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Potential of a Solar Organic Rankine Cycle with Evacuated-Tube Solar Collectors as Heat Source for Power Generation in Thailand

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Abstract

This paper presents a potential of a solar organic Rankine cycle (ORC) with evacuated-tube solar collectors with $F_R(\tau\alpha)$ of 0.81, F_RU_L of 2.551 W/m^{2}K as heat source for generating electricity under the climate of Thailand. The power output of the ORC power plant was 280 kW and the ORC working fluid was R245fa. The weather conditions of Chiang Mai (18.783 °N, 98.983 °E), Ubon Ratchathani (15.233 °N, 104.783 °E), Hat Yai (6.91 °N, 100.43 °E) and Bangkok (13.66 °N, 100.56 °E) represented the northern, northeastern, southern and central part of Thailand, respectively were taken as the input data of the calculations. It could be found that at Chiang Mai, the levelized electricity cost was lowest which was 0.37 USD/kWh and the annual solar-to-electricity efficiency was 4.44%. At Bangkok and Ubon Ratchathani, the levelized electricity costs were slightly higher than that of Chiang Mai. At Hat Yai, the levelized electricity cost was found to be highest which was 0.43 USD/kWh.

Key words: Solar organic Rankine cycle; Solar collector; Electrical power generation; Performance analysis; Levelized electricity cost

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INTRODUCTION

World net electricity generation increased from 13.29×10^{12} kWh in 2001 to 18×10^{12} kWh in 2006, with a growth rate of 6.3 percent per year (EIA, 2004; EIA, 2009). Coal retains the largest market share of the world electricity generation (roughly 40 percent) while natural gas and renewables retained the market share at roughly 21 and 19 percent, respectively (EIA, 2006). The coal and natural gas power plants have caused many environmental problems such as global warming, ozone layer destruction and atmospheric pollution. Gagnon *et al*. (2002) found that the greenhouse gas emissions from coal and natural gas power plant were 1050 and 443 g of carbon dioxide equivalent per kWh (gCO$_2$e/kWh), respectively. A solution for reduction of environment problems is the use of renewable energy such as solar energy, wind energy, geothermal energy and biomass as heat sources for electricity generation. The greenhouse gas emissions of renewable energy power plants were less than 41 gCO$_2$e/kWh (Pehnt, 2006; Fthenskis *et al*., 2008).

At present, concentrating solar power (CSP) technology can be exploited through three different systems, i.e. the parabolic trough system, the tower system and the dish/Stirling engine system. All the CSP technologies will be appropriate for countries having high direct normal solar radiation. There were some reports showed that the average direct normal solar radiation values for power generation should be above 1500 kWh/m^2-year (IEA, 2003; Bravo *et al*., 2007; Purohit & Purohit, 2010). The investment and electricity generation costs for CSP technologies are also shown in Table 1 (IEA, 2003). For Thailand (Department of Alternative Energy Development and Efficiency & Ministry of Energy, 2006), the annual direct normal solar radiation was in a range of 1350-1400 kWh/m^2-year which was rather low for the CSP technologies. Ketjoy and Rakwichian (2006) studied techno-economic feasibility of a solar parabolic technology for power generation in Thailand. The required maximum electrical power was 800 kW. It was found that the cost of energy (COE) was 25.52 Baht/kWh or 0.85 USD/kWh (30 Baht is about 1 USD). Wibulswas (1998) and Vorayos *et al*. (2009) reported the diffuse component of the solar radiation in Thailand was quite high since the country is in the monsoon area and it was about 50% of the total solar radiation. A solution for this problem (low annual direct normal solar radiation) was the use of evacuated-tube solar collectors instead of solar concentrators as a heat source for running organic Rankine cycle (ORC) to generate electrical power. The ORC works similar to the Rankine steam power plant but it uses an organic working fluid instead of water. There are some reports on the ORC with different low temperature heat sources such as waste heat (Hung, 2001), solar thermal (Achary *et al*., 1983; Jing *et al*., 2010), biomass (Drescher & Bruggemann, 2007) and geothermal (Heberle & Bruggemann, 2010), etc. Wang *et al*. (2010) studied performance analysis of a low-temperature solar organic Rankine cycle system utilizing R245fa with flat-plate collector as heat source. The average overall efficiency was 0.88%. Wei *et al*. (2007) also studied performance analysis and optimization of an ORC system using R245fa as working fluid.

Table 1
Investment and Electricity Generation Cost for CSP Technologies (IEA, 2003)

System	Investment cost		Electricity generation cost	
	(€/kW)	(USD/kW)	(€/kWh)	(USD/kWh)
The parabolic trough system	2,800-3,200	3,733.33-4,266.67	0.12-0.15	0.16-0.2
The tower system	4,000-4,500	5,333.33-6,000	0.15-0.20	0.2-0.27
The dish/Stirling engine system	10,000-12,000	13,333.33-16,000	0.20-0.25	0.27-0.33

(1 € is about 1.33 USD)

The objective of this work was to investigate performance and economic analyses of a R245fa solar organic Rankine cycle (SORC) with evacuated-tube solar collectors as heat source at several locations in Thailand at Chiang Mai (18.783 °N, 98.983 °E), Ubon Ratchathani (15.233 °N, 104.783 °E), Hat Yai (6.91 °N, 100.43 °E) and Bangkok (13.66 °N, 100.56 °E) which represented the northern, the northeastern, the southern and the central parts of the country, respectively. Figure 1 shows the locations of these provinces.

