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A 4E Analysis of a Solar Organic Rankine Cycle Applied to a Paint Shop in the Automotive Industry

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Abstract: In a conventional automotive manufacturing plant, the paint shop alone can represent 36% of the total energy consumption, making it the most demanding area in terms of electricity and fossil fuel energy consumption. This study explores the possibility of decentralizing the production of electrical power and heat simultaneously, using an Organic Rankine Cycle (ORC) system integrated with a Parabolic Trough Collector (PTC) in a paint shop. To date, no similar system has been explored or implemented by the automotive industry. To increase the efficiency of the integrated system, wasted heat generated during the paint manufacturing process is recovered and used to pre-heat the organic fluid in the ORC system. A 4E analysis (Energy, Exergy, Economic, and Environmental) is conducted to determine the practical viability of the proposed system. When applied to the southern region of the USA, this system's installed capacity is projected to be 11 times higher than the two unique SORC pieces of equipment currently running in Louisiana and Florida. The goals are to reduce the reliance on external primary energy sources and decrease the carbon emission footprint from production activity. The system is evaluated for a location in Alabama, USA. The designed SORC, using toluene, can produce 712.2 kW_{el} net and 13,132 kg/h of hot water, with an overall energy efficiency of 31.02%; exergy efficiency of 34.23; and ORC efficiency of 27.70%. This leads to an electrical energy saving of 5.9% for the manufacturing plant. The regenerative thermal oxidizer (RTO) heat exchanger, the secondary heat source of the system, has the highest exergy destruction—3583 kW. The system avoids the emission of 4521 tCO_2 per year. A payback period of 10.16 years for the proposed system is estimated. Considering a planning horizon of 10 years, the investment in the system is also justified by a benefit–cost analysis.

Keywords: organic Rankine cycle; 4E analysis; paint shop; waste heat recovery; solar energy; automotive industry

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1. Introduction

Impacts on the environment from vehicle production processes can be estimated in many ways, such as considering the amount of CO_2 emitted into the atmosphere per unit vehicle produced. According to Javadi et al. [1], the carbon intensity to produce a vehicle is 0.69 tons of CO_2. In 2021, the worldwide production of vehicles, including cars and commercial types, was approximately 76,364,000 units [2]. Therefore, the emission of CO_2 into the Earth's atmosphere was 52,690,965 tons. It would require 2.7 billion trees to be absorbed—an area of 224,460 km^2 of forest, which is almost the size of the United Kingdom [3]. Considering that 49.5% of greenhouse gas carbon is due to the purchased electricity to produce vehicles [1], the implementation of technologies to reduce energy consumption or produce decentralized green energy around manufacturing plants becomes attractive for all industries seeking carbon neutral production and a reduction in costs.

The ORC has not been used in the automotive industry, as per the authors' assessment, and could be applied as a reliable technology to convert heat into electricity, using renewable energy sources and wasted heat from manufacturing processes (normally low-temperature streams).

In 2023, almost 2900 ORC systems were identified worldwide, representing an installed capacity of 4.5 GW [4]. In 2016, the USA led the ORC-installed capacity with approximately 800,000 MW_{el} being produced, mainly by using geothermal primary energy sources [5].

Solar energy has also been used in powering up ORC systems; nevertheless, there are only two solar-powered ORC systems operational in the southeastern part of North America, both having 65 kW_{el} capacity—one in Louisiana and the other in Florida [6]. While having some of the world's largest values of direct normal irradiation, the USA's west coast has not yet taken full potential from solar energy as a supply source for ORC systems. In Arizona, the third and last Solar ORC system in the country is located, producing 1000 kW_{el}.

By putting together solar energy with waste heat as sources of energy for ORC systems, the USA seems to underestimate its huge territorial and industrial potential. Many opportunities for waste heat recovery in several production processes could provide a considerable rise in energy production from Solar ORC equipment. One of the most crucial aspects of production processes in the automotive industry is the paint shop. Apart from the vehicle body, surface treatments are overseen for the protection of the substrate from weather and corrosion in the case of the metallic parts or for ensuring proper appearance, color, and shine for the vehicle. This crucial part of the manufacturing process has the highest energy consumption of all manufacturing phases of an automotive plant, representing 36% of the energy involved (chassis assembly 32%, press shop 12%, final assembly 10%, and body shop 10%) [7].

Moreover, the paint shop represents an important process area of manufacturing that has high demands on both electricity and thermal energy, making it very suitable for the integration of co-generated and recovered energy from other processes. Grid electricity and fossil fuels are currently the major carriers used by the automotive industry to satisfy the power demand of its manufacturing operations. One of the reasons for this is the relatively mature and well-known equipment involved in bringing electrical power from an external source. Additionally, the paint shop operation and maintenance teams do not need to have specific expertise to run a decentralized power plant as is here proposed. This condition, the energy cost level, and relative comfort environmental limits have not pressed the industry to innovate and start investing in capital expenditures yet. However, especially during this decade, industries and countries have established new environmental limits, which are already affecting production indicators such as "energy consumed per vehicle produced" and "CO_2 equivalent emission per vehicle produced". The system here proposed by the authors is one possible answer for the automotive industry to reach a more energy-efficient and environmentally friendly production process.

This work proposes an original approach that combines a specifically designed Solar Organic Rankine Cycle system with low-temperature waste heat recovery for the automotive industry—a completely new concept in this industry.

This work, in pursuance of the same aim, probes into the ORC system running with some other alternative primary energy source. Solar energy is selected as a principal source for the integrated system, capitalizing on well-established technologies like parabolic thermal concentrators. Furthermore, abundant solar energy in most parts of the USA, with special focus on the southern region, is harnessed.

The recovery of wasted energy from paint shop manufacturing processes, more specifically, the exhausts of RTO equipment, is the innovation of this work. Having this source as a secondary energy source for the ORC system, and increasing its efficiency, and reducing the carbon footprint of production activity are discussed. In an automotive paint shop, this heat is wasted by being exhausted to the atmosphere [7–9]. During the application of paints on the surfaces of cars and their curing inside ovens, volatile organic compounds (VOCs) are present in the process air and should not be exhausted to the atmosphere without proper treatment. The equipment mostly used by the automotive industry is called a Regenerative Thermal Oxidizer (RTO). Inside this equipment represented on Figure 1 [10], the process air suffers oxidation inside the combustion chamber, and most of the energy

used remains in the equipment. However, residual energy is still present in the air stream and exhausted to the atmosphere after the oxidation of the VOCs.

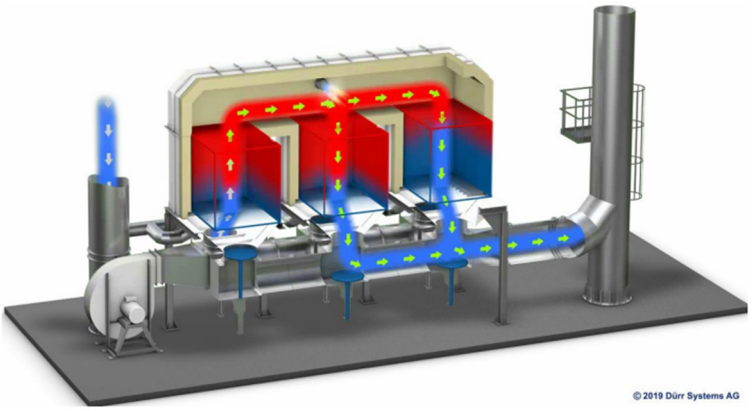


Figure 1. Representation of RTO by Company Durr.

The temperature of the air stream exhausted to the atmosphere varies depending on the paint process and the efficiency of the RTO equipment. For this research, the waste energy in the exhaust air is at 150 °C; however, it can change depending on the paint process and VOC level present in the exhaust streams.

The recovery of low-temperature waste heat from a paint shop RTO was explored earlier [11] through the installation of a heat exchanger to the equipment and through conveying the heat to the pretreatment process using hot water. Considering the right ORC work fluid and heat-transferring equipment, this hot air stream might be recovered as part of the organic fluid heating process before the transfer of energy from the primary source, the solar collector system, therefore, increasing the efficiency of the entire equipment and increasing the production of electricity and other useful forms of energy. Bello et al. [12] evaluated a similar system configuration using low-grade temperature between 150 °C and 300 °C with toluene as ORC fluid. The studied system has efficiency from 11.6% to 19.7%, depending on the waste heat temperature. Gomaa et al. [13] have investigated a system using flue gas from rotary kilns from cement industry.

Daniarta et al. proposed the use of wasted heat loss from oven equipment walls as an energy source of an ORC system [14]. To recover higher temperature waste heat from the RTO exhaust and fully capture the solar energy, this paper presents a new system configuration with a far larger generation scale. Notably, the new automotive oven walls are made of insulated materials like rock wool with more than 32 kg/m^3 in density and 150 mm as the minimum panel thickness, which has greatly reduced the heat loss through the oven walls. These ovens' flue gas flow is small as well, greatly reducing any potential for power production from oven waste heat. This could be a stepping-stone study to establish the SORC as a sustainable engineering solution for the southern U.S. automotive industry by an assessment of the practical feasibility of the proposed system—still non-existent in any automotive industry. The paint shop in this study can produce 11 times more energy than the already operational SORC systems in Louisiana and Florida since the total areas of the plants in these two states are relatively smaller compared to the plant suggested here located in the state of Alabama.

