



## Thermodynamic and sustainability analysis of a municipal waste-driven combined cooling, heating and power (CCHP) plant

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## 1. Introduction

Smart energy systems have received much attention from the energy planners and energy experts over the last years. Using renewable and alternative energy sources is one of the main characteristics of smart energy systems [1]. In the future energy systems, electricity seems to be the most important among all the energy sectors mainly due to the growing demand in different areas like transportation, heating/cooling productions, etc. [2]. Moving from the current energy systems to the next generation smart energy systems has its own challenges and requires much efforts to successfully pass through this transition [3]. In smart energy systems, besides electricity grids, district cooling and heating networks are also much important. Thus, sustainable yet cost-effective heat and cold production solutions are vital [4].

Among renewable technologies, solar and wind systems are the most favorable and mature ones. In Europe, for example, wind farms are dominating the north while solar systems (both thermal and electrical systems) are much penetrating in the energy systems of the south [5]. These two interesting sources, however, suffer from irregular profiles of accessibility [6]. Therefore, the existence of controllable sources of supply besides solar and wind energies is crucial in any renewable-based energy system [7]. This is why biogas and biomass driven energy systems, as well as waste-incineration plants, are the undeniable parts of energy systems with high penetration of renewables [8]. Among these, waste incineration is of special interest in Europe so that waste-driven heat, power and CHP plants cover the base loads of district energy and electricity networks of many energy systems in this continent [9].

Waste incineration plants are, however, argued to be sustainable or not due to the considerable amount of greenhouse gases emitted when combusting municipal solid waste [10]. But, to make the argument fair, one should consider both the emission made by an incineration process and that released if the alternative method of waste disposal (i.e. landfilling) is used [11]. Having said this, one could simply judge why using waste incineration technologies in all the electricity, heat and cold sectors is quite popular in many of the leading countries of renewable supply such as Denmark, Sweden, etc. [12]. The following literature review presents some of the most recent findings in the field of waste to energy.

Bourtsalas et al. [13] studied utilizing waste energy in district heating of South Korea. They considered waste with the chemical formula of  $C_6H_{9.9}O_{2.3}$  and the heating value of 27600 kJ/kg and calculated the average heat recovery from this waste to energy plant as 1.5 MWh per ton of waste. Manente et al. [14] considered district heating of Ferrara in Northern Italy with the heat demand of 170 GWh/year as the case study being covered by a municipal solid waste driven CHP. A hybrid power production system comprising a combination of a concentrated solar system and municipal solid waste is investigated by Sadi and Arabkoohsar [11] in Denmark. They modeled the waste to the energy system to stabilize the power output of the solar power plant and consequently, pave the way to reliably increase the share of solar energy in the Danish energy matrix. Rudra and Tesfagaber [15] modeled a plant operating with municipal solid waste in

57 order to supply domestic heating of a case study and produce hydrogen via gasification. Three different  
58 gasification setups were simulated using Aspen plus software for indirect and direct gasification processes  
59 based on the various gasification agents. They concluded that 4 liters of hot water with a temperature of 100  
60 °C plus 0.199 kg hydrogen can be produced from 1 kg of waste. Kabalina et al. [16] tried to understand how  
61 a decrease in cooling, heating and electricity loads would affect the thermodynamic and economic  
62 performance of a poly-generation domestic heating and cooling system based on waste gasification. The  
63 investigation of how heat or cold supply affects the overall energy efficiency of waste-fired cogeneration  
64 systems is presented in [17]. Gao et al. [18] investigated a waste-fired CCHP plant based on energy and  
65 exergy analyses. It is revealed that the exergy efficiency of the CCHP plant may reach up to almost 50% in a  
66 particular value of exhaust gas temperature. Persson and Münster [10] investigated and explained why large-  
67 scale heat recovery from waste plants is not possible without a local heat distribution network. They  
68 presented a literature review and estimated the available waste volume in Europe for district heating supply  
69 in 2030. Münster and Meibom [19] investigated the optimization of waste utilization in the future energy  
70 matrices of Germany and Nordic countries. The optimization is performed for both investment costs and  
71 production. They found out that mixed waste incineration, organic waste digestion in anaerobic way and  
72 gasification are the most economically feasible solutions for CHP systems. Furtenback [20] studied the  
73 Swedish district heating systems including those operating with waste incineration and revealed that 10%  
74 increase in the economic value of waste will decrease waste demand by 4.2% and increase the demand for  
75 fossil fuels, biofuels, electricity and other fuels by 6.0%, 5.5%, 6.0%, and 6.0%, respectively. A new  
76 ammonia-water CCHP system driven by a low-temperature heat source, which was a modified version of a  
77 Kalina cycle, was proposed by Parikhani et al. [21]. The energy and exergy efficiencies of this system are  
78 found as 49.8% and 27.7%, respectively. Also, it is found out that the condenser is the main contributor to  
79 the irreversibility of the system by the exergy destruction ratio of 32%. Thermodynamic assessment of a  
80 CCHP system with a micro gas turbine and an absorption chiller is studied by Mirzaee et al. [22]. In this  
81 work, not only the thermodynamic indicators but also the amount of emitted CO<sub>2</sub> of the plant were  
82 investigated based on various scenarios.

83 Most recently, Arabkoohsar and Nami [17] studied the feasibility of parallelization of a small-scale ORC  
84 with a waste-fired CHP plant with the main objective of increasing the share of the electricity production of  
85 the CHP plant rather than a higher heat output. In the current study, the parallelization of a waste-fired CHP  
86 with an absorption chiller is investigated to present a novel waste-driven CCHP system in Denmark. The  
87 proposed waste-fired trigeneration system not only makes integration between the cold, heat and electricity  
88 sectors, but also improves the energy, exergy and sustainability indices of the plant. The proposed solution is  
89 further reinforced by adding a waste heat recovery unit to the conventional plant. As district heating systems  
90 are subject to a remarkable transformation to their next generation, different possible heat supply methods,  
91 including the existing system (3<sup>rd</sup> generation), low-temperature system and ultralow-temperature designs, are

92 considered in the calculations. A comprehensive thermodynamic assessment of the proposed waste-fired  
 93 CCHP plant is accomplished and the results are presented and discussed.

94

## 95 2. Waste-Fired CCHP Plant and Main Assumptions

96 In this section, the main features of a conventional CHP plant based on a steam cycle power block and driven  
 97 by a waste incineration unit are discussed briefly. Then, the configuration of the proposed waste-fired CCHP  
 98 and the considered assumptions are explained in detail.

