Journal of Engineering Research and Reports

21(9): 27-44, 2021; Article no.JERR.79225
ISSN: 2582-2926

Dual Fueling a Lister Diesel Engine with Producer Gas Generated from Wastepaper and Biosolids

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JERR/2021/v21i917489

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/79225

Original Research Article

Received 09 October 2021
Accepted 18 December 2021
Published 20 December 2021

ABSTRACT

The aim of this study is to investigate if wastepaper and biosolids can be used to dual-fuel a small diesel generator with producer gas produced by a tiny Imbert style downdraft gasifier. The waste paper was formed into 20 cm^3 to 60 cm^3 chunks, dried to a 6% moisture content and gasified. The energy potential that could be provided was up to 3.24 kWh/kg at a diesel usage of 60 ml/6 min Chunks made from Wastepaper and biosolids showed a higher energy output of up to 9.23 kWh/kg at a diesel usage of 45 ml/6 min. run. However, chunks containing waste paper showed not to be a valid fuel option due to its low density, difficulty to gasify, tar production, and tendency to hang up in the gasifier, which caused difficulties in the gasifier and engine and system operation overall.
Biosolids chunks with a volume of 15 cm^3 have the potential to provide up to 3.6 kWh/kg at a diesel usage of 5 ml/6min without operational problems in regards to tar formation and operational stability and energy generated by the genset system.
A ton of biosolids could generate up to 3,600 kWh of energy. Additional savings for disposal of biosolids including trucking could be realized based.

Keywords: Biomass; biosolids; downdraft Imbert style gasifier; dual fueling; gasification; wastepaper chunks.

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1. INTRODUCTION

Today's civilisation is reliant on natural resources for its material resources. Solid, liquid, and gaseous fuel resources are now the most commonly employed to meet the world's energy needs. During US colonial times, wood was the dominant fuel resource, which was surpassed by coal in 1885. In 1949 coal was surpassed by petroleum, followed by natural gas in 1957. Since then, in a single generation the use of petroleum and natural gas quadrupled [1]. The ever-growing energy demand of the increasing population and industry at the end of the 19^{th} century initiated the use of biomass fuel to offset fossil fuel usage. This all resulted in a global temperature rise, known as global warming, over the past 140 years [2]. Associated with global warming, a rise in the CO_2 level in the atmosphere can be noticed [3]. The United States will consume 18,19 million barrels of crude oil per day in 2020 [4]. As a result, achieving energy independence from foreign sources is of tremendous national importance in the United States.

According to the Unites States Census Bureau Energy, the U.S. population more than doubled from 1950 to 2020 to over 331,449,281 and is expected to grow by 79 million by 2060 reaching the 400 million thresholds by 2058 [5, 6]. Energy consumption in 2019 has reached a total of 100.2 quadrillion British thermal units (Btu)/day in [6]. It is expected according to the U.S. Energy Information Administration (EIA) that the renewable energy increases from 21% in 2020 to 42% in 2050 for electric energy production [7]. According to EIA [8], fossil fuels will provide 69 percent of the energy consumed in 2020, with petroleum accounting for almost 35 percent, natural gas 34 percent, and coal 10 percent. Nuclear energy provided 9% of total energy consumption, with renewable energy accounting for around 12%. For the renewable energy sector, biomass feedstock accounts for 39%, wind for 26%, hydroelectric for 22%, solar for 11%, and geothermal for 2% of the total US renewable energy consumption, making biomass the single largest renewable energy source in the U.S. [8]. Indeed, photosynthesis converts solar energy into biomass of up to 220 billion metric tons a year. This biomass can be converted into approximately 10 times today's world energy consumption [9]. A U.S. joint study between the Department of Energy (DOE) and the U.S. Department of Agriculture (USDA) identifies sources for biomass feedstock and estimates an annual biomass of 1,366 million dry tons available for the production of biofuels and energy from forest and agricultural resources [10]. Biomass power is often considered carbon neutral, depending on how carbon neutrality is defined [11].

Because fossil fuels, the world's current principal source of energy, are finite, rising energy and material resource prices are forcing industrial, commercial, agricultural, and municipal companies in the United States and many other countries to create more sustainable modes of operation [12,13]. Many studies suggest that the costs of fossil fuel exploration and extraction will continue to rise, perhaps to unprecedented levels [13-16]. There is a growing demand for low-tech, low-cost solutions to our energy, resource, and waste management concerns in both the United States and the developing globe. Finding acceptable technologies for alternative energy systems will be one of the solutions to reducing the negative effects of fossil fuel use [17]. Biomass energy is not in an ideal form for direct use and requires conversion technologies such as: 1) biochemical (the use of enzymes and yeast - which is costly and time-consuming), or 2) thermochemical which is the fastest, cleanest and most efficient [18]. The thermochemical conversion of biomass includes: pyrolysis, combustion and gasification of the biomass. Gasification with air results in producer gas, a mixture of carbon monoxide, hydrogen, methane, carbon dioxide and nitrogen gases [19]. Gasification can potentially convert 60%-90% of the biomass energy into a gas that can then be burnt to produce industrial or residential heat, run engines for mechanical or electrical power, or to produce synthetic fuels [20]. Various designs exist for gasification, most commonly fixed bed, fluidized bed, updraft and downdraft gasifiers. These designs are based upon the input of oxidizer flow and the direction of gas output in the system.

The thermo-chemical and biochemical methods are now employed to transform biomass into energy. One of the four basic processes of thermochemical conversion of biomass to energy is gasification, which produces syngas or producer gas. The other three are combustion, pyrolysis, and liquefaction [21]. Brusca et al. [22] propose using gasification to generate energy from glycerol, a major byproduct of the production of biodiesel, a biochemical process. The glycerol undergoes steam reformation and is gasified in this thermo-chemical process.

