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Exergoeconomic Analysis of a Solar Powered ORC using Zeotropic Mixtures for Combined Heat & Power Generation

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Abstract:

As a part of the transition of the energy system towards renewables, new technologies and combinations of technologies are emerging. These include utilization of medium temperature industrial processes or availability of surplus heat from renewables. For these applications, organic Rankine cycles may be cost efficient solutions, if both expander work and condenser heat may be utilized as valuable products. In this study, a solar powered organic Rankine cycle using a zeotropic mixture is investigated from a design perspective. Both an Exergy and Exergoeconomic analysis were conducted. The investigated unit is capable of co-producing approximately 30 kW electricity and 160 kW district heating with a exergetic efficiency of > 60 %. The unit is able to compete with existing renewable power generating systems in terms of specific cost of electricity.

Keywords:

Exergy, Exergoeconomic Analysis, Organic Rankine Cycle, Zeotropic Mixtures, District Heating.

1. Introduction

The climate crisis is the defining crisis of our time, and the escalation has been substantial in the last decade. The global threat is substantial and we as a society have the possibility of changing our current heading [1, 2]. In the last decade, the focus on finding new solutions to slow down or reverse our impact on the climate has been growing. This is also due to the heightened commitment from many governing bodies to pass laws and set goals that push the transition towards a carbon-neutral society. The European Union has published the Strategic Energy Technology Plan (SET-plan) which highlights 10 innovations and reaches areas that boost the progress to reach the goals set by the European Union [3]. The overall goal set by the European Union is to reduce the total emissions by 40 % between 1990 and 2030 [4]. In Denmark, the ambitions have been set high and goals of reducing the total emission by 70 % by 2030 and achieving net zero emissions by 2050 have been established by the Danish government. These goals will be achieved by increasing the supply of renewable energies and through energy optimisation. This will be guaranteed by investing in programmes such as the EUDP programme which focuses on research, development and demonstration (R&D) of new technologies related to renewable energy [5–7].

Due to their flexibility, safety, and low maintenance, ORC's appears to be a promising technology. They have favourable characteristics to exploit waste heat or low-temperature heat sources stemming i.e. from power-to-X or pyrolysis plants for conversion into work or electricity [8–10]. The combinations of heat source and ORC are many. However, in recent years extensive research has been carried out investigating solar-powered ORC systems. The use of solar irradiation as the driving force of the ORC shows great promise as a renewable energy technology due to the high compatibility between the achievable temperature of the solar collector matches well with the working temperature of the ORC cycle [8, 11, 12]. The Parabolic Trough Collector (PTC) is the most mature solar concentrating technology and is typically chosen due to their reasonable cost and relatively high efficiency. Furthermore, they perform well in lower solar resources and/or more cloudy climates [11–13].

The investigation of working fluids for ORC systems is covered in great length in literature where many have applied exergy analysis while fewer have performed an exergoeconomic analysis. The performance and economics of an ORC system are tightly linked to the working fluid. A higher efficiency may be achieved by choosing the correct working fluid, even with less expensive components [9, 14]. Many studies also consider the use of fluid mixtures as the working fluid. The great interest in fluid mixtures for use in power cycles stems from the possibility to reduce the irreversibility during a two-phase heat transfer process by utilizing the temperature glide of the working fluid mixture [14]. Rayegan and Tao [15] developed a methodology specifically for the selection of working fluids for solar-driven ORC systems. The method based the selection of working on several different parameters such as the molecular components of the fluids, temperature-entropy diagram and effects on the thermal and exergy efficiency. Tchanche et al. [9] investigated the performance of a low-temperature solar ORC based on thermodynamic criteria such as working pressure, mass and

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volume flow of different working fluids. Isentropic working fluids proved favourable such as butane and n-pentane. R152a, R600a, R600 and R290 also resulted in attractive performances. Habka and Ajib [16] investigated the performance of zeotropic mixtures in a small solar-driven ORC for combined heat and power. They further compared the mixture with pure fluids. The results showed that the mixture R409A outperformed the pure fluid R134a and R245fa, and could reduce the production cost of the energy unit to 16.20%. In a similar study done by Wang and Zhao [17], a low-temperature solar-driven ORC using both pure fluid and zeotropic mixtures is investigated. They also introduced an internal heat exchanger (IHEX) to the ORC. The IHEX improves the overall efficiency of the cycle. They found that when superheating the zeotropic mixtures and introducing the IHEX, a significant increase in thermal efficiencies can be gained. Garg et al. [18] investigated hydrocarbons mixed with carbon dioxide for flammability suppression of the hydrocarbons in a medium-temperature concentrated solar-powered ORC. Their study showed that extending the heat recovery in the IHEX into the two-phase region resulted in higher efficiency and is advantageous. However, at the same time, an exergy analysis showed that irreversibility in the IHEX was caused by the shifting of the pinch point towards the warm end of the IHEX. With a mixture of propane and CO_2 a real cycle efficiency of 15–18% was achieved at a source temperature of 573 K.

