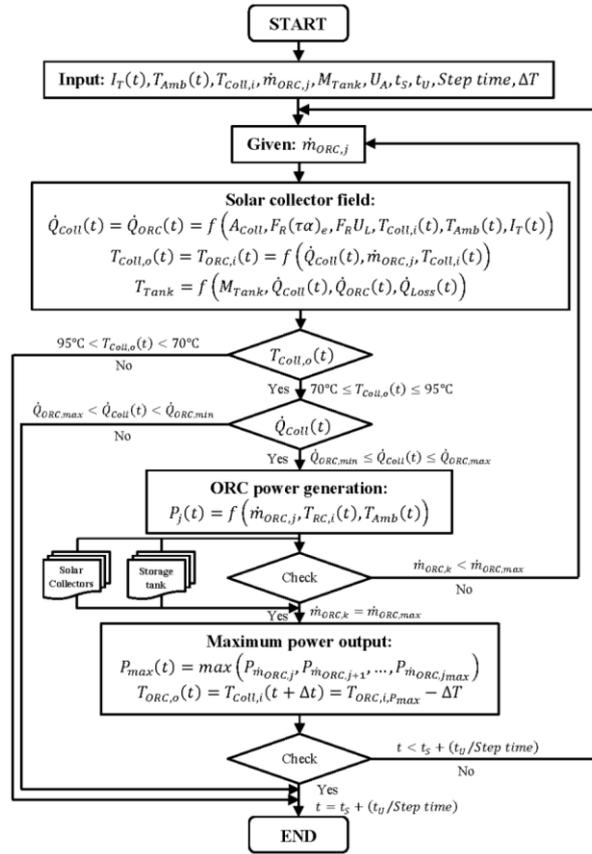


Fig. 6 Calculation step of the SORC power generation [30].

3. Economic analysis

Economic analysis in terms of levelized cost of electricity (LCOE) was done in the study following the methodology presented in Sonsaree et al. [16]. This is a good indicator that helps to compare other power technologies using electricity cost (USD/kWh). In this assessment, the investment cost of the ORC power plant was set at around 2500 USD/kW_e [16] for both cases (20 kW_e and 60 kW_e). The initial conditions of the system are shown in Table 1.

Table 1 Initial economic condition of the small-scale SORC power system [31].

Descriptions	Data
Operation day, (day/year)	353
Cost of solar collectors (USD/m ²)	
FP solar collectors	112.3
ET solar collectors	154.4
CPC solar collectors	196.5
Construction and engineering, (%)	10
O&M cost (percent of investment cost per year)	5
Insurance rate, $k_{insurance}$ (%/year)	0.6
Real debt interest rate, i_d (%)	7.325
Depreciation period, n (year)	25

4. Results and discussions

In this study, a small-scale SORC power plant with low-temperature heat (< 100 °C) was investigated. Four different ORC capacities with different collectors (FP, ET, and CPC) were designed as follows; (I) SORC-I, (II) SORC-II, (III) SORC-III, and (IV) SORC-IV and are shown in Fig. 4. Their performances in six areas of Thailand were y evaluated in terms of power output and LCOE, and the results are discussed below.

4.1. Power output

The power output (MWh/Year) of different ORC capacities with different collectors in the six selected areas of Thailand are shown in Table 2 and Fig. 7. It showed that when the solar collectors are combined with the ORC-IV, the system was able to generate the highest amount of electricity. This is followed by ORC-III, the ORC-II, and the ORC-I combined systems, respectively. With consideration to the type of solar collectors, both ET-SORC and CPC-SORC systems were able to generate electricity higher than that the FP-SORC system. The reason behind is that the ET and the CPC solar collectors can produce higher temperature of hot water to be supplied to the ORC system. When ET and CPC solar collectors were compared, the power output of the ET-SORC system appeared similar to the CPC-SORC system as the limit of inlet hot water temperature of the ORC system did not exceed 95 °C. It means that the CPC solar collectors are not appropriate for a small-scale SORC power plant. In addition, the appropriated number of solar collectors and size of the TES-I for each system configuration in order to generate maximum power output is shown in Table 3 and Table 4, respectively.

