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Article

Numerical Comparison of a Combined Hydrothermal Carbonization and Anaerobic Digestion System with Direct Combustion of Biomass for Power Production

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Abstract: Two of the methods for converting biomass to fuel are hydrothermal carbonization (HTC) and anaerobic digestion (AD). This study is aimed at designing and analyzing two scenarios for bioenergy production from undervalued biomass (sawdust). In one of the scenarios (direct combustion or DC), raw biomass is burned in a combustor to provide the heat that is required by the Rankine cycle to generate electricity. In the other scenario (HTC-AD), the raw biomass first undergoes HTC treatment. While the solid product (hydrochar) is used to produce power by a Rankine cycle, the liquid by-product undergoes an AD process. This results in fuel gas production and it can be used in a Brayton cycle to generate more power. Energy and mass balance analysis of both scenarios were developed for each unit process by using Engineering Equation Solver (EES). The required data were obtained experimentally or from the literature. The performances of the proposed systems were evaluated, and a sensitivity analysis was presented to help in finding the best operational conditions.

Keywords: hydrothermal carbonization; anaerobic digestion; bioenergy; direct combustion; power cycles; Engineering Equation Solver

1. Introduction

The rising demand for energy around the globe is leading to economic and environmental problems, as the current supply of energy is highly reliant on fossil fuels. New sources and systems of energy should be explored to reduce the dependence on scarce, expensive, and polluting fossil fuels. Biomass is accounted as one of the most abundant and available wastes, and it is a carbon carrier that can be used to produce bio-energy [1]. However, raw biomass is less attractive due to the existence of several drawbacks, such as high moisture content, low energy density, hydrophilicity, and high alkali content which makes transportation, storage, and usage of the biomass difficult [2]. Thermochemical and biochemical conversion technologies, such as torrefaction, pyrolysis, gasification, hydrothermal carbonization (HTC), and anaerobic digestion (AD) are used to tackle these barriers. Among these technologies, anaerobic digestion and hydrothermal carbonization are highly taken into account, due to their relatively lower temperatures and their ability to deal with high moisture content biomass [3].

HTC is a wet process that involves the reaction of biomass with hot (180–260 °C), pressurized (2–6 MPa) liquid water. During this process, numerous chemical reactions take place, including hydrolysis, condensation, and decarboxylation [4]. The produced char is called hydrochar to distinguish it from biochar, which is obtained from non-hydrothermal processes, such as torrefaction and pyrolysis [3]. The inputs to this system usually include raw biomass, water, and energy (heat) and

the outputs are hydrochar, a gas stream and a liquid stream (process water) [5]. AD is a collection of processes, by which microorganisms break down biodegradable material in the absence of oxygen. The main product of AD is biogas, which consists of methane, carbon dioxide, and traces of other gases [6]. In addition to biogas, digestate is a by-product of AD that consists of left-over indigestible material and dead micro-organisms. Biomass can also directly combust to produce energy. Although thermochemical processes (like HTC), and biochemical processes (like AD), are highly noticed in the recent years, direct combustion (where the raw biomass is burnt in excess air to produce heat) is perhaps the simplest way to convert biomass to bioenergy [7–9]. Hence, the proposed systems to convert biomass to bioenergy should be compared with the direct combustion.

Research on biomass conversion has been extensively conducted in the lab scale; however, there is a sensible gap regarding the practical and industrial design and environmental assessments. The integration of the biomass treating processes can not only make the whole process more energy-efficient, but it can also further reduce the waste considerably based on the circular economy [4]. Reza et al. [10] used the digestate from an AD process operating at thermophilic conditions (50–60 °C) as a feed for HTC. The energy recovery of this combination was 20% higher than energy recovery from HTC and 60% higher than the one for AD. The AD-HTC process that was proposed by Reza et al. [10] can be reversed to HTC-AD [11], such that the biomass is firstly fed to the HTC process, where its alkali content dissolves in the process water (PW) and it can produce hydrochar with lower ash content that is more suitable for boilers [12]. It is worthy to mention that proper process condition should be considered to ensure that the ash content will reduce in HTC; otherwise, there is a possibility of increase in ash content in some cases [13]. In addition to the use of hydrochar for power generation, the process water can enter an existing AD system. The pH of the PW is in the range of 2.7–3.5 [14,15] and, hence, it can accelerate the hydrolysis step in AD. Ease of conversion in the AD system is expected, as hydrolysis is considered to be the limiting factor of AD systems [16].

