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Conference paper

Energy and exergy analysis of a parabolic trough driven an ORC cycle for heat and power supply

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ABSTRACT

Converting solar energy using the Parabolic Trough Collector (PTC) to produce electrical energy and supply industrial heat is one of the most prominent and most popular sustainable and renewable, widely used throughout the worldwide due to its effectiveness and benefit returns. For this reason, this study aims to investigate the effectiveness of these power plants under a specific climatic conditions and analysis the results come out from the simulation using an EES developed model. The analysis investigates the energy and exergy of the PTC plant coupled with Turboden ORC cycle. The presented model allows us to preview the theoretical results and derive the expected results smoothly, with the possibility of development for a better control of the use of renewable energies in the industrial field. The thermal efficiency of the ORC cycle increases as the heat output increases until it reaches an almost constant value above 2801 [kW] in heat output with a output capacity of the ORC cycle about 1 [MW].

1. INTRODUCTION

The energy and exergy analysis of a parabolic trough collector driven Organic Rankine Cycle (ORC) for the supply of heat and electricity involves the evaluation of the efficiency and performance of this

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system. Several research papers focus on this topic (Abou Houran et al., 2024; Ahmad et al., 2022; Bellos & Tzivanidis, 2021; Polanco Piñerez et al., 2021; Wang et al., 2017), evaluating different aspects such as energy efficiency, thermal performance and environmental impact (Karoua et al., 2023). Studies have been carried out on the use of solar energy to drive ORCs (Ahmad et al., 2022), particularly with parabolic trough collectors, to improve energy production and reduce environmental impact.

The analysis typically involves evaluating the net power output, thermal efficiency and performance of different working fluids such as toluene, cyclohexane and benzene in the ORC system (Xu et al., 2015). Researchers have validated thermodynamic models to ensure accurate predictions of power output and efficiency. The results of these studies will help determine the optimal locations for implementing solar ORC systems to increase their efficiency and market penetration, especially in regions with high solar radiation.

Overall, the research on energy and exergy analysis of parabolic trough driven ORC systems highlights the importance of optimizing parameters, selecting appropriate working fluids and considering environmental factors to improve the overall performance and sustainability of these systems.

In this study, a parabolic trough collector field was coupled with ORC cycle of one MW to insure the thermal needed and produce electricity and heat. A model of energy and exergy analysis was developed to investigate the performance of the power plant.

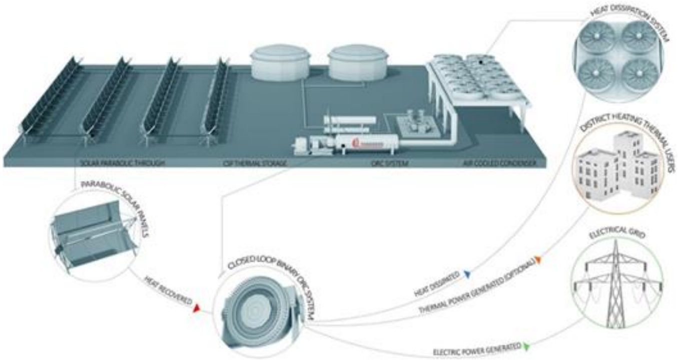

Fig 1. Turboden ORC cycle powered by a parabolic trough collector.

2. MATHEMATIC MODELLING:

2.1 Parabolic Trough Collector:

Parabolic trough collector, as an imaging-concentrating collector, which utilizes only the solar Direct Normal Irradiation (DNI), which reaches in its aperture (A_0).

$$Q_s = DNI \cdot A_o \tag{1}$$

The solar energy incident on the absorber tube is evaluated by the following relationship:

$$Q_{abs} = Q_s \cdot \rho \cdot \delta_{opt} \cdot \tau \cdot \alpha \tag{2}$$

The working fluid captures a part of this solar energy and its temperature level increases. This energy amount is the useful energy (Ahmad et al., 2022):

$$Qu = \dot{m} \cdot cp \cdot \left(T_{out} - T_{in}\right) \tag{3}$$

$$Qu = h \cdot A_{aint} \cdot \left(T_{abs} - T_f\right) \tag{4}$$

Where h is the heat convection coefficient of the working fluid (Wang et al., 2017):

$$Nu = 0.023 \times Re^{0.8} \times Pr^{0.4} \tag{5}$$

$$Re = \frac{4\dot{m}}{\pi \cdot D_{vint} \cdot \mu} \tag{6}$$

$$Pr = \frac{Cp \times \mu}{k} \tag{7}$$

2.1.1 Thermal losses:

The next important part of the thermal analysis is the thermal losses calculations.