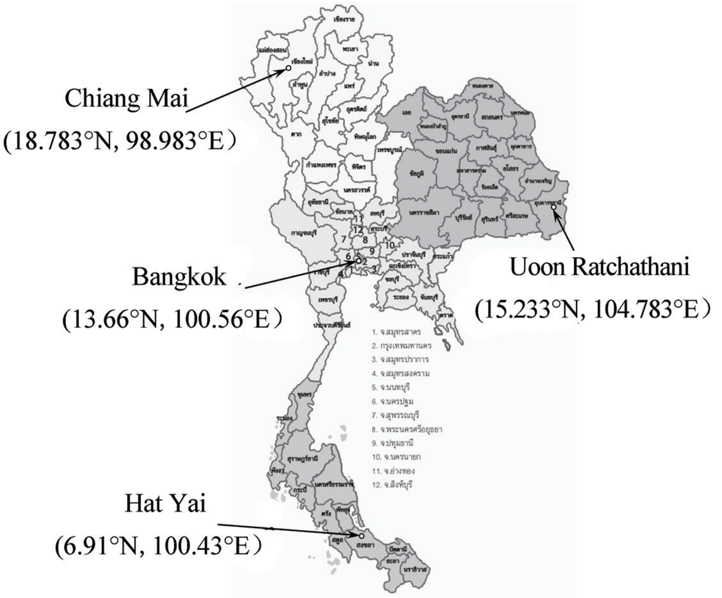


Figure 1
The Location of Chiang Mai, Ubon Ratchathani, Hat Yai and Bangkok

1. MATERIALS AND METHODS

1.1 Solar Organic Rankine Cycle (SORC)

A schematic diagram of the SORC was shown in Figure 2. The unit consisted of a set of solar collectors with a thermal energy storage and an ORC. There was a water closed loop to extract heat from the solar system which was transferring to the ORC evaporator. The working fluid of the ORC leaving the evaporator at high pressure with saturated vapor then entered the turbine to generate power and condensed in the condenser as saturated liquid. After that it was compressed to the evaporator where it was reheated from the solar system and the new cycle restarted. There was an internal heat exchange (IHE) for exchanging heat between the fluid leaving the turbine and the fluid entering the evaporator for improving the cycle efficiency. All the above described processes were shown in a temperature versus entropy diagram in Figure 3. It could be noted that the refrigerant was a dry-type therefore the state of the fluid during expansion was superheated.

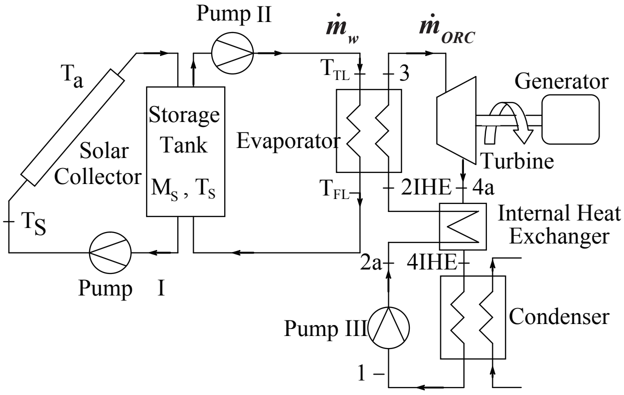


Figure 2
Solar Organic Rankine Cycle (SORC)

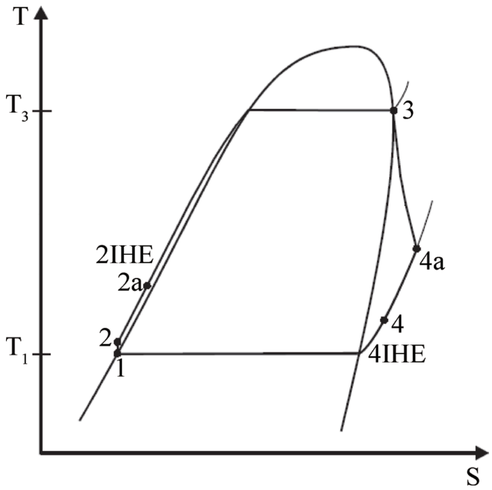


Figure 3
T-s Diagram of the ORC

For simplicity in the analysis, some assumptions were taken as follow: steady state conditions, no pressure drops in the other components than the turbine and the pump, such as the evaporator, the condenser, the IHE, the solar collectors and the piping system, were ignored. The energy equations of the all components were summarized as follows:

a) Evaporator

$$\dot{Q}_{EVA} = \dot{m}_{ORC}\left(h_3 - h_{2IHE}\right) = \dot{m}_W C_p\left(T_{TL} - T_{FL}\right) \tag{1}$$

b) Turbine

$$\dot{W}_{TUR} = \dot{m}_{ORC}\left(h_3 - h_4\right)\eta_{TUR} \tag{2}$$

$$\eta_{TUR} = \frac{h_3 - h_{4a}}{h_3 - h_4} \tag{3}$$

c) Condenser

$$\dot{Q}_{CON} = \dot{m}_{ORC}\left(h_{4IHE} - h_1\right) \tag{4}$$

d) Pump

$$\dot{W}_{PUMP} = \frac{\dot{m}_{ORC}v_1\left(P_2 - P_1\right)}{\eta_P} = \dot{m}_{ORC}\left(h_{2a} - h_1\right) \tag{5}$$

$$\eta_{PUMP} = \frac{h_2 - h_1}{h_{2a} - h_1} \tag{6}$$

e) Internal heat exchanger (IHE)

$$\dot{Q}_{\mathrm{IHE}}=\dot{m}_{\mathrm{ORC}}C_{p4a}(T_{4a}-T_{4IHE})=\dot{m}_{ORC}C_{p2a}(T_{2IHE}-T_{2a})=\varepsilon_{ORC}(\dot{m}C_p)_{\min}(T_{4a}-T_{2a}) \tag{7}$$

The heat exchange process between the hot water and the working fluid in the evaporator of the ORC was shown in Figure 4. The energy balances could be expressed as

$$\dot{m}_{ORC}\left(h_3 - h_{PP\_ORC}\right) = \dot{m}_W\left(h_{TL} - h_{PP\_W}\right) \tag{8}$$

$$\dot{m}_{ORC}\left(h_{PP\_ORC} - h_{2IHE}\right) = \dot{m}_W\left(h_{PP\_W} - h_{FL}\right) \tag{9}$$

$$\Delta T_{PP} = T_{PP\_W} - T_{PP\_ORC} \tag{10}$$

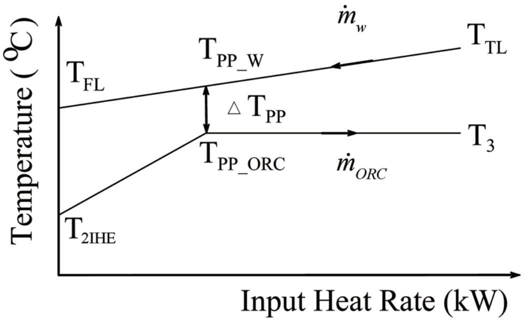


Figure 4
Diagram of the Heat Exchange Process Between the Hot Water and the Working Fluid in the Evaporator of the ORC