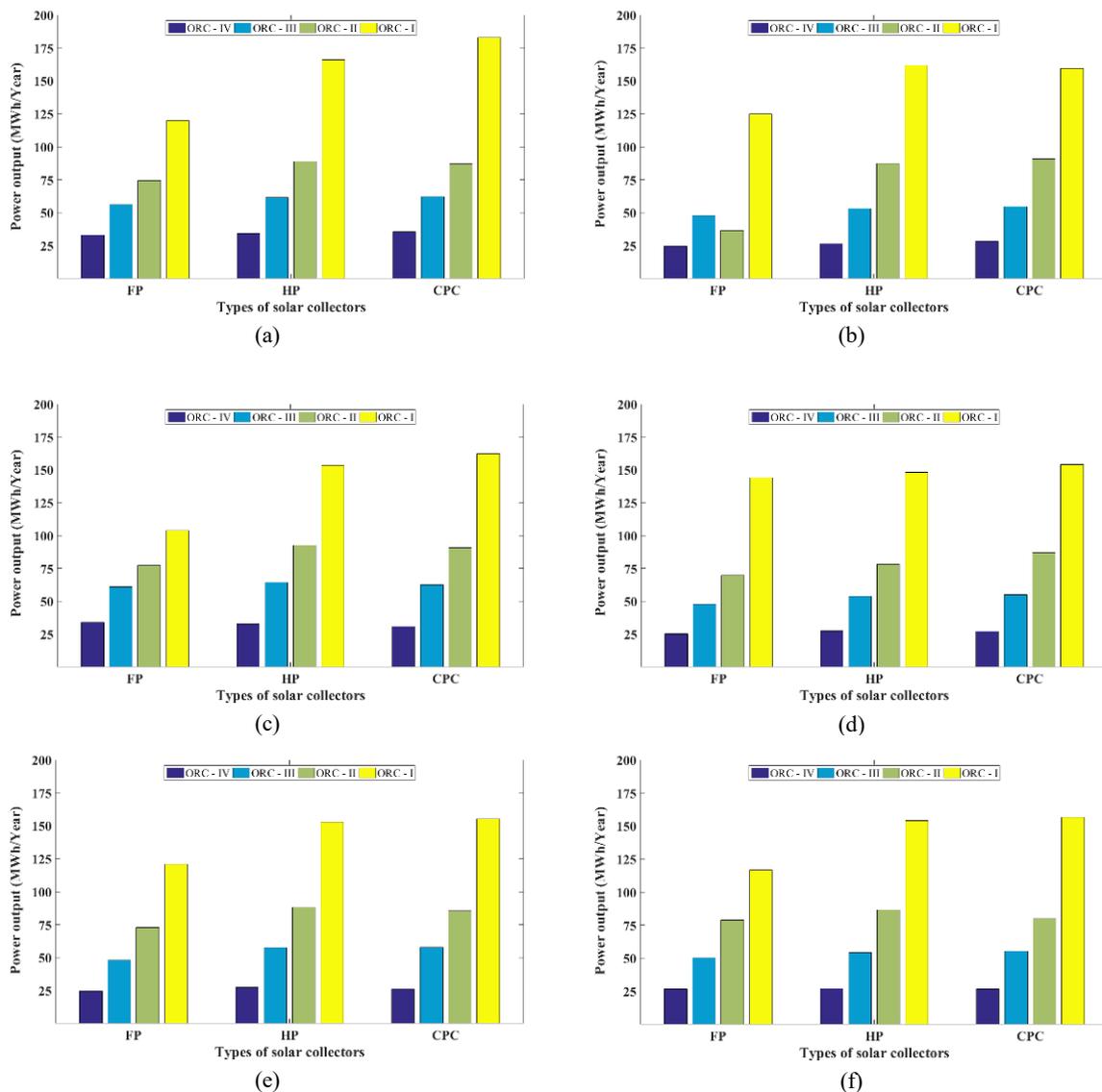


Fig. 7 Maximum power output (MWh/Year) of different configuration (SORC-I, SORC-II, SORC-III, and SORC-IV) with three different solar collectors (FP, ET, and CPC solar collectors) in six areas of Thailand: (a) Chiang Mai, (b) Bangkok, (c) Ratchaburi, (d) Songkhla, (e) Nakhon Ratchasima, and (f) Chon Buri.

Table 2 Maximum power output (MWh/Year) of different ORC system capacity integrated by different solar collectors in the six selected areas.

