An Evaluation of Influential Variables on the Energy Efficiency of Hydrothermal Liquefaction

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Introduction

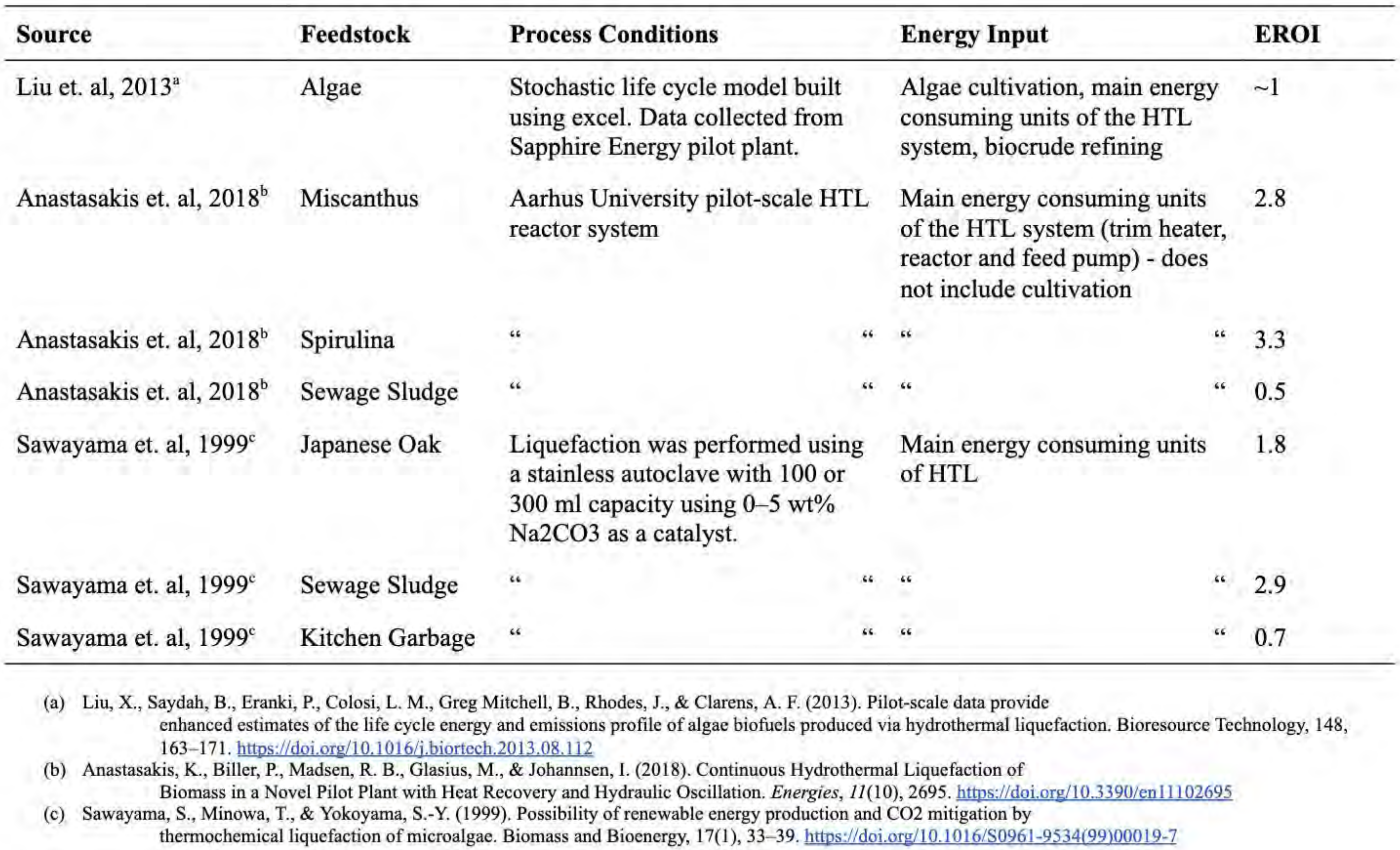
1. Nonrenewable energy sources are limited and harmful to the environment.
2. Biomass can be used as an alternative energy source to oil, coal, and natural gas.
    a. Renewable feedstocks can include wood, algae, food waste, sewage sludge.
3. Waste biomass is constantly being generated and is a cost effective feedstock for thermochemical conversion.
4. Multiple thermochemical conversion methods exist to generate biofuels from biomass.
5. Hydrothermal Liquefaction (HTL) is an effective conversion method for sewage sludge because it allows for a wet feedstock.
6. In order to be used commercially, the production of sustainable fuels must have a competitive energy efficiency with the production of conventional fuels.
7. Energy Return on Investment (EROI) is a valuable way of measuring energy efficiency of energy processes.

Problem Statement

There are very few studies that currently exist evaluating energy return on investment for HTL. Studies that have been published on the energy efficiency of HTL only evaluate the EROI of a single set of process conditions. In order to assess HTL as a competitive energy process, more information is needed on its energy efficiency and the impact of process variables on EROI.

Therefore, in this study we will determine the main factors that impact EROI of HTL and analyze the EROI based on these factors. This information will allow anyone looking at our study to see a range of possible EROIs for HTL and project the EROI for their process. With biofuels rising in popularity, this information will be extremely useful for those interested in using HTL technology.

