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ENHANCED EXERGOECONOMIC ANALYSIS OF A HYBRID SOLAR-BIOMASS ORGANIC RANKINE CYCLE COGENERATION PLANT

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ABSTRACT

This study aims to examine available avenues to improve thermo-economic performance of a hybrid solar-biomass organic Rankine cycle (ORC) cogeneration plant. The ORC unit is rated at about 630 kWe, and it is related to a real solar-ORC plant which currently runs in Ottana (Italy). The implemented hybrid configuration had been conceived as an efficient way to improve dispatchability and operating hours in the aforementioned existing concentrated solar power (CSP) plant and other similar ones, through biomass retrofit. Beyond what is available in literature on hybrid solar-biomass systems, enhanced exergoeconomic analysis is performed in this study, by considering intrinsic irreversibilities and cost rates in the respective components, which are imposed by the assumptions of systemic and economic constraints, and can thus not be eliminated. Results show that relative cost rates of between 2% and 73% of total cost rates could be theoretically avoided. Also, it was obtained that investment cost rates of solar field, thermal energy storage tanks, furnace heater, recuperator and ORC preheater need be reduced, for acceptable economic performance of the hybrid plant. This type of information is highly essential for improved design and quicker market penetration of fully-renewable energy systems.

Keywords: organic Rankine cycle (ORC), enhanced exergoeconomic analysis, hybrid solar-biomass plant, avoidable investment

NONMENCLATURE

Abbreviations	
CSP	Concentrated Solar Power
HTF	Heat Transfer Fluid
LFC	Linear Fresnel Collectors
ORC	Organic Rankine Cycle
Symbols	
AV	Avoidable
$\dot{C}$	Exergy Cost Rate (€/h)
$\dot{E}$	Exergy Rate (kW)
f^e	Enhanced Exergoeconomic Factor
R_{cr}	Relative Avoidable Cost Rates

1. INTRODUCTION

As one of the renewable energy resources that are freely accessible to all, application of solar energy for thermal and electrical power production has attracted huge attention in recent times. However, due to the transient nature of solar irradiation, it is often difficult to follow scheduled energy profiles with solar systems, and their conversion technologies are often characterized with low efficiencies and reliability. One way to salvage the above-mentioned challenges is through hybridization with more dispatchable renewable resources, such as biomass. In this regard, new research studies are springing up to analyze the techno-economic feasibilities of hybrid solar-biomass systems [1]. Amongst the conversion technologies widely studied, organic Rankine cycle (ORC) has been highly adopted for exploiting low-enthalpy resources [2]. In fact, a number of concentrated solar power (CSP)-ORC plants are already in practical use around the world. However, most of them have high annual shut-down period, due to the aforementioned challenges with solar irradiation availability [3]. To ameliorate this, a novel scheme had been proposed by the authors [4], for biomass retrofit to existing CSP-ORC plants, for improved dispatchability and higher annual operation hours. Although studies exist in the literature on hybrid solar-biomass plants [1], the proposed scheme is the first to focus on possible ways to improve existing CSP-ORC plants with biomass retrofit, to the best of authors' knowledge.

The objective in this paper is to investigate potential improvement opportunities in the hybrid CSP-biomass ORC plant, through enhanced exergoeconomic analysis. The main contribution is thus an interplay of classical enhanced exergoeconomic methodology and newly-proposed hybrid system. This adequately facilitates the decision on whether improvement efforts for each component of the hybrid plant should be focused on thermodynamic improvement to reduce irreversibility, or economic improvement to reduce component investment cost. The applied methodology is particularly suited for retrofit studies, which deals with improvement of existing and practical systems, such as it is investigated in this paper.