f) Heat gain rate from the solar collector

For evacuated-tube solar collector, the useful heat rate from the solar collector could be calculated from (Bliss, 1959)

$$\dot{Q}_{coll} = A_c F_R [I_T(\tau\alpha) - U_L(T_{fi} - T_a)] \tag{11}$$

g) Solar hot water system

The model for evaluating the temperature of water in the thermal energy storage was applied from a lump model by considering the storage be unstratified. With the finite difference method, the temperature of water in the thermal energy storage could be evaluated (Kiatsiriroat *et al.*, 1998) as

$$T_s^{t+\triangle t}=T_s^t+\frac{\triangle t}{M_sC_p}\{A_cF_R[I_T(\tau\alpha)-U_L(T_s-T_a)]-\dot{m}_wC_p(T_{TL}-T_{FL})-U_A(T_s-T_a)\} \tag{12}$$

Where $T_S^{t+\Delta t}$ is water temperature at time $t+\Delta t$ and T_S^t is water temperature at time t. I_T is the total solar radiation. T_a is the ambient temperature which could be determined from (Chaichana *et al*., 2010).

$$T_a = \frac{1}{2}\left[(T_{\max} + T_{\min}) + (T_{\max} - T_{\min}) \sin\left(\frac{2\pi}{24}(t-9) \right) \right] \tag{13}$$

$T_{\max}$ and $T_{\min}$ are the maximum and minimum ambient temperature at each location.

h) The annual solar-to-electricity efficiency is defined as

$$\eta_{STE} = \frac{E_{net,year}}{I_{T,year} A_c} \times 100 \tag{14}$$

i) The solar-to-electricity efficiency of each month is defined as

$$\eta_{STE} = \frac{E_{net,month}}{I_{T,day} D A_c} \times 100 \tag{15}$$

Where $I_{T,year}$ and $I_{T,day}$ are the total solar radiation for a day and the total solar radiation for a year on the solar collector, respectively. D is the number of days in each month (for example in January, D = 31).

1.2 Conditions for Analysis

The evacuated-tube solar collectors with $F_R(\tau\alpha)$ of 0.81, $F_R U_L$ of 2.551 W/m^{2}K were used for generating heat water. The power output of the ORC power plant was set at 280 kW. The weather conditions of Chiang Mai, Ubon Ratchathani, Hat Yai and Bangkok were taken as the input data of the calculation and the values were shown in the appendices. The solar collector was tilted at the angle from horizontal plane similar to the latitude of each location and south facing. The overall coefficient of heat loss (UA) and the pressure of the thermal energy storage were 5 W/K and 5 bar, respectively and the pump I was stopped to prevent boiling of water when the water in the thermal energy storage approaches the boiling point. The conditions for the ORC analysis were:

a) Condensing temperature: 35 °C.
b) Effectiveness of internal heat exchanger (ε): 0.85.
c) Isentropic efficiencies of turbine and pump: 0.85 and 0.8, respectively.
d) Working fluid: R245fa, and the properties were based upon REFPROP (NIST, 2000).
e) The set pinch-point temperature difference (ΔT_{PP}): 8 °C.

1.3 Economic Analysis

The economic analysis of the integrated system was calculated in a term of levelized electricity costs, LEC which could be calculated by (Pitz-Paal *et al*., 2003)

$$LEC = \frac{crf.C_{invest} + \dot{C}_{o\&m}}{E_{annual\ net}} \tag{16}$$

$$crf = \frac{i_d(1+i_d)^n}{(1+i_d)^n - 1} + k_{insurance} \tag{17}$$

There was no precise information about the current capital cost of commercialised ORC. Verloop (2003) afforded a cost of 1600 USD/kW for a 175 kW plant and Invernizi *et al*. (2007) considered a specific cost characteristic of ORC plants of 3,333.33-4,000 USD/kW or 2,500-3,000 €/kW in a range of 50-100 kW. According to these data, a value for the cost of the ORC plant was estimated at 1,500 USD/kW or 1,125 €/kW for a 280 kW plant. Table 2 summarized the cost input data for the economic analysis.

Table 2
Cost Data Used for the Economic Evaluation of SORC for Power Generation

Investment cost	
Evacuated-tube solar collectors (USD/m^2)	183.33
ORC power plant (USD/Unit)	420,000
Thermal energy storage (USD/kg)	1.67
Land (USD/m^2)	3.33
Surcharge for construction and engineering (% of equipment cost)	10
Pump, pipe and other (USD)	64,667
Operating & maintenance (o & m) cost	
Person for operating the system (USD/year)	12,000
Person for operating maintenance (USD/year)	8,000
Operating & maintenance equipment cost (% of investment cost per year)	1
Financial parameters	
Annual insurance rate, $k_{insurance}$ (%/year)	0.6
Real debt interest rate, i_d (%)	7
Depreciation period, n (year)	25

2. RESULTS AND DISCUSSION

The annual power generation of the system at various evaporating temperatures and solar collector areas at the selected locations were given in Figure 5. It was found that the annual power generation increased with the increase of solar collector area. However, when the area was over 7500 m^2, the electricity generation was slightly increased since the temperature of the thermal storage was protected not to reach its the boiling point. To investigate the effect of a change in the evaporating temperature on the annual electricity generation, it was observed that when the evaporating temperature was below 105 ^{o}C, the annual electricity generation was increased with the increase of the evaporating temperature because the thermal efficiency of the ORC was increased with the increase of the evaporating temperature (Tchanche *et al*., 2009; Thawonngamyingsakul and Kiatsiriroat, 2010). But when the evaporating temperature was over this value, the annual electricity generation tended to decrease since the solar collector had low performance and the period for supporting the ORC was short.

