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Increase in Efficiency in Electric Power Production Using a Coupled System Heat Pump - Solar Thermal Installation for Industrial Applications

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The efficiency of an organic Rankine cycle (ORC) using low-temperature solar thermal energy, is 11 %, which increases the volume of the storage system and the solar thermal installation area that supplies the heat load to the ORC. Through a thermodynamic study of a coupled system heat pump-solar thermal installation using the R123 refrigerant, the efficiency of the ORC was increased significantly, and the installation area of the collector network and the volume of the storage system were reduced. Two case studies were evaluated: case 1, a sugar mill, and case 2, a fruit and vegetable cold room. Refrigerant R123 was selected with ODP = 0.02 and GWP = 77. The coupled system heat pump - solar thermal installation was designed to supply the power required by the process. The area of the solar thermal installation was reduced by 81 % compared to the area used to produce the same power in Case Study 1. The efficiency of the ORC increased from 11 to 14.5 % in both case studies. With the increase in efficiency and reduction in the installation area, the impact on the Earth is minimized, and greenhouse gas emissions are eliminated.

1. Introduction

Energy consumption in the industrial sector approximately accounted for 32 - 34 % of global energy consumption in 2014, and of this percentage, 74 % corresponded to the demand for heat and 26 % to the demand for electrical energy (Kumar et al., 2019). By 2019, electrical energy consumption in industrial sector had increased to 41.9 % (34.36 EJ) of the total energy consumed (IEA, 2021), in addition, this sector was responsible for emitting 8.76 Gt of CO_2 this same year mainly due to the burning of fossil fuels. In the world, the objective is to carry out the decarbonization of the planet by replacing the burning of fuels with the use of solar thermal energy as one of the alternatives to produce the energy required by the industrial sector. The transition towards the use of solar energy allows the reduction or elimination of greenhouse gases, thereby contributing to achieving the objective of not increasing the temperature beyond 1.5 °C (Schwerdtle et al., 2023).
Regardless of the type of energy used, renewable or non-renewable, in general the aim is for energy production to be as efficient as possible. The area of opportunity with respect to efficiency in the production of electrical energy from solar thermal energy is large, the efficiencies reported so far are low. Hossin et al. (2020) obtained an efficiency of 6.5 % to produce electrical power through an organic Rankine cycle (ORC) and using low-temperature solar thermal energy (120 °C) and the R245fa refrigerant. Martínez-Rodríguez et al. (2022a) reported an efficiency of 0.11 % when feeding an ORC that uses R245fa with a heat source consisting of a network of flat plate solar collectors (105 °C) with an absorber area of 3,609 m^2. The proper selection of the working fluid, the cycle configuration, the characteristics of the expander (evaporator-condenser pressure ratio), the efficiency of the heat exchangers (evaporator and condenser) and the temperature in the evaporator (source), impact in thermal efficiency of the ORC. One of the most influential variables is the temperature in the evaporator; if the pressure ratio in the turbine is constant, the thermal efficiency of ORC decreases. The use of an Alumina-Water nanomaterial as a working fluid and a device with a geometry that favors the formation of swirls during fluid transit also play an important role in increasing efficiency by around 0.153 % (Sheikholeslami and Ebrahimpour, 2022). The chemical nature of the working fluid also plays a role, as organic substances with

