DTU Library

Techno-economic analysis of a power generation system consisting of a foil-based concentrating solar collector and an organic Rankine cycle unit

Desai, Nishith B.; Pranov, Henrik ; Haglind, Fredrik

Published in:
Proceedings of ECOS 2019: 32nd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems

Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

Techno-economic analysis of a power generation system consisting of a foil-based concentrating solar collector and an organic Rankine cycle unit

***Nishith B. Desai*[a]*, Henrik Pranov*[b] *and Fredrik Haglind*[c]**

[a] *Technical University of Denmark, Kongens Lyngby, Denmark, nbdes@mek.dtu.dk*
[b] *Heliac ApS, Hørsholm, Denmark, hjp@heliac.dk*
[c] *Technical University of Denmark, Kongens Lyngby, Denmark, frh@mek.dtu.dk*

Abstract:

Parabolic trough collector based plants, using thermal oil as a heat-transfer fluid, is the most mature technology of the concentrating solar power technologies. Solar power tower system is proposed as a promising alternative to the parabolic trough collector based plants for large-scale applications. Due to the high initial and operational costs, the use of concentrated solar power plant is limited to the regions with high solar radiation and large-scale capacity. Recently, a cost-effective polymer foil-based novel concentrating solar collector system, which uses a focusing plastic film that is adhered to a glass plate, has been proposed. Apart from low installation cost, this system also avails the advantages of two-axis tracking and low operation and maintenance cost. In this paper are presented techno-economic analyses of a parabolic trough collector based plant and a foil-based solar collector powered plant with a capacity of 1 MWe including a conventional two-tank thermal energy storage and an organic Rankine cycle power system. The objective is to identify which is the more appropriate solar field technology for such plant. Four different thermal energy storage capacities (1 h, 3 h, 6h, and 9 h) were considered in the analysis. Optimum solar field areas for each storage capacities were evaluated. The results suggest that the foil-based concentrating solar system can reduce the levelized cost of energy by up to about 40 % compared to parabolic trough collector based plants. Furthermore, the results indicate that hexamethyldisiloxane is the working fluid that achieves the best performance for the foil-based and parabolic trough collector based plants.

Keywords:

Concentrating solar power; Foil-based collector; Organic Rankine cycle; Parabolic trough collector; Renewable energy

1. Introduction

Concentrating solar power (CSP) is a developing technology among different technologies based on renewable energy sources. Today, there are power plants based on the CSP technology with an electrical power generation capacity of a few kWe to 100 MWe and more used in various sun-rich regions around the world. However, CSP hasn't been successful in capturing larger markets due to its high cost of installation and high levelized cost of energy (LCOE). Despite of the high cost, CSP plants with thermal energy storage can work as a base load power plant due to its high capacity factor. Parabolic trough collector (PTC) based plants, using thermal oil as a heat-transfer fluid (HTF), is the most mature technology. However, the installation of PTC-based plants is limited to the regions with high solar radiation because of high cost of installation and operation. Solar power tower systems and the linear Fresnel reflector (LFR) technology with flat mirrors and simple structure are proposed as promising alternatives to the PTC-based plants. However, the former is only suitable for large-scale applications (> 100 MWe) and the latter has a low optical efficiency and requires much higher area of installation compared to that of a parabolic trough based plant of the same capacity.

Small to medium-scale (a few kWe to a few MWe) modular CSP plants offer solutions in industrial and off-grid applications. Such plants avail the advantages of low installation cost and standardization reducing the technological risk. For small to medium scale applications, organic Rankine cycle (ORC) power systems have been demonstrated to be an efficient solution for power generation [1]. Conventional CSP plants typically use mirrors, which are expensive to produce, install, and maintain. Therefore, small to medium-scale (up to 5 MWe) CSP plants are not economically viable compared to solar photovoltaic and wind energy based plants. A summary of previous works on medium-scale (500 kWe to 5 MWe) concentrated solar power generation based on the ORC technology is given in Table 1. It can be observed that parabolic trough collector and linear Fresnel reflector are typically used for medium-scale plants. The promising organic working fluids for such plants (highlighted in the Table 1) are n-pentane, isopentane, hexamethyldisiloxane (MM), toluene and cyclohexane.

Recently, a cost-effective polymer foil-based novel concentrating solar collector system, which uses a focusing plastic film that is adhered to a glass plate has been proposed. Such concentrating solar system can be used for district heating and cooling, desalination, industrial process heat applications, power generation, and multi-generation. Apart from low installation cost, this system also avails the advantages of two-axis tracking and low operation and maintenance cost. Currently, a full-scale demonstration of 2 MW foil-based solar field for district heating at Møn, Denmark by Heliac ApS is going on and the plant will be operational by the end of April 2019.

In this paper are presented techno-economic analyses of a parabolic trough collector based plant and a foil-based solar collector powered plant with a capacity of 1 MWe including a conventional two-tank thermal energy storage and an organic Rankine cycle power system. The objective is to identify which is the more appropriate solar field technology for such plant. Four different thermal energy storage capacities (1 h, 3 h, 6h, and 9 h) were considered in the analysis and optimum area corresponding to the storage capacities were determined. Apart from that, techno-economic performance of two different organic working fluid, n-pentane and MM, were compared. This is the first paper presenting an analysis of a foil-based CSP system.

2. Methods

For commercial feasibility of any system, it is important to prove its techno-economic viability. The performance of all components is affected by changes in operating conditions due to variations in the solar radiation. The methodology used to calculate part-load performance of different components and economic analysis is explained in this section.

2.1 System description

An illustration of the foil-based solar concentrator powered electricity generation system is given in Figure 1. The foil-based solar collector concentrates solar energy on the receiver and the collected thermal energy is used to produce electricity in the power cycle. The system is equipped with a conventional two-tank molten salt-based thermal energy storage (TES) system, storing the excess energy. During low or no solar radiation, the system utilizes the stored energy. High temperature and high pressure working fluid expands through the expander and produces power.