This study is aimed at introducing two different scenarios for bioenergy production while using direct combustion for one scenario and a combination of hydrothermal carbonization and anaerobic digestion for the other one. Both scenarios integrate the power cycles and the biomass conversion processes with heat recovery and internal energy supply. The required data for HTC were obtained from lab-scale experiments. These data include hydrochar's mass yield, heating value, and elemental composition. Engineering Equation Solver (EES) developed the governing thermodynamic equations of the systems. The main goals of this study are to develop and perform numerical analysis on an integrated HTC-AD scenario for converting biomass to energy, and compare the performance of electricity production by the proposed method with direct combustion of the raw biomass.

2. Materials and Methods

Both systems that were analyzed in this study can work with a variety of biomass. For this study, sawdust has been considered as the feedstock, which is tiny pieces of wood that fall as powder from wood as it is cut by a saw [17]. Sawdust is one of the most abundant biomass sources, with more than five-million tonnes of sawdust surplus were available in Canada alone in 2004 [18].

Some of the main primary datasets were obtained by performing lab-scale experiments. The HTC experiments were conducted while using a Parr 600 mL series 4560 mini reactor (Parr Instrument Company, Moline, IL, USA) and approximately 20 g of sawdust was used for each experiment. For HTC, dry biomass to water mass ratio of 1:5 was used. After stirring the sawdust and water mixture in the reactor, it was sealed and pressurized by nitrogen gas to ensure that the pressure inside the reactor is always above saturation pressure of water. The reactor was then heated up to 220 °C and kept at this temperature for 40 min. The reactor was then immediately submerged into ice water until the temperature decreased to below 30 °C. The liquid–hydrochar mixture was removed from the reactor and then separated while using filter paper. The solid sample was placed inside a tin crucible and then left in a furnace overnight at 105 °C to dry.

A higher heating value (HHV) test was performed on the raw feed and solid products of HTC while using the IKA bomb calorimeter (IKAWorks, Wilmington, NC, USA). Moreover, the proximate analysis and ultimate analysis were performed on the obtained hydrochar and the raw sample. More details on the procedure of these characterization tests and the composition of the products can be found in Ref. [15].

In the HTC-AD scenario, HTC was scaled up and combined with Rankine, and Brayton cycles and anaerobic digestion process. Figure 1 shows the schematic of scenario 1. As is shown in Figure 1, biomass is mixed with hot pressurized water. It is worth mentioning that, unlike the lab-scale experiments, the HTC reactor is not pressurized with nitrogen gas, but is instead pressurized with the water that enters the reactor while using a high-pressure pump. Moreover, the required heat for HTC is provided by a heat exchanger that recovers the heat from the Rankine and Brayton cycles. The main product of HTC is wet hydrochar that is utilized in a Rankine cycle after getting dried in the drier. Table 1 is a stream table to help understand the conditions of each stream in the HTC-AD scenario. The liquid by-product of the HTC exchanges its heat with the water stream entering the HTC reactor and then enters into the AD system. A gas stream enriched in methane and hydrogen that enters the Brayton cycle to produce more power is the main output of this AD system. The gas turbine's exhaust is at high temperature [19,20]; hence, before releasing this hot stream to the atmosphere, its heat is transferred to the HTC reactor. If the gas turbine's exhaust heat is insufficient for the HTC process, excess heat is supplied from the lower stages of the steam turbine of the Rankine cycle. The power that is generated by the steam turbine is used wherever electricity was required (for the pumps and the compressor).
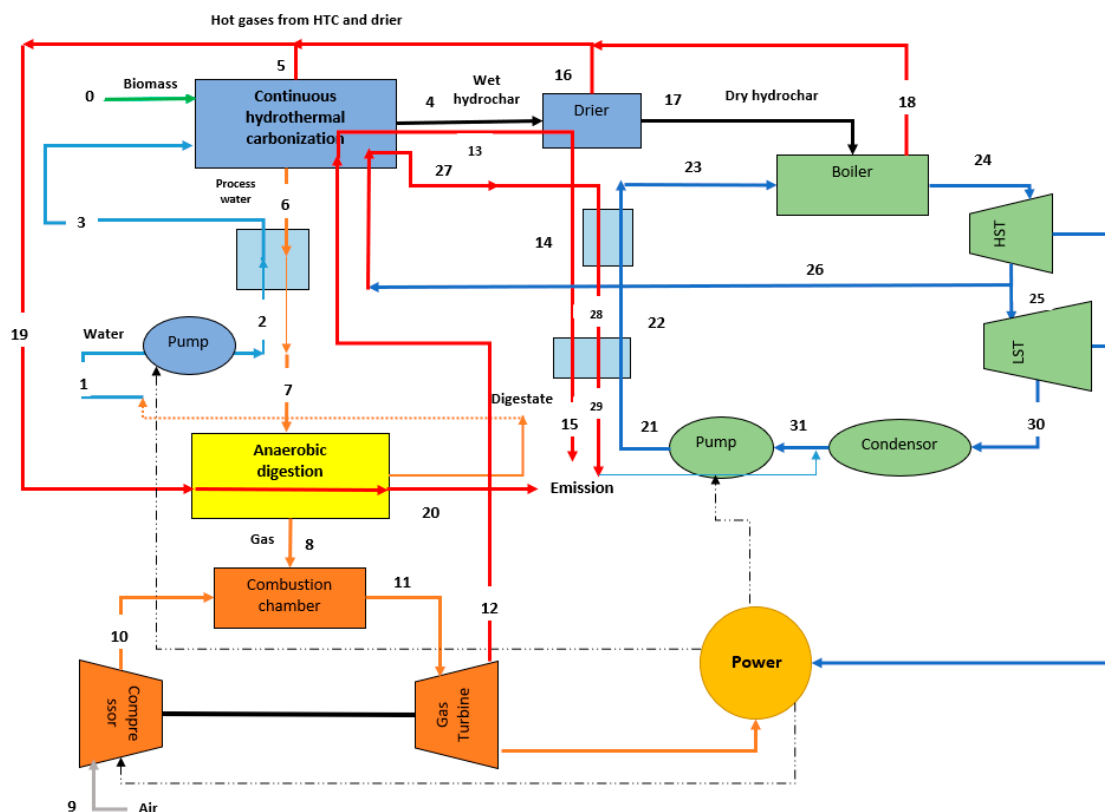