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low boiling points improve efficiency (Liu and He, 2020). ORC efficiencies of up to 40 % have been reported by burning fossil fuels and with an evaporator temperature of 538 °C – 566 °C (Ohji and Haraguchi, 2022). Jørgensen et al. (2019) reported the integration of two two-stage industrial heat pumps placed in parallel at a dairy plant Arla Foods' (Denmark), to increase efficiency in processes. The heat pumps allowed freezing and hot currents (90 °C) to be produced at the same time to cover the requirements of the different processes. They used Ammonia as a refrigerant, which, in addition to being economical, allows achieving minimum temperatures of up to - 50 °C, with ozone depletion potential, ODP, and global warming potential, GWP, values of zero. The cooling capacity of the pump is 1 MW, and its heating capacity is 1.5 MW. This allowed them to reduce their natural gas consumption by 42 % (although they increased the electricity consumption by 11 %) and reduced annual CO_2 emissions by 2,980 t.
At the end of 2022, 571 large-scale solar thermal plants with a capacity of 2.2 GW_{th} were reported. During 2023, the installation of 62 solar thermal projects for industrial applications in the world (331MW) began (Solar Industrial Heat Outlook, 2023-2026). The applications of solar thermal energy have been expanded using a heat pump coupled to a solar thermal installation. The coupled system has been used to produce thermal, electrical and refrigeration energy for an industrial process. Martínez-Rodríguez et al. (2022b) made a thermo-economic evaluation of an ORC assisted with low-temperature solar thermal energy (90 °C) with a thermal efficiency of 12.9 % using the R290 refrigerant. The refrigerants used in a heat pump have focused on reducing the impact on the environment, guaranteeing the energy production required by an industrial process (Schlosser et al., 2020). The main characteristics of a refrigerant are critical temperature and pressure, thermal stability and impact on the environment. Zhou et al (2020) performed an experimental analysis of a heat pump coupled to a PVT collector, a solar thermal collector and a storage tank. The heat pump operates with R22 and the system provides heating under low irradiance and temperature conditions (≤500 W/m^2, ≤6 °C), obtaining a COP of 4.7. Kong et al (2020) studied a SAHP to produce hot water with winter weather conditions in Qingdao (China), in which the freezing point is reached, with an irradiance of 69 W/m^2 and ambient temperature 1.6 °C; they used R134a as a working fluid and a condenser temperature of 26 °C and a COP of 3.09 was achieved.
In other works, the refrigerant that allows achieving the lowest energy cost is sought, using a coupled heat pump – solar thermal installation system (Martínez-Rodríguez et al., 2023). There are other works where it is necessary to use refrigerants with ODP and GWP values greater than zero to guarantee the energy supply required in a process. For example, R32 is used in air conditioning systems (Sutandi, 2020).
The purpose of the work is to increase the efficiency of an ORC for the production of electric power through a coupled system heat pump – solar thermal installation. The proposed system was designed to produce electric energy from cane bagasse from a sugar mill and generate the electric power consumed in a cold room. The working fluid used in the thermodynamic analysis of the heat pump ad the ORC is the refrigerant R123. To increase the efficiency of ORC, the evaporator outlet temperature and the evaporator heat load that is supplied by the heat pump are varied with a source temperature of 60 °C for different compression loads.

2. Design of the coupled system - ORC

The study focuses on the production of electrical power for two industrial processes. In Case Study 1, power is produced from the burning of sugarcane bagasse, and in Case Study 2, it is a cold chamber that consumes power generated by photovoltaic (PV) cells. A thermodynamic analysis of the ORC is carried out for each case study. In the analysis, the power required by the process and the pressure of 101.33 kPa at the turbine outlet are set. A refrigerant was selected that reaches the highest temperature levels with the least impact on the environment. In the design of the heat pump, operating conditions are evaluated that guarantee a COP > 2, which guarantees the profitability of the power consumed against the heat produced. The design of the coupled system – ORC is based on the lowest levels of irradiance that occur throughout the year during the winter period. The proposed system is described in Figure 1. It consists of an ORC connected to a coupled system heat pump – solar thermal installation. The main components of the solar thermal installation are the network of low-temperature solar collectors and a thermal storage system.

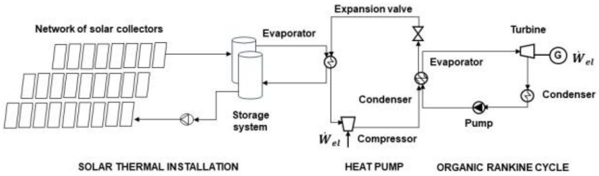

Figure 1: Schematic of the proposed coupled system - ORC to generate electric power for industrial applications