Gasification is heating a carbonaceous material with a limited amount of a gasifying agent, typically oxygen, air or steam to produce syngas if the gasifying agent is steam or oxygen or to produce producer gas if the gasifying agent is air. It is a thermochemical process, which increases the hydrogen to carbon content of the feedstock [23]. Most of the fuel energy in syngas or producer gas is derived from its CO and H_2 content. Syngas and producer gas also usually contain lesser amounts of CO_2 and CH_4, producer gas also contains approximately 50% N_2. Other names for syngas depending on the feedstock, gasifying agent or time and place of production include town gas, water gas and blast furnace gas. Producer gas is sometimes known as wood gas if the feedstock is wood. Gasification has four stages; drying, pyrolysis, oxidation and reduction [24]. The heat generated in the oxidation stage powers the other three stages: it dries the fuel in the drying stage, pyrolyzes the combustible gases out of the fuel in the pyrolysis stage, and reduces the fuel to make syngas or producer gas in the reduction stage. Syngas, often known as producer gas, is mostly produced through the chemical processes listed below [12,25,26,27]:

CHxOy (biomass) + O2 (21% of air) + H2O (steam) = CH4 + CO + CO2 + H2 + H2O

(unreacted steam) + C (char) + tar (1)

2C + O2 = 2CO (partial oxidation reaction)(2)

C + O2 = CO2 (complete oxidation reaction) (3)

$C + 2H_2 = CH_4$ (hydrogasification reaction)(4)

$C + H_2O = CO + H_2$ (water gas reaction) (5)

$C + CO_2 = 2\,CO$ (Boudouard reaction) (6)

$CO + H_2O = CO_2 + H_2$ (watergas shift reaction) (7)

$CO + 3\,H_2 = CH_4 + H2O$ (steam reformation reaction) (8)

The fractions of the products are determined by the temperature and residence time of the reactants, which are influenced by the amount of gasifying agent used and the gasifier design. Gasification avoids the complex treatments and conditions typical of fuels obtained from pyrolysis, liquefaction, and biochemical processes by breaking down all of the biomass into mostly simple gases. Syngas and producer gas, on the other hand, frequently contain pollutants such as ash, sand, char, and tar. Internal Combustion Engines (ICEs) are more tolerant of pollutants than turbines, making them better suitable for usage with syngas or producer gas, especially in smaller systems where equipment cost is a major consideration, as they do not require as large a clean-up train as turbines [28,29, 30]. Tar is a major problem as a contaminant in syngas or producer gas used in any engine as it tends to stick and plug pores in filters and engine components it comes in contact with [31]. In small engines using a downdraft gasifier such as the Imbert gasifier using appropriately sized fuel with a low moisture content and operating it at a appropriately high combustion temperature is a good way to avoid tar problems [20,32]. Imbert gasifiers were used extensively during petroleum fuel shortages in WWII to power motor vehicles, even airplanes [33].

The composition of producer gas can vary widely due to biomass type and gasifier conditions. The typical composition of producer gas by volume may be in the range of 18–20%H_2, 18–20%CO, 2%CH_4, 11–13%CO_2, traces of H_2O and balance N_2 [34]. A Lower heating Value (LHV) of carbon monoxide is 10 MJ/kg, the LHV of hydrogen is 120 MJ/kg [35]. Thus, any process that generates producer gas or syngas aims at maximizing the amount of hydrogen.

Airflow rate is one of the key parameters effecting gasifier performance. Airflow rate in gasifiers is usually stated as Equivalence Ratio (ER) or Superficial Velocity (SV) [25]. Equivalence Ratio is the ratio of the amount of air entering the gasifier to the amount needed for the complete combustion of the burning biomass. Superficial Velocity is the airflow rate (volume/ sec) divided by the area of the narrowest portion of the gasification zone resulting in a velocity (length/ sec). Increasing the ER from a minimal value towards 0.5 generally increases temperature but decreases residence time, increases gas production but decreases the LHV of the gas (because more of the fuel value of the biomass is combusted), and lowers the tar content of the producer gas or syngas [25]. Generally, for gasification there is an optimal ER in the range of 0.2 –0.4 [25,36], that results in a fairly energetic gas with low tar content. SV also seems to have an optimal range of 0.4 – 0.6 m/s, a SV of 0.7 m/s increases tar production, probably due to a lower residence time [25, 35, 36].

Properties of Producer Gas (PG) compared with Pure Combustible Fuel Gases (PCFG) + Air is shown by Szwaja et al. [37] can have a range in Lower Calorific Value (LCV) between 5.0 and 121 MJ/kg [21]. Gasification temperature also greatly effects producer gas composition. Generally, gasification at temperatures between 800 C and 900 C favor CO and H_2 production (higher heating value), higher producer gas yields and less tar [25]. Unfortunately, gasification at 800 C or higher also favors the formation of slag or clinkers from ash [38].

At first glance, it would appear that power derating for a gasoline or diesel engine operating on producer gas would be severe given the disparity of the fuel's LHV values. However, the derating is mitigated by the disparity of stoichiometric air/fuel ratios for the two fuels, 1.2 for producer gas and 14.9 for gasoline or 14.5 for diesel fuel [34,39,40]. Thus, the amount of energy burned in the engine per revolution is not as different when operating on producer gas or petroleum fuel as the difference in LHV would imply. Typically, ICEs are derated by approximately 30 – 40% when operated on producer gas rather than petroleum fuel [32,41]. Compared to combustion of the same biomass, gasification generally results in lower emissions of carbon monoxide, sulfur and nitrogen compounds such as NO [29]. Trading off nitrogen compound emissions with exhaust gas recirculation and retarding of the injection/ ignition timing may lead to an optimal condition where nitrogen compound emissions and engine power and operation are acceptable [42]. Integrated gasification combined cycle (IGCC) systems for power and heat production have been shown to offer better energy efficiency and environmental performance than conventional combustion-based technology [29]. IGCC systems extract power from surplus heat generated by the gasification and burning of fuel via steam powered turbines [43].

Electrical generation using a producer gas powered engine might be applicable as a means of reducing greenhouse emissions and providing electricity in rural areas, which typically have available biomass [34]. A big advantage of producer gas use in spark ignition (SI) engines as opposed to compression ignition (CI) or diesel engines is the ability to run on producer gas fuel alone rather than in the dual fuel mode necessary in CI engines operating with producer gas, thus eliminating the need for any petroleum fuel. High thermal efficiency is possible with producer gas fueled SI engines resulting from higher compression ratios allowed by the high antiknock characteristics (low flame speed) of CO and CH4 and diluents N2 and CO2 in producer gas compared to those possible in gasoline powered SI engines [34]. These counteract the knocking tendencies (high flame speed) of the hydrogen in syngas and also decrease the cylinder temperatures and pressures and lower NO_x emissions [34]. It should be noted, that much of the energy in producer gas comes from its hydrogen content. Without increasing the compression ratio, a SI gasoline engine running on producer gas is estimated to have a thermal efficiency of 10% - 15% as opposed to 15% - 20% running on gasoline due to the lower energy content of the syngas – air mixture compared to the gasoline-air mixture [44]. However, milling of the engine block and/or cylinder head and/or changing the engine pistons is necessary to increase the compression ratio of a gasoline SI engine.

Producer gas is used as fuel in diesel or compression ignition engines in the dual fuel mode in which diesel fuel is used as the pilot fuel and producer gas is introduced through the engine intake air and provides the bulk of the fuel charge [12, 43, 26, 27].

