Prospects for energy recovery during hydrothermal and biological processing of waste biomass

Léda Gerber Van Doren^{*†a,b,c}, *Roy Posmanik*^{† b,c}, *Felipe A. Bicalho*^{b,c,d}, *Jefferson W. Tester*^{b,c}, *Deborah L. Sills*^{b,c,d}

a) College of Agriculture, Forestry & Natural Resource Management, University of Hawai'i Hilo

b) Cornell Energy Institute, Cornell University

c) Department of Chemical and Biomolecular Engineering, Cornell University

d) Department of Civil and Environmental Engineering, Bucknell University

†: Léda Gerber Van Doren and Roy Posmanik contributed equally to this manuscript.

*Corresponding Author:

Dr. Léda Gerber Van Doren, Email: leda.gerber@gmail.com; Phone: 607-255-2773

ABSTRACT

Thermochemical and biological processes represent promising technologies for converting wet biomasses, such as animal manure, organic waste, or algae, to energy. To convert biomass to energy and bio-chemicals in an economical manner, internal energy recovery should be maximized to reduce the use of external heat and power. In this study, two conversion pathways that couple hydrothermal liquefaction with anaerobic digestion or catalytic hydrothermal gasification were compared. Each of these platforms is followed by two alternative processes for gas utilization: 1) combined heat and power; and 2) combustion in a boiler. Pinch analysis was applied to integrate thermal streams among unit processes and improve the overall system efficiency. A techno-economic analysis was conducted to compare the feasibility of the four modeled scenarios under different market conditions. Our results show that a systems approach designed to recover internal heat and power can reduce external energy demands and increase the overall process sustainability.

KEYWORDS

Biomass Conversion, Thermochemical Processes, Anaerobic Digestion, Pinch Analysis, Techno-economic Analysis

ABBREVIATIONS

AD, Anaerobic Digestion; CHG, Catalytic Hydrothermal Gasification; CHP, Combined Heat and Power; DM, Dry Matter; HTG, Hydrothermal gasification; HTL, Hydrothermal liquefaction; TEA, Techno-Economic Analysis

1. INTRODUCTION

Biomass, currently the world's largest source of renewable energy, makes up more than 10% of global energy supply (Bridgwater, 2006; IEA, 2016). Biomass can be converted to energy products *via* biological or thermochemical processes, generating a variety of end-products including biogas, bio-oil or syngas. These products can be used as fuels, for electricity generation and transportation, as well as sources of heat. In addition to dedicated lignocellulosic biomass feedstocks such as wood and energy crops (Bridgwater, 2006; Hoogwijk et al., 2003), alternative feedstocks, such as municipal solid waste, food waste, manure and algae, represent resources for bioenergy production (Curry and Pillay, 2012; Delrue et al., 2012; Macias-Corral et al., 2008; Sills et al., 2012; Vardon et al., 2011).

Many of these biomass feedstocks contain large amounts of water. Among thermochemical processes for biomass feedstocks with high water contents, hydrothermal processing is an attractive process and is a research subject of high interest (Elliott et al., 2009, 2015; Jones et al., 2014; Luterbacher et al., 2009). Hydrothermal processes include liquefaction and gasification in a water-rich media occurring over a range of temperature and pressure conditions (Sinaĝ et al., 2012). One advantage of hydrothermal processes is that they produce valuable and energy-dense products while enabling efficient energy integration and lowering the enthalpic penalty associated with the vaporization of water at lower pressure (Peterson et al., 2008). In addition, carrying out thermal processes in aqueous media leads to less selective, faster, and more complete conversion of biomass than can be achieved by biological processes. Typical hydrothermal liquefaction (HTL) conditions range from 280 to 380°C, 70 to 300 bar for 10 to 60 min. HTL converts a wide

variety of biomass feedstocks into a refinable bio-crude oil that is suitable for upgrading along with conventional liquid fuels (Peterson et al., 2008), as well as an aqueous phase.

