International Scholars Journals

African Journal of Wood Science and Forestry ISSN 2375-0979 Vol. 8 (4), pp. 001-010, April, 2020. Available online at www.internationalscholarsjournals.org © International Scholars Journals

Full Length Research Paper

Lifecycle assessment of biofuel production from wood pyrolysis technology

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Accepted 21 May, 2019

Due to a stronger dependency on biomass for energy, there is a need for improved technologies in biomass-to-energy conversion in Tanzania. This paper presents a life cycle assessment (LCA) of pyrolysis technology used for conversion of wood and wood waste to liquid biofuel. In particular, a survey of environmental impacts of the process is presented. The LCA covered the steps from feedstock collection and supply, the facility itself and the end-use of the product with emphasis on different geographic, temporal, technical and environmental scenarios. The assessment was conducted starting from process synthesis, establishment of LCA parameters, and product parameters. The importance of the biofuel project is the economic growth, reduced national dependency on petroleum fuels and change in the standard of lining in the rural areas of Tanzania were critically analyzed. The study shows that biofuel has little negative impacts to human health and the environment during its life cycle. The impacts of the project on air quality, land use sustainability and on forestry and agriculture were analyzed and control strategies were recommended for offsetting the negative impacts. The biofuel have excellent performance in the combustion facilities, with lower emission levels below standard limits compared to petroleum fuels.

Key words: Biofuel, life cycle assessment; geographical/temporal scenarios, sensitivity analysis, land use sustainability, air quality.

INTRODUCTION

Fast pyrolysis of wood-waste under reduced residence time of product vapours and fast heat transfer can produce biofuel with properties closer to No. 6 fuel oil at an efficiency of about 80% (Beckman and Graham, 1994). In Tanzania, this fuel can be used as a cooking fuel to minimize detrimental effects of use of fuel wood and also as a source of value added chemicals.

The international community is currently assessing environmental impacts of biomass utilization, with emphasis on new technologies for biomass-to-energy conversion. Wood-waste pyrolysis into liquid bio-fuel is among the new technologies for biomass conversion. The most applicable technology is fluidized-bed pyrolysis using sand as a heat carrier (Oasmaa and Czernic, 1999). The product yield depends on feedstock properties, process type, operating conditions, and product collection efficiency. Such processes are accompanied by emissions, which can be minimized by installing air pollution control equipment. The opportunity for biomass processing in Tanzania lies on the lack of electricity in rural areas, where the energy is solely derived from biomass, dependency on which has remained the same for the last 24 years (UNDP, 2001). The key towards successful biomass power utilization is to use modern conversion systems like Sweden, Norway and the European Union. Other countries using the biomass resources efficiently to maximize the energy produced include Finland and South Africa, which has increased biomass use between 1980 and 1997. Because of low electricity consumption per capita, Tanzania will still rely on biomass for a longer future, necessitating improvements in the conversion technologies, like wood pyrolysis.

This project is very advantageous to Tanzania, where most of the energy comes from biomass (91% of the total energy), while approximately 8% is imported, and 1% comes from electricity. The higher price of petroleum fuels is necessitating development of efficient utilization of renewable energy. Based on the strong dependency on biomass for fuel, means of processing the biomass into more efficient fuels are needed, such as pyrolysis of wood into liquid biofuel. Since the fuel can be easily transported, and easily stored at the reduced volume, the project will provide environmentally and economically friendly biofuel. The project will assist in poverty alleviation and on the need for sustaining remaining forests, and reduced environmental effects of use of fuel wood. All these factors are acting as stimulants for the biofuel production in Tanzania. There is also a problem of wood waste disposal in the wood processing industries, which can be solved by using the wood waste as the raw materials.

METHODOLOGY

Definition and importance of LCA

LCA is a systematic analytical method to identify, evaluate, and help minimize the environmental impacts of a specific process or competing processes. Material and energy balances have been used to quantify the emissions, resource depletion, and energy consumption of all processes from the transformation of wood waste (as raw materials) into useful products from the biofuel and the final disposal of all products and byproducts. The results have been used to evaluate the environmental impacts of the process so that efforts can be focused on mitigating possible effects.

The primary purpose of conducting this life cycle assessment was to answer many of the questions that are repeatedly raised about biomass power in regards to CO_2 , and energy use, and to identify other environmental effects that might become important once such systems are further implemented. Since the inventory of each highlighted process block are responsible for significant emissions and energy consumption, the LCA was used to identify design improvements that can reduce the environmental impacts. All results presented are functions of the size of the plant for this specific technology, and care should be exercised when applying them to larger or smaller facilities or generalized biomass systems.

In this study, LCA was applied in assessing the environmental aspects and potential impacts associated with the biofuel life cycle. The LCA was conducted by compiling an inventory of relevant inputs and outputs of the process and evaluating the potential environmental impacts associated with those inputs and outputs from raw material acquisition through production, use and disposal. Using this method it was possible to detect the shifting of environmental burdens from one stage to another. The LCA also helped in identifying and evaluating the resource depletion associated with wood waste pyrolysis process (Olsen and Christensen, 2001; Kadam et al., 1999) . Using this method, material and energy balance concepts were used to quantify the emissions, resource depletion, and energy consumption of all processes required to make the process of interest to operate, including raw material extraction, transportation, processing, and final disposal of products and by-products. This assessment has been performed in conjunction with a techno-economic feasibility study, so that the total economic and environmental benefits and drawbacks of a process were quantified and used to reflect design changes that may reduce certain emissions.