2. METHODOLOGY

The scheme of the hybrid CSP-biomass ORC plant studied in this paper is illustrated in Fig 1. As shown, the ORC is jointly fed by thermal power from solar field and biomass furnace. The solar field consists of Linear Fresnel Collectors (LFC), with thermal oil as heat transfer fluid (HTF). Two-tank Thermal Energy Storage (TES) system is integrated with the solar field. TES cold tank stores HTF to be heated by useful energy collected from the sun, after which the HTF is stored in the TES hot tank, from where it feeds the ORC. The biomass section consists of a control-based modular boiler, with the combustion zone dominated by convection heat transfer processes, and separated from HTF heater. Hot combustion flue gases exiting the furnace heater preheat the inlet air into the combustion chamber, before escaping to the atmosphere. A three-way valve upstream of the ORC regulates the flow of HTF from solar field and biomass furnace. Similarly, another three-way valve downstream of the ORC controls the distribution of HTF into the TES cold tank and cold side of the furnace heater. The same thermal fluid is considered for both the solar field and biomass furnace heater, as well as TES medium. The ORC is of recuperative subcritical configuration, and water is considered as condensation medium. Design characteristics of the hybrid plant are highlighted in Table 1. In order to apply enhanced exergoeconomic analysis to the hybrid CSP-biomass ORC plant, exergy rate was defined for each stream as numbered in Fig 1. Next to this, net exergy input (fuel), net exergy output (product) and destroyed exergy (irreversibility) were determined for each component.

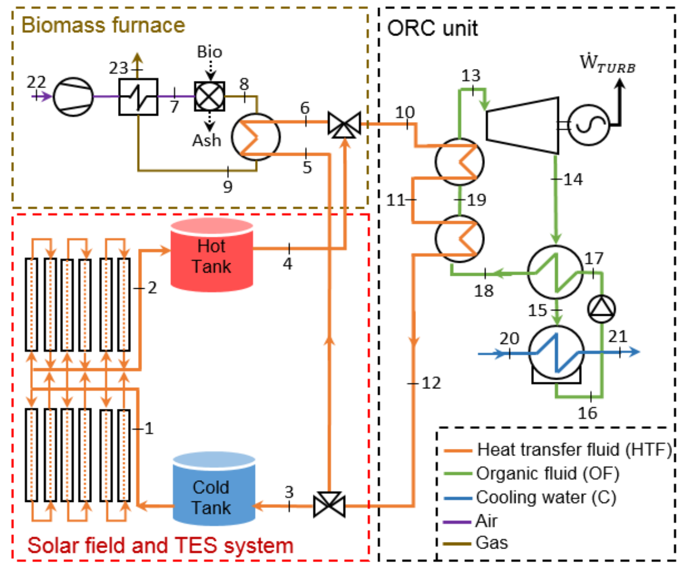

Fig 1 Conceptual scheme of the hybrid CSP-biomass ORC plant

Then, cost rate balance equations were expressed for all system components, which are necessary to apply the Specific Exergy Costing (SPECO) approach [5]. These include auxiliary equations which facilitated simultaneous solutions of the cost rate balance equations, from where specific cost of exergy was obtained for each stream. In addition, specific cost associated with fuel (c_f) as well as specific cost associated with product (c_p) were obtained for each component of the hybrid plant. Furthermore, the destroyed exergy in each component ($\dot{E}_D$) was divided into avoidable ($\dot{E}_D^{AV}$) and unavoidable ($\dot{E}_D^{UN}$) parts. This was done by assuming thermodynamic parameters that would lead to maximum achievable efficiency and infinite investment cost of the respective components [6]. Destroyed exergy obtained for each components under these conditions are unavoidable, and by subtracting them from the actual total destroyed exergy values, the avoidable parts of the irreversibility were obtained. Furthermore, the avoidable cost rate due to destroyed exergy ($\dot{C}_D^{AV}$) was obtained for each component, as follows:

$$\dot{C}_D^{AV} = c_f \cdot \dot{E}_D^{AV}. \quad (1)$$

In order to split the investment cost rate ($\dot{Z}$) for each component into avoidable ($\dot{Z}^{AV}$) and unavoidable ($\dot{Z}^{UN}$) parts, unavoidable investment cost per unit of product exergy $\left(\dot{Z}/\dot{E}_P\right)^{\boldsymbol{UN}}$ was obtained for each component, by assuming exceedingly inefficient thermodynamic parameters for the respective components. Then, the unavoidable investment costs for the components were calculated by:

$$\dot{Z}^{UN} = \dot{E}_P \cdot \left(\dot{Z}/\dot{E}_P\right)^{\boldsymbol{UN}}, \qquad (2)$$

where $\dot{E}_P$ is product exergy for the component under real thermodynamic conditions. Avoidable investment costs were obtained by subtracting unavoidable costs from the total costs in the respective components:

