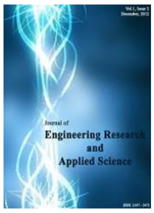
Journal of Engineering Research and Applied Science
Available at www.journaleras.com
Volume 5(2), December 2016, pp 458-465
ISSN 2147-3471 © 2016



Environmental impacts of biomass combustion for heating and electricity generation

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Accepted 22 July 2016

Abstract
Environmental impacts are of primary importance for the design of combustion systems at any scale. An important issue for plant operators is to forecast the influence of changing the combustion process on the plant efficiency and pollutant emissions level at the same time. Biomass pyrolysis thermally converts biomass feedstock into biochar, bio-oil, and syngas in the absence of air/oxygen. Products generated from biomass pyrolysis offer options for alleviating greenhouse gas (GHG) emissions and for providing realistic options in mitigating coal combustion particulate matter (PM) emissions as the generated heat and electricity. Modern biomass combustion power plants are reduce waste-water discharges to levels that are accommodated within the local municipal sewer system. Water supply and water quality are critical issues for plant siting and operations, and most boiler facilities include a water treatment plant to produce high-purity water for the boiler. Air emissions generally constitute the largest environmental concern for most combustion systems and have become a principal inhibitor to expanded development in many regions with poor air quality due to the high cost of stringent emission control or emission offsets. Indirect effects leading to deforestation and agricultural expansion with high greenhouse gas emissions elsewhere in the world when biomass is produced as an energy crop may further reduce the sustainability of bioenergy and potentially increase exposures to criteria and other pollutants.

Keywords: Biomass combustion; environmental impacts; heating; electricity generation

1. Introduction

Biomass is energy from organic matter, i.e. all materials of biological origin that is not embedded in geological formations [1]. Biomass can be used in its original form as fuel, or be refined to different kinds of solid, gaseous or liquid biofuels [2]. These fuels can be used in all sectors of society, for production of electricity, for transport, for heating and cooling, and for industrial processes. In developed countries, bioenergy is promoted as an alternative or more sustainable source for hydrocarbons, especially for transportation fuels, like bioethanol and biodiesel, the use of wood in combined heat and power generation and residential heating [3].

In developing countries bioenergy may represent opportunities for industrial development and economic growth. In least developed countries traditional biomass is often the dominant domestic fuel, especially in more rural areas without access to electricity or other energy sources. There are multiple challenges and opportunities for bioenergy as a potential driver of sustainable development, given enough economic and technological support [1-4].

Around the world, woody biomass is used for cooking, production of electricity and heat for industries, towns and cities and production of liquid biofuels. The primary energy supply of forest biomass used worldwide is estimated at about 56 EJ, which means woody biomass is the source of over 10% of all energy supplied annually [5]. Overall woody biomass provides about 90% of the primary energy annually sourced from all forms of biomass (Figure 1). On the other hand, woody biomass used is in the form of cut branches and twigs, wood chip and bark, and pellets made from sawdust and other residues. Some of it is wood from demolition and construction, from urban parks and gardens and from industrial wood waste streams (broken pallets, building form work and industry packing crates). Wood is also the source of more than 52 million tonnes of charcoal used in cooking in many countries, and for smelting of iron and other metal ores [1, 5, 6, 7].

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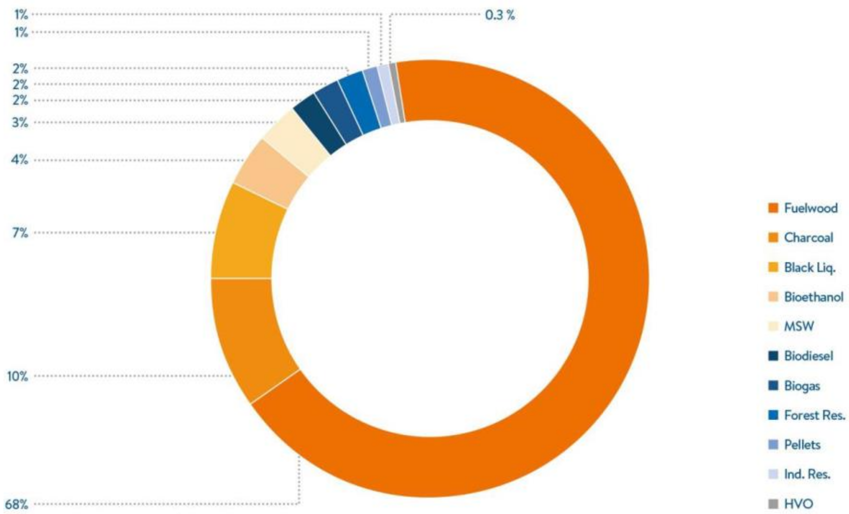

Figure 1. Primary energy supply of biomass resources globally ın 2013 [1].

