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Sustainability Enhancement of a Biomass Boiler through Exergy Analysis

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Abstract: Investigations on exergy resources are important from the point of energy sustainability. In the presented study an energy and exergy analysis of the operating biomass and natural gas boilers at the University of Idaho (UI) district energy plant is conducted. Exergy flows through the components of the steam cycle associated with the biomass boiler are quantified to identify major sources of exergy destruction in the district heating system. It is found that the biomass boiler has reduced energy and exergy efficiency compared to the natural gas boilers. Thermal efficiency varies from 76 to 85%, while exergy efficiency is significantly lower at 24 to 27% for all the boilers. Exergy accounting reveals that the biomass boiler and furnace account for the greatest exergy destruction, at approximately 68% of the exergy provided by the fuel. Steam use on campus represents about 6% of exergy losses while the pressure reducer is responsible for 4%.

1. Introduction

Fossil fuels such as coal, oil, and natural gas are by far the largest sources of energy on the planet. While there is much debate on how long fossil fuels will be available in sufficient quantities, it is known that the greenhouse gas (GHG) emissions created after combustion have negative impacts on the environment and GHG concentrations have increased substantially since the pre-industrial era [1]. Research into sustainable energy generation is growing, however development is not yet at a point where fossil fuels can be replaced fully. For a system to be completely sustainable it must also be reversible, however all real processes are inherently irreversible and thus must impact the environment. Ultimately no activity can be perfectly sustainable, but it is possible to approach sustainability on a timespan that can be benefit both current and future generations [2].

District energy (DE) has been shown to be an energy efficient means of providing heating, cooling, and electricity to multiple buildings with reduced environmental impacts, such as CO_2 production, compared to more conventional systems [3,4]. Energy can be from a variety of sources such as fossil fuels, geothermal, solar, or biomass. DE systems can be more economically feasible based on the proximity to these sources and Lake, et al. have reviewed case studies investigating identification, energy sources, and design considerations of DE systems [5]. Older district energy systems commonly use low pressure steam; however newer designs produce hot and/or chilled water in a central location. This makes them ideal for scenarios such as industrial processes with excess waste heat or high population density locations where individual heating and cooling equipment can be eliminated.

Exergy accounting can provide a means to measure the potential impacts on the environment from an energy source [6]. Exergy is commonly considered to be the maximum work that can obtained from a system within a specified reference environment, or the quality of the energy source [7–9]. Unlike energy, exergy is not a conserved quantity and thus can account for inputs, losses, and wastes of a process [10]. Links between energy, exergy, and sustainable development have been made by Dincer and Rosen [6,11–14] and suggest that exergy might provide a basis for measuring the potential an energy source has of impacting the environment. Kallert et al. have investigated the advantages of using exergy methods to improve the efficiency of small scale DE networks utilizing different fuel sources [15].

The main University of Idaho (UI) campus in Moscow, Idaho, USA utilizes a DE system for heating and cooling needs. Steam requirements are met using a biomass fueled boiler, together with three supplementary natural gas boilers. Nearly all of the steam produced on campus is supplied by the biomass boiler, resulting in over $1M in saving annually compared to natural gas [16]. Boilers play a critical role in any district energy system and comprise a significant portion of U.S. energy consumption [17]. Because of this, it is important that fuel is consumed in an efficient and sustainable manner to minimize the production of greenhouse gases. Efforts to identify exergy losses commonly focus on boilers without including potential losses from the rest of the steam cycle. Methods to estimate exergy losses in steam boilers have been developed by Behbahaninia et al. to identify primary sources of exergy destruction [18]. Terhan et al. conducted a study to investigate sources of exergy losses in natural gas boilers [19]. The energy and exergy losses through the flue gas emphasize the importance of breaking down exergy flows through the entire boiler and steam network to locate losses. Da Silva et al. have identified potential improvements to reduce exergy losses in a coal fired steam generator [20]. Gürtük, et al. investigated sources of exergy destruction in a circulating fluidized bed boiler cogeneration (CHP) system [21]. They also determined that the exergy efficiency of the boiler was low when compared to other boilers in similar configurations.