Ashouri et al. [19] performed an exergo-economic analysis and optimization of a double pressure ORC with a solar collector and storage tank. Results show that system can reach the efficiency of 22.7%. The exergoeconomic analysis revealed that the solar collector has the highest $\dot{Z} + \dot{C}_D$ due to both high exergy destruction and high investment costs of the collector. Following the collector, the storage tank, condenser, turbine, recuperator and evaporators had the highest destruction. Le et al. [20] carried out similar thermodynamic and economic optimization of a subcritical ORC (Organic Rankine Cycle) using a pure (n-pentane and R245fa) or a zeotropic mixture working fluid (mixtures of the two). In the study, a maximization of exergy efficiency and minimization of the LCOE (Levelized Cost of Electricity) was found which showed that the n-pentane-based ORC showed the highest maximized exergy efficiency of 53.2% and the lowest minimized LCOE of 0.0863 $/kWh. Regarding ORCs using zeotropic working fluids, 0.05 and 0.1 R245fa mass fraction mixtures present comparable economic features and thermodynamic performances to the system using n-pentane at minimum LCOE.

In this study, a solar-powered ORC with a storage tank will be investigated. The sytem is designed to have a 200 kW heat input which is converted into 30 kW of electricity and 160 kW of district heating. The system is constrained to off-the-shelf components. The system will be evaluated based on thermodynamic performance, exergetic performance and exergoeconomic performance. Furthermore, three different working fluids will be investigated, one pure fluid and two mixtures. By conducting the various analysis, options for improvement of the design should be identified and ranked in terms of priority. The analysis differentiates from available literature as it focusses on medium scale (e.g. 100-1000 kW thermal) ORC systems to be coupled to solar thermal collectors, with the aim to supply both electricity and district heating. As the system is synthesized by off-the-shelf components, exergoeconomic analysis was used to differentiate the value of various improvement possibilities. The design of the system is part of a EUDP-project abbreviated Fullspec, which stands for full spectrum solar power.

2. Methods

This section covers the theory and working principles of the system and the methods used for performing an exergy analysis and exergoeconomic analysis.

2.1. System Description

The system investigated in this study is illustrated in Fig 1. The system can be dived into three main loops: 1) Solar loop, 2) ORC loop and 3) District Heating loop. The solar loop consists of the PTC field and storage tank. In the solar loop, a thermal oil is used as heat transfer fluid. In the analysis it is assumed that the thermal oil is heated to 250 °C in the PTC field and transferred to a stratified storage tank. The thermal oil is then used as a heat source for the ORC loop by transferring heat in the evaporator. The thermal oil used in the solar loop is Gobaltherm® Omnisol.

The ORC loop is a standard ORC configuration with an IHEX and a liquid receiver. Here the liquid working fluid from the receiver is pressurized through the ORC pump. In the IHEX heat is recovered to preheat the working fluid from state 2 to 3. The working fluid is evaporated in the evaporator and then expanded through the expander resulting in the production of electricity. Lastly, the working fluid condenses in the condenser, transferring heat to the DH water and hereby heating it.

Three different working fluids are investigated. The different working fluids in three cases are 1) pure iso-pentane, 2) iso-pentane/CO_2 (0.99/0.01) and 3) iso-pentane/undecane/CO_2 (0.89/0.10/0.01). Here all ratios are given regarding mass basis. This numbering of cases will be used onwards. Case 1 might be viewed as the base case. The two mixtures additionally investigated are due to a desire to 1) avoid vacuum with in the system when the system is offline, and 2) maintain or increase performance compared to case 1.

2.2. Thermodynamic Model

The modelling of the system was done using Engineering Equation Solver (EES) [21] where all thermodynamic properties were determined using REFPROP [22]. All parameters used for the modelling of the system is presented in Table 1. The system was modelled in a steady state where mass and energy balances were applied to control volumes for each

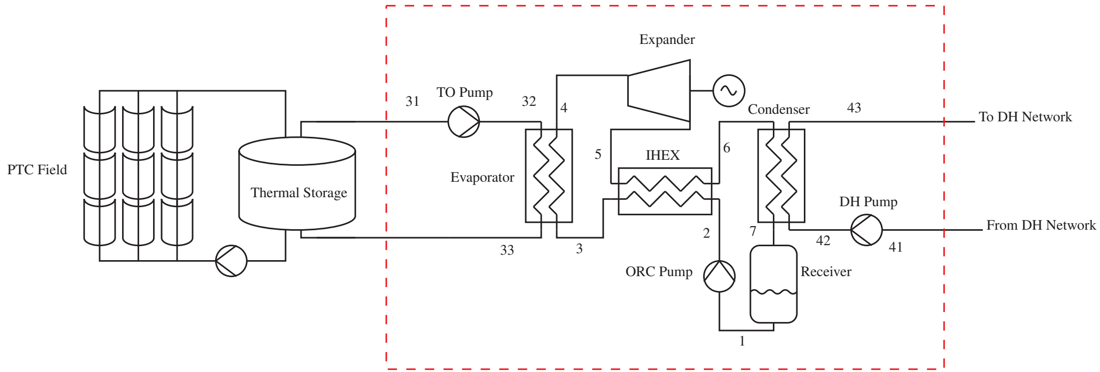

Figure 1: Schematic of the PTC powered ORC. The red dashed line mark the boundaries of the system investigated.