The aqueous phase produced by HTL accounts for a significant fraction of the organic carbon, typically between 10–40% depending on the process conditions (Tommaso et al., 2015) and the lipid content of the feedstock (Leow et al., 2015). Valorizing the HTL-aqueous phase through an additional process may improve the overall economic feasibility of the HTL process (Marcilla et al., 2013). Anaerobic digestion (AD), a candidate technology, can be integrated with HTL to valorize the residual carbon. AD involves the microbial degradation of organic materials under anaerobic conditions and results in the formation of biogas, a mixture of methane and carbon dioxide. Based on toxicity and biodegradability of the post-HTL aqueous phase for algae biomass, Tommaso et al. (2015) suggest that AD could be used to convert the aqueous phase produced by HTL into biogas. Catalytic hydrothermal gasification (CHG), a second candidate technology, can also be integrated with HTL to convert residual carbon to high energy methane gas (Elliott et al., 2015). CHG (also termed as low-temperature gasification), operated at ~350°C and 21MPa with a metal catalyst, produces a methane-carbon dioxide gas product (Elliott et al., 2006). The gas produced from AD or CHG may be used to generate heat and electricity, with combined heat and power (CHP) systems (Luterbacher et al., 2009; Steubing et al., 2012) or heat only with a boiler. These complementary processes may therefore eliminate some of the energy inputs required for HTL and therefore may be applied in the future, especially for full-scale biorefineries, where AD and CHP units already exist.

HTL also generates a significant amount of heat. Most of it can be recovered through heat integration. Pinch analysis, an established method used to optimize heat

integration between high and low temperature streams, can help identify the benefits and drawbacks of alternative process configurations from an energy efficiency perspective (Kemp, 2006; Maréchal and Kalitventzeff, 1998). Although pinch analysis has been widely applied in the field of thermochemical processes for biomass conversion (Gassner and Maréchal, 2009; Gerber et al., 2011; Luterbacher et al., 2009; Tock et al., 2010), it has only been applied in few studies within the fields of biological processes. Fernández-Polanco and Tatsumi (2016) used pinch analysis to study the energy integration between thermal pretreatment and AD to minimize the external heat and electricity requirements for the overall system. Hofmann et al. (2013) simulated process integration between AD and HTL in a configuration that treats the digestate from AD using HTL. Although they included an upgrading unit to the bio-crude oil, Hofmann et al. (2013) did not include any post treatment for the HTL aqueous phase. Moreover, these authors recognized the high potential for heat integration and recommended the application of pinch analysis in future studies. Furthermore, numerous authors have advised that heat integration applied to HTL conversion processes for wet biomasses is critical for scale up and economic analysis (Chen et al., 2016; Hadhoum et al., 2016). To the best of our knowledge, none of the published literature (Chen et al., 2016; Elliott et al., 2015; Fernández-Polanco and Tatsumi, 2016; Hadhoum et al., 2016; Hoffmann et al., 2013; Tommaso et al., 2015) currently includes heat integration between HTL and subsequent processes that valorize the aqueous phase.

The objective of this study is to conduct energy integration for HTL of a model wet biomass feedstock followed by AD or CHG to produce methane gas to be combusted in a co-generation engine (to generate electricity & heat) or in a boiler (to generate heat). A techno-economic analysis (TEA) was applied to analyze the economic tradeoffs among

alternative process configurations. Accounting for thermodynamics and economics in a systems modeling framework can improve the conceptual design of emerging biomass to energy processes.

2. MATERIAL AND METHODS

2.1. Scenarios

Microalgae was modeled as a representative feedstock for conversion of wet biomass to energy products using HTL. Two processes that valorize the HTL aqueous phase were simulated: AD, a low temperature and relatively slow process, and CHG, a high temperature and relatively fast process. In addition, since both processes generate gas products, biogas for AD and syngas for CHG, utilization of the produced gas using either a co-generation engine for CHP production or combustion in a boiler for heat production were compared. Consequently, the scenarios modeled here were: 1) HTL + AD + CHP; 2) HTL + AD + Boiler; 3) HTL + CHG + CHP; and 4) HTL + CHG + Boiler (Fig. 1). As the produced heat or electricity may not be sufficient to heat and power the modeled processes, the import of grid electricity or of natural gas to supply additional requirements were also accounted for.