Province	FP-SORC				ET-SORC				CPC-SORC			
	I	II	III	IV	I	II	III	IV	I	II	III	IV
Chiang Mai	33.15	56.24	74.35	120.06	34.24	61.46	88.97	166.13	35.73	62.09	87.11	182.89
Bangkok	24.48	47.87	36.43	125.03	26.61	53.10	87.26	161.86	28.36	54.75	90.78	159.49
Ratchaburi	34.00	61.09	77.28	103.84	32.86	64.53	92.71	153.30	30.85	62.58	90.67	162.31
Songkhla	25.27	47.81	69.63	144.09	27.39	53.69	78.12	147.97	27.14	55.02	86.95	154.19
Nakhon Ratchasima	24.59	48.05	72.91	120.77	27.35	57.52	88.30	152.89	26.22	57.95	85.42	155.35
Chon Buri	26.85	50.42	78.73	116.90	26.99	54.41	86.75	154.20	26.86	55.23	79.97	156.70

In Table 3, the system configuration in Chiang Mai, Bangkok, Ratchaburi, Songkhla, Nakhon Ratchasima, and Chon Buri based on the suitable numbers of the collectors, capacity of the ORC system, and size of the TES-I could produce, respectively, the following maximum power output: 182.89, 161.86, 162.31, 154.19, 155.35, and 156.70 MWh/Year, respectively. The system configuration for each area required 2000 unit of CPC collectors, 1930 units of ET collectors, 1940 units of CPC collectors, 1980 units of CPC collectors, 1710 units of CPC collectors and 1830 units of CPC collectors, respectively. All the systems were combined with one unit of a 60 kW_e ORC power generations and TES-I size of 50000 liters.

Table 3 Suitable number of the solar collectors.

Province	Solar collectors (Units)	FP-SORC				ET-SORC				CPC-SORC			
		I	II	III	IV	I	II	III	IV	I	II	III	IV
Chiang Mai		790	1640	1990	2000	610	1220	1790	1980	610	1070	1560	2000
Bangkok		570	1120	1740	2000	470	930	1410	1930	450	830	1410	1680
Ratchaburi		890	1610	1960	2000	620	1280	1780	2000	540	1070	1550	1940
Songkhla		640	1280	1900	2000	540	980	1450	1980	480	970	1460	1980
Nakhon Ratchasima		420	1100	1710	1990	480	990	1490	1950	410	870	1220	1710
Chon Buri		630	1250	1860	2000	500	1010	1460	2000	470	890	1240	1830

However, when the total capacity of the ORC power plant is the same (like in the SORC-III and the SORC-IV) as shown in Table 2, it was found that the SORC-IV generated more electricity than that of the SORC-III because of higher thermal efficiency of the ORC-IV [31]. Nevertheless, when part load operation was considered (especially plant configurations of the SORC-III (three units of a 20 kW_e ORC power generation), and the SORC-IV (one unit of a 60 kW_e ORC power generation)), the power demand could be less than the power output that the system can generate. Further, the ORC machine of the SORC-III system can operate independently (For example sometimes operation can use only one, two, or three units of a 20 kW_e ORC power generation). A comparison of the six areas, as shown in Table 2, revealed that the SORC power plant in Chiang Mai with SORC-IV produce the highest power output of 182.89 MWh/Year, with 2000 units of CPC solar collectors, and TES-I size of 50000 liters.

4.2. Environment evaluation

The estimation of the CO₂ emission was based on a carbon dioxide intensity factor for Thailand of 0.462 kg CO₂ eq./kWh [32] was considered. The results of this study showed that the reduction in CO₂ emission depended on the amount of electricity production. The power output data shown in Table 2 was used to estimate CO₂ emission, and the results are shown in Table 5. The system configuration in Chiang Mai, Bangkok, Ratchaburi, Songkhla, Nakhon Ratchasima, and Chon Buri can reduce CO₂ emission based on the maximum power output of the systems as follows: 84.50, 74.78, 74.99, 71.24, 71.77, and 72.40 Ton CO₂ eq./Year, respectively. Moreover, in Chiang Mai area, when the FP solar collectors combined with SORC-I, SORC-II, SORC-III, and SORC-IV, the system can reduce CO₂ emission by 15.31, 25.98, 34.35, and 55.47 Ton CO₂ eq./Year, respectively.

Table 4 Sizes of thermal energy storage I (TES-I) and II (TES-II).