$$\dot{Z}^{AV} = \dot{Z} - \dot{Z}^{UN}, \qquad (3)$$

The purchase costs of solar field and TES were taken as 160 €/m^2 and 45 €/kWh, respectively [8]. For ORC and biomass components, purchase costs were obtained from Turton *et al*. [9]. Shell and tube configuration was assumed for heat exchangers, and using effectiveness-NTU approach, heat exchange surface areas were obtained as 28.2 m^2, 54.7 m^2, 58.6 m^2, 106.4 m^2, 440 m^2 and 415 m^2 for air preheater, furnace heater, ORC preheater, condenser, evaporator and recuperator, respectively. Costs associated with engineering, procurement and construction (EPC) as well as taxes were factored into Z, at 11%. The performance of the hybrid solar-biomass ORC plant was assessed using the enhanced exergoeconomic factor (f^e) and relative avoidable cost rates (R_{cr}), given by:

$$f^e = \frac{\dot{Z}^{AV}}{\dot{Z}^{AV} + \dot{C}_D^{AV}}, \qquad (4)$$

$$R_{cr} = \frac{\dot{Z}^{AV} + \dot{C}_D^{AV}}{\dot{Z} + \left(c_f \cdot \dot{E}_D\right)}. \qquad (5)$$

By using total investment cost rates obtained under real thermodynamic conditions in Eq. (4), conventional exergoeconomic factor is obtained for each component, and an informed comparative analysis could therefore be performed. The assumed conditions implemented for obtaining unavoidable destroyed exergy and unavoidable investment cost rates in this study are highlighted in Table 2.

Table 1 - Design characteristics of hybrid CSP-biomass ORC plant

Solar Field		**ORC unit**	
Collector focal length	4.97 m	Working fluid	$C_6H_{18}OSi_2$
Collector length	99.45 m	Heat sink	Water
Design DNI	900 W/m^2	Net electrical power	629 kW
Net Effective area (A_{sf})	8400 m^2	Design thermal power input	3178 kW
Optical efficiency (η_{opt})	64%	Design HTF mass flow rate	11.05 kg/s
Heat transfer fluid	Therminol SP-I	Pump isentropic efficiency	80%
Mean ambient temperature	20 °C	Pump motor efficiency	98%
Design inlet temperature	165 °C	Turbine isentropic efficiency	85%
Design outlet temperature	275°C	Electromechanical efficiency	92%
TES system		**Biomass Combustion**	
Storage capacity	15.4 MWh	Furnace thermal duty	1430 kW
Tank useful volume	330 m^3	Fuel composition (dry basis, % by weight)	48.3%C, 5.9%H, 0.1%N_2, 38.5%O_2, 7.2%Ash
Aspect ratio	0.32		
Ambient wind speed (v_a)	3 m/s		
Insulation thickness	0.5 m	LHV (dry basis)	16.3 MJ/kg
Insulation thermal conductivity	0.16 W/m^{2}K	Moisture content	20%
		Stoichiometric air-fuel ratio	5
		Excess air	150%
		Combustion efficiency	99%

Table 2 – Assumptions for unavoidable conditions for destroyed exergy

Component	Unavoidable conditions	Component	Unavoidable conditions
Solar field	$\left(\frac{\dot{E}_D}{\dot{E}_P}\right)_{\boldsymbol{sf}}^{UN} = 0.7638$ [7]	Furnace heater	ΔT_{min} = 3 K
Hot tank	Perfect insulation	ORC preheater	ΔT_{min} = 3 K
Cold tank	Perfect insulation	Evaporator	ΔT_{min} = 5 K

Air preheater	ΔT_{min} = 12 K	Recuperator	*effectiveness* = 0.9
Combustion chamber	Adiabatic condition; air-fuel ratio = 1 (high gas temperature)	Condenser Pump Turbine	ΔT_{min} = 3 K η_{is} = 0.95; η_{mech} = 1 η_{is} = 0.97; η_{mech} = 1