In this paper a case study is developed to investigate the sustainability and boiler evolution of the district energy plant and quantify the primary exergy losses in the biomass boiler steam cycle at the main University of Idaho campus energy plant. Accounting for exergy flows and destruction rates provides a means to assess how efficient the use of a resource is and can be a measure of the potential for causing environmental harm through waste emissions [22,23].

2. Methods

To begin the exergy analysis, the reference, or "dead," state must be defined. Exergy is always evaluated with respect to a dead state since useable work requires a difference between the states of the system and the surrounding environment [24]. The reference state is often determined by the ambient weather conditions at the time of the analysis. The specific physical exergy for each flow state, which is a measure of the maximum work that can be generated from the flow while interacting with the dead state, can be expressed as

$$\psi = h_{out} - h_0 - T_0(s_{out} - s_0) + \frac{{V_{out}}^2}{2} + gz_{out} \tag{1}$$

The exergy destruction rate of a steady state system can be formulated as

$$\sum(\dot{X}_{Q_{in}} - \dot{X}_{Q_{out}}) + \sum(\dot{X}_{W_{in}} - \dot{X}_{W_{out}}) + \sum \dot{m}(\psi_{in} - \psi_{out}) - \dot{X}_{des} = \frac{dX_{sys}}{dt} \tag{2}$$

The exergy rate associated with work is defined as

$$\boldsymbol{\dot{X}_W = \dot{W}} \tag{3}$$

The exergy rate associated with heat transfer can be defined as follows, where T_b is the system boundary absolute temperature where heat is being transferred

$$\boldsymbol{\dot{X}_Q = \dot{Q}\left(1 - \frac{T_o}{T_b}\right)} \tag{4}$$

The exergy rate provided by the fuel input to the furnace can be approximated as the average higher heating value of the wood chip fuel multiplied by the mass flow rate

$$\boldsymbol{\dot{X}_{fuel} = \dot{m}_{fuel} HHV_{fuel}} \tag{5}$$

In general terms, the exergy efficiency is defined as

$$\boldsymbol{\eta_X = \frac{product\ exergy\ output}{exergy\ input}} \tag{6}$$

An exergy efficiency of 100% would represent a completely reversible, and thus sustainable process, whereas an efficiency of 0% would correspond to the opposite, since the resource is completely without anything useful being accomplished [25]. The exergy efficiency can be written as the ratio of exergy transfer between the hot and cold fluids as follows for heat exchangers such as boilers, where $\dot{m}_{cold}$ and $\dot{m}_{hot}$ are defined as the mass flow rate of feed water and flue gases in this analysis, respectively

$$\eta_X = \frac{\dot{m}_{cold}(\psi_{out} - \psi_{in})_{cold}}{\dot{m}_{hot}(\psi_{out} - \psi_{in})_{hot}} \tag{7}$$

3. Case study: University of Idaho

Originally built in 1926 with 3 lump coal fired boilers, the energy plant at the main UI campus has gone through a series of upgrades over the years, with the timeline shown below in Figure 1. The last shipment of coal arrived in 1985 and today over 95% of campus steam requirements are met using a biomass boiler, along with 3 natural gas boilers used as backups. The energy plant provides over 120 million kg of steam to campus annually for heating and cooling needs. A steam turbine is not used to produce electricity at the energy plant since the campus steam requirements are too low in the warm summer months for efficient operation. Steam pressure levels through the boilers are quite low as a result, minimizing pumping costs.