2.2. Modeling approach

The four potential process configurations were designed and evaluated using the modeling approach described in Fig. 2. First, all processes were modeled and simulated using a flow sheet modeling software. Then, these simulation results were used as inputs to perform the energy integration of the process systems using pinch analysis (Kemp, 2006) to maximize

internal heat recovery and to determine the optimal energy integration of the system.

Finally, the economic performances of the configurations are calculated using TEA (Short et al., 1995).

2.2.1. Flow sheet model

The Aspen Plus flow sheet modeling software (AspenTech, 2016) was used to simulate the HTL and CHG units. The software accounts for the complexity of interactions among thermodynamic parameters and the wide range of chemical species present in the incoming feedstock, the produced biocrude oil and the leftover biomass in the aqueous phase.

Simulations, based on data from Jones et al. (2014), calculated the different product fractions and the thermal and power energy requirements using equations of state (Tables S1 and S2). The feedstock flow at the inlet of the HTL was assumed to be 200 kg/h (DM), a result of a total flow of 1,000 kg/h and a solids content of 20%. A reaction temperature of 350°C and a pressure of 20 MPa were assumed, both for the HTL and the CHG. Using the data of Jones et al. (2014), the efficiency of bio-crude oil production was assumed to be 51% in terms of mass, and was common to all scenarios considered in the present case study. The flow sheet models for the HTL and the CHG are available in Figures S1 and S2 of the supplementary material, along with the inputs and results of the simulations (Tables S1 and S2).

The AD process was simulated based on data from Tommaso et al. (2015) and Jones et al. (2014), to estimate methane production of the aqueous phase from HTL. The heat requirements for AD were calculated based on engineering design equations (Tchobanoglous et al., 2003); power requirements were calculated based on reported values

(Clavreul et al., 2012; Dieterich et al., 2014; Murphy and Power, 2009; Uellendahl et al., 2008). The AD model is described in detail in section 1.3 of the supplementary material. For the CHP scenario, an electrical efficiency of 28% and a thermal efficiency of 47% were assumed, respectively (U.S. EPA, 2015). For the boiler scenario, a standard non-condensing boiler with a 90% thermal efficiency was assumed. The details of the co-generator and of the boiler are available in section 1.3 of the supplementary material.

2.2.2. *Energy integration*

Pinch analysis was used to conduct energy integration and calculate the heat balance of the system, the minimal energy required from external utilities, and the required temperature at which this heat has to be supplied. The results were used as a basis to design the heat exchanger network of the system. The power balance of the system was also performed, to determine whether external grid electricity is required, or if the net power balance allows for electricity export. The details of the pinch analysis calculations are available in section 2 of the supplementary material.

2.2.3. *Techno-economic analysis*

Although energy integration provides a basis for comparing the different scenarios on a thermodynamic basis, additional insights that result from an economic analysis is necessary before process scale-up and commercialization. Therefore, a TEA (Short, et al., 1995) was performed for each scenario. The total capital investment was calculated using equipment costing methods (Turton et al., 2003; Ulrich, 1996). A profitability analysis of the facility was performed with these capital costs and the yearly operating costs, using a discounted cash-flow method that calculates indicators of overall economic performance, such as the

minimum bio-crude oil selling price or the net present value. To explore the effect of market variability on the four scenarios, a sensitivity analysis was performed on the TEA indicators by considering three cases associated with alternative market conditions: reference, best and worst (Table 1). TEA calculations are presented in section 3 of the supplementary material.

