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RESEARCH ARTICLE

Towards an off-grid fecal sludge treatment unit: demonstrating energy positive thermal treatment [version 1; peer review: 2 approved, 2 approved with reservations]

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Abstract

Background: There is an unmet demand for community-scale fecal sludge treatment units (FSTUs) that serve communities of between 1,000 and 50,000 people and are able to operate in non-sewered and off-grid environments. An emerging industry standard for FSTUs includes as a key criteria energy independence in steady-state. Theoretically, there is sufficient thermal energy available in fecal sludge to provide the electrical power needed to run the FSTU. However, such a system had never been implemented.

Methods: Biomass Controls has previously demonstrated the thermal treatment of fecal sludge using the Biogenic Refinery, a thermal FSTU deployed in three sites in India. In this article we describe testing where a Biogenic Refinery was paired with a thermal fluid heat exchanger and organic Rankine cycle generator to generate electrical power.

Results: This Biogenic Refinery combined heat and power system generated sufficient electrical power to offset electrical parasitic loads in steady-state operation and produce a surplus of 1.2 kWe.

Conclusions: The results of the study demonstrate that there is an excess of energy available and reliable mechanisms to generate electrical energy using an FSTU. Additional steps are necessary to transition to a true off-grid FSTU.

Keywords

fecal sludge, fecal sludge treatment, thermochemical, energy independence, energy neutrality, energy positivity, thermal, fecal sludge treatment unit, energy generation

Open Peer Review

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Introduction

Community scale fecal sludge treatment units (FSTUs) are an important technology in meeting the needs of the 2.5 billion people without adequate sanitation (Rose *et al.*, 2015; WHO/UNICEF, 2017). Many of these communities also lack access to consistent electricity supply (IEA and Bank, 2019). To encourage the development of FSTUs that meet these needs, the International Standards Organization (ISO) is developing the ISO/PC318 standard for community scale resource oriented sanitation treatment systems (ISO/PC318, 2019). Key criteria for compliance with this emerging standard include: (1) the inactivation of pathogens present in fecal sludge and (2) energy independence in steady-state operation. The first key criteria may be met through a variety of different treatment techniques including thermal treatment, high pH processes, composting, irradiation, and aerobic digestion. To meet the second key criteria, the treatment process must be energy neutral or energy positive, and operate on faecal sludge only without supplemental energy from other sources.

Thermal treatment technologies are a promising approach that could meet both of these criteria (Onabanjo *et al.*, 2016; Yermán *et al.*, 2015). In contrast to other pathogen elimination strategies, high temperature thermal treatment offers rapid inactivation of pathogens in a small footprint, without requiring disinfecting chemicals. Further, thermal treatments, including pyrolysis, gasification, and combustion, can liberate stored energy present in the fecal sludge providing thermal energy useful for processing the fecal sludge and for conversion to electrical energy to run the process (Syed-Hassan *et al.*, 2017).

This paper focuses on the demonstration of energy independence in steady-state operation, which is a key criteria for compliance with emerging standard ISO/PC318. In the present work, the Biomass Controls Biogenic Refinery (BR), an existing thermal FSTU, was paired with a thermal fluid heat exchanger and organic Rankine cycle (ORC) generator to make a combined heat and power (CHP) unit. The BR is currently used as an FSTU in several communities in India fulfilling pathogen inactivation requirements given in Environmental Protection Agency (EPA) 40 CFR Part 503 (US EPA, 2018). The objective of the present study is to demonstrate that there is sufficient electrical power produced by the BR CHP to offset the electrical power necessary to run the BR CHP.

To provide this demonstration, first, we describe the BR CHP system and its modules as well as the test protocol followed. Next, we present a thermal power balance based on measurements of the system during steady-state operation to provide energy available in the thermochemical process. Last, we present measurements of electrical power generated by the ORC, as well as the electrical power consumed by the BR CHP system to calculate net power produced. The result of the study is a demonstration that the key requirements for the emerging standard for community scale FSTUs are achievable.

Methods
Description of the Biogenic Refinery
The BR CHP system consists of four connected modules: (1) the pyrolysis-combustion module responsible for pyrolysing the feedstock and liberating thermal energy from the feedstock; (2) the oil working fluid heat exchanger module responsible for directing a portion of the available thermal energy towards the ORC module; (3) the ORC module responsible for converting thermal energy to electricity; and (4) the hydronic heat exchanger module responsible for extracting additional thermal energy for the purpose of drying incoming feedstock.

The BR system is a thermal FSTU capable of refining any biogenic matter into inert carbon with significant volume reduction, carbon sequestration in the form of biochar, and controlled emissions. The BR uses a pyrolysis-combustion process to inactive pathogens while producing thermal energy and biochar, useful as an agricultural soil amendment, as outputs (Jeffery *et al.*, 2011). The BR is capable of processing approximately 150 kg dry basis of feedstock per day (based on 8 hours of operation), consistent with the ISO/PC318 goal of serving small communities. This amounts to a >18 kg/hr (dry basis) average across a daily 8 hour process period.

Thermal energy from the feedstock is released by the pyrolysis-combustion module and exits in hot exhaust gases. This thermal energy is extracted from the hot exhaust gases by a heat exchanger filled with a thermal working fluid, in our case oil. The thermal energy from the oil working fluid is transferred to the ORC module. The thermal energy remaining in the hot exhaust gases is transferred by the hydronic heat exchanger to further heat the water which is later used for drying.

Description of ORC electrical generation
The ORC module uses the thermal energy from the BR to generate electricity. A schematic of the BR CHP system operation can be seen in Figure 1.

The thermal energy is delivered from the BR to the ORC module using an oil working fluid (Duratherm FG by Duratherm Extended Life Fluids, Lewiston, USA). This working fluid is used to evaporate a different organic working fluid within the ORC. This evaporated fluid is used in conjunction with a scroll expander and runs an electric generator. Following electrical generation, the working fluid is condensed using a water heat exchanger within the ORC, and the heated water is used for heating. The ORC used in the BR CHP system had a rated electrical generation capacity of 4 kWe with a nominal 8% generation efficiency. Because the ORC has only 8% efficiency in generating electricity, 92% of the original thermal energy remains available for heating applications following energy conversion. In the BR CHP, this energy is used to heat water which is then further heated by the BR hydronic heat exchanger module and ultimately used for the drying of incoming feedstock.