Table 1. Summary of previous works on concentrated solar power generation based on the organic Rankine cycle technology.

Authors	Solar field type	Working fluid for solar field	Storage	Working fluids for ORC (**highlighted promising working fluids**)	Max. temp. of ORC	Type of analysis	Remarks
He et al. [2]	PTC	Thermal oil	Single tank thermocline	**n-Pentane**, R113, R123	205°C	Energy	Simulation studies using TRNSYS software.
Casartelli et al. [3]	PTC, LFR	Thermal oil	No	**Toluene**	295°C	Energy, Economic	Cost of LFR field should be about 50% of PTC field for cost parity.
Cocco and Serra [4]	LFR	Thermal oil	Two-tank direct, thermocline	**Siliconic oil**	305°C	Energy, Economic	Thermocline storage system – 420 €/MWh); Direct two-tank systems – 430 €/MWh.
Cocco and Cau [5]	PTC, LFR	Thermal oil	Two-tank direct	**Siliconic oil**	305°C	Energy, Economic	For 1 MWe plant (2 hrs storage): PTC-based plant – 340 €/MWh; LFR-based plant – 380 €/MWh.
Rodríguez et al. [6]	LFR	Thermal oil	Two-tank, thermocline	**Cyclopentane**	300°C	Energy, Economic	Thermocline technology enables 33% on average reduction in the cost of thermal energy storage.
Desai and Bandyopadhyay [7]	PTC, LFR	Thermal oil, Organic fluid	No	**R113**, **n-pentane**, Cyclohexane, MDM, MM, Heptane, Toluene, R245fa, **Water**, and other	337°C	Energy, Economic	LFR field cost to reach cost parity with PTC based plant: SRC-based plants – 48% of PTC field cost; ORC-based plants (with OMTS – 58% of the PTC field cost.
Garg et al. [8]	PTC	Thermal oil	Packed bed	**Isopentane**, R152a, butane, isobutene, R245fa, and other	275°C (HTF)	Energy, Economic	Waste heat and solar energy powered 5, 50 and 500 kWe systems.
Tzivanidis et al. [9]	PTC	Thermal oil	Single tank direct	**Cyclohexane**, toluene, water, MDM, and other	270°C (HTF)	Energy, Economic	Analysis of 1 MWe plant with different PTC technologies and ORC working fluids.
Russo et al. [10]	LFR	Thermal oil	Thermocline	Not given	300°C (HTF)	Energy	Simulation studies of a 1 MWe plant (ORC-PLUS Project).
Petrollese and Cocco [11]	LFR	Thermal oil	Two-tank direct	**MM**, n-Heptane, Toluene	222°C	Energy, Economic	Multi-scenario approach for solar ORC plant design.
Bellos and Tzivanidis [12]	PTC	Thermal oil	Single tank direct	**Toluene**, cyclohexane, MDM, n-pentane	300°C (HTF)	Energy	Solar-waste heat power system using different ORC working fluids.

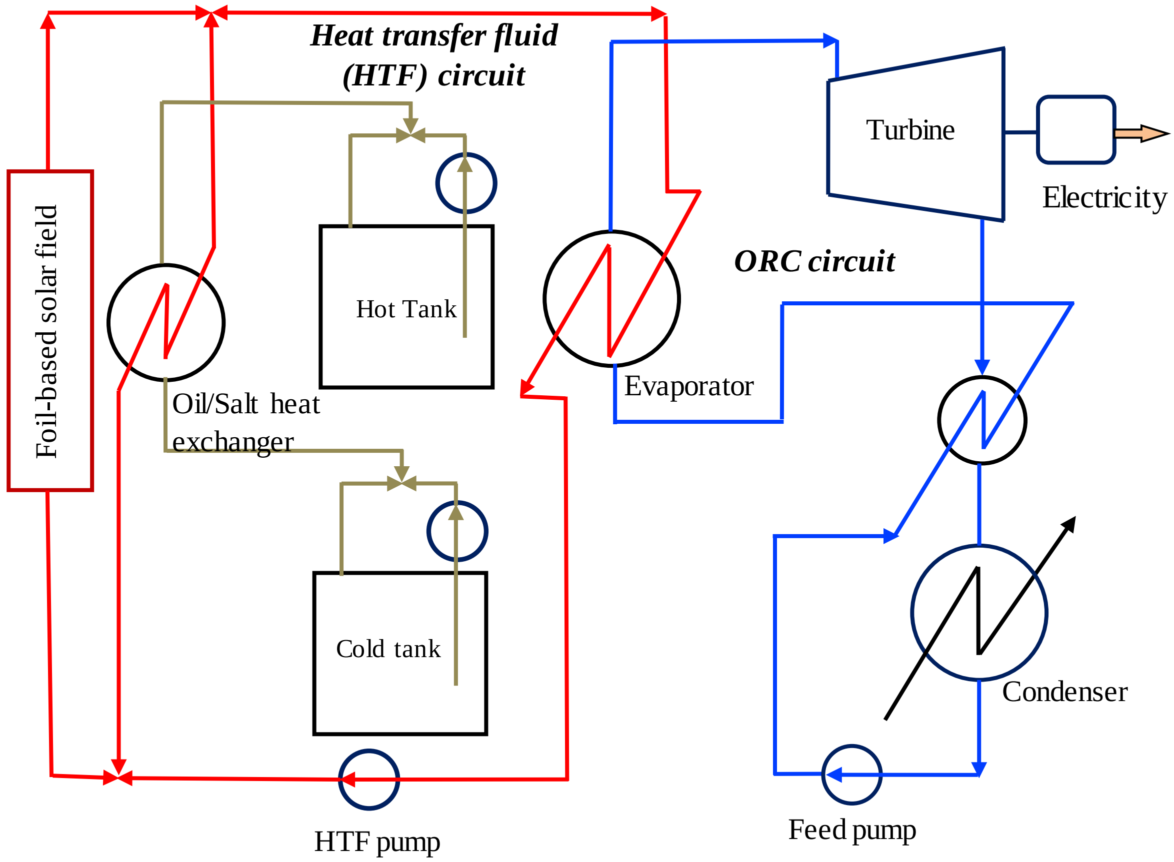

Figure 1a. Foil-based concentrating solar collector powered organic Rankine cycle system.