Consider the levelized electricity cost (LEC) of the system. The minimum LEC was found at the collector area of 5000 m^2 and the evaporating temperature of 105 ^{o}C. The results for all locations were shown in Table 3. From this Table, the lowest and highest values of LEC were found at Chiang Mai and Hat Yai which were 0.37 and 0.43 USD/kWh, respectively. At Ubon Ratchathani and Bangkok, the LEC values were 0.39 and 0.38 USD/kWh, respectively.

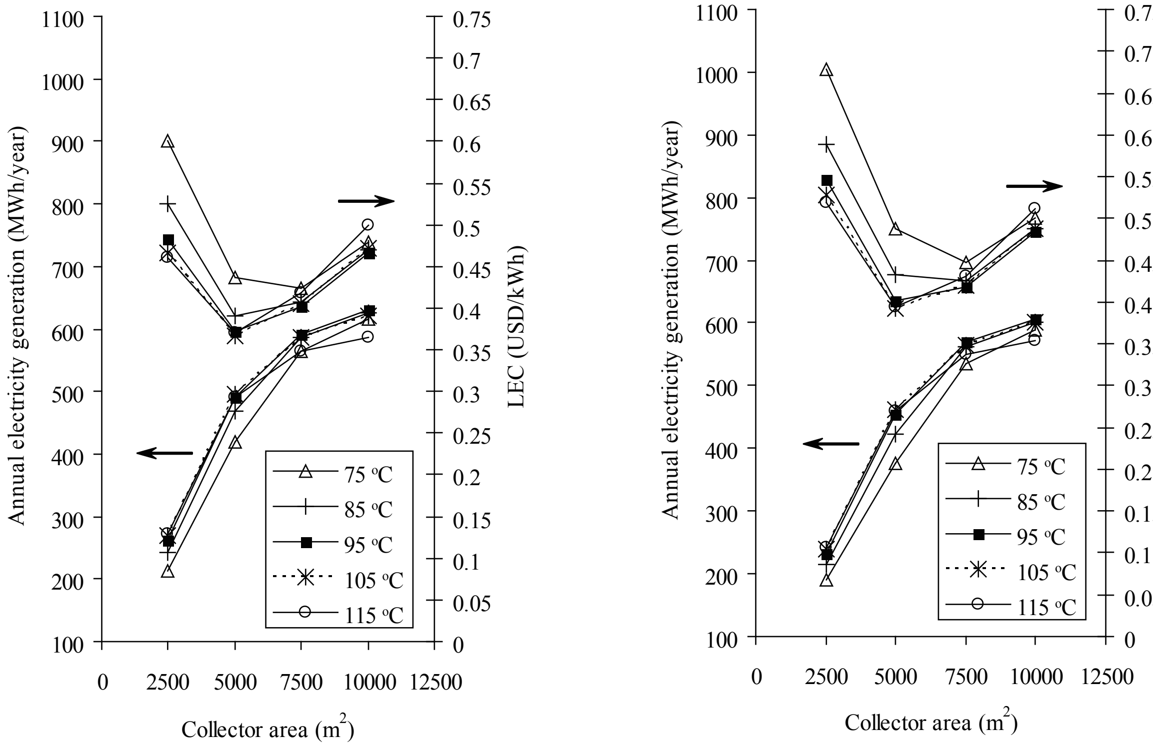
Table 3
The Results at the Minimum Values of Levelized Electricity Costs

Location	Minimum values of LEC (USD/kWh)	Collector area (m^2)	Evaporating temperature (^{o}C)	Annual electricity generation (MWh)	Annual solar energy collected (MWh)	Annual solar-to-electricity efficiency (%)
Chiang Mai	0.37	5000	105	495.56	11168.55	4.44
Ubon Ratchathani	0.39	5000	105	462.91	10566.16	4.38
Hat Yai	0.43	5000	105	423.60	10048.54	4.22
Bangkok	0.38	5000	105	474.31	10700.44	4.43

The investment cost at minimum values of LEC was shown in Table 4. It was noted that the investment cost was approximately 1,600,000 USD and the details were shown in Figure 6. The evacuated-tube solar collector retained the largest share of the total investment cost (roughly 57%) while the storage tank held the lowest share of the total investment cost was approximately 1%. The ORC power plant, land, construction and engineering and pump, pipe and others held the share at roughly 26, 3, 9 and 4%, respectively.

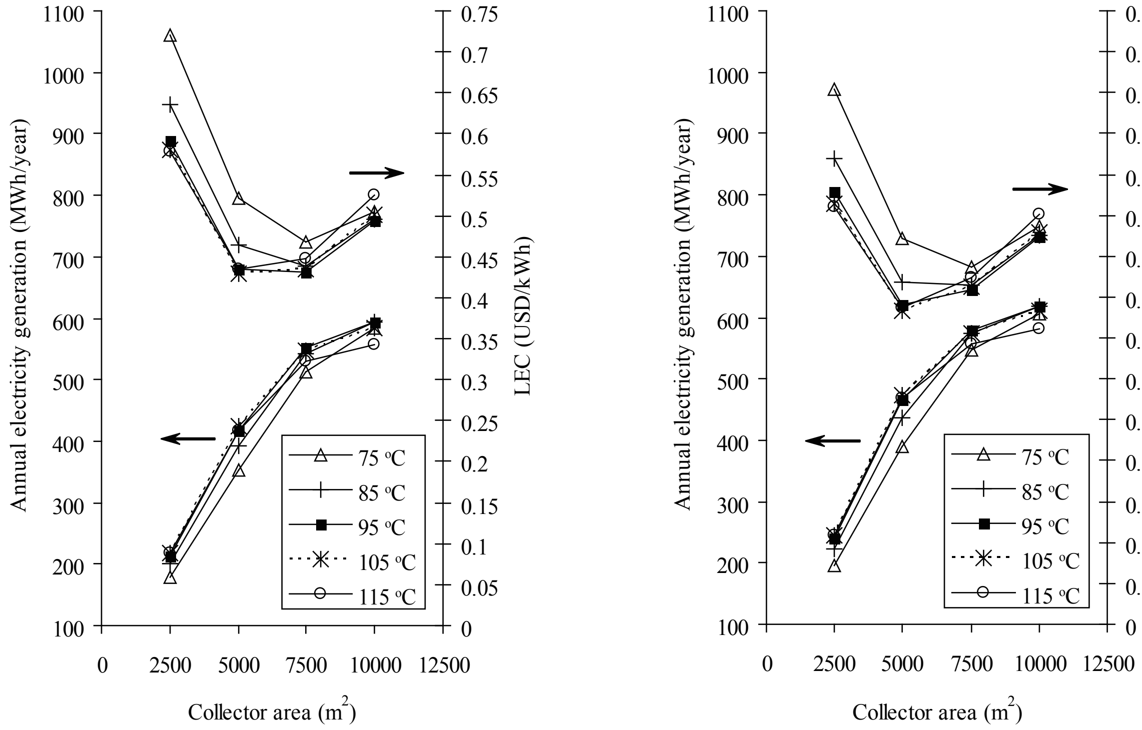
Table 4
Investment Cost at Minimum Value of LEC