The pilot fuel is necessary to ignite the producer gas as the producer gas auto-ignition temperature (500°C) is higher than is achieved by the fuel charge in the diesel engine on the compression stroke [45,46], although Reed reports that a slow speed, single cylinder, direct injection diesel engine was able to run on 100% producer gas for extended periods when operating conditions allowed [20]. Dual fueling diesel engines with a compression ratio greater than 17:1 may not be practical [47]. The amount of diesel fuel necessary as the pilot fuel is variable and largely depends on the quality and energy content of the producer gas [41]. The Food and Agricultural Organization of the United Nations (FAO) recommends a minimum of 8 – 9 cubic mm of diesel per cycle as pilot fuel for stable combustion [48]. Producer gas is able to substitute 60% - 90% of the diesel fuel required to run a diesel engine at a specific power level [20,49]. Dual fueling a diesel engine allows use of a lower energy producer gas or one that varies more in energy content [41] than would be practical in a spark ignition engine. The diesel engine governor in dual fuel mode increases or decreases the amount of diesel fuel injected as necessary to maintain engine output in the face of decreasing or increasing producer gas energy content [12, 43, 26, 27].

According to Raman and Ram, the dual fuel energy efficiency of a diesel engine is roughly 20% when using producer gas, however this efficiency is only attained when the engine is running at full power, and efficiency drops rapidly at partial load and throttle settings [50]. They state that at full load diesel engine power generation efficiency is about 28%, this falls off to about 17% when the diesel engine is operated at 20% load. Producer gas power generation efficiency is reported as 21% at full load and only 9 % at 20% load [50], a much steeper drop in efficiency than for the diesel engine power generation efficiency going from full to partial load [12, 43,26, 27].

Emissions from dual fueled (producer gas and diesel) compression ignition (CI) engines are generally less than when running on diesel alone. Greenhouse CO_2 is reduced by the degree of substitution of biomass-based producer gas for diesel as biomass generally is considered carbon neutral [44], depending on the definition of carbon neutrality [11]. SO_2 and SO_3 are considered culprits in acid rain production [44] and are reduced from levels emitted from a diesel engine running on 100% diesel when the engine is dual fueled with producer gas [29]. According to Whitty et al producer gas has a much wider ignition range than conventional hydrocarbon fuels so it can be burned leaner, reducing CO emissions over levels obtained from burning diesel [29]. Particulate matter (PM) emission levels are also reduced from diesel levels when the engine is dual fueled with producer gas [23,51]. In well-tuned dual fuel system VOC (volatile organic compound) emission levels are reduced from those obtained from a CI engine running on 100% diesel [29,26].

Nitrogen oxide (NO_x) compounds are considered the major cause of ecosystem acidification [44]. They are generated from the oxidation of N_2 which can happen in engines at combustion temperatures greater than 2500 °F [29]. NO_x emissions increase with increasing flame temperatures, also with the amount of excess air and with the degree of fuel-air mixing [29]. NO_x emissions increase with higher ratios of nitrogen containing fuel and sulfur containing fuel [29]. Thermal effects dominate, however, [29,44,51] so controls that lower combustion temperatures including those developed for other gas fired technologies such as water injection and exhaust recirculation can be effective [29] using producer gas as fuel. Some balancing of emission controls may be necessary to achieve acceptable emission levels for different pollutants. For example, higher compression ratios raise combustion temperatures increasing NO_x emissions but decrease CO emissions [12,43,26,27].

The downdraft Imbert-style gasifier as shown in Fig. 1, has been proven to be the most successful design for small scale power generation due to its low tar production, an inhibiting by-product of the process. Downdraft gasification has not yet been successful for large scale (MW) power production. The downdraft gasifier has 5 major zones: drying, conversion, charring, oxidation, and reduction zone. The Imbert design is a downdraft design in which the gasifier contains a throated combustion zone such that the diameter for the pyrolysis zone decreases into and through the combustion zone and increases again through the reduction zone [17,43,26].

Gasifiers are rather straightforward devices. Their operation's mechanics, such as feeding and gas cleanup, are likewise straightforward. The successful operation of gasifiers, on the other hand, is not so straightforward. Because the thermodynamics of gasifier operation are not fully understood, there are no clear guidelines. Nonetheless, the temperature, air supply, and other operating variables of the reactors we create are governed by nontrivial thermodynamic rules[21]. Biomass largely consists of hydrocarbons. Hydrocarbons combined with the proper amount of oxidizer break down largely into the fuel gases hydrogen, carbon monoxide and methane starting at temperatures above 600 °C (1112 °F) [20]. Reaction times at this temperature are comparatively slow and the breakdown of hydrocarbons at lower temperatures tends to produce larger amounts of tar. For these reasons, gasifiers are generally operated such that the temperatures in the combustion and reduction zones are 700 °C (1292 °F) to 1000 °C (1832 °F) [43]. Prolonged operation at temperatures above 1000 °C requires that the gasifier is built from more expensive heat resistant materials [12,26,27, 52].

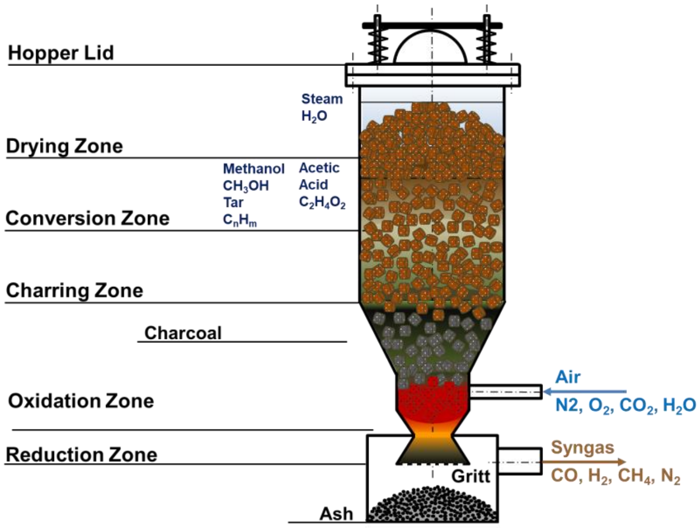

Fig. 1. Imbert Style Gasifier Image [26]