Province	TES-I				TES-II			
	FP-SORC				FP-SORC			
	I	II	III	IV	I	II	III	IV
Chiang Mai	10000	22500	32500	47500	35000	107500	110000	75000
Bangkok	10000	20000	32500	50000	25000	47500	72500	55000
Ratchaburi	10000	22500	27500	50000	60000	95000	87500	50000
Songkhla	10000	22500	32500	50000	37500	42500	65000	92500
Nakhon Ratchasima	7500	20000	22500	50000	10000	40000	85000	67500
Chon Buri	10000	20000	35000	50000	25000	50000	92500	62500
Province	ET-SORC				ET-SORC			
	I	II	III	IV	I	II	III	IV
	Chiang Mai	7500	15000	22500	50000	37500	75000	112500
Bangkok	7500	15000	22500	50000	22500	35000	97500	67500
Ratchaburi	7500	12500	17500	50000	37500	77500	82500	85000
Songkhla	7500	15000	17500	50000	25000	62500	42500	72500
Nakhon Ratchasima	7500	20000	25000	50000	17500	37500	92500	80000
Chon Buri	7500	17500	20000	50000	20000	37500	85000	82500
Province	CPC-SORC				CPC-SORC			
	I	II	III	IV	I	II	III	IV
	Chiang Mai	10000	15000	17500	50000	60000	70000	120000
Bangkok	10000	15000	17500	50000	20000	65000	117500	70000
Ratchaburi	7500	15000	17500	50000	30000	62500	80000	110000
Songkhla	7500	17500	20000	50000	20000	50000	107500	95000
Nakhon Ratchasima	10000	15000	20000	50000	15000	67500	92500	75000
Chon Buri	7500	17500	17500	50000	25000	37500	57500	82500

Table 5 CO₂ emission (Ton CO₂ eq./Year) of different ORC system capacity (SORC-I, SORC-II, SORC-III, SORC-IV) integrated by different collectors (FP, ET, and CPC solar collectors) by area.

Province	FP-SORC				ET-SORC				CPC-SORC			
	I	II	III	IV	I	II	III	IV	I	II	III	IV
Chiang Mai	15.31	25.98	34.35	55.47	15.82	28.39	41.11	76.75	16.51	28.69	40.24	84.50
Bangkok	11.31	22.12	35.57	57.77	12.29	24.53	40.31	74.78	13.10	25.30	41.94	73.68
Ratchaburi	15.71	28.22	35.70	47.97	15.18	29.81	42.83	70.82	14.25	28.91	41.89	74.99
Songkhla	11.67	22.09	32.17	66.57	12.66	24.80	36.09	68.36	12.54	25.42	40.17	71.24
Nakhon Ratchasima	11.36	22.20	33.68	55.80	12.64	26.57	40.80	70.64	12.11	26.77	39.46	71.77
Chon Buri	12.41	23.30	36.37	54.01	12.47	25.14	40.08	71.24	12.41	25.52	36.95	72.40

4.3. Economic evaluation

The economic assessment of small-scale SORC power plants considered the initial investment of solar collectors and the ORC power generation components. As shown on Table 6 and Fig. 8, the lowest LCOE for a system located in Chiang Mai, Bangkok, Ratchaburi, Songkhla, Nakhon Ratchasima, and Chon Buri was 1.029, 0.975, 1.110, 0.913, 1.033 and 1.059 USD/kWh respectively. Such systems require - corresponding to each location mentioned previously - 1980 units of ET collectors, 2000 units of FP solar collectors, 2000 units of ET collectors, 2000 units of FP collectors, 1990 units of FP collectors, and 2000 units of FP collectors. All these systems were combined with one unit of a 60 kW_e ORC power generations and TES-I size of 50000 liters.

As shown by the evaluations, LCOE of between 0.913 and 1.915 USD/kWh were achieved. CSP technologies have an LCOE between 0.20 and 0.30 USD/kWh, while solar photovoltaic systems have LCOE of between 0.14 and 0.47 USD/kWh [33]. Therefore, without government support or subsidies for the initial investment cost of the solar collectors and the ORC power generation, small-scale SORC power plants will not be economically attractive due to their relative higher value of LCOE.