component using the general forms given in (1). Here, $\dot{m}$ is the mass flow rate, $\dot{Q}$ is the heat transfer rate across the control volume boundary, $\dot{W}$ is energy transfer by work, and h is enthalpy. The subscripts i and o denotes inlet and outlet streams, respectively.

$$0 = \sum_i \dot{m}_i - \sum_o \dot{m}_o \qquad \text{and} \qquad 0 = \dot{Q} - \dot{W} + \sum_i \dot{m}_i h_i - \sum_o \dot{m}_o h_o \tag{1}$$

Heat loss to the surroundings was neglected. However, the model did accounts for the pressure loss in the pipes and heat exchanger. The pressure loss through the heat exchanger is based on values from obtained heat exchanger manufactures. The pressure loss through the pipes is determined by the energy equation for pipe flows in (2) where the difference in velocity and height is neglected.

$$\Delta p = \frac{1}{2}\rho u^2 \left(f_f \frac{L}{D} + \sum K \right) \tag{2}$$

The power consumption of the pumps and gross power output of the expander are both determined using their respective isentropic efficiency, η_{pump} and η_{exp}.

The net electrical power output of the system is defined as the gross electricity production where the required electricity of the all pump are subtracted.

$$\dot{W}_{\text{net}} = \eta_{\text{gen}} \dot{W}_{\text{exp}} - \dot{W}_{\text{ORC,pump}} - \dot{W}_{\text{TO,pump}} - \dot{W}_{\text{DH,pump}} \tag{3}$$

The work required by the thermal oil pump accounts for the pressure loss through evaporator and pipes back and forth to the thermal storage.Similar, the worked required by the district heating pump accounts for the pressure loss through the condenser and the pipes connecting to the district heating network. The district heating pump does not take into account the loss through the overall district heating network.

The electric net efficiency of the system is defined as

$$\eta_{net,el} = \frac{\dot{W}_{net}}{\dot{Q}_{evap}} \tag{4}$$

The UA-value of each heat exchanger is determined based on a discretisation of the overall heat transfer in the heat exchangers. For each control volume, the following is applied assuming the cold side of the heat exchanger:

$$\dot{Q}_n = \dot{m}_{n,c} \left(h_{n,o,c} - h_{n,i,c} \right) \tag{5}$$

$$\dot{Q}_n = UA_n \Delta T_{\text{lmtd},n} \tag{6}$$

The overall UA is then determined by

$$UA = \sum_{j=1}^{n} UA_j \tag{7}$$

2.3. Exergy Analysis

To perform exergy analysis and exergoeconomic, the exergy destruction rate ($\dot{E}_{\text{D},k}$) for each component k was determined, using the theory described in [23].

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Table 1: System parameters used in the present study

Parameter		Value	Parameter		Value
Thermal Oil Loop			*ORC Loop*		
TO inlet temperature	T_{31}	250 °C	Evaporator heat input	$\dot{Q}_{\text{evap}}$	200 kW
TO outlet temperature	T_{33}	200 °C	Expander inlet temperature	T_4	225 °C
TO inlet pressure	p_{31}	500 kPa	Expander isentropic efficiency	η_{exp}	225 °C
District Heating Loop			Expander inlet pressure	p_4	3000 kPa
DH outlet temperature	T_{43}	70 °C	Pinch temperature in IHEX and condenser	ΔT_{pinch}	5 K
DH inlet temperature	T_{41}	40 °C	Expander generator efficiency	η_{gen}	0.98
DH inlet pressure	p_{41}	500 kPa	Condenser outlet quality	x_7	0
Overall					
Pump isentropic efficiency	η_{pump}	0.7			

In this study, only the physical part of the exergy is accounted as no changes in chemical composition occurs due to the implied steady state assumption, the system being a closed cycle and no splitting of streams with respect to the working fluid. The physical exergy is determined from (8) where the difference in velocity and elevation has been neglected.

$$e^{\text{PH}} = (h - h_0) - T_0(s - s_0) \tag{8}$$

For the exergy analysis, the fuel and product for each component were used to evaluate the performance of each individual component and the entire system. The general definitions of fuel and product are given by Bejan, Tsatsaronis, and Moran [23] and are presented in Table 2 for relevant components.

From the exergy rate of fuel and product, two exergy destruction ratios and the exergetic efficiency:

$$y^*_{D,k} = \frac{\dot{E}_D}{\dot{E}_{D,\text{tot}}} \qquad \text{and} \qquad \epsilon_k = \frac{\dot{E}_P}{\dot{E}_F} \tag{9}$$

Here y_D is the exergy destruction with a component with respect to the overall fuel input, y^*_D is the exergy destruction with a component with respect to the overall exergy destruction in the system and ϵ is the exergertic efficiency.