Existing Studies



Source	Feedstock	Process Conditions	Energy Input	EROI
Liu et. al, 2013[a]	Algae	Stochastic life cycle model built using excel. Data collected from Sapphire Energy pilot plant.	Algae cultivation, main energy consuming units of the HTL system, biocrude refining	~1
Anastasakis et. al, 2018[b]	Miscanthus	Aarhus University pilot-scale HTL reactor system	Main energy consuming units of the HTL system (trim heater, reactor and feed pump) - does not include cultivation	2.8
Anastasakis et. al, 2018[b]	Spirulina	“ “	“ “	3.3
Anastasakis et. al, 2018[b]	Sewage Sludge	“ “	“ “	0.5
Sawayama et. al, 1999[c]	Japanese Oak	Liquefaction was performed using a stainless autoclave with 100 or 300 ml capacity using 0–5 wt% Na2CO3 as a catalyst.	Main energy consuming units of HTL	1.8
Sawayama et. al, 1999[c]	Sewage Sludge	“ “	“ “	2.9
Sawayama et. al, 1999[c]	Kitchen Garbage	“ “	“ “	0.7

(a) Liu, X., Saydah, B., Eranki, P., Colosi, L. M., Greg Mitchell, B., Rhodes, J., & Clarens, A. F. (2013). Pilot-scale data provide enhanced estimates of the life cycle energy and emissions profile of algae biofuels produced via hydrothermal liquefaction. Bioresource Technology, 148, 163–171. https://doi.org/10.1016/j.biortech.2013.08.112

(b) Anastasakis, K., Biller, P., Madsen, R. B., Glasius, M., & Johannsen, I. (2018). Continuous Hydrothermal Liquefaction of Biomass in a Novel Pilot Plant with Heat Recovery and Hydraulic Oscillation. *Energies*, *11*(10), 2695. https://doi.org/10.3390/en11102695

(c) Sawayama, S., Minowa, T., & Yokoyama, S.-Y. (1999). Possibility of renewable energy production and CO2 mitigation by thermochemical liquefaction of microalgae. Biomass and Bioenergy, 17(1), 33–39. https://doi.org/10.1016/S0961-9534(99)00019-7

Methods and Approach

Goal: To understand the impact of influential variables on the energy return on investment of hydrothermal liquefaction.

Objectives:

1. Evaluate the effect of process variables on the energy return on investment for hydrothermal liquefaction.
2. Further analyze the effect of the most impactful variables on energy return on investment.
3. Contextualize identified EROI trends by incorporating biocrude upgrading and correlating data from literature studies.

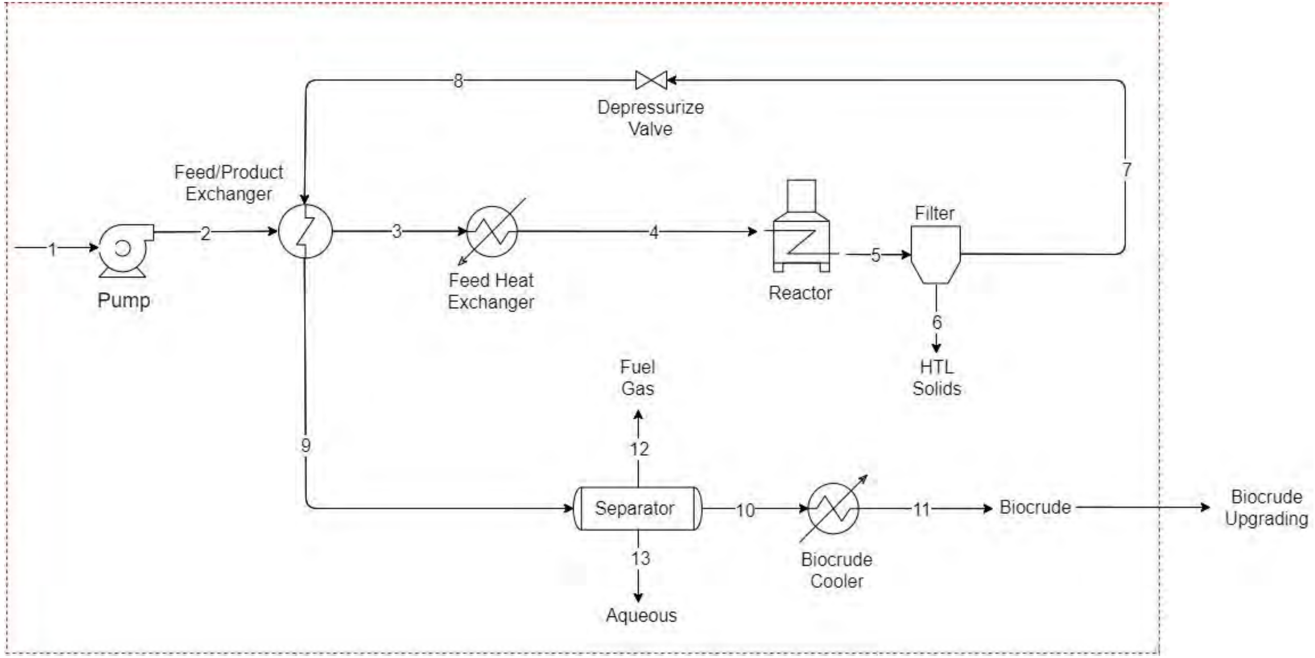
Methods and Approach

This study consists of five main components:

1. Modeling a simplified HTL process based on PNNL’s 2017 HTL study*
2. Calculating an EROI base case using process conditions from PNNL
3. Completing a sensitivity analysis to determine which variables are most impactful on EROI
4. Analyzing the impact on EROI for the important process variables identified in step 3
5. Projecting EROI based on data from the literature

