Small-scale Solar Organic Rankine Cycle Power Plant: A Simplified Formula to Estimate the Power Output of Six Areas in Thailand

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ABSTRACT

In this study, the concept of a small-scale Solar Organic Rankine Cycle (SORC) system for power generation with temperature below 100 °C was proposed. The system was analyzed by using three different capacities (20, 40, and 60 kW_e) of the ORC system with R245fa in combination with solar water heating system (SWHW), using four different models (SORC-I, SORC-II, SORC-III, and SORC-IV). Each type of flat-plate (FP), evacuated-tube (ET), and compound parabolic concentrator (CPC) solar collectors was connected in parallel between 100 and 1200 units. These systems were mathematically modeled and simulated to evaluate maximum power output, CO_2 emission, and economic analysis in terms of levelized cost of electricity (LCOE). The six areas consisting of Chiang Mai, Bangkok, Ratchaburi, Songkhla, Nakhon Ratchasima, and Chonburi represented as the north, central, west, south, north-east and east part of Thailand respectively were selected as the source of weather data of the simulations. The results showed that, without initial investment of collectors, the LCOE of the SORC power plant in Chon Buri represented as the east part of Thailand was the lowest at 0.187 USD/kWh, with power output of 123.2 MWh/Year, and reduce CO_2 emission of 61.2 Ton CO_2 eq./Year, using 1000 units of ET collectors combined with one unit of a 60 kW_e ORC. With initial investment of collectors, the LCOE of the SORC power plant of Bangkok represented as the central part of Thailand was the lowest at 0.626 USD/kWh, with power output of 121.3 MWh/Year, and reduced CO_2 emission of 60.3 Ton CO_2 eq./Year, using 950 units of ET collectors combined with one unit of a 60 kW_e ORC.

Keywords: Electrical power generation, Levelized cost of electricity (LCOE), Solar collectors, Solar Organic Rankine Cycle (SORC) system

INTRODUCTION

Thailand is considered as one of the countries with the highest average of total solar radiation, but its annual direct normal solar radiation is low, within the range of 1350 – 1400 kWh/m^2-year (DEDE, 2017), which is insufficient for Concentrating Solar Power (CSP) technology. In recent years, power systems with small-scale

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Organic Rankine Cycle (ORC) have drawn more attention because they require low-temperature heat source, have high efficiency, small impact on environment (Wang et al., 2014), and active way of converting solar thermal energy into electricity (Mavrou et al., 2015). Furthermore the ORC power technology is suitable for decentralized small-scale power plant (Garg et al., 2016; Quoilin and Lemort, 2009; Sylvain et al., 2013). For solar water heating system (SWHS) combined with the ORC power generation Wang et al. (Wang et al., 2014) proposed a Solar Organic Rankine Cycle (SORC) system, with compound parabolic concentrator (CPC) collectors. Tchanche et al. (Tchanche et al., 2009) studied a 2 kW SORC power generation from hot water with temperature around 90℃ as heat source. Sonsaree et al. (Sonsaree et al., 2016, 2017a, b) presented a combination of vapor compression heat pump (VCHP), solar collector and an ORC power system. The results of these studies showed that power systems can be more effective when large amount of waste heat and a large number of solar collectors are already installed.

From the literature review above, it can be noted that the CSP technologies are inappropriate in Thailand's context. Despite the fact that the ORC system has been extensively applied for power generation from low-temperature heat source, there are only few ones designed with solar collectors to utilize thermal energy with temperature lower than 100℃. The main objectives of this research are to:

- Develop a mathematical model and simulate the performance of a small-scale SORC power generation system based on power output, CO_2 emission, and economic analysis in terms of levelized cost of electricity (LCOE),
- Compare the performance of the power generation system integrated with three types of solar collectors consisting of flat-plate (FP), evacuated-tube (ET) and compound parabolic concentrator (CPC) used for hot water production,
- Obtain the optimal flow rate of hot water for maximum power output,
- Create a simplified formula to find the power of each area of stationary solar collectors.

SYSTEM SIMULATION AND DESCRIPTIONS

The main components of a small-scale SORC power system shown in Figure 1 are the solar collectors, the ORC system, the cooling tower, and the collector pump. In the system operation: the outlet hot water from the ORC system ($T_{ORC,o}$) *(temperature of hot water is lower than the collectors outlet or the ORC inlet hot water temperature ($T_{Coll,o}$ or $T_{ORC,i}$))* is pumped by the collector pump, to the solar collector field to produce increased temperature of hot water *(temperature of hot water is higher than the collectors inlet or the ORC outlet hot water temperature ($T_{Coll,i}$ or $T_{ORC,o}$)).* At this step, the hot water flow rate ($\dot{m}_{ORC}$) is adjusted to achieve a high-temperature hot water in the range of 70 – 95℃. After that, the outlet hot water from the solar collector field ($T_{Coll,o}$) is supplied to the ORC for power generation.

In this study, the system performance was analyzed based on two capacities for the ORC system (20 and 60 kW_e) combined in four different configurations with three types of stationary solar collectors (CPC, ET, and FP solar collectors). The testing configurations are as follows: (i) solar collectors integrated with one unit of a 20 kW_e (SORC-I), (ii) solar collectors integrated with two units of a 20 kW_e (SORC-II), (iii) solar collectors integrated with three units of a 20 kW_e (SORC-III), and (iv) solar collectors integrated with one unit of a 60 kW_e (SORC-IV). These configurations which are shown in Figure 2.