2.4. Exergoeconomic Analysis

The exergoeconomic analysis is, as the name implies, the combination of exergy analysis and the economics regarding the system. Prices for components within the ORC for all three cases along with the price for solar collectors, storage and district heating connection are based on offers collected from suppliers. Prices will not be presented due to confidentiality. Furthermore, price for each component with the ORC are adjusted such that the sum of prices of components matches with the actual retail price of the ORC unit. The actual retail price is based on a fixed percentage of profit desired for the sale of a ORC-unit. Parameters used for the exergoeconomic analysis is presented in Table 4. The exergoeconomic analysis is based upon the cost balances known from conventional economic analysis. In conventional economical analysis, the cost balance will typically be formulated for an entire system, whereas in the exergoeconomic analysis, they will be formulated for each component. The cost balance for the k'th component is given by

$$\dot{C}_{P,k} = \dot{C}_{F,k} + \dot{Z}^{\text{CI}}_k + \dot{Z}^{\text{OM}}_k \tag{10}$$

where $\dot{C}_{P,k}$ is the cost rate associated with the product, $\dot{C}_{F,k}$ is the cost rate associated with the fuel, $\dot{Z}^{\text{CI}}_k$ is the cost rate associated with the capital investment and $\dot{Z}^{\text{OM}}_k$ is the cost rate associated with operation and maintenance (O&M). The capital investment and O&M were be combined to $\dot{Z}_k = \dot{Z}^{\text{CI}}_k + \dot{Z}^{\text{OM}}_k$. The cost balance states that the cost rate associated

Table 2: Fuel and product definitions for various components. Subscripts c and h refers to the hot and cold stream in a heat exchanger

Parameter	Pumps	Expander	Heat Exchanger
Product, $\dot{E}_P$	$\dot{E}_o - \dot{E}_i$	$\dot{W}$	$\dot{E}_{o,c} - \dot{E}_{i,c}$
Fuel, $\dot{E}_F$	$\dot{W}$	$\dot{E}_i - \dot{E}_o$	$\dot{E}_{i,h} - \dot{E}_{o,h}$

with the product must be equal to all expenditures used to generate the product. Similar to the definitions of fuel and products presented in Table 2, definitions of the cost rate associated fuel and product is also created. Furthermore, auxiliary equation are needed. Both are presented in Table 3. The cost rate associated with capital investment of the component is determined based on the lifetime of the component and the yearly operational hours which yields in

$$\dot{Z}_k^{\mathrm{CI}} = \frac{CI_k}{t_{\mathrm{OP}} Y_k} \tag{11}$$

where Y is the expected lifetime of the component in years, t_{OP} is the yearly operation of the system in seconds. Furthermore, the cost rate associated with O&M of each component is assumed to be 5% of the capital investment for the given component and is then determined from the yearly operation.

$$\dot{Z}_k^{\mathrm{OM}} = \frac{0.05 CI_k}{t_{\mathrm{OP}}} \tag{12}$$

2.5. Exergoeconomic Performance Parameters

Based on the thermoeconomic properties previously introduced, several performance parameters were defined. The three employed performance parameters are 1) the cost of exergy destruction, $\dot{C}_{D,k}$, 2) the relative cost difference, r_k and 3) the exergoeconomic factor, f_k.

The cost of exergy destruction does not directly show itself from the cost balance previously presented. However, from the exergy balance and cost balance, one will be able to obtain the cost of exergy destruction of the k'th component, which describes as

$$\dot{C}_{D,k} = c_{F,k} \dot{E}_{D,k} \qquad \text{or} \qquad \dot{C}_{D,k} = c_{P,k} \dot{E}_{D,k} \tag{13}$$

As seen the cost of exergy destruction may be defined in two different ways. The first definition assumes that the rate of product ($\dot{E}_{P,k}$) is fixed and that the unit cost of fuel ($c_{F,k}$) is independent of the exergy destruction. The second definition assumes that the rate of fuel ($\dot{E}_{F,k}$) is fixed and that the unit cost of the product($c_{P,k}$) is independent of the exergy destruction. In general, the first definition gives a lower estimate and the second definition gives a higher estimate with the actual value of $\dot{C}_{D,k}$ being in-between.

The relative cost difference r_k for the k'th component is defined by

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} \tag{14}$$

The relative cost difference displays the relative increase in average cost per exergy unit between product and fuel. The relative cost difference also highlights whether the increase in the cost of the product stems from the price of fuel or the price associated with capital investment and O&M for the component.

Lastly, the exergoeconomic factor is defined for k'th components as

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{F,k} \dot{E}_{D,k}} \tag{15}$$

The exergoeconomic factor expresses a ratio which enables one to highlight whether the increase in cost rate from fuel to product stems from non-exergy-related cost or not. In the denominator of (15) $\dot{Z}_k$ is associated with non-exergy-related cost and $c_{F,k}\left(\dot{E}_{D,k} + \dot{E}_{L,k}\right)$ is associated exergy-related cost. A low value of the exergoeconomic factor for a component indicates that the increase in cost is due to high exergy destruction within the component and vice versa. Often the value of the exergoeconomic factor varies dependent of the component type. For compressors or turbines, the value is typically between 0.35 and 0.75, heat exchanger typically have a value below 0.55 and pumps tend to have a value above 0.7.