**Conceptual Biorefinery Design and Research Targeted for 2022: Hydrothermal Liquefaction Processing of Wet Waste to Fuels*

Modeling the HTL Process

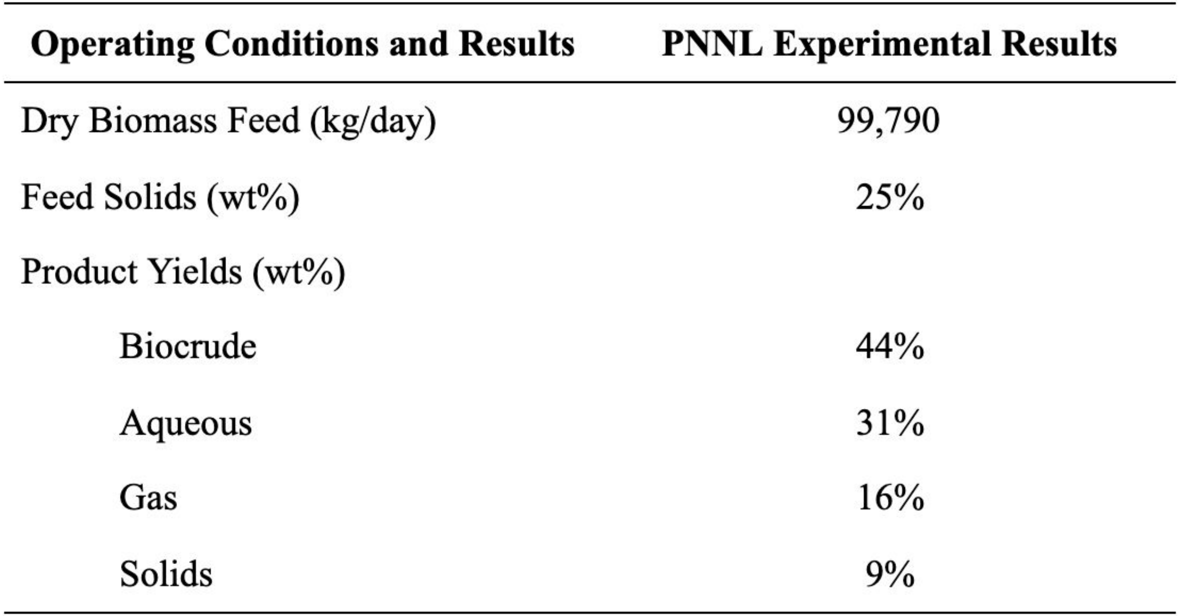


- Using PNNL’s bench scale HTL system as a guide, we created a simplified version of the HTL process.
- Removed extra heat exchangers and pumps for simpler calculations.
- Our analysis does not include the use of recycled hot oil for heat exchangers and the reactor.

Stream Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Temperature (°C)	15.5	15.5	—	346.7	346.7	346.7	346.7	346.7	60	60	43.3	60	60
Pressure (MPa)	0.1	20.8	20.8	20.8	20.8	20.8	20.8	0.2	0.2	0.2	0.2	0.2	0.2

*Stream 3 does not have a set temperature as it depends on water content in the feed

Calculating the EROI Base Case

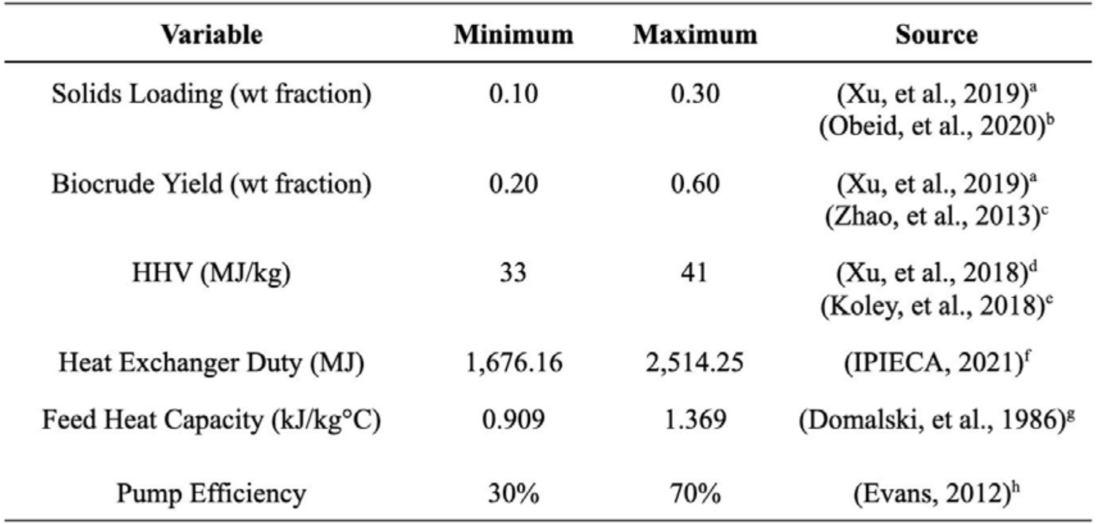


Operating Conditions and Results	PNNL Experimental Results
Dry Biomass Feed (kg/day)	99,790
Feed Solids (wt%)	25%
Product Yields (wt%)	
Biocrude	44%
Aqueous	31%
Gas	16%
Solids	9%

Based on standard EROI

- Covers energy consumption only up to where the fuel leaves the production facility.
- EROI was evaluated only for HTL where biomass is turned into biocrude.