$$Q_{abs} = Qu + Q_{loss} \tag{8}$$

Energy lost between the receiver tube and the glass tube given by eqs (9) and (10) (Abou Houran et al., 2024):

$$Q_{p1} = A_{aext} \cdot \sigma \cdot \frac{T_{ab}{}^{4} - T_{v}{}^{4}}{\left((1/\varepsilon_{ab}) + ((1/\varepsilon_{v}) - 1) \cdot (A_{aext} / A_{vint})\right)} + \left(2 \cdot \pi \cdot k_{air} \cdot \frac{T_{ab} - T_{v}}{ln(D_{vint} / D_{aext})}\right) \tag{9}$$

Energy lost between the glass tube and environment (Housseyn et al., 2018):

$$Q_{p2} = A_{vext} \cdot h_{out} \cdot (T_v - T_{amb}) + A_{vext} \cdot \sigma \cdot \varepsilon_v \cdot \left(T_v{}^4 - T_c{}^4\right) \tag{10}$$

$$Q_{loss} = Q_{p1} + Q_{p2} \tag{11}$$

2.1.2 Thermal efficiency

The thermal efficiency was expressed by the flowing equation:

$$\eta = \frac{Qu}{DNI} \tag{12}$$

2.1.3 Exergy analysis:

Solar exergy (Zhang et al., 2022):

$$E_s = Qs \cdot \left(1 - \left(\frac{4}{3}\right) \cdot \left(\frac{T_{amb}}{T_s}\right) + \left(\frac{1}{3}\right) \cdot \left(\frac{T_{amb}}{T_s}\right)^4\right) \tag{13}$$

Useful exergy (Zhang et al., 2022):

$$E_u = Qu - T_{amb} \cdot (s_2 - s_1) \tag{14}$$

Exergy efficiency (Xu et al., 2015):

$$\eta_{ex} = \frac{E_u}{E_s} \tag{15}$$

2.2 Organic Ranking Cycle

In order to calculate the electrical power produced by the ORC cycle, we have developed the sixth order equation eq (16), which was obtained using the curve fitting function of EES;

$$\tau_n = -1{,}58394 + 588{,}19 \cdot x - 1648{,}84 \cdot x^2 + 2489{,}13 \cdot x^3 - 1825{,}34 \cdot x^4 + 420{,}708 \cdot x^5 + 78{,}3251 \cdot x^6 \tag{16}$$

Where;

$$\tau_n = \frac{\eta_{th}}{\eta_{th\_n}} \tag{17}$$

$$x = \frac{P_{th}}{P_{th\_n}} \tag{18}$$

This equation allows us to determine the variation of the ratio of the thermal efficiency to the nominal thermal efficiency (τ_n) as a function of the ratio of the thermal load (thermal energy from the solar field) to the nominal thermal power (nominal thermal power required by the Turboden machine) (x), (see Fig. 2)

Input and output data for this Turboden machine:

- Input temperature 206°C
- Output temperature 305°C
- Nominal thermal efficiency 24%.
- Nominal thermal power 4820 kW

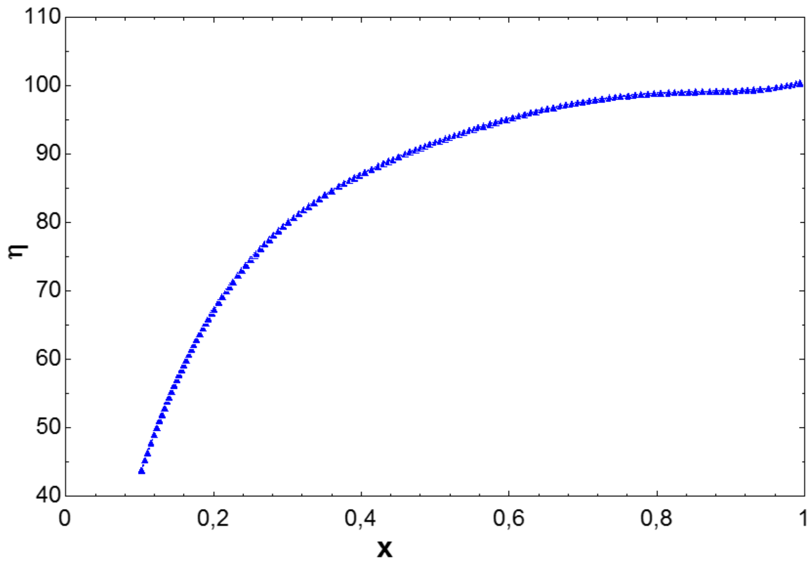

Fig 1. Evolution of the nominal thermal efficiency of the ORC cycle as a function of the load x.