Process synthesis

In the developed process, the received biomass was sorted and fed into a shredder and dried in a fluidized bed drier, using flue gas from the regenerator before storing in the silo. A screw- feeder was used to move the feedstock into the pyrolyzer, where it was exposed to the hot sand from the regenerator. The reaction was conducted under nitrogen or a natural gas environment, fed from a storage tank. The product vapours were quickly removed from the reactor, cleaned in the cyclone then condensed in a water-cooled condenser. Before storage, the liquid-bio oil was allowed to settle so as to reduce the moisture content. The regenerator was fluidized using compressed air from a blower. Hot sand was recirculated between the pyrolyzer and regenerator, acting as a heat carrier.

Identifying the LCA parameters

The project level parameters or the aspects of the LCA scenarios considered include geographic, temporal, technical and environmental aspects (Kadam et al., 1999). The process parameters studied comprised the whole production process (i.e., the feed stock preparation, size reduction, drying and storage, pyrolysis reaction, heat carrier regeneration, vapour and solids separation in cyclones and filters, vapour condensation, scrubbing of the stack gases, biofuel and water separation, and storage of biofuel, as shown in Figure 1. The process comprises of four different geographical locations (G_1, G_2, G_3 and G_4) accessed at different time-frames (T_1, T_2, T_3 and T_4), which can vary depending on market strength and shelf life of the product, respectively.

The geographic scope of this analysis focuses on the sources of the supplied raw materials, location of the facility, storage site for the product and the distribution of product to the customers. The tasks involved in this analysis were plant location, feedstock origins, source of electricity, and the routes for distribution of the product. The temporal scope involved the time frames for the collection of raw material, processing and storage, and use of the product. The temporal analysis involved the following tasks: study of the current situation at biomass sources, study of the future trend after beginning the production and expected differences between current and future scenarios. For the wood waste, three short term periods were examined: 3 years before commencement of the production, 3 years after commencement of the production and 5 years ahead. The study shows that the raw materials are still available, only tipping fees may arise, which can be offset by minimizing the production.

Project parameters

The environmental issues were considered via mass and energy balances, followed by listing all emissions: air emissions, liquid effluents and any solid wastes. To determine the potential environmental impacts of the effluents and emissions, the impacts were classified into different categories, such as global warming potential, acidification potential, eutrophication potential, and natural resource-depletion. The second step was to characterize the impact categories, based on each flow's relative strength of potential influence upon the identified environmental impact or effect (Kadam et al., 1999; Kaltschmitt et al., 1997), as shown in Table 1.

Categories of environmental stressors and their major impacts

The LCA was extended to the classification of inventory data into stressor categories that are potentially linked to ecological and human health. The study involved discovering and establishing a causal relationship between emissions identified in the inventory and an impact on the environment. The intent of this analysis was to index expected emissions, energy use, and material consumption with known consequences. Examples of stressor categories studied include Toxicants, Particulates, Air pollutants, Solid waste, Physical trauma, Climate change, Acidification precursors, Resource depletion, and loadings that can alter our habitat. Two important aspects of this method of classification are that a single stressor is often associated with multiple impacts, and that not all stressors within a category result in equal amounts of damage to the environ-