Sensitivity Analysis



Variable	Minimum	Maximum	Source
Solids Loading (wt fraction)	0.10	0.30	(Xu, et al., 2019)[a] (Obeid, et al., 2020)[b]
Biocrude Yield (wt fraction)	0.20	0.60	(Xu, et al., 2019)[a] (Zhao, et al., 2013)[c]
HHV (MJ/kg)	33	41	(Xu, et al., 2018)[d] (Koley, et al., 2018)[e]
Heat Exchanger Duty (MJ)	1,676.16	2,514.25	(IPIECA, 2021)[f]
Feed Heat Capacity (kJ/kg°C)	0.909	1.369	(Domalski, et al., 1986)[g]
Pump Efficiency	30%	70%	(Evans, 2012)[h]

(a) Xu, Donghai, Yang Wang, Guike Lin, Shuwei Guo, Shuzhong Wang, and Zhiqiang Wu. “Co-Hydrothermal Liquefaction of Microalgae and Sewage Sludge in Subcritical Water: Ash Effects on Bio-Oil Production.” Renewable Energy 138 (August 1, 2019): 1143–51. https://doi.org/10.1016/j.renene.2019.02.020.

(b) Obeid, Reem, David M. Lewis, Neil Smith, Tony Hall, and Philip van Eyk. “Reaction Kinetics and Characterization of Species in Renewable Crude from Hydrothermal Liquefaction of Mixtures of Polymer Compounds To Represent Organic Fractions of Biomass Feedstocks.” *Energy & Fuels* 34, no. 1 (January 16, 2020): 419–29. https://doi.org/10.1021/acs.energyfuels.9b02936.

(c) Zhao, Yun-Peng, Wei-Wei Zhu, Xian-Yong Wei, Xing Fan, Jing-Pei Cao, You-Quan Dou, Zhi-Min Zong, and Wei Zhao. “Synergic Effect of Methanol and Water on Pine Liquefaction.” *Bioresource Technology* 142 (August 1, 2013): 504–9. https://doi.org/10.1016/j.biortech.2013.05.028.

(d) Xu, Donghai, Guike Lin, Liang Liu, Yang Wang, Zefeng Jing, and Shuzhong Wang. “Comprehensive Evaluation on Product Characteristics of Fast Hydrothermal Liquefaction of Sewage Sludge at Different Temperatures.” *Energy*159 (September 15, 2018): 686–95. https://doi.org/10.1016/j.energy.2018.06.191.

(e) Koley, Shankha, Mangesh S. Khadase, Thangavel Mathimani, Hifjur Raheman, and Nirupama Mallick. “Catalytic and Non-Catalytic Hydrothermal Processing of Scenedesmus Obliquus Biomass for Bio-Crude Production – A Sustainable Energy Perspective.” *Energy Conversion and Management* 163 (May 1, 2018): 111–21. https://doi.org/10.1016/j.enconman.2018.02.052.

(f) IPIECA. “Heat Exchangers.” Accessed March 12, 2021. https://www.ipieca.org/resources/energy-efficiency-solutions/efficient-use-of-heat/heat-exchangers/.

(g) Domalski, E. S., Jobe, J., & Milne, T. A. (1986). *Thermodynamic data for biomass conversion and waste incineration* (SERI/SP-271-2839). National Bureau of Standards, Washington, DC (US); Solar Energy Research Inst., Golden, CO (US). https://doi.org/10.2172/7038865

(h) Evans, J. (2012, January 20). *Pump Efficiency—What Is Efficiency?* Pumps and Systems Magazine. https://www.pumpsandsystems.com/pump-efficiency-what-efficiency

Analyzing Important Process Variables

Analyzed how the most impactful variables from the sensitivity analysis changed EROI in a plot.

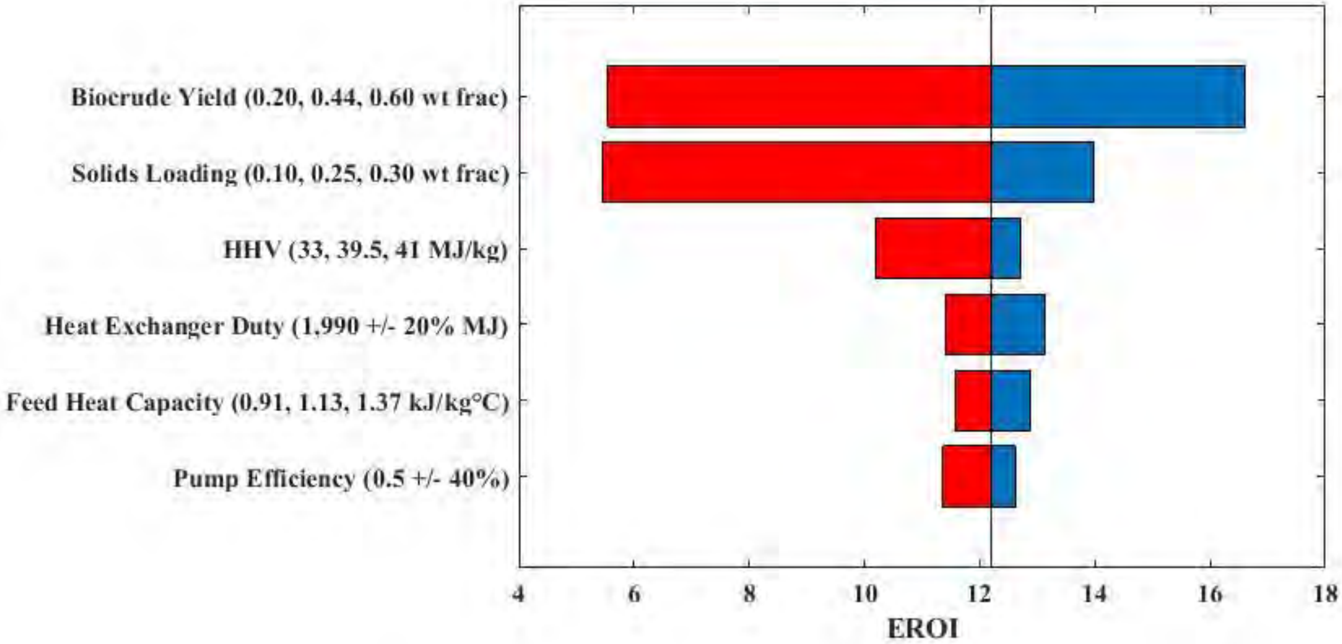
Incorporated biocrude upgrading as a correction factor into EROI using equipment duties from the PNNL study.