Feedstock
FSTUs are intended to primarily treat fecal sludge. However, in a laboratory setting, a sufficient volume of fecal sludge for extended testing is difficult to acquire. Instead, a surrogate feedstock with a similar caloric value, or effective heat of combustion, was sought. The effective heat of combustion of dry feces varies substantially depending on location and source. A study by Gold *et al.* (2017) found effective heats of combustion of 13.4 MJ/kg and 10.9 MJ/kg in Dakar, Senegal and Kampala, Uganda,
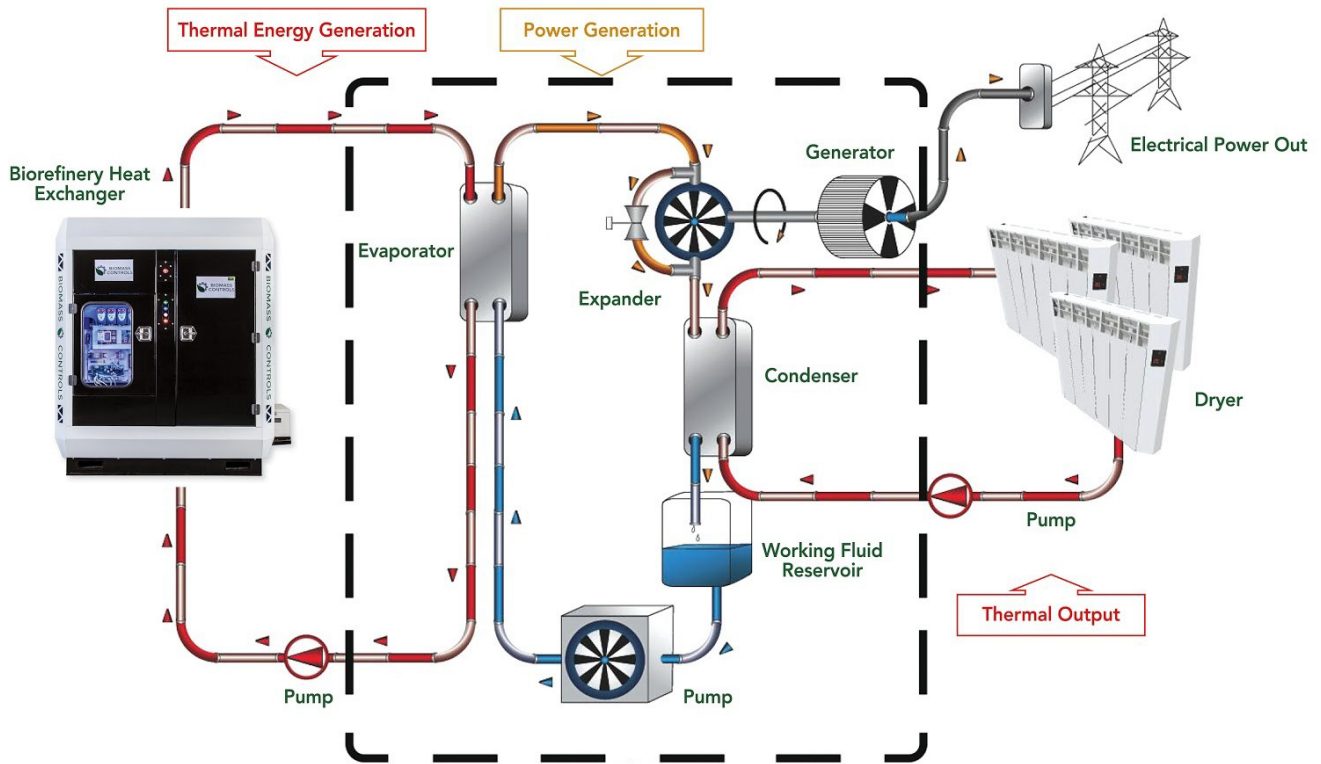
Figure 1. The Biogenic Refinery Combined Heat and Power system uses thermal energy produced through the thermal treatment of feedstocks to generate electrical power using an organic Rankine cycle generator (black dashed box).

respectively. A study by Muspratt *et al.* (2014) found effective heats of combustion of 16.6 MJ/kg, 16.2 MJ/kg, and 19.1 MJ/kg in Dakar, Kampala, and Kumasi, Ghana, respectively. A recent study by Myers *et al.* (n.d.) found effective heats of combustion of 19.6 MJ/kg and 22.3 MJ/kg in samples from India and the United States, respectively. A meta-study by Rose *et al.* (2015) found the average and median for dry feces internationally are 17.2 MJ/kg and 19.1 MJ/kg. Wood pellets (Tractor Supply Company SKU # 3195163) with an effective heat of combustion of 19.2 MJ/kg were identified as an appropriate substitute.

The typical moisture content of fecal sludge treated by operating BRs is 35% moisture on a mass basis, i.e. 35% of the final feedstock mass entering the BR consists of water and 65% of dry fecal sludge. To simulate this moisture content, wood pellets were mixed with the appropriate mass of water in a large tumbler until the water was fully absorbed. The resulting mixture had the consistency of wet sawdust and could be smoothly fed into the BR.

Thermal power balance test

The thermal power balance testing was conducted on the BR with the ORC disconnected. A heat sink was connected to

the oil loop to simulate the thermal energy removed from the system by the ORC. During operation, the BR moves through several operational modes before converging on steady-state. In real world operation, the ORC only generates power during the steady-state. To best simulate this, the BR was brought to steady-state and allowed to run for approximately three hours.

Thermal energy enters the BR through the supplied feedstock which is pyrolyzed and then combusted, releasing most of its energy as

$$Q_{in} = \Delta H_{c,fs} \dot{m}_{fs} \qquad (Equation\ 1)$$

During steady-state, the energy entering the BR through the feedstock is equal to the energy that leaves the BR. This thermal power balance may be given as

$$Q_{in} = Q_{biochar} + Q_{OHX} + Q_{HHX} + Q_{loss} \qquad (Equation\ 2)$$

where $Q_{biochar}$ is the thermal power leaving through extracted biochar, Q_{OHX} is the thermal power extracted transferred to the working fluid by the oil working fluid heat exchanger, Q_{HHX} is the thermal power transfered to water by the hydronic heat

exchanger, and Q_{loss} is the remaining thermal power lost to either radiant and convective heat transfer out of the exterior or jacket of the BR or through the hot gases escaping the stack.

