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

Nami, Hossein; Arabkoohsar, Ahmad; Anvari-Moghaddam, Amjad

Published in:
Energy Conversion and Management

DOI (link to publication from Publisher):
10.1016/j.enconman.2019.112158

Publication date:
2019

Document Version
Accepted author manuscript, peer reviewed version

Thermodynamic and Sustainability Analysis of a Municipal Waste-Driven Combined Cooling, Heating and Power (CCHP) Plant

Hossein Nami*, Ahmad Arabkoohsar, Amjad Anvari-Moghaddam

Department of Energy Technology, Aalborg University, Aalborg, Denmark

*Corresponding author: hona@et.aau.dk

Abstract

District energy systems, i.e. district heating and cooling systems, will be extremely important in the future energy systems in which a 100% sustainable supply and high synergies of different energy sectors are crucial. Therefore, finding efficient and sustainable solutions for the integration of power, cold and heat sectors is significantly important. In this study, a conventional waste-driven combined heat and power cycle, which is the key component of many energy systems in Europe for baseload coverage of heat and electricity networks, is combined with a large-scale absorption chiller to not only create a strong yet reliable synergy between the three energy sectors of cold, heat and power, but also to improve the plant performance in terms of energy and sustainability indices. The proposed scheme is designed and thermodynamically assessed for the energy market of Denmark as the case study of this work. The results showed that the thermal and electrical efficiencies of the proposed hybrid system are better than the conventional configuration for 12% and 1.3%, respectively. In addition, the exergy efficiency, sustainability index and emission reduction of 28.58%, 1.4 and 445.935 kg-CO_2/GJ are obtained for the system operating with a third-generation district heating system.

Keywords: Waste incineration; Waste-driven CCHP; Absorption chiller; District heating and cooling; Sustainability; Exergy.

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

order to supply domestic heating of a case study and produce hydrogen via gasification. Three different gasification setups were simulated using Aspen plus software for indirect and direct gasification processes based on the various gasification agents. They concluded that 4 liters of hot water with a temperature of 100 °C plus 0.199 kg hydrogen can be produced from 1 kg of waste. Kabalina et al. [16] tried to understand how a decrease in cooling, heating and electricity loads would affect the thermodynamic and economic performance of a poly-generation domestic heating and cooling system based on waste gasification. The investigation of how heat or cold supply affects the overall energy efficiency of waste-fired cogeneration systems is presented in [17]. Gao et al. [18] investigated a waste-fired CCHP plant based on energy and exergy analyses. It is revealed that the exergy efficiency of the CCHP plant may reach up to almost 50% in a particular value of exhaust gas temperature. Persson and Münster [10] investigated and explained why large-scale heat recovery from waste plants is not possible without a local heat distribution network. They presented a literature review and estimated the available waste volume in Europe for district heating supply in 2030. Münster and Meibom [19] investigated the optimization of waste utilization in the future energy matrices of Germany and Nordic countries. The optimization is performed for both investment costs and production. They found out that mixed waste incineration, organic waste digestion in anaerobic way and gasification are the most economically feasible solutions for CHP systems. Furtenback [20] studied the Swedish district heating systems including those operating with waste incineration and revealed that 10% increase in the economic value of waste will decrease waste demand by 4.2% and increase the demand for fossil fuels, biofuels, electricity and other fuels by 6.0%, 5.5%, 6.0%, and 6.0%, respectively. A new ammonia-water CCHP system driven by a low-temperature heat source, which was a modified version of a Kalina cycle, was proposed by Parikhani et al. [21]. The energy and exergy efficiencies of this system are found as 49.8% and 27.7%, respectively. Also, it is found out that the condenser is the main contributor to the irreversibility of the system by the exergy destruction ratio of 32%. Thermodynamic assessment of a CCHP system with a micro gas turbine and an absorption chiller is studied by Mirzaee et al. [22]. In this work, not only the thermodynamic indicators but also the amount of emitted CO_2 of the plant were investigated based on various scenarios.