3. RESULTS AND DISCUSSION

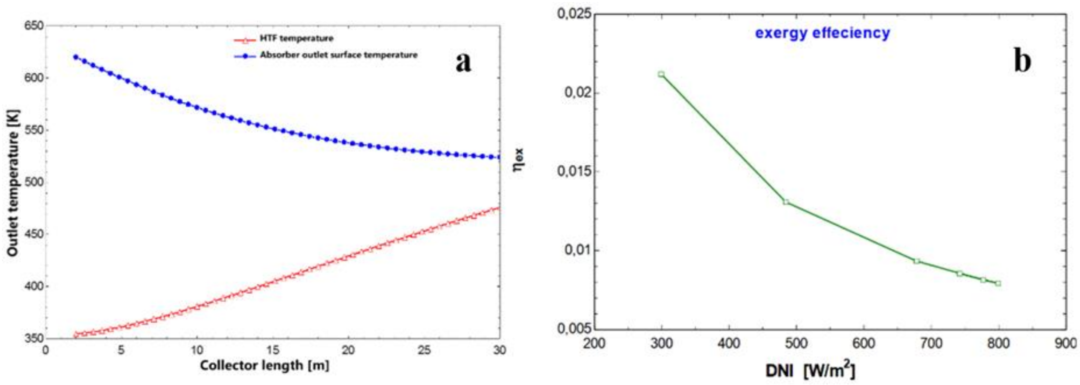

Fig 3 a) Evolution of outlet temperature as a function of collector length, b) exergy variation on function of DNI.

We have studied the variation of the outlet temperature of the heat transfer fluid and the temperature of the outer surface of the receiver tube as a function of the collector length. As shown in Fig. 3, a, we can see that the temperature of the HTF increases as the length of the collector increases, and the opposite is true for the temperature of the outer surface of the receiver tube, which decreases as the length increases. This result can explained by the increase in the heat transfer coefficient between the tube and the heat transfer fluid. The latter absorbs this heat in order to transfer it to the ORC cycle.

The exergy decreases, as the DNI is increase this is due to the increased loss of thermal energy between the collector and the surrounding air because of the increase in temperature at the collector surface, which is not transferred to the heat transfer fluid. (See Fig. 3, b)

Fig 2 shows the variation in electrical power generated as a function of the power provided by the solar array. Under the condition that if the power of the solar field is 10% lower than the nominal power of the Turboden machine, the machine does not produce electricity, as shown in Figure 4. The production does not begin until the thermal power is equal to 400 [kW], then the electrical power is varied proportionally with the thermal power of the solar field. The thermal efficiency of the ORC cycle is increased with the increase of the thermal power until it reaches an almost constant value from there of the value 2801 [kW] in thermal power.

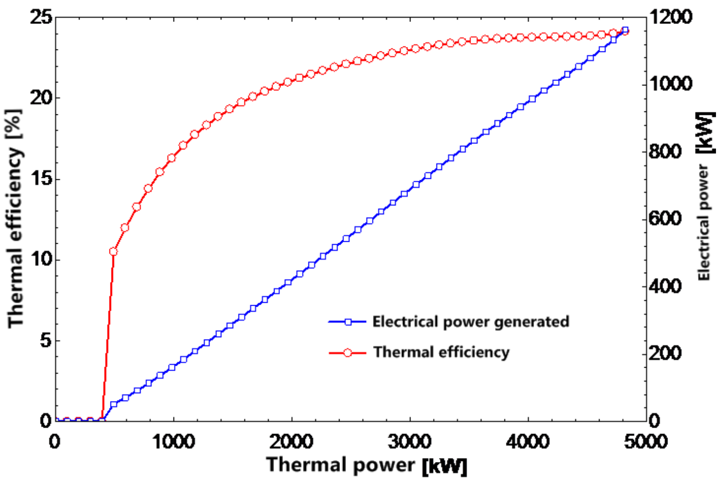

Fig 2. Variation in the electrical power generated as a function of the power provided by the solar field.

4. CONCLUSION

In the light of the results obtained in this study, which aimed to develop a highly efficient simulation model using the EES software. The model analyzed the energy of the solar power plant associated with the ORC cycle to generate electricity and heat, and the results obtained were very encouraging when the electricity generation was from the thermal energy of the solar field. This amounted to 2801 [kW] and the corresponding generation capacity reaches 1 [MW]. In addition, the excess heat generated from the solar field can be exploited in heating applications.