The thermal energy remaining in the biochar is energy that was not extracted through complete combustion of the feedstock. The average thermal power lost to the biochar is determined from the biochar production rate, $\dot{m}_{biochar}$, and the effective heat of combustion of the biochar, $\Delta H_{c,biochar}$, as

$$Q_{biochar} = \Delta H_{c,biochar} \dot{m}_{biochar} \qquad \text{(Equation 3)}$$

The total biochar produced during thermal power balance testing was collected, weighed and divided by operating time to determine a biochar production rate. The effective heat of combustion of biochar from wood pellets can be estimated as 32.3 MJ/kg (Yang *et al.*, 2017). This is similar to the average heat of combustion of biochar made from feces, 30.7 MJ/kg (Myers *et al.*, n.d.).

Thermal power extracted by the oil working fluid heat exchanger is given as

$$Q_{OHX} = \dot{V}_{oil} \rho_{oil} c_{p,oil}(T_{oil,out} - T_{oil,in}) \qquad \text{(Equation 4)}$$

where $\dot{V}_{oil}$ is the volumetric flow rate of oil, ρ_{oil} is the density of oil, $c_{p,oil}$ is the specific heat of the oil, and $T_{oil,out}$ and $T_{oil,in}$ are the temperatures of the oil working fluid entering and leaving the oil heat exchanger. The oil used in the BR CHP oil working fluid heat exchanger was Duratherm FG, whose thermal are seen in Table 1.

The majority of this thermal power is transported to the ORC where it is used in electrical generation. Some thermal power is lost through so called "pipe heat losses", where thermal power being transported in the fluid is lost through conduction to the pipe walls carrying the fluid. These pipe heat losses can be estimated as

$$Q_{PHL} = (T_{out} - T_{amb})/(R_{pipe} + R_{insul}) \qquad \text{(Equation 5)}$$

Table 1. Thermal properties of Duratherm FG oil working fluid.

Temperature (°C)	Density (kg/m³)	Heat Capacity (kJ/kg • K)
25	853.30	1.93
45	839.80	1.99
65	826.40	2.06
85	812.90	2.12
105	799.50	2.19
125	786.02	2.25
145	772.56	2.32
165	759.11	2.38

where T_{amb} is the ambient air temperature, R_{pipe} is the effective thermal resistance for the pipe leading from the oil working fluid heat exchanger to the ORC and R_{insul} is the effective thermal resistance of the insulation wrapping the pipe. The effective thermal resistance for a pipe or hollow cylinder is determined as

$$R = ln(r_o/r_i)/(2 * \pi * L * k) \qquad \text{(Equation 6)}$$

where r_o is the outer radius, r_i is the inner radius, L is the length, and k is the thermal conductivity of the material.

Thermal power is extracted by the hydronic heat exchanger is given as

$$Q_{HHX} = \dot{V}_w \rho_w c_{p,w}(T_{w,out} - T_{w,in}) \qquad \text{(Equation 7)}$$

where $\dot{V}_w$ is the volumetric flow rate of water, ρ_w is the density of water, $c_{p,w}$ is the specific heat of the water, and $T_{w,out}$ and $T_{w,in}$ are the temperatures of the water entering and leaving the hydronic heat exchanger.

The remaining thermal power leaves the system through jacket and stack losses. The total of the jacket and stack losses are calculated using Equation 2 when the other elements of the thermal power balance are known. Jacket losses consist of thermal power convected or radiated away from the exterior of the BR. Stack losses include all thermal power in the hot exhaust gases leaving the system. Jacket temperatures were measured with an infrared thermometer, once every 30 minutes, at four points on each module of the BR: the pyrolysis-combustion module, the oil working fluid heat exchanger module, the hydronic heat exchanger module. Average temperatures were used to calculate total radiative and convective heat transfer from each module of the BR. The exterior of the BR is not a uniform temperature, adding significant uncertainty to calculations of heat transfer from the surface. Further, precise pressure and flow measurements were not taken, limiting the ability to explicitly calculate energy flow in the escaping hot gases. Instead, these losses were lumped together.

During steady-state operation, water, oil and air temperatures of gases were recorded using the following thermocouples and thermistors: stack temperature (Thermocouple Omega Engineering KQIN-18U-6), catalyst temperature (Thermocouple Omega Engineering CAIN-18U-24-NHX), pyrolysis temperature (Thermocouple Omega Engineering CAIN-18U-18-NHX), water and oil temperature (Thermistor QTIQTIP68-14F-96). The flow rate oil was measured using Omega FDT-21 ultrasonic flow meter. The flow rate of water was measured using Omega FTB-30 flow meter. Power draw of the BR CHP system was measured using a WattNode Pulse energy and power meter (Continental Controls Systems, LLCWNB-3Y-400-P). The meter measures energy using a current transformer clamped around the mains power cable for the BR CHP system connected to the wall-outlet. Although thermal energy is provided by the BR for drying incoming feedstock, the dryer itself is not part of the BR CHP system as defined in the ISO/PC 318 standard.

These sensors were integrated with the BR CHP controller with the results recorded in real time using Biomass Controls kelv°n (v1.3.1) data management infrastructure, a proprietary software, which could be applied to any faecal sludge treatment system that uses sensors for digital data collection. Measurements were time-averaged across steady-state operation. Additional measurements, such as feedstock input rate, biochar production rate, and jacket temperatures were measured approximately every 30 minutes throughout the test. Data gathered is available as Underlying data (Schoebitz, 2019)

Data management
Collected data is stored in a standard relational cloud database that provides a flexible and dynamic data management platform (Schoebitz *et al.*, 2018). Open source data science tools were used for data analysis to increase reproducibility, collaboration and communication (Lowndes *et al.*, 2017). R Statistical Software v3.5.1 and the RStudio Integrated Development Environment v1.2.1206 were used for data analysis (R Core Team, 2018; RStudio Team, 2018). The following open source R packages were used to perform data evaluation from initially accessing data to producing the final manuscript: bookdown v0.9, DBI v1.0.0 , dbplyr v1.2.2, here v0.1, hms v0.4.2, lubridate v1.7.4, networkD3 v0.4, purrr v0.3.0, RMySQL v0.10.15, rstudioapi v0.8, snakecase v0.9.2, stringr v1.4.0, tidyverse

v1.2.1 (Allaire *et al.*, 2018; Allaire *et al.*, 2017; Grosser, 2018; Grolemund & Wickham, 2011; Henry & Wickham, 2019; Müller, 2017; Müller, 2018; Ooms *et al.*, 2018; R Special Interest Group on Databases (R-SIG-DB) *et al.*, 2018; Wickham & Ruiz, 2018; Wickham, 2019; Wickham, 2017; Xie, 2016).