1.1. Organic Rankine Cycle (ORC)

The use of the ORC in an energy generation system has the following main advantages: the simplicity of its equipment [15], stability of the system, flexibility, and safety. Another strong advantage of the ORC is the fact of it being considered a practically zero emission (carbon dioxide) process [16], meaning that the reduction in the electricity purchased from the grid also contributes to a decrease in the carbon dioxide emission footprint.

Recent studies have integrated solar energy with ORC systems targeting the production of combined cooling, heating, and power, where solar energy is the primary source of energy [17]. Solar collector devices being related to low-temperature ORC turbines can produce electricity directly and, if also linked with other circuits, might generate cooling and heating power. Another possibility being explored by other studies is the use of the ORC as an addition to micro-turbine systems [18,19] to recover the heat from the exhausted gases (temperatures of 250–300 °C) [17,20].

There are two kinds of Solar ORC systems: direct and indirect. Direct systems transfer the solar energy directly to the organic working fluid belonging to the Rankine cycle. The indirect systems need a heat exchanger, and the heat exchange happens between a working fluid that absorbs the solar energy and then transfers to the organic fluid of the Rankine circuit [15].

Some of the fluids found in the recent literature are ethanol, methanol, octane, toluene, MDM, R113, R114, R123, R141b, R152, R218, R227ea, R290 (high flammability), R236fa, RC318 (extremely high cost), R245fa, R600, and R600a (high flammability) [12,15,20–27]. H. Yu et al. [28] conclude that toluene has the maximum power output in comparison with other organic fluids, improving the overall thermal efficiency when used as the working fluid of a basic or recuperative ORC. Yang et al. [29] have also concluded that toluene has the best performance as an ORC fluid.

Another critical parameter to be considered when designing an ORC system, and related to the working fluid, is the minimum temperature difference between the heat source stream and the organic fluid in the heat recovery system, also called pinch point. High-efficiency models use a minimum temperature between heat streams in the heat recovery system [12]. Usually, this difference in temperature is between 5 K and 20 K [15]. Roumpedakis et al. [27] consider pinch point in an evaporator and condenser equal to 4.5 K and 7.5 K, respectively.

Jafary et al. [17] study ORC systems using PTC collectors transferring heat by means of commercial oil Therminol 66 in the solar system. Yang et al. [29], when proposing their Solar ORC system, use the Therminol VP-1 [30] as the heat transfer fluid (HTF) due to its stable properties at temperatures up to 400 °C [31]. Wang et al. utilize a Parabolic Trough Collector with a tracking system to maximize the sun irradiation [23]. Bellos et al. use the commercial equipment of Eurotrough in their analysis [12,32].

Solar ORC systems may require the necessity of auxiliary equipment to balance the variability of solar irradiation. For example, a storage tank system, which has the target of storing solar energy, meets the energy demands of the system when needed and stabilizes the operation due to the variability of solar irradiation. Also called thermal energy storage (TES) [27–29,33], these tanks are critical elements to be technically defined (size/capacity and media). Thermal energy can be stored in three ways: latent heat, sensible heat, and chemical energy. Latent heat storage systems have been developed and studied, being the most promising technology [34]. When economical aspects play a fundamental role when choosing the system characteristics, sensible heat storage might be selected due to its simplicity, but it normally has lower efficiency in comparison with the latent heat storage tanks. Storage tanks may be used with solar and other waste heat energy sources in ORC, being hybrid systems. For paint shops and the automotive manufacturing systems, where plants may produce 24 h, 7 days per week, the implementation of storage tanks has become vital.

Lizana et al. [19] evaluate three scenarios using TES between solar collectors and an ORC system. For two of them, the ORC is integrated with a conventional hot water tank and a pressurized water tank. A third possibility evaluated is a storage unit based on a phase change material. The results show that the solar latent heat storage tank can supply 54% of useful collector gains. Yu et al. [28] investigate the optimal design and operation of a solar-energy-driven ORC system using a sensible thermal energy storage system. The results show that the overall system efficiency is about 6.9–12% points higher.

This paper deals with the application of a TES system to smooth out energy fluctuation and make energy production during the night or when there is no sunlight possible. All sizing of such systems tries to find the best trade-off between cost and benefit. Future assessments, besides the costs of equipment, have taken consideration of outsourced energy costs at night and other technologies of storage.

1.2. Exergy Analysis

Exergy analysis, one of the four "Es", is an important methodology used to evaluate, design, and optimize a system by applying the first and second thermodynamic laws together [35]. When effectively used by engineers, the exergy analysis method helps to achieve more efficient equipment in terms of energy usage, finding losses and their types, and locating where inefficiency caused by irreversibility appears.

Using the advanced exergy analysis, Liao et al. [36] investigated the interaction among different equipment of the proposed ORC connected to waste heat from flue gas, understanding the components to be optimized for a real potential improvement of the system. Bello et al. [12] studied an ORC driven by solar energy and waste heat where exergy analyses were assessed to examine different working fluids to maximize electricity production. The authors concluded that toluene is the most efficient organic fluid in connection with parabolic trough collectors.

For exergy, thermodynamics, and all other calculations, different software can be used for modeling the systems. Some of the most employed tools found in the literature are Matlab R2024 [37], Aspen Plus V14 [38], EES V11 [39], Cycle Tempo 4.1 [40], TRNSYS 18.06 [41], Thermoflex IPSEpro 2022 [42], EBSILON Professional 2022 [43], and REFPROP v.10 [44]. The work hereafter presented uses the EES, a powerful tool for thermodynamic analysis. Jafary et al. [17] mentions that one of the main EES features is the existence of an accurate database of transfer and thermodynamic properties for hundreds of different materials. It can automatically find and categorize equations that need to be solved simultaneously. Also, it supplies a series of functions to calculate the thermophysical properties of materials.

2. System and Method for Analysis

2.1. System to Be Implemented in a Paint Shop

To provide high corrosion resistance and a good appearance for the vehicles, a paint shop has several processes and integrated equipment to properly treat the surface of the body, also called substrate, which is made of steel in most cases. The vehicle body is conformed in the body shop, where stamped and several steel parts are welded/glued/assembled, giving the shape of the final product. This "body-in-white", without surface treatment and bringing dirt and residues from the conformation processes, is conveyed to the paint shop building.

Figure 2 shows the process sequence in a traditional paint shop (it can vary depending on the company and its specific corrosion and quality requirements—some lines may be excluded from the process sequencing). The paint shop can represent 36% of the total energy consumption of the entire car manufacturing process. There is no other area with higher demand for electricity and fossil fuel energy.

Energy is required to treat baths (temperature control), supply conditioned air to different equipment (booths and work decks, for instance), run conveyors, and exhaust air through powerful fans. Based on a conventional paint shop producing 45 vehicles per hour, the energy consumption of each area is estimated and shown in Table 1 [45].

The air exhausted from the processes of the paint shop (booths and ovens), which contains VOCs, goes to the RTO system to be oxidized and then exhausted to the atmosphere as per levels allowed by the local environmental regulations. As previously mentioned, this air stream with waste energy at 150 °C is a secondary energy source for the SORC system.

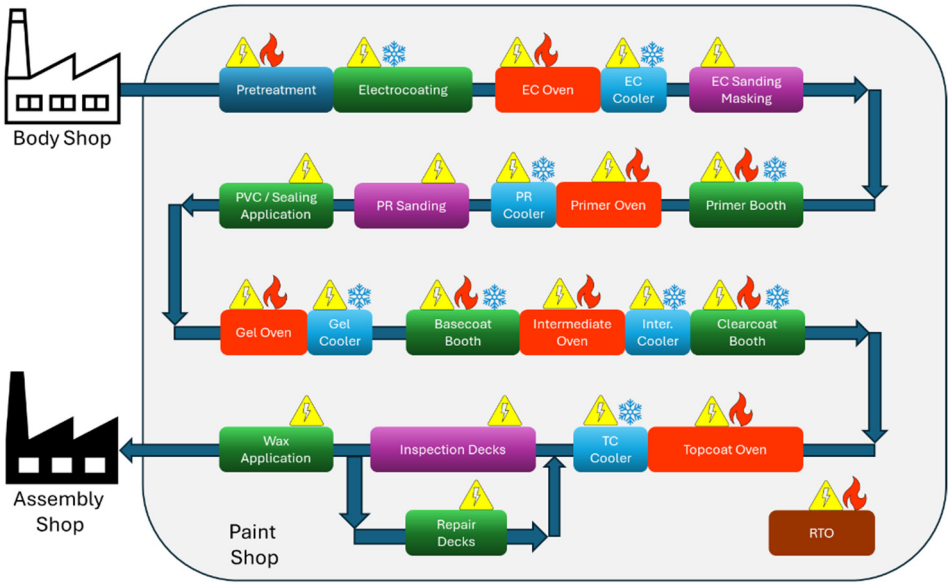


Figure 2. Paint shop processes and main equipment/lines.

Table 1. Total energy consumption in paint shop's main areas/production assumptions.

