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Article

4E Analyses of a Hybrid Waste-Driven CHP–ORC Plant with Flue Gas Condensation

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Abstract: The combination of a waste-driven hybrid heat and power plant with a small organic Rankine cycle unit was recently proposed and investigated from a thermodynamic perspective. The present study provides a more comprehensive assessment from system operation through considering the energy, exergy, exergoeconomic, and exergoenvironmental (4E) aspects in a revised design of this concept to obtain a bigger picture of the system's technical, economic, and environmental effects on existing and future energy systems. The revised design includes a flue gas condensation unit and alternative friendly organic working fluids. For this, the hybrid plant is modeled for its thermal, economic, and environmental performances. Then, the exergy losses and environmental effects of the system are scrutinized, the cost of losses and pollutions are predicted, and lastly, sorts of solutions are introduced to improve the exergoeconomic and exergoenvironmental performances of the system. The results indicate that the highest share of exergy destruction relates to the incineration (equipped with a steam generator) with a levelized cost of approximately USD 71/h for a power plant with almost 3.3 megawatt electricity output capacity. The hybridization proposal with the flue gas condensation unit increases the sustainability index of the system from 1.264 to 1.28.

Keywords: waste-fired CHP; ORC; waste heat recovery; district heating; exergoeconomic analysis

1. Introduction

The future smart energy system (which is to be based on a 100% renewable energy share) is said to be more dependent on the electricity sector rather than the heat, cold, and gas sectors. The penetration of the renewable-based power generation systems into energy markets [1], the increasing growth in the number of electric vehicles [2]; the increasing penetration of heat pumps and chillers in the district cooling and heating system, etc., are some of the most important reasons for this fact. On the other hand, there are many in-service energy production systems in different sectors that have been installed in recent years and will be working for the next 20–30 years. Therefore, in parallel with the innovations for new-coming technologies, feasible solutions that make existing energy plants compatible with future needs are required.

In Denmark and many other European countries, waste-fired combined heat and power (CHP) plants are considered to be popular and widespread energy systems for the co-generation of heat and electricity for district heating and power grids [3]. The incineration of CHP plants with flue gas cleaning, producing about three times more heat compared to power, plays a key role in turning

waste into energy in an environmentally friendly way. This fact makes such power plants be of high potential for revising the design to increase the share of power output instead of a larger heat generation rate.

The literature presents a substantial number of studies in the field of waste-driven CHPs. For example, Rydén et al. [4] evaluated the role of hybrid power plants (comprising waste-fired modules) in the future hybrid energy systems in Sweden. Eriksson et al. [5] scrutinized the operation of the waste incineration co-generation systems in Denmark. Tobiasen and Kamuk [6] investigated the benefits of employing waste-fired CHP plants in district heating systems, optimizing the efficiency of these systems for larger capacities. Tomić et al. [7] studied the effectiveness of different waste heat recovery power plants for the recently adopted legislation/regulation in Europe's energy markets. Munster and Meibom [8] assessed the best methods for using waste in future energy technologies by proposing novel waste-to-energy plants with maximum efficiency and flexibility. Yang et al. [9] accomplished a fundamental technoeconomic investigation of a waste-incineration co-generation plant based on a combined intermediary pyrolysis concept. Nami et al. studied the thermodynamic [10] and economic [11] performance of a municipal waste-fired tri-generation system to supply the energy demand of the neighborhood in terms of electricity, heating, and cooling.

In the present study, some of the produced heat by the waste-fired CHP system was converted to electrical power by employing an organic Rankine cycle (ORC). Although the organic Rankine cycle (ORC) operates with lower efficiency in comparison to a regular Rankine cycle, the capability of operating at lower pressure and temperature levels makes it an interesting and popular solution mainly for the use of low-quality waste heat sources for power production [12–14]. The following four works are a couple of references that give a detailed understanding of the ORC based on the cutting-edge state of the art and practice. Landelle et al. [15] presented a comprehensive examination of the state of the art of ORC. Hoang [16] reviewed heat recovery from diesel engines using ORC technology. In this work, he aggregated and classified working fluids to meet the requirement of each system and reported the thermodynamic and economic analyses of engine ORCs. Park et al. [17] presented a review from the ORC experimental data trends and concluded that the efficiency of heat to power conversion was about 44% of the Carnot cycle efficiency, reporting that R245fa, R123, and R134a are the most popular working fluids, and the typical value for the Back-Work Ratio is around 25.9%. Mahmoudi et al. [18] presented a new review of waste heat recovery by ORC, including statistics on fluids and configurations, and concluded that internal combustion engines and gas turbines are the most used heat sources. Generally, ORC is a recognized concept with relatively developed technology and literature. Thus, there is no intention of presenting an extensive literature survey of that here.

In the most recent study of the authors, they investigated the parallelization of a small-scale ORC with a waste-fired CHP plant to increase its power output rate [19]. Although this hybridization resulted in poorer net heat and overall energy output, the higher electricity output of the system made it be a compatible yet feasible solution for future smart energy systems. However, still, the utilization of effluent waste heat via flue gas condensation seems to be a gap in the body of knowledge for waste-driven CHPs. In the present study, the authors tried to present an optimal design of the technology, a thorough exergy assessment, and a comprehensive economic investigation, as well as a reliable environmental analysis. The thermodynamic and economic performance of the developed waste-driven CHP system is compared for the cases with and without flue gas condensation via presenting an improved version of the integrated waste-fired CHP–ORC system.

2. Materials and Methods

2.1. Primary and Modified Hybrid Plants

The proposed hybrid waste-driven CHP plant in its revised configuration is herein introduced by presenting detailed information about its technical properties. In the traditional arrangement of waste-driven CHP plants, an electric generator driven by a steam turbine generates power and the rejected waste heat of the condenser is used to support the local district heating setup. In the

turbine (ORCT) in a saturated vapor condition. The enthalpy change of the working fluid between the turbine inlet and outlet turns into mechanical power and then the ORCT exiting flow condenses within the ORC condenser (ORCC) before being pressurized and completing the cycle. The low-temperature heat source of the ORC unit is considered as local groundwater with a temperature variety of 5–7 °C [20].

After passing HX3, the exhaust still has considerable heat content and arrives at the second heat exchanger which is applied for district heating applications. It is noteworthy that a cleaning stage that guarantees the contamination of the outlet near zero has been considered for the flue gas condensation line. Wet flue gas cleaning can be considered as an effective approach for bringing the flues to around zero-emission amounts in SO₂, HCl, and NH₃. On the other hand, the customized flue gas scrubber solution assists in capturing minute particle emissions [21].

The properties of the proposed integrated power plant are tabulated in Table 1. It also offers useful data about the literature from which these suppositions have been taken.

Table 1. Technical and physical characteristics of the proposed combined concept.