Figure 1. Schematic of the hydrothermal carbonization-anaerobic digestion (HTC-AD) scenario.

Table 1. Stream table of the hydrothermal carbonization-anaerobic digestion (HTC-AD) scenario.

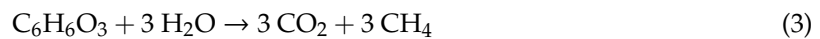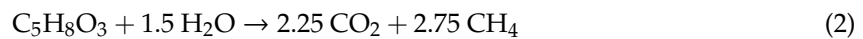| State Number	Temperature (°C)	Mass Flow Rate (g/s)	Other Properties
0	25	16	10% moisture content
1	25	75	$p = 101$ kPa
2	50	75	$p = 1800$ kPa
3	176.6	75	$p = 1800$ kPa
4	95	10.06	Contains 0.7 g/s of water
5	120	0.43	Gaseous mixture (mainly CO_2)
6	180	74.3	Including 4.6 g/s mass yield from biomass flow
7	60	74.3	Mixture of water and acidic components
8	60	5.56	Including 1.54 g CH4, and the rest is CO2
9	25	8.38	$p = 101$ kPa
10	473	8.38	$p = 1717$ kPa
11	1200	13.94	$p = 1717$ kPa
12	350	13.94	Gaseous outlet of GT
13	230	13.94	Gas
14	132.8	13.94	Gas
15	50.53	13.94	Gas emission
16	120	0.7	Steam
17	50	9.36	HHV = 24,600 [kJ/kg]
18	120	86.92	Gaseous mixture (mainly $CO_{2)}$
19	120	88.05	Gaseous mixtures to sustain AD process
20	25	88.05	Gas emission
21	40.53	72.92	$p = 1800$ kPa
22	45	72.92	Rankine process water
23	48	72.92	Rankine process water
24	540	72.92	Superheat steam
25	280	70.4	$p = 850$ kPa
26	280	2.52	$p = 850$ kPa
27	230	2.52	Steam to heat up HTC
28	54.97	2.52	Hot water
29	50.53	2.52	Hot water
30	40	70.4	Saturated steam
31	40	70.4	Saturated water

As shown in Figure 2, the biomass is introduced to the drier as the first processing step in this scenario (direct combustion (DC)). Afterward, the dried biomass is utilized in a boiler to convert a water stream to steam, which can then produce the power after expansion in the turbine. Table 2 reports the stream table of the DC scenario.

Figure 2. Schematic of the second direct combustion (DC) scenario.

Table 2. Stream table of the direct combustion (DC) scenario.

State Number	Temperature (°C)	Mass Flow Rate (g/s)	Other Properties
0	25	16	10% moisture content
1	50	14.40	HHV = 17,800 [kJ/kg]
2	110	1.60	Steam
3	50	4.38	Water back to the cycle
4	110	141.55	Gaseous mixture (mainly CO_2)
5	50	141.55	Gas emission
6	40.53	82.80	p = 1800 kPa
7	66.14	82.80	Rankine process water
8	540	82.80	Superheat steam
9	160	80.02	Entering superheat steam to low pressure GT
10	40	80.02	Saturated steam
11	40	82.80	Saturated water
12	110	2.78	Steam to help with drying

Several assumptions, such as the operational conditions of each equipment section, should be considered, as both systems incorporate several types of equipment. Moreover, some of the data was not obtained via experiments. Hence, this section clarifies the assumptions and data obtained from the literature.