Area of Paint Shop	Total Energy	Unit
Pretreatment	14,677	MWh/year
Electrocoating	8847	
Paint booths	49,082	
Oven and cooler	108,673	
Work decks	105,308	
Conveyor	5278	
Shop ventilation	265,067	
Water treatment plants (DI, wastewater)	1691	
Fire protection process	788	
Concentrator/RTOs	29,679	
Paint robots and application systems	3750	
Paint and material supply systems	3574	
Energy per unit	2.54	MWh/unit
Total electrical energy consumption per year	596,415	MWh/year
Production time per year	5225	h/year
Total prod. running time per year (operation time)	5880	h/year
Total running time of shop ventilation per year	8736	h/year
Bodies per hour	45	units/h
Bodies total	235,125	units/year

2.2. System Description

This work investigates a system consisting of an Organic Rankine Cycle using parabolic trough solar collectors as its primary source of energy, a thermal energy storage tank, and an auxiliary system to recover the waste energy coming from an automotive paint shop process, more specifically, the low-temperature heat exhaust coming from an VOC abatement equipment (Figure 3).

The parabolic trough solar collectors are chosen due to their current mature technology level. To mitigate the fluctuation of electrical power production during part of the night and or periods without sun, the investigated system has an intermediate storage tank linked with the PTC and the ORC equipment.

As an additional source of energy and based on a specific process mostly existent in paint shop automotive facilities, the ORC is incorporated into a secondary circuit, which has residual thermal energy from the treatment of booths and oven air streams. The enthalpy

still present in the air flow is used to preheat the ORC working fluid before the evaporator. Finally, the ORC system receives these two energy sources and converts them into electricity in a turbine.

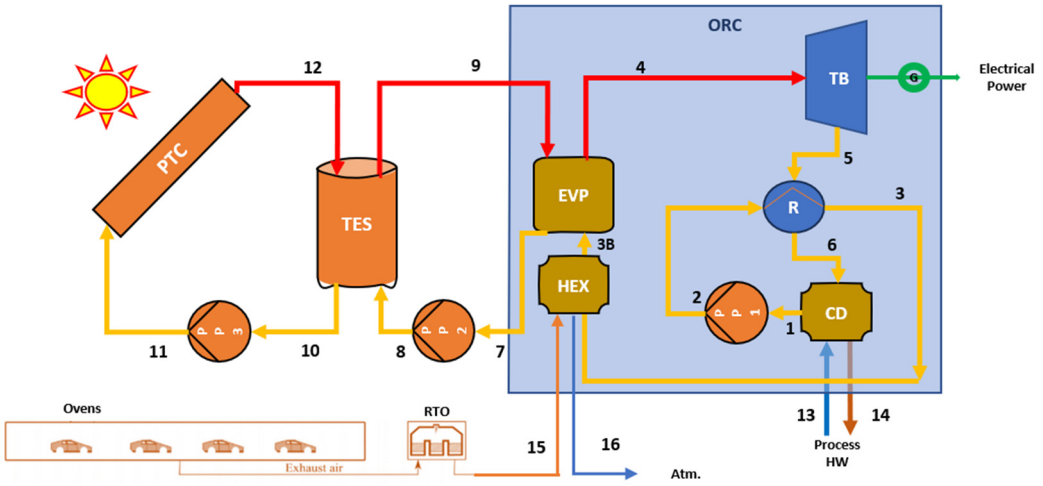


Figure 3. Proposed SORC system.

The southern region of the United States of America has been used as the system's location for the energy production analysis due to the high concentration of the automotive industry in this region. This hypothetical car manufacturing paint shop is in Alabama, USA, with a production capacity of 45 vehicles per hour. This production has been chosen for two reasons: first, to establish a practical exhaust air flow from a hypothetical RTO system, which is a secondary energy source with its wasted heat; second, to establish a practical comparison between the generation and energy consumption of a paint shop with this production throughput. Anyhow, the system can be scaled up and down, and this evaluation must take into consideration the available footprint as well, since it affects directly, as per the previous question, the generation of electricity.

Targeting the production of energy using solar and waste heat from the manufacturing process, the integrated system evaluated in this work is shown in Figure 3 as follows:

Solar is the primary energy and has its dedicated circuit from the parabolic trough concentrators—PTCs—(11–12), thermal energy storage tank (12–10), and the recirculation pump (10–11), which uses thermal oil as media (toluene). It is a closed system with an indirect heat exchanger. The second closed circuit has the function of supplying energy to the ORC evaporator (9–7), using the energy stored inside the intermediate tank (8–9). Thermal oil and a pump (7–8) are a part of the circuit.

The third circuit is the ORC, which consists of an evaporator (3B to 4), a turbine (2-stages)/generator system (4–5), a recuperator (5–6/2–3), a condenser (6–1), the pump (1–2), and an indirect heat exchanger (3–3B). The evaporator receives energy from the primary source circuits, and the organic fluid is preheated twice after the turbine: first through the recuperator, and then by the indirect heat exchanger using energy from the wasted exhaust air of the RTO (secondary).

The system examined hereafter is modeled in the EES. Toluene is chosen as ORC working fluid. All the thermal characteristics of this specific fluid are taken from the EES thermodynamics library.

The two other closed circuits of the SORC system use Therminol VP-1 [30] as a fluid. Its high maximum bulk and film temperatures (400 °C and 430 °C, respectively) are proper for the values expected on the solar collector circuit, as well as thermal energy storage piping. Like toluene, the thermal characteristics of the thermal oil are taken from the EES internal library. The 4E analysis is used as a method of analysis in this work. The following assumptions are used in the calculations to be presented:

Furthermore, the following assumptions have been performed to model the proposed study:

- The potential and kinetic energy of the flow rate are neglected [26];
- The system is assumed to be a steady state;
- The compressor and turbine are isentropic;
- Heat losses in the pipes are neglected.

The Engineering Equation Solver (EES) has been used for the calculations of the proposed system [39]. The power consumption of the pumps in the PTC and TES circuits has been calculated based on losses due to the piping lines and the difference of enthalpy between the entrance and exit of the equipment. Detailed calculations and additional assumptions related to the piping pressure drops in the thermal oil circuits are explored in a specific sub-item.

As previously mentioned, the pinch points inside the heat exchangers have been defined by taking into consideration the literature recommendations [15]. The evaporator exit temperature (equal to the temperature of the turbine inlet) has been calculated using the following equation, which considers the pinch point above mentioned:

$$T_4 = T_9 - T_{PP} \quad (1)$$

2.2.1. Wasted Heat Source

The RTO system is designed to have high energy-efficiency levels, meaning that most of the energy used to oxidize the volatile organic compounds stays inside the system, which is normally ceramic material existent inside the equipment. Therefore, the study proposes to use the remaining energy present in the exhaust stream to preheat the Organic Rankine Cycle fluid. A heat exchanger air/ORC fluid is installed and set to work inside the pinch point limits between low/elevated temperatures. The following equations are used to find the wasted heat system:

$$T_{w,out} = T_{16} = T_3 + T_{PP} \quad (2)$$

$$Q_{w,in} = m_w C_{p,w}(T_{w,in} - T_{w,out}) \quad (3)$$

$$h_{16} = h_{15} - \left(\frac{Q_{w,in}}{m_w}\right) \quad (4)$$

The efficiency of the heat exchanger (HEX) is proved according to the following equation:

$$h_{16} = h_{15} - \left(\frac{Q_{w,in}}{m_w}\right) \quad (5)$$

2.2.2. ORC Working Fluid

The organic working fluid is selected to be dry toluene due to the advantages discussed earlier. Toluene has been used and has shown satisfactory results in several papers evaluating ORC systems [28,46,47] in both the calculations and modeling.

2.2.3. Solar Field Modeling

The direct normal irradiation (DNI), sunshine duration during the months of the year, and the ambient air temperature, are extracted from the National Renewable Energy Laboratory (NREL) [48], based on the coordinates 33.21° N/87.6° E and 53.64 m above sea level—Tuscaloosa, AL, USA. The irradiation vector ($G_{b,1..N}$) is established based on the average of each station (winter, spring, summer, and fall). The ambient temperature ($T_{amb,1..N}$) is also considered based on the average of seasons:

$$G_{b,1..N} = [512, 480, 456, 523]\ (\mathrm{W/m^2});$$
$$T_{amb,1..N} = [9, 19, 25, 15]\ (^\circ\mathrm{C}),$$

where N is the season of the year.

Figures 4–7 illustrate the daily solar irradiation along with ambient temperature for winter, spring, summer, and fall for Tuscaloosa, AL, USA, respectively.