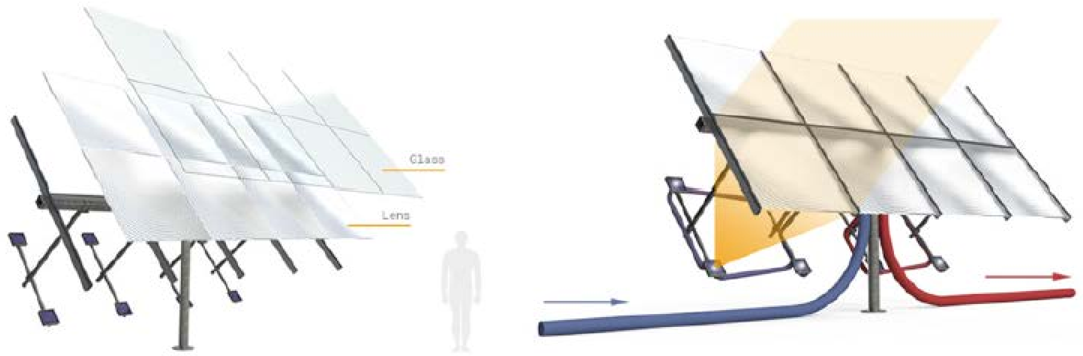

Figure 1b. Illustration of the foil-based concentrated solar power concept.

Figure 1c. Actual installation on Møn, Denmark (a 2 MW solar field for district heating purposes) and at DTU Civil Engineering's test facilities in Kongens Lyngby, Denmark.

2.2 Concentrating solar collector field

The solar collector field useful energy gain (Q_{CL}) is calculated as follows:

$$Q_{CL} = \eta_{o,CL} \cdot DNI \cdot IAM \cdot A_{p,CL} - U_l \cdot \left(T_{m,CL} - T_a\right) \cdot A_{p,CL} \quad (1)$$

where $\eta_{o,CL}$ is the solar field's optical efficiency, U_l is the heat loss co-efficient based on the aperture area of solar field, $T_{m,CL}$ is the mean temperature of solar field, T_a is the ambient temperature, and DNI is the direct normal irradiance. The incidence angle modifier (IAM) for the parabolic trough collector field is the ratio of the optical efficiency at any incidence angle to the efficiency at incidence angle equals to zero. The IAM for the foil-based solar field is one because of the two-axis tracking. The optical efficiency of the solar field is including a cleanliness factor, which is the ratio of the optical efficiency in average dirty conditions to the optical efficiency with the same optical element in clean condition. The shadow losses and end-losses are neglected in the analysis, which are typically calculated based on the solar field layout prepared during the detailed engineering design stage. The value of these losses is small about 3% [13]. The heat losses and pressure drop through piping (typically, calculated during detailed engineering design stage) are also neglected in the analysis. A penalty in net annual energy output for start-up/shut-down and other losses was considered in the analysis.

2.3 Organic Rankine cycle power system

The design power output of the turbine (P_D) and the design gross peak plant electric output ($P_{gross,D}$) is calculated as follows:

$$P_D = \dot{m}_D \cdot \Delta h_{is,D} \cdot \eta_{is,D} \quad \text{and} \quad P_{gross,D} = P_D \cdot \eta_{g,D} \quad (2)$$

where $\dot{m}_D$ is the design mass flow rate of the organic fluid, $\eta_{is,D}$ is the design isentropic efficiency of turbine, $\Delta h_{is,D}$ is the design isentropic enthalpy change in the turbine, and $\eta_{g,D}$ is the generator design efficiency.

The system is equipped with a thermal energy storage for storing the excess energy. When the stored energy is available, the ORC power system runs at full load. However, when the hot storage tank is at a minimum level and solar radiation is not sufficient, the heat transfer fluid mass flow rate is adjusted such that the solar field outlet temperature is controlled. The power system mass flow rate and turbine power output are also affected by the variations in heat transfer fluid flow rate. The turbine power output (P) and power system mass flow rate ($\dot{m}$) can be expressed by a Willans line equation [14]. The turbine power output and mass flow rate relationship can be assumed as a linear relation over a reasonable range [14]:

$$P = a + b \cdot \dot{m} \quad (3)$$

The intercept point, i.e. known as the internal loss, a, or the value of power input at zero flow to maintain the speed, of the Willans line is mainly affected by the turbine size and can be expressed in terms of the maximum power [14]. The internal losses are assumed proportional to the rated output of turbine [14]:

$$a = -y \cdot P_D \quad (4)$$

The value of b is calculated as follows [15]:

$$b = (1 + y) \cdot \frac{P_D}{\dot{m}_D} = (1 + y) \cdot \Delta h_{is,D} \cdot \eta_{is,D} \quad (5)$$

Based on the ORC power system data, available in literature from a plant in USA, Arizona Public

Service Saguaro plant [16] and a manufacturer catalogue [17], the value of y is calculated as 0.12 and used in the analysis.

For heat exchangers, the UA value at part-load conditions was assumed to vary according to the commonly used function for simulating part-load characteristics of heat exchangers in power cycles [18]:

$$\frac{\dot{m}}{\dot{m}_D} = \left(\frac{UA}{UA_D}\right)^{0.8} \tag{6}$$

It is assumed that the mass flow rates of the inner and outer fluids in the shell and tube heat exchanger remain in the same proportion at partial load conditions as at the reference load [18].