It was assumed that HTC is scaled up to a continuous reactor and the flow rate of the biomass to this reactor is 0.016 kg/s. The same mass flow rate was considered for the DC scenario. The initial moisture content of the biomass was 10% and a 1:5 dry biomass to water weight ratio was considered for HTC.

The process water from HTC is acidic and it contains water, acetic acid, and a number of other organic acids [15]. According to Kambo et al. [14], these organic acids mainly contain acetic acid, 5-Hydroxyl Methyl Furfural (HMF), and levulinic acid. Table 3 reports the composition of the process water that was considered in this study. It is worthwhile to note that a more accurate and detailed research study on HTC should consider the presence of other organic compounds, such as glycolic acid or formic acid. In this research due to the high number of equations only three of the components were considered.

Table 3. Composition of the bio-oil from HTC.

Name	Chemical Formula	Weight%
Acetic acid	CH3COOH	40
HMF	C5H8O3	40
levulinic acid	C6H6O3	20

The chemical reactions of these acids in AD were considered based on Buswell and Muller [21] and they are as follows:

$$CH_3COOH \rightarrow CO_2 + CH_4 \tag{1}$$

$$C_5H_8O_3 + 1.5\,H_2O \rightarrow 2.25\,CO_2 + 2.75\,CH_4 \tag{2}$$

$$C_6H_6O_3 + 3\,H_2O \rightarrow 3\,CO_2 + 3\,CH_4 \tag{3}$$

It should be noted that the presence of other elements, such as nitrogen (in other feedstocks such as algae), would result in nitrogen compunds in the bio-oil and bio-gas. Hence, the Equations (1)–(3) should be updated for other feedstocks. Moreover, the addition of materials that help to buffer pH changes and regulate the pH might be required, as the pH of the organic materials entering the AD is around 3, and most of the commercial AD systems work in a pH range of 6.7–7.8 [22].

The composition of the gas stream exiting the HTC reactor was considered to be all carbon dioxide due to its high abundance relative to other process gases, as discussed by Yan et al. [23]. The combustion of the biomass and hydrochar in the boilers, as well as the combustion of the obtained gases from AD in the combustion chamber, was considered with 150% of excess air.

It was assumed that the system operates at steady-state and steady flow conditions. Moreover, the HTC temperature was 220 °C, the AD system operates at 35 °C, the PW leaves the HTC reactor at 180 °C, the air consists of 79% nitrogen, and 21% oxygen and the air, biogas, and combustion products are considered as ideal gases. Regarding the temperature of the PW, it should be noted that this temperature is highly dependent on the design of a continuous HTC system that can discharge the process water at that temperature. Given that, to date, there is no clear report regarding such a reactor, a sensitivity analysis will be performed to investigate the effects of lower temperatures of PW. The efficiencies for all exchangers, turbines, and compressors were considered as 80%, whereas the efficiency was assumed as 70% for the pumps [24]. A temperature approach of 10 °C was considered for all heat exchangers. Moreover, the design is such that the boiler and the gas turbine exhaust supply the required heats for the drier and the HTC reactor, respectively. The compressor and pumps use a portion of the produced power. Table 4 reports other assumptions considered in the EES codes of the scenarios.

Table 4. Other assumptions of the integrated scenarios.

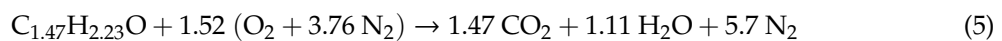|			
Heat capacity of the biomass (kJ/kg.K)	1.5	Ambient temperature (°C)	25
Heat capacity of water at room temperature (kJ/kg.K)	4.18	Ambient pressure (kPa)	101
The heat of vaporization of water (kJ/kg)	2260	Maximum combustor temperature (°C)	900
Compressor exit pressure (kPa)	1717	Compressor compression ratio	17
Methane heating value (MJ/kg)	55.51	The temperature of PW leaving HTC reactor (°C)	180
Flue gas temperature (°C) [25]	150	Exothermic heat of reaction in HTC (kJ/kg) [26]	765
ST inlet temp. (°C)	530	GT exhaust temp. (°C) [27]	350

3. Results

3.1. Experimental Results

Table 5 reports the experimental results from characterization tests on the raw biomass and hydrochar obtained from HTC at 220 °C for 40 min.