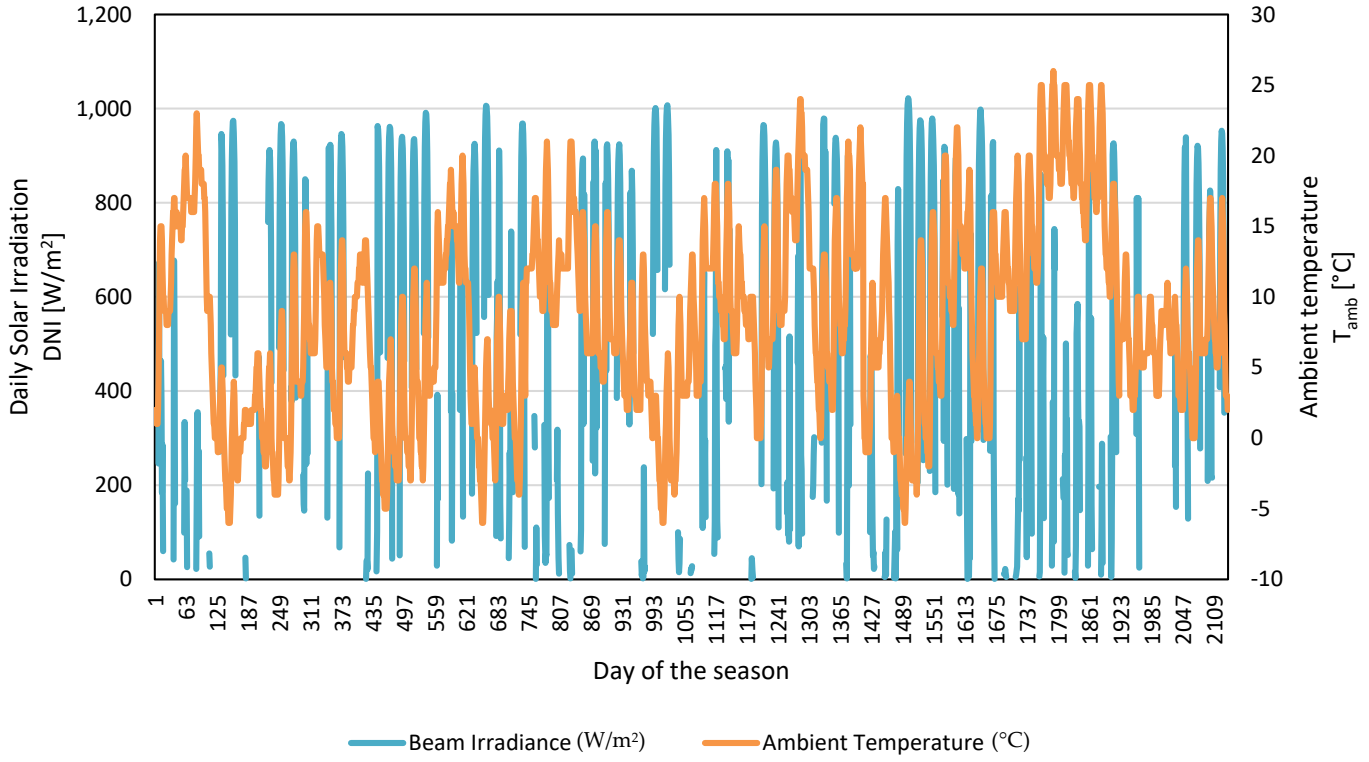


Figure 4. Winter—Tuscaloosa, AL—DNI and ambient temperatures.

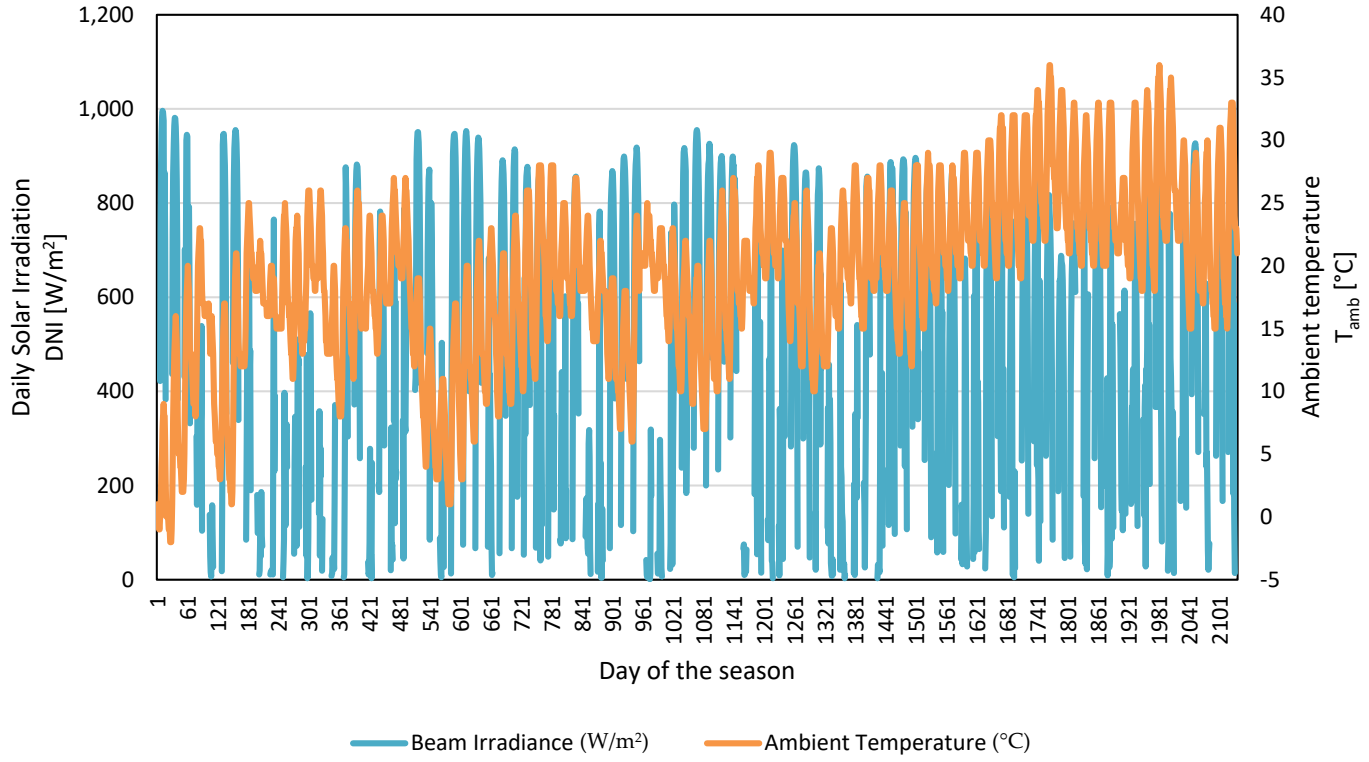


Figure 5. Spring—Tuscaloosa, AL—DNI and ambient temperatures.

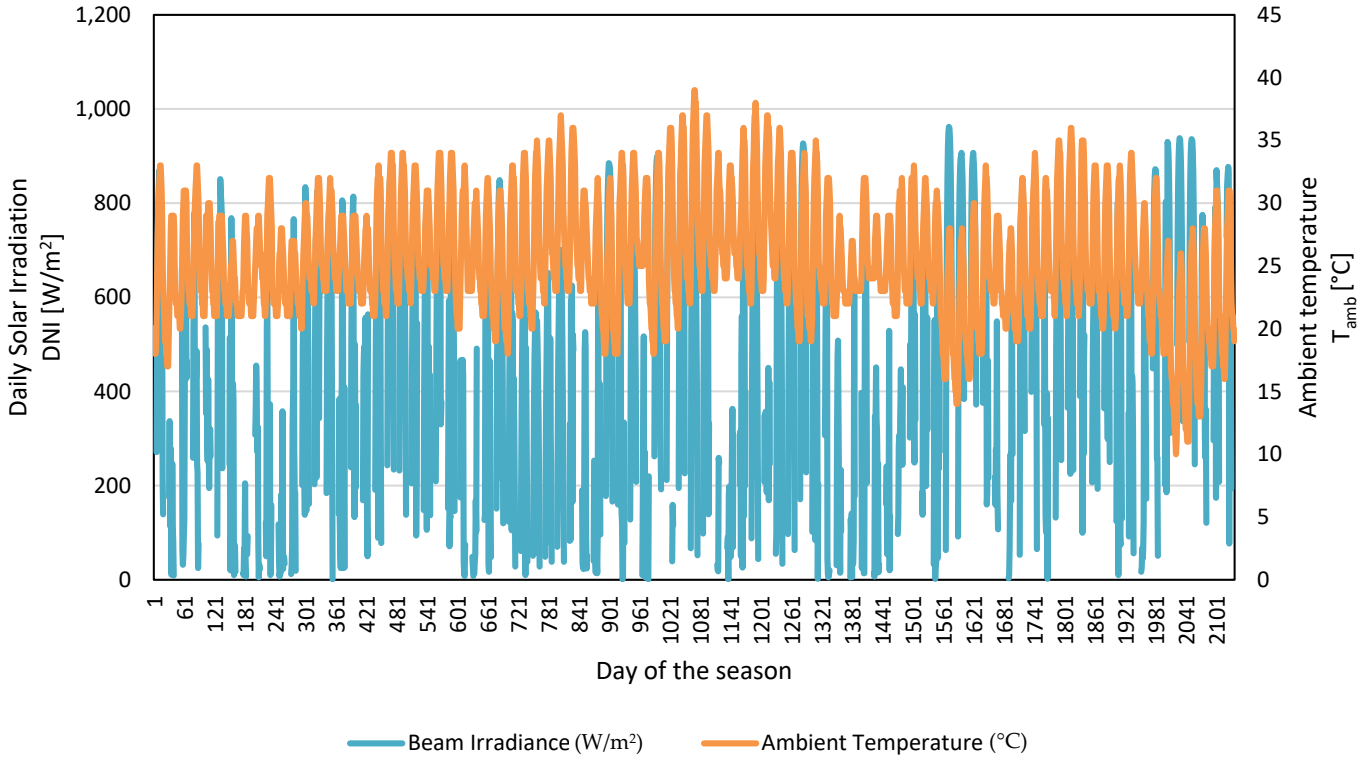


Figure 6. Summer—Tuscaloosa, AL—DNI and ambient temperatures.