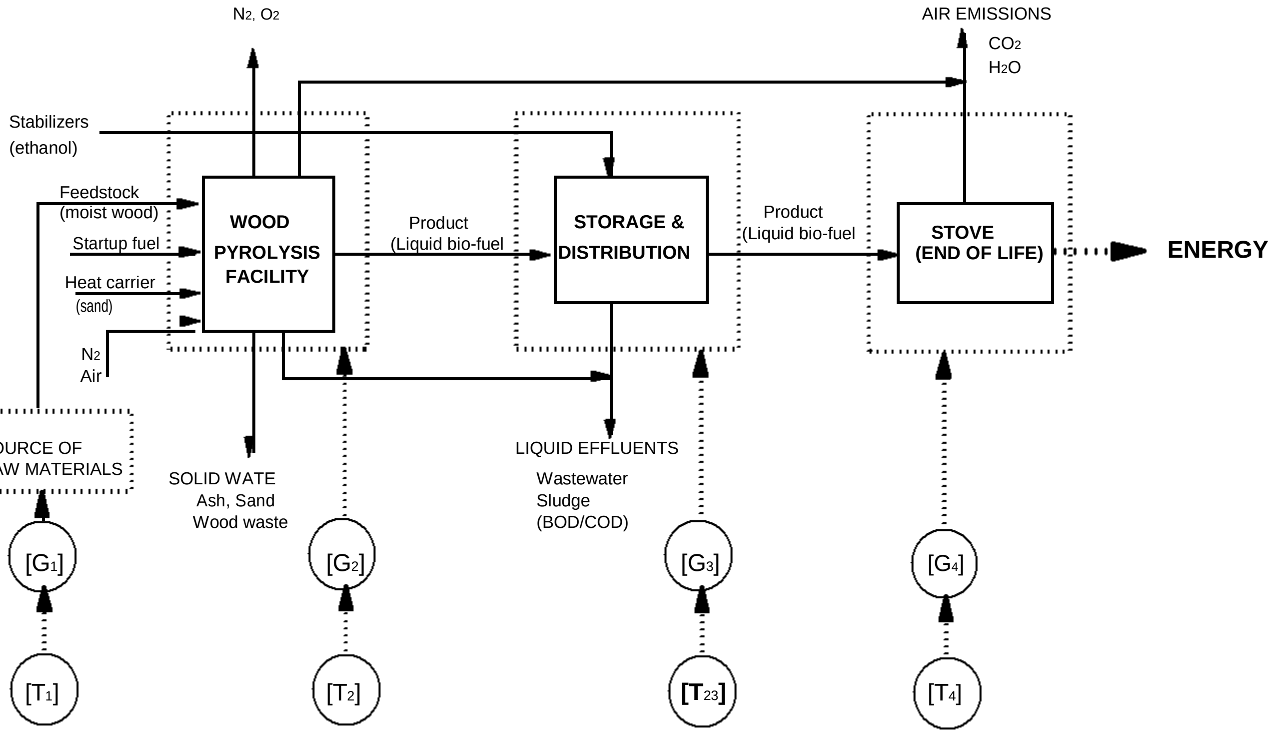

Figure 1. The basis of life-cycle assessment (LCA) of the biofuel project

Table 1. Summary of the environmental inventory flows and the corresponding impacts from the wood-pyrolysis facility.

Environmental flows considered	Associated impact category
(a) Natural resources	
Start-up fuel oil or natural gas (small amount)	NRD
Wood waste (raw material)	NRD
Saw dust, mill waste, agricultural waste	No impact, DPS
(b) Water effluents	
COD/BOD due to organics in water effluents	EP
Total suspended solids (TSS) from sludge and ash dewatering	DU
Nitrates and phosphates from ash dewatering	EP
(c) Air Emissions	
CO_2; CH_4; N_2O	GHG
NO_x; SO_x	AP
CO	DU
Hydrocarbons, Particulates	DU
(d) Solid Waste	
Shredder; Dryer; Ash and sand Non-hazardous	DU, No impact, recycled
(e) Primary energy use (electricity)	
Air compressor; Shredder; Scrubber water pump; Belt conveyor for ash dewatering; Cooling water pump	DU

Note: AP-Acidification potential; EP - Eutrophication potential; DU - Direct use; DPS –Disposal problem solved; NRD – Natural resource depletion; GHG – Green house gas

ment. The impact categories identified were of two categories: Human health (H), and Ecological health (E). The areas Impacted were classified as Local or town (L), Regional (R), and Global (G). Focusing on the wood-waste pyrolysis project, the major stressors identified are shown in Table 2. The list shown in Table 2 is, however, short compared to a thorough version reported by Mann and Spalth (1997).

Table 2. Stressor categories associated with biomass power production with their corresponding impacts.

Stressor Category	Stressors	Major impact category and area impacted
Toxicants	Tars, diesel fuel, and other	H,E,L
	Hydrocarbons SO_2, SO_3, H_2S	H, E, L, R, G,
Particulates	Wood dust, Sand, dust, and ash	H,E,L
Air pollutants	CO, NO_x, CH, NH_3	H,E,L
Solid waste	Char, sand and ash	H,E,L,R
	Accidents	H, L
Physical trauma	Noise	H, L
	Odor	L
Climate change	CO_2, CH_4, Nitrates, Sulfates	E, G
Acidification precursors	NO_2 (HNO_3), CO_2 (HCO_3^-)	E,R,G
	Fossil fuel use	E,R,G
Resource depletion	Water use	E, R
	Ground water pollution	E,L,R
	Topsoil erosion	E, L

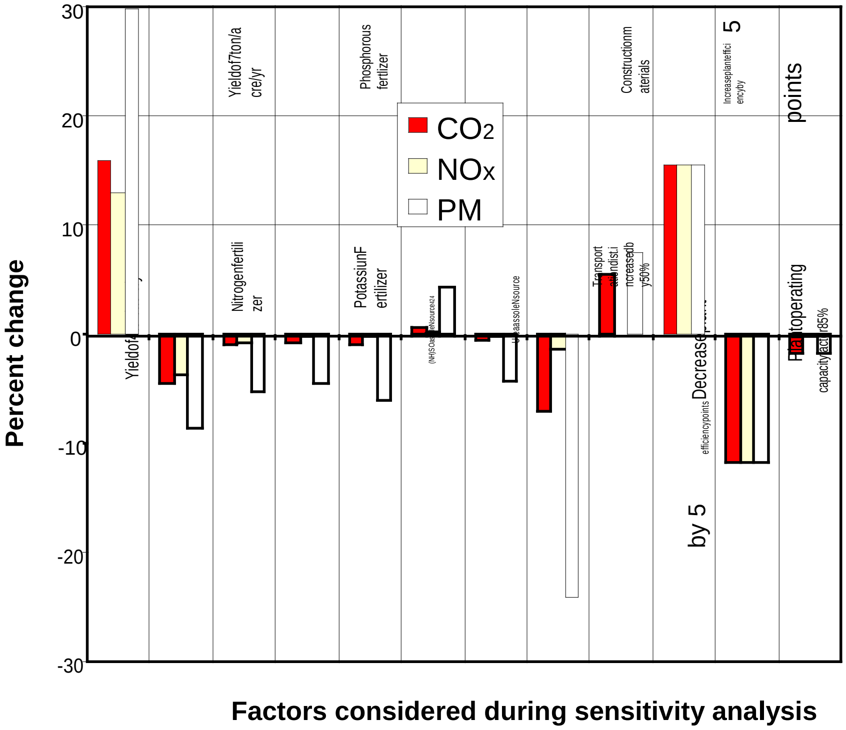

Figure 2. Sensitivity analysis results of net CO_2, NOx and Particulate matter (PM) emissions per MWh of energy produced from the pyrolysis plant