At part-load, the generator efficiency was assumed to vary as follows [19]:

$$\eta_g = \frac{\eta_{g,D} \cdot \left(\frac{P}{P_D}\right)}{\eta_{g,D} \cdot \left(\frac{P}{P_D}\right) + \left[\left(1-\eta_{g,D}\right) \cdot \left(\left(1-F_{cu}\right) + F_{cu} \cdot \left(\frac{P}{P_D}\right)^2\right)\right]} \tag{7}$$

where F_{cu} is the copper loss fraction, referring to the copper losses which are produced in the winding of the stator of the generator. Following Haglind and Elmegaard [19] a value of 0.43 was assumed for F_{cu}.

The variation of organic working fluid pump efficiency at part-load was estimated using a polynomial expression extracted from Veres [20]:

$$\eta_P = \eta_{P,D} \cdot \left[-0.029265 \cdot \left(\frac{\dot{V}}{\dot{V}_D}\right)^3 - 0.14086 \cdot \left(\frac{\dot{V}}{\dot{V}_D}\right)^2 + 0.3096 \cdot \left(\frac{\dot{V}}{\dot{V}_D}\right) + 0.86387\right] \tag{8}$$

where $\dot{V}$ is volume flow rate at the pump inlet and $\eta_{P,D}$ is the pump design efficiency. The change of pump efficiency with rotational speed was neglected compared to the original expression.

2.4 Thermal energy storage

Thermal energy storage tank is modelled as a well-mixed tank. The variations in the value of UA for the storage tank (UA_{Tank}) is calculated as follows [21]:

$$UA_{Tank} = a_{Tank} \cdot T_{salt} + b_{Tank} \tag{9}$$

where T_{salt} is the temperature of salt in the tank, a_{Tank} and b_{Tank} are the experimentally evaluated parameters for the molten salt based storage tank.

2.5 Economic analysis

The annualized cost (AC) for the proposed system is calculated by

$$AC_{sys} = \left(C_{sys} \cdot CRF + C_{O\&M}\right) \quad and \quad CRF = d \cdot \frac{(1+d)^k}{((1+d)^k) - 1} \tag{10}$$

where C_{sys} is capital cost of complete plant, including cost of solar field, heat exchangers, storage tank, ORC power system, land and site development, civil works, and miscellaneous cost, $C_{O\&M}$ is annual operation and maintenance cost, CRF is capital recovery factor, d is discount rate, and k is lifetime.

The levelized cost of energy (LCOE) is calculated as follows:

$$LCOE = AC_{sys}/E_{Annual,net} \quad (11)$$

where $E_{Annual,net}$ is the net annual electricity generation.

3. Results and discussion

The techno-economic analyses were carried out using the Engineering Equation Solver (EES) [22]. DNI data for the place Jodhpur (India) were taken from Ramaswamy et al. [23] and annual simulations were performed. For the ORC unit, the most widely used working fluid for medium temperature and medium-scale plants, n-pentane and MM were used. In order to determine the ORC turbine performance characteristics, the ORC power system data, available in literature from a plant in USA, Arizona Public Service Saguaro plant [16] and a manufacturer catalogue [17], were used. The data given in Table 2 were used to compare the ORC power system performance curve available from the literature and the results are shown in Figure 2. For load up to 40 %, the maximum value of absolute deviation in gross thermal efficiency of the ORC is 0.5 and 0.28 percentage points for n-pentane and MM, respectively. The maximum value of absolute deviation in gross thermal efficiency for load lower than 40 % is about 2.2 % and 1 % for n-pentane and MM, respectively. The CSP plant was modelled with thermal energy storage and during low radiation the stored energy is used in such a way that the plant will operate at near full load. Therefore, the occurrences of ORC power system operation at a load below than 40 % is much lower. The solar field performance characteristics for the installed PTC-based system were taken from Desai et al. [15] and for foil-based system from data provided by Heliac ApS, Denmark. For the molten salt storage tank, the variations of UA value with temperature was taken from an experimentally developed correlation by Herrmann et al. [20]. The data used for the techno-economic analysis of the PTC-based and foil-based solar plants are given in Table 3 and Table 4. A total 10 % penalty in net annual energy output for start-up/shut-down (transient effect) and other related losses was considered in the analysis [26]. Four different thermal energy storage capacities, 1 h, 3 h, 6 h and 9 h, were considered for the analysis. In order to determine the optimum value of LCOE (for a given place, solar collector field and storage capacities), the variations in LCOE with respect to solar field area were determined [24]. The results for PTC-based and foil-based solar plants for different discount rates (3 % and 10 %) and ORC power system with n-pentane working fluid are depicted in Figure 3. Typically, a discount rate in a range of 3 to 10 % is used in literature [15, 31].

Table 2. Data used for comparisons between the ORC power system performance curves.

Input Parameter	APS Saguaro plant	Turboden
Thermal oil inlet and outlet temperature	300°C and 120°C	270°C and 140°C
ORC working fluid	n-Pentane	MM
Evaporation pressure	22.3 bar	12.01 bar (assumed)
Power cycle inlet temperature	204°C	215°C (assumed)
Gross electrical efficiency at design condition	20.7 %	20 %
Gross output	1000 kWe	600 kWe
Condensation temperature	25°C (assumed)	40°C
Temperature driving force at design condition	Regenerator: 20°C; Condenser: 5°C (assumed)	Regenerator: 20°C; Condenser: 5°C (assumed)
Design isentropic efficiency of turbine ($\eta_{is,D}$)	0.73 (calculated)	0.71 (calculated)
Willans line equation parameter	y = 0.12 (calculated)	y = 0.12 (calculated)
Generator efficiency parameters	$\eta_{g,D} = 0.93$, F_{cu} = 0.43 (assumed)	$\eta_{g,D} = 0.93$, F_{cu} = 0.43 (assumed)
Design isentropic efficiency of pump ($\eta_{P,D}$)	0.7 (assumed)	0.7 (assumed)