### 99 2.1. Conventional waste-fired CHP plant

100 A simplified schematic diagram of a conventional waste-fired CHP is presented in Fig. 1. In this system, a  
 101 waste-fired boiler is employed to run a Rankine steam power cycle. Here, the heat flow supplied to the local  
 102 district heating network is harvested from the condenser of the steam cycle [23]. Such plants are mostly used  
 103 for base-load coverage [24]. For regular plants based on this design, the energy conversion efficiency of 70-  
 104 82% is expected [25].

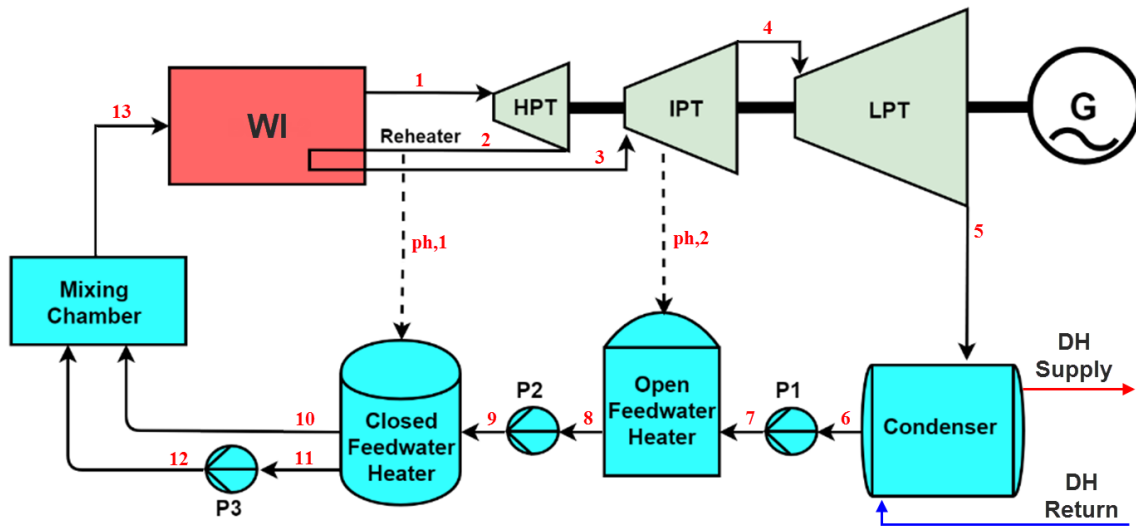


Fig. 1 Schematic diagram of a waste-fired CHP system connected to district heating [11].

105 Ref. [26] presents a comprehensive information about the characteristics of the employed waste-incineration  
 106 unit of this work. The LHV (lower heating value) of the waste source is a function of many parameters, such  
 107 as the compositions, moisture, ash contents, etc. Here, the composition of the waste source are taken from  
 108 Ref. [27], with the LHV of 12500 kJ/kg. Table 1 gives information about the municipal solid waste used in  
 109 the simulations of this work and the incineration process.

110 **Table 1** The waste incineration unit main features [1].

Item	Information/value
Type of waste	Municipal solid waste

Waste compositions (weight percent)	5.91% Ash
	47.18% Carbon
	6.25% Hydrogen
	39.57% Oxygen
	0.91% Nitrogen
	0.18% Sulphur
LHV of the waste (kJ/kg)	12,500
Effluent temperature (K)	438
Excess air in the incineration process	80% [25]
Combustion product temperature (K)	1373

111 2.2. The proposed waste-fired CCHP

112 The schematic of the proposed waste-fired CCHP is illustrated in Fig. 2. As the figure shows, the generated  
113 high-pressure steam is fed to the ST (steam turbine) where the enthalpy drop is converted into the  
114 mechanical power to drive the electricity generator. The ST exiting flow is the energy source of the district  
115 heating and cooling supply here. HE1 (heat exchanger 1) performs as the condenser for the Rankine cycle,  
116 and meanwhile, transfers the rejected heat of the steam to a pressurized water stream to feed the district  
117 heating and cooling supply tools. Here, HE3 is the flue gas condensation unit which supplies much energy to  
118 the cold and heat supply tools via recovering the waste heat of the plant through the exhaust. HE2 and HE4  
119 are where district heating is supported and Gen (the generator of the chiller) is where the required heat for  
120 cold production is delivered. In the chiller, the absorbent is LiBr (lithium bromide) and the refrigerant is  
121 water. A solution of water-LiBr is created in the absorber. Then, this strong solution is pressurized, passes  
122 through the solution heat exchanger (SHE) and is finally fed to the Gen. In the Gen, the solution is heated  
123 and the water content gets vaporized and moves to the condenser, while the weak solution flows back to the  
124 absorber. Finally, the Gen exiting flow is combined with the flow coming out of the HE2 in the FWT2 (feed  
125 water tank 2) and completes the cycle. Note that a flue gas cleaning step is considered in the heat recovery  
126 unit to reduce the pollution of the effluent to almost zero [28].