Sensitivity analysis

A sensitivity analysis was conducted to identify the parameters that had the largest effects on the results of this study and to minimize the impact of incorrect data on the conclusions. Each parameter was changed independent of all others so that the magnitude of its effect on the base case could be assessed. One variable may affect one block in the overall life cycle assessment. For instance, changing the biomass yield affects the acreage required to grow the biomass, which in turn affects the amount of fertilizer, pesticides, and herbicides used, and the average distance to deliver the biomass to the plant. However, varying the amount of materials used to build the power plant affects only the emissions associated with plant construction and decommissioning. These affects were taken into account automatically in the LCA model.

The sensitivity cases are shown in Figure 2. A summary of the effects on the major emissions, energy use, and resource consumption relative to the base case for several of the parameters varied is also shown. The percentages shown represent the deviation from the base case values when comparing the results on per unit of energy produced (that, MWh) basis. The positive several factors and thus several process steps or it may affect only number

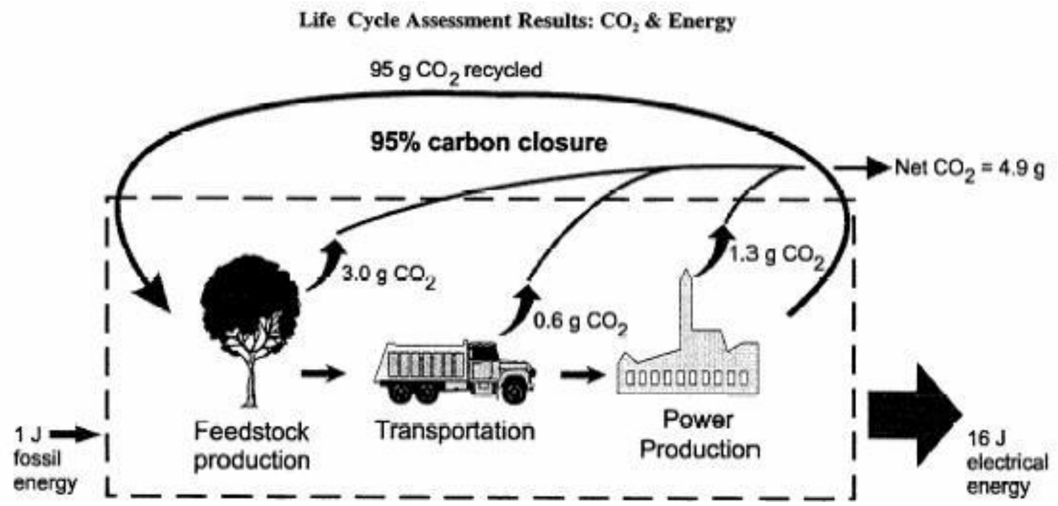

Figure 3. Carbon dioxide cycle between plants producing biomass (raw material) and utilization in biomass-energy conversion

indicate a percent increase while the negative numbers signify a decrease. The cases that had little effect on the life cycle assessment results are excluded from this plot. For easier interpretation, graphical representations of the CO_2, NOx, and particulate matter (PM) are shown in the sensitivity analysis results. The plot shows that particulate matter shows more sensitivity to the changes than the CO_2 and NOx.

RESULTS AND DISCUSSION

Air quality issues for biomass utilization

Case study of CO_2 emissions

Because the trees absorb carbon dioxide as they grow, the net amount of CO_2, added to the atmosphere for every unit of energy produced from the biofuel can be reduced through the use of biomass power. Carbon closure, defined as the percentage of carbon in the biomass to the power plant that is recycled through the system, was found to be approximately 95%. A 100% carbon closure would represent a zero-net CO_2 process. How much carbon the soil can accumulate was found to have the largest effect on carbon closure. Literature values for soil carbon build-up ranged from a loss of 4.5 to a gain of 40.3 Mg/ha/seven years (Kadam et al., 1999). Applying these values, carbon closure was found to be as low as 0.3% and as high as 200% (that is, a net reduction in the amount of atmospheric CO_2). Other sensitivity cases predict that carbon closure will be greater than 94% if there is no change in the amount of carbon stored in the soil.

The net energy production of the system was found to be highly positive. One unit of energy, in the form of fossil fuels consumed within the system, is required to produce approximately 16 units of electricity that can be sent to the grid. The life cycle efficiency of the system, defined to be the energy delivered to the grid less the energy consumed by the feedstock and transportation subsystems, divided by the energy in the feedstock to the power plant, is 34.9%. The power plant efficiency, defined in the traditional sense as the energy delivered to the grid divided by the energy in the biomass feedstock, is 37.2%. With power plant parasitic losses excluded, the feedstock production accounts for 77% of the system energy consumption. Figure 3 shows the carbon dioxide cycle between plants producing biomass (raw material) and utilization in biomass-energy conversion.