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

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

2. Waste-Fired CCHP Plant and Main Assumptions

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

2.1. Conventional waste-fired CHP plant

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

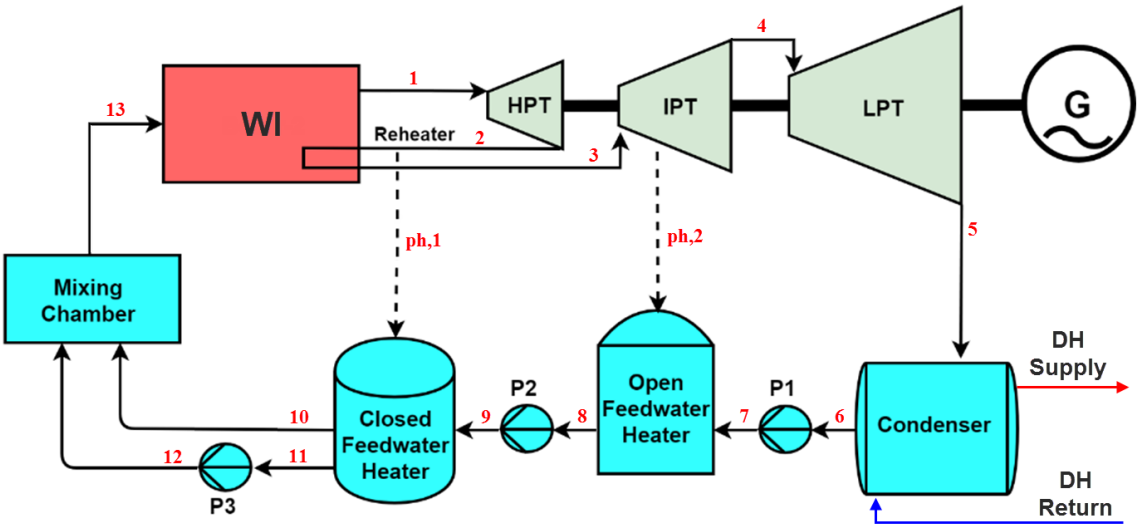


Fig. 1 Schematic diagram of a waste-fired CHP system connected to district heating [11].

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

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

2.2. The proposed waste-fired CCHP

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

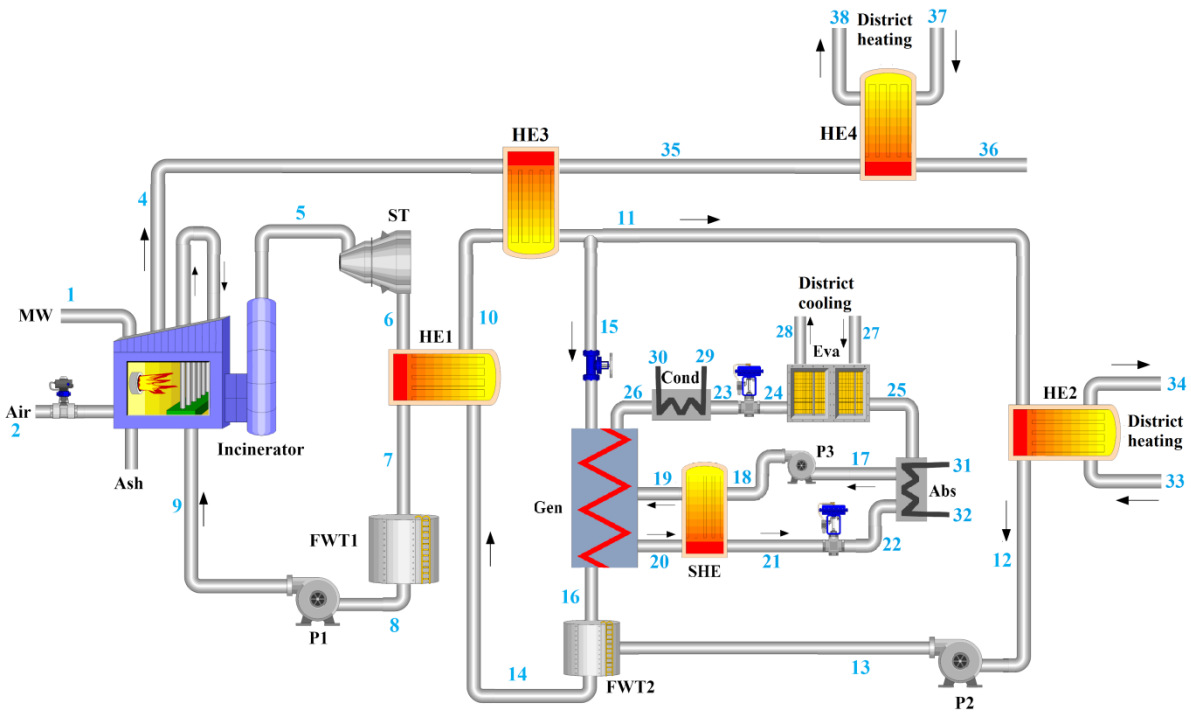


Fig. 2 Simplified configuration of the waste-fired CCHP plant.