The design of the coupled system heat pump – solar thermal installation was carried out considering the environmental conditions of the original case studies to compare the importance of the proposal of this work. The design of the solar collector network aims to provide the heat load required by a heat pump to produce electrical power required by industrial process using an ORC. The heat pump model for high-quality heat production was validated with the results obtained by Shao et al. (2020) using the refrigerant R134a and the proposed model for power production was validated with the results obtained by Shao et al. (2017) using R123. The results of the heat pump and ORC validations can be requested from the corresponding author by e-mail.
ORC systems are a technical, viable and sustainable solution for small and large scale electrical energy generation and are also suitable for the conversion of low and medium level heat into electricity. The proposed ORC operates in subcritical conditions; the energy balance at each stage is presented in Eqs.(1-4).

$$\dot{W}_{turbORC} = \dot{m}_{ref}(h_1 - h_2)\eta_{turb-gen} \tag{1}$$

$$\dot{Q}_{condORC} = \dot{m}_{ref}(h_2 - h_3) \tag{2}$$

$$\dot{W}_{pumpORC} = \dot{m}_{ref}(h_4 - h_3)/\eta_{pumpORC} \tag{3}$$

$$\dot{Q}_{evapORC} = \dot{m}_{ref}(h_1 - h_4) \tag{4}$$

Where, $\dot{W}_{turbORC}$, is the power generated by the turbine; $\dot{Q}_{condORC}$, is the heat load on the condenser, $\dot{Q}_{evapORC}$, is the heat load on the evaporator, and $\dot{W}_{pumpORC}$, is the power needed to operate the pump, in kW. $(h_1 - h_2)$ is the difference in enthalpies of the expansion in the turbine, $(h_2 - h_3)$ is the difference in enthalpies of the condensation process, $(h_4 - h_3)$ is the difference in enthalpies of the pumping compression process and $(h_1 - h_4)$ is the difference in enthalpies of the vaporization process, kJ/kg; and $\dot{m}_{ref}$, is the mass flow of the refrigerant, kg/s. The efficiency of the turbine-generator, $\eta_{turb-gen}$, and the pump, $\eta_{pumpORC}$, report a value of 90%. To evaluate the performance of the ORC, the thermal efficiency, η_{ORC}, is calculated with Eq(5).

$$\eta_{ORC} = \frac{\dot{W}_{net}}{\dot{Q}_{evapORC}} = \frac{\dot{W}_{turbORC} - \dot{W}_{pumpORC}}{\dot{Q}_{evapORC}} \tag{5}$$

The electrical energy produced by the turbine is established based on the demand of the case study. A simple ORC was designed and the fluid is vaporized at high temperature and pressure. The mass flow rate of the ORC working fluid varies to ensure the production of electrical energy. Two scenarios were evaluated, in addition to the base case, to determine the scenario with the best thermal efficiency of the ORC and the smallest area of the solar collector network and the thermal storage system.
Heat pumps provide high temperature thermal energy from a low temperature heat source from process waste heat or a renewable source. Heat pumps are a highly efficient, sustainable and profitable alternative. Eqs(6-8) shows the energy balances in each stage of the heat pump cycle.

$$\dot{Q}_{condHP} = \dot{m}_{ref}(h_3 - h_4) \tag{6}$$

$$\dot{Q}_{evapHP} = \dot{m}_{ref}(h_2 - h_1) \tag{7}$$

$$\dot{W}_{compHP} = \dot{m}_{ref}(h_3 - h_2)/\eta_{comp} \tag{8}$$

Where $\dot{Q}_{condHP}$ is the heat load to supply, kW; and $\dot{Q}_{evapHP}$ and $\dot{W}_{compHP}$, are the compression work and the heat load in evaporator, respectively, kW. $(h_3 - h_4)$ corresponds to the difference in the enthalpies of the condensation process of the heat pump, $(h_2 - h_1)$ is the difference in the enthalpies of the refrigerant evaporation process, and $(h_3 - h_2)$ is the difference in the enthalpies of the compression process, kJ/kg; and $\dot{m}_{ref}$, is the refrigerant mass flow rate in heat pump, kg/s. η_{comp} is the isentropic efficiency of the compressor, as reported in 90 %.
The coefficient of performance of the heat pump, COP_{HP}, is obtained by the Eq(9).

$$COP_{HP} = \frac{\dot{Q}_{condHP}}{\dot{Q}_{condHP} - \dot{Q}_{evapHP}} \tag{9}$$