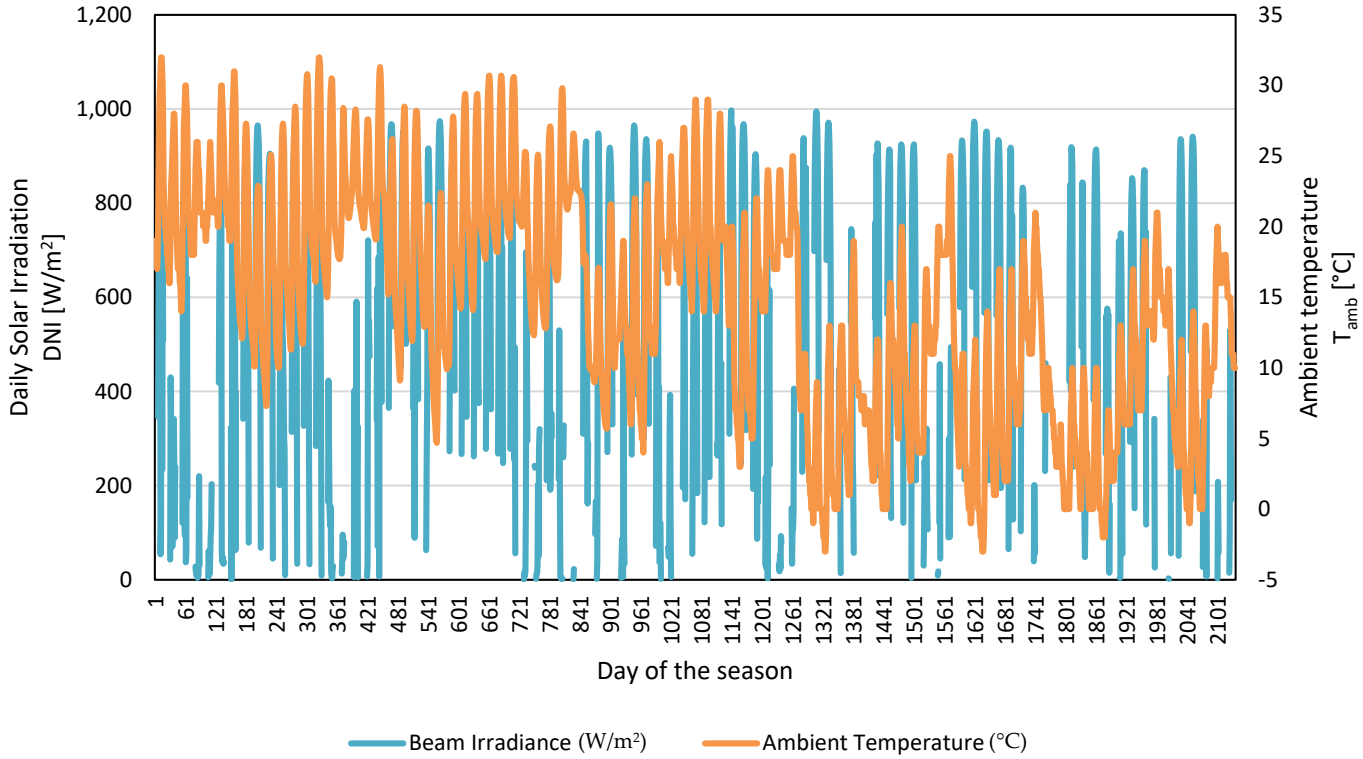


Figure 7. Fall—Tuscaloosa, AL—DNI and ambient temperatures.

The calculation considers one collector from the Eurotrough [32] company, the equipment ET-150, with the aperture area informed earlier in Table 2.

Table 2. Assumptions for the proposed system.

Description	Parameter	Value	Unit
condenser temperature [12]	T_1	40	°C
pinch point [12]	T_{PP}	20	°C
temperature difference in recuperator [12]	ΔT_{rec}	20	°C
electromechanical efficiency generator [12]	η_{mg}	0.98	-
turbine isentropic efficiency [12]	η_t	0.85	-
organic fluid pump efficiency [12]	η_p	0.7	-
waste heat source mass flow rate	m_w	34.25	kg/s
specific mass flow rate of thermal oil on the solar field	m_a	0.02	kg/s-m^2
area of the aperture informed by ET-150 manufacturer	A_c	828	m^2
temperature of thermal oil to evaporator	T_9	T_{crit}	°C
temperature from collector to TES	T_{12}	T_9 + PP	°C
temperature wasted heat—assumption to be constant	T_{15}	150 °C	°C
pressure through HEX wasted heat	P_{15}	5000	Pa
pressure at stream 16	P_{16}	P_{15}	Pa
tank heat loss coefficient	Q_{loss}	0.5	W/m^2-K
thermal losses through storage tank walls	U_L	Q_{loss}	W/m^2-K
temperature fluid at exit of storage tank	T_7	$T_9 - 7$ °C	°C
outlet cooling water condenser temperature	T_{14}	95 °C	°C
inlet cooling water condenser temperature	T_{13}	T_{14} − PP	°C
mass fraction of vapor at stream 14	x_{14}	0	-
mass fraction of vapor at stream 13	x_{13}	0	-
inlet heat transfer fluid temperature in evaporator [39]	T_9	318.6	°C

The available power from the sun is calculated by considering the arrays mentioned before ($G_{b,1...N}$).

$$Q_{sol_{arraw},\,i} = G_{b,1...N} \times A_c \tag{6}$$

for i = 1 to N.

The efficiency of the collector follows the equation:

$$\eta_{col} = 0.7408 - 0.0432\left[\frac{(T_{col,in} - T_{amb})}{G_b}\right] - 0.000503 G_b\left[\frac{(T_{col,in} - T_{amb})}{G_b}\right]^2 \tag{7}$$

where T_{10} is the entrance temperature of the fluid inside the collector, and T_{amb} is the ambient temperature [12].

The calculation of the useful heat produced in the PTC ($Q_{in,TES}$) is determined by the following:

$$Q_{in,TES} = m_{col} C_{p,oil}(T_{col,out} - T_{col,in}) \tag{8}$$

where m_{col} is the flow rate of the fluid inside the collector circuit, $C_{p,oil}$ is the specific heat of the thermal oil, $T_{col,out}$ is the exit temperature of the fluid in the collector circuit, and $T_{col,in}$ is the entrance temperature of the fluid in the collector circuit, which is equal to the temperature from the collector to the TES (T_{12}).

The study here presented considered a zero incident angle as per the above thermal efficiency equation. Therefore, the focus and emphasis have been given to the ORC system [12].

2.2.4. Storage Tank—Thermal Energy Storage (TES)

Thermal energy storage (TES) is one of the key elements of solar PTC systems, and three mixing zones are defined in the storage tank. Figure 8 illustrates the different zones and the thermal oil interaction in the system, from the solar collectors (streamlines 10 and 12) to the ORC (streamlines 8 and 9).

The volume of the tank (103.5 m^3), mass of thermal oil (27,488 kg), and areas of the tank (29.9 m^2 for each zone) are calculated following E. Bellos et al.'s methodology [49]. The specific heat capacity and density of the oil are calculated using the EES library [39].

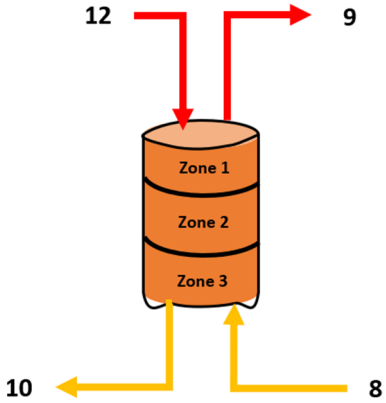


Figure 8. Representation TES—interaction with PTC/ORC.

2.3. Methodology

This study evaluates the performance and energy production of the system modeled above, considering the turbine pressures and temperatures close to the organic fluid critical values. For the PTC and TES circuits, the fluid is kept the same for both ORC fluid possibilities.

The waste energy coming from the RTO is considered constant, meaning the same mass flow rate, temperature, and pressure throughout the year.

To maximize the available energy rejected by the condenser, and therefore making possible the use of this heating load to produce hot water to the paint shop (an important utility for some processes), the temperature of the hot water produced is fixed at 95 °C.

The usage of a two-stage turbine is considered due to the pressure difference between the entrance and exit of the equipment. This study considers a recuperator behind the RTO heat exchanger using the turbine exit stream to pre-heat the organic fluid.

Using the EES [39] to model and calculate the system proposed, the equations have been introduced in the software, which uses its internal library to define the thermodynamic properties based on the fluid, temperature, pressure, ratio, enthalpy, entropy, etc. The constant parameters and assumptions have been mentioned in the previous sections.