Other challenging gaseous emissions

Fossil fuel and biomass combustion both result in sulfur and nitrogen emissions. Among other things, these emissions can contribute to acid deposition, reduced visibility due to haze, and ground level ozone formation. Emissions limitations on sulfur and nitrogen oxides have been established to protect against adverse environmental and health impacts. Biomass feedstock contains relatively little sulfur and varying amounts of nitrogen. Sulfur emissions from biomass-fired facilities without sulfur emissions controls are similar to those from coal- and oil-fired facilities that have such controls. On the other hand, nitrogen emissions from biomass -fired facilities depend on the conversion process and the nitrogen content of the biomass. Recently, policy instruments of an economic character, such as carbon dioxide (CO_2) taxes and nitrous oxide (N_2O) fees, have been introduced in some countries. These instruments have been designed to give price signals about the future environmental impacts of fossil fuels and thus increase the competitive edge of the bio-fuels, so that prices of the former has gone up with taxes and levies. These instruments thus correct prices to reflect negative external effects. Price increases are then concentrated on fossil fuels, which have undesirable external effects like carbon dioxide emissions.

Except for some feedstock from the waste stream that are contaminated with paints and preservatives, biomass feedstock contain relatively low levels of such toxic metals as mercury, cadmium and lead. Concern about environmental mercury and cadmium levels in land and water have increased in recent years, with most of these contaminants coming from fossil fuel combustion and waste incineration. Just as the mandated removal of lead from gasoline has successfully reduced lead levels in soil and water, the use of bioenergy feedstock could reduce atmospheric concentrations of mercury and cadmium as well as the corresponding contamination of land and water. Power generation using biomass or fossil fuels produces air-borne emissions such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and CO_2. However, the implementation of the standards to control emissions of volatile organic compounds (VOCs) increases the operating costs.

The bio-energy offers many advantages. Most forms of biomass contain very small amounts of sulfur; therefore, a biomass power plant emits very little sulfur dioxide (SO_2), an acid rain precursor. Coal, however, usually con-tains up to 5% sulfur. Combining biomass with coal can significantly reduce the power plant's SO_2 emissions compared to a coal-only operation. The amount of SO_2 reduced depends on both the percent of heat obtained from biomass and the sulfur content of the coal. There is approximately a one-to-one relationship between SO_2 reductions and the percent of total heat input from biomass. For example, using biomass for 5% of a coal-fired power plant's heat input would reduce SO_2 emissions by approximately 5%.

Recent biomass confirming tests at several coal-fired power plants (e.g. Sweden and U.S.) have demonstrated that NO_x emissions can be reduced relative to coal-only operations. By carefully adjusting the combustion process, NO_x reductions at twice the rate of biomass heat input have been documented. In other words, if biomass is co- fired at a 5% heat input rate then the power plant could achieve NO_x reductions of 10%. Pilot-scale tests have also shown that even more significant NO_x cuts can be achieved by using biomass in a reburn configuration. Reburn involves injecting up to 20% of a boiler's fuel above the primary combustion zone. It is emerging as an important NO_x control option for power plants. In tests, biomass has shown to be as effective a reburn fuel as natural gas. For example, the emission levels of particulates, CO, SO_2 and the NO_x, were reported to be in higher ratios of 2.23, 1.42, 238.0 and 1.63, respectively, when emissions from a combustion system were compared between No. 6 fuel oil and bio- oil crude (Graham and Huffman, 1995). The higher ratio for the SO_2 emissions gives biomass pyrolysis oils a major advantage towards acid rain effects.

Plants absorb CO_2 during their growth cycle. When managed in a sustainable cycle, like raising energy crops or replanting harvested areas, BioPower generation can be viewed as a way to recycle carbon. Thus, BioPower generation can be considered a carbon-neutral power generation option. Landfills produce methane gas, which is produced from decomposing biomass material. Decomposing animal manure, whether it is land-applied or left uncovered in a lagoon also generates methane. Methane (CH_4), which is the main component of natural gas, is normally discharged directly into the air, but it can be captured and used as a fuel to generate electricity and heat. Using animal manure and landfill gas for energy production can reduce odors associated with conventional disposal or land applications.

The pyrolysis facility incorporates various features to improve the control of emissions. The initial processing and mixing of the feedstock prior to pyrolysis reduces the variations in composition of the feedstock. For the regenerator, the feedstock is the coke coated on sand particles, which is expected to be of similar composition. About 10% of stoichiometric air will be supplied to the regenerator to maintain a low gas velocity and minimal disturbance to the sand bed.

Low organic emissions are ensured from the regenerator through mixing and retention time control at relatively high temperature of 700°C. The non- condensable gas from the pyrolyzer will be burnt together with coke coated on sand to provide heat and reduce emissions from the facility. In the future, this gas can be collected and stored.

Flue *g*as *s*crubbers

A scrubber should be installed to eliminate the acidic and particulate components of the regenerator flue gas. It is important to make sure that the emissions remain below requirements of emission regulations. The regenerator emissions are mainly particulates, SO_2 , NO_2, CO, which must be reduced below the maximum permit. It is quite likely the emissions will be even lower because woody feedstock will be used. A wet scrubber preceded by a gas-cleaning cyclone cools and cleans the flue gases from the induced draft fan. A demister section can be installed before the scrubber to remove liquid droplets.

The discharged gas is vented to the atmosphere via a stack reaching to more than twice the building height. The scrubber overflow will provide makeup for the ash quench tank and surplus will be neutralized to insure satisfactory pH level below discharging to the sanitary sewer.