In the evaporator and condenser there is 5 °C of superheating and subcooling. The mass flow rate of the refrigerant varies depending on the heat load that the condenser must deliver to the ORC evaporator and the target temperature in each of the analyzed scenarios. This mechanical device extracts heat from a network of

low-temperature solar collectors at 60 °C and delivers it to the electrical energy production process at different temperatures.
The modeling of the solar collector network is based and validated on the methodology proposed by Martínez-Rodríguez et al. (2019) where the target temperature is reached by the number of solar collectors connected in series and the heat load required to be supplied to the process is determined adding the heat load of each series in parallel that make up the network arrangement (n-parallel x n-series). The thermal storage system in this study consists of a low temperature (<100 °C) thermally insulated water tank. The data of the average environmental conditions that were used for the design of the solar thermal installation are in Table 1.

Table 1: Average weather conditions for the winter period.

	Light hours (h)	Solar Irradiation ($kWh/m^2/d$)	Wind velocity (m/s)	Ambient temperature (°C)	Global Radiation (W/m^2)
Average	8.5	4.90	1.94	21.2	577

The selection of the working fluid is essential to improve the performance of ORC and HP based on the thermodynamic properties and environmental impact (ODP~0 and GWP<200) that it presents. The working fluid used is R123 and has the following physical properties: boiling temperature = 27.82 °C, critical temperature = 183.7 °C and critical pressure =3.662 MPa; and the following environmental characteristics: 1.3 y of lifetime in the atmosphere, ODP = 0.02 and GWP = 77, classification ASHRAE: B1 (NIST, 2024).
To evaluate the proposed methodology, two industrial processes with different demand for electrical energy were selected. The first case study is about a sugar mill that produces sugar, bioethanol, and electrical energy. In the plant, 38 t/h of sugar cane are processed for 18 h and 3,147 kW of electricity are produced with the burning of bagasse (Martínez-Rodríguez et al., 2021). In the second case, a refrigeration chamber was considered to preserve 1,800 t of apples and 850 t of potatoes per year, at a temperature of between 5 - 10 °C, the electrical demand is 34 kW (condensing unit, pump, fans, lights) and operates for 24 h (Martínez-Rodríguez et al., 2022a).
In each case study, 3 scenarios were analyzed; the first of them, called the base case, which produces the electrical power required by the industrial sector using a solar thermal installation connected directly to an ORC, the main components of the solar thermal installation being the solar collector network and storage system. In the other two scenarios, a coupled system heat pump – solar thermal installation delivers the heat load to the ORC evaporator, calling this new device coupled system – ORC.

3. Results and analysis

3.1 First case study: sugar mill that produces sugar, bioethanol and electrical energy

Table 2 shows the result of the proposed device coupled system – ORC for case study 1, which produces 3,147 kW of electrical power from sugarcane bagasse. Case study 1 considers the scenarios called base A scenario, scenario 1 and scenario 2. For base A scenario, the solar thermal installation supplies directly the energy required by the evaporator of ORC. In scenario 1, the source temperature is 105 °C with a thermal efficiency of the ORC of 0.110 and with a reduction in the absorber area of the solar collector network of 70 %. In scenario 2, the heat pump condenser temperature is maximized (144 °C) to increase the efficiency of the ORC, the COP of the heat pump is 2.53. In each scenario, the emission of 56,578 tCO_2 are eliminated, these would be emitted into the atmosphere by the burning of natural gas.
In scenarios 1 and 2, where coupled system – ORC is used, the absorber area of the solar collector network is reduced by 70 % and 81 %, respectively, compared to base A scenario. Also, the thermal storage system achieves a reduction of 70 % and 81 %, due to the heat load on the ORC evaporator is reduced by 40 and 50 % respectively, increasing the efficiency of the ORC by 30 %.

Table 2: Results of the proposed system to generate power.