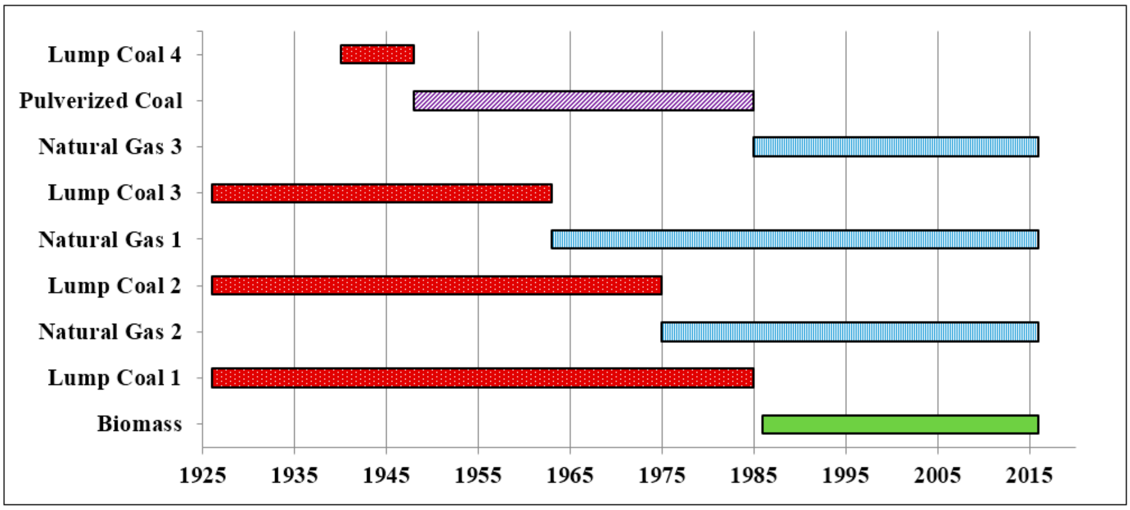

Figure 1. Timeline of boiler evolution at the UI district energy plant from 1926 to 2017.

Each one of the boilers has a different equipment configuration, shown in Table 1, with natural gas boiler 2 having no equipment installed and providing a usual baseline when considering the impacts of additional equipment. Since the biomass boiler supplies most of the steam required on campus, efforts have been made to improve its efficiency as much as possible. Additional air is added using computer controls as needed to maintain 2-6% excess oxygen levels in the exhaust.

Table 1. Additional equipment installed on individual boilers.

Component	Biomass	NG 1	NG 2	NG 3
Multi-cone cyclonic separator	X			
Economizer	X	X		
Air Pre-heater	X			X
New (<3 years) Burner Package				X

Biomass fuel comes to the UI energy plant in the form of wood chips composed primarily of western red cedar. Wood chips are sourced from the local logging industry and sizes range from

1–15cm. Higher heating values have previously been calculated experimentally and range between 20.22–20.97 MJ/kg on a bone dry basis [26]. The use of biomass at UI provides the opportunity for the logging industry in the northwest to dispose of waste from producing lumber in an environmentally responsible manner, while at the same time allowing UI to produce steam sustainably at reduced costs and minimal reliance on fossil fuels.

Figure 2 shows the schematic diagram of the steam cycle through the biomass. An economizer is used to preheat the feed water before it enters the boiler. A pressure reducer is used to reduce the steam pressure to levels more suitable for the needs in campus buildings. On an annual basis, 3% of the steam is lost in the cycle and required makeup water is introduced in the hot lime softener (HLS) tank. This allows for the water to be preheated before entering the de-aerator. Condensate from the absorption chiller and campus is returned at atmospheric pressure to the condensate tank.

On average, 0.5% of the wood chips by weight leaves the furnace as fly ash, which is removed from the flue gas in the multi-cone cyclonic separator. Heat energy in the flue gas is recovered using an air preheater. This reduces the flue gas temperature, and thus energy losses, while increasing the overall efficiency of the cycle. It is important to note that the temperature of the flue gas entering the stack can only be reduced so much however, as the increased potential for condensation forming can lead to accelerated corrosion. Under-fire air introduced in the furnace is at ambient conditions.