In case the total investment cost of FP, ET, and CPC solar collectors are subsidized by 80 percent, the initial investment cost of the solar collectors (shown in Table 1) will be at 22.5, 30.9, and 39.3 USD/m², respectively. If the capital cost of the ORC power plant is set at around 1000 USD/kW, and

the economic evaluation redone, the results are shown in Table 7. Based on this analysis, the system can become more economically attractive as the LCOE have now values of between 0.378 and 0.912 USD/kWh. Moreover, a comparison of results (as shown in Table 7) in terms location showed that Bangkok province had the lowest LCOE of 0.378 USD/kWh, using a system with 1930 units of FP solar collectors, and TES-I size of 50000 liters.

The maximum power outputs, from January to December, in the six areas using the suitable number of solar collectors designed for the configuration of each area are shown in Table 8 and Fig. 9. For instance, in Chiang Mai Province, the SORC power plant could produce a maximum monthly power output from January to December as follows: 17.64, 17.83, 17.88, 17.14, 13.91, 10.31, 11.99, 12.44, 14.08, 15.16, 16.72, and 17.78 MWh/Month, respectively. The suitable number of CPC collectors in each month were determined as follows: 1160, 910, 1080, 1160, 1510, 2000, 1820, 1760, 1460, 1310, 1230, and 1230 units, respectively. For the results in the Bangkok area, the maximum monthly power outputs that could be produced from January to December were as follows: 14.02, 14.95, 15.63, 14.62, 14.01, 12.63, 10.42, 11.57, 11.75, 12.55, 14.36, and 15.36 MWh/Month, respectively. The suitable number of CPC collectors in each month were determined as follow: 1420, 1340, 1320, 1360, 1400, 1580, 1930, 1860, 1830, 1550, 1210, and 1210 units, respectively.