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

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

3. Thermodynamic modeling

3.1. Energy analysis

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

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

$$\sum \dot{m}_i = \sum \dot{m}_o \tag{2}$$

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 $\dot{W}$ is the mechanical power. Also, subscripts i and o refer to the inlet and outlet flows, respectively. 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	$\dot{m}_1 LHV_{waste} + \dot{m}_2 h_2 + \dot{m}_9 h_9 = \dot{m}_4 h_4 + \dot{m}_5 h_5$	(3)
ST	$\dot{W}_{ST} = \dot{m}_5 (h_5 - h_6)$, $\eta_{is,ST} = \dfrac{\dot{W}_{ST}}{\dot{W}_{is,ST}}$	(4)
HE1	$\dot{m}_6 (h_6 - h_7) = \dot{m}_{14} (h_{10} - h_{14})$, $eff_{HE1} = \dfrac{Max\{(T_6 - T_7),(T_{10} - T_{14})\}}{T_6 - T_{14}}$	(5)
HE2	$\dot{m}_{11} (h_{11} - h_{12}) = \dot{m}_{33} (h_{34} - h_{33})$, $eff_{HE2} = \dfrac{Max\{(T_{11} - T_{12}),(T_{34} - T_{33})\}}{T_{11} - T_{33}}$	(6)
HE3	$\dot{m}_4 (h_4 - h_{35}) = (\dot{m}_{11} h_{11} + \dot{m}_{15} h_{15} - \dot{m}_{10} h_{10})$, $eff_{HE3} = \dfrac{Max\{(T_4 - T_{35}),(T_{11} - T_{10})\}}{T_4 - T_{10}}$	(7)
HE4	$\dot{m}_{35} (h_{35} - h_{36}) = \dot{m}_{37} (h_{38} - h_{37})$, $eff_{HE4} = \dfrac{Max\{(T_{35} - T_{36}),(T_{38} - T_{37})\}}{T_{35} - T_{37}}$	(8)
SHE	$\dot{m}_{20} (h_{20} - h_{21}) = \dot{m}_{18} (h_{19} - h_{18})$, $eff_{HE2} = \dfrac{Max\{(T_{20} - T_{21}),(T_{19} - T_{18})\}}{T_{20} - T_{18}}$	(9)

P1	$\dot{W}_{P1} = \dot{m}_8(h_9 - h_8)$, $\eta_{is,P1} = \dfrac{\dot{W}_{is,P1}}{\dot{W}_{P1}}$	(10)
P2	$\dot{W}_{P2} = \dot{m}_{12}(h_{13} - h_{12})$, $\eta_{is,2} = \dfrac{\dot{W}_{is,P2}}{\dot{W}_{P2}}$	(11)
P3	$\dot{W}_{P3} = \dot{m}_{17}(h_{18} - h_{17})$, $\eta_{is,P3} = \dfrac{\dot{W}_{is,P3}}{\dot{W}_{P3}}$	(12)
Gen	$\dot{m}_{15}(h_{15} - h_{16}) = \dot{m}_{26}h_{26} + \dot{m}_{20}h_{20} - \dot{m}_{19}h_{19}$	(13)
Cond	$\dot{m}_{26}(h_{26} - h_{23}) = \dot{m}_{29}(h_{30} - h_{29})$	(14)
Eva	$\dot{m}_{24}(h_{25} - h_{24}) = \dot{m}_{27}(h_{27} - h_{28})$	(15)
Abs	$\dot{m}_{31}(h_{32} - h_{31}) = \dot{m}_{17}h_{17} - \dot{m}_{25}h_{25} - \dot{m}_{22}h_{22}$	(16)

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

$$\eta_I = \frac{\dot{Q}_{DH} + \dot{Q}_{DC} + \dot{W}_{net}}{\dot{m}_1 LHW_{MW}} \tag{17}$$

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

where,

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

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

$$\dot{W}_{net} = \dot{W}_{ST} - \dot{W}_{P1} - \dot{W}_{P2} - \dot{W}_{P3} \tag{21}$$

3.2. Exergy analysis

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

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

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

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

$$e_{mixture}^{ch} = \sum_i n_i e_{0,i}^{ch} + \overline{R}T_0 \sum n_i \ln x_i \tag{23}$$

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

Finally, the exergy rate of each ith stream in the system can be written as:

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

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

$$\dot{E}_D = \dot{E}_F - \dot{E}_P \tag{25}$$

$$\eta_{II} = \frac{\dot{E}_P}{\dot{E}_F} \tag{26}$$

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

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)