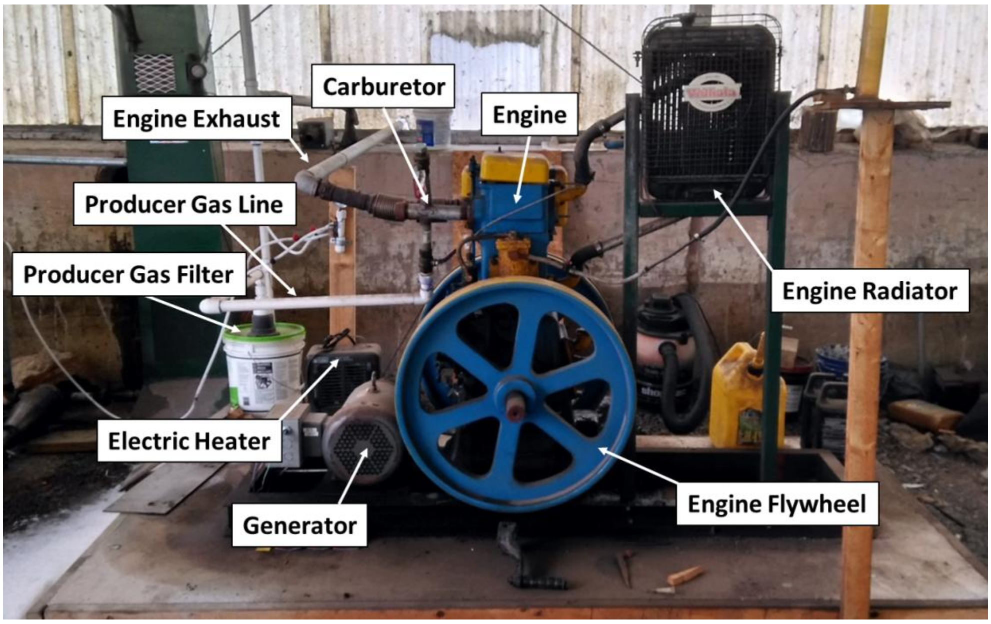

Fig. 2. Genset [27]

A pilot-scale downdraft, Imbert-type research gasifier system shown in Figs. 2 & 3 below was designed and constructed to be used at Clearwater Educational Research Facility (CERF), located at the municipal wastewater treatment plant of Minoa, NY [43,26,27]. The System contains a Basant 6hp (4.5kW), 650 rpm, 1 cyl., 1.4l Lister diesel engine and a Baldor squirrel cage induction motor MM3709 230/460 V, 7.5hp (5.6 kW), 3 phase, 3500 rpm motor with a D1325 frame. A 1500-Watt 120 Volt portable electric heater is used as a load for the generator. The designed research gasifier system operates as follow: First, the producer gas generated in the gasifier is cooled in the producer gas radiator. Then filtered in the hay filter and mixed with a small amount of outside air in the engine carburetor. The engine governor controlled the amount of diesel mixed with the producer gas air mixture to be ignited and to maintain a constant engine speed. Insufficient producer gas or weak producer gas is overcome with a larger amount of diesel added to the mixture for combustion.

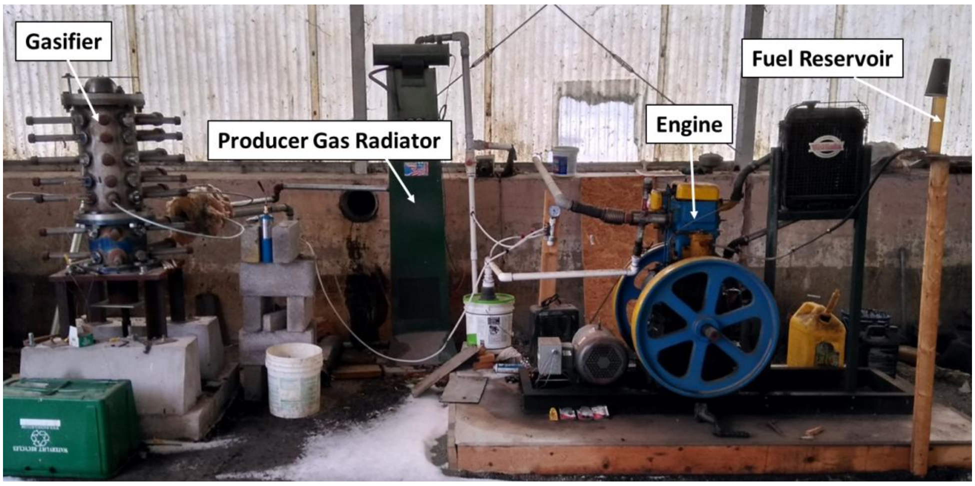

Fig. 3. Gasifier Genset System [27]

The research gasifier system allows to study in small pilot scale of dual fueling the diesel-powered gen-set with producer gas produced from sewage sludge and other feed stock. Sewage sludge is produced at the Minoa Waste Water Treatment Plant (WWTP) from its Sequential Batch Reactor (SBR).

According to the EPA, the average person in the US generates about 1/8 kg (dry basis) of sewage sludge per day, with approximately 13,000 to 15,000 publicly owned treatment plants generating 110 – 150 million tons of wet sludge annually [52,53]. Given the projected US population increase of 42% by 2050, these numbers may increase to 150 – 215 million tons annually by 2050. Disposal of sewage sludge is a major expense for small municipalities like Minoa, NY. Landfill disposal cost can be over $90 per metric tons of the generated 200 to 230 metric tons per year, not including the cost of transporting the sludge to the landfill facility [28]. By generating electricity from the sludge small municipalities can avoid much of the cost of disposal of what is considered hazardous waste and in addition can offset the cost of electricity used by the municipality.

Wastepaper (paper and cardboard products) as determined experimentally using a bomb calorimeter has a higher heat of combustion, 3.66 watt-hours (Wh)/g, than sewage sludge, 3.04 Wh/g, and burns more readily in the calorimeter [54].

Producer gas is generated from a gasifier when the oxidizing agent is air, its main constituents are carbon monoxide, hydrogen and nitrogen. Syngas is produced from a gasifier when the oxidizing agent is steam or oxygen, its main constituents are carbon monoxide and hydrogen [55]. Producer gas has a lower heating value (LHV) of 4 – 7 MJ/NM^3, syngas has a higher LHV of 10 – 28 MJ/NM^3 [56] because it is not so heavily diluted with inert nitrogen.

The average person in the US generated approximately 1.25 lbs. of wastepaper per day in 2015 [21, 57]. According to the EPA, approximately 40% of a typical landfill in 2007 was made up of paper products [21], showing that ample wastepaper is available to mix with sludge for gasification without reducing the amounts of paper currently recycled for making paper or energy via combustion. The goal of this project is to explore the feasibility and cost effectiveness of gasifying and producing electricity from the sewage sludge and wastepaper Minoa produces and avoid much of the cost of disposal of what is considered hazardous waste and in addition offset the cost of electricity used by the municipality.

