Towards an off-grid fecal sludge treatment unit: demonstrating energy positive thermal treatment [version 1; peer review: 1 approved, 1 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
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Author roles: Myers T: Conceptualization, Formal Analysis, Investigation, Methodology, Project Administration, Supervision, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing; Schoebitz L: Data Curation, Formal Analysis, Methodology, Software, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing; Woolley S: Conceptualization, Writing – Review & Editing; Sanchez Ferragut J: Data Curation, Investigation, Writing – Review & Editing; Thostenson J: Investigation, Writing – Review & Editing; Jooss K: Project Administration, Supervision, Writing – Review & Editing; Piascik J: Conceptualization, Funding Acquisition, Project Administration, Writing – Review & Editing; Frechette A: Methodology; Hotz N: Methodology; Stoner BR: Conceptualization, Funding Acquisition; Hallowell J: Conceptualization, Funding Acquisition, Project Administration, Writing – Review & Editing

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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 (Onabango 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, pair was 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 inactivate 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,
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

$$ Q_{in} = \Delta H_v m_f $$  \hspace{1cm} (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

$$ Q_{in} = Q_{biochar} + Q_{ORC} + Q_{HHX} + Q_{loss} $$  \hspace{1cm} (Equation 2)

where $Q_{biochar}$ is the thermal power leaving through extracted biochar, $Q_{ORC}$ is the thermal power extracted transferred to the working fluid by the oil working fluid heat exchanger, $Q_{HHX}$ is the thermal power transferred to water by the hydronic heat exchange system.
exchanger, and $Q_{\text{jout}}$ 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, $m_{\text{biochar}}$, and the effective heat of combustion of the biochar, $\Delta H_{c,\text{biochar}}$ as

$$Q_{\text{biochar}} = \Delta H_{c,\text{biochar}} m_{\text{biochar}}$$  \hspace{1cm} \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

$$Q_{\text{HX}} = \dot{V}_w \rho_w c_w (T_{w,\text{out}} - T_{w,\text{in}})$$ \hspace{1cm} \text{(Equation 4)}$$

where $\dot{V}_w$ is the volumetric flow rate of oil, $\rho_w$ is the density of oil, $c_w$ is the specific heat of the oil, and $T_{w,\text{out}}$ and $T_{w,\text{in}}$ 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 properties are shown 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

$$Q_{\text{pipe}} = (T_{\text{amb}} - T_{\text{amb}})/(R_{\text{pipe}} + R_{\text{insul}})$$ \hspace{1cm} \text{(Equation 5)}$$

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

$$R = \ln((r_o/r_i)/(2\pi L L + k))$$ \hspace{1cm} \text{(Equation 6)}$$

$$\text{where } r_o \text{ is the outer radius, } r_i \text{ is the inner radius, } L \text{ is the length, and } k \text{ is the thermal conductivity of the material.}$$

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

$$Q_{\text{HX}} = \dot{V}_w \rho_w c_w (T_{w,\text{out}} - T_{w,\text{in}})$$ \hspace{1cm} \text{(Equation 7)}$$

where $\dot{V}_w$ is the volumetric flow rate of water, $\rho_w$ is the density of water, $c_w$ is the specific heat of the water, and $T_{w,\text{out}}$ and $T_{w,\text{in}}$ 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 QT1QTIP68-14F-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, LLCWBN-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, lms 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.

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**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

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<th>Table 2. Final power balance.</th>
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<tr>
<td>Parameter</td>
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<tr>
<td>Fuel Input</td>
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<tr>
<td>Biochar Output</td>
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<td>Oil Heat Exchanger</td>
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<td>Hydronic Heat Exchanger</td>
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<td>Water Loop Loss</td>
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<td>Jacket Heat Loss</td>
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<td>Stack Heat Loss</td>
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The thermal power balance is visualized as a Sankey Diagram in Figure 3.
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/larnsc/CHP_article/blob/master/manuscript/chp_research_article_manuscript.Rmd


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Grant information

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The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

References
Open Peer Review

Current Peer Review Status: ?  ✔

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

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**Santiago Septien Stringel**
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 have read this submission. I 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.