Emin Açıkkalp[1,2,*]
Thomas Zeng[1]
Andreas Ortwein[1,3]
Holger Burkhardt[4]
Werner Klenk[4]

Exergy, Exergoeconomic and Enviroeconomic Evaluation of a Biomass Boiler-Steam Engine Micro-CHP System

Biomass-based micro-combined heat-and-power (CHP) systems could play an important role in future renewable energy systems by providing net stability and balance electricity fluctuations from wind and solar systems by demand-driven and base load operations. A biomass boiler-steam engine micro-CHP system was investigated via exergy-based analysis methods to evaluate the optimization potential concerning exergy, environmental, and economic aspects. It was shown that the system has low exergy efficiency compared to systems from the literature and that the boiler is mainly affected by capital cost. Major improvements in terms of exergy efficiency as well as economics should therefore be focused on the boiler.

Keywords: Biomass boiler, Exergy analysis, Micro-cogeneration, Steam engine

Received: January 25, 2018; *revised:* July 09, 2018; *accepted:* July 23, 2018

DOI: 10.1002/ceat.201800041

1 Introduction

In future energy systems driven by renewable energy sources, biomass-based micro-combined heat-and-power (CHP) systems could play an important role due to their ability to provide net stability and to balance electricity fluctuations from wind and solar systems by demand-driven and base load operation [1]. In the last decades, the development of biomass-based micro-CHP systems has become popular; they attracted attention especially for residential applications and as alternative to other fossil fuel-based micro-CHP systems. For traditional micro-CHP steam cycles with a capacity of less than 30 kW_{el}, the electrical efficiency is 6–8 % while organic Rankine cycles are capable of 15 % electrical efficiency [2]. To improve their performance, small-scale steam cycles still require extensive research and development.

However, current research is focused on non-biomass-based micro-CHP systems. Bouvenot et al. [3] conducted a dynamic simulation of a micro-CHP system fired with wood pellets and of electricity generation by a steam engine for building applications. They found that the electrical efficiency of the system is 9 % and the overall efficiency is 95 % at full-load operation while an electrical efficiency of 9 % and an overall efficiency of 88 % can be calculated at part-load operation. Badami and Mura [4] discussed the utilization of a small-scale wood waste steam engine. They made a theoretical design analysis of the system and discussed the results. Accordingly, this system has an electrical power output of 23 kW_{el} corresponding to an electrical efficiency of 14 % and a thermal output of 104 kW_{th}. The overall efficiency is 78 % while these performance indicators are nearly constant in the working range of interest. Ferrara et al. [5] modeled a small-scale steam engine system to be used with renewable resources. The exergy efficiency is 87 % and the electrical efficiency of the cycle is 9 % while its Carnot efficiency is calculated with 17 %. Alanne et al. [6] made a thermo-economic analysis of a rotary steam engine for micro-CHP applications. Their system has an electrical capacity of 1–20 kW with an electrical efficiency of 9 %, a thermal efficiency of 77 %, and an overall efficiency of 86 %. Finally, Antonelli and Martorano [7] investigated a steam engine for small-sized power plants. They found that volumetric engines may be considered for micro-cogeneration in small-size plants (i.e., 5–50 kW_{el}) and these engines can have a thermal efficiency of about 25 %. In addition, some studies on how to determine the optimum exergoeconomic performance can be seen in refs. [8–13]. However, most of the studies are focused on plant design and evaluating basic performance criteria of the systems. In contrast, a retrofit technology based on a steam engine technology to be included in an existing biomass heating system has not been investigated, so far. Detailed analyses including the second law of

[1]Dr. Emin Açıkkalp, Thomas Zeng, Prof. Andreas Ortwein
eacikkalp@gmail.com, emin.acikkalp@bilecik.edu.tr
DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH, Torgauer Strasse 116, 04347 Leipzig, Germany.
[2]Dr. Emin Açıkkalp
Bilecik S.E. University, Engineering Faculty, Department of Mechanical Engineering, Bilecik 11230, Turkey.
[3]Prof. Andreas Ortwein
University of Applied Sciences Merseburg, Department of Engineering and Natural Sciences, Eberhard-Leibnitz-Strasse 2, 06217 Merseburg, Germany.
[4]Holger Burkhardt, Werner Klenk
Burkhardt GmbH, Kreutweg 2, 92360 Mühlhausen, Germany.

thermodynamics, the economic performance, and their combination should also be performed. Accordingly, a micro-CHP steam engine for retrofitting combustion plants in the medium output range was examined. Currently, a few retrofitting systems for small-scale biomass boilers are available on the market, i.e. Stirling engines (e.g., from the company Hoval) [1]. The selected micro-CHP system includes a 300-kW_{th} biomass boiler and a 10–30-kW_{el} steam engine with a nominal capacity of maximum 30 kW_{el}. To evaluate the effectiveness of this system, an exergy-based analysis was conducted. Firstly, exergy analysis was applied to reveal irreversibilities and inefficiencies of the system. Secondly, an exergoeconomic analysis consisting of specific exergy cost (SPECO) analysis and the exergetic cost effectiveness (ECE) methods were performed to evaluate economic and energetic parameters together. Thirdly, an enviroeconomic analysis was conducted to determine the release and price of CO_2. Finally, the considered system was compared with a theoretical cycle to determine the improvement potential of the system.

2 System Description

A simplified scheme is shown in Fig. 1, including a biomass boiler (B), a heat recovery steam generator (HRSG), a steam engine (SE), a pump (P), a heat exchanger (HE), and a condenser (COND). The pump is neglected because of its low power capacity. The biomass boiler produces hot water for the heating network and has a nominal heat capacity of 300 kW_{th}. The boiler efficiency is assumed at 85 % and air excess is 0.86. As fuel, low-quality woodchips are used. For the analyses, three subsamples (approximately 5 L each) were taken and merged from the woodchip storage. The merged fuel samples obtained from the sampling were analyzed according to the European standards for solid biofuels [14]. The C, H, and O content, which is required to calculate the chemical energy provided by the fuel (Eq. 11), is listed in Tab. 1.