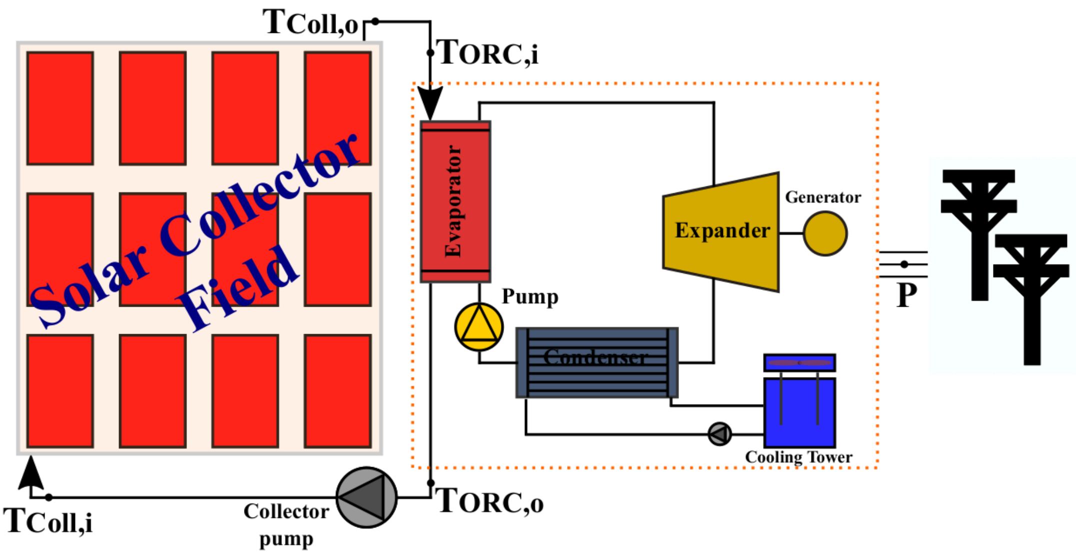


Figure 1. Schematic diagram of the proposed system.

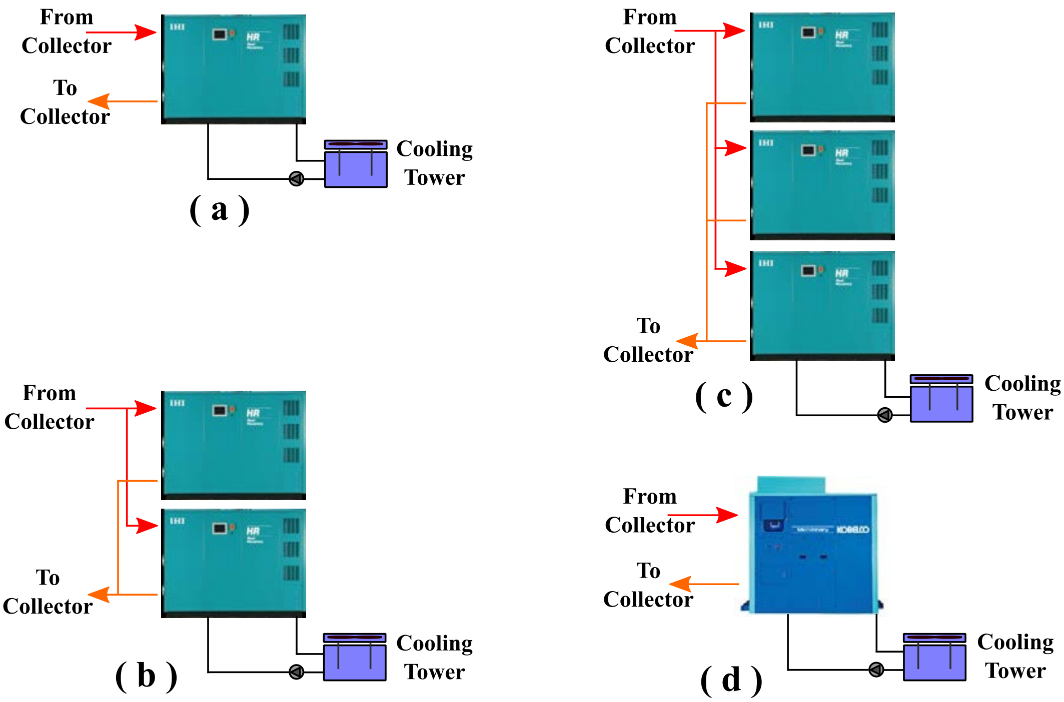


Figure 2. (a) Solar collectors integrated with one unit of a 20 kW_e (SORC-I), (b) Solar collectors integrated with two units of a 20 kW_e (SORC-II), (c) Solar collectors integrated with three units of a 20 kW_e (SORC-III), and (d) Solar collectors integrated with one unit of a 60 kW_e (SORC-IV).

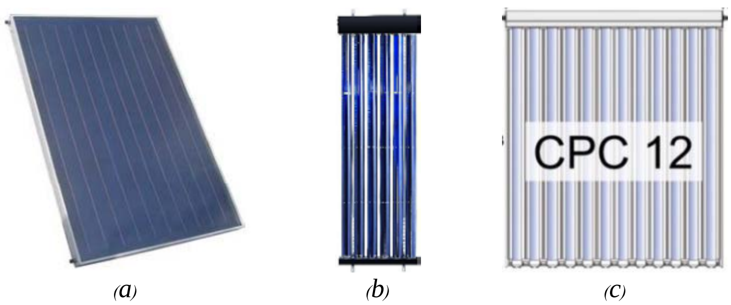


Figure 3. (a) FP solar collectors; Model: Superline M-1 FSB PU from Ezince Company (Ezinc, 2017), (b) ET solar collectors; Model: DF120/6 from EuroSun Solar system GmBH (GlobalMarket, 2017), and (c) CPC solar collectors; Model: CPC12 from Solar bayer Company (Solarbayer, 2017).

Solar collectors

Based on Figure 1, the water passing through the solar collectors absorbs heat from solar energy and is then directly supplied to the ORC system for power generation (Sonsaree et al., 2017b). The energy equations from the solar collectors could be calculated as follows:

- The solar collector efficiency (η_{Coll}):

$$\eta_{Coll} = F_R(\tau\alpha)_e - F_R U_L \left(T_{Coll,i} - T_{Amb}\right)/I_T \qquad (1)$$

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

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

Where T_{Amb} is the ambient temperature, and I_T is the solar radiation.