This study explores the usage of sewage sludge and paper waste for possible dual fueling of a small genset powered by diesel and producer gas from a sewage sludge and paper fueled gasifier.

2. MATERIALS AND METHODS

2.1 Gasifier System Start Up

Successful operation of a gasifier requires an adequate char-bed for each run that is formed from the leftover pyrolyzed fuel from the previous run. Based on operating experience, the char bed should extend to the lighting port or air intake nozzles of the gasifier. To produce a suitable char bed for the later dual fueling runs wood chips of an approximately size of 2 cm X 2 cm X 0.6 cm were used. The wood chips were dried to approximately 7% moisture content. The gasifier system was operated as described by Bates & Doelle [12,43,27] for approximately 30 minutes to form a suitable char bed for the dual fueling operation.

2.2 Gasifier System Operation

The genset (engine and generator) has a Basant 4.5 kW (6 horsepower) Lister design engine driving a 5.6 kW (7.5 horsepower) Baldor 3 phase squirrel cage induction motor fitted with capacitors and configured as a generator. Producer gas from the gasifier passed through a cyclone filter to remove particulates, was cooled in the radiator, further filtered in a hay filter and mixed with a small amount of outside air in the engine carburetor before entering the engine. The engine governor controlled the amount of diesel introduced to the engine so that the engine speed remains constant when the engine ran on diesel alone, reducing the amount of diesel injected to a minimum of 0.382 l/hour [58] or 19.6 cubic mm per cycle, in excess of the 8 –9 cubic mm recommended[2] as a minimum to maintain stable combustion. The governor introduced more diesel to make up for insufficient or weak syngas to bring the engine up to set speed. However, if the producer gas introduced into the engine would cause the engine to exceed the set speed the governor became ineffective. Load to the generator was a 1500-watt 120 V portable electric heater [12, 26,27].

During start up of the gasifier it is important that the char bed is not overly disturbed beyond a moderate tamping to shake down the ashes from the bed to the ash pit. To prevent tar forming and entering the engine while the gasifier was at a lower temperature starting vacuum to the gasifier was provided by a 1 hp (0.75kW) Shop Vacuum Cleaner (shop vac) and the gasifier lit by momentarily touching a propane torch flame to the fuel through the lighting port. The diesel engine was then started, and generator load applied. Once the gasifier temperature at the lighting port reached 1400 F the shop vac was turned off and engine vacuum applied to the gasifier by opening carburetor and producer gas line valves to the gasifier and closing the carburetor outside air valve until it was 95% closed. Engine fuel level in the graduated cylinder diesel fuel reservoir was noted as well as volts and amps supplied by the generator to the generator load, the portable electric heater. The gasifier top was opened approximately 15 minutes into the run and the fuel tamped down with a steel rod (rodded). At the same time and at the end of the run voltage and amperage supplied to the heater were noted. Also at the end of the run diesel fuel level in the fuel reservoir was noted [12,26, 27].

Energy content of the diesel fuel used by the engine during the run, D_{en}, was calculated by [26]:

$$D_{en} = \text{milliliters of fuel consumed X 40.7 kWh/gallon X 3785 ml per gallon} \quad (9)$$

where 40.7 kWh is the energy content of 1 gallon of diesel fuel [59].

Energy provided to the generator load (heater), G_{en}, was calculated by:

$$G_{en} = \text{Avg. volts measured x Avg. amps measured / 1000 watts per hour x 2 runs/hour} \quad (10)$$

Genset efficiency, G_{eff}, for each run was calculated from:

$$G_{eff} = 100 \text{ X } G_{en} / D_{en} \quad (11)$$

Baseline runs for determining genset efficiency with the engine operating on diesel fuel alone were first conducted [26]. The average genset efficiency running on diesel alone, G_{effd}, was used to calculate the quantity of diesel, d_{alone}, the genset would require to generate G_{en} for dual fuel runs if the genset were operated on diesel fuel alone by [12,26,27]:

$$d_{alone}\ (\text{ml}) = G_{en} / G_{effd} \text{ x 40.7 kWh per gallon/ 3785 ml per gallon} \quad (12)$$

Diesel fuel savings (%), D_{fs}, for a dual fuel run were calculated from:

$$D_{fs} = 100 \text{ x } (d_{alone} - \text{actual quantity of diesel used (ml)})/ d_{alone} \quad (13)$$

Cold gas efficiency for small downdraft gasifiers experimentally determined is 30% -60% [60,61], 40% is used for the woodchip fuel energy calculation. The woodchip fuel energy was calculated from:

Wood Energy (kWh/kg) = (100/ Geff) x Diesel Fuel Savings (ml) x 0.01076 diesel energy content (kWh/ml) x (1/weight of wood used (kg)) x 1/cold gas efficiency factor 0.4 (14)

2.3 Dual Fueling with Paper

Wastepaper consisting of newspaper, light cardboard, magazine and printer type paper, was pulped in a high consistency mixer, partially dewatered, formed into chunks having 60 cm³ as shown in Fig. 4 below, oven dried and used at a 6% Moisture Content (MC), oven dry (OD) basis. The chunks fueled the gasifier for each run. Runs lasted 6 minutes or 0.1 hours to ensure an adequate char bed for the next run. The gasifier was operated as it was with woodchips. Previous to the three runs using 60 cubic centimeter chunks trial runs with chunks of approximately 20, 40, 60 and 80 cubic centimeters were conducted to determine the best size of chunks to be used in this gasifier. During each run approximately 825g of chunks were used except as noted. As noted above, successful operation of the gasifier requires an adequate char-bed for each run that is formed from the leftover fuel from the previous run [26].

Once the gasifier temperature at the lighting port reached 1400°F, the vacuum from the shop vac was turned off, its inlet valve closed and the engine vacuum was applied to the gasifier by opening carburetor and producer gas line valves to the gasifier and closing the carburetor outside air valve until it was approximately 66% closed [12,26]. The carburetor outside air valve was adjusted throughout the run, typically once or twice, to maximize engine speed. Since the paper runs were typically only 6 minutes long the gasifier was not opened and rodded during the run. The engine governor setting was not changed during the run. At the start of each run engine fuel level in the graduated cylinder diesel fuel reservoir (+/- 1 ml) was noted as well as volts and amps supplied by the generator to the generator load, the portable electric heater. At three minutes into each test run and at the end of the run voltage and amperage supplied to the heater and diesel fuel level were noted again. The amount of paper chunks consumed in each run was determined by noting the fuel level in the gasifier before and after each run.