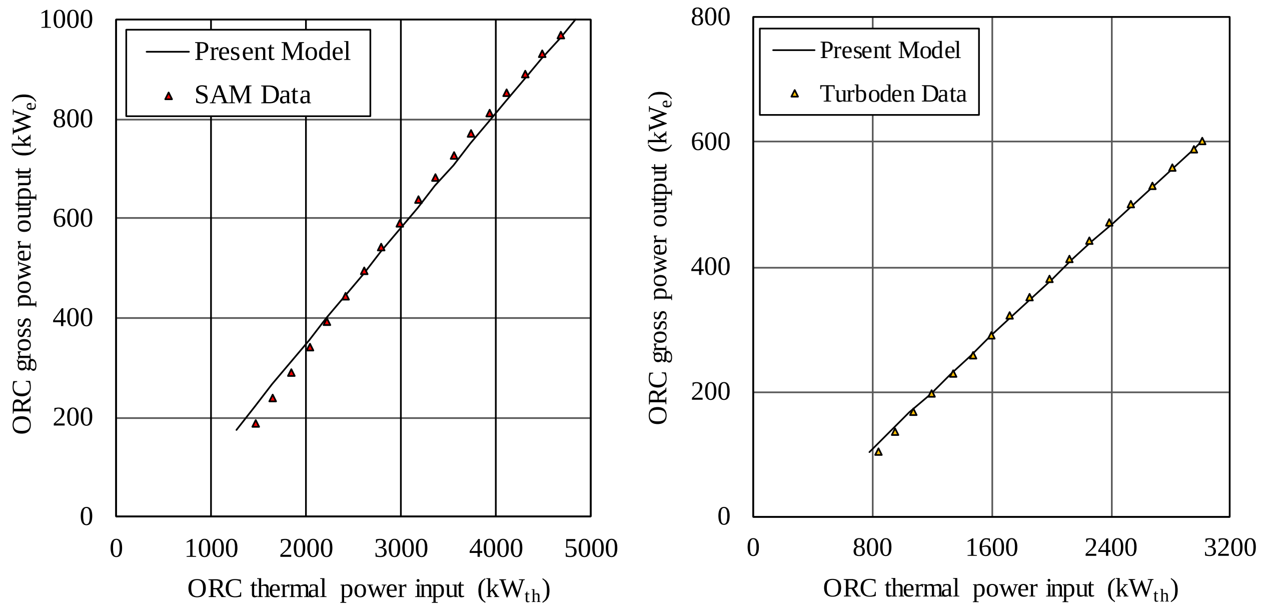

Figure 2. Comparisons between the ORC power system performance using (i) System advisor model (SAM) for the 1 MW APS Saguaro plant and the present model (left figure) and (ii) Turboden data for a 600 kW plant and the present model (right figure).

Table 3. Data used for the analysis of PTC-based and foil-based power plants.

Input Parameter	Value
Place	Jodhpur (India)
Solar collector field efficiency model parameters	*For PTC field* [15]: $\eta_{o,CL}$ = 0.7; U_l = 0.1 W/(m^2·K); *For foil-based solar field*: η_o = 0.833; U_l = 0.85 W/(m^2·K) and 0.68 W/(m^2·K) (with improvements)
Solar collector tracking mode	*For PTC:* focal axis N-S and tracking E-W; *For foil-based collector:* two-axis tracking
PTC incidence angle modifier (K_θ)	Euro Trough design [25]
Specific land requirement	3.5·A_p [7]
Solar collector field heat transfer fluid	Therminol VP-1
Solar field outlet temperature at design	246°C (for n-Pentane); 265°C (for MM)
Solar field inlet temperature at design	165°C
Storage heat transfer fluid	Hitec XL
Storage tank UA	0.00017·T_{salt} + 0.012 (kW/m^2); T_{salt} is the temperature of salt (°C) [19]
ORC turbine inlet temperature at design	206°C (for n-Pentane); 225°C (for MM)
ORC working fluid evaporating pressure at design	24.67 bar (for n-Pentane); 12.01 bar (for MM)
ORC working fluid condensing pressure at design	0.984 bar (for n-Pentane); 0.09374 (for MM)
Design condition ambient temperature (T_a)	30°C
Gross peak plant output at design ($P_{gross,D}$)	1 MWe
Penalty for start-up/shut-down and other losses	10 % of net power output [26]
Parasitic electric energy use for solar field, TES pump, antifreeze pumping, and cooling towers	12 % of net power output [16]
TES electric heating system efficiency	0.9
Temperature driving force at design (ΔT_{min})	20°C (for regenerator); 5°C (for condenser)
Isentropic efficiency of turbine at design ($\eta_{is,D}$)	0.72
Turn down ratio of turbine (P_{min}/P_{max})	0.1 [23]
Willans line equation parameters	$a = -y \cdot P_D$ [14], y = 0.12; $b = (1+y) \cdot \Delta h_{is} \cdot \eta_{is,D}$ [15]
Generator efficiency parameters	$\eta_{g,D}$ = 0.93, F_{cu} = 0.43 [19]
Isentropic efficiency of pump at design ($\eta_{P,D}$)	0.7

Table 4. Data used for the economic analysis.

Parameters	Value
Solar field and heat transfer fluid system cost, C_{SF} (€)	*For PTC*: $\frac{C_{SF}}{C_{SF,ref}} = \left(\frac{Capacity_{SF}}{Capacity_{ref}}\right)^{0.85}$; $C_{SF,ref}$ = 179,776,800 € [16], $Capacity_{ref}$ = 984,000 m^2 [16] *Foil-based collector:* 250 (for current plants) and 150 (for future plants)
Land and site development cost (€/m^2 of land)	5.5 [27]
Specific cost of Hitec XL (€/kg)	0.96 [28]
Storage tank cost (€/m^3)	677 [4]
Civil works cost (€)	$154.4\cdot(kW_e) - 0.000484\cdot(kW_e)^{0.75}$ [29]
Miscellaneous cost (€/kWe)	167 [27]
Complete power block cost (€/kW)	1626 (for Pentane) [30]; 1846 (for MM) [7]
Oil to salt heat exchanger cost (€)	130,520 [27]
Annual operating and maintenance cost	*For PTC-based plant:* Fixed cost (on total investment) - 2 %; Variable cost - 4 €/MWh. *For foil-based plant:* Fixed cost (on total investment) – 1.4 %; Variable cost – 2.8 €/MWh
Lifetime (y)	25

Note: Parameters for cost correlations have been updated to the monetary value of 2018 using the Chemical Engineering Plant Cost Index.