Item	Information/Value	Ref.
Flue gas outlet temperature (°C)	45	-
Considered working fluids for the ORC	R124 R134a	
Design condition of the ORC turbine (°C/MPa)	Sat. Vap 0.7–1.3 1.2–2.2	
The temperature of the ORC condenser (°C)	10	
Evaporator/condenser pinch point temperature difference (°C)	5/3	
Condenser coolant temperature and pressure (°C and MPa)	5–7 and 0.12	
Properties of the municipal solid waste	Values	-
Waste mass compositions	Ash	0.0591
	Carbon	0.4718
	Hydrogen	0.0625
	Oxygen	0.3957
	Nitrogen	0.0091
	Sulfur	0.0018
LHV of the waste (MJ/kg)	12.500	[22]
Combustion extra air (%)	80.0	[23]
Temperature of the gasses after combustion (°C)	1100.0	[24]
Temperature of the flue gas at the beginning of stack (°C)	165.0	[24]
HPT inlet temperature and pressure (°C and MPa)	550 and 10	[24]
IPT inlet temperature and pressure (°C and MPa)	500 and 3	
LPT inlet temperature and pressure (°C and MPa)	300 and 0.25	
LPT outlet temperature and pressure (°C and MPa)	90 and 0.07 (vapor)	
Condenser outlet temperature and pressure (°C and MPa)	90 and 0.07 (condensed)	
DH supply stream temperature and pressure (°C and MPa)	80 and 1.2	
DH return stream temperature and pressure (°C and MPa)	40 and 1.2	

In this system, the isentropic efficiency of pumps and turbines is considered to be 85% and the generator efficiency is set at 95%.

2.2. Mathematical Modeling

To design an energy converting system, not only efficiency improvement but also concerns associated with the product costs and environmental impacts should be addressed. Exergoeconomic

analysis is a strong tool combining conventional exergy analysis with economic principles. This method of evaluation provides some useful information for designers and operators not obtainable with thermodynamic and economic tools, separately. Exergoeconomic analysis also gives some information about the economic influence of losses and irreversibilities on the system product cost [25].

The exergoeconomic and exergoenvironmental models of the integrated waste-fired CHP–ORC power plant are presented hereunder.

2.2.1. Exergoeconomic Analysis

The prerequisite for the exergoeconomic analysis is a precise exergy analysis of the system. Exergy is the minimum/maximum theoretical required/useful work of a system when it moves from an equilibrium state to the dead state (usually considered as standard ambient condition, 298 K, and 101 kPa) [26]. For a deep understanding of exergy definition and exergy analysis, the readers are referred to the textbooks of Szargut et al. [27] and Kotas [28]. Neglecting kinetic, potential, electrical, and surface tension effects, the overall exergy of material flow can be defined by the summation of physical and chemical exergies:

$$ex_i = ex_i^{ph} + ex_i^{ch} \quad (1)$$

Specific chemical and physical exergies can be defined as

$$ex_{ii}^{ch} = \sum_i y_i(ex_i^{ch}) + \bar{R}T_0 \sum_i y_i(\ln y_i) \quad (2)$$

$$ex_i^{ph} = (h_i - h_i^0) - T_0(s_i - s_i^0) \quad (3)$$

Considering each component as a control volume, under the steady-state condition, exergy destruction in the k^{th} component due to irreversibilities can be written as follows:

$$\dot{E}x_{D,k} = \sum_j (1 - \frac{T_0}{T_j}) \dot{Q}_j - \dot{W}_{cv} + \sum_i \dot{E}x_i - \sum_o \dot{E}x_o \quad (4)$$

The exergy rate in each stream is defined as

$$\dot{E}x_i = \dot{m}_i(ex_i^{ph} + ex_i^{ch}) \quad (5)$$

Following the same method as regular thermo-economic analysis and calling the flow of resources of a system as ‘fuel (F)’, the flow of productions as ‘product (P)’, and the other remaining flows with no practical usefulness as ‘losses (L)’, a fuel-product (F-P) definition can be applied for the whole system (where, F-P \geq irreversibilities) or any of the components of the system. Table 2 outlines the F-P equations for all of the components of the referenced waste-fired CHP–ORC plant with flue gas condensation. In this table, the total produced exergy is the exergy rate related to the net produced power as well as the exergy rate of supplying heat. The net produced power is defined as

$$\dot{W}_{net} = \dot{W}_{ST} + \dot{W}_{ORCT} - \dot{W}_{PUMPS} \quad (6)$$

Moreover, the total input exergy of the system is the rate supplied by the municipal waste ($\dot{E}x_{mw}$) [21].

Table 2. Fuel (F)-product (P) definition for the different components of the hybrid system [26].

Components	Fuel	Product	Number
Incinerator	$\dot{E}x_1 + \dot{E}x_2 + \dot{E}x_9$	$\dot{E}x_4 + \dot{E}x_5$	(7)
ST	$\dot{E}x_5 - \dot{E}x_6$	\dot{W}_{ST}	(8)
P1	\dot{W}_{P1}	$\dot{E}x_9 - \dot{E}x_8$	(9)
FWT2	$\dot{E}x_{13} + \dot{E}x_{16}$	$\dot{E}x_{14}$	(10)
Evap	$\dot{E}x_{15} - \dot{E}x_{16}$	$\dot{E}x_{17} - \dot{E}x_{20}$	(11)
P2	\dot{W}_{P2}	$\dot{E}x_{13} - \dot{E}x_{12}$	(12)
ORCT	$\dot{E}x_{17} - \dot{E}x_{18}$	\dot{W}_{ORCT}	(13)
ORCP	\dot{W}_{ORCP}	$\dot{E}x_{20} - \dot{E}x_{19}$	(14)
HX1	$\dot{E}x_6 - \dot{E}x_7$	$\dot{E}x_{10} - \dot{E}x_{14}$	(15)
HX2	$\dot{E}x_{11} - \dot{E}x_{12}$	$\dot{E}x_{22} - \dot{E}x_{21}$	(16)
HX3	$\dot{E}x_4 - \dot{E}x_{23}$	$\dot{E}x_{11} + \dot{E}x_{15} - \dot{E}x_{10}$	(17)
HX4	$\dot{E}x_{23} - \dot{E}x_{24}$	$\dot{E}x_{26} - \dot{E}x_{25}$	(18)
Total	$\dot{E}x_{mw}$	$\dot{W}_{net} + \dot{E}x_{22} + \dot{E}x_{26} - \dot{E}x_{21} - \dot{E}x_{25}$	(19)

The next phase of exergoeconomic analysis is formulating the cost balance equation for different components. The cost balance equation reveals that the summation of the cost rates relates to the inlet exergy streams together with the general system costs (owing to capital investment, operating-maintenance costs, etc.) should be identical to the entire cost rates of the outlet exergy streams. Therefore, for the k^{th} component cost balance equation is as follows:

$$\sum_i \dot{C}_{i,k} + \dot{C}_q + \dot{Z}_k = \dot{C}_{w,k} + \sum_e \dot{C}_{e,k} \quad (20)$$

where,

$$\dot{C}_k = c_k \times \dot{E}x_k \quad (21)$$

where \dot{C}_k , c_k , and \dot{Z}_k are the cost rate related to exergy stream, the cost per unit of exergy, and the levelized capital investment cost of the components, respectively. The latter is obtained by applying the capital recovery factor as below [26]:

$$\dot{Z}_k = \frac{CRF \times \varphi}{3600N} Z_k \quad (22)$$

$$CRF = \frac{i_r(1 + i_r)^m}{(1 + i_r)^m - 1} \quad (23)$$

in which, \dot{Z}_k , φ , N , i_r and m are the capital investment cost of the k^{th} component, the maintenance factor (1.06 [26]), the system operating hours (7446 h per year [26]), the interest rate (4% for the case of Denmark) and the lifetime of the system (20 years), respectively. The number 7446 h based on the operation factor of 0.85 is proposed by Bejan et al. [26], meaning that a CHP plant is in service for 85% of the total annual 8760 h. Capital investment cost functions related to the key components of the referenced hybrid CHP-ORC system with flue gas condensation are listed in Table 3. It should be highlighted that the cost function considered for the incineration unit comprises the cost of the pollution control unit as well.

Table 3. Cost functions for the key components of the proposed system [22,29,30].