Assumptions for unavoidable conditions for investment cost rates			
Solar field	$\dot{Z}^{UN} = 0.98 \cdot \dot{Z}$	Furnace heater	ΔT_{min} = 80 K
Hot tank	10% heat loss	ORC preheater	ΔT_{min} = 45 K
Cold tank	8% heat loss	Evaporator	ΔT_{min} = 50 K
Air preheater	ΔT_{min} = 200 K	Recuperator	*effectiveness* = 0.70
Combustion chamber	Ambient properties at inlet; Exit gas temperature = 750 K	Condenser Pump Turbine	ΔT_{min} = 20 K η_{is} = 0.70 η_{is} = 0.70

3. RESULTS AND DISCUSSION

The cost rates due to destroyed exergy for conventional and enhanced exergoeconomic analyses of the hybrid plant are highlighted in Table 3. Also, the comparison between exergoeconomic performance of the hybrid solar-biomass ORC plant based on conventional and enhanced analyses is provided in Table 4. A valuable insight into the importance of enhanced exergoeconomic analysis is provided by comparing the sum ($\dot{C}_D^{AV}$+$\dot{Z}^{AV}$) with the sum ($\dot{C}_D$+$\dot{Z}$), as depicted in Table 4. The former (avoidable cost rates) evaluates the cost reduction opportunities in each component of the hybrid solar-biomass ORC plant. The components with high values of avoidable cost rates are more prospective to enhance economic performance of the hybrid plant, and should logically be prioritized for efforts aimed at overall system improvement. In this regard, more attention should be directed at the combustion chamber, turbine, evaporator, recuperator and condenser, amongst others. Premised on the assumptions made for enhanced exergoeconomic analysis in this study, relative avoidable cost rates obtained for the hybrid plant show that between 2% and 73% of total cost rates could be theoretically achieved. Furthermore, comparison of conventional and enhanced exergoeconomic factors for each component is shown in Fig 2. The contribution of cost of investment to total cost is shown by conventional exergoeconomic factor, for each component, while the enhanced exergoeconomic factor illustrates contribution of avoidable cost to total avoidable cost. Except for solar field where both values are equal to 100% (due to zero cost of solar energy), conventional exergoeconomic factors for all the components are higher than the enhanced ones, for corresponding components. What this implies is that the actual cost improvement that could be achieved for the respective components is partly due to reduction in investment cost, but mostly due to reduction in destroyed exergy and associated costs. In particular, results of enhanced exergoeconomic analysis place emphasis on the need to reduce investment costs of solar field, thermal energy storage tanks, furnace heater recuperator and ORC preheater. Exemplarily for recuperator, conventional exergoeconomic factor shows that about 48% of the total costs associated with the component are due to investment expenses. However, enhanced exergoeconomic factor shows that about 35% of the total avoidable costs associated with the recuperator are due to investment costs. Analyzing this comparison for each system component reveals the best approach to achieve cost improvement for the whole system, either by adopting cheaper components or by optimizing thermodynamic performance for lower irreversibility costs. Thus, the application of enhanced exergoeconomic analysis aids the decision on how to improve performance with more certainty, thereby providing the designer with better iterative cost minimization procedure.

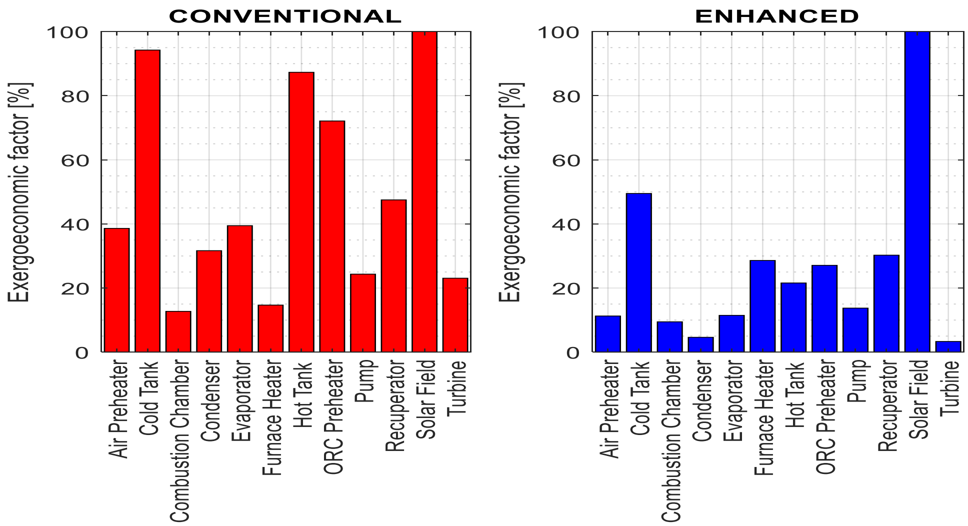

Fig 2 Comparison of conventional and enhanced exergoeconomic factors for the hybrid solar-biomass plant