Table 3: Cost of fuel and product definitions for various components. Subscripts c and h refers to the hot and cold stream in a heat exchanger

Parameter	Pumps	Expander	Heat Exchanger
Product, $\dot{C}_P$	$\dot{C}_o - \dot{C}_i$	$\dot{C}_w$	$\dot{C}_{o,c} - \dot{C}_{i,c}$
Fuel, $\dot{C}_F$	$\dot{C}_w$	$\dot{C}_i - \dot{C}_o$	$\dot{C}_{i,h} - \dot{C}_{o,h}$
Auxiliary equation	None	$c_i = c_o$	$c_{i,h} = c_{o,h}$

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2.6. Levelised Cost of Electricity

The levelised cost of electricity (LCOE) is a measurement that enables one to assess and compare alternative methods of energy production. The LCOE of an energy-generating system should be seen as the average total investement and O&M cost of the system per unit of total electricity generated over an assumed lifetime. Alternatively, the LCOE can be seen as the average minimum price at which the electricity generated by the system is required to be sold to break even with the total costs of building and operating the system over its lifetime [24]. The overall assumptions used for the calculation of LCOE is presented in Table 4. The LCOE is determined by

$$\mathrm{LCOE} = \frac{\sum_{y=1}^{Y} \frac{CI_y + O\&M_y}{(1+r_r)^y}}{\sum_{y=1}^{Y} \frac{W_y}{(1+r_r)^y}} \tag{16}$$

where CI is the capital investment per year, O&M is the cost of the operational and maintenance per year, W is the electricity production per year and r_r is the discount rate. No fuel term is used as the solar input is assumed to be free of charge. The value of O&M in year 1 is estimated as 5% of the investment cost of entire system, equal to the definition used in the exergoeconomic analysis. After year 1 the cost of O&M increases with r_{OM} percent per year. This yields in

$$O\&M_y = O\&M_1 \left(1 + r_{\mathrm{OM}}\right)^y \quad \text{for} \quad y > 1 \tag{17}$$

The yearly production of electricity is determined by

$$W_y = \dot{W}_{net} t_{\mathrm{OP}} \quad \text{for} \quad y = 1, 2 \ldots Y \tag{18}$$

3. Results and Discussion

A comparison between the different cases has been carried out and the main thermodynamic findings are presented in Table 5. The overall electrical efficiency of the system is greatest for the third case, followed by case 1 with the second highest. This relates to the output of the expander. As the inlet conditions of the expander are equal for all three cases, outlet conditions determine the possible output of the expander. Here lower outlet pressure contributes to more power output. This also means that one should strive to find working fluids that allow for a lower condensation pressure. On the other hand, case 2 has the greatest overall efficiency due to a higher district heating output. However, as electrical efficiency is valued highest, Case 3 is promising as the electrical efficiency of the system increases compared to case 1 while avoiding vacuum in a non-operational state. The gained efficiency does come at a price as the sizing of heat exchangers is influenced by the choice of the working fluid. Compared to case 1, the UA-values of the condenser and IHEX in case 3 are $\approx 38\,\%$ and $\approx 127\,\%$ greater, respectively. One of the reasons that increases in UA-values are observed for mixtures is the temperature glide occurring in the condensation phase which affects the temperature differences. This is quite evident when comparing the process in the condenser for cases 1 and 3. As seen Fig 2, a larger temperature difference can be clearly seen the in the condenser (state 6-7) for case 1 to case 3 and even though $\dot{Q}_{\mathrm{cond}}$ is smaller than in case, the UA-value needed is still greater. The temperature glide of the mixtures and the desired $\Delta T_{\mathrm{pinch}} = 5[\mathrm{K}]$ in the condenser and IHEX further results in condensation starting in the IHEX. This means that two-phase flow will exit the IHEX and enter the condenser. Especially in case 3, where a large portion of the process is in the two-phase region. These conditions should be taken into account when building the system as it might lead to maldistribution in the condenser.

Table 4: Economical parameters used for the exergoeconomic analysis and determination of LCOE. All components are assumed to have equal expected lifetime.

Parameter		Value
Expected lifetime	Y	20 years
Discount rate	r_r	5%
Yearly increase of O&M	r_{OM}	0.25%
Yearly operation	t_{OP}	6000 hours

Table 5: Thermodynamic performance parameters

Case	η_{net} [-]	$\dot{W}_{\mathrm{net}}$ [kW]	$\dot{Q}_{\mathrm{cond}}$ [kW]	$\dot{Q}_{\mathrm{IHEX}}$ [kW]	p_{cond} [kPa]	UA_{cond} [kW K^{-1}]	UA_{evap} [kW K^{-1}]	UA_{IHEX} [kW K^{-1}]
1	0.1295	25.90	172.3	123.8	395.6	11.71	5.204	9.592
2	0.1273	25.47	172.8	146.6	413.0	12.51	4.961	11.56
3	0.1418	28.37	169.7	187.1	345.0	16.84	5.905	21.90

3.1. Exergy Analysis

The results of the exergy analysis are presented in Table 6. There are four major components that stand for 98 % of all the exergy destruction in the system and they are the heat exchanger and expander. This also shows that the pumps are almost neglectable. Based on the analysis, the expander is in all three cases the component associated with the largest amount of exergy destruction, followed by the evaporator, condenser, IHEX and pumps. The expander stands for 37 % to 43 % of the overall exergy destruction. The high exergy destruction in all three is related to the relatively low isentropic efficiency of the expander. The expander also has the lowest exergetic efficiency of major components. This combination of high exergy destruction and low exergetic efficiency could suggest that the expander would be the first component to optimize in order to reduce the exergy destruction.