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

$$SI = \frac{1}{D_p} \tag{41}$$

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

$$D_p = \frac{\dot{E}_D}{\dot{E}_{in}} \tag{42}$$

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

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

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

where,

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

$$\dot{E}_{DC} = \dot{E}_{27} - \dot{E}_{28} \tag{45}$$

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

4. Results and Discussion

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

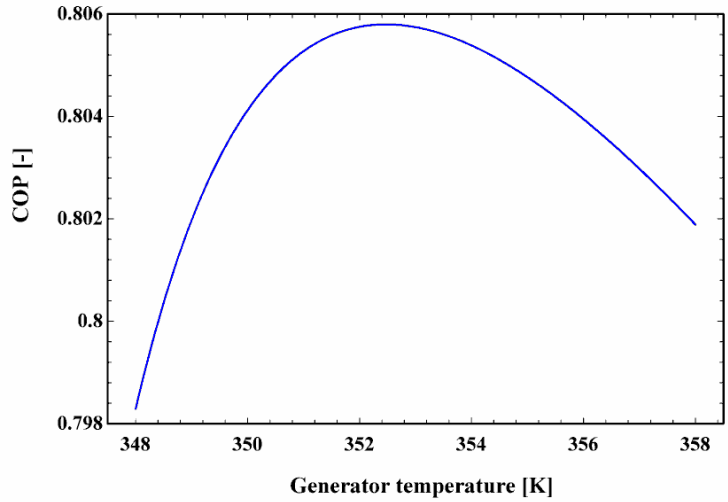


Fig. 3 COP of the absorption chiller versus the generator temperature.

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

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

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

the very high rate of irreversibilities (exergy destructions) within the system, which is not favorable from a sustainability point of view. However, since the proposed cogeneration system is based on a combustion 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
η_I (%)	74.33	83.280
η_{elec} (%)	23.19	23.490
η_{II} (%)	26.710	26.510
SI (-)	-	1.361

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

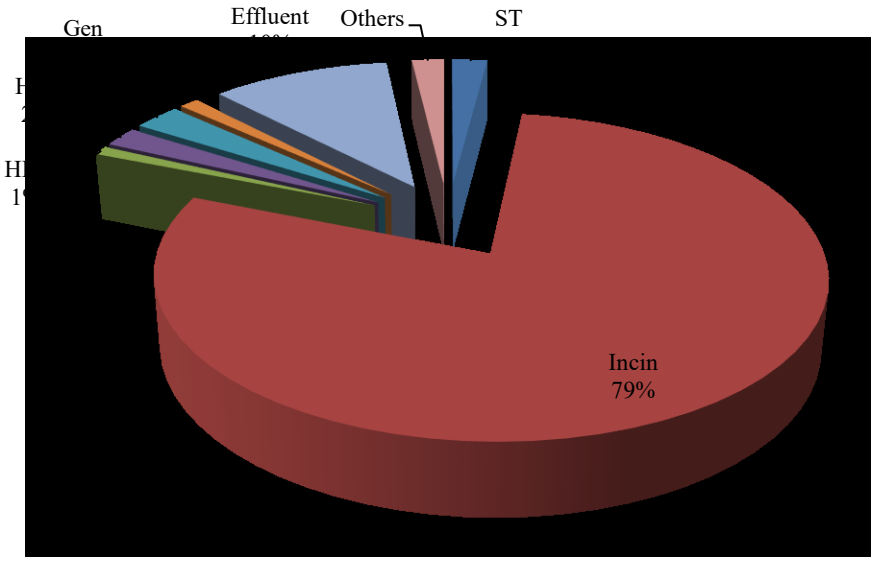


Fig. 4 Percentage of exergy destruction caused by components of the proposed waste-fired CCHP system.