The current foil-based solar field receiver is mainly optimized for the district heating applications, and there is a significant potential for improvement of its thermal performance. Moreover, foil-based concentrating solar collectors are easy to produce compared to the mirror based concentrating solar collector. Annually, a single machine can produce 100 GW worth of lenses, which is equivalent to more than 5 times the global installed CSP capacity today. High production rate, along with the use of standard components in the rest of the system, ensures scalability and security of supply. As a result, a high cost reduction potential for future foil-based CSP plants exist. The analysis of the foil-based CSP plant, considering medium to large-scale production cost (150 €/m^2) and 20 % improvement in the heat-loss coefficient of the receiver, is also done. The results for the optimized condition of future foil-based CSP plants are shown in Figure 3. Considering the current cost of the foil-based solar field and performance parameters, the results indicate that the average LCOE is about 20 % lower than that of the PTC-based plants. Assuming large-scale production and improved receiver performance, the results suggest that the foil-based concentrating solar system can reduce the levelized cost of energy by up to about 40 % compared to PTC-based plants.

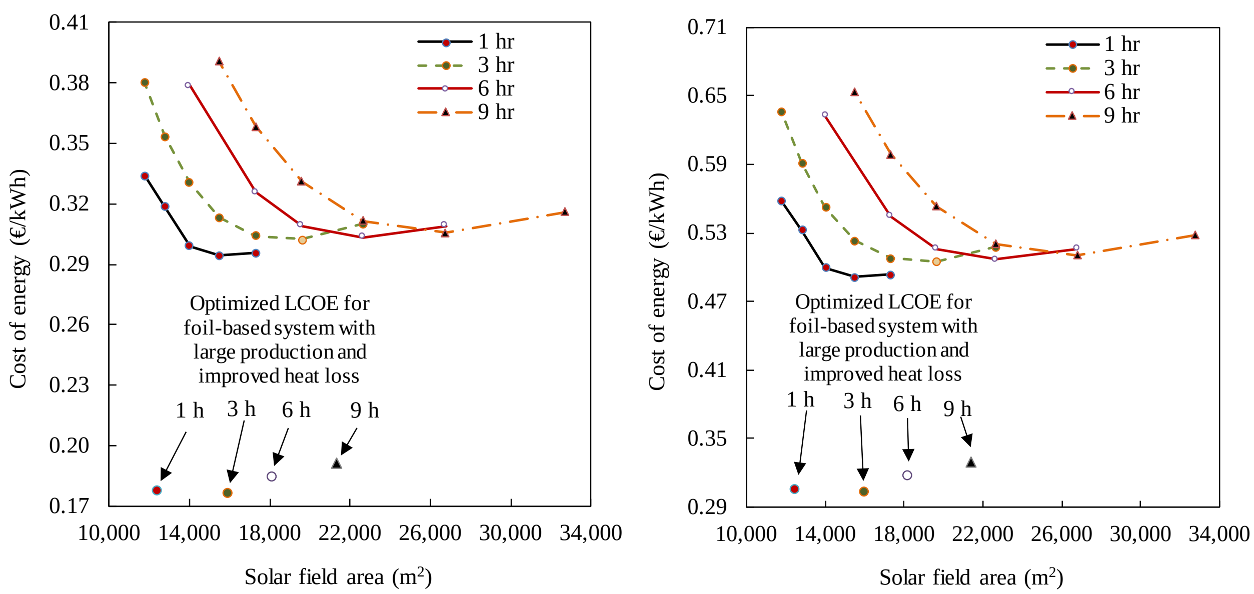

Figure 3a. Variations in LCOE with PTC area. Discount rates: 3% (left figure) and 10% (right figure).

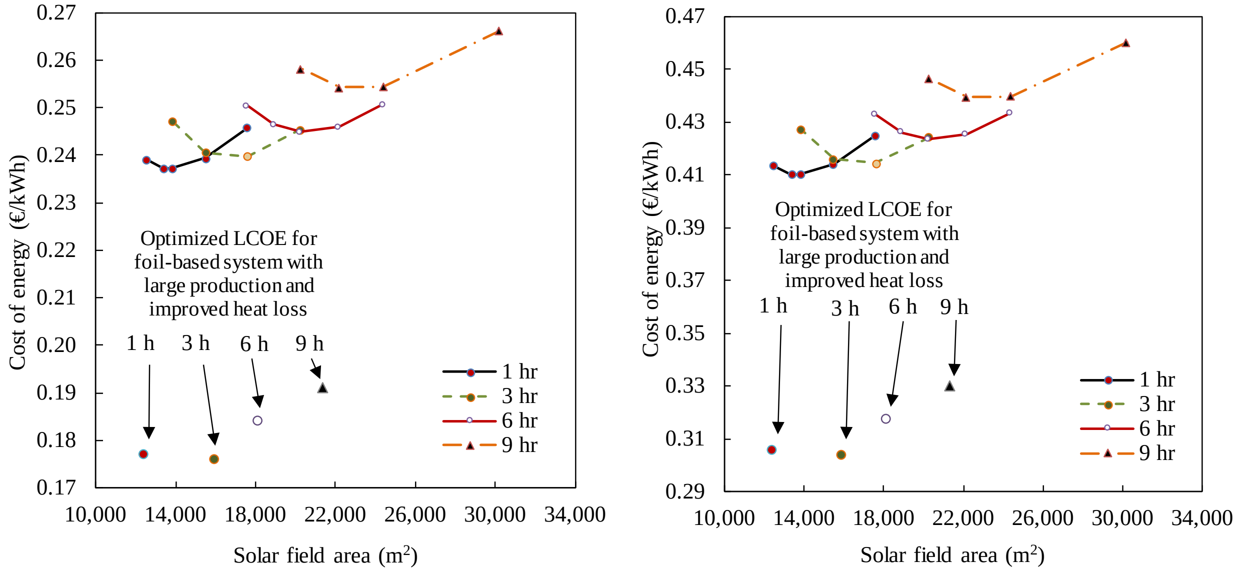

Figure 3b. Variations in LCOE with foil-based solar field area. Discount rates: 3 % (left figure) and 10 % (right figure).