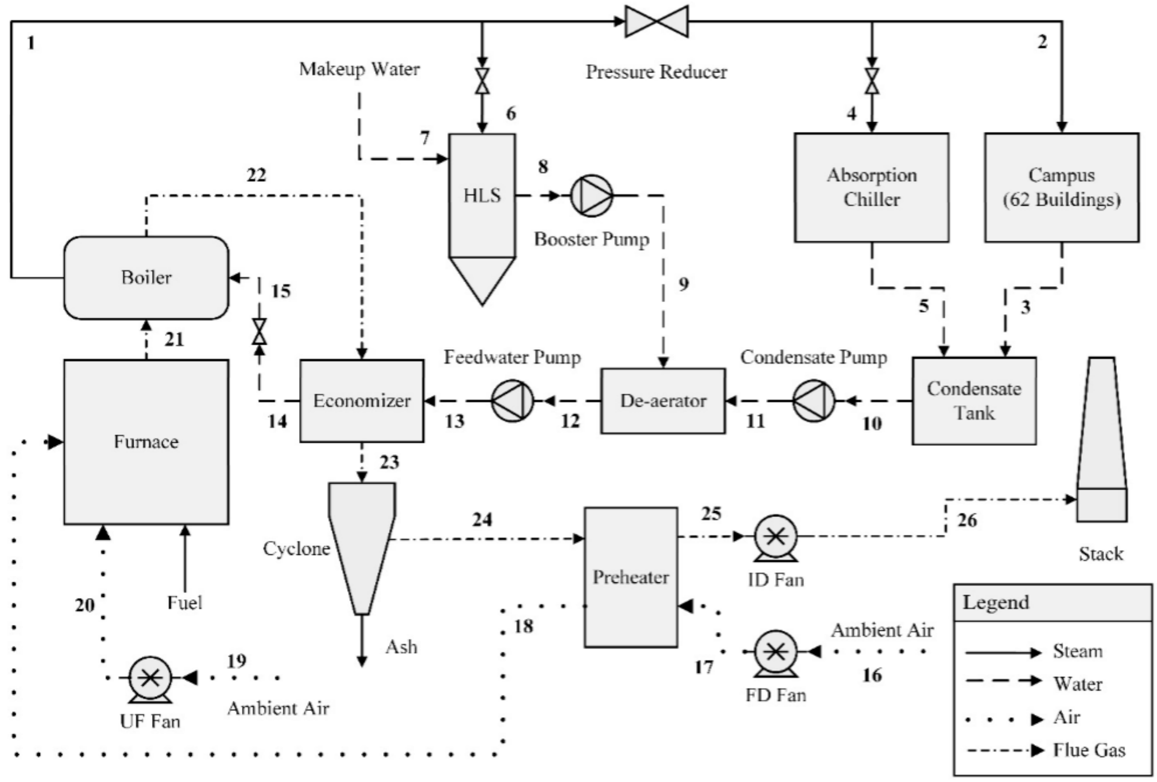

Figure 2. Flow diagram of the steam cycle including the biomass boiler.

4. Analysis

Generally, the biomass boiler operates throughout the year and is only shut down for maintenance purposes. Additional boilers are brought online as needed during peak load times in the winter. Because of this, measurement data is not available for the 3 natural gas boilers. To account for this when comparing the exergetic performance of the boilers, a baseline is created using the average thermal efficiencies of each boiler and the flow conditions presented in Table 2. Yearly steam production is known, allowing for the load requirements to be determined given a certain flow condition.

Table 2. Reference water and steam flow conditions to determine exergy efficiency of each boiler.

Point	$\dot{m}$ (kg/s)	T (K)	P (kPa)	h (kJ/kg)	s (kJ/kg-K)	ψ (kJ/kg)
Dead state	-	294.2	91.7	88.18	0.3107	-
Inlet (water)	3.878	294.2	1034	88.1	0.3107	0
Outlet (steam)	3.878	454.5	1034	2778	6.573	848

To identify sources of exergy destruction in the steam cycle through the biomass boiler, the cycle was analyzed with ambient conditions at the time of measurement of 300.4 K and 101.7 kPa. Temperatures and pressures are monitored at each major component and the thermodynamic properties of each state point have been summarized in Table 3.

Table 3. Data for flows and conditions of steam cycle when T_0 = 300.4 K, P_0 = 101.7 kPa.

Point	$\dot{m}$ (kg/s)	T (K)	P (kPa)	h (kJ/kg)	s (kJ/kg-K)	ψ (kJ/kg)
0	-	300.4	101.7	114.2	0.3982	-
1	2.949	452	977.3	2776	6.593	801.3
2	1.876	426.1	515.4	2749	6.811	709.2
3	1.819	373.2	101.7	419.5	1.308	31.99
4	0.9412	390.8	184.4	2703	7.154	559.1
5	0.9412	373.2	101.7	419.5	1.308	31.99
6	0.132	387.8	167.2	2698	7.187	544.8
7	0.05627	295.9	667.1	96.15	0.3358	0.7061
8	0.1882	385.4	223	470.8	1.443	42.71
9	0.1882	385.4	632.6	471.4	1.443	43.23
10	2.761	362.0	116.6	372.4	1.18	23.39
11	2.761	362.1	377.5	372.9	1.18	23.69
12	2.949	385.4	155.4	471.7	1.445	42.9
13	2.949	385.9	1625	474.2	1.448	44.67
14	2.949	396.5	1625	519	1.562	55.06
15	2.949	396.5	977.3	518.5	1.563	54.43
16	3.246	314.8	101.7	315.2	6.914	0.3389
17	3.246	315.3	102.1	315.7	6.914	0.7382
18	3.246	387	102.1	388.2	7.121	10.97
19	0.5127	300.4	101.7	300.7	6.867	-
20	0.5127	300.8	102.1	303.8	6.867	2.996
21	4.295	1829	101.7	2040	8.853	1143
22	4.295	486.5	101.7	489.5	7.356	41.98
23	4.295	456.5	101.7	458.8	7.291	30.84
24	4.292	456.5	101.4	458.8	7.291	30.63
25	4.292	402.7	101.4	404	7.164	14.19
26	4.292	403.2	101.7	404.5	7.164	14.54