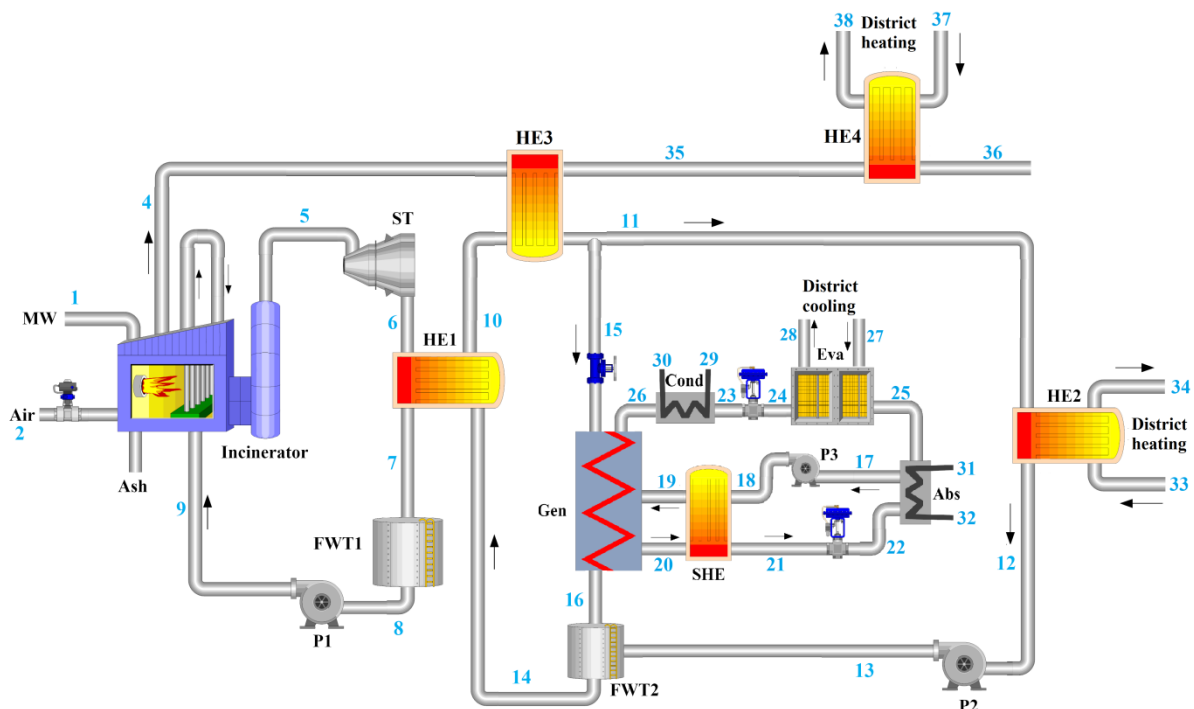


Fig. 2 Simplified configuration of the waste-fired CCHP plant.

127 It is supposed that the whole system operates under the steady-state conditions and there are no heat losses  
 128 from the pipings, heat exchangers, etc. Table 2 details the operating points and conditions considered in this  
 129 study. For the case of district heating, three different scenarios were considered: *i*) 3<sup>rd</sup> generation heat  
 130 network with the supply and return temperatures of 80 and 40 °C, *ii*) low-temperature heating network with  
 131 the supply and return temperatures of 55 and 30 °C, and *iii*) ultralow-temperature heating network with the  
 132 supply and return temperatures of 40 and 25 °C. Naturally, the maximum capacity of the power plant does  
 133 not affect the technical performance indices of the cycle. Thus, the plant is sized for 1 kg/s of waste as the  
 134 driving fuel.

135 **Table 2** List of input data and the main framework

Input data	Value	Unit
Municipal waste mass flow rate [1]	1	kg/s
ST isentropic efficiency [1]	90	%
Pumps isentropic efficiency [1]	75	%
Electric generator efficiency [29]	95	%
Coolant water temperature	283	K
District heating supply / return temperature [1]	353-313 / 313-298	K
District cooling supply / return temperature [30]	278 / 285	K
Generator temperature [31]	348 - 358	K
Heat exchangers effectiveness [1]	≤85	%
Flue gas outlet temperature [17]	≥318	K
Ambient temperature	283	K
Ambient pressure	1.013	bar
Pinch temperature in heat exchangers	5	K

136 **3. Thermodynamic modeling**

137 3.1. Energy analysis

138 In order to analyze the performance of the proposed CCHP from the first law of thermodynamics point of  
 139 view, each component of the system is supposed to be a control volume and the energy conservation and the  
 140 mass balance equations are written for that based on the following two general equations [32]:

$$\sum \dot{m}_i h_i + \dot{Q} = \sum \dot{m}_o h_o + \dot{W} \quad (1)$$

$$\sum \dot{m}_i = \sum \dot{m}_o \quad (2)$$

141 In the equations above,  $\dot{m}$  is the mass flow rate,  $h$  is the specific enthalpy,  $\dot{Q}$  is the rate of heat transfer and  
 142  $\dot{W}$  is the mechanical power. Also, subscripts  $i$  and  $o$  refer to the inlet and outlet flows, respectively.  
 143 Equations associated with the energy analysis of the system components are listed in Table 3.

**Table 3** The governing energy equations on the components of the proposed waste-fired CCHP plant.

Component	Equation
Incinerator	$\dot{m}_1 LHV_{waste} + \dot{m}_2 h_2 + \dot{m}_9 h_9 = \dot{m}_4 h_4 + \dot{m}_5 h_5 \quad (3)$
ST	$\dot{W}_{ST} = \dot{m}_5 (h_5 - h_6), \eta_{is,ST} = \frac{\dot{W}_{ST}}{\dot{W}_{is,ST}} \quad (4)$
HE1	$\dot{m}_6 (h_6 - h_7) = \dot{m}_{14} (h_{10} - h_{14}), eff_{HE1} = \frac{Max\{(T_6 - T_7), (T_{10} - T_{14})\}}{T_6 - T_{14}} \quad (5)$
HE2	$\dot{m}_{11} (h_{11} - h_{12}) = \dot{m}_{33} (h_{34} - h_{33}), eff_{HE2} = \frac{Max\{(T_{11} - T_{12}), (T_{34} - T_{33})\}}{T_{11} - T_{33}} \quad (6)$
HE3	$\dot{m}_4 (h_4 - h_{35}) = (\dot{m}_{11} h_{11} + \dot{m}_{15} h_{15} - \dot{m}_{10} h_{10}), eff_{HE3} = \frac{Max\{(T_4 - T_{35}), (T_{11} - T_{10})\}}{T_4 - T_{10}} \quad (7)$
HE4	$\dot{m}_{35} (h_{35} - h_{36}) = \dot{m}_{37} (h_{38} - h_{37}), eff_{HE4} = \frac{Max\{(T_{35} - T_{36}), (T_{38} - T_{37})\}}{T_{35} - T_{37}} \quad (8)$
SHE	$\dot{m}_{20} (h_{20} - h_{21}) = \dot{m}_{18} (h_{19} - h_{18}), eff_{HE2} = \frac{Max\{(T_{20} - T_{21}), (T_{19} - T_{18})\}}{T_{20} - T_{18}} \quad (9)$

$$P1 \quad \dot{W}_{P1} = \dot{m}_8(h_9 - h_8), \eta_{is,P1} = \frac{\dot{W}_{is,P1}}{\dot{W}_{P1}} \quad (10)$$

$$P2 \quad \dot{W}_{P2} = \dot{m}_{12}(h_{13} - h_{12}), \eta_{is,2} = \frac{\dot{W}_{is,P2}}{\dot{W}_{P2}} \quad (11)$$

$$P3 \quad \dot{W}_{P3} = \dot{m}_{17}(h_{18} - h_{17}), \eta_{is,P3} = \frac{\dot{W}_{is,P3}}{\dot{W}_{P3}} \quad (12)$$

$$Gen \quad \dot{m}_{15}(h_{15} - h_{16}) = \dot{m}_{26}h_{26} + \dot{m}_{20}h_{20} - \dot{m}_{19}h_{19} \quad (13)$$

$$Cond \quad \dot{m}_{26}(h_{26} - h_{23}) = \dot{m}_{29}(h_{30} - h_{29}) \quad (14)$$

$$Eva \quad \dot{m}_{24}(h_{25} - h_{24}) = \dot{m}_{27}(h_{27} - h_{28}) \quad (15)$$

$$Abs \quad \dot{m}_{31}(h_{32} - h_{31}) = \dot{m}_{17}h_{17} - \dot{m}_{25}h_{25} - \dot{m}_{22}h_{22} \quad (16)$$