3. RESULTS AND DISCUSSION

3.1. Energy Integration

The energy flows associated with each of the studied scenarios (Fig. 3) demonstrate that a significant percentage of the energy content of the algal biomass remains in the aqueous phase in the form of soluble organic carbon and is not recovered as bio-crude oil by the HTL process. Bio-crude oil yields from HTL of microalgae depend on feedstock composition as well as residence time and temperature. Most studies on HTL of algae conducted batch experiments to study the effect of feedstock composition on oil yields. For example, Biller and Ross (2011) showed the following trend for oil yields: lipids > protein > carbohydrates. Consequently, low lipid algae such as *Spirulina* has been reported to have bio-crude oil yields around 33% (Vardon et al., 2011). On the other hand, high lipid species such as *Chlorella* and *Nannochloropsis* that have relatively higher oil contents —36% and 43%, respectively (Biller and Ross, 2011; Brown et al., 2010) are more desirable for liquid fuel production using HTL. Our simulations, based on Jones et al. (2014), modeled a continuous HTL process of algae with an average oil yield of 50%, which is conservative with respect to the importance of valorizing the aqueous phase. The data shown in Fig. 3,

therefore, demonstrate that post-HTL processing of the aqueous phase is necessary to recover the residual dissolved organic carbon. The energy remaining in the aqueous phase was estimated as 1,370 MJ/h (equivalent to 380 kW) based on the calculated mass yield of the aqueous phase and its elemental composition (see supplementary material).

Our model demonstrates that CHG, a thermochemical process, recovers more of this energy in the form of syngas than AD, a biological process, does in the form of biogas (Fig. 3). Although Tommaso et al. (2015) found that the low toxicity of the aqueous phase made it amenable to energy production through AD, the limited removal of organic matter (44–60%) and the high concentration of CO₂ in the biogas mixture (30–40%) are the main reasons for the lower energy return from AD compared to CHG (Fig. 3). In addition to the valorization of the dissolved organic carbon, CHG can potentially recycle nutrients from the HTL-aqueous phase (Cherad et al., 2013; Elliott et al., 2015). Nutrient recycling is essential for microalgal biofuel production, since algae cultivation requires large amounts of nutrients, which is reflected in the costs and environmental footprint for algal biofuel (Beal et al., 2015).

Utilization of biogas or syngas were simulated, comparing a co-generation engine for CHP production with combustion in a boiler for heat production. Based on our model, heat recoveries for the CHP scenarios were estimated as 2.9 and 6.1 % of the initial biomass energy for AD and CHG, respectively (Fig. 3). Electricity recoveries for the CHP were estimated at 2.5 and 5.3% of the initial biomass energy for AD and CHG, respectively (Fig. 3). Heat recoveries from the boiler scenarios were estimated as 6 and 12% of the initial biomass energy for AD and CHG, respectively (Fig. 3). However, the results

presented in Fig. 3 do not account for heat and power consumed or temperatures during processing. These are accounted for in the pinch analysis discussed below.

The composite curves demonstrate the thermal energy required for each of the process configurations (Fig. 4). The system can be designed based on the composite curves, by finding the point of closest temperature approach between the hot and the cold streams — i.e., the pinch point. This temperature represents the point below which any external heat should not be supplied, and above which any external cooling should not be supplied. In the four scenarios, the pinch point occurred at 350°C. The composite curves demonstrate that the main difference for thermal energy requirements are between the AD and CHG scenarios, due to the higher heat and power demands of the CHG process (supplementary material). Furthermore, integrating the heat flows minimizes heat requirements for the scenarios as demonstrated by the horizontal differences between the hot and cold curves (Fig. 4). Both AD scenarios involve a lower amount of heat transferred compared to CHG, due to the lower operating temperature for AD (Table 2). Since CHG combined with a boiler is completely autonomous with respect to heat, there is no associated temperature of heat supply for this scenario (Table 2). The boiler scenarios required less heat than the CHP scenarios, and the CHG + CHP scenario required the most external heat of the four alternative scenarios.