Diesel fuel energy content, energy provided to the generator load, genset diesel efficiency, equivalent quantity of diesel and diesel fuel savings were calculated as for woodchip dual fueling above.

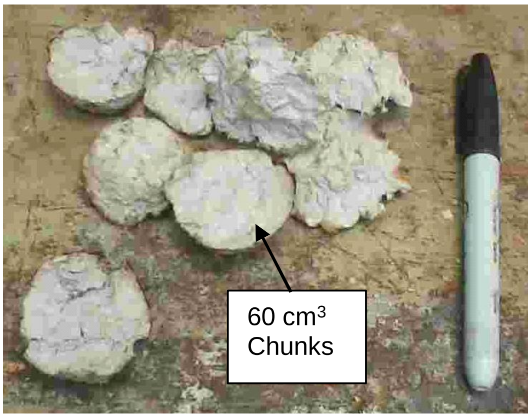

Fig. 4. Paper chunks used in gasifier

As a check, calculated wastepaper fuel energy content from each run was compared to that determined by bomb calorimeter testing, 3.67 kWh/kg (5647 Btu/lb) and the measured density of the fuel, 0.08 g per cubic centimeter (chunks as loaded in gasifier). Engine efficiency with wastepaper producer gas as fuel is assumed to be 17%, the same as the engine with diesel fuel. Given that the gasifier volume was 10309 cm³, a full gasifier load of paper chunks as fuel weighed 825 g. Cold gas efficiency was assumed as 40%, the same as for the woodchip runs in a prior experiment, for the wastepaper fuel energy calculation [26,27]. The wastepaper fuel energy was calculated from:

Paper Energy (kWh/kg) = (100/ Geff) x Diesel Fuel Savings (ml) x 0.01076 diesel energy content (kWh/ml) x (1/ Paper Usage (fraction of full load used) x 0.83 kg (weight full load)) x 1/cold gas efficiency factor 0.4 (15)

The effects of the paper fuel 6% moisture content are assumed to be negligible as effects of fuel moisture content on gasification reported in the literature are not significant until much higher levels [62,63].

2.4 Dual Fueling with Biosolids and Mixed Paper

The genset and gasifier system used was the same as used for the paper wood chunks dual fueling above except that a shaker rod was added connecting the engine to a grate shaker fork as shown in Fig. 5 after the engine slightly stuck, indicating some tar contamination of the engine, after a run including straight biosolids with a high percentage of fines. The shaker rod translated engine vibration to the gasifier grate to help prevent buildup and clogging of the oxidation and reduction zones with ash and fines. This is especially important with biosolids or sewage sludge as its ash content is very high, approximately 40% -50% [64,65]. Paper fuel was prepared as described above in the paper dual fueling procedure. Biosolids, the residue from sewage that has been aerobically digested with microbes followed by aerobic endogenous digestion of the microbes at the Minoa WWTP for a total period of 25 – 30 days, were, after one or more of a variety of treatments subsequently described, formed into chunks of approximately 60 cubic centimeters and oven dried. Fig. 5 shows some of the biosolids fuel after oven drying.

Fig. 5. Biosolid fuel after oven drying

Diesel energy, energy provided to the generator, genset efficiency and diesel fuel savings were calculated as above for the paper runs but the fuel energy for the combined paper and biosolid fuel were calculated from:

Biosolid and Paper Energy (kWh/kg) = (100/ Geff) X Diesel Fuel Savings (ml) X 0.01076 diesel energy content (kWh/ml) X (1/ (dried paper weight + dried biosolid weight)) X cold gas efficiency factor 2.5 (16)

After oven drying the biosolids and paper chunks to a moisture content of 6%, they were weighed, mixed and used as fuel in the gasifier for each run. Biosolids have a very high ash content and any fuel bridging or channeling is likely to cause cool spots in the oxidation and/or reduction zones of the gasifier and allow tar to pass through to the engine without any immediate engine degradation or noticeable change in engine performance. Only after the engine cools down will tar contamination be evident with the engine being stuck or the crankshaft not being able to rotate. It is recommended, that any run dual fueling with producer gas from biosolids be immediately followed before the engine cools by a ten-to-twenty-minute period of running on diesel fuel alone to burn any tar deposits in the combustion chamber. To prevent tars in the producer gas care was taken to not introduce more fines than necessary into the fuel and to ensure residual ash was removed from the char bed by rodding the char bed before each run. Even with thorough rodding slight engine sticking indicating some tar contamination of the engine occurred after the second biosolid run so after the third biosolid run. It is highly recommended that after biosolids dual fueling runs before the engine cools down the engine is run for a 10 to 20-minute period on diesel to clean out any formed tar deposits.

3. RESULTS AND DISCUSSION

3.1 Paper Dual Fueling

Results from dual fuel (diesel and gasified wastepaper) runs with 20, 40 and 80 cubic centimeter paper chunks and 3 dual fuel runs with 60 cubic centimeter paper chunks are shown in Table 1 below. Runs 1 – 3 were done with the engine fueled by 20, 40 and 80 cubic centimeter paper chunks and diesel. Runs 4-6 were conducted with the engine dual-fueled with 60 cubic centimeter paper chunks and diesel. It can be seen, that the genset efficiency, G_{eff}, was higher on the average with the 60 cubic centimeter chunks. Calculated paper energy was not very consistent nor very close generally to the calorimeter measured value of 3.67 kWh/kg. However, the higher paper energy numbers were not far from the bomb calorimeter determined number, only 11.5% less. Without being able to measure the amount of material in the char bed for each run the weight of paper chunks for each run was an approximation at best and probably explains the bulk of the discrepancy. Other potential sources of error include the average voltage and amp readings and the assumptions of a constant 17% engine efficiency with diesel and producer gas. Also, the cold gas efficiency was only estimated.

Wood is the ideal biomass for gasification as its energy content and density are relatively high and its ash content very low. Almost every other type of biomass will have a lower energy content and/or density and a much higher ash content causing more potential oxidation and reduction zone cool spots associated with tars passing out of the gasifier and fuel flow problems as well as a higher potential for slagging problems.