2.1 Retrofit Micro-CHP System

In contrast to the standard installation of the boiler, the hot flue gas with a temperature of 569 °C, which is the average tem-

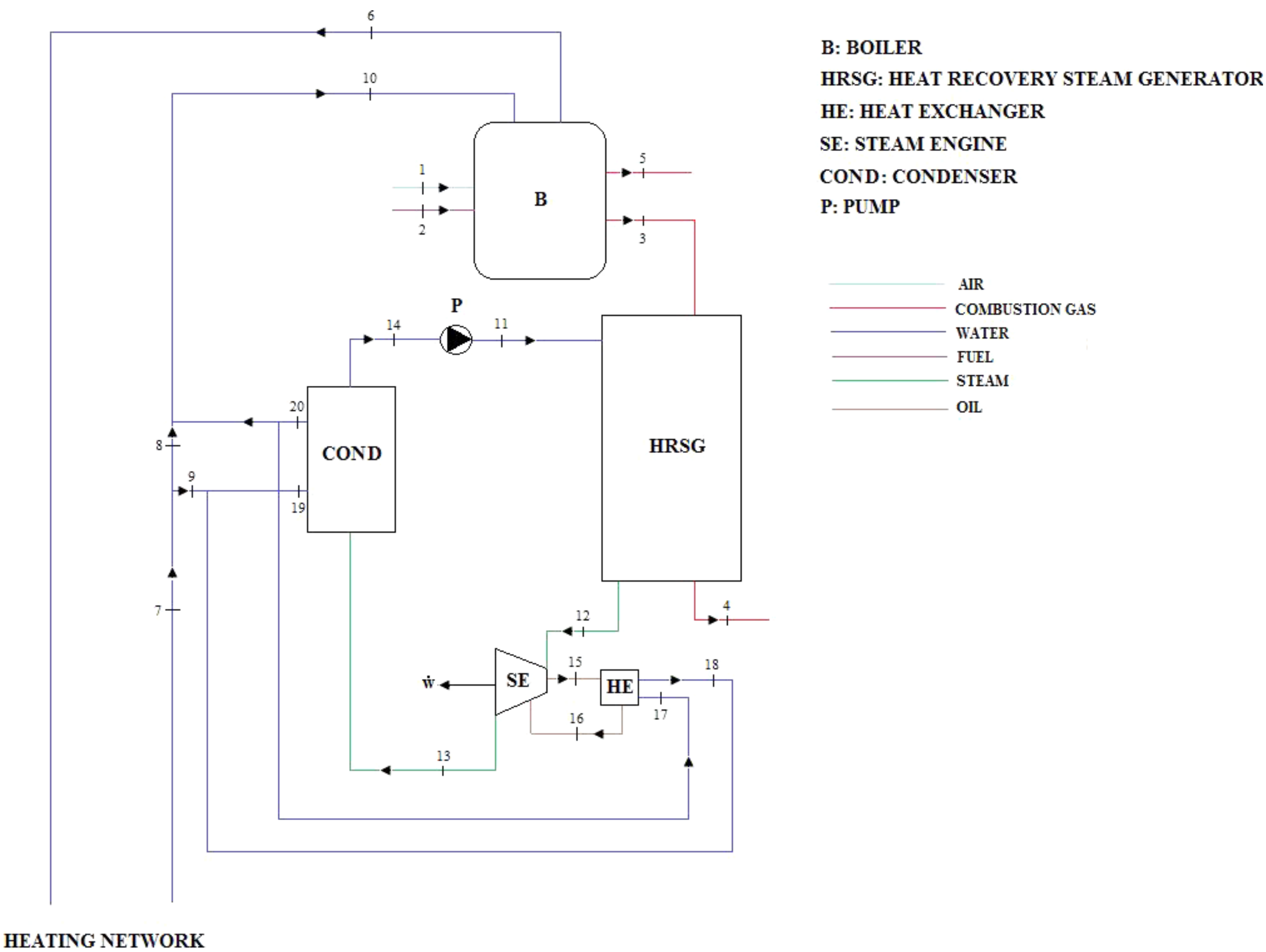

Figure 1. Schematic of the system.

Table 1. Fuel properties on a dry basis.[a)]

Fuel composition	Value
C [wt %]	50.97
H [wt %]	6.23
O [wt %]	42.8
w [wt %]	7.86
Lower heating value (LHV) [kJ kg^{-1}]	18 700

[a)] Except for w, which is specified on the as-received basis.

perature obtained from the measurements, is directed to the HRSG to obtain superheated steam. Water coming from the condenser enters the HRSG for the production of superheated steam. The superheated steam is used in the steam engine to generate power and the residual heat is rejected in the condenser. Both the heat from the exhaust systems of the combustion processes and the process heat can be used. The efficiency of the steam generator is assumed to be 96 % [3]. For the retrofit micro-CHP system, the required temperature, pressure and mass flows were measured during full-load operation of an installed demonstration plant. The mass flow of the combustion air 1 was calculated using Eq. (8), the mass flows of the streams 2, 15, and 16 were derived from heat balances, and the mass flows of streams 8 and 9 were obtained from the mass balance. The measured and calculated values are summarized in Tab. 2.

For comparison, two ideal systems are defined to determine the maximum capacity of the micro-CHP units. For these calculations, the boiler efficiency is assumed to be 100 %. The water return to the boiler and the temperature of the water entering the HRSG are constant. The effectiveness of the HRSG and the isentropic efficiency of the steam expander are equal to 1. The flue gas temperature entering the HRSG is assumed to be 650 °C (ideal system 1) and 569 °C (ideal system 2).

3 Thermodynamic Analyses

3.1 Exergy Analysis

Exergy can be described as the maximum potential work of a system and, in contrast to energy, which is conserved, exergy is not conserved. Thus, every system has irreversibility (or entropy generation), which results in loss of potential work. Using exergy analysis, the location and amount of irreversibility of a given system can be determined. Generally, the exergy balance equation consists of three terms: the fuel exergy rate, the product exergy rate, and the exergy destruction rate. The fuel exergy rate is the provided exergy to obtain the desired output. The product exergy is the desired output of the considered system and, finally, the exergy destruction rate is the lost work potential in the system. The general exergy balance can be written as:

$$\dot{E}x_{\mathrm{F}} - \dot{E}x_{\mathrm{P}} = \dot{E}x_{\mathrm{D}} \tag{1}$$

Table 2. Mass flow rates, temperatures, pressure and exergy rates of the points for the retrofit micro-CHP system.