Data	Investment cost (USD)
1. Solar collectors	916,667
2. ORC power plant	420,000
3. Storage tank	21,667
4. Land	41,667
5. Construction and engineering	142,300
6. Pump, pipe and others	64,667
Total	1,606,967



(a) Chiang Mai

(b) Ubon Ratchathani



(c) Hat Yai

(d) Bangkok

Figure 5
The Values of Levelized Electricity Costs Versus Collector Area for Various Values of the Evaporating Temperature of the ORC

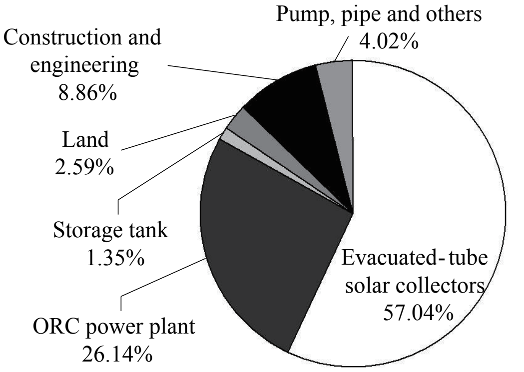


Figure 6
The Contribution of the Investment Cost at Minimum Value of LEC

Figure 7 shows the power generation and solar-to-electricity efficiency of each month at minimum values of LEC. At Chiang Mai, the high electricity generation occured in March and April (in the summer season). But the high electricity generation was found at Ubon Ratchathani, Hat Yai and Bangkok occured in August since those regions are under the influence of the southwest monsoon with cloudy skies, thus the diffuse solar radiation was rather high. According to the report (Wibulswas, 1998; vorayos *et al*., 2009), in Thailand, the diffuse component of the solar radiation was approximately 50% of the total solar radiation. The solar-to-electricity efficiency shown in Figure 7 was between 3.74 and 4.70. At Chiang Mai, Ubon Ratchathani, Hat Yai and Bangkok, the annual solar-to-electricity efficiencies were 4.44, 4.38, 4.22 and 4.43%, respectively. Note that the maximum efficiency was found at Chiang Mai because of the highest annual solar energy was collected. The results were shown in Table 3.

The effects of the solar collector cost and the cost of the ORC plant on the LEC at several regions were shown in Figures 8 and 9, respectively. It could be noted that the LEC at the four locations were decreased with the decrease of the cost of the solar collector and the ORC plant. Furthermore, the LEC was found to be less sensitive to the cost of the ORC power plant compared to the cost of the solar collector.

At present, the Thai Government has a policy to encourage the electricity generation from renewable energy, i.e., wind energy, solar energy, biomass, etc. The electricity cost from solar energy could be taken from the electrical charge (3.5 Baht/kWh or 0.12 USD/kWh) plus an adder (8 Baht/kWh or 0.27 USD/kWh) of which the total sale price was 11.5 Baht/kWh or 0.39 USD/kWh. At Chiang Mai, Ubon Ratchathani and Bangkok are recommended for SORC system application.

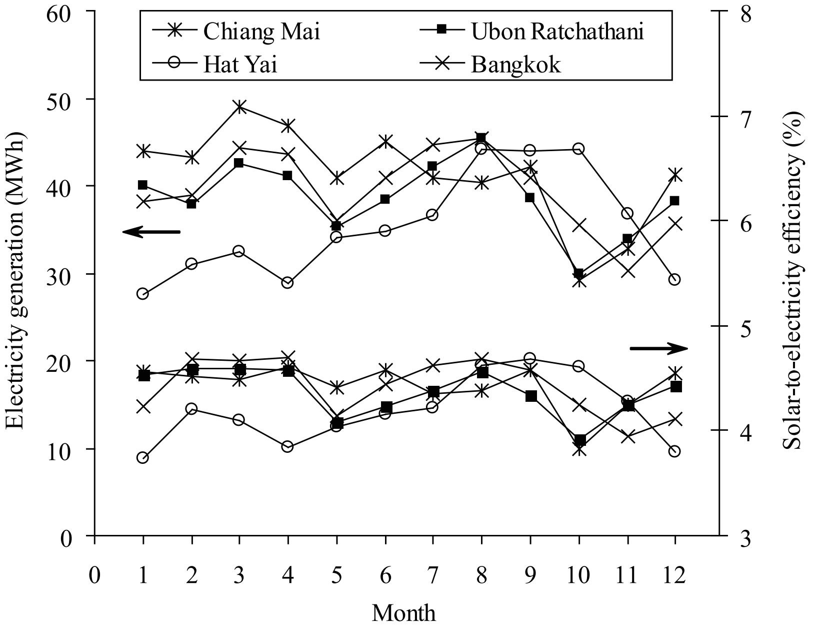


Figure 7
The Electricity Generation and Solar-to-Electricity Efficiency at Minimum Values of Levelized Electricity Cost