The large amount of exergy destruction within the evaporator is mostly due to the specification of the system, where thermal oil must return at 200 °C. This creates large temperature differences throughout the heat exchanger. A lower outlet temperature could be considered with the goal of reducing exergy destruction as the evaporator is a heat exchanger with the greatest amount of exergy destruction.

It is quite interesting to note that case 3 has the highest exergetic efficiency for all heat exchangers. This also highlights the benefits of utilizing the temperature glide which allows lower temperature differences and therefore, lower exergy destruction. The mixture of case 3 has a quite significant temperature glide, as seen from Fig 2. The effects of the temperature glide are particularly clear in the condenser where both case 2 and 3 have lower exergy destruction and higher exergetic efficiency compared to case 1. However, for case 2 the benefit of the mixture is only present in the condenser as lower exergetic efficiencies are seen in the evaporator and IHEX compared to case 1.

When investigating the overall performance of the system, case 3 has the best performance of the three cases with a system exergetic efficiency of 64.1 % and a total exergy destruction of 35 kW. Case 2 results in the lowest thermal efficiency of the 3 cases. However, opting for case 2 to obey the no-vacuum criteria will only result in a 1.0 % decrease in exergetic performance while opting for case 3 will result in a 4.4 % increase in exergetic performance. As expected a small difference is observed in the overall performance, due to the two cases being almost identical.

3.2. Exergoeconomic Analysis

The main findings of the exergoeconomic analysis is presented in Table 7. The exergoeconomic parameters will be evaluated based on the procedure suggested by [23]. Here the analysis starts by investigating the value of $\dot{Z} + \dot{C}_D$ and ranking the components based on their value. This couple with firstly evaluating the value of r and secondly, evaluating

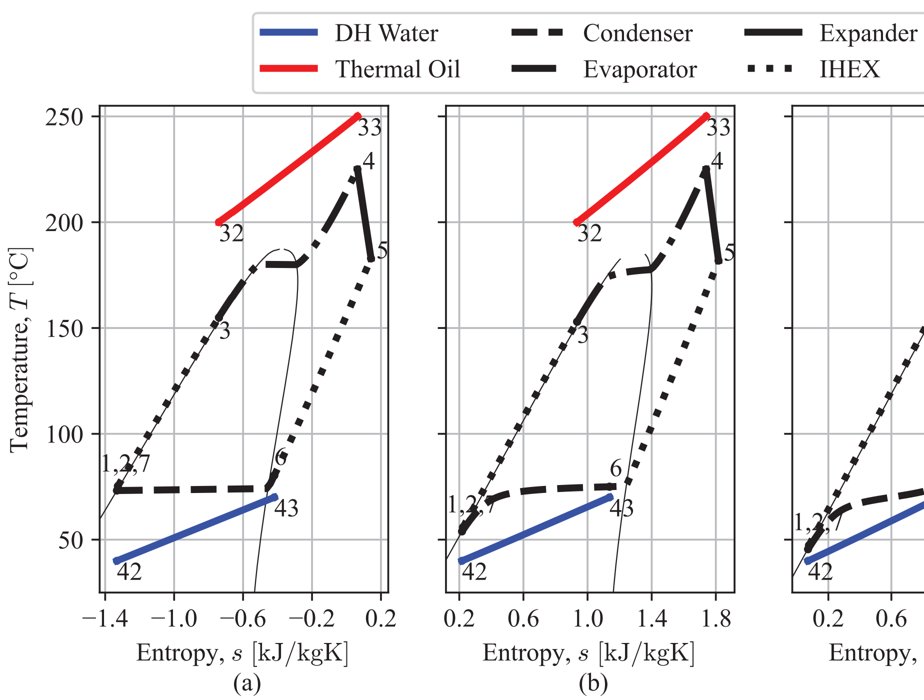

Figure 2: T,s-diagram for (a): Case 1, (b): Case 2 and (c): Case 3. It should be noted DH water and Thermal oil is used for visualisation and entropy is only for the working fluid

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the value of f.