Since CHG produces more methane gas compared to AD (Fig. 3), it also produces more electricity and heat, either through combustion in a CHP or boiler. However, when looking at the overall system and the results from energy integration, the higher production of methane gas via CHG is not necessarily more advantageous than AD. The CHG + CHP

scenario, is completely autonomous in terms of power, and even allows for electricity export to the grid (Table 3). It requires, however, twice the external heat from natural gas compared to AD (Table 2). For the two CHP scenarios (AD and CHG), there is therefore, a tradeoff in terms of heat and electricity. AD is more favorable with respect to heat, whereas CHG is more favorable with respect to power generation. For the two boiler scenarios, both AD and CHG are autonomous or almost autonomous in terms of heat (Table 2). Similarly, both boiler scenarios are almost equivalent for their requirements of external electricity (Table 3).

To demonstrate the advantages of heat integration, the minimum heat requirements for each scenario (Table 2) were compared with the total heating requirements for each process, as illustrated by the hot composite curves (Fig. 4). The total heating requirements represent a process design with no heat exchanger for internal heat recovery, and with heat supplied exclusively from an external utility such as a natural gas boiler. Performing this comparison, energy integration may save up to 85% of external heat by internal heat recovery for the scenarios with combined heat and power, and up to 99% for the scenarios with combustion. These potential savings illustrate the interest of designing and investing in heat exchanger networks to recover the internal waste heat from multiple process components.

3.2. Economic performances

Capital and operating costs associated with the four scenarios for the reference case are summarized in Fig. 5. Both the investment and operating costs of AD are much lower than for CHG. Since AD is operated at atmospheric pressure, lower-pressure and less expensive

equipment for processing the aqueous phase is required compared to CHG. Additionally, the lower capital costs for the AD scenarios result from a simpler heat exchanger network, since less heat is transferred compared to the CHG scenarios (Fig. 4). Although processing times are much shorter for CHG than for AD and should intuitively result in lower capital costs, this is not the case since CHG requires expensive resistant materials, high-pressure pumps and large heat exchangers that transfer large amounts of heat at high temperatures. While the capital costs for heat exchangers, pumps, and reactors were significant for both AD and CHG scenarios, the investment in co-generation engine or boiler were very small, and probably negligible relative to the total costs of each system (Fig. 5a).

The lower capital costs of the AD system lead to lower maintenance and labor costs (compared to CHG), which dominate the operating costs (Fig. 5b). This was a direct consequence of the process design performed using pinch analysis, which optimizes energy integration and minimizes other operating costs, such as external heat and power requirements. The four scenarios with internal heat and power recoveries were compared to a case where all energy inputs would be supplied by external utilities. For the scenario using AD with CHP, the net economic balance increases from a negative value of -\$5/ton with no heat integration to a positive value of \$24/ton. For the scenario using AD with a boiler, the net balance increases from \$5/ton with no heat integration to \$29/ton with heat recovery. For the two CHG scenarios, the net economic balance remains negative; however, energy savings due to the heat integration reduce the total operating costs significantly and therefore minimize the total deficit. For the CHG-CHP scenario, the net balance increases from -\$336/ton with no heat integration to -\$281/ton with heat

integration. For the CHG-boiler scenario, the net balance increases from -\$315/ton with no heat integration to -\$273/ton with heat integration. This comparison demonstrates that the overall process may generate an additional profit by adding heat and power recovery.

In addition to the revenue from bio-crude oil, subsidies included as part of the reference case contribute significantly to the economic viability of the modeled scenarios. These subsidies for green fuel production are equivalent to those used in the early development of large-scale bio-ethanol production in the United States (Hill et al., 2006). Since subsidies are controversial and have a critical influence on process profitability, the sensitivity analysis presented below includes a case with no subsidies (worst), and an improved case with higher subsidies matching those used for the production of biofuels in the European Union (Charles and Wooders, 2012). Besides subsidies, other parameters of the TEA that are subject to high uncertainty were included in the sensitivity analysis (Table 1), such as the process performance (i.e. lifetime, capacity factor), finance (loan conditions) and resource prices (i.e. electricity, natural gas). The feedstock price is also subject to high uncertainty, and depends not only on the market conditions but also on its nature.