Table 5. Experimental results from characterization on the biomass and hydrochar.

Sample Name	Yields (%)			Ultimate Analysis (wt%)					Proximate Analysis (wt%)			Calorimetry
	Solid	Liquid	Gas	C	H	N	S	O	Ash	FC	VM	HHV (MJ/kg)
Raw	-	-	-	49.22	6.10	0.01	0	44.57	0.10	17.80	82.10	17.8
Hydrochar	65	32	3	63.51	5.33	0.02	0	31.12	0.02	31.24	68.74	24.6

The empirical formula of the raw biomass and the hydrochar can be obtained as $C_{1.47}H_{2.23}O$ and $C_{2.72}H_{2.74}O$, respectively, based on the ultimate analysis that is reported in Table 5, and the molar number of the elements. These formulas were then used in the combustion equations in the boilers.

$$C_{2.72}H_{2.74}O + 2.9\,(O_2 + 3.76\,N_2) \rightarrow 2.72\,CO_2 + 1.37\,H_2O + 10.9\,N_2 \tag{4}$$

$$C_{1.47}H_{2.23}O + 1.52\,(O_2 + 3.76\,N_2) \rightarrow 1.47\,CO_2 + 1.11\,H_2O + 5.7\,N_2 \tag{5}$$

It should be noted that the ash content is an important element to consider when it comes to energy production from biomass. The ash content of the feedstock in this study was negligible (0.1%), but this may not be the case for other feedstocks. For instance, according to Phyllis database [28], the sawdust of different woods may contain up to 2% of ash content. In such situtations, more treatments, like de-ashing before the combustion or utilizing specific boilers that can handle the ash content of the feedstock, should be considered.

3.2. Modeling Results

The preliminary results of the scenarios that are given in Table 6 are based on the assumptions and the calculations discussed above. As can be seen in Table 6, the direct combustion of biomass with 10% moisture content shows a better relative performance. The total power that is produced by the DC scenario is 101 kW, which is 5.21 kW higher than the HTC-AD scenario. In addition, the efficiency of the DC scenario is around 2% higher than that of the HTC-AD scenario.

Table 6. Composition of the bio-oil from HTC.

| Item	HTC-AD Scenario	DC Scenario
Biomass flow rate (g/s)	16	16
Total produced power (kW)	95.79	101
Efficiency (%)	37.37	39.40
Power by the steam turbine (kW)	90.03	103.10
Power by the gas turbine (kW)	11.74	-
Net power consumed by the HTC reactor (kW) (supplied from the boiler and GT exhaust)	6.90	-
The power produced by exothermic reactions (kW)	11.02	-
Net energy consumed by the drier (kW) (supplied from the boiler)	1.59	5.92

It is worth reminding the reader here that these results do not consider the complexities of the integration in the HTC-AD scenario and the possible problems with slagging and fouling in the DC scenario due to the direct use of biomass without treatments. Moreover, it should be noted that the assumptions considered in obtaining the results that are reported in Table 5 had significant effects on the results. Out of the many assumptions listed above, the uncertainty that is associated with some parameters warrants further investigation. Hence, in the following sections, the effects of moisture content, HHV, and water in the HTC process on the total produced powers and efficiencies of both scenarios are investigated.

3.3. Sensitivity Analysis

3.3.1. Biomass Moisture Content

The moisture content of the biomass is one of the key parameters for selecting a technology that deals with biomass to bioenergy conversion. Figure 3a,b show the effects of this parameter on both of the scenarios.
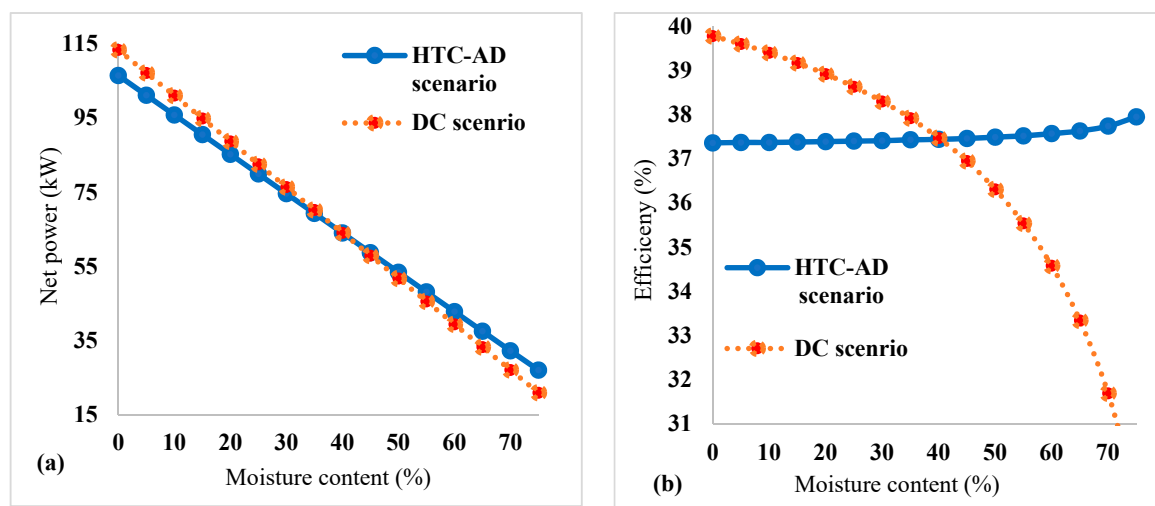
Figure 3. Effects of biomass moisture content on (**a**) net power, and (**b**) efficiency of each scenario.