The expander is in all three cases the component with the greatest value of $\dot{Z} + \dot{C}_D$ and the value is more than 3 times greater than that of other components. However, this is expected as the expander is the most expensive component of all, coupled with having the highest exergy destruction. This indication suggests that the expander would be the first component where design changes or choice of expander type should be considered. For the rest of the components, the

Table 6: Fuel, Product and Exergy destruction

Case	ORC Pump	IHEX	Evaporator	Expander	Condenser	TO Pump	DH Pump
			Fuel, $\dot{E}_F$ [kW]				
1	3.636	37.448	86.716	43.412	31.896	0.183	0.014
2	3.482	41.723	86.683	42.553	30.882	0.161	0.013
3	3.808	51.806	86.683	47.369	28.345	0.161	0.013
			Product, $\dot{E}_P$ [kW]				
1	2.749	33.612	76.395	29.737	23.527	0.154	0.010
2	2.582	36.742	75.834	29.132	23.600	0.135	0.002
3	2.797	46.939	77.783	32.361	23.180	0.135	0.002
			Destruction, $\dot{E}_D$ [kW]				
1	0.887	3.836	10.321	13.675	8.369	0.029	0.004
2	0.900	4.981	10.849	13.421	7.282	0.026	0.011
3	1.011	4.867	8.900	15.007	5.164	0.026	0.011
			Exergetic Efficiency, ϵ [-]				
1	0.756	0.898	0.881	0.685	0.738	0.840	0.729
2	0.741	0.881	0.875	0.685	0.764	0.840	0.172
3	0.735	0.906	0.897	0.683	0.818	0.840	0.172
			Exergy Destruction Ratio, y_D^* [-]				
1	0.024	0.103	0.278	0.368	0.225	0.001	0.000
2	0.024	0.133	0.290	0.358	0.194	0.001	0.000
3	0.029	0.139	0.254	0.429	0.148	0.001	0.000
		Total Exergy Destruction, $\dot{E}_{D,\text{tot}}$ [kW]			System Exergetic Efficiency, ϵ_{tot} [-]		
1		37.122			0.614		
2		37.469			0.608		
3		34.985			0.641		

Table 7: Exergoeconomic Perfomance Parameters

Case	ORC Pump	IHEX	Evaporator	Expander	Condenser	TO Pump	DH Pump
			$\left(\dot{Z} + \dot{C}_D\right) \cdot 10^{-3}$ [DKK/s]				
1	1.68	0.66	0.78	5.70	1.27	0.43	0.42
2	1.72	0.88	0.81	5.73	1.17	0.43	1.78
3	1.76	1.12	0.66	6.00	0.89	0.43	1.78
			Relative Cost Difference, r [-]				
1	1.99	0.17	0.15	1.30	0.39	10.11	132.27
2	2.08	0.20	0.15	1.30	0.37	11.20	557.03
3	2.01	0.20	0.12	1.21	0.30	11.55	599.53
			Exergoeconomic Factor, f [-]				
1	0.84	0.34	0.08	0.65	0.10	0.98	1.00
2	0.83	0.33	0.05	0.65	0.16	0.98	0.99
3	0.82	0.49	0.08	0.62	0.26	0.98	0.99

three cases differ with regards to the ranking of highest to the lowest value of $\dot{Z} + \dot{C}_D$.

When further investigating the relative cost difference, r, for the expander, a value above 1 can be observed. This indicates that a majority of the increase in the cost of the product stems from the price of the capital investment and O&M, rather than the price of the fuel. The same conclusion can be made for all pumps. Especially for thermal oil pump and district heating pump, the value of r is very high. On the contrary, the increase in the cost of the product for all heat exchangers stems from the price of the fuel rather than capital investment and O&M. The fact that all the more mechanically complicated component have a higher value of r, is as expected due to the much higher price of components such as turbo machinery and pump compared to heat exchangers. Furthermore, components which do add much thermodynamic value to the system also then to have high values of r. This is seen from both the thermal oil and district heat pump. The pump does not have to overcome high pressure differences and should mainly ensure flow, hereby having close to zero exergy destruction associated with these components. Therefore, a high value of r is inevitable.

Last, the exergoeconomic factor, f, is investigated. This factor should ideally be 0.5, meaning that the cost is evenly distributed between the cost of capital investment and O&M and the cost of exergy destruction. However, the value tends to depend on the type of component. The exergoeconomic factor for the pumps and expander for all cases is above 0.5. Therefore, it could be cost-effective to decrease the capital investment of these components at the expense of their efficiency. Especially, the values for the pumps as their values are quite close to 1. The value of the expander may be over 0.5 but as the value for an expander is between 0.35 and 0.75, a value of 0.65 is quite acceptable. Therefore, the expander may not be the right component to optimize as few economical benefits would stem from it. As expected, it would be beneficial to increase the capital investment for both the evaporator and condenser as most of the cost is associated with the cost of exergy destruction. Especially, the evaporator which also relates to the high exergy destruction and the boundary conditions set for the system. The value of f for the IHEX is greater compared to the evaporator and condenser. In case 1 and 2, a greater investment could be beneficial but the IHEX in case 3 is very close to the optimum of 0.5.

When comparing the exergy analysis and the exergoeconomic analysis, similar conclusions may be drawn for some components, whereas conflicting conclusions can be drawn from others. The pumps in the system would not harm the exergy efficiency of the system greatly if the pumps were downgraded to cheaper models with lower efficiencies due to their low contribution to the overall exergy destruction. In most cases, both the exergy and exergoeconomic analysis indicates that more could be invested in the heat exchangers which would reduced to exergy destruction and benefit the system. Here the exception is the IHEX in case 3 as the exergoeconomic factor is 0.49. The expander is a component that stands out in all cases as the exergy analysis would suggest improving it as it is the greatest contributor to the exergy destruction of the system. However, it would not be cost effective to improve the expander as shown by the exergoeconomic analysis.