Components	Cost Functions	Number
Incinerator	$Z_{Incin} = 275.8\dot{m}_{mw} + 18231500$	(24)
ST	$Z_{ST} = 6000\dot{W}_{ST}^{0.6}$	(25)
P1	$Z_{P1} = 3540\dot{W}_{P1}^{0.65}$	(26)
Evap	$Z_{Evap} = 309.14A_{Evap}^{0.85}$	(27)
P2	$Z_{P2} = 3540\dot{W}_{P2}^{0.65}$	(28)
ORCT	$Z_{ORCT} = 4750\dot{W}_{ORCT}^{0.75}$	(29)
ORCP	$Z_{ORCP} = 200\dot{W}_{ORCP}^{0.65}$	(30)
ORCC	$Z_{ORCC} = 516.62A_{ORCC}^{0.6}$	(31)
HX1	$Z_{HE1} = 516.62A_{HE1}^{0.6}$	(32)
HX2	$Z_{HE2} = 309.14A_{HE2}^{0.85}$	(33)
HX3	$Z_{HE3} = 309.14A_{HE3}^{0.85}$	(34)
HX4	$Z_{HE4} = 309.14A_{HE4}^{0.85}$	(35)

Several parameters such as the average cost per unit product exergy ($c_{P,k}$), the average cost per unit fuel exergy ($c_{F,k}$), exergoeconomic factor (f_k) and the cost rate associated with the exergy destruction within each component ($\dot{C}_{D,k}$) are playing important roles in the economic analysis of the energy conversion systems. These parameters are formulated as follows [26]:

$$c_{P,k} = \frac{\dot{C}_{P,k}}{\dot{E}x_{P,k}} \quad (36)$$

$$c_{F,k} = \frac{\dot{C}_{F,k}}{\dot{E}x_{F,k}} \quad (37)$$

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}} \quad (38)$$

$$\dot{C}_{D,k} = c_{F,k} \times \dot{E}x_{D,k} \quad (39)$$

In the cost balance equation formulated for a component (Equation (20)), there is no cost term obviously related to the exergy destruction. Consequently, the cost related to the exergy destruction of each component or process is a concealed cost, but a crucial parameter which is only shown by an exergoeconomic analysis.

2.2.2. Exergoenvironmental Analysis

One of the main objectives of the current research is to adequately address the environmental impact of the hybrid system and highlight it in the form of a sensible cost for society, and compare this cost with the conventional waste-driven CHP plant, via an exergoenvironmental analysis. Generally, there is still this argument whether a waste-fired technology is environmentally friendly because an incineration process releases pollutants. However, the true justification claims that the pollution emitted from the waste incineration process is negligible compared to that of landfilling the waste. The average emission from the landfilling of municipal solid waste sources is about 840 kg of CO₂-e (equivalent CO₂) per ton, whereas emission from the same amount of waste being incinerated is about 415 kg CO₂-e per ton.

For the exergoenvironmental analysis of this study, the released CO₂ and NO_x out of a waste incineration process are taken into account. The mass flow rate of emitted CO₂ is simply obtained from the combustion reaction molar balance, and the rate of generating NO_x in terms of 'gram per kg of fuel' in the combustion chamber can be defined as follows [31]:

$$\dot{m}_{NO_x} = \frac{15 \times 10^{14} \tau^{0.5} \exp\left(\frac{-71100}{T_{PZ}}\right)}{P^{0.05} \frac{\Delta P^{0.5}}{P}} \quad (40)$$

where τ represents the residence time in the combustion zone which is considered to be 0.002 s. P , ΔP , and T_{PZ} are the incinerator inlet pressure, the non-dimensional pressure drop in the incinerator, and combustion flame temperature, respectively. The environmental cost associated with CO₂ and NO_x can be presented as the following equation:

$$\dot{C}_{env} = c_{NO_x} \dot{m}_{NO_x} + \dot{c}_{CO_2} \dot{m}_{CO_2} \quad (41)$$

In the above equation, c_{NO_x} and c_{CO_2} are supposed to be USD 6.853/kg and USD 0.024/kg, correspondingly.

In addition to the above function, this study reports the rate of the CO₂-e emission of a waste incineration process, which is obtained as follows:

$$E_{CO_2e} = \sum E_{\lambda} GWP_{\lambda} \quad (42)$$

where E_{λ} is the emission of various destructive greenhouse gases like CO₂, N₂O, etc. and GWP_{λ} shows the global warming potential of the assumed greenhouse gas in comparison to the pollution of CO₂ (ton of CO₂ per ton of the given gas). E_{λ} is obtained as

$$E_{\lambda} = \sum \mu_{\lambda} \xi M \quad (43)$$

where μ_{λ} is the emission concentration of the assumed gas, M is the waste mass, and ξ indicates the outlet gas volume. The values of M , ξ , and GWP are obtained from Ref. [32].

As such, a sustainability analysis is accomplished to quantify the sustainability index (SI) of the hybrid power plant. A sustainability analysis states that it is essential to not only use renewable and environmentally friendly energy sources but also to efficiently use available non-renewable sources to have a sustainable development [33]. The sustainability index indicates that there is a relationship among the exergy destruction and environmental impacts of a system defined by

$$SI = \frac{1}{D_P} = \frac{1}{\frac{\dot{E}x_{in,total}}{\dot{E}x_{D,total}}} \quad (44)$$

In the end, it bears mentioning that a computer program is developed by using Engineering Equations Solver (EES) software by applying the cost balances equations as well as applicable auxiliary equations for system components. These equations, however, are accomplished by considering the fuel and product instructions in the SPECO method [34].

3. Results and Discussions

The results of the exergoeconomic and exergoenvironmental investigations carried out on the hybrid power plant are herein presented, discussed, and compared with those related to the simple CHP plant and the hybrid CHP–ORC plant without the waste heat recovery loop. For this, first of all, the optimal technical operation of the plant found in [21] is reviewed quickly.

The optimal values of the ORC higher pressure in different levels of ORC supply rates ($\dot{m}_{11}/\dot{m}_{10}$) for various working fluids are shown in Figure 2. Note that the corresponding pressure to the maximum value of the generated power in the ORC system is determined as its optimal pressure. As can be seen from this figure, the lowest operating pressure belongs to the R123 which can be considered as an advantage for this working fluid from a turbomachinery point of view.

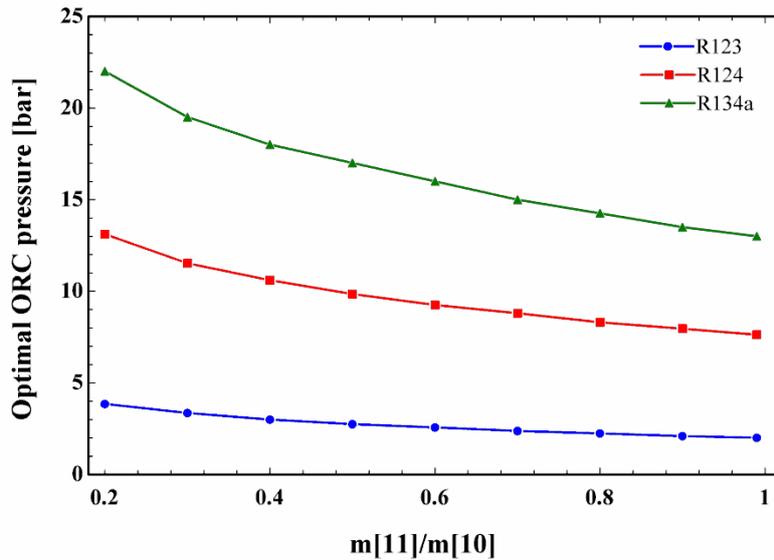


Figure 2. ORC optimal pressure in different levels of ORC supply rates for various working fluids (for a heat source temperature of 90 °C).