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

$$\alpha = \frac{\dot{m}_{15}}{\dot{m}_{10}} \tag{46}$$

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

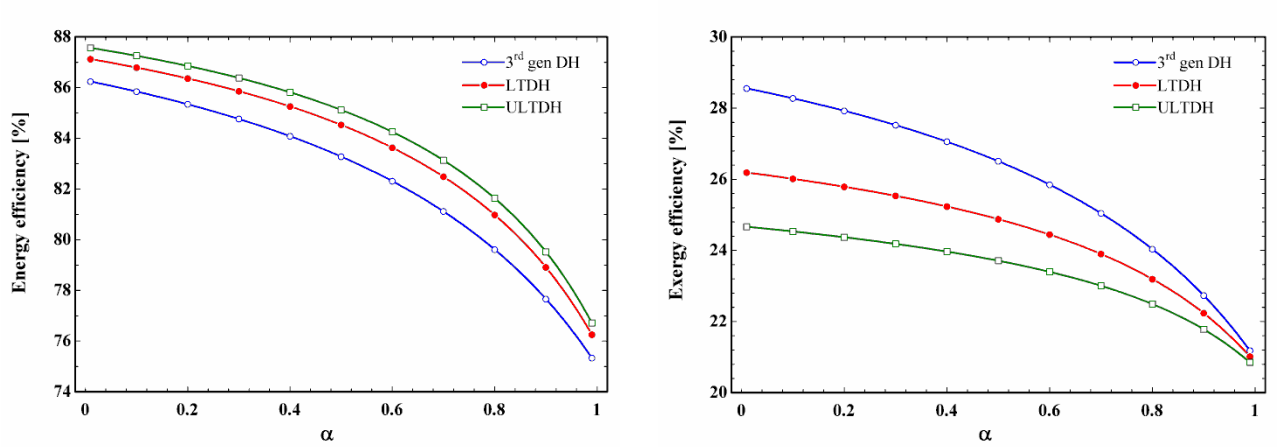
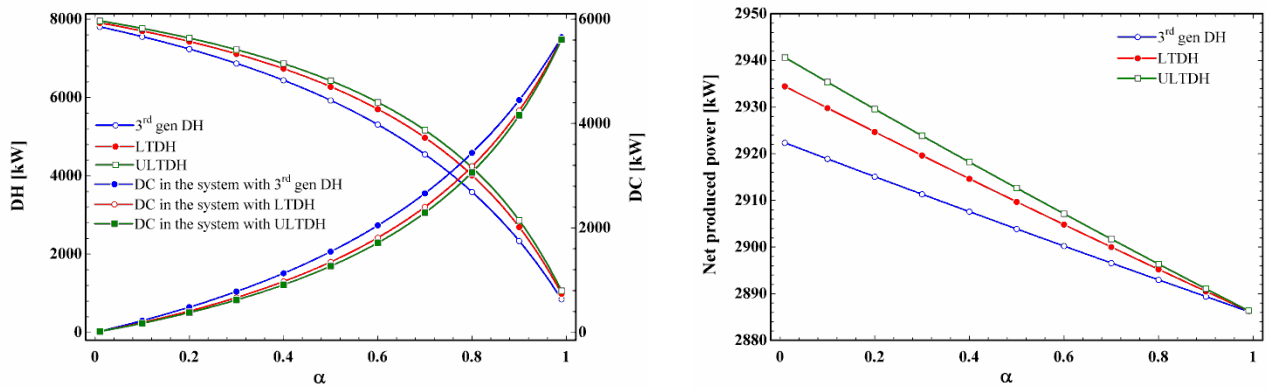


Fig. 5 Proposed waste-fired CCHP system efficiency versus α

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

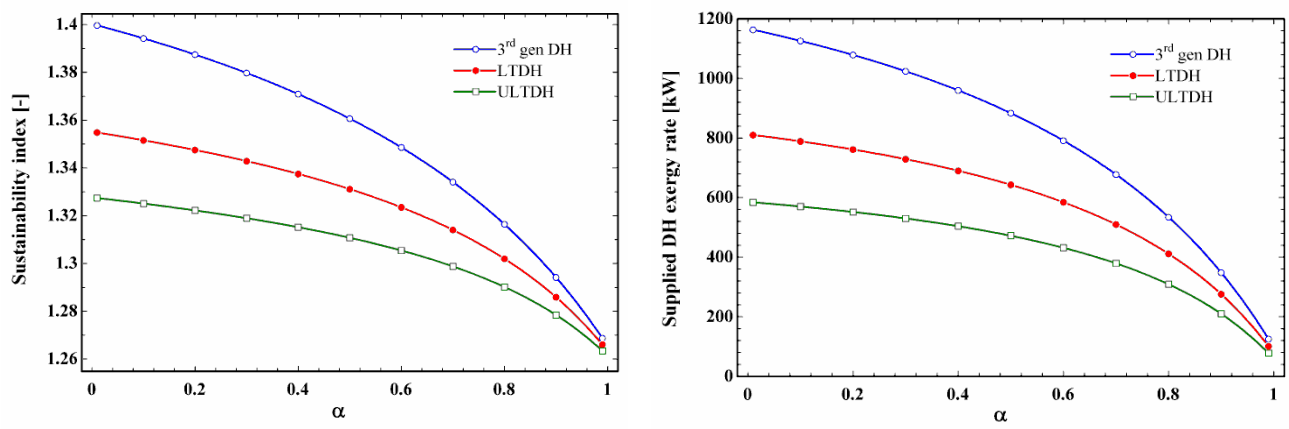


(a) (b)

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

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

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



(a) (b)

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

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

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

with the system supporting a 3rd generation district heating. This is while, for the low-temperature case, the growth in the power production was not that much to compensate for the exergy drop of the delivered heat.