144 To investigate the whole system performance, energy utilization factor as the first law efficiency and heat-to-  
 145 power efficiency as the electrical efficiency are defined. It is worth mentioning that electricity has a higher  
 146 priority compared to heat and cold [33].

$$\eta_l = \frac{\dot{Q}_{DH} + \dot{Q}_{DC} + \dot{W}_{net}}{\dot{m}_1 LHW_{MW}} \quad (17)$$

$$\eta_{elec} = \frac{\dot{W}_{net}}{\dot{m}_1 LHV_{MW}} \quad (18)$$

147 where,

$$\dot{Q}_{DH} = \dot{m}_{37}(h_{38} - h_{37}) + \dot{m}_{33}(h_{34} - h_{33}) \quad (19)$$

$$\dot{Q}_{DC} = \dot{m}_{27}(h_{27} - h_{28}) \quad (20)$$

$$\dot{W}_{net} = \dot{W}_{ST} - \dot{W}_{P1} - \dot{W}_{P2} - \dot{W}_{P3} \quad (21)$$

### 148 3.2. Exergy analysis

149 Unlike the energy analysis, exergy is not conserved within the components and is destroyed over any real  
 150 thermodynamic process, except completely reversible ones [34]. Therefore, exergy analysis is a powerful  
 151 tool to investigate system irreversibility and determine the exact location, quality, and quantity of losses.

152 Exergy is a maximum theoretical obtainable power from a system reaching a complete thermodynamic  
 153 equilibrium with the environment, while there is interaction only between the system and the environment  
 154 [35]. Since changes in elevation and speed are ignored in this study, then potential and kinetic exergy are  
 155 neglected. In this way, exergy can be divided into two parts: physical and chemical exergy. The specific  
 156 physical exergy is a function of streams' conditions and ambient conditions [36,37]:

$$e_{ph} = h_i - h_0 - T_0(s_i - s_0) \quad (22)$$

157 here, subscripts  $i$  and  $0$  symbolize the stream and ambient conditions, respectively. Specific chemical exergy  
 158 for a mixture of ideal gases is related to the departure of the chemical composition of a stream from the  
 159 chemical equilibrium of a reference environment. Since changes of composition occur during the combustion  
 160 process of the presented CCHP system, chemical exergy should be taken into account. Specific chemical  
 161 exergy is defined as follows [38,39]:

$$e_{mixture}^{ch} = \sum_i n_i e_{0,i}^{ch} + \bar{R}T_0 \sum_i n_i \ln x_i \quad (23)$$

162 where,  $x_i$  and  $e_{0,i}^{ch}$  are the molar fraction of the  $i^{\text{th}}$  component in the mixture and standard chemical exergy of  
 163 the component, respectively.

164 Finally, the exergy rate of each  $i^{\text{th}}$  stream in the system can be written as:

$$\dot{E}_i = \dot{m}_i (e_i^{ph} + e_i^{ch}) \quad (24)$$

165 To determine the exergy destruction and exergy efficiency, defining fuel and product exergy rates ( $\dot{E}_F$  and  
 166  $\dot{E}_P$ ) for the system components is much helpful [40,41]. Fuel is the consumed exergy in each component to  
 167 generate the desired product exergy. Exergy destruction and efficiency can be written as [42]:

$$\dot{E}_D = \dot{E}_F - \dot{E}_P \quad (25)$$

$$\eta_{II} = \frac{\dot{E}_P}{\dot{E}_F} \quad (26)$$

168 Fuel and product equations of the system components are listed in Table 4.

**Table 4** Exergy balance equations adopted on the components of the proposed waste-fired CCHP plant.

Component	Fuel	Product
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Incinerator	$\dot{E}_1 + \dot{E}_2 + \dot{E}_9$	$\dot{E}_4 + \dot{E}_5$	(27)
ST	$\dot{E}_5 - \dot{E}_6$	$\dot{W}_{ST}$	(28)
HE1	$\dot{E}_6 - \dot{E}_7$	$\dot{E}_{10} - \dot{E}_{14}$	(29)
HE2	$\dot{E}_{11} - \dot{E}_{12}$	$\dot{E}_{34} - \dot{E}_{33}$	(30)
HE3	$\dot{E}_4 - \dot{E}_{35}$	$\dot{E}_{11} + \dot{E}_{15} - \dot{E}_{10}$	(31)
HE4	$\dot{E}_{35} - \dot{E}_{36}$	$\dot{E}_{38} - \dot{E}_{37}$	(32)
SHE	$\dot{E}_{20} - \dot{E}_{21}$	$\dot{E}_{19} - \dot{E}_{18}$	(33)
P1	$\dot{W}_{P1}$	$\dot{E}_9 - \dot{E}_8$	(34)
P2	$\dot{W}_{P2}$	$\dot{E}_{13} - \dot{E}_{12}$	(35)
P3	$\dot{W}_{P3}$	$\dot{E}_{18} - \dot{E}_{17}$	(36)
Gen	$\dot{E}_{15} - \dot{E}_{16}$	$\dot{E}_{26} + \dot{E}_{20} - \dot{E}_{19}$	(37)
Cond	$\dot{E}_{26}$	$\dot{E}_{23}$	(38)
Eva	$\dot{E}_{25} - \dot{E}_{24}$	$\dot{E}_{27} - \dot{E}_{28}$	(39)
Abs	$\dot{E}_{22} + \dot{E}_{25}$	$\dot{E}_{17}$	(40)

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169 To design an energy conversion system, special focus should be paid on its environmental impacts besides  
170 the efficiency concerns. Sustainable development can be defined as a mode of human development in which  
171 resources are used to cover the needs without affecting the environment. To improve environmental  
172 sustainability, not only renewable energy sources should be utilized, but also the available non-renewable  
173 energy sources should be used in the most efficient form, with the aim of reducing the environmental  
174 impacts. For this, sustainability index is defined as [43].

$$SI = \frac{1}{D_p} \quad (41)$$

175 here,  $D_p$  is the depletion factor defined by Connelly and Koshland [44] as the ratio of exergy destruction to  
176 the input exergy:

$$D_p = \frac{\dot{E}_D}{\dot{E}_{in}} \quad (42)$$

177 In this equation,  $\dot{E}_D$  is the total destroyed exergy within the system, which can be obtained via applying  
 178 exergy balance equation to the system components, while  $\dot{E}_{in}$  is the total input exergy of the system (exergy  
 179 rate associated with the municipal waste). In fact, sustainability index demonstrates how decreasing the rate  
 180 of exergy destructions improves the environmental friendliness of a given system.