Table 4 displays the minimum bio-crude oil selling price for each scenario under different market conditions (reference, best, worst), calculated using the discounted cash-flow diagram method with the parameters listed in Table 1. Compared to the cost of conventional fossil fuels, 0.55 USD/L for bio-crude oil (U.S. EIA, 2016), the scenarios with CHG are never profitable, even under the best possible economic conditions and process performances. For the reference case, CHG leads to minimum bio-crude oil selling prices that are twice as high compared to AD. Both AD scenarios are likely to be profitable under

best-case conditions, but they are still almost twice the price of conventional fossil fuels under reference case conditions, even considering subsidies and a no-cost feedstock. Thus, it is not clear whether the co-generation engine or the boiler is the most economical solution for biogas conversion to energy services. This depends on market prices of natural gas and electricity. For the reference case, both options (co-generation or boiler) are equivalent, while the boiler is more advantageous under best-case conditions and less advantageous under worst-case conditions (Table 4).

The results of the sensitivity analysis suggest that the hydrothermal processes presented here would be better suited—from an economics perspective—for converting waste biomass to energy (reference and best cases) rather than for the conversion of expensive feedstocks, such as algae. This still leaves a broad range of feedstock options for HTL with a variety of chemical compositions, such as manure (Hoffmann et al., 2013), food waste (Posmanik et al., 2017), wastewater sludge (Vardon et al., 2011), waste wood from forest industry or other agricultural waste including unused parts of crops (Akhtar and Amin, 2011). While waste feedstocks such as manure and sewage sludge are likely to incur no cost if processed on-site, or, as in the case of food waste, generate income through tipping fees (Bishop and Shumway, 2009; Usack and Angenent, 2015), a cultivated feedstock such as algae will incur additional expenses (Davis et al., 2016). Besides the economic advantage and the production of useful energy services, hydrothermal processing of waste biomass can eliminate pollution, produce clean water (in the case of CHG), and potentially even marketable nutrients through recovery of nutrient via CHG or AD.

3.3. Future perspective

The use of pinch analysis to perform energy integration at a process systems level identifies potential opportunities of internal heat and power recovery, thus minimizing the imports of external heat and grid electricity. The application of pinch analysis to a case study that compares alternative scenarios for post-processing of HTL-aqueous phase shows how an in-depth analysis of the energy flows involved with each process component can be performed. In addition, this study demonstrates how individual components of a system can potentially interact with each other synergistically, which results in the design of a process with an overall improved efficiency.

Combining energy integration tools with techno-economic analysis provides additional insight on the significance of each system component and flow for overall process profitability and for scenario comparison. Linking experimental data with a broader systems perspective accounting for energetic and economic aspects helps identify research priorities in terms of promising process combinations, as illustrated by the case study of coupling HTL of waste biomass with either a biological or thermo-chemical post process to valorize residual organic matter. The proposed methodological framework can also easily be extended beyond pinch analysis, TEA, and sensitivity analysis, to integrate additional tools, such as Monte-Carlo simulations for uncertainty analysis or life-cycle assessment for a large-scale evaluation of environmental impacts of a given process or technology.

4. CONCLUSIONS

The application of a systems modeling framework to four alternative scenarios for the post-treatment of hydrothermal processing illustrate the importance of maximizing biomass

valorization in energy conversion and waste management. Waste to energy processes should focus not only on the main energy product (e.g., bio-crude oil), but also consider the production of energy products from residual by-products. Moreover, an integrated systems approach designed to recover internal heat and power allows for large reductions in external energy demands and lowers environmental risks and costs. As a consequence, the overall process sustainability improves in terms of thermodynamics, economics, and waste treatment services.