As discussed in prior work [26] G_{eff} for the genset powered by diesel alone was approximately 17%. It is evident that if calculated from diesel usage alone genset efficiency improves with dual fueling using gasified wastepaper, but gains were not as dramatic as when the genset was dual fueled with gasified woodchips, where average diesel fuel savings were 74% [26]. The dried paper pulp chunk fuel was very low density, approximately 1/3 that of the woodchips used in the prior study [26]. This caused the fuel to be exhausted very quickly, necessitating 6-minute runs instead of 30-minute runs as when the gasifier was fueled with woodchips [26]. In addition, the paper fuel's low density made bridging and channeling more of a problem because its low weight and friction with the gasifier interior wall made it more prone to hanging up [6,7]. Bridging is a clog in the fuel preventing flow of the fuel downward through the gasifier. Channeling is the formation of large passages through the fuel allowing most of the airflow to pass through them and only a little to pass through the remainder. Bridging and channeling result in non-uniform gasifying conditions in the oxidation and reduction zones of the gasifier making the quality of the producer gas and tar control erratic [6]. Fuel densification may be explored as a way to avoid this problem. However, it is apparent from the d_{alone} and D_{fs} columns in Table 2 that dual-fueling with low density wastepaper chunks can save a considerable amount of diesel fuel in operating the genset even under less than optimal conditions [26].

As discussed in the Woodchip Dual Fueling section above the governor on the Basant diesel engine is a spring-loaded device working with spinning centrifugal weights that allows higher engine rpm and generator voltage at a given setting for dual fueling than when running on diesel alone. For operating a portable resistance heater the higher voltages and amperages allowed by this governor as described above were not much of a problem but for other applications the higher voltages and amperages may not be allowable. For these cases the governor may need to be adjusted occasionally when dual fueling or changed to a different type that controls the amount of producer gas allowed into the engine [12, 26].

3.2 Paper and Biosolid Dual Fueling

Table 2 below shows the results of 8 runs with mixed paper and biosolid gasifier fuel. The first three runs were conducted with the gasifier air inlet valve 12.5 % open, the last 5 runs were with the gasifier air inlet valve 25% open. The first four runs were 6 minutes long, the second four runs were 4 minutes long. Biosolids from runs 1,2,5,6,7 were unprocessed from the drying shed, biosolids from runs 3,4 and 8 were processed through the filter press. The dried biosolids tended to disintegrate into small chunks and fines, especially those from the drying shed. The engine on Run 6 was slightly stuck upon startup indicating the gasifier on Run 5 allowed some tar through to the engine. This is not surprising considering that the bulk of material gasified during Run 5 was biosolids from the drying shed. The fines and ash from the biosolids probably restricted airflow through the combustion and reduction zones creating cooler pockets allowing tars to pass uncracked through the gasifier. In light of subsequent testing with biosolids alone the paper chunks helped flow of air and ash through the oxidation and reduction zones of the gasifier.

3.3 Biosolids Dual Fueling

It was expected that biosolids would be very difficult to gasify, because previous deashing results showed that biosolids have a high ash content. It was expected to have to blend wastepaper with the biosolids in order to be able to gasify the biosolids. Instead, it was found the paper harder to gasify alone, the biosolids alone provided a larger quantity of more stable, combustible producer gas that produced much electricity when fueling the genset. Despite frequent rodding of the gasifier and installation of the shaker rod tar remained a problem when fueling the gasifier with biosolids alone. It is suspected that the large amounts of ash produced and not completely shaken down into the ash pit created areas in the oxidizing and reduction zones that the air could not adequately reach leading to cool spots and tars not completely cracked contaminating the producer gas. Replacing the shaker rod with a more vigorous positive shaker shook most of the ash

Table 1. Genset Wastepaper Run Results

Run	Chunk Size (cm^3)	Diesel Usage (ml)	Average Volts	Average Amps	Paper Usage (fraction of full gasifier load)	G_{en} (kWh)	D_{en} (kWh)	G_{eff} (%)	d_{alone} (ml)	D_{fs} (%)	Paper Energy (calculated) (kWh/kg)
1	20	60	124	11.2	0.6	0.14	0.63	22.02	75.92	26.54	3.24
2	40	50	125	11.3	0.5	0.14	0.53	26.87	77.22	54.44	3.24
3	80	55	125	11.3	0.8	0.14	0.58	24.43	77.22	40.40	2.23
4	60	40	137	11.3	0.7	0.15	0.42	36.82	84.63	111.58	1.85
5	60	55	130	11.8	0.8	0.15	0.58	26.53	83.86	52.48	2.23
6	60	40	134	12.2	0.7	0.16	0.42	38.88	89.37	123.43	1.85

Table 2. Genset Paper and Biosolid Run Results

Run	Diesel Usage (ml)	Average Volts	Average Amps	paper used (kg)	biosolids used (kg)	G_{en} (kWh)	D_{en} (kWh)	G_{eff} (%)	d_{alone} (ml)	D_{fs} (%)	Paper and Biosolid Energy (calculated) (kWh/kg)
1	55.0	131.0	10.1	0.3	1.1	0.13	0.59	22.36	72.33	31.51	2.16
2	50.0	135.0	11.5	0.3	1.1	0.16	0.54	28.86	84.87	69.75	3.37
3	45.0	140.0	11.4	0.2	0.3	0.16	0.48	32.96	87.25	93.89	9.23
4	40.0	131.0	11.4	0.2	0.4	0.15	0.43	34.70	81.64	104.11	7.29
5	20.0	154.0	12.9	0.2	1.2	0.13	0.22	61.48	72.33	261.65	2.34
6	15.0	149.0	11.3	0.1	0.8	0.11	0.16	69.17	61.03	306.87	2.75
7	30.0	149.5	11.6	0.1	0.9	0.12	0.32	35.78	63.14	110.47	3.44
8	15.0	144.3	11.3	0.2	0.4	0.11	0.16	66.68	58.83	292.23	4.41

Table 3. Biosolid Run Results

Run	diesel used (ml)	Average Volts	Average Amps	biosolids used (kg)	G_{en} (kWh)	D_{en} (kWh)	G_{eff} (%)	d_{alone} (ml)	D_{fs} (%)	Biosolid Energy (calculated) kWh/kg
1.0	50.0	127.0	10.6	0.3	0.1	0.5	20.5	58.9	17.8	1.0
2.0	100.0	122.0	10.4	1.0	0.2	1.1	20.1	115.4	15.4	0.4
3.0	25.0	147.5	14.2	0.8	0.2	0.3	79.7	114.5	358.0	3.2
4.0	25.0	158.0	15.0	0.7	0.2	0.3	90.2	129.6	418.3	4.3
5.0	10.0	151.0	14.5	0.8	0.2	0.1	208.3	119.7	1097.0	3.5
6.0	5.0	165.0	15.6	0.7	0.2	0.1	328.1	94.3	1785.6	3.6