Reproducibility
For this study we have used a Biomass Controls Biogenic Refinery and kelv°n software, proprietary equipment and software.

The results presented can be reproduced using any thermochemical fecal sludge treatment unit, however, careful consideration to how much energy is released in different treatment processes would be needed to generalize the results.

Kelv°n data plotter can be integrated with any set of sensors and is freely available to download.

Results
Thermal power balance
A thermal power balance in the Biogenic Refinery was constructed using the aforementioned measured system temperatures and flow rates. This thermal power balance can be seen in Figure 2. Specific details on the thermal power calculations for each element follows.
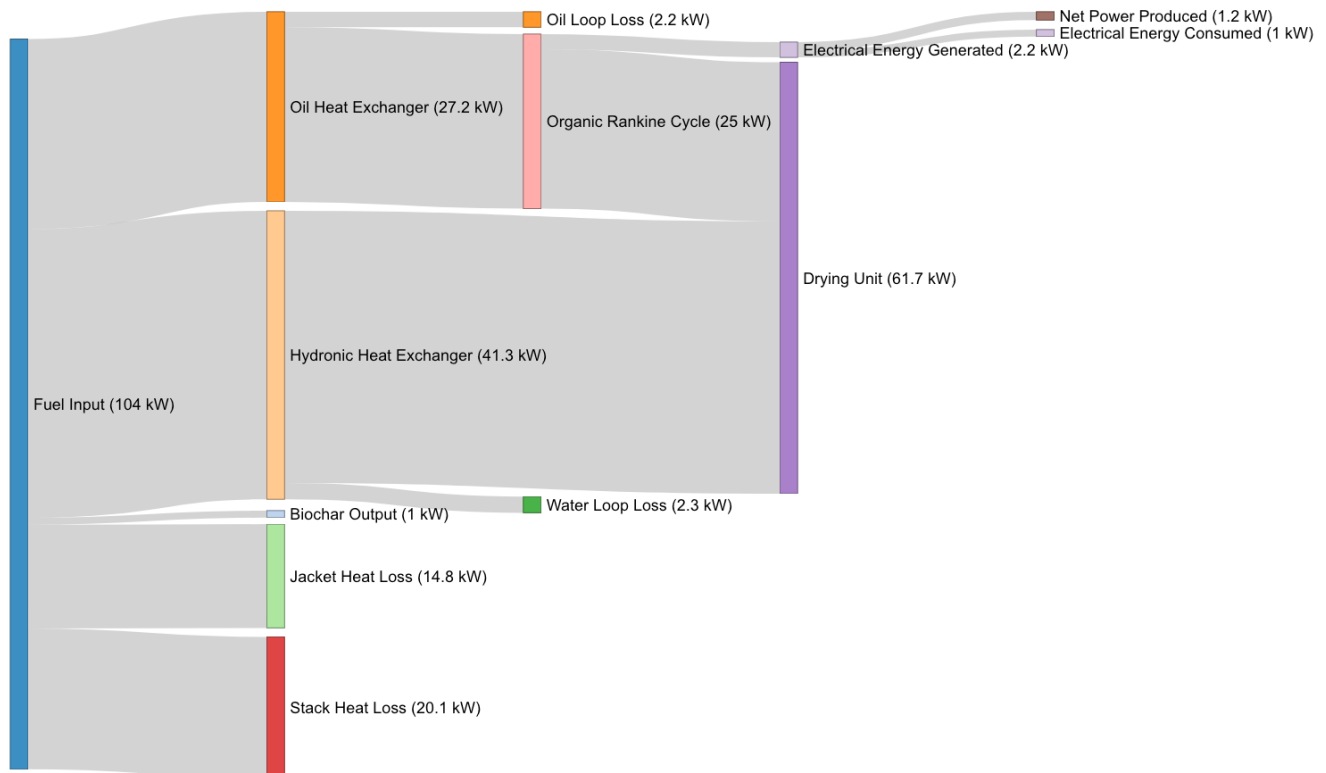

Figure 2. A Sankey diagram of energy flow of the Biogenic Refinery Combined Heat and Power unit during steady-state operation.

Feedstock input

The surrogate feedstock described above was fed steadily into the BR. The fuel feed rate was measured to average 21.1 kg/hr on a dry basis. The calorific value of the feedstock was 19.2 MJ/kg on a dry basis, resulting in a total heat input of 112.5 kWth. Of this, 8 kWth were necessary to evaporate the water contained in the fuel prior to combustion. The remaining 104.5 kWth were released into the system.

Biochar output

An average of 0.108 kg/hr of biochar was produced during operation. The biochar has an estimated caloric value of 33.8 MJ/kg. Therefore, 1 kWth of the original 104.5 kWth released into the system were not combusted and removed as biochar.

Oil working fluid heat exchanger

The oil working fluid heat exchanger circulated Duratherm FG oil through the BR with an average flow rate of 12.7 ± 1.9 L/min, as measured by an ultrasonic flow meter. The average measured temperature of oil coming into the system was 88.2 ± 4 °C and the average measured temperature of oil entering the ORC was 153.5 ± 9.3 °C, both measured with thermistors connected to the BR controller.

Using known thermal properties of the chosen Duratherm oil, it can be calculated that 25 kWth of power were delivered from the system. The thermal energy in the oil loop was continuously transferred to a heat exchanger as part of the ORC system, where a portion of this thermal energy was subsequently converted into electricity. An additional 2.2 kWth were extracted by the oil heat exchanger, but were dissipated as "loop losses", or thermal energy losses through the oil pipe assembly into the ambient air.

Hydronic heat exchanger output

The hydronic heat exchanger circulated water through the BR with a measured flow rate of 13.8 ± 6.6 L/min. The average measured temperature of water coming into the system was 36.3 ± 7.7 °C and the average measured temperature of water exiting the system was 81.7 ± 5.4 °C .

Using known thermal properties of water, it can be calculated that 38.9 kWth were delivered by the hydronic heat exchanger. This thermal energy was continuously dissipated through a radiator to simulate a connected, upstream fuel drying system. An additional 2.3 kWth were extracted by the hydronic heat exchanger, but were dissipated as "loop losses", or thermal energy losses through the water pipe assembly into the ambient air.