In Figure 2, the ORC heat source temperature is supposed to be 90 °C. Naturally, the variation in the source temperature affects the obtained optimal pressure values. Figure 3 illustrates the effect of changing the source temperature of the ORC on the optimal pressure of the cycle. This figure is presented for the working fluid of R123 only because the same trend is observed for the other two working fluids as well. Referring to Figure 3, increasing the ORC heat source temperature results in higher optimal pressure levels. It should be mentioned that since the ORC inlet flow is supposed to be in the saturated vapor condition, then a higher source temperature leads to a higher evaporation temperature and higher operating pressure as well.

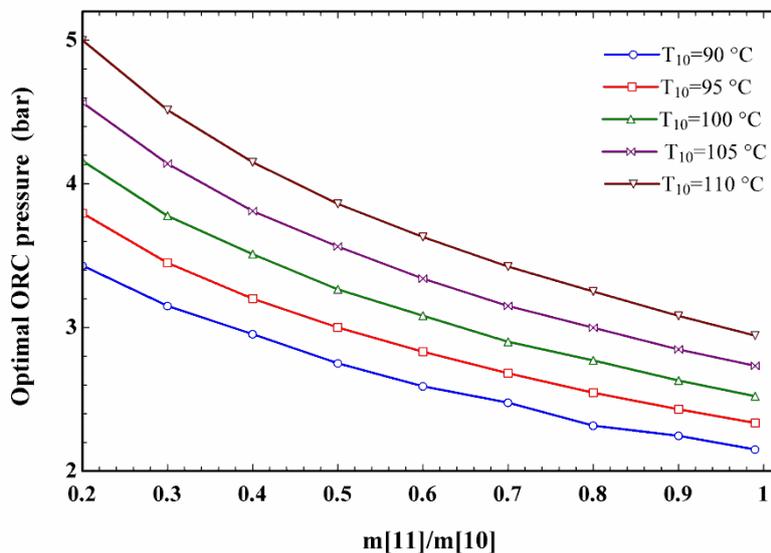


Figure 3. ORC optimal pressure in different heat source temperatures for the case of R123.

Table 4 indicates the technical measures related to the first thermodynamic law (energy analysis). One needs this information for accomplishing the aimed analyses. In the proposed design, a share of the high-temperature water in the first heat exchanger goes to the evaporator for running the ORC unit, while the remaining is exploited for heat generation. The ORC unit works based on the optimum evaporator pressure matching with the maximum power output. Recovering the waste heat of the base system increases the performance of the power plant from the perspective of both power

and heat generation. In a common power plant, a rise in the exit pressure of the steam turbine is required to support it for providing the needed temperature for the district heating supply. As waste heat recovery can be used for the additional reheating of the pressurized water, the heating of the pressurized water up to the ultimate temperature is not necessary through the CHP condenser, generating more power in the main system. As such, more power is likely to be produced by the ORC unit when the waste heat recovery unit is added to the system resulting from the greater temperature rate of heat supply for the ORC section. Furthermore, around 0.6 MW (megawatt) further supplied heat is delivered as a consequence of recovering a share of the outlet heat (see HX4 in Figure 1) and an increase for the mass flow rate of the pressurized hot water. In addition, as can be seen, changing the ORC working fluid does not affect the entire system performance considerably. This is because only a small share of power is produced by ORC and the main share refers to the steam turbine.

Table 4. Technical properties of the conventional and modified integrated concepts.

Parameter (Unit)	Conventional Concept	Modified Concept	
		With R123	With R124/R134a
An hourly mass flowrate of the fuel (kg/h)		3600.000	
Transferred heat to the water within the boiler (MW)		12.500	
HX1 outlet water temperature (°C)	90.000	85.000	85.000/85.000
Steam cycle outlet power (MW)	2.860	2.920	2.920/2.920
ORC outlet power (MW)	0.340	0.370	0.380/0.380
Net outlet power (MW)	3.200	3.290	3.300/3.300
Pressure of the turbine exhaust (bar)	0.850	0.710	0.710/0.710
The heat content of the exhaust (wasted) (MW)	3.240	1.700	1.700/1.700
The temperature of the outlet flue gas (°C)	165.000	45.000	45.000/45.000
Heat injected to DH grid (MW)	3.480	4.070	4.070/4.070
Energy efficiency (%)	53.750	59.110	59.110/59.110
Electrical efficiency (%)	25.90	26.580	26.580/26.580
Obtained payback time (Year)	7.400	6.700	6.700/6.700

As presented in Table 4, applying various organic fluids in the ORC has an insignificant impact on the system's thermodynamic performance. The same justification can be perceived in Figure 4, in which quantities of the net generated power in the ORC unit are analyzed and compared for different working fluids and ORC supply rates. Hence, reporting the technical and economic results attained for one of them in the following seems to be reasonable. However, this figure shows the effect of flue gas condensation on the net produced power by the ORC unit which is considered in this study for the first time.

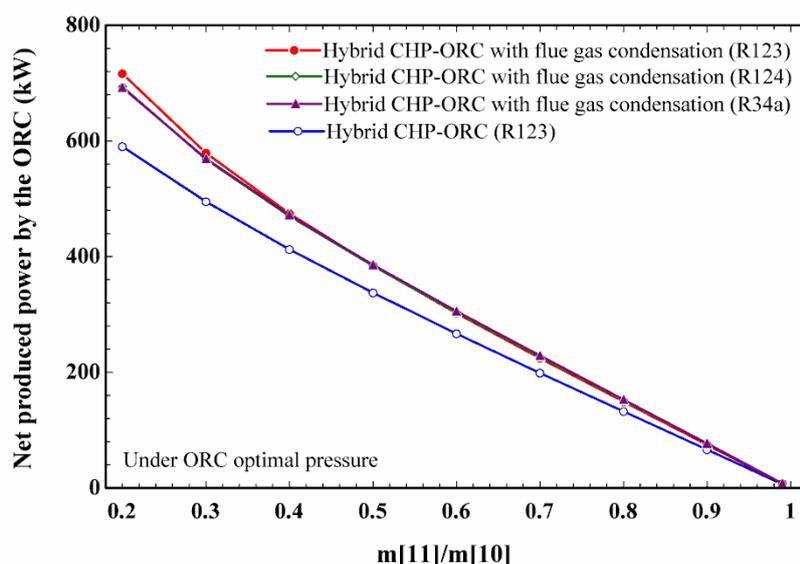


Figure 4. The produced power in the ORC unit with different working fluids for different amounts of $\dot{m}_{11}/\dot{m}_{10}$.

Results associated with the exergoeconomic analysis are reported in detail in Tables 5–7 for the conventional CHP plant, the hybrid CHP–ORC system, and the hybrid CHP–ORC with flue gas condensation, respectively. In all of these three cases, it is supposed that the system operates with a capacity of 1 kg/s municipal waste and pressurized hot water temperature of 90 °C providing heat for the local district heating network via HX2. When a small-scale ORC is coupled to the CHP plant (Tables 6 and 7), it is assumed that half of the heated water is applied to drive the ORC and the rest is used to provide the domestic heating.

Table 5. Results of the exergoeconomic analysis for the waste-fired simple CHP plant.