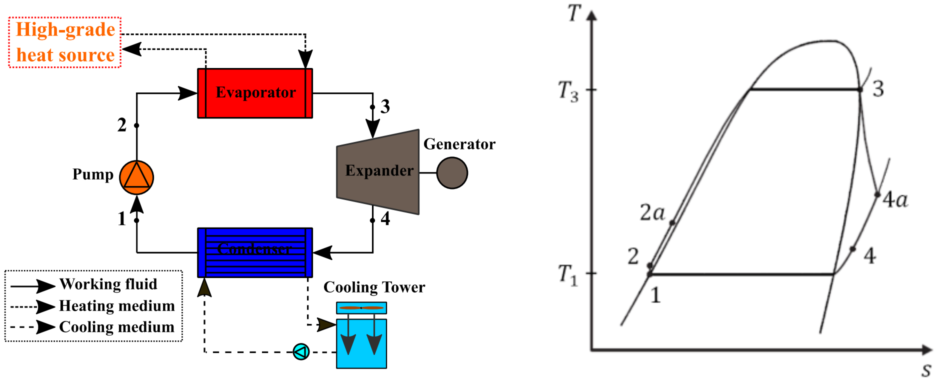
In this study, 100 to 2000 units (in 50 units increment) of FP, ET, and CPC solar collectors connected in parallel were used for hot water production as shown in Figure 3, having optical efficiency ($F_R(\tau\alpha)_e$) of 0.747, 0.572, 0.623, overall heat transfer coefficient ($F_R U_L$) of 4.38, 0.75, 1.30 W/m^2-K, and collector area of 2.243, 2.369, 2.215 m^2 per unit (Gross area), respectively.

Organic Rankine Cycle (ORC)

ORC is an alternative technology applicable for a small-scale power generation. It is used for low-temperature heat recovery by converting low-temperature thermal energy to electricity. The ORC system has the same operating principle as that of the steam Rankine cycle but an organic working fluid is used instead of water. Historically the cycle has been employed for the conversion of heat from low-to-medium temperature source (e.g. solar, geothermal, biomass combustion, process waste heat), with systems being operational, often with little need for maintenance, over 2 – 3 decades (Freeman et al., 2015). Moreover, the ORC technology is well established worldwide with a number of commercial systems in operation, and typical sizes range from the order of a few kW to 10 MW for a wide range of working fluids and operating temperature (Vélez et al., 2012).

The ORC system mainly consists of a condenser, pump, evaporator, turbine expander and generator. A schematic diagram of the ORC system and the corresponding T-s diagram are shown in Figure 4. At state 2, low-temperature heat transfer fluid (HTF) of the ORC system is heated by a heat source via a heat exchanger to state 3 at which the HTF turns into saturated vapor state with high pressure using an evaporator. From state 3 to 4, the vapor is expanded through a turbine expander to generate power. Finally, it is condensed to a saturated liquid in the condenser at state 1 to complete the cycle.

In this study, the performance characteristic of an ORC with capacity of 20 and 60 kW_e with R-245fa as working fluid (model: HR20W (IHI, 2017) in Table 13, and MB-70H (KOBELCO, 2017) in Table 14, respectively) was simulated to find the power output capabilities of the system.



(a) (b)

Figure 4. (a) Schematic diagram of the ORC system,
(b) T-s diagram of the ORC system (Sonsaree et al., 2017b).

Simulation conditions

In this study, the weather data from Chiang Mai (18.80 °N, 98.98 °E), Bangkok (13.75 °N, 100.52 °E), Ratchaburi (13.54 °N, 99.82 °E), Songkhla (13.54 °N, 99.82 °E), Nakhon Ratchasima (7.21 °N, 100.56 °E), and Chon Buri (13.75 °N, 100.52 °E) represent the north, central, west, south, north-east and east part of Thailand, respectively (Sonsaree et al., 2017b), were taken as input data for system simulations. This is shown in Figure 5. Moreover, Hourly global radiation estimation based on the studies of Duffie JA and Bechman WA (JA and WA, 2013), and Zhang et al. (Zhang et al., 2017) was taken into account. The system was modeled and evaluated for an optimal flow rate of hot water for the maximum power output.

The calculation step is presented in Figure 6. The hot water flow rate (Ton/h) from the performance characteristics of the ORC power generation shown in Table 13 (a 20 kW_e ORC from IHI Company) and Table 14 (a 60 kW_e ORC form KOBELCO Company) were obtained. In order to obtain the optimal hot water flow rate supplied to the solar collector field, flow rate was varied between the minimum and maximum ($\dot{m}_{ORC,k}, \dots, \dot{m}_{ORC,max}$) amount allowed by the ORC system. For the systems at hand it would be a flow rate of 12 to 28 Ton/h for a 20 kW_e ORC from IHI Company, and 25 to 75 Ton/h for a 60 kW_e ORC from KOBELCO Company. The increments were in the order of 1 Ton/h.

At this step, it is also possible to calculate the heat input to the ORC system ($\dot{Q}_{ORC}$) and the collectors outlet or the ORC inlet hot water temperature ($T_{Coll,o}$ or $T_{ORC,i}$) from the hot water flow rate obtained. To find out the power output (kW$_e$) of the system, interpolation of the data presented in the performance characteristics of the ORC power generation (Table 13 and Table 14) was used in combination with the hot water flow rate and temperature found in the previous step, and the cooling water temperature (°C) (equal to ambient temperature (T_{Amb}) in this study). Then, the system simulation selected the hot water flow rate that would achieve the highest power output during the system operation. At this step, the highest power output was also selected. Finally, the ORC outlet or the collectors inlet hot water temperature ($T_{ORC,o}$ or $T_{Coll,i}$) was supplied to the solar collector field to start the next cycle. During the simulations, heat loss from the system such as the piping system was neglected. Besides that, the power input of the collector pump as shown in Figure 1 was neglected. The thermodynamic properties of the HTF were calculated by REFPROP NIST7.0 (NIST, 2000).