- Included all heat exchangers, pumps, and compressors in the hydrotreating process, hydrocracking process, hydrogen plant, product cooling system, and steam system.
- Biocrude upgrading plant processes biocrude from 10 HTL plants.

Literature Projection

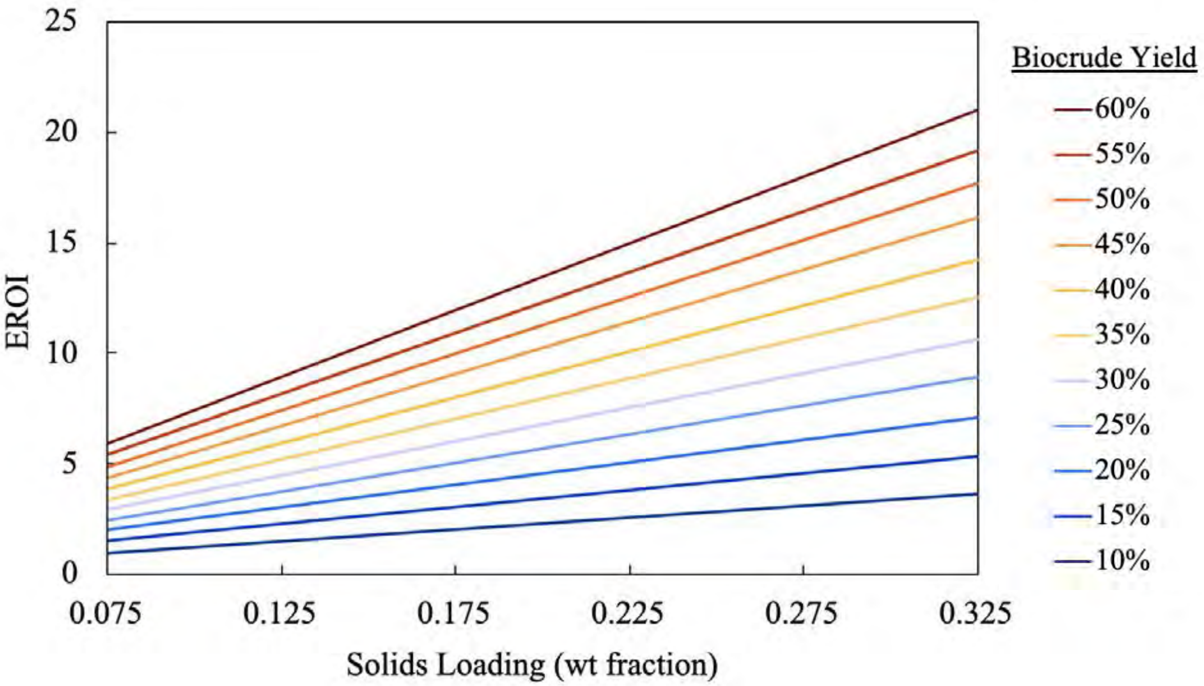
Superimposed data onto our plot from published HTL studies to demonstrate how our trends could be used to estimate EROI based on process variables and feedstock composition.

Sensitivity Analysis



- The sensitivity analysis determined that biocrude yield, solids loading, and heating value are the most impactful factors on the EROI of HTL.
- Based on these results, further analysis was done to determine how EROI changes when changing these variables.