The emitted CO_2 is reported in terms of the total produced exergy (kg of CO_2/GJ of total supplied exergy) in the plant. Based on Table 6, the lowest emission belongs to the system operating with 3rd generation district heating with released CO_2 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)	3rd 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_2 in terms of produced exergy (kg/GJ)	445.935	458.045	454.534
η_I (%)	86.280	87.450	99.6
η_{elec} (%)	23.64	25.79	27.04
η_{II} (%)	28.58	27.83	28.05
SI (-)	1.4	1.386	1.390

5. Conclusion

The parallelization of a LiBr-H_2O absorption chiller with a conventional waste-driven CHP plant is analyzed. In fact, a waste-fired CCHP system, including a Rankine power cycle, a single-effect absorption chiller, and some supplementary heat exchangers is proposed with the aim of supplying the energy demand of a district area in terms of electricity, heat, and cold. This idea was considered due to the fact that local energy supplying systems are attracting more and more attention to highly-integrated energy systems. To further improve the technical performance of the CCHP system, the energy content of the effluent is harvested to improve the system efficiency by decreasing the condenser pressure of the power block. In addition, the performance of the system when connected to the three different district heating schemes of the 3rd generation, low-temperature, and ultralow-temperature designs was thoroughly investigated. Comprehensive energy and exergy analyses were performed to examine the thermodynamic performance of the proposed

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

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

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

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

Acknowledgment

This research is part of the "HeatReFlex-Green and Flexible Heating/Cooling" project (www.heatreflex.et.aau.dk) funded by Danida Fellowship Centre and the Ministry of Foreign Affairs of Denmark under the grant no. 18-M06-AAU.

References

[1] H. Nami, A. Arabkoohsar, Improving the power share of waste-driven CHP plants via parallelization with a small-scale Rankine cycle, a thermodynamic analysis, Energy. 171 (2019) 27–36. doi:10.1016/j.energy.2018.12.168.

[2] J. Kester, L. Noel, G. Zarazua de Rubens, B.K. Sovacool, Policy mechanisms to accelerate electric

vehicle adoption: A qualitative review from the Nordic region, Renew. Sustain. Energy Rev. 94 (2018) 719–731. doi:https://doi.org/10.1016/j.rser.2018.05.067.

[3] M. Sadi, A. Arabkoohsar, Modelling and Analysis of a Hybrid Solar Concentrating-Waste Incineration Power Plant, J. Clean. Prod. (2019).

[4] A. Inayat, M. Raza, District cooling system via renewable energy sources: A review, Renew. Sustain. Energy Rev. 107 (2019) 360–373. doi:10.1016/J.RSER.2019.03.023.

[5] M. Pacesila, S.G. Burcea, S.E. Colesca, Analysis of renewable energies in European Union, Renew. Sustain. Energy Rev. 56 (2016) 156–170. doi:https://doi.org/10.1016/j.rser.2015.10.152.

[6] E. Akarslan, F.O. Hocaoglu, R. Edizkan, Novel short term solar irradiance forecasting models, Renew. Energy. 123 (2018) 58–66. doi:https://doi.org/10.1016/j.renene.2018.02.048.

[7] A.A.A. Ali Sulaiman Alsagri, Ahmad Arabkoohsar, Combination of Subcooled Compressed Air Energy Storage System with an Organic Rankine Cycle for Better Electricity Efficiency, A Thermodynamic Analysis, J. Clean. Prod. (2019) In Press.

[8] S. Guo, Q. Liu, J. Sun, H. Jin, A review on the utilization of hybrid renewable energy, Renew. Sustain. Energy Rev. 91 (2018) 1121–1147. doi:https://doi.org/10.1016/j.rser.2018.04.105.

[9] European Waste Incineration Directive, (2007).

[10] U. Persson, M. Münster, Current and future prospects for heat recovery from waste in European district heating systems: A literature and data review, Energy. 110 (2016) 116–128. doi:10.1016/J.ENERGY.2015.12.074.

[11] M. Sadi, A. Arabkoohsar, M. Sadi, A. Arabkoohsar, Modelling and Analysis of a Hybrid Solar Concentrating-Waste Incineration Power Plant, J. Clean. Prod. (2018). doi:https://doi.org/10.1016/j.jclepro.2018.12.055.

[12] L. Makarichi, W. Jutidamrongphan, K. Techato, The evolution of waste-to-energy incineration: A review, Renew. Sustain. Energy Rev. 91 (2018) 812–821. doi:https://doi.org/10.1016/j.rser.2018.04.088.