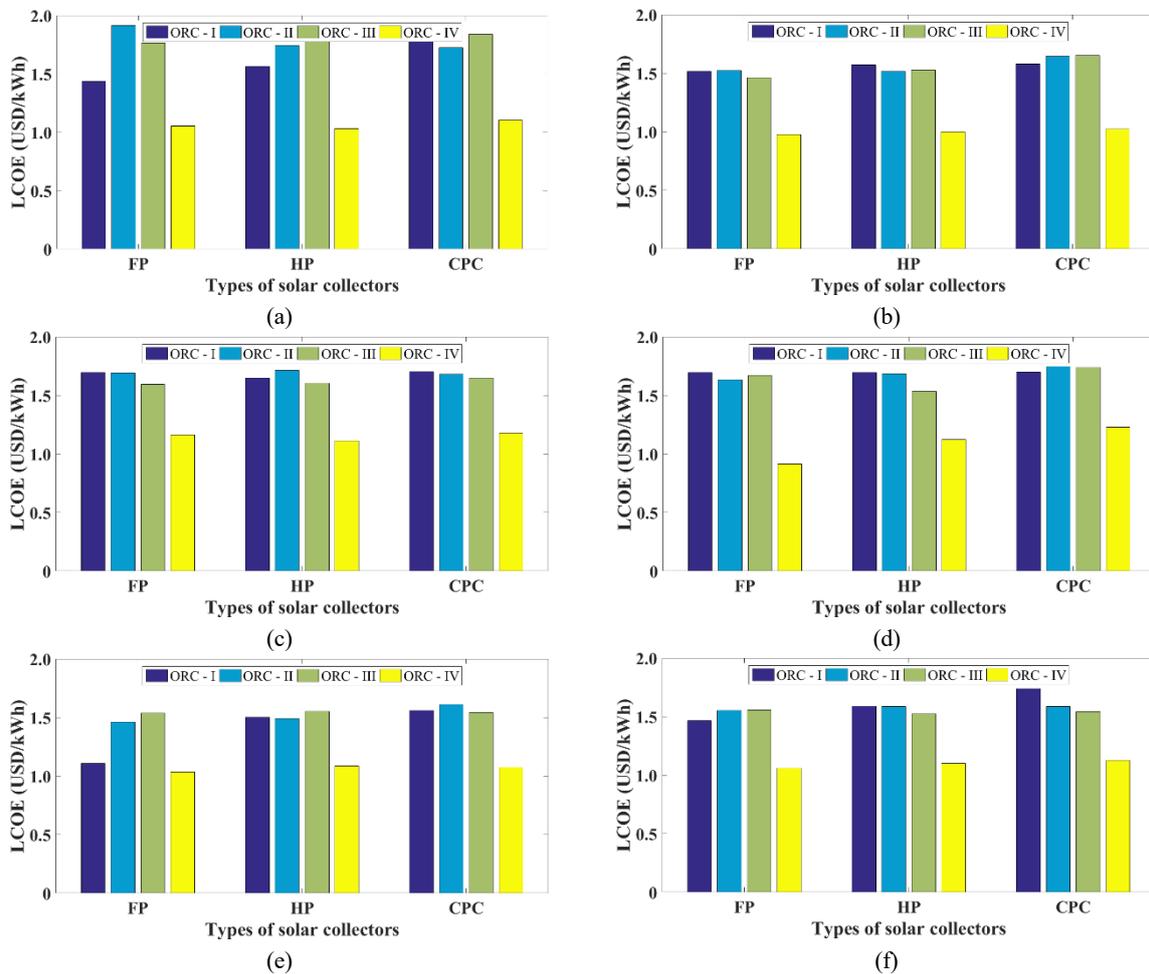


Fig. 8 LCOE (USD/kWh) of different configuration (SORC-I, SORC-II, SORC-III, and SORC-IV) with three different collectors (FP, ET, and CPC solar collectors) in six areas of Thailand: (a) Chiang Mai, (b) Bangkok, (c) Ratchaburi, (d) Songkhla, (e) Nakhon Ratchasima, and (f) Chon Buri.

Table 6 LCOE (USD/kWh) of different ORC system capacity (SORC-I, SORC-II, SORC-III, and SORC-IV) integrated by different collectors (FP, ET, and CPC solar collectors) at six areas by area.

Province	FP-SORC				ET-SORC				CPC-SORC			
	I	II	III	IV	I	II	III	IV	I	II	III	IV
Chiang Mai	1.437	1.915	1.764	1.053	1.564	1.743	1.780	1.029	1.832	1.724	1.839	1.103
Bangkok	1.518	1.524	3.089	0.975	1.572	1.516	1.526	0.999	1.578	1.645	1.650	1.025
Ratchaburi	1.695	1.693	1.592	1.161	1.647	1.712	1.606	1.110	1.704	1.680	1.646	1.175
Songkhla	1.697	1.633	1.671	0.913	1.694	1.684	1.536	1.121	1.698	1.745	1.738	1.229
Nakhon Ratchasima	1.109	1.463	1.538	1.033	1.503	1.492	1.552	1.086	1.559	1.611	1.540	1.073
Chon Buri	1.464	1.552	1.558	1.059	1.588	1.586	1.523	1.100	1.739	1.586	1.541	1.126

Table 7 LCOE (USD/kWh) of different ORC system capacity integrated by different collectors by area when the investment cost of solar collectors is subsidized by 80 percent and the capital cost of the ORC power plant is set around 1000 USD/kW_e.

Province	FP-SORC				ET-SORC				CPC-SORC			
	I	II	III	IV	I	II	III	IV	I	II	III	IV
Chiang Mai	0.613	0.912	0.809	0.459	0.628	0.699	0.720	0.410	0.812	0.676	0.745	0.456
Bangkok	0.660	0.659	0.633	0.404	0.604	0.555	0.641	0.378	0.587	0.685	0.686	0.389
Ratchaburi	0.807	0.784	0.684	0.475	0.657	0.677	0.592	0.433	0.640	0.639	0.601	0.466
Songkhla	0.786	0.670	0.688	0.418	0.639	0.691	0.524	0.425	0.604	0.657	0.702	0.469
Nakhon Ratchasima	0.431	0.613	0.674	0.445	0.544	0.557	0.636	0.422	0.566	0.668	0.633	0.410
Chon Buri	0.618	0.657	0.703	0.449	0.584	0.581	0.606	0.426	0.654	0.577	0.559	0.428

Table 8 Suitable numbers of solar collectors and the maximum power output of the system configurations in each month (Jan to Dec) by area.