181 Finally, the overall exergy efficiency of the waste-fired CCHP plant is defined as the ratio of exergy products  
 182 to the exergy rate associated with the burnt municipal solid waste, as follows:

$$\eta_{II,total} = \frac{\dot{W}_{net} + \dot{E}_{DH} + \dot{E}_{DC}}{\dot{E}_{MW}} \quad (43)$$

183 where,

$$\dot{E}_{DH} = \dot{E}_{38} - \dot{E}_{37} + \dot{E}_{34} - \dot{E}_{33} \quad (44)$$

$$\dot{E}_{DC} = \dot{E}_{27} - \dot{E}_{28} \quad (45)$$

184 More details about estimating specific chemical exergy of the utilized waste can be found in [45].

185

#### 186 **4. Results and Discussion**

187 The results of the simulations on the proposed CCHP system are presented and discussed in this section. In  
 188 the beginning, the chiller performance is optimized considering the generator temperature as a key variable.  
 189 Since the condenser of the power block (HE1) provides part of the heat required for the chiller, the generator  
 190 temperature will affect the lower pressure of the power cycle. The effects of the lower pressure level on the  
 191 waste-fired power cycle performance are discussed in detail in Ref. [1]. Fig. 3 represents the change in the  
 192 chiller coefficient of performance (COP) with a change in the generator temperature. As can be seen, the  
 193 COP hits a maximum value in a generator temperature of around 352 K. Therefore, this temperature is set as  
 194 the generator temperature in the rest of the simulations.

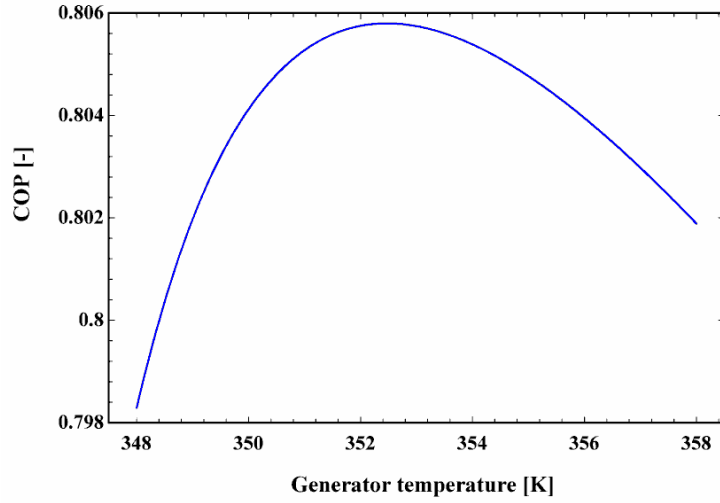


Fig. 3 COP of the absorption chiller versus the generator temperature.

195 Technical characteristics of the proposed waste-fired CCHP are listed in Table 5, resulting from the energy  
 196 and exergy analysis carried out on the proposed CCHP system and the conventional waste-fired CHP system  
 197 shown in Fig. 1. In both of the plants, the mass flow rate of municipal waste was supposed to be 1 kg/s. For  
 198 the case of CCHP system, half of the harvested heat from the HE1 was fed the chiller and the rest was sent to  
 199 HE2 to supply district heating ( $\dot{m}_{11} = \dot{m}_{15} = 0.5\dot{m}_{10}$ ), while district heating system was considered to operate  
 200 based on the 3<sup>rd</sup> generation scheme (i.e. where the supply and return temperatures are 353 K and 313 K).

201 As can be seen, the produced net power by the proposed CCHP system was a little bit more than that  
 202 generated by the conventional CHP. This is because the waste heat recovery system employed in the CCHP  
 203 allows for the reduction of the condenser pressure and as a result, increases the power production compared  
 204 to the conventional plant. The exergy efficiency of the CCHP system was a bit lower than the exergy  
 205 efficiency of the conventional system though as the exergy value of supplied heat is much higher than that of  
 206 the supplied cold. Then, it is clear that in the lower rates of chiller supply in the CCHP system, the exergy  
 207 efficiency will grow significantly. For example, utilizing all the recovered heat from the condenser (HE1) for  
 208 district heating use (i.e. no cold production) via the 3<sup>rd</sup> generation district heating scheme results in an exergy  
 209 efficiency of 28.6%.

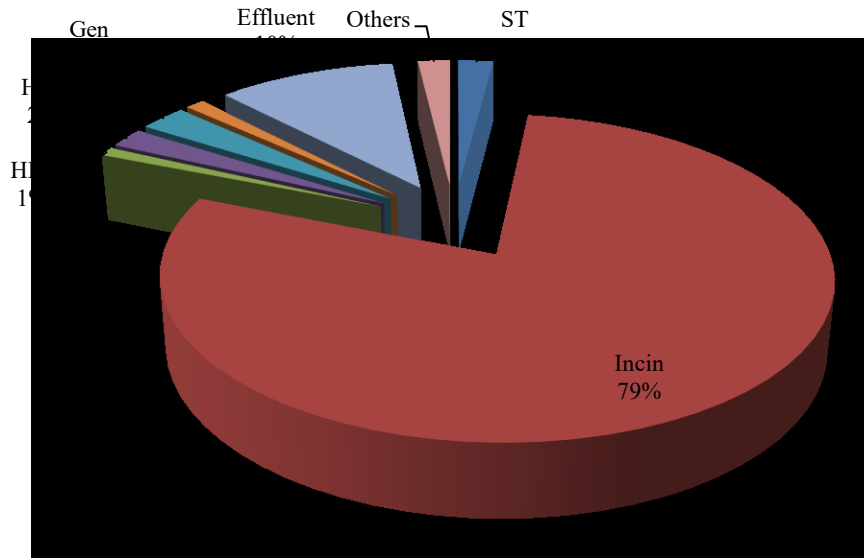
210 According to Table 5, the first law efficiency of 83.28% is obtained for the CCHP system, while the  
 211 electrical and exergetic efficiencies are 23.49 and 26.51%, respectively. This big difference between the first  
 212 and second law efficiencies is because the first law efficiency only quantifies energy (see Eq. 17) while the  
 213 second law efficiency accounts the quality of the energy instead of its magnitude. Since the exergy of heat  
 214 and cold flows are extremely lower compared to the exergy of electricity flow, the electrical efficiency of the  
 215 plant is so close to its exergetic efficiency. In addition, the calculated sustainability index of 1.361 indicates