[13] A.C. (Thanos) Bourtsalas, Y. Seo, M. Tanvir Alam, Y.-C. Seo, The status of waste management and waste to energy for district heating in South Korea, Waste Manag. 85 (2019) 304–316. doi:10.1016/J.WASMAN.2019.01.001.

[14] G. Manente, A. Lazzaretto, I. Molinari, F. Bronzini, Optimization of the hydraulic performance and integration of a heat storage in the geothermal and waste-to-energy district heating system of Ferrara, J. Clean. Prod. 230 (2019) 869–887. doi:10.1016/J.JCLEPRO.2019.05.146.

[15] S. Rudra, Y.K. Tesfagaber, Future district heating plant integrated with municipal solid waste (MSW) gasification for hydrogen production, Energy. 180 (2019) 881–892. doi:10.1016/J.ENERGY.2019.05.125.

[16] N. Kabalina, M. Costa, W. Yang, A. Martin, Impact of a reduction in heating, cooling and electricity loads on the performance of a polygeneration district heating and cooling system based on waste gasification, Energy. 151 (2018) 594–604. doi:10.1016/J.ENERGY.2018.03.078.

[17] A. Arabkoohsar, H. Nami, Thermodynamic and economic analyses of a hybrid waste-driven CHP–ORC plant with exhaust heat recovery, Energy Convers. Manag. 187 (2019) 512–522. doi:10.1016/j.enconman.2019.03.027.

[18] P. Gao, Y. Dai, Y. Tong, P. Dong, Energy matching and optimization analysis of waste to energy CCHP (combined cooling, heating and power) system with exergy and energy level, Energy. 79 (2015) 522–535. doi:10.1016/J.ENERGY.2014.11.050.

[19] M. Münster, P. Meibom, Optimization of use of waste in the future energy system, Energy. 36 (2011) 1612–1622. doi:https://doi.org/10.1016/j.energy.2010.12.070.

[20] Ö. Furtenback, Demand for waste as fuel in the swedish district heating sector: A production function approach, Waste Manag. 29 (2009) 285–292. doi:10.1016/J.WASMAN.2008.02.027.

[21] T. Parikhani, H. Azariyan, R. Behrad, H. Ghaebi, J. Jannatkhah, Thermodynamic and thermoeconomic analysis of a novel ammonia-water mixture combined cooling, heating, and power (CCHP) cycle, Renew. Energy. 145 (2020) 1158–1175. doi:10.1016/J.RENENE.2019.06.100.

[22] M. Mirzaee, R. Zare, M. Sadeghzadeh, H. Maddah, M.H. Ahmadi, E. Acıkkalp, L. Chen, Thermodynamic analyses of different scenarios in a CCHP system with micro turbine – Absorption chiller, and heat exchanger, Energy Convers. Manag. 198 (2019) 111919. doi:10.1016/J.ENCONMAN.2019.111919.

[23] M. Münster, Use of Waste for Heat , Electricity and Transport – Challenges when performing Energy System Analysis, (n.d.).

[24] A. Arabkoohsar, G.B. Andresen, A smart combination of a solar assisted absorption chiller and a power productive gas expansion unit for cogeneration of power and cooling, Renew. Energy. 115 (2018) 489–500. doi:10.1016/J.RENENE.2017.08.069.

[25] A.M. Pantaleo, P. Ciliberti, S. Camporeale, N. Shah, Thermo-economic assessment of small scale biomass CHP : steam turbines vs ORC in different energy demand segments, Energy Procedia. 75 (2015) 1609–1617. doi:10.1016/j.egypro.2015.07.381.

[26] Y. Chungen, Advancing grate-firing for greater environmental impacts and efficiency for

decentralized biomass / wastes combustion, in: 11th Eur. Conf. Ind. Furn. Boil., Algarve, Portugal, 2017: pp. 18–21.

[27] C.S. M. Edjabou, T. F. Astrup, Composition of municipal solid waste in Denmark Maklawe Essonanawe Edjabou, (2016).

[28] A. Tabasová, J. Kropáč, V. Kermes, A. Nemet, P. Stehlík, Waste-to-energy technologies: Impact on environment, Energy. 44 (2012) 146–155. doi:https://doi.org/10.1016/j.energy.2012.01.014.

[29] F. Marty, S. Serra, S. Sochard, J.-M. Reneaume, Simultaneous optimization of the district heating network topology and the Organic Rankine Cycle sizing of a geothermal plant, Energy. 159 (2018) 1060–1074. doi:10.1016/J.ENERGY.2018.05.110.