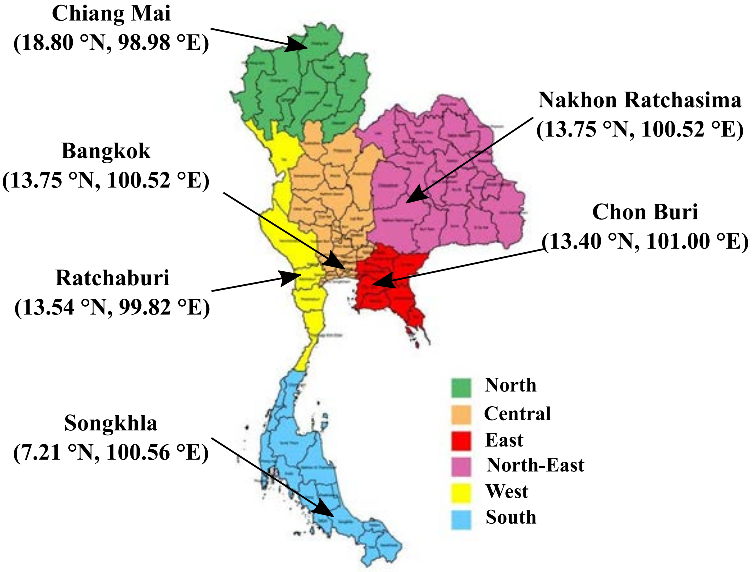


Figure 5. The location of Chiang Mai, Bangkok, Ratchaburi, Songkhla, Nakhon Ratchasima, and Chon Buri (Sonsaree et al., 2017b).

ECONOMIC ANALYSIS

In the present study, economic analysis in terms of levelized cost of electricity (LCOE) was done following the methodology presented in the work of Sonsaree et al. (Sonsaree et al., 2017b), which could be calculated by:

$$LCOE = \left[\mathrm{c} \times (C_{Invest}) + \dot{C}_{O\&M}\right] / Annual\ Power\ Output \quad (3)$$

$$c = [i_d(1+i_d)^n]/[(1+i_d)^n - 1] + k_{insurance} \quad (4)$$

Where C_{Invest} is the investment cost (USD), and $\dot{C}_{O\&M}$ is the operation and maintenance cost (USD/Year). In this assessment, the investment cost of the ORC power plant was set at around 2500 USD/kW$_e$ (Sonsaree et al., 2017b). The initial conditions of the system are shown in Table 1.

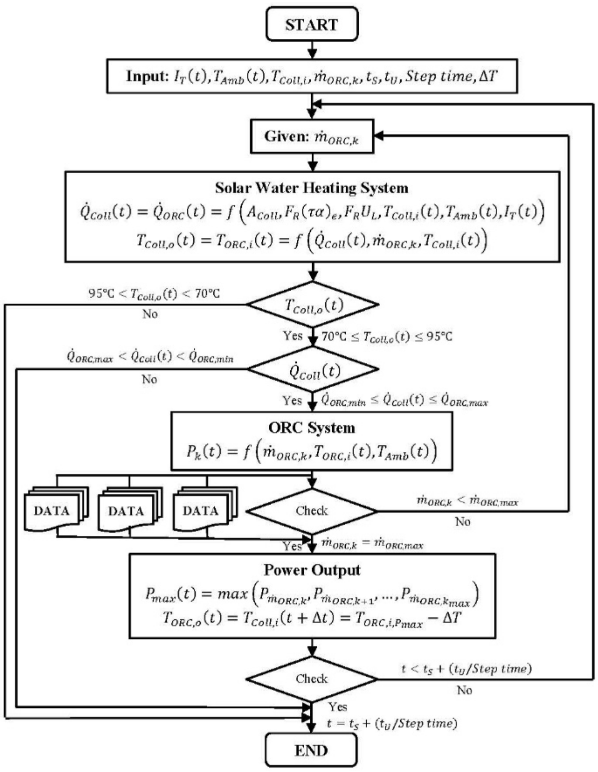


Figure 6. Step to evaluate the maximum power output with the optimal hot water flow rate.

Table 1. Initial condition of the ORC system.

Descriptions	**Data**
Operation day, (day/year)	353
Cost of solar collectors (USD/m^2)	
FP collectors	112.3
ET collectors	154.4
CPC 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

RESULTS AND DISCUSSION

In this study, a small-scale SORC power plant with low-temperature heat (<100 ˚C) was proposed and investigated. Four different ORC capacities with different collectors (FP, ET, and CPC collectors) ware designed as (i) SORC-I, (ii) SORC-II, (iii) SORC-III, and (iv) SORC-IV. Their performances in six areas in Thailand were mathematically evaluated in terms of power output, environmental impact, and LCOE as shown in the following:

Power output

The maximum power output (MWh/Year) in the six selected areas in Thailand having different ORC capacities (SORC-I, SORC-II, SORC-III, and SORC-IV) with different solar collectors are shown in Table 2. It was found that the higher the capacities of the ORC system the more electricity of a system were generated. In addition, the maximum power output of ORC power system was found to be dependent on the appropriated number of solar collectors as shown in Table 3. It was also revealed that the system configuration in Chiang Mai, Bangkok, Ratchaburi, Songkhla, Nakhon Ratchasima, and Chon Buri could produce the maximum power output based on the suitable numbers of collectors as follows: 110.6 MWh/Year and 850 units of ET collectors (SORC-IV), 121.3 MWh/Year and 950 units of ET collectors (SORC-IV), 108.9 MWh/Year and 950 units of ET collectors (SORC-IV), 114.7 MWh/Year and 1000 units of ET collectors (SORC-IV), 121.2 MWh/Year and 950 units of ET collectors (SORC-IV), and 123.2 MWh/Year and 1000 units of ET collectors (SORC-IV), respectively.

Figure 7 presents an example fluctuation of the hourly hot water flow rate (kg/s), hot water temperature (˚C), and power output (kW$_e$) versus the time and months at Chon Buri area from the ET-SORC-IV with 1000 units of the collectors. The results showed that when the systems obtained the optimal flow rate of hot water for maximum power output, the collector outlet temperature or the ORC inlet hot water temperature could be maintained at around 95 ˚C during the system operation.

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

Province	I	II	III	IV	I	II	III	IV	I	II	III	IV
	FP-SORC				ET-SORC				CPC-SORC			
Chiang Mai	17.1	38.1	57.1	76.1	28.9	59.9	93.3	110.6	24.2	56.0	84.6	101.8
Bangkok	22.6	48.5	74.7	89.8	31.2	72.0	108.0	121.3	29.8	69.7	102.2	114.8
Ratchaburi	17.8	36.7	54.6	70.0	25.3	62.3	93.4	108.9	17.8	57.5	83.2	100.2
Songkhla	23.4	45.1	60.5	81.0	32.5	67.9	104.3	114.7	23.4	63.8	95.6	111.2
Nakhon Ratchasima	24.7	49.3	74.0	86.4	30.5	71.3	107.0	121.2	24.7	67.3	102.3	113.2
Chon Buri	23.6	51.3	70.9	88.4	29.3	73.9	108.4	123.2	34.8	69.6	104.4	116.1

Table 3. Suitable number of solar collectors (Units) at six areas in Thailand.