into the ash pit and rectified the tar situation at least some of the time. Table 3 below shows the biosolid run results. Run 1 was with biosolids from the filter press that tended to disintegrate into small chunks and fines after drying. Run 2 biosolids were from the drying shed and tended to disintegrate into small chunks and fines after drying. While no tar formation was noted from these runs the gasifier needed to be heavily rodded after Run 2 to enable it to be lit for the next run indicating that it was clogged with fines and ash. Runs 1 and 2 were not very impressive as far as fuel savings, either, indicating that the clogging reduced the quantity and/or quality of the producer gas as well. Runs 3 – 6 were with manually pressed biosolids previously processed through the filter belt formed into chunks of roughly 15 cubic centimeters. Runs 3 and 4 were fortified with fiber, runs 5 and 6 were not fortified. The chunks from runs 3-6 all remained relatively coherent after drying so fortification with fiber was not necessary. Runs 3 –6 was very impressive both from how steady and stable the engine ran while being dual fueled and also from how much power was generated. The electric heater overheated and shut down at the end of Run 5 and 4 minutes into Run 6 necessitating Run 6 being shortened to only 4 minutes. The engine was slightly stuck, and the gasifier needed severe rodding upon startup of Run 4 and after Run 6 indicating tar was generated and allowed to pass to the engine during Runs 3 and 6. The shaker rod was exchanged for the more vigorous shaker for Runs 5 and 6. The ash pit was checked before Run 4 and before and after Run 6. The ash pit was empty when checked before Run 4 and after Run 6 indicating that during Runs 3 and 6 agitation of the grate was insufficient to shake the ash and fines through the grate. No signs of tar reaching the engine were seen for Run 5 and a large amount of ash, 584 grams, was present in the ash pit after the run indicating that for that run grate agitation was sufficient to ensure that the ash generated during Run 5 migrated through the grate to the ash pit which ensured adequate air circulation through the gasifier oxidation and reduction zones to prevent any tars migrating into the engine.

Given during Run 6 that grate agitation was not sufficient to shake ashes in the gasifier oxidation and reaction zones through the grate into the ash pit and tar consequently reached the engine a more powerful and positive grate shaker is needed for any future runs with biosolids with this gasifier. The ashes must be removed from the oxidation and reduction zones to ensure adequate air circulation in and to keep fuel flowing through those zones. The CERF experimental gasifier grate only can move laterally approximately 0.25 cm so potential agitation is limited, especially if during the run some ash or char particles fall behind the grate supports and temporarily jam or reduce motion of the grate. Any gasifier CERF would consider using in the future should have a grate with at least 1 cm range of lateral motion and an agitator capable of shaking it at least twice a second.

3.4 Outlook

Dual fueling the genset with producer gas with wastepaper chunks only reduced diesel consumption by approximately 30%. Whereas dual fueling the gasifier with producer gas from biosolids reduced diesel consumption by 70% - 90%. In addition, fueling the gasifier with paper chunks resulted in a more difficult operation as with the chunks made from biosplids.

Paper chunks with a volume of 20 cm³ and 60 cm³ have the potential to provide up to 3.24 kWh/kg and 1.85 kWh/kg at a diesel usage of 60 ml/6 min. and 40 ml/6 min. respectively. Chunks made from Wastepaper and biosolids showed a higher energy output of up to 9.23 kWh/kg at a diesel usage of 45 ml/6 min. run. However, tar formation and associated operational difficulties showed that paper chunks and paper and biosolids chunks are not valid option for operating the genset system.

Biosolids chunks with a volume of 15 cm³ have the potential to provide up to 3.6 kWh/kg at a diesel usage of 5 ml/6min without operational problems in regard to tar formation and operational stability and energy generated by the genset system.

Based on this, a ton of biosolids could generate up to 3,600 kWh of energy. For the Minoa waste water treatment plant with an annual production of 200 to 230 metric tons of biosolids an energy production potential between of 720 to 828 MWh/year can be achieved. Additional savings of up to $20,700/year at a $90 per metric ton tipping (not including transportation) fee could be realized.

Additional potential revenue could come from the produced char from biosolids. Biochar is the solid carbon residue of pyrolysis, gasification or other processes that heat biomass while limiting its access to air [66,67,68]. Biochar can be a very valuable soil amendment that increases its organic content, decreases bioavailability of heavy metals, increases soil water retention, soil aeration and permeability and decreases soil density [67]. Biochar and ash derived from gasification of biosolids can be seen in Fig. 6 below. Biochar yields from gasification range from 5% to 15% [68]. Assuming the yield from the CERF gasifier is 10% and CERF produces 47 dry tons of biosolids annually[10], CERF should be able to produce 4.7 tons/ year of biochar. Biochar may be applied to the soil along with the ash, the ash performing a liming effect in increasing soil pH [66]. Assuming, that ash makes up 50% of the dry biosolids, CERF should be able to produce 23.5 tons of ash annually. Biochar produced at higher temperatures such as those achieved in gasification are good at adsorbing soil contaminants [69]. As this is a comparatively new product and biochar properties vary considerably with how it is produced, market prices are extremely variable, from $80 per ton to over $13,000 per ton [68]. Further experimentation with ash and biochar from the CERF gasifier on crops or a remediation material is needed.

Fig. 6. Ash/Biochar

4. CONCLUSION

This study explored the potential of using wastepaper and biosolids, a by-product from waste water treatment, as feedstock for a small Imbert style downdraft gasifier. The producer gas from the gasifier was used to dual fuel a small Lister diesel engine powered genset.

The gasifier system was started up with hardwood chips 2 cm x 2 cm x 0.6 cm prior to using biosolids and wastepaper as fuel.

The wastepaper was first pulped and then the wet pulp was formed into 20 cm^3 to 60 cm^3 chunks, dried to a 6% moisture content and gasified. The energy potential that could be provided was up to 3.24 kWh/kg at a diesel usage of 60 ml/6 min. The wastepaper fuel was generally difficult to gasify because of its low density, tar production, and tendency to hang up in the gasifier, which caused difficulties in the gasifier system operation.

Chunks made from Wastepaper and biosolids showed a higher energy output of up to 9.23 kWh/kg at a diesel usage of 45 ml/6 min. run. However, tar formation and associated operational difficulties showed that chunks made from paper and biosolids are not valid option for operating the genset system.

Biosolids chunks with a volume of 15 cm^3 have the potential to provide up to 3.6 kWh/kg at a diesel usage of 5 ml/6min without operational problems in regard to tar formation and operational stability and energy generated by the genset system.

A ton of biosolids could generate up to 3,600 kWh of energy. For the Minoa waste water treatment plant with an annual production of 200 to 230 metric tons of biosolids an energy production potential between of 720 to 828 MWh/year can be achieved. Additional savings of up to $20,700 at a $90 per metric ton tipping (not including transportation) fee could be realized.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
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