216 the very high rate of irreversibilities (exergy destructions) within the system, which is not favorable from a  
 217 sustainability point of view. However, since the proposed cogeneration system is based on a combustion  
 218 process (i.e. incineration), not much can be done for smoothening the rates of exergy destructions [46].

**Table 5** Technical parameters values in the presented waste-fired CCHP and conventional CHP.

Parameter (Unit)	Conventional CHP	Proposed CCHP
Municipal waste mass flow rate (kg/s)	1.000	1.000
Net output electricity (MW)	2.866	2.904
District heating supply (MW)	6.392	5.926
District cooling supply (MW)	-	1.547
Exhausted waste heat (MW)	3.250	1.750
Steam mass flow rate in the power cycle (kg/s)	2.980	2.980
Exhaust temperature (K)	438.000	322.000
$\eta_I$ (%)	74.33	83.280
$\eta_{elec}$ (%)	23.19	23.490
$\eta_{II}$ (%)	26.710	26.510
SI (-)	-	1.361

219 Details of the total destroyed exergy within the designed CCHP system is shown in Fig. 4. As it was  
 220 expected, the highest value of exergy destruction is associated with the incinerator (Incin), which is  
 221 inevitable due to the existence of all the irreversibility sources such as chemical reaction, mixing, heat losses  
 222 from the control volume, etc. in this control volume [46]. The second highest exergy loss (and not  
 223 destruction) belongs to the flue gas flow which is discharged to the ambient. The effluent temperature is  
 224 obtained based on the HE4 effectiveness. Under the base condition, exhaust gases are emitted to the  
 225 atmosphere with a temperature of 322 K, causing 10% of exergy losses. The absorption chiller generator is  
 226 the third component with the highest exergy destruction rate and causes 3% exergy destruction within the  
 227 system.

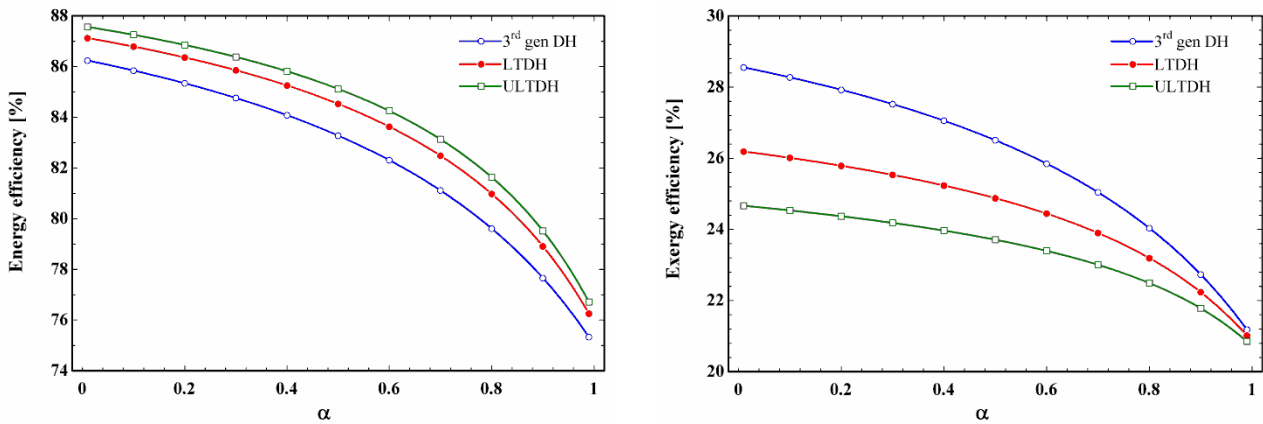


**Fig. 4** Percentage of exergy destruction caused by components of the proposed waste-fired CCHP system.

228 Naturally, the performance of the designed waste-fired CCHP is a direct function of chiller supply ( $\dot{m}_{15}$ ). In  
 229 addition, it is clear that during different seasons, cooling and heating demands vary. Therefore, it is decided  
 230 to study the effects of a change in the chiller supply on the entire system performance operating with  
 231 different district heating designs. Then, a new assessment parameter is defined as:

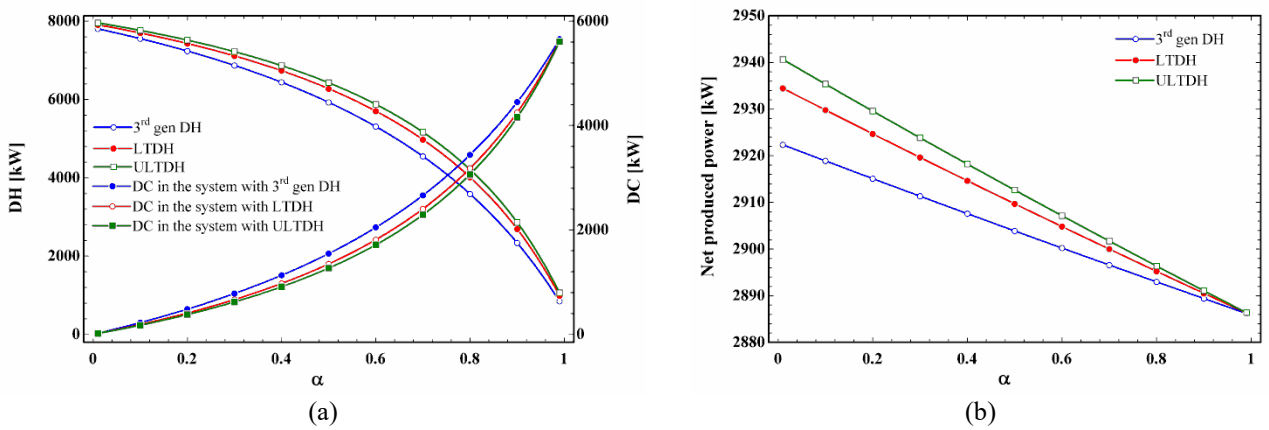
$$\alpha = \frac{\dot{m}_{15}}{\dot{m}_{10}} \quad (46)$$