Province	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
	Power output (MWh/Year)												
Chiang Mai (ET-SORC-IV)	17.64	17.83	17.88	17.14	13.91	10.31	11.99	12.44	14.08	15.16	16.72	17.78	182.89
Bangkok (FP-SORC-IV)	14.02	14.95	15.63	14.62	14.01	12.63	10.42	11.57	11.75	12.55	14.36	15.37	161.86
Ratchaburi (ET-SORC-IV)	17.13	16.80	15.54	14.82	12.18	12.00	11.98	10.49	9.79	13.78	13.55	14.24	162.31
Songkhla (FP-SORC-IV)	13.38	16.10	15.26	14.78	13.16	12.10	12.13	12.41	12.14	13.09	9.81	9.81	154.19
Nakhon Ratchasima (FP-SORC-IV)	13.53	15.59	13.76	13.08	11.86	12.62	12.21	10.41	11.33	12.47	14.09	14.39	155.35
Chon Buri (FP-SORC-IV)	14.50	15.07	15.52	13.69	11.80	12.59	10.41	11.35	11.63	13.56	13.23	13.36	156.70
Number of solar collectors (Units)													
Chiang Mai (ET-SORC-IV)	1160	910	1080	1160	1510	2000	1820	1760	1460	1310	1230	1230	
Bangkok (FP-SORC-IV)	1420	1340	1320	1360	1400	1580	1930	1860	1830	1550	1210	1210	
Ratchaburi (ET-SORC-IV)	1110	980	1210	1270	1710	1830	1740	1930	1940	1330	1330	1330	
Songkhla (FP-SORC-IV)	1490	1080	1270	1320	1560	1690	1670	1680	1650	1430	1980	1980	
Nakhon Ratchasima (FP-SORC-IV)	1210	1050	1240	1300	1510	1430	1450	1710	1640	1310	1110	1110	
Chon Buri (FP-SORC-IV)	1250	1090	1090	1330	1620	1480	1830	1760	1640	1200	1290	1290	

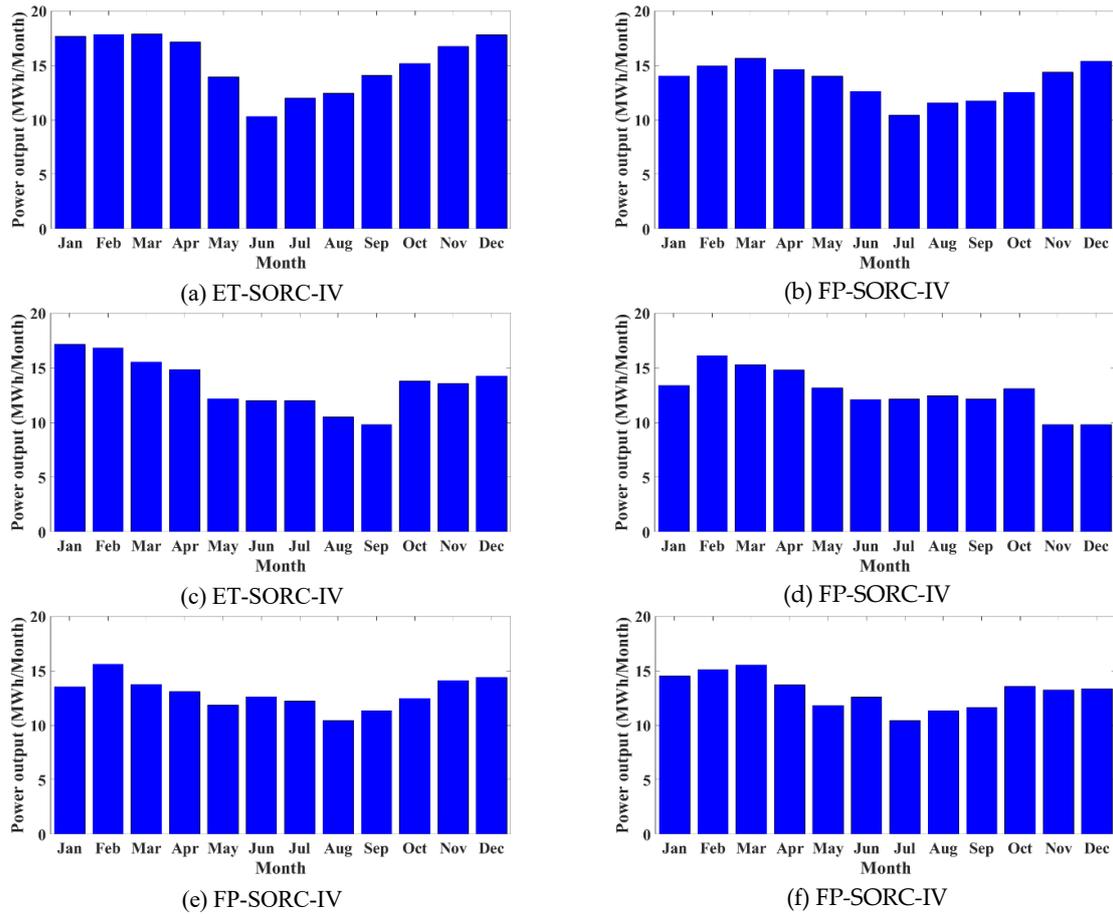


Fig. 9 Maximum power output of the system configurations (MWh/Month) in each month in the six areas of Thailand: (a) Chiang Mai, (b) Bangkok, (c) Ratchaburi, (d) Songkhla, (e) Nakhon Ratchasima, and (f) Chon Buri.