Point	$\dot{m}$ [kg s^{-1}]	T [°C]	p [kPa]	$\dot{E}x$ [kW]
1	0.142	25	100	0
2	0.016	25	–	342.06
3	0.11	569	184	37.48
4	0.11	170	184	8.23
5	0.0444	569	184	15.17
6	2.39	87	300	59.95
7	2.39	61	300	11.65
8	1.72	61	300	8.39
9	0.67	61	300	3.27
10	2.39	66	300	26.29
11	0.022	57	1820	0.18
12	0.022	350	1820	23.25
13	0.022	98	94.34	10.07
14	0.022	57	94.34	0.17
15	0.1	122	580	2.94
16	0.1	109	580	2.25
17	1.72	79	300	31.80
18	1.72	79.4	300	32.17
19	2.39	74	300	36.9
20	2.39	79	300	44.19

The exergy efficiency (φ)[1)] illustrates how the considered system is close to an ideal one ($\varphi = 1$) and can be expressed as:

$$\varphi = \frac{\dot{E}x_{\mathrm{F}}}{\dot{E}x_{\mathrm{P}}} = 1 - \frac{\dot{E}x_{\mathrm{D}}}{\dot{E}x_{\mathrm{F}}} \tag{2}$$

The exergy destruction ratio (y) is a measure of the contribution of the exergy destruction rate within each component $(\dot{E}x_{\mathrm{D}})$ to the reduction of the overall exergetic efficiency (φ). It can be used to compare dissimilar components of the same system [15]. The exergy destruction ratio (y) is calculated according to

$$y = \frac{\dot{E}x_{\mathrm{D,k}}}{\dot{E}x_{\mathrm{F,tot}}} \tag{3}$$

The specific exergy (ex) of any liquid and steam is calculated by

$$ex = ((h - h_{\mathrm{o}}) + T_{\mathrm{o}}(s - s_{\mathrm{o}})) \tag{4}$$

1) List of symbols at the end of the paper.

Under the assumption of an ideal gas, the specific exergy of a gas (ex_{gas}) can be expressed according to

$$ex_{gas} = c_{p(T),gas}\left[T - T_o - T_o \ln\left(\frac{T}{T_o}\right)\right] + RT_o \ln\left(\frac{P}{P_o}\right) \quad (5)$$

The specific exergy ($ex_{solid,fluid}$) of a solid or an uncompressible liquid, assuming an average specific heat (c_{avg}) [16], is expressed by

$$ex_{solid,fluid} = c_{avg}\left[T - T_o - T_o \ln\left(\frac{T}{T_o}\right)\right] \quad (6)$$

First of all, the specific heat of the combustion gas and air ($c_{p,gas}$) must be obtained and the combustion process should be defined. According to ref. [3], the combustion equation of woodchips and the air flow rate of the air are described by

$$C_xH_yO_z + \left(x + \frac{y}{4} - \frac{z}{2}\right)(1 + e_{air})O_{2,(g)} \rightarrow xCO_2 + \frac{y}{2}H_2O_{(g)} + \left(x + \frac{y}{4} - \frac{z}{2}\right)e_{air}O_{2,(g)} \quad (7)$$

$$\dot{m}_{air} = \dot{m}_{fuel}(1 - w)\frac{\left(x + \frac{y}{4} - \frac{z}{2}\right)}{M_C + M_H + M_O}(1 + e_{air})\frac{\left(\chi_{O_2}M_{O_2} + \chi_{N_2}M_{N_2}\right)}{\chi_{O_2}} \quad (8)$$

Using the mass composition of the combustion gas, the specific heat of the combustion gas ($c_{p,gas}$) can be defined according to [16]:

$$c_{P(T),gas} = 0.7401 + \frac{0.9415T}{10^3} - \frac{0.1184T^2}{10^6} - \frac{4.0855T^3}{10^{10}} + \frac{2.0698T^4}{10^{13}} \quad (9)$$

According to [16], the specific heat of the combustion air ($c_{p,air}$) can be calculated by

$$c_{P(T),air} = 1.0679 - \frac{0.5378T}{10^3} + \frac{1.3544T^2}{10^6} - \frac{9.8872T^3}{10^{10}} + \frac{2.4484T^4}{10^{13}} \quad (10)$$

The chemical exergy (ex_{fuel}) of the fuel is the main exergy source of the micro-cogeneration system, which is obtained by [17]:

$$ex_{fuel} = \left(\frac{C}{3} + H\right) \quad (11)$$

Another useful index is the sustainability index (SI) representing the sustainability that is measurement from the exergy destruction ratio according to the fuel exergy of the energy conversion system, which has a strong relationship with the exergy efficiency and can be defined according to Eq. (12). A higher *SI* value indicates a more efficient energy conversion system and, consequently, a higher environmental benefit. For a more detailed explanation, see [18].

$$SI = \frac{1}{1 - \varphi} = 1 - DP \quad (12)$$

DP is the depletion ratio suggested by Connelly and Koshl and represents the relation between the exergy destruction rate $(\dot{E}x_D)$ and the fuel exergy rate $(\dot{E}x_F)$ and can be calculated according to [19]:

$$DP = \frac{\dot{E}x_F}{\dot{E}x_D} \quad (13)$$

The exergy efficiency ratio of the micro-CHP ($\varphi_{micro\text{-}CHP}$) system is expressed as the ratio of the total products (which are the sum of the power output and the exergy of heat) to the fuel exergy (which is equal to the chemical exergy of the fuel in the considered system).

$$\varphi_{micro-CHP} = \frac{\dot{E}x_P}{\dot{E}x_F} = \frac{\dot{W} + \dot{E}x_Q}{\dot{E}x_F} \quad (14)$$

The exergy balance equations are summarized in Tab. 3.

Table 3. Exergy and cost balance equations (SPECO).