Table 3. Cost rates of destroyed exergy for conventional and enhanced analyses

Component	c_f (€/kWh)	$\dot{E}_D$ (kW)	$\dot{C}_D$ (€/h)	$\dot{E}_D^{AV}$ (kW)	$\dot{C}_D^{AV}$ (€/h)	$\dot{Z}$ (€/h)
Solar field	0	5219.7	0	4732.10	0	22.62
Hot tank	0.0477	17.60	0.84	17.60	0.84	5.76
Cold tank	0.0532	6.62	0.35	6.62	0.35	5.76
Air preheater	0.0275	50.37	1.38	49.87	1.37	0.87
Combustion chamber	0.0122	1192.0	14.51	903.29	10.99	2.14
Furnace heater	0.0275	357.33	9.82	30.68	0.84	1.69
ORC preheater	0.0532	14.72	0.78	14.05	0.75	2.03
Evaporator	0.0532	145.84	7.76	127.67	6.80	5.06
Recuperator	0.0810	66.76	5.41	33.30	2.70	4.89
Condenser	0.0810	76.68	6.21	36.64	2.97	2.88
Pump	0.0992	2.94	0.29	2.37	0.24	0.094
Turbine	0.0810	111.60	9.04	97.51	7.90	2.71

Table 4. Results for enhanced exergoeconomic analysis

Component	$(\dot{Z}/\dot{E}_P)^{UN}$ (€/kW)	$\dot{Z}^{UN}$ (€/h)	$\dot{Z}^{AV}$ (€/h)	$\dot{C}_D^{AV}$ (€/h)	$\dot{C}_D^{AV}+\dot{Z}^{AV}$ (€/h)	$\dot{C}_D+\dot{Z}$ (€/h)	R_{cr} (%)
Solar field	0.0347	22.16	0.45	0	0.45	22.62	2.0
Hot tank	0.0060	5.52	0.23	0.84	1.07	6.60	16.2
Cold tank	0.0177	5.41	0.35	0.35	0.70	6.11	11.4
Air preheater	0.0258	0.70	0.17	1.37	1.54	2.25	68.5
Combustion chamber	0.0009	0.99	1.15	10.99	12.14	16.65	73.0

Furnace heater	0.0027	1.35	0.34	0.84	1.18	11.51	10.3
ORC preheater	0.0364	1.75	0.28	0.75	1.03	2.81	36.5
Evaporator	0.0046	4.18	0.88	6.80	7.68	12.82	59.9
Recuperator	0.0170	3.72	1.17	2.70	3.87	10.30	37.5
Condenser	0.0396	2.73	0.14	2.97	3.11	9.09	34.2
Pump	0.0049	0.06	0.04	0.24	0.27	0.39	70.9
Turbine	0.0038	2.44	0.27	7.90	8.17	11.75	69.5

4. CONCLUSIONS

Improvement potentials in a conceptual hybrid CSP-biomass ORC cogeneration plant have been analyzed in this study, using enhanced exergoeconomic methodology. The studied hybrid scheme proposed lucid configuration for biomass retrofit to existing CSP-ORC plants, beyond what is available in the state-of-the-art. The enhanced exergoeconomic analysis facilitated the decision on the best approach to apply cost minimization measures to each component of the hybrid plant, and thus to the system as a whole. Results showed that relative avoidable cost rates of between 2% and 73% of total cost rates could be theoretically avoided. Also, it was obtained that investment costs of solar field, thermal energy storage tanks, furnace heater, recuperator and ORC preheater should be reduced, for acceptable economic performance of the hybrid plant. This type of information is highly essential for improved design and quicker market penetration of fully-renewable energy systems.

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