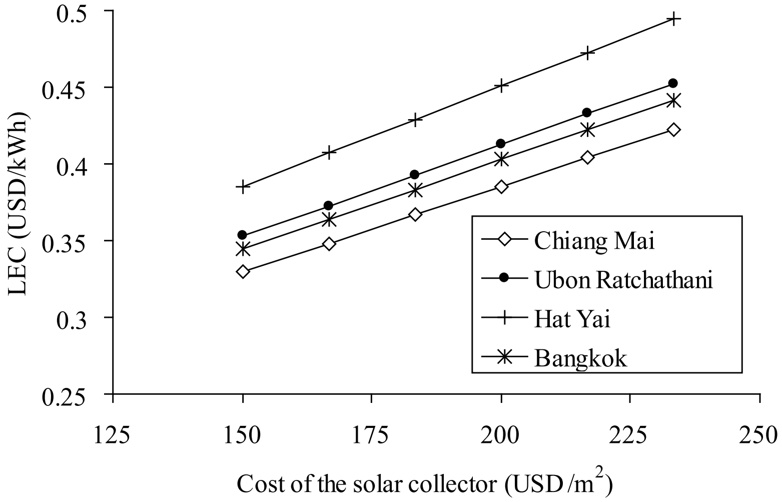


Figure 8
Effect of a Change in the Solar Collector Cost on the Levelized Electricity Cost at the Real Debt Interest Rate is 7%

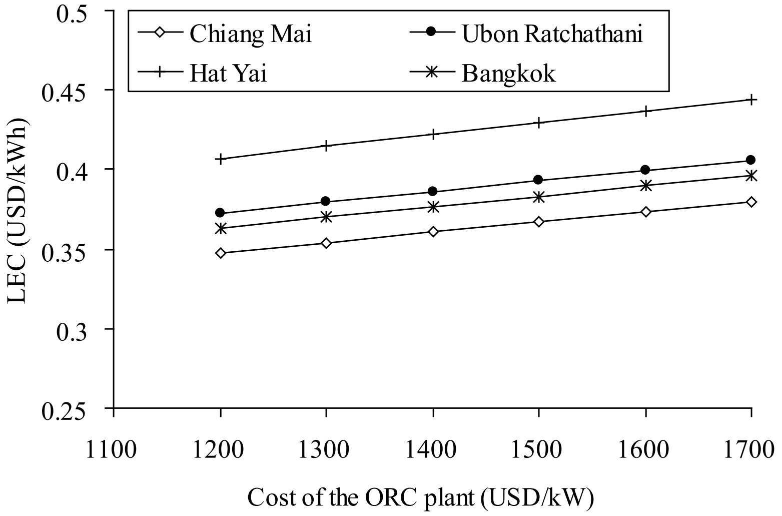


Figure 9
Effect of a Change in the Cost of the ORC Plant on the Levelized Electricity Cost at the Value of the Evacuated-Tube Solar Collector is 183.88 USD/m^2 and the Real Debt Interest Rate is 7%

CONCLUSION

This paper presents an economic consideration of a solar organic Rankine cycle with evacuated-tube solar collector as heat source. The organic Rankine cycle was operating with R245fa and the weather conditions of Chiang Mai, Ubon Ratchathani, Hat Yai and Bangkok were taken as the input data of the calculation. The reference values of the evacuated-tube solar collector, the real debt interest rate and the cost of the ORC plant used in the economic evaluation were 183.33 USD/m^2, 7% and 1500 USD/kW, respectively. It could be found that at Chiang Mai, the lowest values of levelized electricity cost was found which was of 0.37 USD/kWh and the annual solar-to-electricity efficiency was 4.44%, while the levelized electricity cost at Ubon Ratchathani and Bangkok were slightly higher than that of Chiang Mai which were 0.38 and 0.39 USD/kWh, respectively. At Hat Yai, the highest levelized electricity cost was 0.43 USD/kWh.

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REFERENCES

[1] Achary, S. K., Obermeier, E., & Schaber, A. (1983). Use of R-114 as the Working Fluid in a Flat-Plate Collectors System for Electric Power Generation. *Applied Energy*, *13*, 59-68.

[2] Bliss, R.W. (1959). The Derivation of Several "Plate Efficiency Factors" Useful in the Design of the Flat Plate Solar Heat Collector. *Solar Energy*, *3*, 55-64.

[3] Bravo, J., Casals, X., & Pascua, I. (2007). GIS Approach to the Definition of Capacity and Generation Ceilings of Renewable Energy Technologies. *Energy Policy*, *35*(10), 4879-4892. DOI:10.1016/j.enpol.2007.04.025

[4] Chaichana, C., Kiatsiriroat, T., & Nuntaphan, A. (2010). Comparison of Conventional Flat-Plate Solar Collector and Solar Boosted Heat Pump Using Unglazed Collector for Hot Water Production in Small Slaughterhouse. *Heat Transfer Engineering*, *31*(5), 419-429.

[5] Department of Alternative Energy Development and Efficiency & Ministry of Energy. (2006). *Potentials of Concentrating Solar Power Technologies in Thailand*. A Research Report.

[6] Drescher, U., & Bruggemann, D. (2007). Fluid Selection for the Organic Rankine Cycle (ORC) in Biomass Power and Heat Plants. *Applied Thermal Engineering*, *27*, 223-228. DOI:10.1016/j.applthermaleng.2006.04.024.

[7] Energy Information Administration (EIA). (2004). International Energy Outlook 2004. DOE/EIA-0484. Retrieved from http://ftp.eia.doe.gov/pub/pdf/international/0484(2004).pdf

[8] Energy Information Administration (EIA). (2006). International Energy Outlook 2006. DOE/EIA-0484. Retrieved from http://www.fypower.org/pdf/EIA_IntlEnergyOutlook(2006).pdf

[9] Energy Information Administration (EIA). (2009). International Energy Outlook 2009. DOE/EIA-0484. Retrieved from http://www.setav.org/ups/dosya/25025.pdf

[10] Fthenskis, V. M., Kim, H. C., & Alsema, M. (2008). Emissions from Photovoltaic Life Cycles. *Environmental Science and Technology*, *42*(6), 2168-2174.

[11] Gagnon, L., Belanger, C., & Uchiyama, Y. (2002). Life-Cycle Assessment of Electricity Generation Options: The Status of Research in Year 2001. *Energy Policy*, *30*, 1267-1278.

[12] Heberle, F., & Bruggemann, D. (2010). Exergy Based Fluid Selection for a Geothermal Organic Rankine Cycle for Combined Heat and Power Generation. *Applied Thermal Engineering*, *30*, 1326-1332. DOI:10.1016/j.applthermaleng.2010.02.012

[13] Hung, T. C. (2001). Waste Heat Recovery of Organic Rankine Cycle Using Dry Fluids. *Energy Conversion and Management*, *42*, 539-553.