Component	$\dot{E}x_F$	$\dot{E}x_P$	Cost balance and auxiliary equations
Boiler	$\dot{E}x_2$	$(\dot{E}x_3 + \dot{E}x_5 - \dot{E}x_1) + (\dot{E}x_6 - \dot{E}x_{10})$	$\dot{C}_2 + \dot{Z}_B = (\dot{C}_3 + \dot{C}_5 + \dot{C}_1) + (\dot{C}_6 - \dot{C}_{10}), c_3 = c_5,$ $c_6 = c_{10}, \frac{(\dot{C}_6 - \dot{C}_{10})}{(\dot{E}x_6 - \dot{E}x_{10})} = \frac{(\dot{C}_3 - \dot{C}_5)}{(\dot{E}x_3 - \dot{E}x_5)}$
Heat recovery steam generator	$(\dot{E}x_3 - \dot{E}x_4)$	$(\dot{E}x_{12} - \dot{E}x_{11})$	$(\dot{C}_3 - \dot{C}_4) + \dot{Z}_{HRSG} = (\dot{C}_{12} - \dot{C}_{11}), c_3 = c_4, c_{12} = c_{11}$
Steam engine	$(\dot{E}x_{12} - \dot{E}x_{13})$	$\dot{W}$	$(\dot{C}_{12} - \dot{C}_{13}) + \dot{Z}_{SE} = \dot{C}_W, c_{12} = c_{13}$
Condenser	$(\dot{E}x_{13} - \dot{E}x_{14})$	$(\dot{E}x_{20} - \dot{E}x_{19})$	$(\dot{C}_{13} - \dot{C}_{14}) + \dot{Z}_{COND} = (\dot{C}_{20} - \dot{C}_{19}), c_{13} = c_{14}, c_{20} = c_{19}$
Heat exchanger	$(\dot{E}x_{15} - \dot{E}x_{16})$	$(\dot{E}x_{17} - \dot{E}x_{18})$	$(\dot{C}_{15} - \dot{C}_{16}) + \dot{Z}_{HE} = (\dot{C}_{17} - \dot{C}_{18}), c_{15} = c_{16}, c_{17} = c_{18} = c_{20} = c_{19}$

3.2. Exergoeconomic Analysis

After the exergy analyses were conducted, two different exergoeconomic approaches were employed: the SPECO method presented by Lazzaretto and Tsatsaronis [20] and the ECE method presented by Yucer and Hepbasli [21]. Firstly, the SPECO approach is defined. In this approach, the cost balance equation can be calculated as:

$$\dot{C}_{\mathrm{F}} + \dot{Z}^{T} = \dot{C}_{\mathrm{F}} \quad (15)$$

$$c_{\mathrm{F}}\dot{E}x_{\mathrm{F}} + \dot{Z}^{\mathrm{T}} = c_{\mathrm{P}}\dot{E}x_{\mathrm{P}} \quad (16)$$

where $\dot{Z}^{\mathrm{T}}$ is the investment cost rate (€ h^{-1}) and it is calculated by

$$\dot{Z}^{\mathrm{T}} = \frac{PEC\Phi CRF}{N} \quad (17)$$

In Eq. (17), *PEC* is the purchased equipment cost (listed in Tab. 4), *CRF* is the capital recovery factor, which is used to determine the present value of the money, and Φ is the operating and maintenance factor, which is assumed to be 1.073 [22]. *N* represents the yearly operating hours of the system, which is assumed to be 7500 h $year^{-1}$. *CRF* can be written as

$$CRF = \frac{i(1+i)^{n}}{i(1+i)^{n} - 1} \quad (18)$$

where *i* represents the inflation rate, which is assumed as 2 %, and *n* is the life time of the facility, assumed to be 20 years. According to Eq. (19), the cost of the exergy destruction rate $(\dot{C}_{\mathrm{D}})$ in a process is the product of the exergy destruction rate $(\dot{E}x_{\mathrm{D}})$ and the specific fuel costs (c_{F}). Thus, more fuel is required to compensate for the exergy destruction rate [23].

Table 4. Purchase equipment cost of the components.[a)]

Component	*PEC* [€]
Boiler	100 000
Heat recovery steam generator	10 000
Steam engine	48 000
Condenser	2000
Heat exchanger	1200

[a)] According to a telephone interview with the micro-CHP manufacturer (November 13, 2017).

$$\dot{C}_{\mathrm{D}} = c_{\mathrm{F}}\dot{E}x_{\mathrm{D}} \quad (19)$$

Finally, two exergoeconomic parameters, i.e. the relative cost ratio (*r*) and the exergoeconomic factor (*f*), can be used for the evaluation, which are defined by

$$r = \frac{c_{\mathrm{P}} - c_{\mathrm{F}}}{c_{\mathrm{F}}} \quad (20)$$

$$f = \frac{\dot{Z}^{\mathrm{T}}}{\dot{Z}^{\mathrm{T}} + \dot{C}_{\mathrm{D}}} = \frac{\dot{Z}^{\mathrm{T}}}{\dot{Z}^{\mathrm{T}} + c_{\mathrm{F}}\dot{E}x_{\mathrm{D}}} \quad (21)$$

Accordingly, the cost balance equations for the SPECO analysis are summarized in Tab. 3.

The ECE analysis includes both the effect of the exergy destruction rate and the costs of the used equipment and focuses on the component that costs more and causes a higher exergy destruction rate. In this analysis, *a* is the contribution of a specific component to the overall system, defined according to

$$a = \frac{PEC_{\mathrm{k}}}{PEC_{\mathrm{total}}} \quad (22)$$

Moreover, *b* is the contribution of the exergy destruction rate of a component to the total exergy destruction rate:

$$b = \frac{\dot{E}x_{\mathrm{D,k}}}{\dot{E}x_{\mathrm{D,total}}} \quad (23)$$

Finally, *ECE* is calculated by

$$ECE = ab \quad (24)$$

The analysis of the system performance can be completed with the estimation of the total cost of the destructed exergy C_{total} (total exergy cost) in € a^{-1}. The cost of the fuel necessary to produce a useful exergy equal to the destroyed exergy (C_{Total} in € a^{-1}) can be calculated according to Eq. (25). The all-system exergy destruction rate cost of a system ($\dot{c}_{total}$ in € $kW^{-1}a^{-1}$) can be calculated by [24]:

$$\dot{c}_{\mathrm{total}} = \frac{C_{\mathrm{total}}}{\dot{E}x_{\mathrm{F}}} \quad (25)$$

$$C_{\mathrm{total}} = \dot{E}x_{\mathrm{D,total}}N\frac{1}{\varphi} \;\; z \quad (26)$$

where *z* is the total fuel cost.