Two options are available for scrubber design: wet and dry scrubbers capable of efficient removal of acid gases and fine particulates (< 10 μm), respectively. Because cyclones are installed for solids handling, a wet scrubber will be used in this case, to trap the acid gases. Alkaline water solution will be used, which can efficiently remove HCl, SO_2 and NO_x. A wet scrubber can also handle hot gases containing sticky particles and droplets. Such systems are most effective in removing the particles larger than 0.5 μm, at typical pressure drop of 40 inH_2O. With higher-pressure drop (40 - 50 in H_2O), the wet scrubber can eliminate particles less than 0.1 μm (Lee and Huffman, 1996). The fact that a wet scrubber can eliminate NOx, reduces the cost of the pyrolysis facility because there is no need for a separate NO_x treatment. Other types of wet scrubbers include venture and packed bed and spray tower scrubbers. The venturi scrubber can efficiently remove particles with d_p > 1 μm, but the consumption of water is high, 5 - 7 gallons/1000 ft^3 gas (Brereton, 1996). The packed bed wet-scrubber has a poor efficiency in removing particulates, high pressure drops, and is also vulnerable to the problem of accumulated dissolved and suspended solids. The good choice is the spray tower wet scrubber, which has satisfactory efficiency for particulates larger than 10 μm (Newman, 1991). It has lower energy consumption, except for liquid pumping. The composition and flow rate of the scrubbing agents/media to quench and neutralize the gas must be determined experimentally and from stoichiometry. Most commonly used scrubbing media are caustic soda (NaOH), soda ash (Na_2CO_3) and slaked lime ($Ca(OH)_2$).

A variety of regulations concerning air emissions applies to facilities that use wood or wood wastes as fuel. With the exception of small commercial and residential installations, most wood boilers are required to install some type of emissions control equipment. In USA and Canada, for instance, the permits are issued at the state / provincial level, but regulations can vary among locations in a state or province. Developers in developing countries need to check whether the permits are issued on national or municipal basis. The biofuel facility will receive wood wastes from different sources. To maintain the quality of the feedstock and product, the following will be maintained: avoid construction wood waste because of paints; sort before shredding; and dry the feedstock to similar moisture content. A common reason for cost overruns for wood-fired industries and power plants is the cost of air emissions equipment required by regulators but not anticipated by plant engineers and developers. It is important to contact air pollution agencies early in the planning process and to fully understand the regulations that apply and how they effect plant design and equipment specifications.

In general, the emissions regulated by environmental agencies include particulate matter, NO_x, CO, lead and hydrocarbon (Table 2) . Most countries require that the best available control technology (BACT) be used at facilities requiring permits. The selection of technology is usually site-specific, and can include cyclone separators, wet or dry scrubbers, or electrostatic precipitators. Regulators require detailed information on the type of wood waste to be used, and whether the wood will be contaminated with materials such as lead paint, creosote, formaldehyde (from plywood), asbestos, tar or other potential pollutants. Periodic monitoring by the government officials may be a condition included in the air permit.

There is increasing concern about whether significant amounts of dioxin are a byproduct of the combustion / thermochemical conversion of solid wastes, and whether there is reason to be concerned about associated public health risks. Research results vary and there is not a consensus of opinion among experts. In addition, it is not clear to what extent dioxin is produced as a result of the combustion of wood and wood wastes. Research results to date indicate that combustion temperature, the duration of combustion and the degree of contamination by non-wood products may have important effects on dioxin emissions from wood-waste processing facilities. Hence, public review of proposed recycled wood waste burners may focus on demonstrated performance of combustion equipment and whether clean wood wastes will be burned (Sinclair and Diduck, 2001).

Land use sustainability

Increased landfill life

The wood wastes, which are currently being land filled, can be used to produce energy or fuels, if uncontaminated and does not generate unacceptable emissions or operating difficulties. Bioenergy systems, which can use these materials, provide the required community service. Woody material and yard trimmings comprise approximately 20% of the total amount of non-hazardous waste entering a landfill. A portion of this material is contaminated and unsuitable for anything other than disposal, so that a need for “clean” wood waste as a raw material necessitates sorting to reduce the amount of material sent to landfills, and extend the landfill capacity. This practice also eliminates methane emissions that would have resulted from the landfilled biomass.

Improved land use, quality and sustainability

The growing large quantities of biomass for energy ecologically affect the wildlife habitat and biodiversity, soil fertility and erosion, and water quality. The ecological implications of such a land use change will very likely be positive — provided perennial biomass crops displaced annual agricultural crops. However, the ecological implications of displacing more natural land cover (such as forests and wetlands) with biomass crops would very likely be negative. Thus, only acreage capable of supplying wood to the bioenergy plant should be planted with perennial trees.