[14] IEA. (2003). Renewables for Power Generation, International Energy Agency Report. Retrieved from http://www.antoniolima.web.br.com/arquivos/renewpower_2003.pdf

[15] Invernizzi, C., Iora, P., & Silva, P. (2007). Bottoming Micro-Rankine Cycles for Micro-Gas Turbines. *Applied Thermal Engineering*, *27*, 100-110.

[16] Jing, L., Gang, P., & Jie, J. (2010). Optimization of Low Temperature Solar Thermal Electric Generation with Organic Rankine Cycle in Different Areas. *Applied Energy, 87*, 3355-3365. DOI:10.1016/j.apenergy.2010.05.013

[17] Ketjoy, N., & Rakwichian, W. (2006). Techno-Economic Study of Solar Parabolic Trough-Biomass Hybrid Power Plant. In *Proceedings of the Second National Conference on Energy Network of Thailand*, *Nakornrachasima, Thailand*, *27-29 July 2006.*

[18] Kiatsiriroat, T., Siriplubpla, P., & Nuntaphan, A. (1998). Performance Analysis of a Refrigeration Cycle Using a Direct Contact Evaporator. *Int. J. Energy Res., 22*, 1179-1190.

[19] National Institute of Standard and Technology (NIST). (2000). REFPROP Version 7, Thermodynamic Properties of Refrigerants and Refrigerant Mixtures Software.

[20] Pehnt, M. (2006). Dynamic Lifecycle Assessment of Renewable Energy Technologies. *Renewable Energy*, *31*, 55-71. DOI:10.1016/j.renene.2005.03.002

[21] Pitz-Paal, R., Dersch, J., & Milow, B. (2003). European Concentrated Solar Thermal Road-Mapping Research Report on SES6-CT-2003-502578. European Commission.

[22] Purohit, I., & Purohit, P. (2010). Techno-Economic Evaluation of Concentrating Solar Power Generation in India. *Energy Policy*, *38*, 3015-3029. DOI:10.1016/j.enpol.2010.01.041

[23] Tchanche, B. F., Papadakis, G., Lambrinos, G., & Frangoudakis, A. (2009). Fluid Selection for a Low-Temperature Solar Organic Rankine Cycle. *Applied Thermal Engineering*, *29*, 2468-2476. DOI:10.1016/j.applthermaleng.2008.12.025

[24] Thawonngamyingsakul, C., & Kiatsiriroat, T. (2010). Working Fluid Selection for a Low-to-Intermediate Temperature Organic Rankine Cycle. In *Proceedings of the SAME^2-PU Conference, Phayao University, Thailand, 25 August 2010* (pp. 170-177).

[25] Verloop, J. (2003). Technical Opportunities for Micro-Generation. In *Proceedings of the Sixth Annual International Conference Economics of Infrastructures, TU Delft.*

[26] Vorayos, N., Wongsuwan, W., & Kiatsiriroat, T. (2009). Development of Solar Hot Water Systems in Thailand, Engineering Journal, Chiang Mai University. *Energy. J. CMU*, *16*(2), 55-69.

[27] Wang, J. L., Zhao, L., & Wang, X. D. (2010). A Comparative Study of Pure and Zeotropic Mixtures in Low-Temperature Solar Rankine Cycle. *Applied Energy, 87*, 3366-3373. DOI:10.1016/j.apenergy.2010.05.016

[28] Wei, D., Lu, X., Lu, Z., & Gu, J. (2007). Performance Analysis and Optimization of Organic Rankine Cycle (ORC) for Waste Heat Recovery. *Energy Conversion and Management*, *48*, 1113-1119. DOI:10.1016/j.enconman.2006.10.020

[29] Wibulswas, P. (1998). Research and Development of Solar Thermal Energy in Thailand. *ASEAN J. Sci. Technol. Develop*, *5*(1), 15-23.

NOMENCLATURE

a	Ambient
A	Area (m^2)
A_c	Collector area (m^2)
CON	Condenser
C_{invest}	Total investment of the plant (USD)
C_p	Specific heat (kJ/kg.K)
$\dot{C}_{o\&m}$	Operating and maintenance cost (USD/year)
D	Number of days in each month
EVA	Evaporator
E_{net}	Net electricity (kWh)
FL	From load
F_R	Heat removal factor
h	Enthalpy (kJ/kg)
IHE	Internal heat exchanger
i_d	Real debt interest rate
I_T	Total solar radiation on the tilted surface (W/m^2)
$I_{T,day}$	Total solar radiation for a day on the tilted surface (kWh/m^2-day)
$I_{T,year}$	Total solar radiation for a year on the tilted surface (kWh/m^2-year)
$k_{insurance}$	Annual insurance rate
LEC	Levelized electricity costs (USD/kWh)
$\dot{m}$	Mass flow rate (kg/s)
M_S	Mass of water in thermal energy storage (kg)
n	Depreciation period in years (year)
ORC	Organic Rankine cycle
PP	Pinch-Point
$\dot{Q}$	Heat rate (kW)
$SORC$	Solar organic Rankine cycle
t	Time (s)
T	Temperature (K)
TL	To Load
TUR	Turbine
U	Overall heat transfer coefficient (W/m^2.K)
U_L	Overall heat loss coefficient (W/m^2.K)
v	Specific volume (m^3/kg)
W	Water
$\dot{W}$	Power (kW)
ε	Effectiveness of internal heat exchanger
η_{STE}	Solar-to-electricity efficiency (%)
$\tau\alpha$	Optical efficiency of collector

APPENDIX

The total solar radiation on the tilted surface at Chiang Mai, Ubon Ratchathani, Hat Yai and Bangkok as shown in Figures 10, 11, 12 and 13, respectively. Figure 14 shows the total solar radiation for a day on the tilted surface.