5. Results and Discussion

Table 4 shows the energy and exergy efficiencies of each boiler, given the flow conditions from Table 3. It is expected that the energy and exergy efficiency values for the biomass boiler are lower than the natural gas boilers due to the lower heating value of the fuel, despite having equipment installed to improve efficiency.

Table 4. Efficiencies of boilers when steam temperature leaving boiler is 455 K.

Boiler	Thermal	Exergy
Biomass	76%	24%
NG 1	85%	27%
NG 2	78%	25%
NG 3	85%	27%

The efficiencies of each boiler are of some interest. Natural gas boiler 3, built in 1940, has comparable performance with the newest boiler due to the equipment upgrades introduced throughout its life. With no upgrades, natural gas boiler 2 still uses 1960s technology and has a noticeably reduced energy efficiency compared to the other natural gas boilers. The efficiency of the biomass boiler is lower, but it is utilizing a waste stream from another industry and is more environmentally friendly than the other boilers. It is this lower efficiency that leads to the need to identify the primary sources of exergy destruction.

Figure 3 shows the exergy flow rates into and out of the biomass boiler and furnace with the values obtained by multiplying the mass flow rate by the specific flow exergy found in Table 3. Substantial amounts of the incoming exergy is destroyed in the combustion and phase change processes. Some exergy in the flue gas is later recovered in the economizer and air preheater before reaching the stack and ultimately 62 kW of the exergy is exhausted to the atmosphere once leaving the exhaust stack.