Harvesting of traditionally non-merchantable timber from existing forests would affect a considerably larger land area than would be affected by producing the same quantity of biomass crops given the relatively low biomass productivity of forest compared with more intensively managed biomass crops. However, management and harvesting of forests would require less frequent site

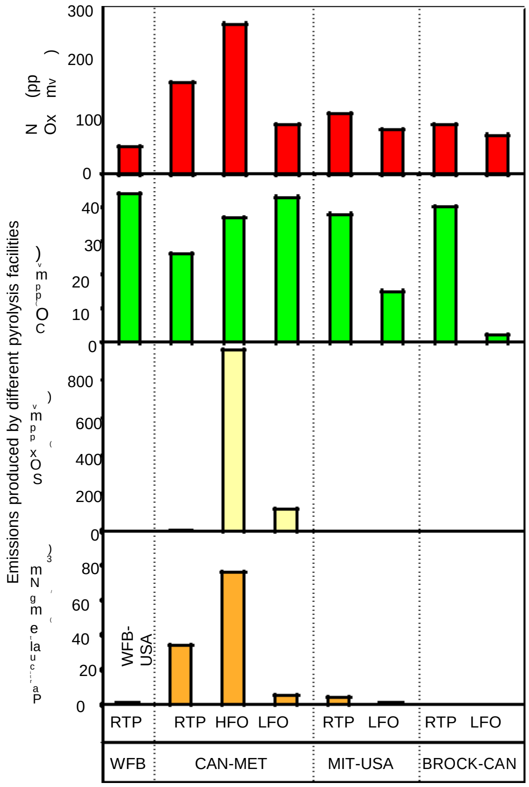

Figure 4. Comparison of emission levels between bio-crude oil and petroleum fuel oil from different producers in North America. Note: RTP – Rapid Thermal Pyrolysis bio-crude; HFO – Heavy fuel oil (No. 6); LFO – Light fuel oil (No. 2); and WFB – Waste Fuel Burner.

entry than that required for biomass crops. The implications of all these changes could be positive, provided ecological objectives are carefully considered in land management decisions. Without such ecological considerations, both in the making and in the carrying out of land management decisions, the impact on forest ecology could be quite negative.

Energy crops are perennial plants grown on under-utilized agricultural lands without replacing natural forests, grasslands, wetlands, or high value agricultural land. They require less herbicides and pesticides compared to row crops, thus reducing the chemical runoff into surface water and groundwater. This reduction protects and improves surface water and groundwater quality. Their extensive root systems hold soil and minimize erosion, thus improving surface water quality. They can filter agricultural chemicals, preventing them from entering the water streams, and they can intercept nutrients that could migrate into groundwater.

Performance of the biofuel in the combustion facilities

As stated earlier, the best use of the biofuel will be in special cooking stoves. There is a huge advantage in terms of reduced quantities of emissions compared to direct use of wood. In this case, the emissions other than CO_2, made during pyrolysis at the plant are controlled from entering the environment and from affecting the health of end users at homes. However, further use of biofuel is expected ranging from firing in boilers and other stationary engines, beside production of value added chemicals. It is thus important to examine all possible emissions from such applications.

A summary of emissions data for various combustion systems using biofuel (Graham and Huffman, 1995) is presented in Figure 4 for four different manufacturers. The particulate emission data reported for Waste-Fuel Burner (WFB) corresponds to gases exiting the baghouse. The WFB system was then integrated from charcoal and slow pyrolysis tars to Rapid Thermal Pyrolysis (RTP^{TM}) bio-crude since 1989, showing that the biofuel are more convenient than charcoal. With a thermal capacity of 6 MW_{th} (20 MBTU/h) at continuous operation, this is a huge fuel burner.

To indicate the level of compliance to the state or government environmental regulations, it is better to express the detected emission levels as a percentage of the permitted rate (for example, 44 ppm_v CO is the same as 17% of the permitted rates in Wisconsin). All emission rates for heavy fuel oil (HFO) are higher than those from RTP^{TM}. Except for CO and SO_x emissions from CANMET, the emissions detected when light fuel oil (LFO) was employed are lower than those of bio-crude. With the easy delivery and handling of RTP^{TM} compared to HFO, the former is more environmentally acceptable. The results of a complete analysis for selected compounds were reported as shown in Figure 5.

Figure 5 shows also that the emission rates were well below the allowable levels for all components except SO_x (full compliance is attained using bio-crude), which were higher than the allowable levels especially for large size units. Under these circumstances, special consideration for small size boilers is essential.

SUMMARY OF RESULTS AND DISCUSSION

Given that biofuel production from biomass has considerable potential to contribute to energy supplies in Tanzania, it is important to assess the environmental consequences up-front, while system components are still being defined. By analyzing the emissions, resource consumption, and energy use of the entire system, including biomass production, transportation, and electricity generation, the dominant sources of environmental impacts can be determined and the resulting effects can be reduced. For these reasons, a life cycle assessment of a biomass power plant, including all its upstream production and downstream disposal processes, was conducted.

General trends can be seen when examining the resources, emissions, and energy over the life of the biomass-to-biofuel system described in this paper. In years preceding power plant construction and operation, all of the

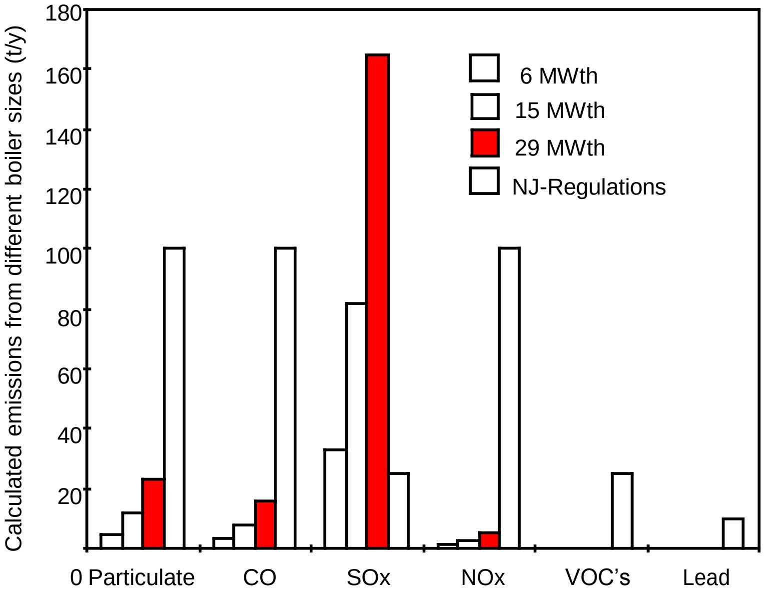

Figure 5. Calculated emissions for various boiler sizes.