3.3 Enviroeconomic Analysis

Finally, the evaluation performed in this paper is the enviroeconomic analysis to investigate how much CO_2 is released from the system (α_{CO_2}) and to determine the price of the released CO_2 (C_{CO_2}), which are expressed in Eqs. (27) and (28) [25]. In this method, it is clear to define how much CO_2 is released, and the related costs. That is why this method is added to the analyses.

$$\alpha_{CO_2} = \beta_{CO_2}\dot{F}uel_{\mathrm{consumed}}N \quad (27)$$

$$C_{CO_2} = \mu_{CO_2}\alpha_{CO_2} \quad (28)$$

4 Results and Discussion

Exergy, exergoeconomic and enviroeconomic analyses were applied to a biomass boiler-steam engine micro-CHP system. The results are given in Tabs. 5–8 and Figs. 2–5.

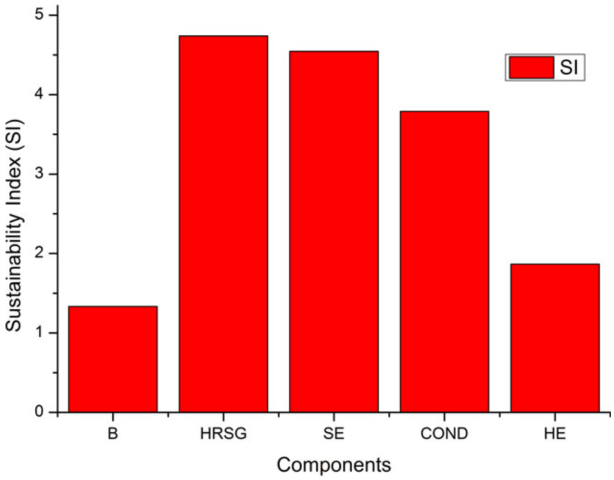

Figure 2. *SI* values of the components for the retrofit micro-CHP system.

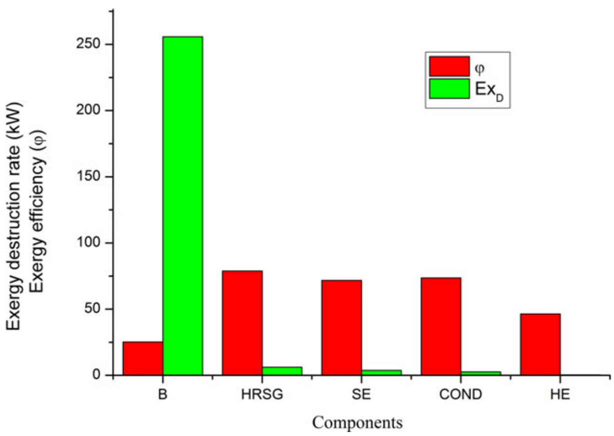

Figure 3. Exergy efficiencies and exergy destruction rates of the components for the retrofit micro-CHP system.

The electricity production of the retrofit system is 9.46 kW. The results of the exergy analysis are given in Tab. 5. The importance of the exergy destruction rate $\left(\dot{E}x_{\mathrm{D}}\right)$ is that it results from the irreversibilities or entropy generation in the system causing a decrease in the system efficiency. As it is seen, the exergy destruction rate $\left(\dot{E}x_{\mathrm{D}}\right)$ of 255.75^kW of the boiler (B) is the highest, corresponding to more than 90^% of $\dot{E}x_{\mathrm{D}}$ of the whole system. This is an expected result because the exergy destruction rates in chemical reactions are commonly very high [16]. The lowest exergy destruction rate $\left(\dot{E}x_{\mathrm{D}}\right)$ in the system is located at the heat exchanger and its value is 0.32^kW, while the $\dot{E}x_{\mathrm{D}}$ values of the HRSG, the steam engine, and the condenser are 6.18, 3.72, and 2.61 kW, respectively. Another important criterion is the exergy efficiency (φ) because it provides information about how much the considered system or component is close to a reversible one.

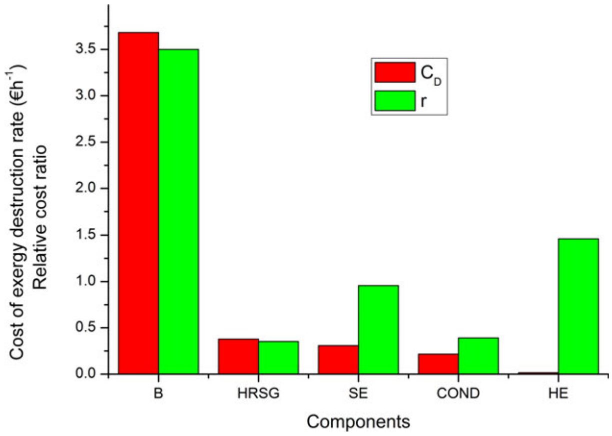

Figure 4. Relative cost differences and cost of exergy destruction rates of the components for the retrofit micro-CHP system.

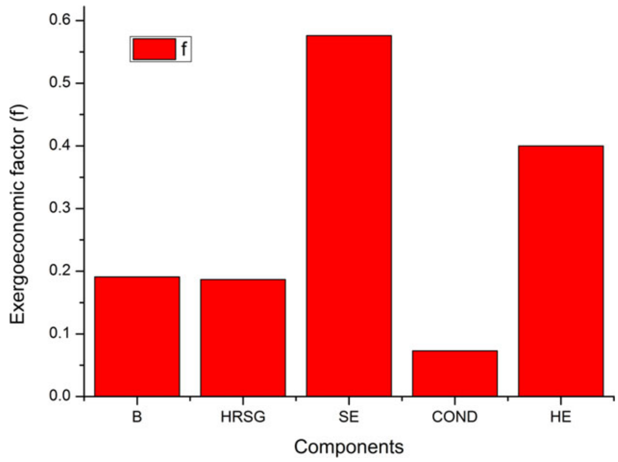

Figure 5. Exergoeconomic factors of the components for the retrofit micro-CHP system.