Increasing the moisture content of the biomass feedstock decreased the total power that was produced by both scenarios. With an increase in the moisture content from 0 to 70%, the power that was produced from the HTC-AD scenario dropped from 106.4 kW to 32.24 kW, while, for the DC scenario, it was from 113.30 kW to 27.08 kW. Regarding efficiency, the DC scenario shows a considerable decrease in the overall efficiency with an increase in the moisture content. However, for the HTC-AD scenario, the efficiency showed a slight increase with an increase in the moisture content. This interesting result shows that the main advantage of processes that use HTC for treating the biomass is when the moisture content is higher. The processes that involve an initial stage of drying exhibit a reduction in efficiency due to higher amounts of moisture, which is energy intensive to remove. The power consumption of the drier in the DC scenario increases from 5.91 kW to 22.39 kW, when the moisture increases from 10% to 50%. As shown in Figure 3, the HTC-AD scenario shows a better performance than the DC one when the moisture content of the biomass is over 40%.

3.3.2. HHV of the Raw Biomass and Obtained Hydrochar

Higher heating value (HHV) is one of the critical properties when it comes to the design and calculations of thermal conversion systems for biomass. HHV can be considered to be a specific property of each biomass, as its value is different from one biomass to another. The HHV of the hydrochar not only depends on the severity of the HTC process, but it is also highly dependent on the fiber structure and chemical composition of the biomass [29]. Figure 4a,b show the effects of changes in the HHV of the raw biomass in the net power and efficiency, respectively. It is assumed that HHV of the hydrochar in the HTC-AD scenario is 6.8 MJ/kg higher than the corresponding HHV of the biomass-based on the results of the experiments (Table 5). It should also be noted that the moisture content is as its initial assumption (i.e., 10%).
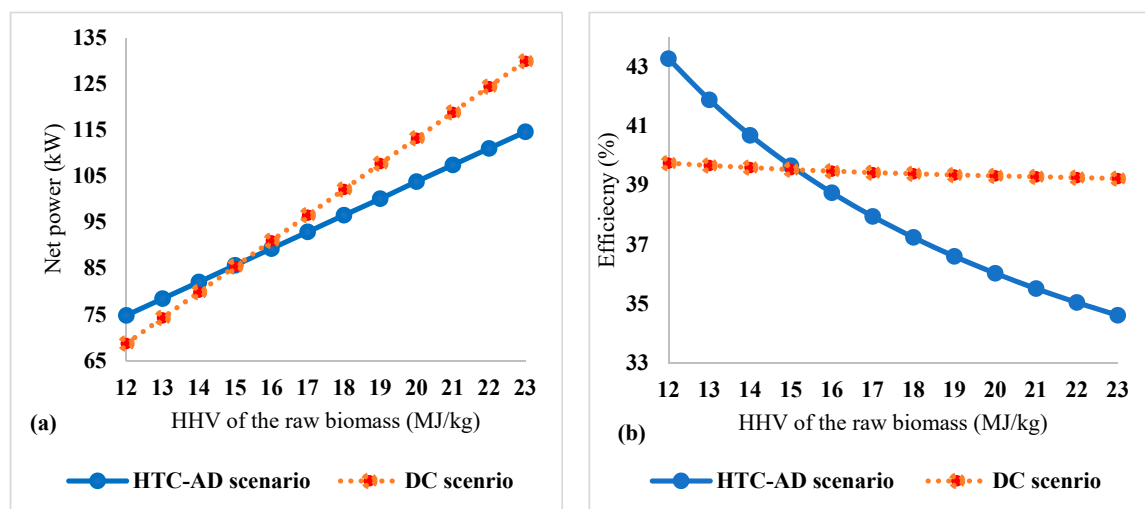
Figure 4. Effects of biomass higher heating value (HHV) on (**a**) net power and (**b**) efficiency of each scenario.