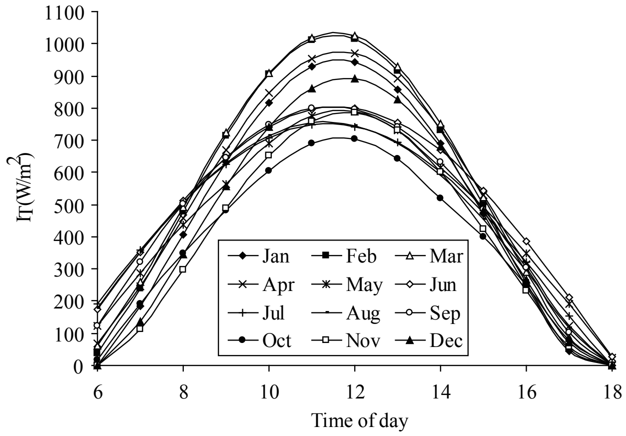

Figure 10
The Total Solar Radiation on the Tilted Surface at Chiang Mai

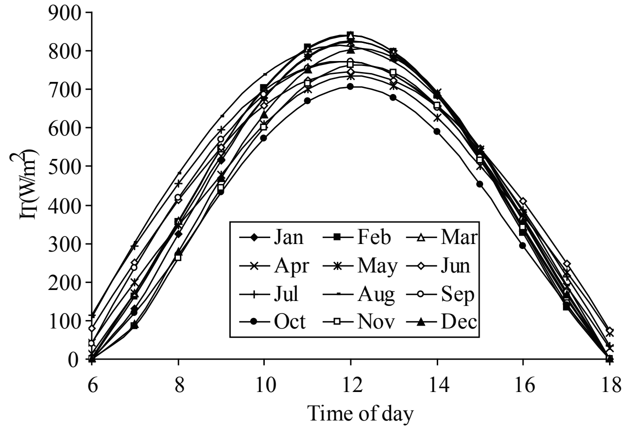

Figure 11
The Total Solar Radiation on the Tilted Surface at Ubon Ratchathani

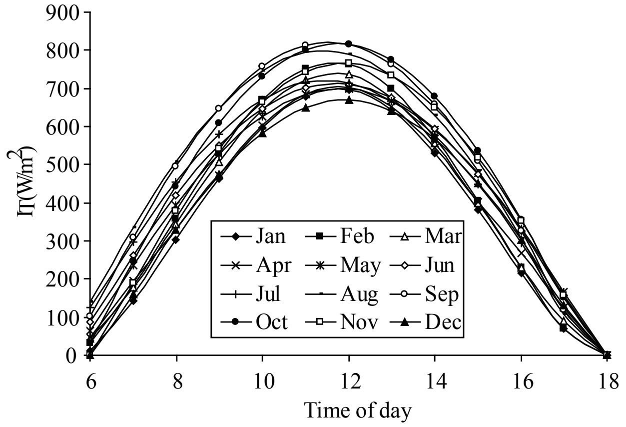

Figure 12
The Total Solar Radiation on the Tilted Surface at Hat Yai

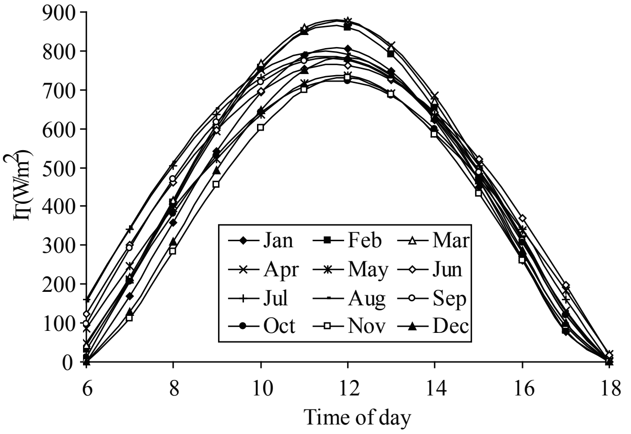

Figure 13
The Total Solar Radiation on the Tilted Surface at Bangkok

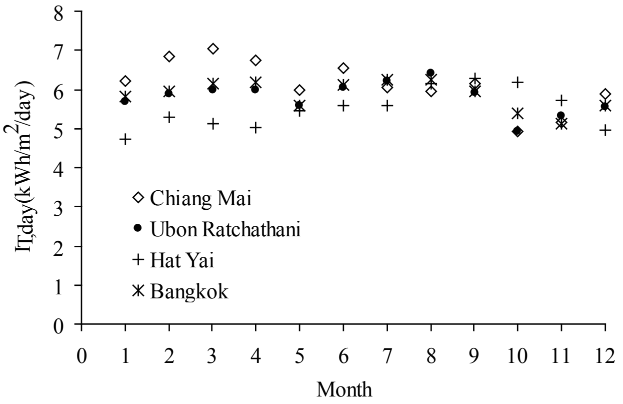

Figure 14
The Total Solar Radiation for a Day on the Tilted Surface

Table 5
The Average Maximum-Minimum Temperature in Past 10 Year Period (2000-2009)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Chiang Mai												
T_{max} (°C)	31.4	34.1	33.6	37.6	35.2	33.3	32.9	32.9	32.5	32.7	31.4	30.2
T_{min} (°C)	13.2	15.3	17.8	22.0	22.4	23.5	23.2	23.1	22.8	21.4	17.3	14.0
Ubon Ratchathani												
T_{max} (°C)	32.1	34.0	35.7	36.6	34.6	33.6	32.7	32.1	32.1	32.6	32.1	31.6
T_{min} (°C)	17.6	19.7	22.4	24.2	24.2	24.3	24.1	24.0	23.7	22.5	20.2	18.4
Hat Yai												
T_{max} (°C)	31.2	33	34.1	34.6	33.9	33.7	33.5	33.6	33.1	32.2	30.9	30.4
T_{min} (°C)	22.2	22	23	23.6	23.9	23.7	23.5	23.5	23.4	23.3	23.2	22.8
Bangkok												
T_{max} (°C)	32.8	33.7	34.5	35.7	34.2	33.7	33.2	33.2	33.1	33.4	33.3	32.7
T_{min} (°C)	23.3	24.9	26.2	27.1	26.3	26.1	26.0	25.8	25.4	25.2	24.4	23.3

Table 6
The Mass of Water in the Thermal Energy Storage for Various Values of the Evaporating Temperature of the ORC

Evaporating temperature (°C)	Mass of water in the thermal energy storage (kg)
75	25000
85	19000
95	15000
105	13000
115	10000