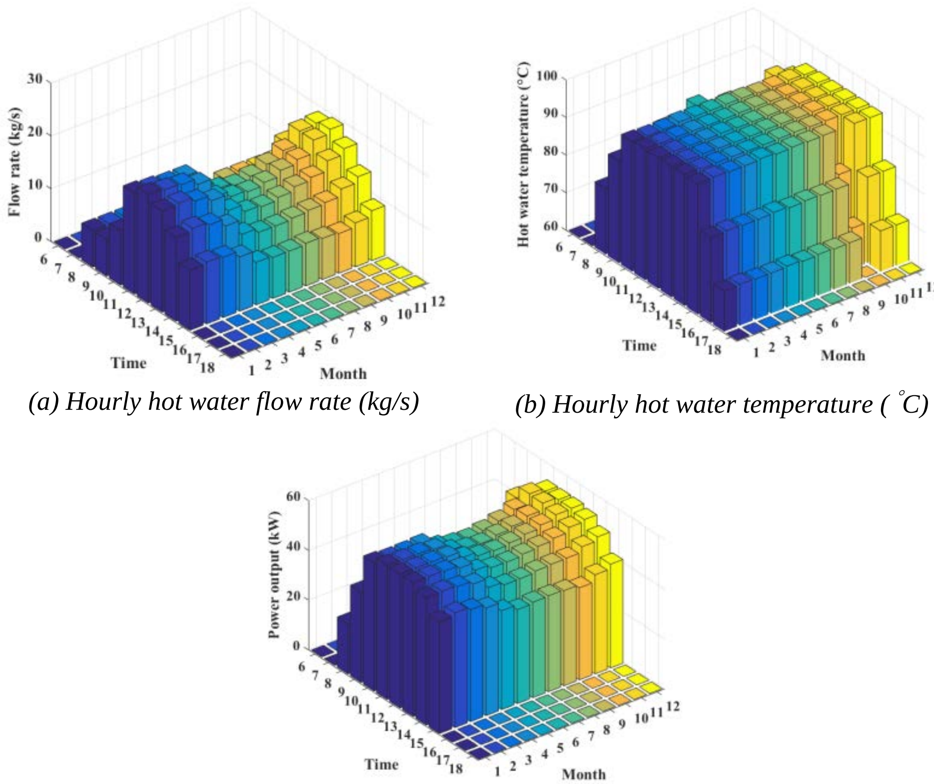
Province	I	II	III	IV	I	II	III	IV	I	II	III	IV
	FP-SORC				ET-SORC				CPC-SORC			
Chiang Mai	400	700	1050	950	300	650	950	850	400	700	1000	900
Bangkok	400	750	1150	1050	300	700	1050	950	400	750	1100	1000
Ratchaburi	400	850	1150	1050	400	700	1050	950	400	750	1150	1000
Songkhla	600	900	1200	1200	400	750	1150	1000	600	800	1200	1100
Nakhon Ratchasima	400	800	1200	1050	300	700	1050	950	400	750	1150	1000
Chon Buri	400	850	1200	1150	400	750	1100	1000	400	800	1200	1050

Table 4. CO_2 emission (Ton CO_2 eq./Year) of different ORC system capacity integrated by different collectors at six areas in Thailand.

Province	I	II	III	IV	I	II	III	IV	I	II	III	IV
	FP-SORC				ET-SORC				CPC-SORC			
Chiang Mai	8.5	18.9	28.4	37.8	14.3	29.8	46.4	55.0	12.0	27.8	42.0	50.6
Bangkok	11.3	24.1	37.1	44.6	15.5	35.8	53.7	60.3	14.8	34.6	50.8	57.1
Ratchaburi	8.8	18.3	27.1	34.8	12.6	31.0	46.4	54.1	8.8	28.6	41.3	49.8
Songkhla	11.6	22.4	30.1	40.2	16.2	33.7	51.8	57.0	11.6	31.7	47.5	55.3
Nakhon Ratchasima	12.3	24.5	36.9	42.9	15.1	35.5	53.2	60.2	12.3	33.4	50.9	56.3
Chon Buri	11.7	25.5	35.2	44.0	14.5	36.7	53.9	61.2	17.3	34.6	51.9	57.7

Environment evaluation

To estimate CO_2 emission, carbon dioxide intensity factor in Thailand which is 0.497 kg CO_2 eq./kWh (EPPO, 2017b) was considered. The results found that, the quality of CO_2 emission of the system can could be reduced depending on the amount of electricity production. The power output in Table 2 could provide estimates of CO_2 emission (by multiplying the carbon dioxide intensity factor) as shown in Table 4. It also showed that the system configuration in Chiang Mai, Bangkok, Ratchaburi, Songkhla, Nakhon Ratchasima, and Chon Buri could reduce the maximum CO_2 emission based on the suitable number of solar collectors as follows: 55.0, 60.3, 54.1, 57.0, 60.2, and 61.2 Ton CO_2 eq./Year, respectively.



(a) Hourly hot water flow rate (kg/s) *(b) Hourly hot water temperature (°C)*

(c) Hourly power output (kWe)

Figure 7. Hourly hot water flow rate (kg/s), hot water temperature (°C), and power output (kW_e) of the ET-SORC-IV at Chon Buri: 1000 units of ET collectors combined with one unit of a 60 kW_e ORC system.

Economic evaluation

The levelized cost of electricity (LCOE) was assessed in two cases: with and without initial investment of solar collectors. These are explained below.

1) Without initial investment of collectors: In this calculation, the objective is to determine the appropriate ORC capacity for maximum power generation when the collector investment is not taken into account. Based on Table 5, results showed that the LCOE of Chiang Mai, Bangkok, Ratchaburi, Songkhla, Nakhon Ratchasima, and Chonburi was at the lowest of 0.209, 0.190, 0.212, 0.201, 0.190, and 0.187 USD/kWh, which requires 850 units of ET collectors (SORC-IV), 950 units of ET collectors (SORC-IV), 950 units of ET collectors (SORC-IV), 1000 units of ET collectors (SORC-IV), 950 units of ET collectors (SORC-IV), and 1000 units of ET collectors (SORC-IV), respectively.