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NOMENCLATURE

A_0	Parabolic trough aperture (m²)
A_{aint}	Inner surface of the absorber (m²)
Cp	Specific heat at a fixed pressure (J/kg-K)
DNI	Direct Normal irradiation (W/m²)
D_{vint}	Inner diameter of the glass tube (m)
Es	Sun exergy (W)
Eu	Useful exergy (W)
h	Heat transfer coefficient (W/m²-K)
h_{out}	Convection coefficient between cover and ambient (W/m²-K)
k	Thermal conductivity (W/m-K)
	Mass flow rate (kg/s)
Nu	Nusselt number (-)
Pr	Prandtl number (-)
P_{th}	Thermal energy from the solar field
P_{th_n}	Nominal thermal power (nominal thermal power required by the Turboden machine)
Q_{abs}	Solar energy incident on the absorber tube (W)
Q_{loss}	Thermal losses form the absorber tube to environment (W)
Q_{p1}	Energy lost between the receiver tube and the glass tube (W)
Q_{p2}	Energy lost between the glass tube and environment (W)
Q_s	Available solar irradiation in collector (W)
Q_u	Useful absorber energy by HTF (W)
Re	Reynolds number (-)

s_1 , s_2	Specific entropy at state 1 and 2 [kJ/kg-K]
T_{abs}	Absorber temperature (K)
T_{amb}	Ambient temperature (K)
T_c	Cover temperature (K)
T_f	Mean HTF temperature (K)
T_{in}	Inlet temperature of the HTF to the absorber tube (K)
T_{out}	Outlet temperature of the HTF to the absorber tube (K)
T_s	Equivalent sun temperature (K)
T_v	Cover temperature (K]
x	Load charge or energy demand
Greek Symbols	
α	Absorber absorbance
δ_{opt}	optical efficiency
ε_{ab}	Absorber emissivity (-)
ε_v	Glass emissivity (-)
η_{ex}	Exergy efficiency (-)
η_{th}	Thermal efficiency (-)
η_{th_n}	Nominal thermal efficiency (-)
μ	Dynamic viscosity (kg/m-s)
ρ	Reflector reflectance (-)
σ	Stefan-Boltzmann coefficient (W/m²-K⁴)
τ	Cover transmittance (-)
τ_n	nominal thermal efficiency

ABBREVIATIONS

EES	Engineer equator solver	HTF	Heat transfer fluid
ORC	Organic Rankine cycle	CSP	concentrating solar power
PTC	Parabolic trough collector		

REFERENCES

Abou Houran, M., Dagestani, A. A., Nutakki, T. U. K., Albani, A., Ifseisi, A. A., Riaz, F., & Peng, F. (2024, 2024/03/01/). Energy and exergy analysis of a novel solar-based system merged with power cycle. *Applied Thermal Engineering, 240*, 122080. https://doi.org/https://doi.org/10.1016/j.applthermaleng.2023.122080

Ahmad, S., Ali, M., Ali, F., Ahmad, S., Ahmad, D., & Iftikhar, O. (2022, 2022). Design and Experimental Investigation of Thermosiphoning Heat Transfer through Nanofluids in Compound Parabolic Collector. *Engineering Proceedings, 12*(1), 39. https://doi.org/10.3390/engproc2021012039

Bellos, E., & Tzivanidis, C. (2021, 2021/9). Investigation of a Novel CO2 Transcritical Organic Rankine Cycle Driven by Parabolic Trough Solar Collectors. *Applied System Innovation, 4*(3), 53. https://doi.org/10.3390/asi4030053

Housseyn, K., Abdelhafid, M., Abderrahmane, H., Noureddine, M., Kamel, A., Adel, B., & Ahmed, B. (2018, 2018). Experimental investigation and exergy analysis of an air heater with a solar concentrator used for drying processes. *International Journal of Heat and Technology, 36*(3), pp-791.

Karoua, H., Laissaoui, M., Bouhallassa, A., & Lecheheb, S. (2023, 16-18 Dec. 2023). Modeling and Performance Estimation of 153 MWe Parabolic Trough Power Plant in Djamaa Algeria. 2023 14th International Renewable Energy Congress (IREC),

Polanco Piñerez, G., Valencia Ochoa, G., & Duarte-Forero, J. (2021, 2021/09/01/). Energy, exergy, and environmental assessment of a small-scale solar organic Rankine cycle using different organic fluids. *Heliyon, 7*(9), e07947. https://doi.org/https://doi.org/10.1016/j.heliyon.2021.e07947

Wang, X., Shu, G., Tian, H., Liu, P., Jing, D., & Li, X. (2017, 2017-09-15). Dynamic analysis of the dual-loop Organic Rankine Cycle for waste heat recovery of a natural gas engine. *Energy Conversion and Management, 148*, 724-736. https://doi.org/10.1016/j.enconman.2017.06.014

Xu, G., Song, G., Zhu, X., Gao, W., Li, H., & Quan, Y. (2015, 04/2015). Performance evaluation of a direct vapor generation supercritical ORC system driven by linear Fresnel reflector solar concentrator. *Applied Thermal Engineering, 80*, 196-204. https://doi.org/10.1016/j.applthermaleng.2014.12.071

Zhang, S., Liu, M., Zhao, Y., Liu, J., & Yan, J. (2022, 2022-09-01). Energy and exergy analyses of a parabolic trough concentrated solar power plant using molten salt during the start-up process. *Energy, 254*, 124480. https://doi.org/10.1016/j.energy.2022.124480