Jacket and stack losses

Jacket and stack heat losses compose the remainder of the unaccounted for power leaving the system. A total of 14.8 kWth account for jacket heat losses and the remaining 20.1 kWth are estimated to be stack heat losses. The pyrolysis-combustion module had a measured average surface temperature of 141.5 °C. The result is an estimated jacket heat loss of 7.1 kWth, of which 2 kWth were due to convection and 5.2 kWth due to radiation. The oil working fluid heat exchanger module had an average surface temperature of 130.2 °C. The result is an estimated jacket

heat loss of 5.7 kWth, of which 1.3 kWth were due to convection and 4.5 kWth due to radiation. The hydronic heat exchanger had an average surface temperature of 68 °C. The result is an estimated jacket heat loss of 7.1 kWth, of which 0.7 kWth were due to convection and 1.3 due to radiation kWth.

The ambient air temperature was 25.6 ± 0.5 °C. The average temperature leaving the pyrolysis-combustion module was 880.8 ± 28.1 °C. This temperature exceeds IWA 28:2018 temperature threshold requirement for pathogen free outputs. The average temperature leaving the oil working fluid heat exchanger module was 210.3 ± 64.1 °C. The average temperature leaving the hydronic heat exchanger module, or the entire BR, was 110.6 ± 4.4 °C.

Table 2 shows the complete thermal power balance. Out of 104.5 kWth that went into the BR in the form of fuel, a sum of 64.9 kWth were captured as thermal power output, while a total of 39.5 kWth can be accounted as power losses.

Electrical power balance

During steady-state operation of the Biogenic Refinery, the ORC generator was engaged and allowed to produce power. The ORC received approximately 25 kWth of power from the oil working fluid heat exchanger. This was converted into approximately 2.2 kWe of electrical power, an efficiency of 8.8 %, slightly exceeding the nominal 8% efficiency of the ORC. For the purposes of this test, the electrical power was released through a heating element and not used to power the system or charge a battery.

The average power draw from the BR CHP system during steady-state was 1 kWe. Figure 4 shows the power consumed by the CHP system compared to the power generated by the ORC during steady-state operation. The BR CHP system produced 1.2 kWe net power as the calculated difference between these terms.

Conclusions

The present study demonstrated that the BR CHP system is capable of simultaneously meeting two key criteria of the

Table 2. Final power balance.

Parameter	Thermal Power (MJ/kg)
Fuel Input	104.5
Biochar Output	1.0
Oil Heat Exchanger	25.0
Oil Loop Loss	2.2
Hydronic Heat Exchanger	38.9
Water Loop Loss	2.3
Jacket Heat Loss	14.8
Stack Heat Loss	20.1

The thermal power balance is visualized as a Sankey Diagram in Figure 3.

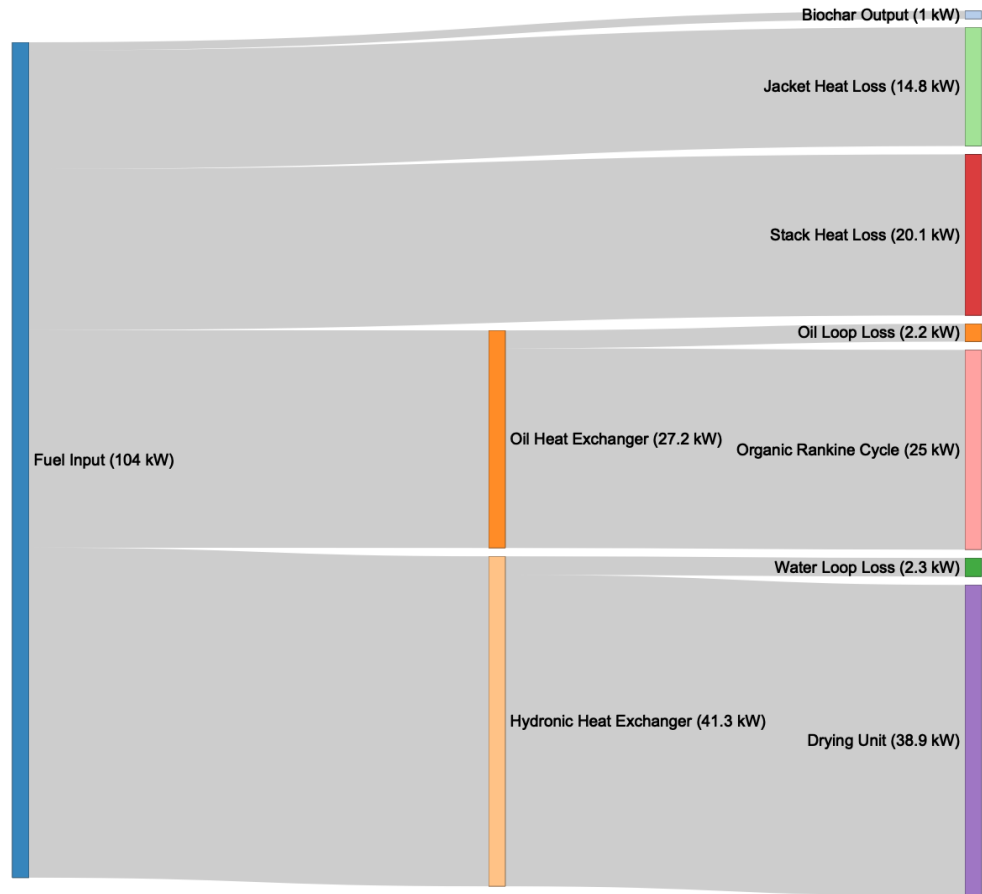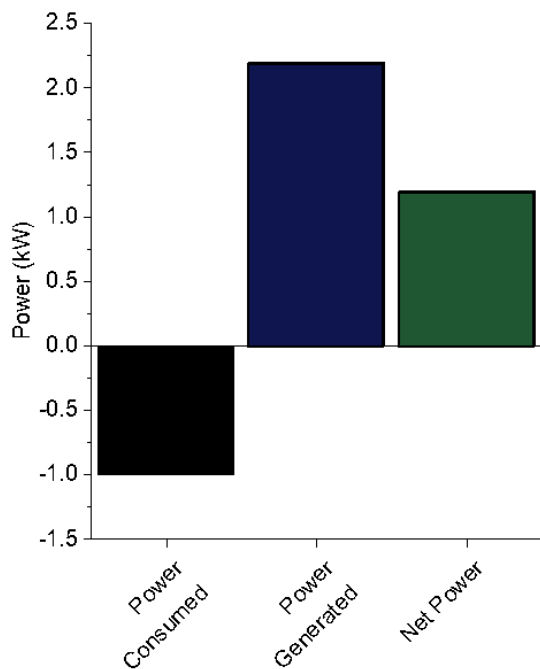**Figure 3.** Thermal power balance of the Biogenic Refinery.