2) With initial investment of collectors: In this calculation, the initial investment of collectors was considered for a small-scale SORC power system. From Table 6, the results showed that, the LCOE of Chiang Mai, Bangkok, Ratchaburi, Songkhla, Nakhon Ratchasima, and Chonburi was at the lowest of 0.641, 0.626, 0.702, 0.686, 0.631, and 0.639 USD/kWh, which requires 850 units of ET collectors (SORC-IV), 900 units of ET collectors (SORC-IV), 950 units of ET collectors (SORC-IV), 900 units of ET collectors (SORC-IV), 950 units of ET collectors (SORC-IV), and 950 units of ET collectors (SORC-IV), respectively.

Table 5. LCOE (USD/kWh) of different ORC system capacity integrated by different collectors at six areas in Thailand *(without initial investment of collectors)*.

Province	I	II	III	IV	I	II	III	IV	I	II	III	IV
	FP-SORC				ET-SORC				CPC-SORC			
Chiang Mai	0.449	0.404	0.404	0.303	0.266	0.257	0.247	0.209	0.318	0.275	0.273	0.227
Bangkok	0.340	0.317	0.309	0.257	0.247	0.214	0.214	0.190	0.258	0.221	0.226	0.201
Ratchaburi	0.432	0.419	0.423	0.329	0.304	0.247	0.267	0.212	0.432	0.267	0.277	0.230
Songkhla	0.329	0.341	0.381	0.285	0.236	0.227	0.221	0.201	0.329	0.241	0.241	0.266
Nakhon Ratchasima	0.312	0.312	0.312	0.267	0.252	0.216	0.216	0.190	0.312	0.229	0.225	0.204
Chon Buri	0.325	0.300	0.325	0.261	0.263	0.208	0.213	0.187	0.221	0.221	0.221	0.199

Table 6. LCOE (USD/kWh) of different ORC system capacity integrated by different collectors at six areas in Thailand *(with initial investment of the collectors).*

Province	**I**	**II**	**III**	**IV**	**I**	**II**	**III**	**IV**	**I**	**II**	**III**	**IV**
	FP-SORC				**ET-SORC**				**CPC-SORC**			
Chiang Mai	1.159	1.064	1.064	0.752	0.851	0.851	0.820	0.641	1.212	1.063	1.044	0.804
Bangkok	0.975	0.873	0.862	0.677	0.788	0.761	0.761	0.626	1.046	0.924	0.928	0.770
Ratchaburi	1.241	1.215	1.180	0.868	1.023	0.879	0.917	0.702	1.901	1.119	1.146	0.880
Songkhla	1.093	1.058	1.093	0.818	0.928	0.848	0.842	0.686	1.675	1.060	1.060	0.891
Nakhon Ratchasima	0.894	0.894	0.894	0.704	0.806	0.768	0.768	0.631	1.370	0.956	0.947	0.780
Chon Buri	0.933	0.895	0.933	0.727	0.847	0.779	0.784	0.639	0.971	0.968	0.971	0.789

From previous evaluations, when the initial investment of collectors for ORC power systems was included and not included, the LCOE ranged between 0.626 – 1.901 USD/kWh, and 0.187 – 0.448 USD/kWh, respectively. On the other hand, if CSP and Photovoltaic technologies were applied for electrical power, the LCOE was between 0.140 – 0.360 USD/kWh, and between 0.250 – 0.710 USD/kWh, respectively. Therefore, a small-scale SORC power plant without investment of collectors is economically attractive due to low LCOE. In other words, the system could be developed and become more profitable when the systems are subsidized by the government.

A simplified formula

In this study, a simplified formula to estimate the power output of a small-scale SORC power plant in each area can be created as follows:

$$P_{SORC} = a + bN_{Coll} + cN_{Coll}^2 + dN_{Coll}^3 + eN_{Coll}^4 + fN_{Coll}^5 \quad (5)$$

When

$$a = A_o + A_1\eta_{SORC} + A_2\eta_{SORC}^2 + A_3\eta_{SORC}^3 + A_4\eta_{SORC}^4 + A_5\eta_{SORC}^5$$
$$b = B_o + B_1\eta_{SORC} + B_2\eta_{SORC}^2 + B_3\eta_{SORC}^3 + B_4\eta_{SORC}^4 + B_5\eta_{SORC}^5$$
$$c = C_o + C_1\eta_{SORC} + C_2\eta_{SORC}^2 + C_3\eta_{SORC}^3 + C_4\eta_{SORC}^4 + C_5\eta_{SORC}^5$$
$$d = D_o + D_1\eta_{SORC} + D_2\eta_{SORC}^2 + D_3\eta_{SORC}^3 + D_4\eta_{SORC}^4 + D_5\eta_{SORC}^5$$
$$e = E_o + E_1\eta_{SORC} + E_2\eta_{SORC}^2 + E_3\eta_{SORC}^3 + E_4\eta_{SORC}^4 + E_5\eta_{SORC}^5$$
$$f = F_o + F_1\eta_{SORC} + F_2\eta_{SORC}^2 + F_3\eta_{SORC}^3 + F_4\eta_{SORC}^4 + F_5\eta_{SORC}^5$$

Where P_{SORC} is the power output (MWh/Year), η_{SORC} is the overall system efficiency (%), which is the maximum power output that a system can generate divided by the thermal energy input depending on the number of solar collectors (Unit), solar collectors area (A_{Coll}), and solar radiation (I_T). In Equation (5) the amount of the solar collectors (N_{Coll}) varies from 200 to 1200 units, and the overall system efficiency (η_{SORC}) in each area are as follows:

1) Chiang Mai: the overall system efficiency (η_{SORC}) varies from 9.26 to 18.96, and the variables A_0, A_1, …, A_5 to F_0, F_1, …, F_5 are shown in Table 7

2) Bangkok: the overall system efficiency (η_{SORC}) varies from 11.05 to 19.24, and the variables A_0, A_1, …, A_5 to F_0, F_1, …, F_5 are shown in Table 8.