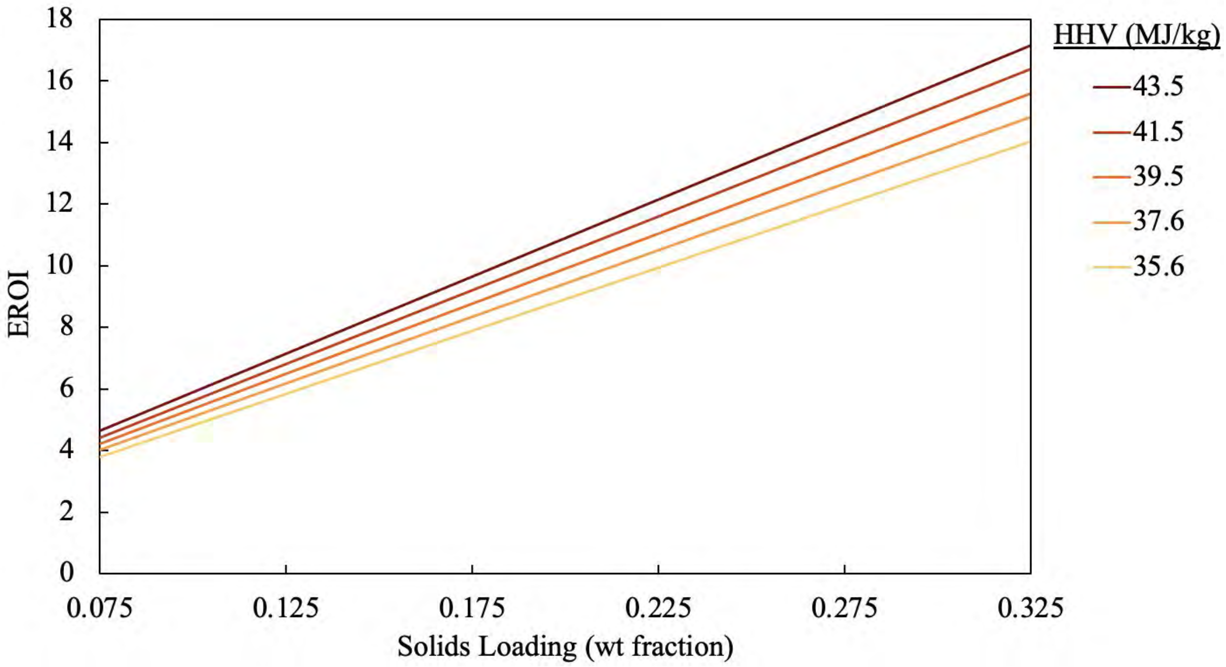
The Effect of Yield and Solids Loading on EROI



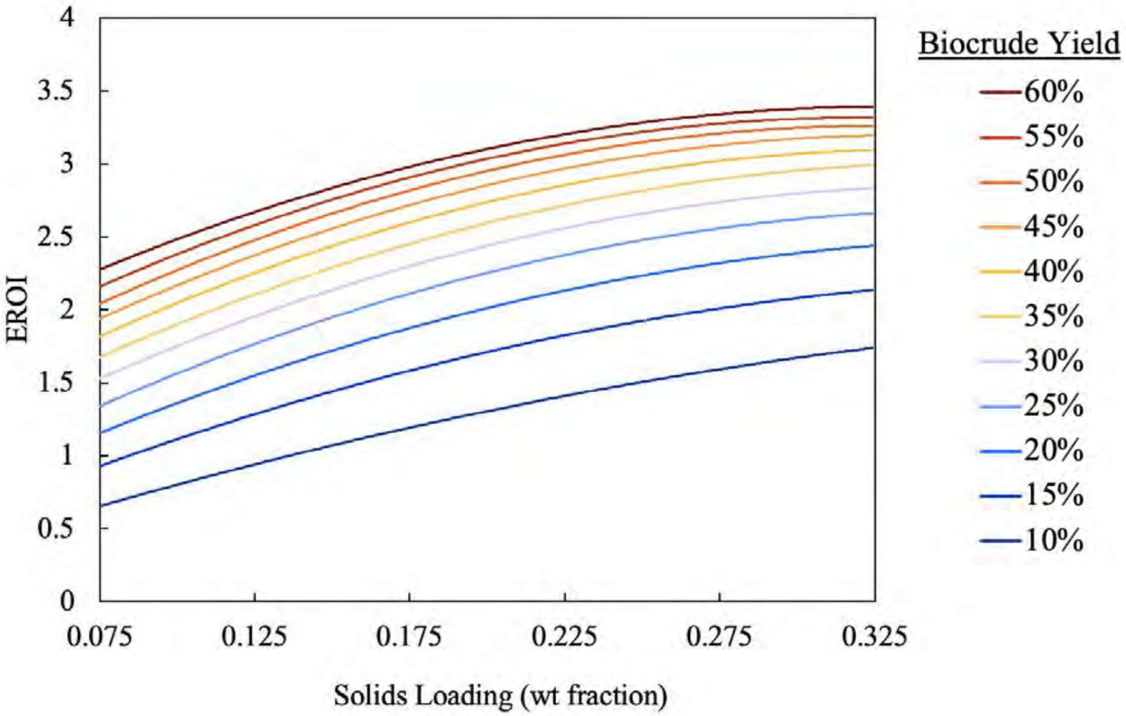
- EROI increases with increasing solids loading (decreasing water content) and increasing yield.
- Solids loading has a greater impact on EROI at higher biocrude yields than lower yields.
  - ○ 10% BC Yield EROI difference is 2.7
  - ○ 60% BC Yield EROI difference is 15.2

The Effect of Heating Value and Solids Loading on EROI

- EROI increases with increasing solids loading and increasing heating value.
- The heating value lines are closer together because EROI is not as sensitive to heating value as it is yield.
- Solids loading has a greater impact on EROI at higher heating values than it does at lower heating values.
  - There is a very small difference in EROI for different heating values at 0.075 wt fraction.