Components	$E\dot{x}_D$ (KW)	ϵ (%)	c_t (USD/GJ)	c_p (USD/GJ)	\dot{Z} (USD/h)	\dot{C}_D (USD/h)	f (%)
Incinerator	9832	31.83	2	14.85	231.5	70.79	76.58
Steam turbine	247.8	92.13	14.9	17.77	16.67	13.29	55.4
Pump1	1.7	94.8	17.77	22.69	0.45	0.11	80.16
HX1	384	73.98	14.9	20.34	0.7668	20.6	3.589
HX2	138.9	87.28	20.34	23.7	1.363	10.17	11.82
Plant	11409.7	26.71	2	19.09	250.75	76.35	76.66

Table 6. Results of the exergoeconomic analysis for waste-fired hybrid CHP–ORC system.

Components	$E\dot{x}_D$ (KW)	ϵ (%)	c_t (USD/GJ)	c_p (USD/GJ)	\dot{Z} (USD/h)	\dot{C}_D (USD/h)	f (%)
Incinerator	9832	31.83	2	14.85	231.5	70.79	76.58
Steam turbine	247.8	92.13	14.9	17.77	16.67	13.29	55.4
Pump1	1.7	94.8	17.77	22.69	0.45	0.11	80.16
HX1	350.4	76.25	14.9	19.74	0.802	18.8	4.1
HX2	77.01	87.28	19.81	23.16	0.8781	4.492	13.79
ORCT	32.38	90.37	31.1	37.73	3.62	3.625	49.97
ORCP	0.375	84.35	37.73	45.23	0.0037	0.051	6.77
ORCC	45.9	-	31.1	32.25	0.2613	5.139	4.839
Evap	136.1	73.63	19.81	27.08	0.2404	9.703	2.417
ORC	214.7	58.39	19.81	37.73	4.125	15.31	21.22
Plant	11743.37	25.85	2	19.99	254.4	77.21	76.72

Table 7. Results of the exergoeconomic analysis for the waste-fired hybrid system with flue gas condensation.

Components	$E\dot{x}_D$ (KW)	ε (%)	c_t (USD/GJ)	c_p (USD/GJ)	\dot{Z} (USD/h)	\dot{C}_D (USD/h)	f (%)
Incinerator	9849	31.72	2	14.89	231.5	70.91	76.55
Steam turbine	255.9	92.03	14.9	17.82	16.89	13.76	55.09
Pump1	1.7	94.8	17.82	22.75	0.44	0.11	80.26
HX1	317.4	77.7	14.94	19.56	0.8456	17.07	4.72
HX2	87.85	87.28	19.81	23.14	0.9675	6.265	13.38
HX3	73.88	73.51	15.04	20.71	0.1866	4.0	4.458
HX4	12.82	87.19	15.04	18.34	0.3441	0.7	33.15
ORCT	36.93	90.37	30.88	37.38	3.995	4.1	49.32
ORCP	0.43	84.35	37.38	44.8	0.004	0.057	6.54
ORCC	52.36	-	30.88	32.05	0.2981	5.821	4.871
Evap	155.2	73.63	19.81	27.07	0.2688	11.07	2.371
ORC	244.9	58.39	19.81	37.38	4.566	17.47	20.73
Plant	11261.37	27.65	2	20.18	255.7	78.07	76.71

According to the tables, since an incinerator comes with various origins of irreversibility, i.e., combustion, mixing, temperature difference, etc., [35], it is responsible for the highest rate of exergy destruction between all components, resulting in the lowest exergetic efficiency as well. Dehghanipour and Ajam [36] demonstrated that a substantial part of the exergy destruction of a waste incineration power plant happens in the incinerator, the steam generator, and the turbine. This is compatible with the information given in the tables below. As seen, the exergy destruction and exergy efficiency of the incinerator are the same for the simple CHP and hybrid CHP–ORC plants because the incinerator (including the steam generator) operates under the same condition in both systems and employing an ORC unit does not affect its exergetic/energetic performance. In the hybrid system with flue gas condensation, the steam turbine outlet pressure is a bit lower. Therefore, the recycled water to the boiler has a lower temperature and results in a little higher exergy destruction in the incinerator. In addition, the capital cost of the incinerator (including the boiler and pollution control unit) is the highest among all of the components. The levelized cost of USD 231.5/hour is the same for the incinerator of all the cases because the incinerator cost is a function of just feeding municipal waste. Furthermore, an exergoeconomic factor of around 76% is obtained for this component. The exergoeconomic factor is applied for comparing the rate of investment cost with the rate of the cost of irreversibility. Thereby, the obtained exergoeconomic factor implies that the capital investment cost of the incinerator is dominant in comparison to the cost rate related to exergy destruction.

Concerning the steam turbine, as Table 7 represents, exergy destruction in the plant with waste heat recovery is greater than that reported for the other two cases. As mentioned before, a decrease in the steam turbine exit pressure is implemented and thereby both the produced power and destroyed exergy increase in this way. Compared with the incinerator, the steam turbine has a lower exergoeconomic factor, indicating that the cost of exergy destruction in this component has a significant effect so that an enhancement in the exergetic performance of the turbine increases the whole system economic index.

The lowest exergoeconomic factor in the simple CHP plant belongs to the HX1 followed by HX2 with the exergy destruction rates of, respectively, 384 and 138.9 kW, showing that the cost of irreversibility in these components has more effect than the investment cost on their economic performance. In fact, the exergy destruction of these components is mainly because of the temperature difference among the hot and cold streams, indicating the need for paying great attention to these components. When the ORC unit is added to improve the share of electricity production, the lowest exergoeconomic factor is for the ORC evaporator. The exergoeconomic factor of around 2.4% and the second law efficiency of around 73% show that much can be done to improve the evaporator exergetic, and consequently, economic performances. One can say that almost all the cost of Evap that has been imposed on the system is due to the exergy destruction within this

component. It seems that the organic working fluid evaporation and the temperature mismatching between the hot and cold streams are the main reasons for the irreversibility in this component.

Reconsidering the tables, one finds the highest exergoeconomic factor for the pump employed in the steam cycle. In this way, replacing the pump with a cheaper one can be suggested to cure the system's economic performance. However, it is necessary to mention that the recommendations made for improving the economic performance of each component utilized in the systems do not necessarily mean an improvement in the whole system performance. This is since the performance of the other equipment can be reduced by changing the operational condition or characteristics of the others.

Overall, regarding the whole system, the exergy destruction in the plant with flue gas condensation is the lowest. Note that the exergy flow discharged to the atmosphere by the effluent is considered as an exergy loss flow when calculating the total exergy destruction rate of the plants. Moreover, as it is proven in Ref. [21], for the case of a hybrid CHP–ORC plant, when the ORC supply rate is half of the heated water, the exergy efficiency will hit its minimum value. This is why the exergy efficiency of the simple CHP plant is higher than that of the hybrid cycle.

Table 8 outlines the exergy rates, unit exergy cost, and levelized costs of different states in the plant with flue gas condensation. As listed, the unit cost of produced power by the steam turbine is USD 17.82/GJ which is comparable with that reported in the exergoeconomic analysis of a municipal waste-to-energy steam reheat power plant for Port Harcourt city [22]. Additionally, the cost of extra electricity produced by the ORC is much higher than that produced by the steam turbine. The average unit cost of supplied fuel for the individual component is the main reason for this. As reported in Table 8, the unit cost of supplied fuel for the ORC turbine (c_{17}) is USD 30.88/GJ, while it takes the value of USD 14.94/GJ for the case of the steam turbine (c_6). Referring to this table, and the results associated with energy analysis, the average unit cost of the electricity and heat produced by the proposed CHP are USD 20.07/GJ and USD 17.96/GJ, respectively.