3) Ratchaburi: the overall system efficiency (η_{SORC}) varies from 8.07 to 16.45, and the variables A_0, A_1, …, A_5 to F_0, F_1, …, F_5 are shown in Table 9.

4) Songkhla: the overall system efficiency (η_{SORC}) varies from 8.58 to 16.47, and the variables A_0, A_1, …, A_5 to F_0, F_1, …, F_5 are shown in Table 10.

5) Nakhon Ratchasima: the overall system efficiency (η_{SORC}) varies from 10.49 to 17.75, and the variables A_0, A_1, …, A_5 to F_0, F_1, …, F_5 are shown in Table 11.

6) Chonburi: the overall system efficiency (η_{SORC}) varies from 8.58 to 16.47, and the variables A_0, A_1, …, A_5 to F_0, F_1, …, F_5 are shown in Table 12.

Table 7. Value of variables A to F *(Chiang Mai)*.

	A	*B*	*C*	*D*	*E*	*F*
0	750339.96435	-268250.21268	37700.177732	-2612.2841272	89.490091202	-1.21511236
1	-8657.7006301	3103.0570776	-437.24925307	30.374297134	-1.0429498945	$1.4189389986\times10^{-2}$
2	37.181140446	-13.353395279	1.8853323556	$-1.3119757996\times10^{-1}$	0.0045111183607	$-6.1430527871\times10^{-5}$
3	-0.072393853342	0.026048848325	$-3.6845399973\times10^{-3}$	$2.5682740307\times10^{-4}$	$-8.8427418834\times10^{-6}$	$1.2053284731\times10^{-7}$
4	$6.3428673485\times10^{-5}$	$-2.2859840967\times10^{-5}$	$3.2386646960\times10^{-6}$	$-2.2608702993\times10^{-7}$	$7.7944767460\times10^{-9}$	$-1.0635517958\times10^{-10}$
5	$-2.0224613813\times10^{-8}$	$7.2986434698\times10^{-9}$	$-1.0354168737\times10^{-9}$	$7.2373515223\times10^{-11}$	$-2.4980046714\times10^{-12}$	$3.4118948502\times10^{-14}$

Table 8. Value of variables A to F *(Bangkok)*.

	A	*B*	*C*	*D*	*E*	*F*
0	9020348.3899	-2925332.9500	375305.16221	-23843.731979	750.98958777	-9.3895042467
1	-153207.29359	50190.137384	-6508.7665969	418.17406077	-13.323116682	$1.6852219614\times10^{-1}$
2	830.51758806	-273.40727201	35.638068383	-2.3017145999	0.073721638807	$-9.3739994290\times10^{-4}$
3	-1.8386988179	0.60681408777	$-7.9302532987\times10^{-2}$	$5.1353615557\times10^{-3}$	$-1.6491511730\times10^{-4}$	$2.1024216706\times10^{-6}$
4	0.0017231366821	$-5.6939392019\times10^{-4}$	$7.4509618583\times10^{-5}$	$-4.8313916362\times10^{-6}$	$1.5535863336\times10^{-7}$	$-1.9831629172\times10^{-9}$
5	$-5.6942762376\times10^{-7}$	$1.8828642881\times10^{-7}$	$-2.4655622670\times10^{-8}$	$1.5998416274\times10^{-9}$	$-5.1480141519\times10^{-11}$	$6.5759234230\times10^{-13}$

Table 9. Value of variables A to F *(Ratchaburi)*.

	A	*B*	*C*	*D*	*E*	*F*
0	-561567.62685	230557.79518	-37061.838123	2919.8183469	-112.8493892	1.7136337670
1	6290.218011	-2583.0788435	415.32620785	-32.729915322	1.2654546688	$-1.9224774285\times10^{-2}$
2	-24.916242397	10.237791314	-1.6470552754	$1.2987186843\times10^{-1}$	$-5.0242387322\times10^{-3}$	$7.6373033133\times10^{-5}$
3	$4.4495724333\times10^{-2}$	$-1.8273668992\times10^{-2}$	$2.9379665996\times10^{-3}$	$-2.3147627548\times10^{-4}$	$8.94634388265\times10^{-6}$	$-1.3583953165\times10^{-7}$
4	$-3.6985856347\times10^{-5}$	$1.5177149279\times10^{-5}$	$-2.4377863849\times10^{-6}$	$1.9185888118\times10^{-7}$	$-7.40615080693\times10^{-9}$	$1.1230245307\times10^{-10}$
5	$1.1658032072\times10^{-8}$	$-4.7805028519\times10^{-9}$	$7.6725574347\times10^{-10}$	$-6.0334844744\times10^{-11}$	$2.3270814263\times10^{-12}$	$-3.5256420419\times10^{-14}$

Table 10. Value of variables A to F *(Songkhla)*.

	A	*B*	*C*	*D*	*E*	*F*
0	-2205856.4144	880034.88746	-138230.51036	10704.00291	-409.2086513	6.1862359996
1	22901.897289	-9151.9008190	1440.1297785	-111.73409545	4.2802458293	$-6.4843370279\times10^{-2}$
2	-82.353952703	32.992236484	-5.2058092557	$4.0507468631\times10^{-1}$	$-1.5564567818\times10^{-2}$	$2.3653224956\times10^{-4}$
3	$1.3694519545\times10^{-1}$	$-5.4976958378\times10^{-2}$	0.0086943687405	$-6.7814181769\times10^{-4}$	$2.6121376741\times10^{-5}$	$-3.9796531491\times10^{-7}$
4	$-1.0538676393\times10^{-4}$	$4.2357573592\times10^{-5}$	$-6.7070474846\times10^{-6}$	$5.2381246837\times10^{-7}$	$-2.0203294684\times10^{-8}$	$3.0820723122\times10^{-10}$
5	3.019714×10^{-8}	$-1.214058904\times10^{-8}$	1.922924139×10^{-9}	$-1.5021571534\times10^{-10}$	$5.7950007313\times10^{-12}$	$-8.8419529815\times10^{-14}$

Table 11. Value of variables A to F *(Nakhon Ratchasima)*.