The highest exergy efficiency (φ) is located at the HRSG (78.9 %), and the boiler (B) has the lowest exergy efficiency (φ) (29.2 %). Furthermore, the SI method can provide further indications about how the exergy efficiency affects the sustainability of the resources. The *SI* values of the boiler (B), the HRSG, the steam engine (SE), the condenser (COND), and the heat exchanger (HE) are found to be 1.412, 4.739, 4.546, 3.788, and 1.866, respectively. The exergy destruction ratios (y) of the boiler, the HRSG, the steam engine, and the heat exchanger are 0.646, 0.016, 0.009, 0.007, and 0.0008, respectively. Finally, the exergy efficiency ($\varphi_{\mathrm{system}}$) and the sustainability index (SI_{system}) for the overall micro-CHP system are calculated. The exergy efficiency of the micro-CHP is found to be 13.06 % and the SI of the micro-CHP is found to be 1.150.

In Tab. 6, the results of the exergoeconomic analysis by using the SPECO method, which indicates the cost of exergy flows, are summarized. The SPECO method exergy flows are costing and, in this method, exergy flows and cost flows are used for an evaluation of the system. The cost rate of the exergy destruction

Table 5. Results of the exergy analysis for the retrofit micro-CHP system.

Component	$\dot{E}x_F$ [kW]	$\dot{E}x_P$ [kW]	$\dot{E}x_D$ [kW]	φ [%]	SI [–]	y [–]
Boiler	342.06	86.31	255.75	25.2	1.334	0.646
Heat recovery steam generator	29.95	23.07	6.18	78.9	4.739	0.016
Steam engine	13.18	9.46	3.72	71.8	4.546	0.009
Condenser	9.9	7.29	2.61	73.6	3.788	0.007
Heat exchanger	0.69	0.37	0.32	46.4	1.866	0.0008

Table 6. Results of the SPECO analysis for the retrofit micro-CHP system.

Component	c_F [€ MJ^{-1}]	c_P [€ MJ^{-1}]	$\dot{Z}^T$ [€ h^{-1}]	$\dot{C}_D$ [€ h^{-1}]	r [–]	f [–]
Boiler	0.004	0.018	0.87	3.683	3.500	0.191
Heat recovery steam generator	0.017	0.023	0.087	0.378	0.353	0.187
Steam engine	0.023	0.045	0.419	0.308	0.957	0.576
Condenser	0.023	0.032	0.017	0.216	0.391	0.073
Heat exchanger	0.013	0.032	0.010	0.015	1.460	0.400

rate $(\dot{C}_D)$ is the highest for the boiler (B) and its value is 3.683 € h^{-1}, while the cost rate of exergy destruction rate $(\dot{C}_D)$ of 0.015 € h^{-1} is lowest for the heat exchanger (HE). The cost rate of the exergy destruction rate $(\dot{C}_D)$ for the HRSG, the steam engine (SE), and the condenser (COND) are 0.378 € h^{-1}, 0.308 € h^{-1}, and 0.216 € h^{-1}, respectively. The relative cost difference ratio (r) is the relative increase in the average cost per exergy unit between the fuel and the product of the component [26], which is the highest for the boiler (3.500) and the lowest for the HRSG (0.353).

Furthermore, the relative cost difference ratios (r) of the steam engine, the condenser, and the heat exchanger are 0.957, 0.391 and 1.460, respectively. Using the exergoeconomic factor (f), a balance between the investment costs and the exergy destruction rate may be obtained. Thus, the exergoeconomic factor (f) provides a comparison between the investment cost and the cost of the exergy destruction rate. If f is higher than 1, a reduction is recommended in the investment cost, and if f is lower than 1, the exergy destruction rates must be decreased. The highest value of f was calculated for the boiler (0.191), and the lowest value, for the condenser (0.073). The exergoeconomic factors (f) of the other components are 0.576 for the steam engine, 0.187 for the HRSG, and 0.400 for the heat exchanger.

The results of the ECE are listed in Tab. 7. In contrast to the SPECO analysis, this method is a component-based method and it combines the exergy destruction rates and the cost of the considered component. A low value of this parameter (ECE) represents a more cost-effective and a more efficient component. Accordingly, the most efficient component is the heat exchanger, since it has the lowest value (0.000008). In contrast, the boiler (B) has the highest value (0.590), exhibiting the highest exergy destruction rate $(\dot{E}x_D)$ and high costs in the system. ECE is 0.0014 for the HRSG, 0.0042 for the steam engine (SE), and 0.0001 for the condenser (COND).

Table 7. Results of the ECE analysis for the retrofit micro-CHP system.

Component	a	b	ECE
Boiler	0.620	0.952	0.590
Heat recovery steam generator	0.062	0.023	0.0014
Steam engine	0.298	0.014	0.0042
Condenser	0.012	0.010	0.0001
Heat exchanger	0.007	0.0012	0.000008

The results of the total cost of destructed exergy (C_{Total}), the irreversibility cost per input exergy, and the environmental and enviroeconomic analyses are presented in Tab. 8. The total cost of destructed exergy (C_{Total}) is found to be 3356.55 € a^{-1} and the irreversibility cost per input exergy $(\dot{c}_{total})$ is calculated as

Table 8. Results of the total exergy cost, the irreversibility cost per exergy input, the enviroeconomic analysis, the exergy efficiency of the system, and the SI of the retrofit micro-CHP system.

Parameter	Value
C_{Total} [€ a^{-1}]	3356.55
$\dot{c}_{total}$ [€ kW^{-1}a^{-1}]	9.81
α_{CO_2} [t_{CO2}a^{-1}]	67.5
C_{CO_2} [€ a^{-1}]	829.45
φ_{sys} [%]	13.06
SI_{system} [–]	1.150

9.81 € $kW^{-1}year^{-1}$. The carbon dioxide emission from the system in a year x_{CO_2} is equal to 67.5 t CO_2 $year^{-1}$. The enviroeconomic value of the system (C_{CO_2}) is calculated as 829.45 € a^{-1}.