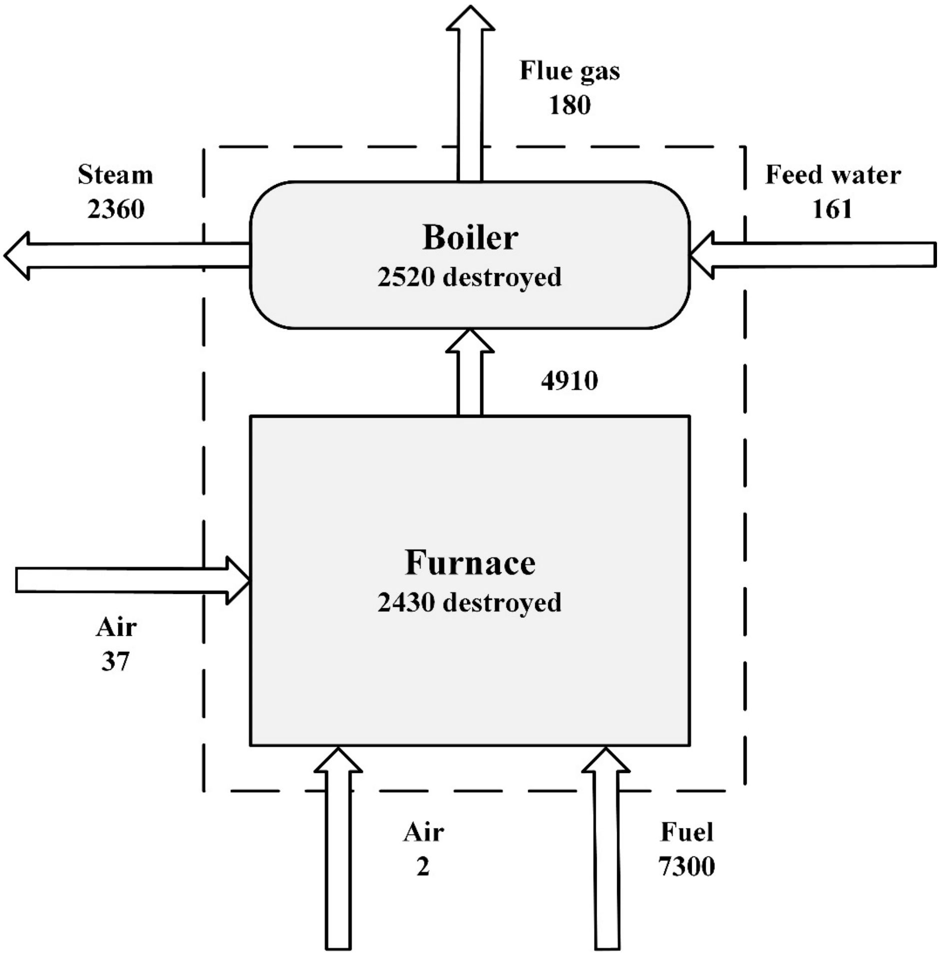

Figure 3. Exergy flow and destruction rates (in kW) for the biomass boiler and furnace.

The exergy destroyed in each component of the system, when compared to the exergy input of the individual component, can be expressed as

$$\dot{\boldsymbol{X}}_{\boldsymbol{des}}(\%) = \frac{\dot{\boldsymbol{X}}_{\boldsymbol{des}}}{\boldsymbol{exergy\ input}} \times \mathbf{100}(\%) \tag{8}$$

Figure 4 shows the percentage of exergy destruction for each component in the cycle. The boiler and furnace account for much of the exergy losses in the system. Other thermal devices such as the air preheater, campus load, and condensate tank destroy a significant portion of the exergy entering the respective component. In comparison, pumps and fans destroy very little of incoming exergy.

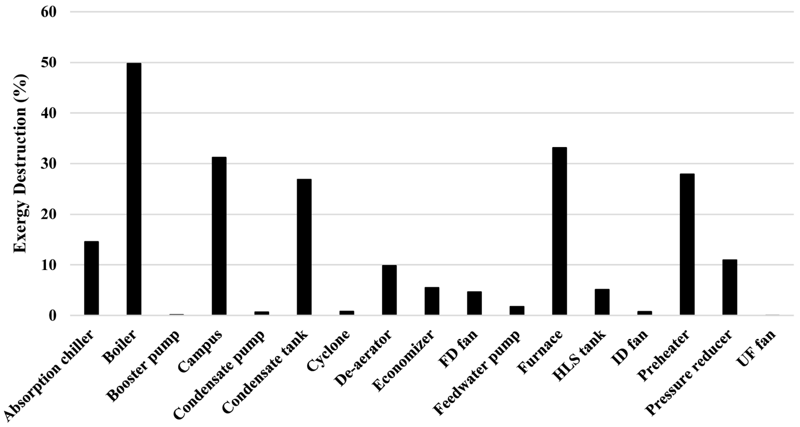

Figure 4. Percentage of incoming exergy destroyed in each component.

To help clarify which components have the largest impact on the total exergy destruction in the system, a common reference point is needed. For example, the air preheater destroys 28% of its exergy input however the total exergy through it is very low compared to components handling steam. Figure 5 below shows the exergy destruction rates in the components when compared to the exergy content of the fuel input, which can be expressed as

$$\dot{X}_{d_{fuel}}(\%) = \frac{\dot{X}_{des}}{\dot{X}_{fuel}} \times 100(\%) \tag{9}$$