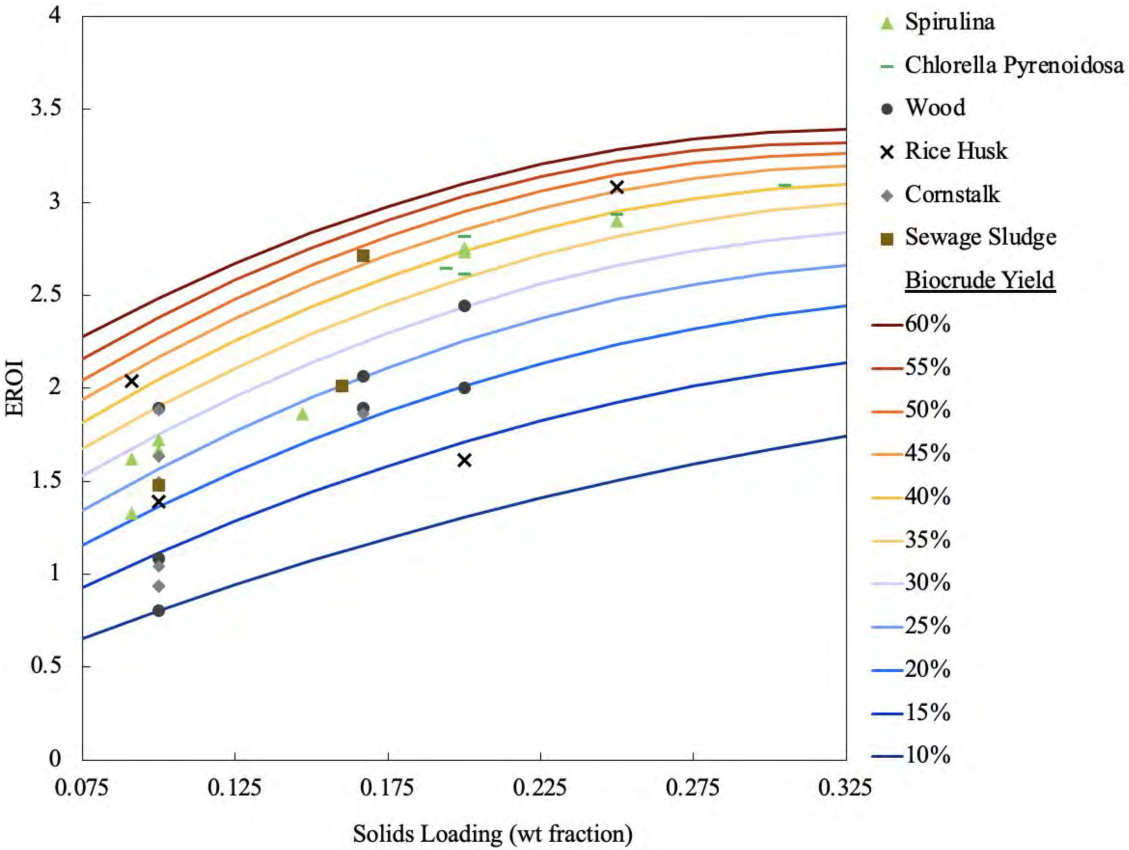
The EROI of Upgraded Biocrude



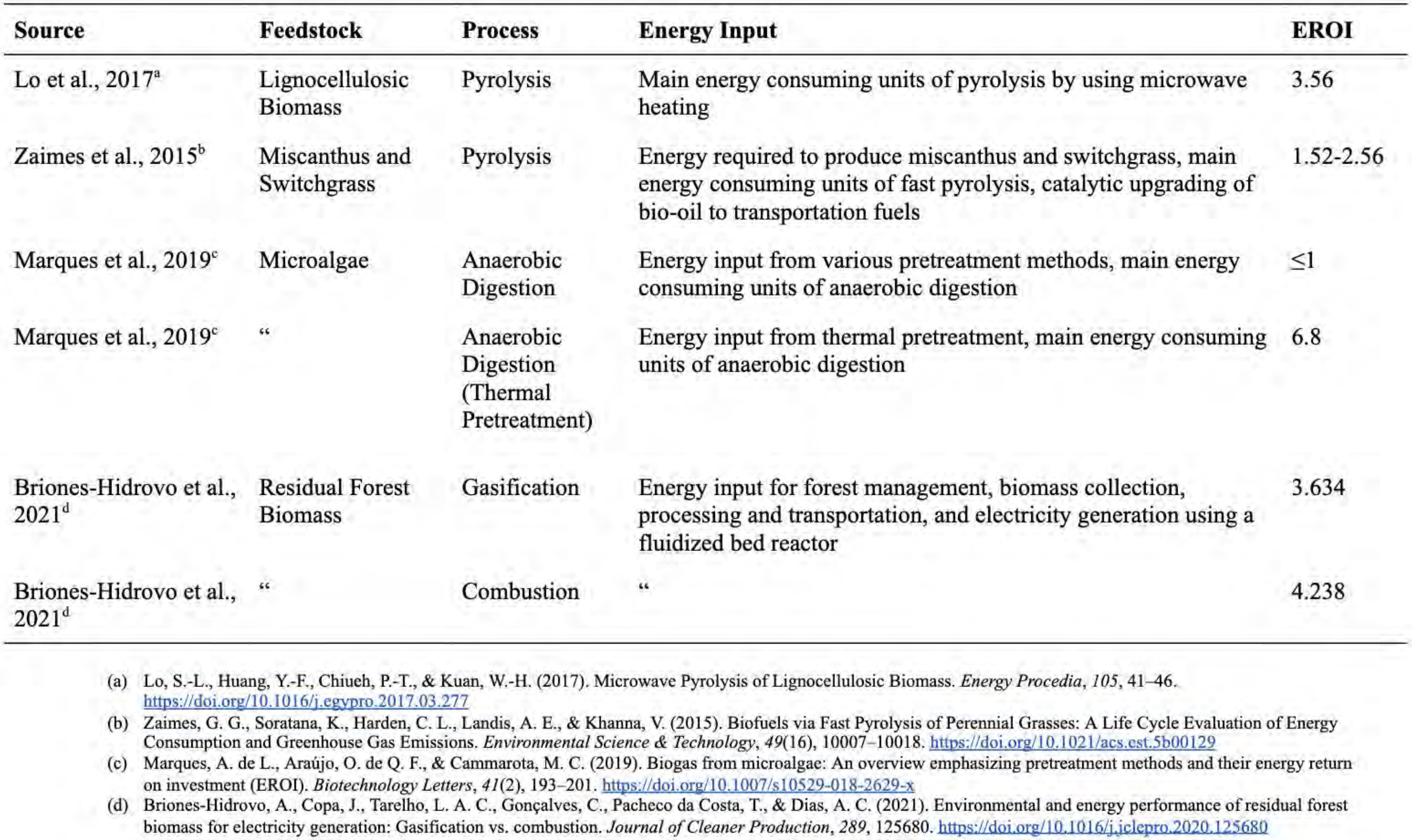
- The values and range of EROI when upgrading is included is much less than for just HTL.
  - Making the upgrading process more efficient would be necessary to increase EROI.
- EROI begins to plateau and the margins begin to narrow at higher yields and solids loading.
  - Suggests that maximum conversion of biomass to biocrude is reached.
- Middle range of solids loading gives best tradeoff between energy efficiency and biomass usage.