232 In fact, when  $\alpha$  is 0.1, it means 10% of the harvested heat from HE1 is fed to run the chiller. The effect of  
 233 changing the value of  $\alpha$  from 0.1 to 0.9 on the CCHP system efficiency is shown in Fig. 5. Here, the  
 234 harvested heat from the power cycle is supplied to all the three district heating concepts of the 3<sup>rd</sup> generation,  
 235 the low-temperature and the ultralow-temperature systems through pressurized water and the results are  
 236 presented and compared. As seen, both of the energy and exergy efficiencies of the system decrease as  $\alpha$   
 237 goes up. The energy and exergy efficiencies are functions of supplied heat and cold and the generated  
 238 electricity. Also, it can be seen that lowering the operating temperatures of district heating system (going  
 239 from the 3<sup>rd</sup> generation design to low- and ultralow-temperatures) increases the energy efficiency but  
 240 decreases the exergetic efficiency of the system.



**Fig. 5** Proposed waste-fired CCHP system efficiency versus  $\alpha$

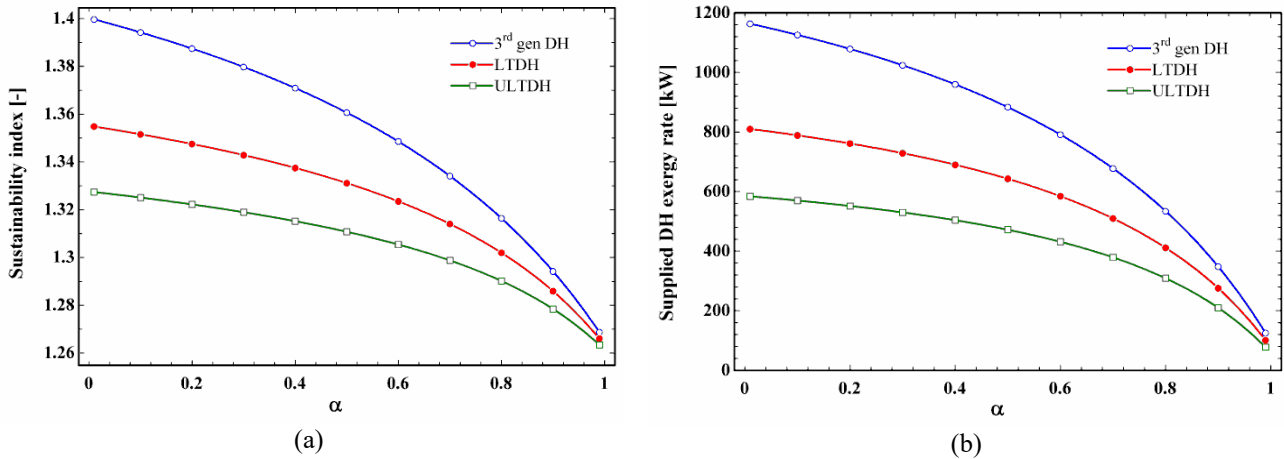
241 Fig. 6 shows the variation in the main parameters of the CCHP system with a change in the value of  $\alpha$  and  
 242 for various district heating temperature designs. As can be seen from Fig. 6(a), in the system operating with  
 243 the 3<sup>rd</sup> generation standard temperatures, increasing  $\alpha$  from 0.1 to 0.9 increases the supplied cold from almost  
 244 21 kW to 5,655 kW and reduces the supplied heat from 7,804 kW to 843 kW. In addition, an increase in  
 245 chiller supply results in a reduction in the system power load. Increasing the rate of the chiller supply raises  
 246 the temperature of pressurized water (heat carrier) coming back to the HE1 and as a result, causes a growth  
 247 in the steam turbine outlet pressure and net output power reduction. Reduction in the supplied heat and  
 248 power as well as the enhancement in the supplied cold lead to a reduction in the system efficiency.



**Fig. 6** Change in the main parameters of the proposed waste-fired CCHP versus  $\alpha$ ; (a) Rate of supplied heat and cold, (b) Net produced power.

249 Fig. 7 indicates the effect of changing the value of  $\alpha$  on the sustainability index of the CCHP system and the  
 250 exergy rate in conjunction with the supplied heat. These two parameters are also assessed for all the three  
 251 different district heating designs (i.e. the 3<sup>rd</sup> generation, the low-temperature, and the ultralow-temperature  
 252 systems). As seen in Fig. 7(a), increasing the cold supply declines the proposed system sustainability. The  
 253 sustainability index of the CCHP system operating with the 3<sup>rd</sup> generation district heating concept decreases  
 254 from 1.4 to 1.269 when  $\alpha$  changes from 0.1 to 0.9. The same trend for the sustainability index versus the  
 255 variation of  $\alpha$  is observed when the system is coupled to the low- and ultralow-temperature district heating

256 systems, but in a specific value of  $\alpha$ , the sustainability index drops as the operating temperature of the district  
 257 heating system gets lower. The fact that increasing the chiller supply rate reduces the exergy rate associated  
 258 with the heat supply is shown in Fig. 7(b). Besides, as can be seen, unlike the energetic efficiency of the  
 259 hybrid system that increases by moving from the 3<sup>rd</sup> generation to the ultralow-temperature district heating  
 260 design (according to Fig. 5), it declines the exergetic performance and the sustainability of the system.



**Fig. 7** Effects of changing the value of  $\alpha$  on the (a): sustainability index of the CCHP system, and (b): exergy rate associated with the supplied heat.

261 As mentioned before, the main objective of the present study is to find a solution for an integration of all the  
 262 energy sectors (electricity, heat and cold) in an environmentally friendly manner via the optimization of an  
 263 existing energy supply plant. This included adding an absorption chiller unit as well as the waste heat  
 264 recovery unit to the existing waste-driven CHP plant. So far, it was well shown how the proposed CCHP  
 265 plant can comply with this and the performance of the system was investigated in various aspects and  
 266 different operating strategies.