Parameters and variables	Base A Scenario	Scenario 1	Scenario 2
• Organic Rankine Cycle			
ORC evaporator outlet temperature, °C	95	95	135
Pressure ratio in ORC	5.5	5.5	13.5
ORC thermal efficiency	0.110	0.110	0.145
Compressor outlet temperature, °C	-	105	144
• Heat Pump			
Heat load in heat pump condenser, kW	-	28,429	22,843
Heat load in heat pump evaporator, kW	-	34,622	13,807

ΔT_{lift} (heat pump), °C	-	65	90
Pressure ratio in heat pump	-	7.1	9.8
Heat pump COP	-	3.78	2.53
Refrigerant: ORC/HP	R123	R123/R123	R123/R123
• Solar Thermal Installation			
Solar collector network outlet temperature, °C	105	60	60
Absorber area of solar collector network, m^2	512,179	144,563	95,897
Volume of thermal storage tank, m^3	7,817	2,206	1,464
$LCOE_{el}$, USD/kWh	0.115	0.115	0.102

3.2 Second case study: frigorific chambers to preserve fruits and vegetables

For case study 2 (cold room), quantitative results of the evaluated variables are comparatively lower than case 1 (sugar mill) since the electrical demand is lower (34 kW). Table 3 displays the main parameters of the proposed system to cold room. The area reduction in the solar thermal installation of scenarios 3 and 4 compared to base B scenario is 39 % and 82 %. For the thermal storage system, a reduction of 56 % and 82 % is achieved, respectively. The emissions eliminated per year are 612 t in all scenarios.

Table 3: Characteristics of the proposed system to generate power for the cold room case study

Parameters and variables	Base B scenario	Scenario 3	Scenario 4
ORC evaporator outlet temperature, °C	90	90	135
ORC thermal efficiency	0.105	0.105	0.145
Compressor outlet temperature, °C	-	105	144
Heat pump COP	-	3.78	2.53
Refrigerant: ORC/HP	R245fa	R123/R123	R123/R123
Solar collector network outlet temperature, °C	105	60	60
Absorber area of solar collector network, m^2	3,609	1,688	637
Volume of thermal storage tank, m^3	55	24	10
$LCOE_{el}$, USD/kWh	0.109	0.115	0.090

As seen in Figure 4a (case study 1) and Figure 4b (case study 2), maintaining the same temperature in the evaporator as in the base case, the absorber area is reduced by 71 % for case 1, and 53 % for case 2. By increasing the temperature of the ORC evaporator up to 135 °C, the efficiency increased 30 % for both cases and the area decreased 81 % and 82 % for cases 1 and 2, respectively. The change in area with increasing ORC efficiency for case study 1 is 30 % greater with respect to the area in case study 2.

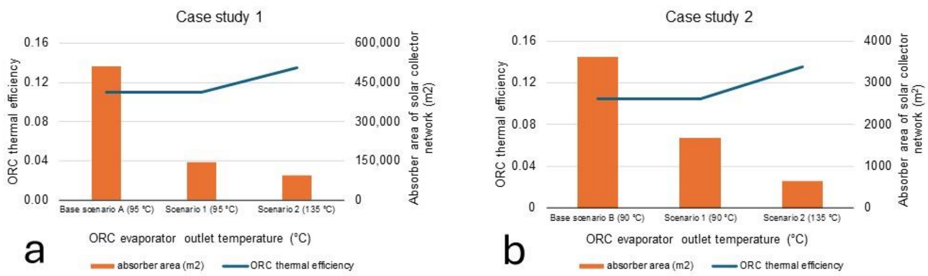

Figure 4: Behavior of the efficiency and the absorber area with respect to the condenser temperature of the heat pump, (a) Case study 1, (b) Case study 2

4. Conclusions

The developed approach can be applied to the design of the coupled system heat pump – solar thermal installation in any geographical location and operating conditions to achieve the design objectives according to the economic or spatial requirements and limitations established by the industrialist. Using the proposed coupled system heat pump – solar thermal installation device that delivers the heat load to the ORC evaporator (coupled system – ORC), the efficiency of the ORC in scenarios 2, 3 and 4 increased compared to the base scenario of study cases 1 (sugar mill) and 2 (cold chamber).

The increase in the efficiency of the ORC reduced the area of the solar thermal installation and the storage system by 82 % for case study 2, with respect to the base case.

The energy cost was reduced by 11 % for case study 1 and 18 % for case study 2 compared to the base case. Regarding emissions, 56,578 tCO_2/y were removed for case study 1 and 612 tCO_2/y for case study 2.

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