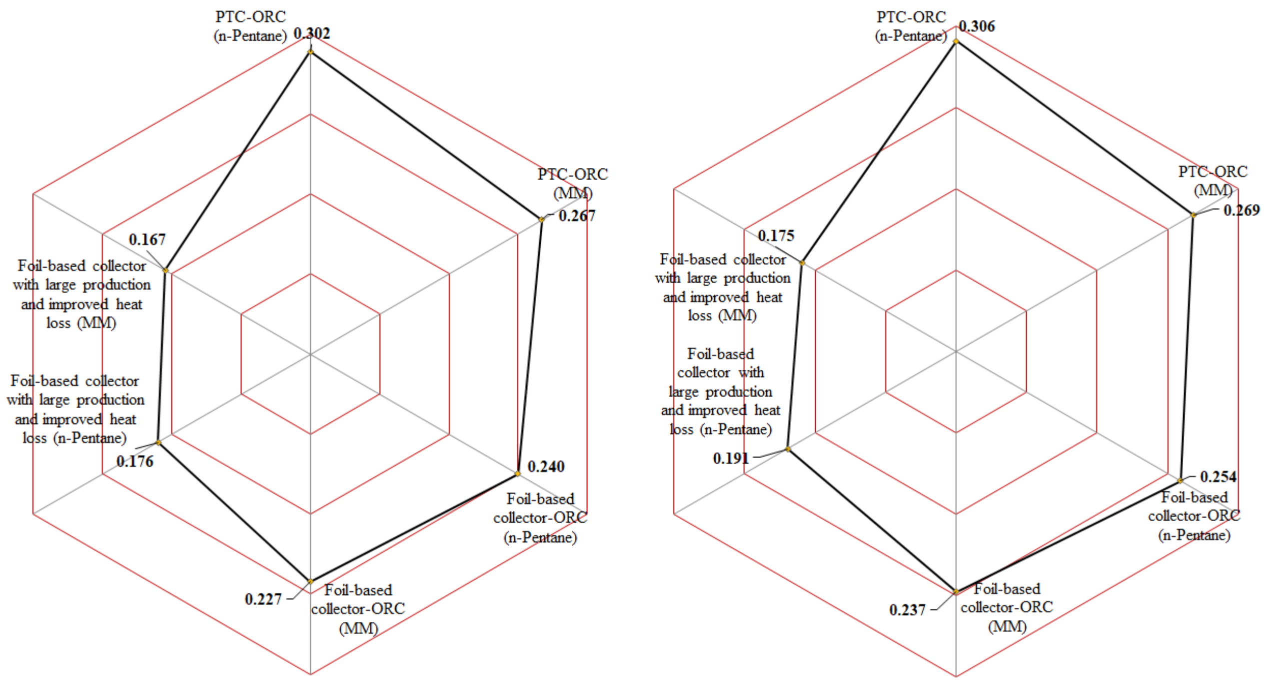

Figure 4. Comparisons of LCOE with discount rate 3 %. Storage capacity: 3 h (left figure) and 9 h (right figure).

Apart from n-pentane, the organic working fluid MM is also used for the analysis. Comparisons between PTC-based and foil-based CSP plants with organic working fluid n-pentane and MM is depicted in Figure 4. For the foil-based CSP plant, a comparison of the techno-economic performance of MM and n-pentane indicates that the former achieves in average about 5 % lower levelized cost of energy than the latter. The power block of the MM-based ORC power system has about 12 % higher specific cost (€/kW); however it also achieves much better thermodynamic performance than n-pentane, resulting in a lower LCOE for the MM-based system. For the PTC-based CSP plant, a comparison of the techno-economic performance of MM and n-pentane indicates that the former achieves in average about 12 % lower levelized cost of energy than the latter (see Figure 4). As the PTC-based system is using an evacuated tube receiver the heat loss at higher operating temperature is lower compared to the foil-based system at the same operating temperature. Therefore, the decrease in LCOE (relative to n-pentane based system) for PTC-based CSP plant with MM working fluid is higher than for foil-based CSP plant with MM as working fluid.

4. Conclusions

In this paper, a comparative analysis between PTC-based and micro-structured polymer foil-based CSP plants was performed. Two different working fluids, n-pentane and MM, were considered for the organic Rankine cycle power system. Optimum solar field areas for different storage capacities were evaluated. The results suggest that the cost of energy for a foil-based CSP plant is about 20 % lower than that of a PTC based CSP plant with n-pentane working fluid for ORC power system. The organic working fluid MM achieves in average about 5 % and 12 % lower cost of energy than n-pentane working fluid for foil-based CSP plant and PTC-based CSP plant, respectively. Considering large-scale production and improved receiver design, the results suggest that the foil-based concentrating solar system can reduce the levelized cost of energy by up to about 40 % compared to parabolic trough collector based plants. The foil-based concentrating solar system is a promising alternative for district heating and cooling, desalination, industrial process heat applications, power generation, and multi-generation.

Acknowledgements

The research presented in this paper has been funded by the European Union's Horizon 2020 research and innovation programme with a Marie Skłodowska-Curie Individual Fellowship under grant agreement no. 794562 (Project: Small-scale CSP). The financial support is gratefully acknowledged.