The following method and sequency are applied to calculate and model an optimized system based on the pre-definitions and inputs (Figure 9):

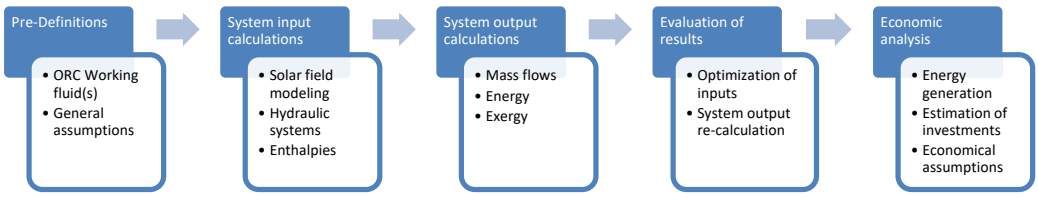


Figure 9. Methodology and sequency.

2.4. Enthalpies, Mass Flow, Energy, and Exergy Calculations

The enthalpies of each point, i.e., the entrance and exit conditions, are calculated using the input data from the EES [39].

Isentropic enthalpies in the exit of the turbine and ORC pump are calculated and used to figure out the corrected enthalpy of the circuit points:

$$h_5 = h_4 - [\eta_{is} \times (h_4 - h_{5,is})] \quad (9)$$

$$h_2 = h_1 - \left[\frac{(h_{2,is} - h_1)}{\eta_{pump}}\right] \quad (10)$$

For the recuperator equipment, the equation is used to calculate the enthalpies of each streamline:

$$h_5 - h_6 = h_3 - h_2 \quad (11)$$

Thermal energy of the system is defined as the following:

$$Q_{in,evap} = Q_{in,TES} + Q_{w,in} \tag{12}$$

$$Q_{in,evap} = m_{ORC} \times (h_4 - h_3) \tag{13}$$

$$Q_G = \eta_{mg} \times m_{ORC} \times (h_4 - h_5) \tag{14}$$

$$Q_{el,PP,ORC} = \frac{m_{ORC} \times (p_2 - p_1)}{\rho_{ORC} \times \eta_{pump}} \tag{15}$$

$$Q_{el} = Q_G - Q_{el,PP,ORC} \tag{16}$$

where Q_{el}, $Q_{el,PP,ORC}$, and Q_G are the electrical energy available, used by the ORC pump, and generated, respectively.

The exergy calculations have been divided into systems (ORC, PTC, and TES). The ambient temperature and pressure ("zero" states) are 288 K and 101,325 Pa, respectively.

First, the exergy is defined for each streamline as follows:

$$\dot{\varepsilon}_i = m_{fluid} \times \{(h_i -) - [T_0(s_i - s_0)]\} \tag{17}$$

where i is the specific system point as per the schematic. The exergy for the collector is calculated as follows [35]:

$$\dot{\varepsilon}_{collector} = Q_{sol} \times \left\{1 - \left(\frac{4}{3} \times \frac{T_{0PTC}}{T_{sol}}\right) + \left[\frac{4}{3} \times \left(\frac{T_{0PTC}}{T_{sol}}\right)^4\right]\right\} \tag{18}$$

where T_{sol} is the solar temperature [27].

The equations have been used to determine the exergy destruction in each main equipment/part of the system [35]:

$$\dot{\epsilon}_{D_{PP1}} = (\dot{\varepsilon}_1 - \dot{\varepsilon}_2) + Q_{el_{PP1}} \tag{19}$$

$$\dot{\epsilon}_{D_{PP2}} = (\dot{\varepsilon}_6 - \dot{\varepsilon}_7) + Q_{el_{PP_TES}} \tag{20}$$

$$\dot{\epsilon}_{D_{PP3}} = (\dot{\varepsilon}_9 - \dot{\varepsilon}_{10}) + Q_{el_{PP_PTC}} \tag{21}$$

$$\dot{\epsilon}_{D_{Evap}} = (\dot{\varepsilon}_8 - \dot{\varepsilon}_6) + \left\{Q_{evap} \times \left[1 - \left(\frac{T_{0_{ORC}}}{T_4}\right)\right]\right\} \tag{22}$$

$$\dot{\epsilon}_{D_{Turb}} = (\dot{\varepsilon}_4 - \dot{\varepsilon}_{5A}) - Q_{Turb} \tag{23}$$

$$\dot{\epsilon}_{D_{cond}} = (\dot{\varepsilon}_{5A} - \dot{\varepsilon}_1) + \left\{Q_{cond} \times \left[1 - \left(\frac{T_{0_{ORC}}}{T_1}\right)\right]\right\} \tag{24}$$

$$\dot{\epsilon}_{D_{HEX}} = (\dot{\varepsilon}_{14} - \dot{\varepsilon}_{15}) + \left\{Q_{RTO_{HEX}} \times \left[1 - \left(\frac{T_{0_{ORC}}}{T_{03A}}\right)\right]\right\} \tag{25}$$

$$\dot{\epsilon}_{D_{TES}} = (\dot{\varepsilon}_{11} - \dot{\varepsilon}_9) + \left\{Q_{TES} \times \left[1 - \left(\frac{T_{0_{TES}}}{T_1}\right)\right]\right\} \tag{26}$$

The efficiencies have been calculated as the following:

$$\eta_{ORC} = \frac{Q_{el}}{Q_{in}} \tag{27}$$

$$\eta_{sys} = \frac{Q_{el}}{Q_{sol} + [m_w \times cp_w \times (T_{w,in} - T_{amb})]} \tag{28}$$

$$\eta_{energy} = \frac{Q_{el}}{Q_{sol} + Q_{w,in}} \tag{29}$$

$$\eta_{exergy} = \frac{Q_{el}}{\left\{Q_{sol} \times \left[1 - \left(\frac{T_{0_{ORC}}}{T_{Sol}}\right)\right]\right\} + \left\{Q_{w,in} \times \left[1 - \left(\frac{T_{0_{ORC}}}{T_{15}}\right)\right]\right\}} \tag{30}$$

2.5. Economic Analysis Calculation

To estimate the capital expenditures (CAPEXs) of the SORC system, assumptions are made based on the ORC and PTC equipment. Similar equipment used in paint shops supported the definition of the ratios used below [45]. The following calculations are considered:

$$Ductwork_{cost} = 0.05 \times ORC_{cost} \tag{31}$$

$$TES_{cost} = 0.125 \times (ORC + PTC)_{cost} \tag{32}$$

$$Piping_{cost} = 0.05 \times (ORC + TES + PTC)_{cost} \tag{33}$$

$$Condenser_{cost} = 0.25 \times ORC_{cost} \tag{34}$$

$$Generator_{cost} = 0.15 \times ORC_{cost} \tag{35}$$

$$Installation_{cost} = 0.125 \times (ORC + PTC + TES + Ductwork + Piping + Condenser + Generator)_{cost} \tag{36}$$

$$CAPEX = (ORC + PTC + TES + Ductwork + Piping + Condenser + Generator + Installation)_{cost} \tag{37}$$

The operational expenditures (OPEXs) of the SORC system are also assumed based on the paint shop references [45]. The ratio has the CAPEX value as a reference:

$$OPEX = 0.025 \times CAPEX \tag{38}$$

and it is considered on a yearly basis. The payback calculation follows the equation below:

$$Simple\ Payback = \frac{\sum Energy\ saving - OPEX}{\sum Total\ CAPEX} \tag{39}$$

The following assumptions related to the energy cost (year base 2023) of an automotive company have been considered: electricity USD 93.78 per MWh; hot water USD 26.80 per MWh [45].

An alternative approach might be considered by using potential greenhouse gas equivalencies (GHGEs) to generate additional revenue selling credits due to the carbon reduction—electricity use avoided through energy efficiency or fossil fuel electricity generation avoided through renewable energy [50].

Based on the net energy production coming from the SORC system, the electricity produced by the turbine–generator set and the energy used for producing hot water for the paint shop processes can be converted to metric tons of avoided carbon dioxide. The market value of carbon credit has varied constantly and depends on the market location. Therefore, here it is assumed to be USD 30 per tCO_2 [51].

For the direct conversion of energy to avoided CO_2 emission, the following equations are used (results in $tonCO_2/year$):

$$\frac{CO_2\ avoided_{electricity}}{year} = 0.000709 \times \frac{kW_{generated}}{year} \tag{40}$$

$$\frac{CO_2\ avoided_{thermal}}{year} = 0.005291 \times \frac{therms\ natural\ gas_{avoided}}{year} \tag{41}$$

This work will further include an economic analysis that will be performed to evaluate the financial viability of the proposed project. Benefits will be measured in monetary terms; all values are expressed in annual worth. An assumption in this analysis is a project discount rate of 4.264%, an inflation rate of 5.0%, and a project planning horizon of 10 years [52,53].

Looking only at the benefit cash flow, the avoided operational and maintenance costs of a fossil steam fuel power plant in 2020 are taken at a value of USD 0.03486 per kWh [54].

Other benefits that can be added to the revenue accrued from the SORC system are the avoided costs for the flue-gas desulfurization system, totaling USD 2.21 per MW [55].

It assumes that the operational and maintenance costs inflate at the same rate over the planning horizon. Furthermore, it also assumes that the residual value of the SORC equipment in the 10th year is zero. Other benefits and associated costs, such as carbon credit revenues, are not considered in this analysis. The present worth of all net benefits and costs above mentioned are calculated according to the following equation:

$$\frac{Benefits}{Costs}_{(i)} = \frac{\sum_{t=1}^{n} Benefits_t (1+i)^{-t}}{\sum_{t=0}^{n} Costs_t (1+i)^{-t}} \quad (42)$$

where i is the project discount rate, and n is the planning horizon. If the benefits (B) divided by costs (C) are higher than 1.0, the investment is justified. In the same way, if benefits–costs is higher than USD 0, the investment is justified as well. It should be noted that this study does not consider any state/federal incentives [56]. These and other benefits, such as the USDA Rural Energy for America Program [57], might be included in a future analysis or further investigations by other papers.