267 In the end, in order to have a clear picture of the effects of the waste recovery unit and different district  
 268 heating supply temperatures, the performance of the conventional power plant equipped with a flue gas  
 269 condensation unit and supporting different district heating systems is investigated as well. Table 6 outlines  
 270 the results of this assessment. According to the table, the highest power production and electrical efficiency  
 271 belong to the CHP plant supplying the ultralow-temperature district heating system. The plants supplying the  
 272 low-temperature and the 3<sup>rd</sup> generation district heating systems come in the second and third places,  
 273 respectively. This is mainly due to the further reduction of the steam turbine outlet pressure as the required  
 274 temperature of district heating falls. In addition, exergy efficiency and sustainability index of the CHP  
 275 system operating with ultralow-temperature case were comparable with those of the CHP plant coupled to  
 276 the 3<sup>rd</sup> generation system while lower exergetic and sustainability performance indices are expected if a low-  
 277 temperature district heating is going to be coupled to the plant. Note that coupling with an ultralow-  
 278 temperature system decreases the rate of exergy provided to the district heating system while increasing the  
 279 power production rate. Then, the net exergy rate (power exergy + heat exergy) of this system is comparable

280 with the system supporting a 3<sup>rd</sup> generation district heating. This is while, for the low-temperature case, the  
 281 growth in the power production was not that much to compensate for the exergy drop of the delivered heat.  
 282 The emitted CO<sub>2</sub> is reported in terms of the total produced exergy (kg of CO<sub>2</sub>/GJ of total supplied exergy) in  
 283 the plant. Based on Table 6, the lowest emission belongs to the system operating with 3<sup>rd</sup> generation district  
 284 heating with released CO<sub>2</sub> of 445.935 kg per GJ of produced exergy.

**Table 6** Results of the proposed waste-fired CCHP system operating with various district heating systems (DH: district heating).

Parameter (Unit)	3 <sup>rd</sup> Gen DH	LTDH	ULTDH
Net electricity generated (MW)	2.923	3.193	3.349
District heating supply (MW)	7.830	7.707	9.070
Exergy rate associated with supplied DH (kW)	1167	789.9	666
District cooling supply (MW)	0	0	0
ST outlet pressure (bar)	0.697	0.253	0.131
Emitted CO <sub>2</sub> in terms of produced exergy (kg/GJ)	445.935	458.045	454.534
$\eta_I$ (%)	86.280	87.450	99.6
$\eta_{elec}$ (%)	23.64	25.79	27.04
$\eta_{II}$ (%)	28.58	27.83	28.05
SI (-)	1.4	1.386	1.390

285

## 286 5. Conclusion

287 The parallelization of a LiBr-H<sub>2</sub>O absorption chiller with a conventional waste-driven CHP plant is analyzed.  
 288 In fact, a waste-fired CCHP system, including a Rankine power cycle, a single-effect absorption chiller, and  
 289 some supplementary heat exchangers is proposed with the aim of supplying the energy demand of a district  
 290 area in terms of electricity, heat, and cold. This idea was considered due to the fact that local energy  
 291 supplying systems are attracting more and more attention to highly-integrated energy systems. To further  
 292 improve the technical performance of the CCHP system, the energy content of the effluent is harvested to  
 293 improve the system efficiency by decreasing the condenser pressure of the power block. In addition, the  
 294 performance of the system when connected to the three different district heating schemes of the 3<sup>rd</sup>  
 295 generation, low-temperature, and ultralow-temperature designs was thoroughly investigated. Comprehensive  
 296 energy and exergy analyses were performed to examine the thermodynamic performance of the proposed

297 hybrid system in detail and the obtained results were compared with those associated with the conventional  
298 design of the waste-fired CHP system. Furthermore, the most exergy destructive components of the cycle  
299 were addressed. The main findings of the study are outlined as follows:

- 300 • The incinerator is the most exergy destructive unit as causes 79% of the total exergy destruction  
301 (destruction + losses).
- 302 • Under the base conditions, the thermal and electrical efficiencies of the proposed hybrid system are,  
303 respectively, 12% and 1.3% better than the conventional CHP plant.
- 304 • Both energy and exergy efficiencies of the designed CCHP decrease with an increase in the chiller  
305 supply.
- 306 • Moving from the 3<sup>rd</sup> generation district heating system to lower operating temperature district  
307 heating systems enhances the energy efficiency of the hybrid system, but reduces the exergetic  
308 performance and sustainability index of the system.
- 309 • Maximum exergy efficiency and sustainability are achieved when no cold production is aimed, but  
310 the integration made between the three local cold, heat and electricity networks makes the system be  
311 worth operating even though the exergy efficiency slightly drops.

312 In the end, the following subjects are suggested for (possible) future research works:

- 313 • Exergy based cost analysis of the proposed CCHP system to estimate the unit cost of products in  
314 terms of \$/GJ.
- 315 • Advanced exergy analysis of the proposed CCHP system in order to recognize the potential  
316 improvements of the exergetic performance of each system via dividing the exergy destruction into  
317 endogenous, exogenous, avoidable and unavoidable parts.

318

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323

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- 444

## **Nomenclature**

### **Abbreviations**

Abs	absorber
CCHP	combined cooling, heating and power
CHP	combined heat and power
Cond	condenser
COP	coefficient of performance
DC	district cooling

DH	district heating
Eva	evaporator
FWT	feed water tank
G	electricity generator
Gen	generator
HE	heat exchanger
HPT	high-pressure turbine
Incin	incinerator
IPT	medium pressure turbine
LPT	low-pressure turbine
LTDH	low-temperature district heating
MW	municipal waste
P	pump
ph	preheating line
SHE	solution heat exchanger
SI	sustainability index
ST	steam turbine
ULTDH	ultralow-temperature district heating
WI	waste incinerator

**Latin letters**

$e$	specific physical exergy (J/kg)
$\dot{E}$	exergy flow rate (W)
$h$	specific enthalpy (J/kg)
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	heat transfer rate (W)
$R$	gas constant (J/kg K)

s entropy (J/kg K)

T temperature (K)

$\dot{W}$  power (W)

**Greek letters**

$\eta_I$  energy (thermal) efficiency (-)

$\eta_{II}$  exergy efficiency (-)

$\eta_{elec}$  electrical efficiency (-)

$\eta_{is}$  isentropic efficiency (-)

**Subscripts**

D destruction

in inlet conditions

is isentropic

out outlet conditions

ph physical

0 ambient conditions

445

446

447