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Figure Captions

Figure 1. Simplified process flow diagrams of the alternative process scenarios considered for treatment of the aqueous phase from hydrothermal liquefaction and energy services production from produced gas.

Figure 2. Computational framework for the evaluation of the four alternative scenarios in terms of energetic and economic performance.

Figure 3. Sankey diagrams showing the energy flows (kW) for each of the four scenarios: a) HTL-AD-CHP; b) HTL-AD-Boiler; c) HTL-CHG-CHP; and d) HTL-CHG-Boiler. HTL, hydrothermal liquefaction; AD, anaerobic digestion; CHG, catalytic hydrothermal gasification; CHP, combined heat & power.

Figure 4. Composite curves of the pinch analysis for the four scenarios, which consist of HTL integrated with post-treatment of the aqueous phase and biogas/syngas conversion to energy products (HTL, hydrothermal liquefaction; AD, anaerobic digestion; CHG, catalytic hydrothermal gasification; CHP, combined heat & power).

Figure 5. Capital costs and operating costs (including expenses and revenue) for the four scenarios, using the reference case. Costs were calculated per ton of biomass processed with a loading rate of 200 kg/h and a project lifetime of 30 years. (HTL, hydrothermal liquefaction; AD, anaerobic digestion; CHG, catalytic hydrothermal gasification; CHP, combined heat & power).

Table 1. Parameters used for techno-economic analysis.

	Reference	Best	Worst
Project lifetime [yr]	30	40	20
Capacity factor [-]	0.9	0.95	0.85
Discount rate [-]	0.1	0.05	0.15
Tax rate [-]	0.2	0.05	0.35
Loan term [yr]	10	20	3
Interest rate [-]	0.06	0.04	0.1
Electricity price [USD/kWh]	0.07	0.07	0.2
Natural gas price [USD/kWh]	0.01	0.01	0.2
Subsidies for green fuel [USD/L]	0.2	0.7	0
Feedstock cost [USD/kg]	0	-0.44	0.5

Table 2. Minimum heat requirements and associated temperatures for the four process scenarios (HTL, hydrothermal liquefaction; AD, anaerobic digestion; CHG, catalytic hydrothermal gasification; CHP, combined heat & power).

Scenario	Pinch Temperature [°C]	Temperature [°C]	Minimum heat required [kW]
HTL-AD-CHP	350	360	63
HTL-AD-Boiler	350	360	2
HTL-CHG-CHP	350	360	124
HTL-CHG-Boiler	350	-	0

Table 3. Power demands and overall balances for the four scenarios. A positive balance means that grid power is required; a negative balance means that excess power is produced and can be exported to the grid (HTL, hydrothermal liquefaction; AD, anaerobic digestion; CHG, catalytic hydrothermal gasification; CHP, combined heat & power).

Scenario	HTL pump [kW]	Pumping and mixing (CHG/AD) [kW]	Engine production [kW]	Balance [kW]
HTL-AD-CHP	15	24	24	+15
HTL-AD-Boiler	15	24	-	+39
HTL-CHG-CHP	15	17	58	-26
HTL-CHG-Boiler	15	17	-	+32

Table 4. Minimum bio-crude oil selling prices (USD/L) for the facility to breakeven at the end of its lifetime, calculated for the four scenarios, and for the three economic cases: reference, best and worst (HTL, hydrothermal liquefaction; AD, anaerobic digestion; CHG, catalytic hydrothermal gasification; CHP, combined heat & power).

	HTL-AD-CHP	HTL-AD-Boiler	HTL-CHG-CHP	HTL-CHG-Boiler
	USD/L			
Reference	0.97	0.95	1.92	1.88
Best	0.26	0.09	0.96	0.78
Worst	1.59	3.28	3.59	5.16

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

Fig. 5.

Numbers represent energy flows (kW)