5. Conclusion

This study investigated the viability of small-scale SORC power plants with low-temperature heat ($< 100\text{ }^{\circ}\text{C}$). The solar collectors used for hot water production before supplying it to the ORC power plants consisted of Flat-Plate (FP), Evacuated-Tube (ET), and Compound Parabolic Concentrating (CPC) solar collectors. Systems were mathematically modelled and simulated under the climate conditions of Chiang Mai, Bangkok, Ratchaburi, Songkhla, Nakhon Ratchasima, and Chonburi, to conduct an investigation of the maximum power output, and an economic analysis in terms of levelized cost of electricity (LCOE). The results are summarized below.

- A small-scale ORC power plant is appropriate for a heat source producing temperature below $100\text{ }^{\circ}\text{C}$, and that the ORC system is a good solution for power generation using low-temperature heat source. The maximum power output and the LCOE of the ORC systems investigated are summarized as follows:
 - In Chiang Mai (representing the northern part of Thailand), the lowest LCOE was 1.029 USD/kWh, and the systems produced a maximum power output of 166.13 MWh/Year, which required 1980 unit of ET collectors. This happened when the systems were combined with one unit of a 60 kW_e ORC system and TES-I size of 50000 liters.
 - In Bangkok (representing the central part of Thailand), the lowest LCOE was 0.975 USD/kWh, and the system produced a maximum power output of 125.03 MWh/Year, which required 2000 unit of FP collectors. This happened when the systems were combined with one unit of a 60 kW_e ORC system and size TES-I size of 50000 liters.
 - In Ratchaburi (representing the western part of Thailand), the lowest LCOE was 1.110 USD/kWh, and the systems produced a maximum power output of 153.30 MWh/Year, which

- required 2000 units of ET collectors. This happened when the systems were combined with one unit of a 60 kW_e ORC system and TES-I size of 50000 liters.
- In Songkhla (representing the southern part of Thailand), the lowest LCOE was 0.913 USD/kWh, and the systems produced a maximum power output of 144.09 MWh/Year, which required 2000 units of FP collectors. This happened when the systems were combined with one unit of a 60 kW_e ORC system and TES-I size of 50000 liters.
 - In Nakhon Ratchasima (representing the north-eastern part of Thailand), the lowest LCOE was 1.033 USD/kWh, and the systems produced a maximum power output of 120.77 MWh/Year, which required 1990 units of FP collectors. This happened when the systems were combined with one unit of a 60 kW_e ORC system and TES-I size of 50000 liters.
 - In Chon Buri (representing the eastern part of Thailand), the lowest LCOE was 1.059 USD/kWh, and the systems produced a maximum power output of 116.90 MWh/Year, which required 2000 units of FP collectors. This happened when the systems were combined with one unit of a 60 kW_e ORC system and TES-I size of 50000 liters.
- The systems can be more viable if the government provides support by subsidizing the investment cost of the solar collectors by 80 percent with the capital cost of the ORC system set around 1000 USD/kW_e.
 - In Chiang Mai Province when the CPC solar collectors were combined with one unit of a 60 kW_e ORC power generation. The highest power output the system could generate was 182.89 MWh/Year, and the monthly maximum power output from January to December were, respectively, as follows: 17.64, 17.83, 17.88, 17.14, 13.91, 10.31, 11.99, 12.44, 14.08, 15.16, 16.72, and 17.78 MWh/Month, respectively. The suitable number of CPC collectors for each month would need to be 1160, 910, 1080, 1160, 1510, 2000, 1820, 1760, 1460, 1310, 1230, and 1230 units, respectively.

In future works, investigation can be done if proposed systems, integrated with other renewable energy systems such as biomass, to allow for 24-hour operation, might work economically and attract interest.

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