3. Results and Discussion

The equations above are used to calculate the power of the system using quarterly vectors for solar irradiation, sun duration, and temperatures [58]. Therefore, the estimated powers are the results taken by the average for each season of the year.

3.1. Validation of the Model

The system here proposed is evaluated by other authors, however, in different fields and applications. This paper intends to study the applications of the suggested system in the automotive industry, using existing wasted energy coming from the manufacturing processes of paint shops.

In order to validate the model used to calculate the system, the authors use E. Bellos et al.'s [12] work as a reference. The following results, results from the model designed in the EES [39], are observed (Table 3):

Table 3. Validation comparison reference and present papers.

Validation Model	$T_{w,in}$	P_{el}	A_{col}	η_{sys}	η_{ORC}	η_{HEX}	η_{col}
Unit	°C	kW	m^2	%	%	%	%
Reference values [12]	150	479.3	3443	11.61	16.35	68.7	72.31
Present values	150	459.3	3443	11.41	15.93	70.1	72.37
Difference (error) %	0	4.2	0	1.7	2.6	−2.0	−0.1

Based on the error percentage calculated not being higher than 5% of the reference values, the model is assumed to be valid, and its results and conclusions are to be explored.

3.2. ORC

The implementation of the SORC system in an automotive paint shop, as proposed, has a potential power net capacity of 712.2 kW. The proposed SORC system might oversee 5.9% of the total electrical energy consumption, not considering the rejected heat of the condenser (the potential production of hot water in several paint shop processes).

The energy efficiency of the entire system is 31.02%. The exergy efficiency with the same earlier conditions is 34.23%. When isolating the ORC circuit, its calculated efficiency is 27.7%.

The process of optimizing the system pressures and temperatures, working close to the maximum possible values due to the fluid characteristics, and using the wasted energy from the RTO system allowed the study results to reach higher energy efficiencies in comparison to recent papers.

For such a similar equipment configuration, where the primary source is solar energy and the secondary source is waste heat, the reported efficiency is about 20% [12], which is much less than the 31.02% efficiency found in this study. For systems not making use of waste heat sources, the overall ORC efficiencies of these systems are about 10% [19], while the proposed one reaches 27.7%. An installed capacity using the theoretical figure for electricity generation of 712.2 kW would be eleven times higher than the existing SORC systems found in Louisiana and Florida. The power of each main equipment is shown below (Figure 10).

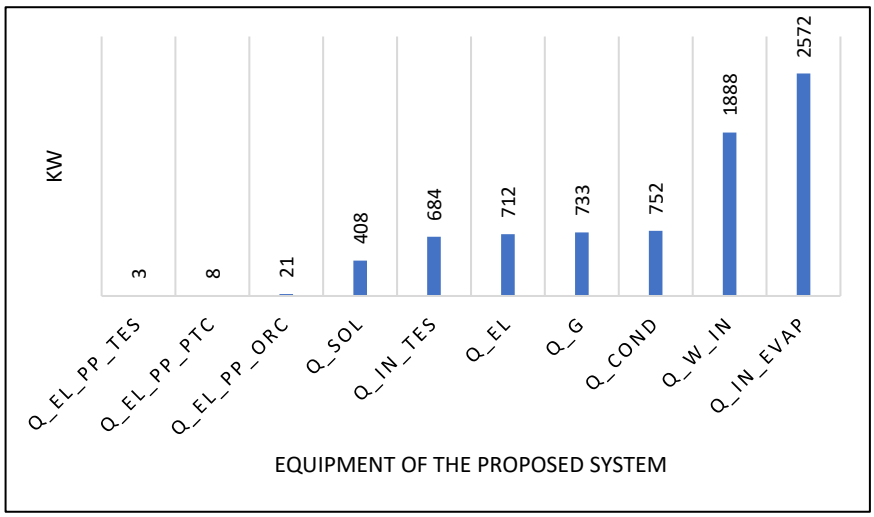


Figure 10. Power of each main equipment of the system in kW.

When focused on the rejected heat of the condenser, the average potential heat power to be used for hot water generation is 752 kW. This amount of heat can generate an average of 13,132 kg/h of hot water to the paint shop processes, feeding areas as pre-treatment tanks, air supply houses, and a paint circulation system. This mass flow can reduce the hot water generation necessity by up to 3%. The temperature difference between the supply and return of hot water is 20 °C.

The mass flows into each area are calculated as shown in Table 4:

Table 4. Mass flow rate of ORC, solar collector, TES, and RTO stream.

System	Mass Flow Rates	Unit
m_{orc}	4	kg/s
m_{col}	17	
m_s	17	
m_w	34	

The model developed is focused on calculating the exergy destruction on the main components of the system. Knowing the equipment with the higher exergy destruction, a future optimization analysis can be explored to increase the overall efficiency of the system.

The exergy destruction of each main equipment is calculated, and the higher values are shown below in Figure 11 (the solar collector and pumps are excluded from the graphic):

The exergy analysis shows an opportunity to investigate and optimize the heat exchanger and evaporator, which present the highest destruction in the proposed system.

Enthalpies, entropies, temperatures, and pressures are calculated based on the proposed system. Below, the EES has plotted the Temperature vs. Entropy (T-S) graphic, focusing on the ORC circuit (Figure 12):

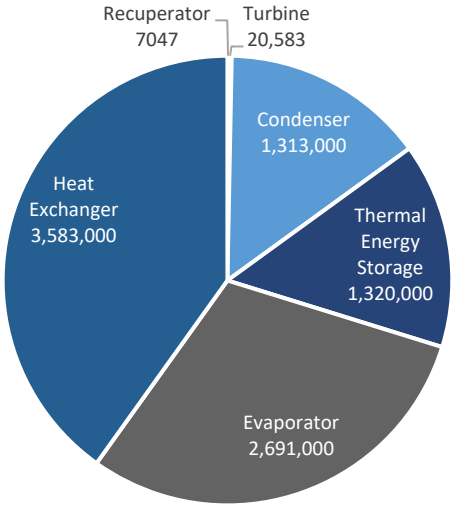


Figure 11. Main equipment exergy destruction in kW.

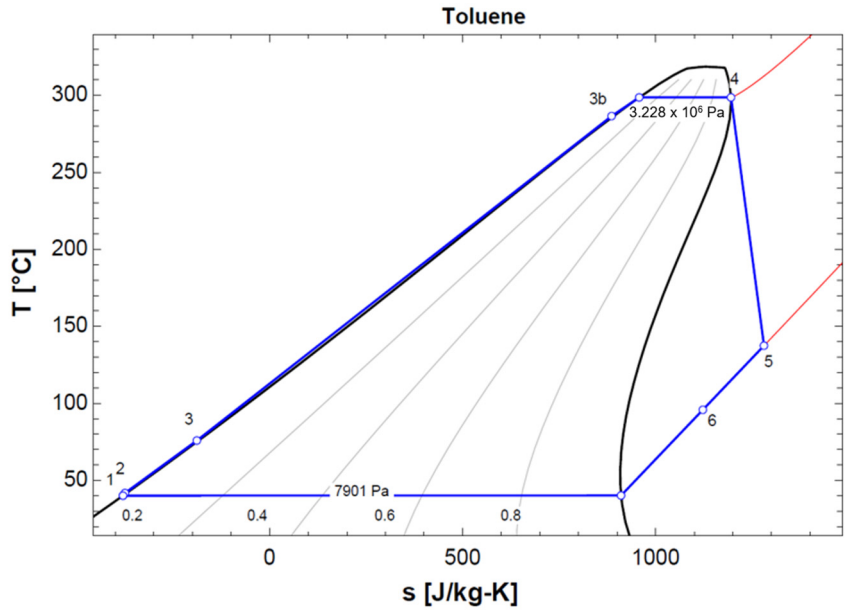


Figure 12. T-S graphic ORC—Toluene working fluid.

The lifespan and thermal stability of the ORC fluid must be researched in the future due to the temperature and pressure assumed in this paper, which are close to the critical point of the fluid.

3.3. Economic Analysis Optimized SORC

An economic analysis has been conducted based on the optimized SORC system using ethylbenzene to estimate the simple payback period. This analysis helps an automotive company to decide whether to fund this suggested system and initiative from an economical and environmental point of view following the assumptions below—Figure 13:

- The CAPEX of USD 5,837,449 has been estimated based on 2023 market prices [45];
- The ORC cost system is USD 3865.00/kW;
- The PTC system is USD 500.00/m^2.