Figure 4. Electrical power balance of the Organic Rankine Cycle.

emerging standard for community scale FSTU, ISO/PC318. Inactivation of pathogens was fast and consistent. The average treatment temperature of the BR ensures pathogen free outputs exceeding the CFR 40 Part 503 and emerging standard ISO/PC318 pathogen threshold requirements, though this will have to be demonstrated through the compliance testing required by the ISO/PC 318 standard (US EPA, 2018). Further, the energy contained in the fecal sludge can be effectively utilized through thermal oxidation, freeing it for use to meet the electrical needs of the FSTU. The BR CHP system produced an electrical energy surplus of 1.2 kW.

This demonstration does not fulfil all of the requirements of the emerging standard. In addition to this energy positivity, a true energy independent system needs suitable energy storage and management techniques. Further, system safety, reliability, and usability, and pathogen output levels must all be verified through official certification testing, upon completion of the emerging standard. While all of these will be the subject of future efforts, the present work shows promise for a near term solution to the global need for community scale waste management.

Data availability

Underlying data

This project contains the following underlying data –

- Raw (folder containing raw data for all calculations)

- chp_article_data_tables_metadata.md (Metadata for all data tables)

Data are available under the terms of the Creative Commons Zero "No rights reserved" data waiver (CC0 1.0 Public domain dedication).

Software availability
R Markdown manuscript showing underlying source code for calculations. https://github.com/larnsce/chp-article/blob/master/manuscript/chp_research_article_manuscript.Rmd

Archived source code: http://doi.org/10.5281/zenodo.2562836 (Schoebitz, 2019)

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Open Peer Review

Current Peer Review Status: ? ✓ ✓ ?

Version 1

Reviewer Report 06 September 2019

? **Bryan W. Weber** (ID)

Department of Mechanical Engineering, University of Connecticut, Storrs, CT, USA

The authors describe a new system for treatment of waste products, focusing on fecal sludge. The system is demonstrated to produce electrical power in excess of its needs during steady state operation using an organic Rankine cycle. In general, the paper is well-written, and the results are important and relevant to the community. I have several concerns about the presentation of the methods and results and some of the calculations could use more explanation, as detailed below.

Introduction, third paragraph:
- The authors presuppose the conclusion of their study here, which is inappropriate at this point. It would be better to say that the objective of the present study is to determine whether such an FSTU system is capable of producing neutral or excess power and leave the conclusion about this hypothesis until the conclusions section.

Methods:
- I find the description of the operation of the system to be very confusing and Figure 1 does not clarify the system sufficiently. Where on Figure 1 is the pyrolysis/combustion occurring? Where are the stack gases directed? Do they go through the oil heat exchanger first, and then through the hydronic system? The authors should label each working fluid in the loops on the diagram. In addition, I do not see the hydronic heat exchanger module on the figure. What are the "Dryers" on the figure?

- The authors should state typical pressure and temperature values in their work of the oil, water, and ORC working fluids.

Description of ORC:
- The authors state "the heated water is used for heating" but do not specify heating of what. What is the water heated by the rejected energy from the ORC used to heat? I believe the authors clarify at the end of the paragraph that the ORC cooling water is combined with the hot water from the hydronic system for drying, but it is not clear.

- Other questions about the ORC overall: What is the working fluid in the ORC? Who is the manufacturer? Is it an off-the-shelf component or custom-built? How is the power output controlled? Is the listed generation capacity the net or gross capacity (does it account for the pump work)?

- I find the discussion of the ORC nominal efficiency to be confusing. This may be because I am not clear about the distinction between the energy transfer from the oil to the ORC working fluid and from the ORC working fluid to the cooling water in this paragraph. My understanding from reading the paragraph is that the hot oil is used to heat the ORC working fluid, and all of the energy from the oil is transferred to the ORC working fluid. The ORC uses 8% of this energy to produce electrical power output, and the remainder can be used for other purposes.

- If this is correct, I'm curious why the efficiency of the ORC is so low. If the temperature of the working fluid is high enough to support further heat transfer after expansion, it seems that additional electrical energy could be extracted. If the temperature of the working fluid after the expansion is relatively low, then it cannot be used for heat transfer. Clarifying this paragraph would significantly help understanding the results, so I think the authors should revise this paragraph substantially.

Feedstock:
- The authors should state how the heating value of the wood pellets is determined and give an uncertainty on the measurement if possible. What is the "appropriate mass of water"? How is the water content of the wood pellets prior to mixing determined? How is the water content of the wet sawdust mixture confirmed?

Thermal power balance test:
- What sort of heat sink was used to replace the ORC? How much power did it absorb compared to how much it is rated to absorb? Was the energy balance of this component checked?

- How is the system brought to steady state? What criteria are used to determine that the system is operating at steady state? The authors could show a typical time-history plot of key measured variables in the system to demonstrate the phases of operation and when the system reaches steady state.

- Eq 1: Typically, symbols that represent power values have a dot over the symbol. I find the phrase "Q_OHX is the thermal power extracted transferred to the working fluid by the oil working fluid heat exchanger" to be very confusing. Which working fluid of which component? Why is working fluid repeated twice? The authors should clarify what is meant here, and try to replace the phrase "oil working fluid heat exchanger" where it appears elsewhere.

- Eq 4: Given that both density and specific heat are functions of temperature, this equation should be an integral with respect to temperature. How did the authors handle these variations? The phrase "whose thermal" should be "whose thermal properties".

- The sentence prior to Eq. 7 has an extra "is". Same comment about density and specific heat being functions of temperature as for Eq. 4.

- The sentence "During steady-state operation, water, oil and air temperatures of gases" does not make sense to me. Can the authors clarify? The authors should label the location of each

thermocouple/thermistor on Fig. 1.