Figure 4a illustrates that, with an increase in the HHV of the biomass from 12 to 23 MJ/kg, the net power that was produced by both scenarios increases. With HHVs lower than 15.5 MJ/kg, the DC scenario produces less power and it has lower efficiency. This can be an indication that direct combustion can be a better option when the heating content of the biomass in its raw form is relatively high. For instance, when the lignin content of the biomass is higher [29].

3.3.3. Water: Biomass Ratio and the Temperature and Composition of Process Water from HTC

The main feature of HTC that makes it different from other thermochemical processes is it being performed under a water medium. All of the biomass particles in the HTC should be in contact with water; however, it is clear that the more water is used, the more energy is required for the process. Hence, the water to biomass ratio is one of the key parameters for the design of an HTC reactor. Figure 5 indicates the effect of water on biomass ratio on the performance of the HTC-AD scenario. As expected, the net power output and efficiency decrease with an increase in the water to biomass ratio. Therefore, it is suggested that the use of water should be minimized after it is ensured that the biomass is fully submerged in the water.
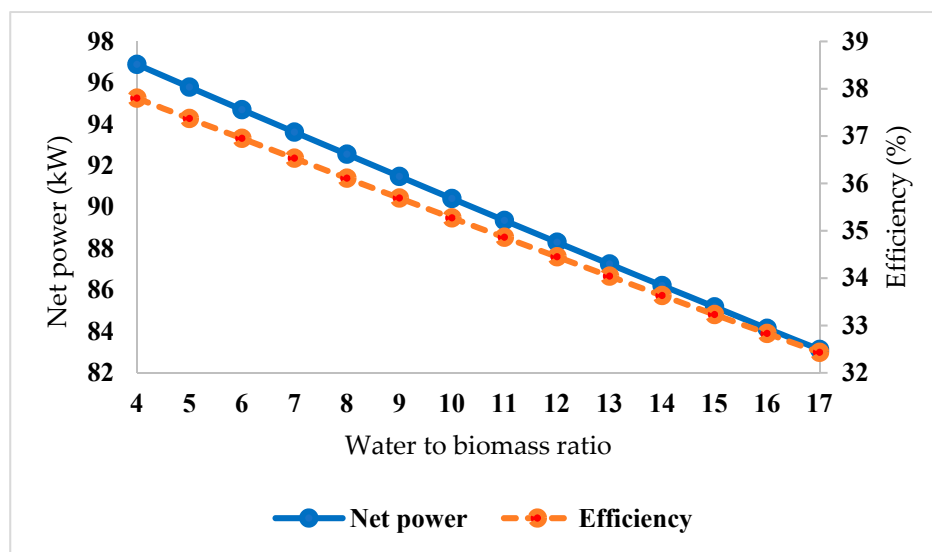
Figure 5. Effects water to biomass ratio on the performance of the HTC-AD scenario.

The other issue that can affect the HTC-AD scenario is the composition of the process of water entering the AD process. This is highly dependent on the type of biomass and HTC process condition. Figure 6 compares the performance of the HTC-AD scenario while considering that 100% of the obtained organic acids are one of the acetic acid, HMF, or levulinic acid. Figure 6 shows that the performance of the bioenergy systems improves if the composition of the PW contains more HMF or levulinic acid. The assumptions of 100% of these components are only from a statistical point of view to show the effects of each of the components clearly and cannot happen in real situation.
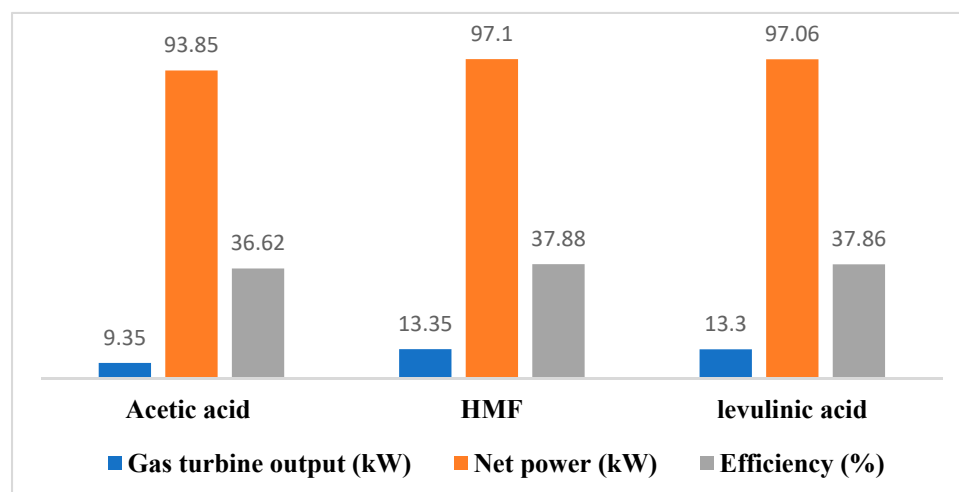
Figure 6. Effect of PW composition on the performance of the HTC-AD scenario.