[30] A. Arabkoohsar, G.B. Andresen, Supporting district heating and cooling networks with a bifunctional solar assisted absorption chiller, Energy Convers. Manag. 148 (2017) 184–196. doi:10.1016/J.ENCONMAN.2017.06.004.

[31] E. Akrami, A. Chitsaz, H. Nami, S.M.S. Mahmoudi, Energetic and exergoeconomic assessment of a multi-generation energy system based on indirect use of geothermal energy, Energy. 124 (2017). doi:10.1016/j.energy.2017.02.006.

[32] M.J. Moran, H.N. Shapiro, D.D. Boettner, M.B. Bailey, Principles of engineering thermodynamics, eighth ed, John Wiley & Sons, 2015.

[33] M. Sadi, A. Arabkoohsar, Exergoeconomic analysis of a combined solar-waste driven power plant, Renew. Energy. 141 (2019) 883–893. doi:https://doi.org/10.1016/j.renene.2019.04.070.

[34] J. Szargut, D.R. Morris, F.R. Steward, Exergy analysis of thermal, chemical, and metallurgical processes, Hemisphere, Philadelphia., USA, 1988.

[35] Çengel YA, Boles MA, Thermodynamics: an engineering approach, fourth, McGraw Hill, Boston, 2002.

[36] H. Nami, I.S. Ertesvåg, R. Agromayor, L. Riboldi, L.O. Nord, Gas turbine exhaust gas heat recovery by organic Rankine cycles (ORC) for offshore combined heat and power applications - Energy and exergy analysis, Energy. 165 (2018) 1060–1071. doi:10.1016/j.energy.2018.10.034.

[37] A. Nemati, H. Nami, M. Yari, Assessment of different configurations of solar energy driven organic flash cycles (OFCs) via exergy and exergoeconomic methodologies, Renew. Energy. 115 (2018) 1231–1248. doi:10.1016/j.renene.2017.08.096.

[38] A. Bejan, G. Tsatsaronis, Thermal design and optimization, John Wiley & Sons, 1996.

[39] H. Nami, F. Ranjbar, M. Yari, Methanol synthesis from renewable H2 and captured CO2 from S-

Graz cycle – Energy, exergy, exergoeconomic and exergoenvironmental (4E) analysis, Int. J. Hydrogen Energy. 44 (2019) 26128–26147. doi:10.1016/J.IJHYDENE.2019.08.079.

[40] V. Zare, M. Yari, S.M.S. Mahmoudi, Proposal and analysis of a new combined cogeneration system based on the GT-MHR cycle, Desalination. 286 (2012) 417–428.

[41] H. Nami, F. Ranjbar, M. Yari, Thermodynamic assessment of zero-emission power, hydrogen and methanol production using captured CO 2 from S-Graz oxy-fuel cycle and renewable hydrogen, Energy Convers. Manag. 161 (2018) 53–65.

[42] A. Nemati, H. Nami, M. Yari, A comparison of refrigerants in a two-stage ejector-expansion transcritical refrigeration cycle based on exergoeconomic and environmental analysis, Int. J. Refrig. 84 (2017) 139–150. doi:10.1016/j.ijrefrig.2017.09.002.

[43] P. Ahmadi, I. Dincer, M.A. Rosen, Energy and exergy analyses of hydrogen production via solar-boosted ocean thermal energy conversion and PEM electrolysis, Int. J. Hydrogen Energy. 38 (2013) 1795–1805. doi:10.1016/J.IJHYDENE.2012.11.025.

[44] L. Connelly, C.P. Koshland, Two aspects of consumption: using an exergy-based measure of degradation to advance the theory and implementation of industrial ecology, Resour. Conserv. Recycl. 19 (1997) 199–217. doi:10.1016/S0921-3449(96)01180-9.

[45] G. Song, L. Shen, J. Xiao, Estimating Specific Chemical Exergy of Biomass from Basic Analysis Data, Ind. Eng. Chem. Res. 50 (2011) 9758–9766. doi:10.1021/ie200534n.

[46] H. Nami, S.M.S. Mahmoudi, A. Nemati, Exergy, economic and environmental impact assessment and optimization of a novel cogeneration system including a gas turbine, a supercritical CO2 and an organic Rankine cycle (GT-HRSG/SCO2), Appl. Therm. Eng. 110 (2017) 1315–1330.

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

η_I	energy (thermal) efficiency (-)
η_{II}	exergy efficiency (-)
η_{elec}	electrical efficiency (-)
η_{is}	isentropic efficiency (-)

Subscripts

D	destruction
in	inlet conditions
is	isentropic
out	outlet conditions
ph	physical
0	ambient conditions