Table 8. Exergy flow rates, unit exergy costs, and cost flow rate for the waste-fired hybrid CHP–ORC system with flue gas condensation.

State Point	Ex (kW)	c (USD/GJ)	Ĉ (USD/h)
1	14,423	2	103.86
2	0	0	0
3	-	-	-
4	1666	15.04	90.18
5	4724	14.94	254.124
6	1515	14.94	81.468
7	118.7	14.94	6.3864
8	118.7	14.94	6.3864
9	149.8	16.56	8.928
10	1631	19.7	115.668
11	918.2	19.81	65.484
12	227.6	19.81	16.2288
13	227.6	19.81	16.2288
14	552.7	19.97	39.744
15	918.2	19.81	65.484
16	329.5	19.81	23.5008
17	436.3	30.88	48.492
18	52.89	30.88	5.8788
19	0.5358	30.50	5.8824
20	2.841	61.15	6.2532
21	153.6	0	0
22	756.3	18.44	50.22
23	1387	15.04	75.06

24	1287	15.04	69.66
25	22.23	0	0
26	109.5	14.62	5.76
\dot{W}_{ST}	2954	17.82	189.54
\dot{W}_{ORCT}	346.4	37.38	46.62

The results associated with the environmental impact of the plants are presented in Table 9. As can be seen, the level of pollution is equivalent to a cost of USD 210.7 for the systems. Since in all three scenarios, the systems are operating with a capacity of 1 kg/s MW, the released pollution (available in the effluent) and their equivalent costs are the same. Therefore, the sustainability index and the CO₂-e per produced exergy are considered to show a bigger picture of the environmental impact of each system. As seen, the highest SI refers to the plant with flue gas condensation due to recovering the available exergy in the effluent and produce more exergy compared with the other two plants. The lowest SI belongs to the hybrid CHP–ORC plant, which is mainly because improving the power share via employing the ORC decreases the supplied heat and subsequently, the exergy rate related to the exchanged heat. However, it should not be neglected that enhancing the power share of the power plant energy output via adding an ORC unit is a valuable benefit that this case is also offering compared to the conventional waste-fired CHP plant.

Table 9. Environmental analysis of the studied systems.

Scenarios	CO ₂ -e	\dot{C}_{env} (USD/h)	SI (-)
Waste-fired simple CHP plant	1.077×10^{-4}	210.7	1.264
Waste-fired hybrid CHP–ORC system	1.113×10^{-4}	210.7	1.228
Waste-fired hybrid CHP–ORC system with flue gas condensation	1.040×10^{-4}	210.7	1.280

As mentioned before, in the present research, an average emission of 0.415 kg of CO₂-e for the incineration of 1 kg of MW is considered. To show the effect of modifying the system configuration, this parameter is divided into the total produced exergy by each system ($CO_2 - e / \dot{E}_{produced}$) and listed in Table 9. As expected, the hybrid CHP–ORC plant has the highest equivalent CO₂ emission, while the plant with flue gas condensation has the lowest one.

The results of a sensitivity analysis carried out on the thermodynamic and economic performance of the system versus various important parameters are presented and discussed hereunder. Here, the results are only related to the waste-driven hybrid CHP–ORC with flue gas condensation. For this sensitivity analysis, it was assumed that all the other parameters were fixed as the effect of changing the value of a certain parameter was assessed.

Figure 5 shows how the electrical and exergy efficiencies of the plant vary as the steam turbine inlet temperature rises. As seen, this has a direct effect on both of these parameters in an almost linear format so that when the steam turbine inlet temperature increases from 773 to 873 K (500–600 °C), the electrical and exergy efficiencies change from 25.87% to 26.9% and from 27.24% to 28.06%, respectively. In this study, however, the turbine inlet temperature of 550 °C is considered in the system modeling due to technical limitations.

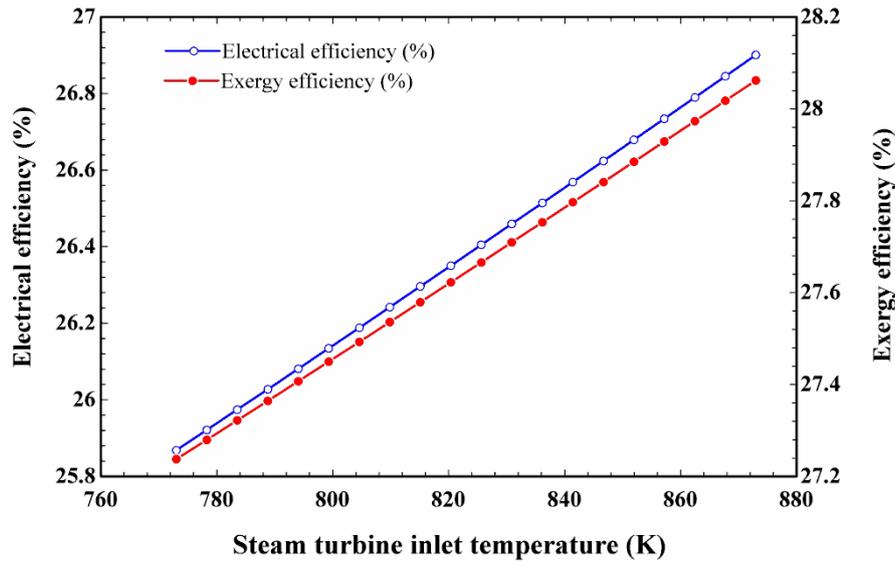


Figure 5. Electrical and exergy efficiencies versus the steam turbine inlet temperature.

Observations confirm that growing the turbine inlet temperature in the same range as above decreases the cost of generated power in the steam turbine from USD 17.99/GJ to USD 17.66/GJ and decreases the cost of supplied heat via HX2 from USD 18.61/GJ to USD 18.28/GJ. This is shown in Figure 6.

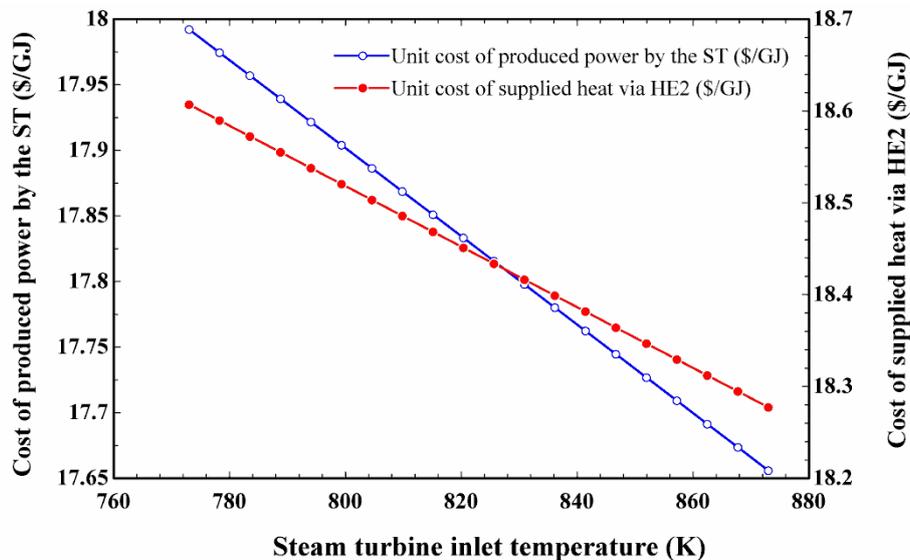


Figure 6. Cost of produced power by the ST and supplied heat via HX2 versus the steam turbine inlet temperature.