Literature Projection

- The data points represented on this graph were obtained from Cheng Feng, who compiled an extensive list of HTL data.
- Given solids loading and yield, we were able to find the EROI of each study correlating to each point.
- Algaes compared to wood tend to have greater yields for the same solids loading, which results in a greater EROI.
- Sewage sludge tends to have a slightly greater yield and therefore greater EROI compared to biomass (wood and cornstalk) at the same solids loading.
- No extensive clear trends could be identified.



EROI Comparison with Other Processes



Source	Feedstock	Process	Energy Input	EROI
Lo et al., 2017[a]	Lignocellulosic Biomass	Pyrolysis	Main energy consuming units of pyrolysis by using microwave heating	3.56
Zaimes et al., 2015[b]	Miscanthus and Switchgrass	Pyrolysis	Energy required to produce miscanthus and switchgrass, main energy consuming units of fast pyrolysis, catalytic upgrading of bio-oil to transportation fuels	1.52-2.56
Marques et al., 2019[c]	Microalgae	Anaerobic Digestion	Energy input from various pretreatment methods, main energy consuming units of anaerobic digestion	≤1
Marques et al., 2019[c]	"	Anaerobic Digestion (Thermal Pretreatment)	Energy input from thermal pretreatment, main energy consuming units of anaerobic digestion	6.8
Briones-Hidrovo et al., 2021[d]	Residual Forest Biomass	Gasification	Energy input for forest management, biomass collection, processing and transportation, and electricity generation using a fluidized bed reactor	3.634
Briones-Hidrovo et al., 2021[d]	"	Combustion	"	4.238

(a) Lo, S.-L., Huang, Y.-F., Chiueh, P.-T., & Kuan, W.-H. (2017). Microwave Pyrolysis of Lignocellulosic Biomass. *Energy Procedia*, *105*, 41–46. https://doi.org/10.1016/j.egypro.2017.03.277

(b) Zaimes, G. G., Soratana, K., Harden, C. L., Landis, A. E., & Khanna, V. (2015). Biofuels via Fast Pyrolysis of Perennial Grasses: A Life Cycle Evaluation of Energy Consumption and Greenhouse Gas Emissions. *Environmental Science & Technology*, *49*(16), 10007–10018. https://doi.org/10.1021/acs.est.5b00129

(c) Marques, A. de L., Araújo, O. de Q. F., & Cammarota, M. C. (2019). Biogas from microalgae: An overview emphasizing pretreatment methods and their energy return on investment (EROI). *Biotechnology Letters*, *41*(2), 193–201. https://doi.org/10.1007/s10529-018-2629-x

(d) Briones-Hidrovo, A., Copa, J., Tarelho, L. A. C., Gonçalves, C., Pacheco da Costa, T., & Dias, A. C. (2021). Environmental and energy performance of residual forest biomass for electricity generation: Gasification vs. combustion. *Journal of Cleaner Production*, *289*, 125680. https://doi.org/10.1016/j.jclepro.2020.125680

Conclusion

- Nonrenewable energy sources such as fossil fuels are harmful to the environment and are running out.
- HTL is a potentially viable renewable energy process but there are very few studies that currently exist evaluating the energy efficiency of HTL.
- This study determined the most influential factors that impact EROI of HTL and analyzed the EROI based in these factors.
    - This information allows for the projection of EROI for an HTL process based on the process conditions.
- It was determined that EROI increases with solids loading, biocrude yield, and biocrude higher heating value.
- The EROI values of HTL alone are much higher than values in literature, however when upgrading is included it is within the same range.
- More work needs to be done to optimize the upgrading process and make it more efficient.
    - The HTL process alone has a very high EROI but when upgrading is included it decreases significantly.

Recommendations for Future Work

- Model the upgrading process to identify opportunities to make it more energy efficient.
- Use the model created to project the EROI of more literature data points in order to determine trends between various biomass feedstocks.
- Investigate the impact of transportation from the HTL plants to the upgrading plants on the overall energy efficiency of the process.
  - For example, look into the potential of colocating.
- Determine the energy potential of the process byproducts (char and fuel gas).
- Reintroduce the simplifications made for the purpose of this study back into the HTL process to make the analysis more comprehensive.

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