stressors are associated with feedstock production, and as expected, there is a yearly increase as the number of fields in production is increased. A majority of the stressors are highest in the two years before plant operation due to activities associated with plant construction. The impacts then tend to level during plant operation even with the construction and decommissioning activities associated with the farm equipment and truck transportation.

Of all air emissions from the system, CO_2 is emitted in the greatest quantity. Feedstock production, primarily the use of fossil fuels in farming operations, is responsible for greater than half of all net CO_2 emissions. Other emissions commonly described as greenhouse gases, specifically methane and nitrous oxide, are emitted in very small quantities and add a minimal amount to the global warming potential of this system. Because carbon dioxide emitted from the power plant is recycled back to the biomass as it grows, biomass pyrolysis systems have the ability to reduce the overall amount of CO_2 added to the atmosphere. The system studied was found to have a 95% carbon closure, with 100% representing total recycle, that is, no net addition of CO_2 to the atmosphere. The amount of carbon that is sequestered by the soil at the plantation most strongly affects the carbon closure of the system. If the range of literature values for soil carbon sequestration is applied, carbon closure may be as low as 83% or as high as 200% (that is, a net reduction in the amount of atmospheric CO_2) . Conducting sensitivity analyses on other assumptions used in this study predicts carbon closures greater than 94%.

The base case analysis assumed that there would be no net accumulation or loss in soil carbon, with a sensitivity analysis showing that if 1.9 Mg/ha over the seven year crop rotation could be sequestered, the carbon cycle could be closed. In other words the system would be a zero-net CO_2 process. Literature values for soil carbon build-up ranged from a loss of 4.5 to a gain of 40.3 Mg/ha/seven years.

The importance of improving biomass utilization technologies in Tanzania has been discussed, starting from economic, environmental and change in social life standards. Too much dependency on biomass necessitates improvement of biomass-to- energy conversion technologies. Such dependency has remained constant for many years in developing countries but has dropped for developed nations. A technique for assessing the environmental aspects and potential impacts associated with the biofuel production, project was applied in this study. The environmental flows considered were natural resources, water effluents, air emission, solid waste, and primary energy consumption (electricity). The important categories were identified as acidification, eutrophication, direct use, disposal problems, and natural resource depletion. The major impact categories were further categorized depending on whether they affect human health or ecological health, and whether the impacted area is local (town), regional or global. The study shows that the impact of the project is positive.

Health and safety issues were also considered in this study. For safe biofuel handling, the material safety data sheet (MSDS) must be prepared and adhered to. Biofuels can have similar effects to petroleum fuels when swallowed, inhaled or directly exposed to skin. Storage tanks and transportation containers capable of resisting the corrosiveness of the biofuel are those made of stainless steel or polyethylene. However, environmentally, biofuels are less harmful than petroleum fuels and they are easily biodegradable in the soil and in aquatic environments. Air emission from biofuel production facilities were found to be minimal and well below regulatory limits. There is a very minimal sulfur emission possibilities compared to the petroleum fuels and coal. To be on safe side, however, the designed process includes a wet scrubber to be installed for collecting finer particulates and acid gases. The combustion of fuel during final use is expected to contribute very little to air emissions because the latter are removed at the production facility.

The biofuel has shown high performance in the combustion facilities, especially in terms of environmental performance (Graham and Huffman, 1995). Very low SO_x levels have been demonstrated compared to HFO and LFO, respectively. However, in terms of NO_x and CO emissions, biofuels range between HFO and LFO. When compared to standard limits, for example New Jersey regulation, the biofuel have high performance except in cases of SO_x for larger combustion facilities (Graham and Huffman, 1995).

The impacts of project to forestry and agriculture in Tanzania were classified according to impacts on land use, solid waste disposal, soil, air quality, water quality, social factors, and wildlife and ecosystem factors. Other factors considered include land use changes, soil acidification, etc. The study shows that the overall impact will be positive in terms of economic, social and environmental factors, provided that the energy forms are established and dependency on wood waste from forest is minimized in a long run.

The use of agricultural and forestry wastes or unused biomass for which there is no effective or economically competitive use will improve the energy economies of our industries, and will also impact the current development of agriculture and forestry industry. Large–scale growing of biomass specifically for energy production including the alteration of agricultural and forestry systems will provide increased quantities of energy feedstock. This will supply a significant proportion of energy needs in Tanzania and will impart a change in national land policy and planning. The specific use of industrial or urban wastes to provide low cost fuels will be an add-on advan-tage to the wood-waste and municipal waste disposal problems in Tanzania.

ACKNOWLEDGEMENTS

The author is very grateful to the financial support from Prof. M. Bergougnou (Professor Emeritus) and Prof. A. Margaritis during the course of this study at the University of Western Ontario, London, Canada.

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