3.3. Levelised Cost of Electricity

Lastly, LCOE may also be used to compare the three systems. The LCOE is presented in Table 8. Here the lowest value of LCOE is found for case 3 with a value of 0.87 DKK/kWh and 1.69 DKK/kWh. Even though, the ORC-unit is more expensive in case 3 compared to case 1 because of the larger heat exchangers needed, the increased performance of the system results in a lower LCOE. Compared to another renewable technology photovoltaics (PV), the LCOE for case 3 is slightly above the LCOE for PV but within the price range of PV systems with battery storage when looking at the ORC-unit isolated. However, when including the solar collectors and storage, the price slightly exceeds to LCOE of PV with battery storage. However, the ORC benefits from producing district heating as well. Therefore, an additional source of income will also be associated with the ORC system.

Table 8: LCOE for all three cases. LCOE are given for the ORC-unit isolated and including the solar field and storage

Parameter	Case 1	Case 2	Case 3
$LCOE_{\mathrm{ORC}}$ [DKK/kWh]	0.89	0.92	0.87
$LCOE_{\mathrm{ORC+Solar}}$ [DKK/kWh]	1.79	1.84	1.69

4. Conclusion

The current study investigates a 200 kW heat input solar driven ORC-unit based on thermodynamic, exergetic and exergoeconomic performance. The study has been investigating three different ORC working fluids, one pure fluid and 2 mixtures. The mixtures are chosen to ensure an offline pressure of 1 atm Iso-pentane is the pure fluid and the two mixture are iso-pentane/CO_2 (0.99/0.01) and iso-pentane/undecane/CO_2 (0.89/0.1/0.01). The greatest electrical net efficiency of the ORC was found for the last mixture at 14.18 % which is a 9.5 % improvement compared to the pure fluid. The first mixture performed worst with an efficiency of 12.73 %. The improvement from pure fluid to second mixture does require greater heat exchangers compared due the temperature glide of the mixture ensuring lower temperature differences. Similar, results are seen from the exergy analysis. Here the second mixture has the smallest overall exergy destruction 34.96

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kW and the highest exergetic efficiency of 64 % due to the utilization of the temperature glide. The expander was in all three cases the component with the largest amount of exergy destruction.

The exergoeconomic factor of the exergoeconomic analysis highlighted the pumps in the system as the components where capital investment should be greatly reduced as it would benefit the overall system economically. For all three cases, the analysis suggested that a greater investment for both the condenser and evaporator could be made improving the components and hereby being both exergetic and economically beneficial. The exergoeconomic analysis illustrated IHEX and expander are two components that are close their optimal operational state with regard to capital investment and thermodynamic efficiency. Even though, the expander is associated with the greatest amount of exergy destruction, no economical benefits will be the result of improving the component.

With the current layout and specific choice of components, the ORC unit isolated will be able to produce electricity at LCOE of 0.87 DKK/kWh which is within the range of PV systems with battery storage but the LCOE of 1.69 DKK/kWh for combined system with the ORC unit, solar field and storage slightly exceeds that of PV systems with battery storage. However, this is without accounting for the extra revenue generated by the district heat.

Nomenclature

Roman Letters

$\dot{C}$	Cost rate [DKK/s]
c	Average cost per unit of exergy [DKK/kJ]
D	Diameter [m]
$\dot{E}$	Exergy flow rate [kW]
f	Exergoeconomic factor [−]
f_f	Friction Factor [−]
h	Specific enthalpy [kJ/kg]
K	Minor Losses [−]
L	Length [m]
$\dot{m}$	Mass flow rate [kg/s]
p	Pressure [kPa]
$\dot{Q}$	Heat transfer rate [kW]
r	Relative Cost Difference [−]
r_r	Discount rate [−]
$\dot{S}$	Entropy flow rate [kJ/(Ks)]
T	Temperature [°C]
t	Time [s]
u	Velocity [m/s]
$\dot{W}$	Power [kW]
Y	Lifetime [year]
y^*	Exergy desctruction ratio [−]
$\dot{Z}$	Non-exergy related cost rate [DKK/s]

Greek Letters

η	Efficiency [−]
ν	Kinematic viscosity [m^2/s]
ρ	Density [kg/m^3]

Subscripts

k	Component
0	Reference state
[1;43]	State points
c	Cold Side
D	Destruction
F	Fuel
gen	generation
h	Hot Side
i	inlet
L	Loss
o	Outlet
P	Product
pinch	Pinch point
s	Isentropic
tot	Total system
y	Year

Superscripts

CI	Capital Investment
OM	Operation & Maintenace
OP	Operational
PH	Physical

Acronyms

DH	District heating
IHEX	Internal heat exchanger
LCOE	Levelized cost of electricity
O&M	Operation and Maintenance
ORC	Organic Rankine Cycle
PTC	Parabolic Trough Collector
TO	Thermal Oil

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