Figure 7 illustrates how the isentropic efficiency of the turbines affects the cost of power production in the system. As shown, a reduction in the cost of produced power is achieved when the isentropic efficiency of the turbines increases. In fact, the figure reveals that although increasing the turbine isentropic efficiency leads to higher values of capital investment cost, the effect of the enhancement in the amount of output electricity is stronger economically. According to the figure, increasing the isentropic efficiency from 0.85 to 0.95 results in USD 0.33/GJ and USD 0.59/GJ drop in the cost of produced power for the ST and ORCT, respectively. Isentropic efficiency of 0.9 and 0.85 is supposed for ST and ORCT in the system modeling, respectively.

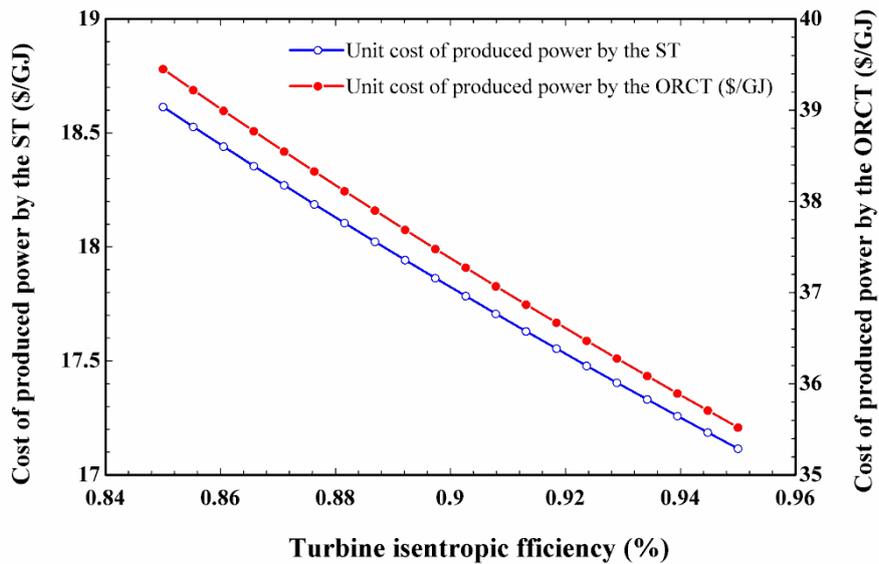


Figure 7. Cost of produced power versus the steam and ORC turbines inlet temperatures.

The impact of the ambient temperature on the system performance is examined in Figures 8–10. According to Figure 8, the ambient temperature growth reduces the exergy efficiency of the system. As the main part of the district heating supply in the system is via HX2, the cost of heat supply via this heat exchanger is evaluated. According to the figure, an increase in the ambient temperature causes a higher value of heat supply cost. This is mainly due to a reduction in the rate of delivered thermal exergy, while the initial capital cost of equipment is fixed. As such, it can be read from the figure that increasing the ambient temperature causes an increment in the cost of steam turbine power, while it decreases the cost of ORCT power. The net output power and exergy rate of the incinerated municipal waste are independent of the ambient temperature and decreasing the exergy rate associated with the lower supplied heat is the main reason for the exergy efficiency reduction.

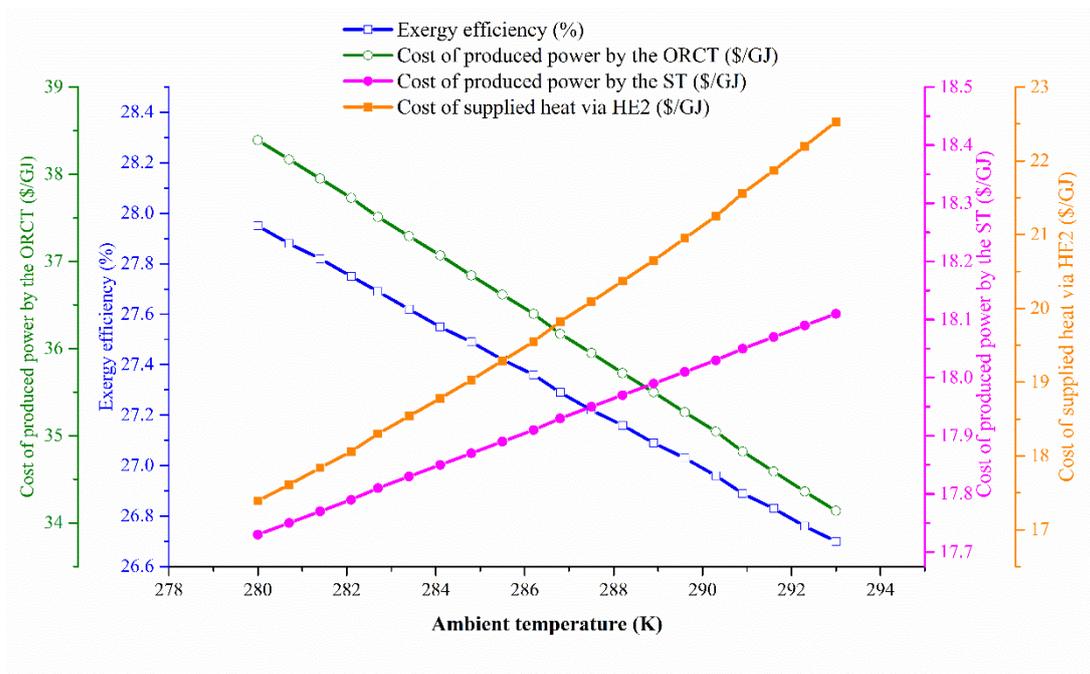


Figure 8. A change in the cost of generated power in turbines, the cost of supplied heat through HX2, and exergy efficiency with ambient temperature variations.

As seen in Figure 9, as the weather becomes warmer, the rate of exergy supplied via the HX2 and HX4 decreases almost linearly.

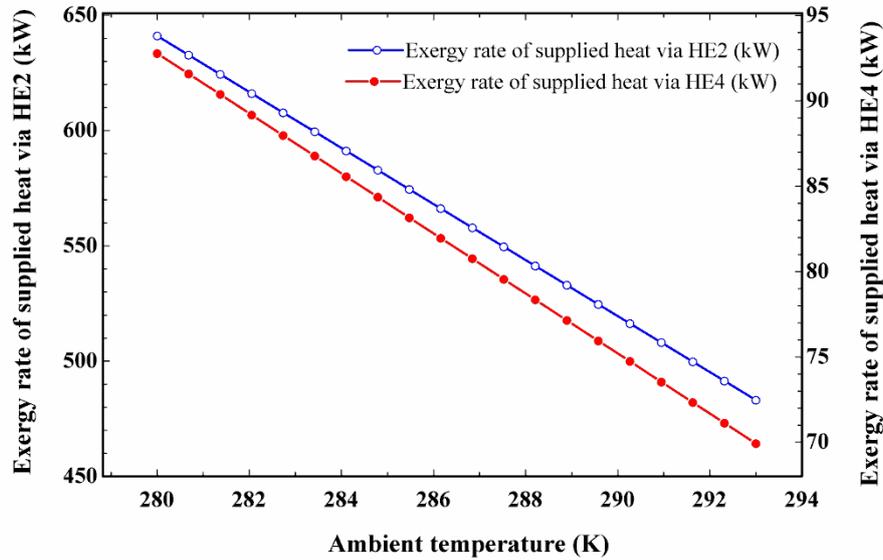


Figure 9. Change in the rate of supplied heat exergy with ambient temperature.