- "Although thermal energy is provided by the BR for drying incoming feedstock": Is the feedstock dried to lower than 35% moisture content? If so, how low?

Results:
- Overall in the results section, the authors are inconsistent about indicating uncertainties in measured and calculated quantities. They should present uncertainties for all of these quantities in the article, and also describe how the uncertainties are estimated or calculated.

Thermal power balance:
- The Sankey diagram in Fig. 2 includes electrical energy output, but the authors stated that the ORC was taken out of the loop for the thermal power balance test. This seems inconsistent and the authors should please clarify. The authors note in the text that the fuel input power is 104.5 kW but only show 104 kW on the diagram, although other numbers are specified to one decimal place. The authors should be consistent.

Feedstock input:
- The authors should explain how the number of 8 kW was calculated for the evaporation of water.

Biochar output:
- The authors previously stated that the heat of combustion of biochar is 32.3 MJ/kg, but here they list 33.8 MJ/kg as the caloric value. Which is correct, and which was used?

Oil working fluid heat exchanger:
- How did the authors estimate that 2.2 kW were lost in the oil loop? Are these the pipe losses discussed previously? In that context, they were mentioned only for the pipes carrying ORC working fluid.

Jacket and stack losses:
- The authors previously stated that jacket and stack losses would be lumped together due to difficulty in measuring or estimating the required temperatures and flow rates. However, they are separately calculated in this section. How was this done?

Table 2 and Fig. 3:
- What information is present in this table and figure that isn't present in Fig. 2?

Electrical power balance:
- How is the power draw of the system calculated? Does it include all the fans, pumps, electronics, and other accessories necessary to run the system, including the oil, water, and working fluid pumps? I don't think that Fig. 4 adds anything to the manuscript and could be removed.

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and is the work technically sound?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?

Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: Non-Financial: This reviewer has advised several undergraduate student teams in collaboration with staff at Biomass Controls, including the authors of this work. This advising has been part of the normal duties of faculty at the University of Connecticut. Financial: This reviewer's wife is employed part-time by Biomass Controls.

Reviewer Expertise: Combustion, thermodynamics

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 06 September 2019

https://doi.org/10.21956/gatesopenres.14031.r27702

Thomas A. Trabold (iD)
Golisano Institute for Sustainability, Rochester Institute of Technology, Rochester, NY, USA

This paper presents an analysis of a hybrid pyrolysis-combustion system applied to treatment of fecal sludge. I believe the work provides a meaningful contribution to the literature and is suitable for indexing. The comments below are offered to improve the quality of the final manuscript.

- More details need to be provided on the operation of the Biogenic Refinery and the integration of the organic Rankin cycle (ORC).

    - Include a more detailed description of the mechanization of the Biogenic Refinery. For example, why is the system operated as a combined pyrolysis (oxygen free) stage followed by a combustion stage, instead of a single-stage gasification system that would run at higher temperature and provide roughly the same biochar yield?

    - Explain why the ORC is the best energy conversion device. Why is utilizing thermal energy from combustion of syngas generated in the pyrolysis stage in an 8% efficient ORC better than generating syngas that can be converted to electricity at an efficiency of between ~25% (ICE genset) and ~60% (solid oxide fuel cell). If cost was the primary consideration,

this should be stated so.

- In the section on "Description of the ORC electrical generation" include more details on the ORC device, such as the manufacturer and system specifications. I agree with one of the earlier reviewers (Septien Stringel, 2019[1]) that combining a biomass thermochemical conversion system with renewable energy generation to make the integrated system essential net energy positive is quite unique and needs to be emphasized.

- Editorial:

  - Abstract: change "criteria" to "criterion".

  - Keywords: add "biochar" and "pyrolysis".

  - Both "fecal" and "faecal" are used, but need to be consistent throughout the manuscript.

  - Page 3, right column: change "inactive" to "inactivate".

  - Page 3, right column: include "NY" after "Lewiston".

  - Page 5: text under Equations 4 and 7 should change the order of "leaving" and "entering".

  - Page 5, left column: replace "…Duratherm FG whose thermal…" with "…Duratherm FG whose density and heat capacity…".

  - Page 5, right column, bottom paragraph: insert "of" in the phrase "flow rate oil".

References
1. Septien Stringel S: Peer Review Report For: Towards an off-grid fecal sludge treatment unit: demonstrating energy positive thermal treatment [version 1]. *Gates Open Research*. 2019; **3** (1176). Reference Source

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and is the work technically sound?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Organic waste valorization; biofuel production via anaerobic digestion, fermentation, thermochemical processes; fuel cell systems for mobile and stationary applications; food system sustainability

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 08 May 2019

https://doi.org/10.21956/gatesopenres.14031.r27057

✔️ **Swaib Semiyaga**
Department of Civil and Environmental Engineering, College of Engineering, Design, Art and Technology, Makerere University, Kampala, Uganda

I would like to thank the authors for this well written paper. This topic is very relevant, as we are faced with challenges of decentralized faecal sludge management in several urban settings. This study has demonstrated that a Biogenic Refinery (BR) together with a combined heat and power (CHP) can be operated using the energy from a feedstock (faecal sludge) to generate heat and a net positive power in addition to inactivation of pathogens in faecal sludge. The paper can be indexed, after clarification on the following few observations:

- It is a good innovation to have off-grid solutions due to the nature of several places with limited power access, yet in need of such services. However, the study has not shown whether the produced power is enough to run the FSTU.

- The moisture content of the feedstock required in BR is 35%, yet FS can be over 95% water. I understand you mentioned that the dryer unit is not part of this BR-CHP system. However, feedstock preparation by reducing moisture content from 95% to 35% requires vast amounts of energy input. I propose you further analyze the drying requirements of feedstock using the generated heat energy for drying. This is important to check the adequacy of the produced heat in meeting the feedstock drying requirements.

- What is the reference used on 8 kWh requirement to evaporate the initial water in the feedstock? It would also be important to indicate a note that this may vary for different feedstocks.

- Also include the thermal properties of water, as you did for oil.

- There is unnecessary repetition in presentation of results. Information on Figure 3 can be got from Figure 2.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and is the work technically sound?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Faecal sludge management

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 26 April 2019

? **Santiago Septien Stringel** (iD)
Pollution Research Group, University of KwaZulu-Natal, Durban, South Africa

This paper presents the evaluation of a thermal process technology that allows generating biochar, heat and electricity from the treatment of faecal sludge. The technology was evaluated through an energy balance where the key parameters were determined from measurements during the operation of the machine. The authors concluded that this process enables reaching high enough temperatures to ensure pasteurization of the output streams and it was demonstrated to be energy positive. Both criteria are important to achieve certification of the technology under the ISO/PC318 standards that are currently under development.