In the next step, the results were compared with both ideal systems. For the ideal system 1, the electrical power obtained from the system is around 20.204 kW_{el}, the exergy destruction rate in the boiler is 228.64 kW, and the overall exergy efficiency (φ_{system}) and the sustainability index (SI_{system}) of the system are 19.8 % and 1.247, respectively. Similarly, the ideal system 2 has 18.4 kW_{el} electrical power output, an exergy destruction rate $(\dot{E}x_D)$ of the boiler of 240.20 kW, and an overall exergy efficiency and sustainability index of 19.2 % and 1.238, respectively. Comparing ideal system 1 with the retrofit micro-CHP system, the overall exergy efficiency (φ_{system}) increases by 6.7 %, the electrical power output increases by 10.0 kW_{el}, the sustainability index (SI_{system}) increases by 7.9 %, while the exergy destruction rate $(\dot{E}x_D)$ of the boiler decreases by 11 %. Comparing ideal system 2 with the retrofit micro-CHP system, the electrical power output increases by 9.0 kW, the overall exergy efficiency (φ_{system}) increases by 6.1 %, and the sustainability index (SI_{system}) increases by nearly 7 %, while the exergy destruction rate $(\dot{E}x_D)$ of the boiler decreases by 5.9 %.

Finally, the results from the calculations are compared with various micro-CHP systems. However, a similar system has not been analyzed in the literature, so far. Thus, three small-scale micro-CHP were chosen. For the first type, four different organic Rankine cycles (ORC), namely, the simple ORC, the regenerative ORC with a regenerative heat exchanger, the regenerative ORC with an open feed liquid heater, and the regenerative ORC with a closed feed liquid heater, were chosen from ref. [27]. Their exergy efficiencies (φ_{system}) range from 6.77 % to 8.07 %, which is approximately 6–7 % lower than for the retrofit micro-CHP system. For the second type, a micro-CHP that has a gas-fueled internal combustion engine, a system with an electrical capacity of 5 kW_{el} and a heating capacity of 12.5 kW_{th} was chosen from ref. [23]. Its exergy efficiency (φ_{system}) was calculated as 33.8 %, which is more than twice that of the retrofit micro-CHP system. Thirdly, two ORC systems driven by geothermal and solar energy and with an electrical capacity of 50 kW_{el} were investigated in ref. [28]. According to the results, the exergy efficiencies (φ_{system}) range from 22.7 % to 25.0 %, depending on the working fluid and for the single-pressure layout. For the double-pressure layout, the exergy efficiencies (φ_{system}) range from 17.5 % to 20.0 %. Thus, the exergy efficiency of the considered system is relatively low.

5 Conclusions

A micro-CHP system based on a biomass boiler and a steam engine was investigated by using exergy, exergoeconomic and enviroeconomic analyses. A comparison of the results with other micro-CHP systems in the literature highlights that it has relatively low exergy efficiency [21–23]. This means that the considered system has improvement potential in terms of exergy efficiency. Since the lowest exergy efficiency is located at the boiler and similar results are valid for the sustainability index, further efficiency improvements shall be focused on the boiler. In this case, the boiler efficiency should be improved, and one way to improve the combustion or, as another solution, to increase the exergetic efficiency is to choose a boiler with a lower capacity. However, the comparison of the retrofit system with the ideal system highlights that the maximum exergy efficiency that can be obtained is 19.8 %. The upper limit for the electrical power output is about 20 kW_{el}. This means that the investigated system has 10 kW_{el} theoretical improvement potential in terms of power output. Under any condition, the exergy destruction rate of the boiler is higher than 225 kW.

Furthermore, the results from the SPECO analysis show that steam engine is strongly related to the operating conditions, and according to the exergoeconomic factor, the boiler is mainly affected by the capital costs. According to the ECE results, the boiler and the steam engine exhibit the highest values, respectively. Consequently, these components should be focused on for further economic improvements. For the economic improvements, the capacities of the components can be checked and they can be exchanged by more suitable ones. Another way is to decrease the exergy destructions by decreasing the irreversibilities in it, such as by increasing the combustion efficiency and increasing the effectiveness of the HRSG with condensing technology.

Therefore, if the flue gas temperature entering the HRSG can be increased, the exergy and cost efficiency as well as the electrical power output of the system increase.

Acknowledgment

E.A. appreciates the Alexander von Humboldt Foundation for a George Foster fellowship. Part of the study was conducted within the project "Steam-Based CHP – Development of a Small, Steam-Based CHP System for the Retrofit of Combustion Systems of Intermediate Power" (project ID 03KB118) funded by the Federal Ministry of Economic Affairs and Energy (BMWi) on the basis of a decision by the German Bundestag.

The authors have declared no conflict of interest.

Symbols used

a	[–]	contribution of a specific component
b	[–]	contribution of the exergy destruction of a component to the total exergy destruction
c	[€ MJ^{-1}]	unit exergy cost
C	[€ h^{-1}]	exergy cost rate
CRF	[–]	capital recovery factor
DP	[–]	depletion ratio
e	[–]	excess air
ex	[kJ kg^{-1}]	specific exergy
$\dot{E}x$	[kW]	exergy rate
f	[–]	exergoeconomic factor
i	[%]	interest rate
k	[–]	inverse of exergy efficiency
$\dot{m}$	[kg s^{-1}]	mass flow rate

n	[years]	life time of the system
N	[h $year^{-1}$]	yearly operating hours of the system
P	[kPa]	pressure
r	[–]	relative cost difference
T	[K]	temperature
w	[wt %]	water content
$\dot{W}$	[kW]	power output
y	[–]	exergy destruction ratio
z	[€]	total cost of fuel
$\dot{Z}$	[€ h^{-1}]	capital investment cost flow rate

Greek symbols

α_{CO_2}	[t_{CO2} $year^{-1}$]	released CO_2
β_{CO_2}	[$kg_{CO2}kW^{-1}h^{-1}$]	CO_2 emission value for the energy option
μ_{CO_2}	[€ a^{-1}]	cost of CO_2
Φ	[–]	operating and maintenance factor
φ	[%]	exergetic efficiency
χ	[–]	volume fraction

Subscripts

avg	average
D	destruction
F	fuel
k	k-th component
o	environmental conditions
P	product
Q	heat
sys	system
x,y,z	numbers of atoms of elements

Abbreviations

CHP	combined heat and power
ECE	exergetic cost effectiveness
HRSG	heat recovery steam generator
ORC	organic Rankine cycle
PEC	purchase equipment cost
SI	sustainability index
SPECO	specific exergy cost

References

[1] D. Büchner, A. Ortwein, E. Höftberger, V. Lenz, *Encyclopedia of Sustainability Science and Technology* (Ed: R. A. Meyers), Springer, Luxemburg **2018**.