Figure 10 investigates the fuel exergy cost of the ST and the ORCT versus the ambient temperature. As seen, growing the ambient temperature rises the fuel exergy cost of ST and reduces the fuel exergy cost of the ORCT.

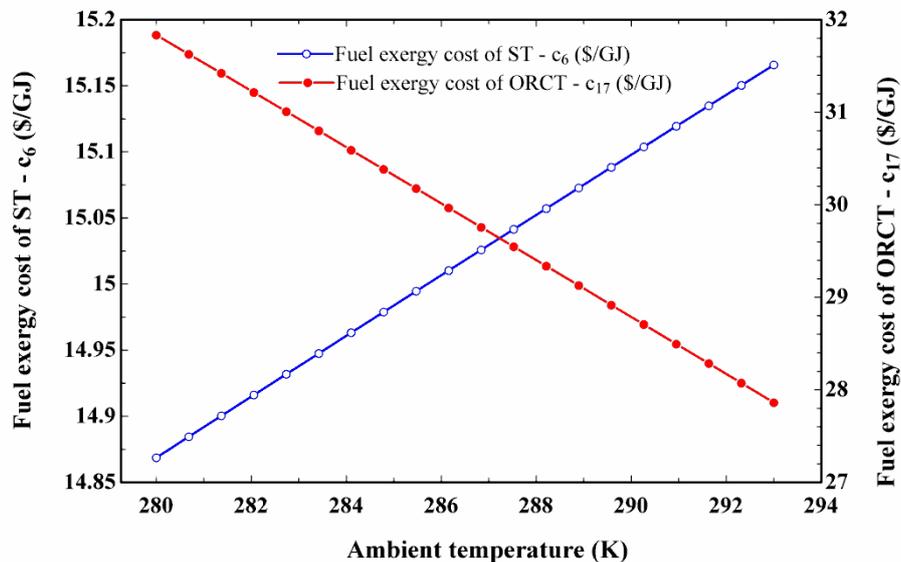


Figure 10. Fuel exergy cost of ST and ORCT versus the ambient temperature.

Figure 11 specifies the alteration in the cost of generating electricity by changing the unit cost of MW. As shown, increasing the unit cost of MW results in a linear growth in the cost of electricity generation via both ORCT and ST. MW is the input fuel for the whole system and a higher value for its cost will raise the cost of products. When the unit cost of MW changes from USD 1.5/GJ to USD 2.5/GJ, the cost of produced power by the ST and ORCT increases from USD 16.57/GJ to USD 19.08/GJ and from USD 34.78/GJ to USD 39.97/GJ, correspondingly. The unit cost of MW is considered to be USD 2/MJ in the modeling of this work, as stated by Jack et al. [22].

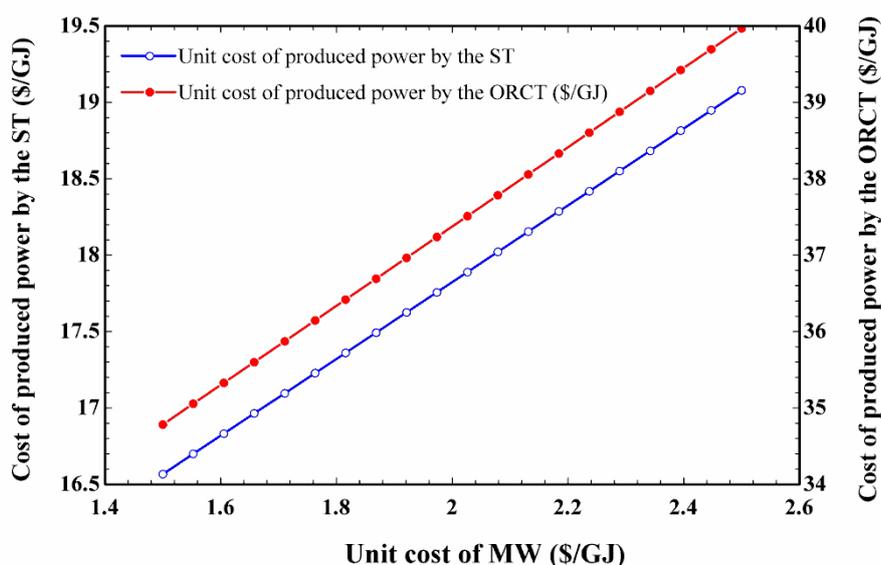


Figure 11. Cost of the power produced by turbines versus the unit cost of MW.

4. Conclusions

Considering the increasing trend for energy demand in recent years resulting from population growth and the development of industrial divisions, modifying the current energy systems with the aim of efficiency improvement and heat loss reduction, like those applied in this study, can be a promising idea for sustainable development. In this regard, a comprehensive exergoeconomic and exergoenvironmental analysis of the integrated waste-driven CHP–ORC plant with a flue gas condensation unit was carried out in this study and the results were compared with simple conventional waste-fired CHP plants and the hybrid system, while no flue gas condensation unit is hired. Thus, it can be considered as a great modification from both technical and environmental viewpoints. The proposed configuration is a strong general model which can be applied for various application such as district cooling and heating in different regions and conditions.

The results of the analysis indicate that the most important exergy destruction term relates to the incineration with a levelized cost of approximately USD 71/h for a power plant with almost 3.3 MW electricity output capacity. The hybridization proposal with the flue gas condensation unit increases the sustainability index of the system from 1.264 to 1.28. It was shown that the unit cost of generated power by the steam turbine is USD 17.82/GJ while the cost of the generated extra power by the ORC is much higher than that. The unit cost of supplied fuel for the ORC turbine is USD 30.88/GJ it is USD 14.94/GJ for the steam turbine. The sensitivity analysis reveals that ambient temperature has diverse impacts on the CHP part and the ORC part. The growth of the ambient temperature will decrease the overall exergy efficiency of the system, causing a higher value of heat supply cost, and bringing an increment in the cost of steam turbine power, while decreasing the cost of ORCT power. Generally, it is concluded that adding the ORC unit to the CHP plant improves the net power generation of the system but decreases the exergetic efficiency. Therefore, for making this integration feasible exergoeconomically, the flue gas condensation unit should be added to the hybrid system.

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Nomenclature

A	heat transfer surface area (m^2)
c	cost per exergy unit (USD/GJ)
CRF	capital recovery factor
\dot{C}	cost flow rate (USD/s)
DH	district heating
e	specific physical exergy (kJ/kg)
$Evap$	evaporator
$\dot{E}x$	exergy flow rate (kW)
FWT	feed water tank
GJ	gigajoule
h	specific enthalpy (kJ/kg)
HX	heat exchanger
HPT	high pressure turbine
$Incin$	incinerator
IPT	intermediate pressure turbine
LHV	low heating value (kJ/kg)
LPT	low pressure turbine
MW	municipal waste
\dot{m}	mass flowrate (kg/s)
$ORCC$	ORC condenser
$ORCP$	ORC pump
$ORCT$	ORC turbine
P	pump
\dot{Q}	heat transfer rate (kW)
R	gas constant (kJ/kg K)
s	specific entropy (kJ/kg K)
ST	steam turbine
T	temperature
U	overall heat transfer coefficient ($kW/m^2 K$)
\dot{W}	power (kW)
Z_k	capital investment cost (USD)
\dot{Z}	levelized investment cost of the system components (USD/s)

Greek letters

ε	exergy efficiency
η	energy efficiency (-)

Subscripts

ch	chemical
D	destruction
env	environmental
in	inlet condition
is	isentropic
k	k^{th} component
$ORCG$	ORC unit generator
out	outlet condition
ph	physical
0	ambient condition

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