References

[1] Quoilin, S., Van Den Broek, M., Declaye, S., Dewallef, P. and Lemort, V., Techno-economic survey of Organic Rankine Cycle (ORC) systems. Renew Sustain Energy Rev 2013;22:68–186.

[2] He Y-L., Mei D-H., Tao W-Q., Yang W-W., Liu H-L., Simulation of the parabolic trough solar energy generation system with Organic Rankine Cycle. Appl Energy 2012;97:630–641.

[3] Casartelli D., Binotti M., Silva P., Macchi E., Roccaro E., Passera T., Power block off-design control strategies for indirect solar ORC cycles. Energy Proc 2015;69:1220–1230.

[4] Cocco, D., Serra, F., Performance comparison of two-tank direct and thermocline thermal energy storage systems for 1 MWe class concentrating solar power plants. Energy 2015;81:526–536.

[5] Cocco D., Cau G., Energy and economic analysis of concentrating solar power plants based on parabolic trough and linear Fresnel collectors. Proc IMechE Part A: J Power and Energy 2015;229(6):677–688.

[6] Rodríguez, J.M., Sánchez, D., Martínez, G.S., Ikken, B., Techno-economic assessment of thermal energy storage solutions for a 1 MWe CSP-ORC power plant. Sol Energy 2016;140:206–218.

[7] Desai N.B., Bandyopadhyay S., Thermo-economic analysis and selection of working fluid for solar organic Rankine cycle. Appl Therm Eng 2016;95:471–481.

[8] Garg, P., Orosz, M.S., Kumar, P., Thermo-economic evaluation of ORCs for various working fluids. Appl Therm Eng 2016;109:841–853.

[9] Tzivanidis, C., Bellos, E., Antonopoulos, K.A, Energetic and financial investigation of a stand-alone solar-thermal Organic Rankine Cycle power plant. Energy Convers Manage 2016;126:421–433.

[10] Russo, V., Mazzei, D., Liberatore, R., Thermal energy storage with integrated heat exchangers using stratified molten salt system for 1 MWe CSP. In AIP Conference Proceedings 2018;2033(1):090025.

[11] Petrollese, M., Cocco, D., Robust optimization for the preliminary design of solar organic Rankine cycle (ORC) systems. Energy Convers Manage 2019;184:338–349.

[12] Bellos, E., Tzivanidis, C., Investigation of a hybrid ORC driven by waste heat and solar energy. Energy Convers Manage 2018;156:427–439.

[13] Heller, P. (editor), The Performance of Concentrated Solar Power (CSP) Systems: Analysis, Measurement and Assessment. Woodhead Publishing 2017.

[14] Mavromatis S.P., Kokossis A.C., Conceptual optimisation of utility networks for operational variations—I. targets and level optimisation. Chem. Eng. Sci. 1998;53:1585–1608.

[15] Desai, N.B., Kedare S.B., Bandyopadhyay S., Optimization of design radiation for concentrating solar thermal power plants without storage. Sol Energy 2014;107:98–112.

[16] NREL, 2018. National Renewable Energy Laboratory, <www.sam.nrel.gov/> accessed 15.12.2018.

[17] Turboden, 2018. <www.turboden.com> accessed 22.11.2018.

[18] Patnode, A.M., Simulation and performance evaluation of parabolic trough solar power plants. M.Sc. Thesis, University of Wisconsin-Madison, 2006.

[19] Haglind, F., Elmegaard, B., Methodologies for predicting the part-load performance of aero-derivative gas turbines. Energy 2009;34(10):1484–1492.

[20] Veres, J., Centrifugal and Axial Pump Design and Off-Design Performance Prediction; Technical Report; NASA: Sunnyvale, CA, USA, 1994.

[21] Herrmann, U., Kelly, B., Price, H., Two-tank molten salt storage for parabolic trough solar power plants. Energy 2004;29(5-6):883–893.

[22] Klein, S., 2018. “Software F-Chart, EES-Engineering Equation Solver” V10.478.

[23] Ramaswamy, M.A., Rao, B., Thirumalai, N.C., Suresh, N.S., Estimation of Hourly Direct Normal Irradiance (DNI) for 22 Stations in India. CSTEP, Bangalore, India, 2013.

[24] Desai, N.B., Bandyopadhyay, S., Line-focusing concentrating solar collector-based power plants: a review. Clean Technologies and Environmental Policy 2017;9(1):9–35.

[25] Schenk, H., Hirsch T., Fabian Feldhoff J., Wittmann M., Energetic Comparison of Linear Fresnel and Parabolic Trough Collector Systems. J. Sol. Energy Eng. 2014;136:041015.

[26] Manzolini, G., Bellarmino, M., Macchi, E., Silva, P., Solar thermodynamic plants for cogenerative industrial applications in southern Europe. Renew Energy 2011;36(1):235–243.

[27] IIT Bombay, Solar Thermal Simulator Version 2.0, 2014.

[28] Pan, C.A., Ferruzza, D., Guédez, R., Dinter, F., Laumert, B., Haglind, F., Identification of optimum molten salts for use as heat transfer fluids in parabolic trough CSP plants: A techno-economic comparative optimization. In AIP Conference Proceedings 2018;2033(1):030012.

[29] Krishnamurthy P., Mishra S., Banerjee R., An analysis of costs of parabolic trough technology in India, Energy Policy 2012;48:407–419.

[30] Arvay P., Muller M.R., Ramdeen V., Economic Implementation of the Organic Rankine Cycle in Industry, ACEEE Summer Study Energy Efficiency in Industry 2011, New York, USA;1–12.

[31] Rovira, A., Barbero, R., Montes, M.J., Abbas, R., Varela, F., Analysis and comparison of Integrated Solar Combined Cycles using parabolic troughs and linear Fresnel reflectors as concentrating systems. Appl Energy 2016;162:990–1000.