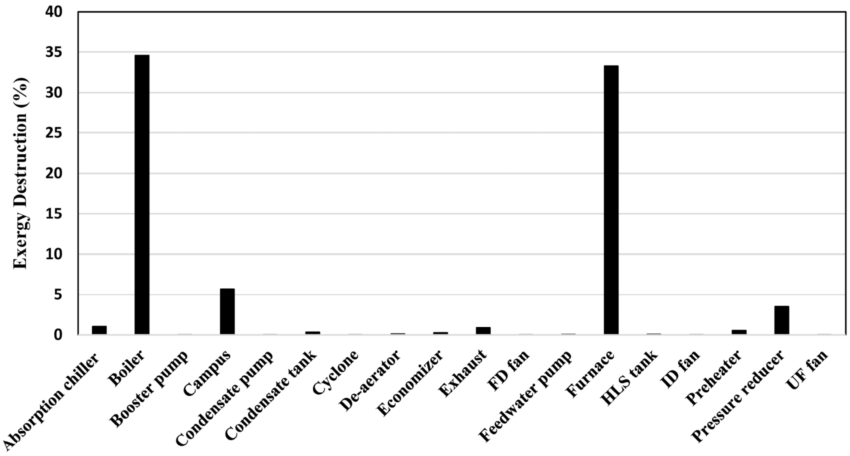

Figure 5. Percentage of exergy destroyed in each component relative to exergy input with fuel.

Many components in the cycle destroy significant amounts of flow exergy, indicating that improvements could be made. However, these flow exergies are often very small compared to the exergy input from the fuel, which is apparent in Figure 5. The largest sources of exergy destruction using Equation (9) are found in the boiler and furnace at approximately 35% and 33% of losses, respectively, followed by the heating equipment used on campus at 6% and the pressure reducer at 4%. Exergy destruction in most other components is negligible when compared to the exergy supplied by the fuel. Improvements and optimization efforts for the system are often more rational if they start at the components with the largest opportunities for improvement, to improve or maximize the potential benefits.

6. Conclusions

An investigation, based on the second law of exergy, of the boilers at the UI district energy plant has been conducted. Four different boilers, each with different configurations, are evaluated and the thermal and exergy efficiency of each is compared. Energy efficiency varies from 76 to 85%, while exergy efficiency is significantly lower at 24 to 27%. Much of the reduced exergy efficiency for both fuel types is due to the exergy destroyed during the combustion process, an unavoidable characteristic of combusting fuel. The reduced heating value of the wood chip fuel is the primary cause for the reduced efficiency when compared to natural gas, however the proximity of the fuel source still results in substantial economic savings and increases the sustainability footprint of the school thanks to reduced transportation costs. This minimizes the ancillary emissions created by regular shipments of wood chips delivered by trucks. Utilizing biomass as a fuel source is generally considered to be an environmentally friendly means to operate boilers since it does not emit net CO_2 when combusted, unlike fossil fuels. If the fuel cannot be sourced locally the transportation costs, both economically and environmentally, could be costlier than fuels such as natural gas.

The study demonstrates which components in the steam cycle would benefit from enhancement and/or optimization. The biomass boiler and furnace account for the greatest exergy destruction, at approximately 68% of the total exergy provided by the fuel. Steam use on campus represents 6% of exergy losses while the pressure reducer is responsible for 4%. Possible methods of reducing exergy losses in these components include improvements in the heating equipment on campus as well as modifying the current plant by installing a steam turbine and generator for electricity production. Since work is considered to be pure exergy, this would substantially increase the exergy efficiency of the system.

Expanding the scope of this assessment to the natural gas boilers would provide further insight into the sustainability of the energy plant and provide a comparison of biomass against fossil fuels in a similar environment. The multiple configurations for each boiler also allow for the comparison between equipment such as economizers and preheaters. An in depth investigation into the piping and heating equipment on campus would reveal where losses are occurring as well.

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Nomenclature

AF	air fuel ratio	PR	pressure reducer
boost	booster	ψ	specific exergy (kJ/kg)
Cond	condensate	PTA	percent theoretical air
CT	condensate tank	$\dot{Q}$	heat transfer rate (kW)
DA	de-aerator	s	specific entropy (kJ/kg-K)
DE	district energy	T	temperature (K)
η	efficiency	TES	thermal energy storage
econ	economizer	UF	under-fire
FD	forced draft	V	velocity (m/s)
feed	feed water	$\dot{X}$	exergy rate (kW)
g	gravitational constant	z	height (m)
GHG	greenhouse gas		
h	specific enthalpy (kJ/kg)	*Subscripts*	

HLS	hot lime softener	0	reference property
HV	heating value (kJ/kg)	act	Actual
ID	induced draft	des	destroyed
$\dot{m}$	mass flow rate (kg/s)	f	Flow
P	pressure (kPa)	X	Exergy
PH	air preheater		

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