The analysis focuses on the estimated energy saving accruable from running the SORC, which will reduce the electricity and hot water expenses for the paint shop. Presented below are results for the economic analysis (Table 5):

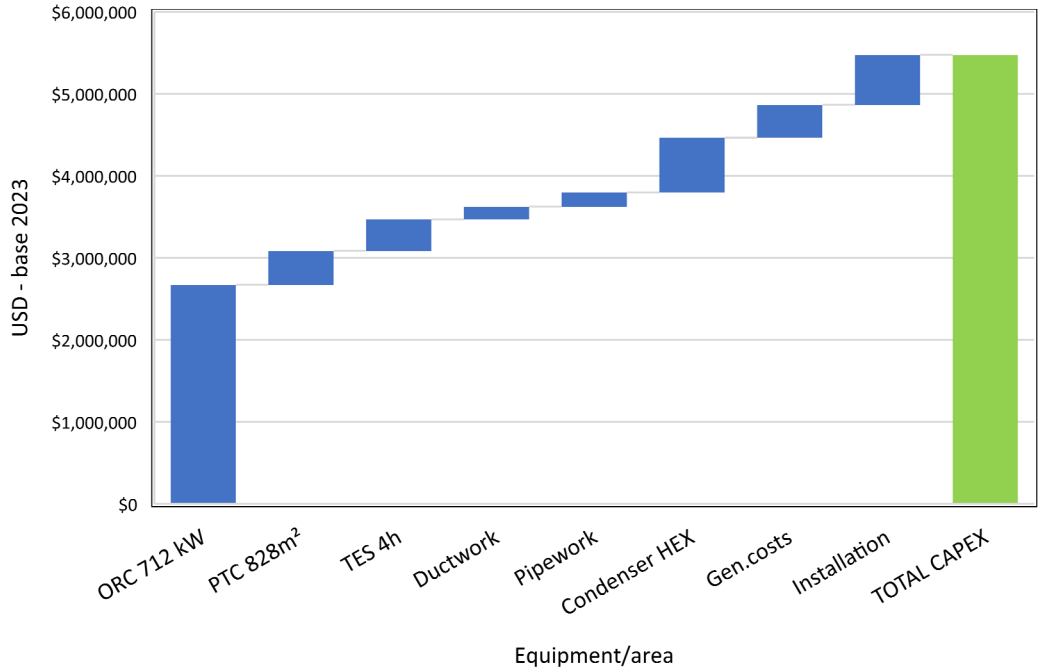


Figure 13. CAPEX breakdown based on 2023 market prices.

Table 5. Payback estimation SORC 2023—net savings.

Net Energy Production SORC Optimized (MW)	Energy Cost ($USD/MWh)	Energy Saving ($USD/Year)	OPEX ($USD/Year)	Total Net Saving ($USD/Year)
0.712 0.752	103.16 29.47	432,017 130,331	136,833	425,515

The simple payback estimated of the optimized SORC is 12 years and 10 months. Remark: no inflation, correction of costs/prices, tax incentives are considered on this payback estimation.

3.3.1. Payback Considering CO_2 Emission Credits

Below, the alternative payback estimation taking into consideration extra revenue coming from CO_2 credits is shown (Table 6).

Table 6. Extra revenue from GHGE emissions avoided.

Energy Source	GHGEs Avoided (tCO_2/Year)	Σ GHGEs Avoided (tCO_2/Year)	CO_2 Emission Credit Price ($USD/$tCO_2$)	Extra Revenue ($USD/Year)
Electricity Natural gas	2969 798	3767	30.00	113,022

The alternative simple payback estimated now, summing the energy production savings and the revenue from carbon credits, is 10 years and 2 months.

3.3.2. Benefit–Cost Analysis

Table 7 shows the present worth values.

Table 7. Benefit–cost analysis calculation.

Year	Cost	Benefits	Benefit Desulfurization	Energy Cost Avoided	PW Cost	PW Sum Benefits
0	USD 5,473,322				USD 5,473,322	
1	USD 136,833	USD 145,984	USD 9255	USD 562,348	USD 131,237.10	USD 688,240.56
2	USD 143,674.70	USD 153,283.70	USD 9717.64	USD 590,465.16	USD 132,163.50	USD 693,098.86
3	USD 150,858.43	USD 160,947.89	USD 10,203.52	USD 619,988.41	USD 133,096.44	USD 697,991.44
4	USD 158,401.36	USD 168,995.28	USD 10,713.70	USD 650,987.84	USD 134,035.97	USD 702,918.57
5	USD 166,321.42	USD 177,445.04	USD 11,249.38	USD 683,537.23	USD 134,982.13	USD 707,880.47
6	USD 174,637.49	USD 186,317.30	USD 11,811.85	USD 717,714.09	USD 135,934.97	USD 712,877.41
7	USD 183,369.37	USD 195,633.16	USD 12,402.45	USD 753,599.79	USD 136,894.54	USD 717,909.61
8	USD 192,537.84	USD 205,414.82	USD 13,022.57	USD 791,279.78	USD 137,860.88	USD 722,977.34
9	USD 202,164.73	USD 215,685.56	USD 13,673.70	USD 830,843.77	USD 138,834.04	USD 728,080.84
10	USD 212,272.97	USD 226,469.84	USD 14,357.38	USD 872,385.96	USD 139,814.07	USD 733,220.36
				Present worth	**USD 6,828,176**	**USD 7,105,195**

For the system here analyzed, the ratio sum benefits, and the cost is 1.04; the difference B–C is USD 277,020, concluding that the investment is justified.

4. Conclusions

This work aims to investigate an alternative solution for using solar and waste heat from the paint shop process to simultaneously produce heating and electrical power through a Solar ORC system in the automotive industry located in the southern region of the USA. In this regard, Organic Rankine Cycle technology, not yet applied in the automotive industry, makes available a trustworthy process for converting heat into electricity.

Currently, the automotive manufacturing process is mainly powered by grid electricity and fossil fuels. This paper presents an innovative system that integrates a specially designed Solar Organic Rankine Cycle system with low-temperature waste heat recovery for paint shops.

According to the 4E analysis, this system, never investigated in the automotive sector, is technically and economically feasible.

The Therminol VP-1, as the working fluid, is assumed inside the closed collectors and storage systems. The third closed circuit is the ORC, which uses solar energy and wasted energy from the paint shop, the last source targeting to pre-heat the organic fluid in the system, increasing the efficiency of the entire equipment. Toluene has been chosen as the organic fluid of the SORC. The SORC system has the capacity to produce 712.2 kW_{el} and 752 kW_{therm}. If applied to the southern region of the USA, this system would have an installed capacity of 11 times higher than the existing SORC equipment running in Louisiana and Florida.

The results for the modeled equipment give an energy efficiency of 31.02%, an exergy efficiency of 34.23%, and an ORC efficiency of 27.70%. Among other components, the exergy analysis identified an RTO HE at the top of the list with respect to having the largest exergy destruction, which amounts to more than 40% of the total exergy destruction in the system. It, thus, points toward areas for future investigation to improve system efficiency and reduce payback periods.

This study estimated the simple payback period of the system using two approaches: one by not accounting for the potential revenue from GHG emission credits and another including these. If carbon credits were not considered in this analysis, the payback would have been 12.9 years, and, with the carbon credits received, this would reduce to 10.2 years. The benefit–cost analysis comes out in favor of an investment in this SORC system.

The authors further recommend that a prototype of the system should be built in an industrial setting to validate the results and refine the integration of the various parts. Further research can then take off from the one performed here on dynamic analysis for energy generation throughout the day.

As a final comment, eventually in the long term, the authors see the automotive manufacturing plants growing more in areas where solar energy is more abundantly available. Other systems, such as the reverse Rankine cycle and any technology using solar energy as the source, might be explored and improved to support economically and environmental manufacturing in places closer to the Equatorian Line.

Author Contributions: R.N.M.M.: conceptualization, investigation, methodology, modeling, and manuscript writing. M.E.: Investigation, supervision, writing. S.A.: conceptualization, review of the manuscript, and supervision. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: Author Ronaldo Nilo Miyagi Martire was employed by Dürr Systems Inc.. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Nomenclature

Abbreviations	
CAPEX	Capital Expenditure
CLT	Collector (PTC)
cond	Condenser
CPC	Compound Parabolic Collector
DNI	Daily Solar Irradiation
ETC	Evacuated Tube Collector
EVA	Evaporator (ORC circuit)
FPC	Flat Plate Collector
gen	Generator
GHGE	Greenhouse Gas Equivalencies
HEX	Heat Exchanger
HTF	Heat Transfer Fluid
HW	Hot Water
LFR	Linear Fresnel Reflector
O&M	Operations–Maintenance
ORC	Organic Rankine Cycle
PD	Parabolic Dish
PTC	Parabolic Trough Concentrator
RTO	Regenerative Thermal Oxidizer
SORC	Solar Organic Rankine Cycle
ST	Solar Tower
T-S	Temperature vs. Entropy graphic
turb	Turbine
VOC	Volatile Organic Compound
A	Area
amb	Ambient
apert	Aperture
cp	Constant pressure specific heat
D	Density
G_b	Direct normal irradiation
H	Enthalpy
hydr	Hydraulic
m	Mass flow
η	Efficiency

P	Pressure
Pd	Pressure drop
PP	Pinch point/pump
$PP1$	Pump circuit 1
PP_2	Pump circuit 2
$PP3$	Pump circuit 3
$PPoint$	Pinch point
Q	Power/heat
Q_{el}	Electrical power
S	Entropy
sp	Static pressure
T	Temperature
v	Density
$visc$	Viscosity
Vp	Friction loss equivalence
δ	Difference (delta)
$\dot{\epsilon}$	Exergy (destruction)
$\dot{\varepsilon}$	Exergy

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