In addition to the parameters that are discussed above, the PW temperature of the HTC process can play an important role in the reduction of energy usage by the HTC reactor and, consequently, the whole process. Figure 7 indicates the energy that was consumed by the HTC reactor, as well as the output power and efficiency of the HTC-AD scenario while varying the temperature of the PW.
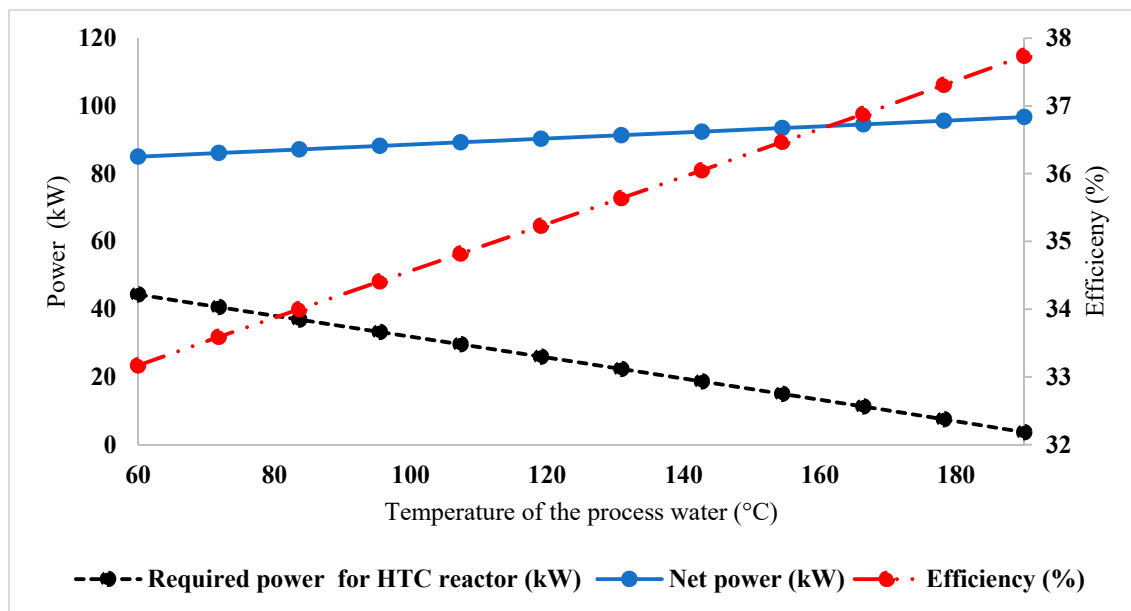
Figure 7. Effect of temperature of PW on the performance of the HTC reactor and overall scenario.

While considering a temperature of 220 °C for the HTC process, the ability of the reactor to discharge the process water to the heat exchanger in as high temperature as possible is crucial. The efficiency of the system can increase by around 5% with an increase in the temperature of the discharged PW from 40 °C–190 °C. This again shows the importance of designing reactors that can recover the heat.

4. Discussion

This paper investigated two possible scenarios for producing power from biomass. The HTC-AD scenario integrated HTC and AD with power cycles, whereas the DC scenario only utilizes integrated direct combustion of the biomass with the Rankine cycle. It was shown that a 16 g/s sawdust biomass stream with 10% moisture content can produce 95.79 kW power for the HTC-AD scenario, whereas the DC scenario can produce 101 kW. While considering the complexity and potential capital costs of the HTC-AD scenario, the direct use of the biomass might seem like a better option for sawdust. However, it was shown that an increase in moisture content makes the HTC-AD scenario superior in terms of efficiency and produced power. In an integrated system, several parameters can have significant impact on the objective parameters of the system. For instance, it was shown that the benefits of the HTC-AD scenario are more sensible when the initial HHV of the biomass is lower, water to biomass ratio is lower, the type of the biomass generates acids, like HMF in its liquid yield, and there is heat recovery from the HTC unit. Further environmental and economic investigations are required to complete this study.

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