My major critique of this work is that its originality is not emphasized enough and there is a lack of analysis of the results. As currently written, the paper looks more like a report of results than a scientific paper. The technology presented in the paper is novel because it combines a small-scale faecal sludge thermal treatment process with a unit for electricity generation. This feature is rare for the processing of faecal

sludge at such a small scale. The authors should insist in this novelty that makes their technology unique, and the different sections of the papers should be re-written accordingly. On the other hand, the results section could also display the experimental results obtained during the operation of the process, and not only focus on the results of the calculations. Moreover, the results from the calculations should be analysed in a deeper level. For example, the authors could include the determination of the thermal efficiency of their process, explain the reasons of efficiency losses and propose eventual solutions to improve this. Concerning the written quality of the paper, most of the parts are clear and well-structured, nevertheless a few parts are too repetitive or confusing, and some terms are incorrectly employed.

This paper presents a good example of an efficient thermal process technology for faecal sludge treatment that is worthy to be disseminated. Therefore, the indexing of the present paper will be useful for the sanitation community. However, the paper in its actual form needs to be improved significantly before indexing.

I have included, here below, a list of specific comments for the improvement of the manuscript quality.

- General observations:

  - I have never heard about the term "faecal sludge treatment unit (FSTU)". We commonly employ: "faecal sludge treatment plant (FSTP)".

  - Instead of using the term "thermal power balance", it will be more correct to use "heat balance" or "energy balance".

  - The brand and model of instruments should be written in italics.

  - There are too many terms in your keywords (it should be limited to the most 5-6 relevant terms).

- Introduction:

  - General observations: There are not enough references in the introduction. You should include more references about thermal processes of faecal sludge that are currently available or are under development at the different scales, as well as the beneficiation of biochar issued from faecal sludge pyrolysis. You could also include a summary of the relevant results of investigations about faecal sludge thermal decomposition. In all this, you could include references from sewage sludge, which is a similar material.

  - Likewise, you could discuss about the different means to produce electricity in small-scale plants (as your case), and give more information about the organic Rankine Cycle and its applications.

  - In the problem statement and presentation of the scope of your work, you have to emphasize the novelty of your technology with respect to what has been previously done.

  - Paragraph 1, line 16: You must define "energy neutral" and "energy positive".

  - Paragraph 1, line 16-18: The explanation "operate…..sources" is incorrect. You mean that the only source of energy in the process will come from faecal sludge, without the input of

any additional source of energy.

- Paragraph 4, last sentence: You are concluding in the introduction, which is incorrect. This should be placed in the conclusion.

- Methods:

  - Title: Typically it is "Materials and Methods".

  - Figure 1: The captions of figures are conventionally written without any conjugated verbs.

  - Section "Feedstock", paragraph 2, first sentence: The moisture content of 35% is too low to be from a raw faecal sludge. So, I think that you are referring to previously dewatered or dried sludge. You have to specify this.

  - Section "Thermal power balance test", equation 1: You have to introduce the variables in the text (as you have done for the other equations).

  - Section "Thermal power balance test", paragraph 3, line 2: We cannot use the term "complete combustion" as this will imply that the biochar was completely burnt. I suggest to change "not extracted….. feedstock" to "remaining in the solid after thermal decomposition of the feedstock".

  - Section "Thermal power balance test", paragraph 3, line 3: The thermal energy in the biochar cannot be considered as a thermal loss, as this energy can be released in a later stage.

  - Section "Thermal power balance test", paragraph 4, last two sentences: The values of the calorific value of the biochar seem quite high. Are they in ash-free basis?

  - Section "Thermal power balance test", paragraph 5, last sentence: The oil has already been described. Avoid this type of repetition.

  - Section "Thermal power balance test", paragraph 8: The explanation in this paragraph is quite confusing. It is not clear how you calculated the heat losses: did you calculate them through difference using the general heat balance and knowing the other terms, or by the corresponding heat transfer equations?

  - Section "Thermal power balance test", paragraph 10: You must indicate how the feedstock mass flowrate was measured.

  - Section "Thermal power balance test", paragraph 10, line 4 – 5: Avoid advertising the products from Biomass Controls (here in "which could... data collection").

  - Section "Thermal power balance test", paragraph 10, last sentence: There is a full stop (".") missing at the end of the sentence.

- Section "Data management", paragraph 1, line 4-5: I don't understand how the use of open source data tools can enhance collaboration and communication.

- Section "Reproducibility": You don't explicitly mention how you tested reproducibility.

- Results:

  - General observations: This section should show and comment on the measurement of the different parameters of the process during its operation (example: evolution of the temperatures at the different locations as a function of time).

  - Title: Typically, it is "Results and discussion".

  - Section "Biochar output": You could mention the char yield, an important pyrolysis parameter.

  - Section "Oil working fluid heat exchanger", paragraph 1, line 3: You have to mention how you measured the flowrate in the Materials and Methods, not here.

  - Section "Oil working fluid heat exchanger", paragraph 2, line 6: Incorrect use of the word "extract". The 2.2 kWth represents thermal losses, and it is not possible to extract useful energy from it.

  - Section "Jacket and stack losses": You have to comment on the thermal losses. Are these values high or low? Can they be reduced? How?

  - Section "Jacket and stack losses", paragraph 1: You have to indicate in the Materials and Methods how the convective and radiative contributions in the heat losses were respectively calculated.

  - Section "Jacket and stack losses", paragraph 2: You have to be clearer about what the "average temperatures" correspond to.

- Conclusions:

  - General observation: In the conclusion, you have to emphasize that you have proven the feasibility of your process, which presents the novelty to combine heat treatment of faecal sludge at relative small-scale with electricity production. You can also comment about the thermal efficiency of your process and how this could be improved.

  - Paragraph 1, line 4: You cannot say that "the inactivation of pathogens was fast and consistent" without any tests.

  - Paragraph 2: The term of "energy positivity" does not exist.

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and is the work technically sound?

Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Faecal sludge, thermal drying, solar drying, mechanical properties, biochar, pyrolysis, hydrothermal carbonization, photocatalysis

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.