	A	*B*	*C*	*D*	*E*	*F*
0	-4074920.1044	1425067.3164	-197299.24294	13527.604420	-459.60719788	6.1938728653
1	43601.098071	-15255.053772	2113.0815112	-144.95575936	4.9275924409	$-6.6443349476\times10^{-2}$
2	-169.39308475	59.330830410	-8.2276268041	0.56507408336	$-1.9232374223\times10^{-2}$	$2.5965147913\times10^{-4}$
3	0.30456233534	$-1.0677880567\times10^{-1}$	0.014822812045	$-1.0191513610\times10^{-3}$	$3.4727083360\times10^{-5}$	$-4.6940832021\times10^{-7}$
4	$-2.5669177883\times10^{-4}$	$9.0040525289\times10^{-5}$	$-1.2505966431\times10^{-5}$	$8.6035388691\times10^{-7}$	$-2.9334451406\times10^{-8}$	$3.9678106742\times10^{-10}$
5	$8.1991238317\times10^{-8}$	$-2.8761492847\times10^{-8}$	$3.9949650840\times10^{-9}$	$-2.7485492129\times10^{-10}$	$9.3723112184\times10^{-12}$	$-1.2678721718\times10^{-13}$

Table 12. Value of variables A to F *(Chon Buri)*.

	A	*B*	*C*	*D*	*E*	*F*
0	-8974892.6718	3248419.7611	-464541.15804	32829.167004	-1147.1508783	15.864479687
1	95094.606071	-34425.11471	4923.8657396	-348.03382145	12.16357318	-0.16824565452
2	-354.58684102	128.41000398	-18.373423147	1.2991722240	-4.5421985744×10^{-2}	6.2849874923×10^{-4}
3	6.0084527104×10^{-1}	-2.1766030660×10^{-1}	0.031153985197	-2.2036036955×10^{-3}	7.7067944138×10^{-5}	-1.0667153828×10^{-6}
4	-4.7312252554×10^{-4}	1.7143417216×10^{-4}	-2.4543712107×10^{-5}	1.736471801×10^{-6}	-6.0745323358×10^{-8}	8.4098491688×10^{-10}
5	1.4057956197×10^{-7}	-5.0947538390×10^{-8}	7.2953012348×10^{-9}	-5.1623346901×10^{-10}	1.8061906712×10^{-11}	-2.5009629374×10^{-13}

Table 13. The performance characteristic of a 20 kW_e ORC; Model: HR20W (IHI, 2017).

Hot water flow rate (Ton/h)	**Cooling water temperature (°C)**	**Cooling water flow rate (40 Ton/h)**			
		Hot water temperature (°C)			
		95	**85**	**75**	**70**
28	20	20	18	12	9
	25	20	16	10	7
	30	20	13	8	6
20	20	20	16	10	8
	25	20	14	9	7
	30	17	12	7	5
12	20	17	12	8	6
	25	15	10	6	5
	30	13	9	5	4

Table 14. The performance characteristic of a 60 kW_e ORC; Model: MB-70H (KOBELCO, 2017).

Hot water flow rate (Ton/h)	**Cooling water temperature (°C)**	**Cooling water flow rate (120 Ton/h)**					
		Hot water temperature (°C)					
		95	**90**	**85**	**80**	**75**	**70**
75	15	60	55	47	39	32	24
	20	60	52	44	35	28	21
	25	57	49	40	32	24	17
	30	52	45	36	27	20	14
70	15	59	54	46	38	31	24
	20	59	51	43	35	27	20
	25	56	48	40	31	24	16
	30	51	43	35	27	20	13
60	15	58	51	44	38	31	24
	20	57	49	41	33	26	19
	25	54	46	38	30	23	16
	30	49	41	33	26	19	13
50	15	56	48	42	37	30	23
	20	55	48	40	32	25	18
	25	52	44	36	29	22	15
	30	42	34	28	22	16	11
40	15	51	44	39	33	27	21
	20	50	43	36	29	23	17
	25	47	39	32	25	19	13
	30	42	34	28	22	16	11
30	15	46	40	35	30	24	18
	20	45	38	31	25	20	15
	25	41	34	28	22	17	12
	30	36	29	24	19	14	9
25	15	43	38	33	28	22	17
	20	43	35	29	24	19	14
	25	38	31	26	20	16	11
	30	33	27	22	17	13	9

CONCLUSION

In this study, a concept of a small-scale SORC power plant applied for low-temperature heat source (< 100 °C) was proposed and investigated. The solar collectors consisting of FP, ET, and CPC collectors were used for hot water production before supplying to the ORC power generation. The system was mathematically modeled and simulated under the climate of Chiang Mai, Bangkok, Ratchaburi, Songkhla, Nakhon Ratchasima, and Chonburi, to investigate the maximum power output, the environmental impact, and the economic analysis in terms of levelized cost of electricity (LCOE). Results can be summarized as follows:

- A small-scale ORC power plant was found appropriate for below 100 °C heat source. The ORC system appeared as a good solution for power generation from low-temperature heat source.
- This technology can help achieve the strategy of Thailand government of energy intensity reduction of around 30 percent by 2036 (EPPO, 2017a).

- The system can become more profitable when the government supports and subsidizes the investment of solar collectors and the ORC system.
- The LCOE, the power output, and the CO_2 emission of different models of the system with and without initial investment of the collectors are as follows:
  - *Without initial investment of the collectors;* Chon Buri represents the east part of Thailand, the LCOE of the SORC power plant was the lowest at 0.187 USD/kWh, with power output of 123.2 MWh/Year, and reduced CO_2 emission of 61.2 Ton CO_2 eq./Year, using 1000 units of ET collectors combined with one unit of a 60 kW_e ORC.
  - *With initial investment of the collectors;* Bangkok represents the central part of Thailand, the LCOE of the SORC power plant was the lowest at 0.626 USD/kWh, with power output of 121.3 MWh/Year, and reduced CO_2 emission of 60.3 Ton CO_2 eq./Year, using 950 units of ET collectors combined with one unit of a 60 kW_e ORC.

In future works, the proposed system will become more economically attractive especially in developing a thermal power plant that operates 24 hours per day, with the integration of renewable energy sources such as biomass and geothermal energy.

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