[2] L. Dong, H. O. Liu, S. Riffat, *Appl. Therm. Eng.* **2009**, *29*, 2119–2126. DOI: https://doi.org/10.1016/j.applthermaleng.2008.12.004

[3] J. P. Bouvenot, B. Latour, M. Siroux, B. Flament, P. Stabat, D. Marchio, *Appl. Therm. Eng.* **2014**, *73*, 1041–1054. DOI: https://doi.org/10.1016/j.applthermaleng.2014.08.073

[4] M. Badami, M. Mura, *Energy* **2009**, *34*, 1315–1324. DOI: https://doi.org/10.1016/j.energy.2009.04.031

[5] G. Ferrara, G. Manfrida, A. Pescioni, *Energy* **2013**, *58*, 78–85. DOI: https://doi.org/10.1016/j.energy.2013.03.035

[6] K. Alanne, K. Saari, M. Kuosa, J. Jokisalo, A. R. Martin, *Appl. Therm. Eng.* **2012**, *44*, 11–20. DOI: https://doi.org/10.1016/j.applthermaleng.2012.03.026

[7] M. Antonelli, L. Martorano, *Appl. Energy* **2012**, *97*, 642–647. DOI: https://doi.org/10.1016/j.apenergy.2011.11.054

[8] L. G. Chen, B. Yang, Y. L. Ge, F. R. Sun, *Int. J. Low-Carbon Technol.* **2014**, *9*, 29–37. DOI: https://doi.org/10.1093/ijlct/cts031

[9] B. Yang, L. G. Chen, Y. L. Ge, F. R. Sun, *Int. J. Low-Carbon Technol.* **2014**, *9*, 262–267. DOI: https://doi.org/10.1093/ijlct/cts072

[10] L. G. Chen, G. S. Tao, F. R. Sun, *Int. J. Sustainable Energy* **2012**, *31*, 43–58. DOI: https://doi.org/10.1080/1478646X.2010.534795

[11] B. Yang, L. G. Chen, F. R. Sun, *J. Energy Inst.* **2011**, *84*, 5–12. DOI: https://doi.org/10.1179/014426010X12845670050761

[12] H. L. Feng, L. G. Chen, F. R. Sun, *Appl. Math. Model.* **2011**, *35*, 4661–4673. DOI: https://doi.org/10.1016/j.apm.2011.03.036

[13] G. S. Tao, L. G. Chen, F. R. Sun, *Rev. Mex. Fis.* **2009**, *55*, 192–200.

[14] DIN EN ISO 17225-1, *Brennstoffspezifikationen und Klassen*, Beuth-Verlag, Berlin **2014**.

[15] F. Petrakopoulou, *Ph.D. Thesis*, Berlin Technical University, Berlin **2011**.

[16] F. Kreith, *The CRC Handbook of Thermal Engineering*, CRC Press, Boca Raton, FL **2000**.

[17] H. Qian, W. Zhu, S. Fan, C. Liu, X. Lu, Z. Wang, D. Huang, W. Chen, *Energy* **2017**, *131*, 251–258. DOI: https://doi.org/10.1016/j.energy.2017.05.037

[18] M. A. Rosen, I. Dincer, M. Kanoglu, *Energy Policy* **2008**, *36*, 128–137. DOI: https://doi.org/10.1016/j.enpol.2007.09.006

[19] L. Connelly, C. P. Koshland, *Resour., Conserv. Recycl.* **1997**, *19*, 199–217. DOI: https://doi.org/10.1016/S0921-3449(96)01180-9

[20] A. Lazzaretto, G. Tsatsaronis, *Energy* **2006**, *31*, 1257–1289. DOI: https://doi.org/10.1016/j.energy.2005.03.011

[21] C. T. Yucer, A. Hepbasli, *Energy Buildings* **2013**, *62*, 343–349. DOI: https://doi.org/10.1016/j.enbuild.2013.03.005

[22] L. Galanti, A. F. Massardo, *Appl. Energy* **2011**, *88*, 4795–4802. DOI: https://doi.org/10.1016/j.apenergy.2011.06.022

[23] A. Campos-Celador, E. Pérez-Iribarren, J. M. Sala, L. A. del Portillo-Valdés, *Energy* **2012**, *45*, 228–236. DOI: https://doi.org/10.1016/j.energy.2012.01.020

[24] C. Martin, M. A. Villamanan, C. R. Chamorro, J. Otero, A. Cabanilles, J. J. Segovia, *Energy* **2006**, *31*, 330–344. DOI: https://doi.org/10.1016/j.energy.2005.01.008

[25] H. Caliskan, I. Dincer, A. Hepbasli, *Energy Buildings* **2012**, *55*, 747–756. DOI: https://doi.org/10.1016/j.enbuild.2012.03.024

[26] A. Bejan, G. Tsatsaronis, M. Moran, *Thermal Design and Optimization*, John Wiley & Sons, New York **1996**.

[27] B. F. Tchanche, G. Lambrinos, A. Frangoudakis, G. Papadakis, *Appl. Energy* **2010**, *87*, 1295–1306. DOI: https://doi.org/10.1016/j.apenergy.2009.07.011

[28] D. Tempesti, G. Manfrida, D. Fiaschi, *Appl. Energy* **2012**, *97*, 609–617. DOI: https://doi.org/10.1016/j.apenergy.2012.02.012