Production of woody biomass on agricultural land does not automatically displace the amount of food or fibre produced per unit area, as there are many alternative ways to have production of both biomass and other outputs from the same land [8]. It is common practice in many countries to establish dispersed multi-purpose plantings on farmed land that shelter livestock, crops and pastures, while sequestering carbon, reducing wind erosion and drying of surface moisture, and adding to habitat and wildlife linkages [1]. These properly planned plantings of suitable species produce yet more biomass in a sustainable way, as well as round wood for sawmills and other end uses such as for pulp and paper, or for fencing [8-14].

In some countries, including Brazil, USA, Turkey, New Zealand, China, Australia, South Africa, and elsewhere, the replanting is often done across entire landscape. While the suitability of species chosen and sustainability of some of these plantings can be questioned, this is not a new practice, and similar plantings or reversion of cleared land to forest has occurred in the past in southeast Sweden, the north-eastern states of the USA, and elsewhere.

In general, the long-term outcomes of these earlier reforestation programs have been good, despite the loss of production from those farms. So, land use changes need to be assessed using a short list of rational criteria to weigh up the benefits and costs [1, 3, 5, 7].

Bioenergy is a versatile energy source. In contrast to other energy sources, biomass can be converted into solid, liquid and gaseous fuels. Moreover, bioenergy can be used for heating homes, electrifying communities and fuelling the transport sector.

Globally, bioenergy (including waste) accounted for 14% of the world's energy consumption in 2012 with roughly 2.6 billion people dependent on traditional biomass for energy needs. The consumption pattern of bioenergy varies geographically [1, 5, 6].

The use of biomass for electricity is prominent in Europe and North America [1]. Cogeneration plants enable the use of biomass with increased efficiency, so much so that the combined efficiency of producing heat and electricity crosses 80%. The Europe and Americas continent contribute more than 70% of all consumption of biomass for electricity. In 2013, 462 TWh of electricity was produced globally from biomass. In the past few years, biomass is seeing increasing uptake in developing countries where significant population lacks access to electricity. Biogas and decentralised bioenergy systems are becoming more cost competitive. Figure 2 shows the global final energy consumption in 2013 [1].

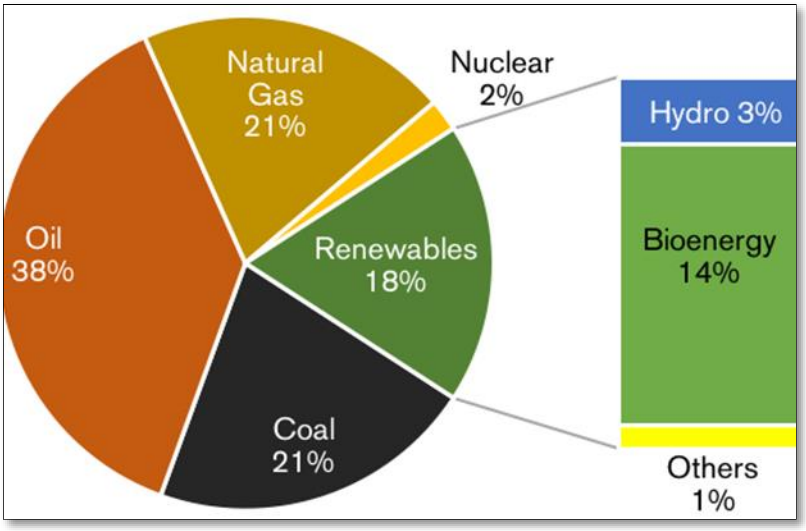

Figure 2. Global final energy consumption in 2013 [1].

2. Biomass combustion for heating and electricity generation

Biomass using modern technology differs from traditional biomass in two key characteristics; firstly that the source of organic matter should be sustainable and secondly, that the technology used to obtain the energy, should limit or mitigate emissions of flue gases and account for ash residue management [9]. Also, the efficiency of conversion is higher leading to less use of fuel. Modern biomass is largely used in some regions, notably in northern Europe and parts of North America. In Finland, about 60% of bioenergy is produced in forest industry using black liquor, bark, sawdust, and other industrial wood residues. In Sweden, about 40% of bioenergy use is in the forest industry, using residues such as bark, chips, black liquor and tall oil. A similar development occurred in the ethanol and sugar industry where bagasse and straw are used for the processes and power production [1, 3, 5, 7].

Modern biomass technologies include liquid biofuels used to power automobiles and to produce heat in boilers, industrial and residential cogeneration and bio-refineries used in generating electricity, liquid biofuels and pellet heating systems. Combined heat and power (CHP) or cogeneration means the simultaneous production and utilisation of heat and/or steam and electricity. CHP, particularly together with district heating and cooling (DHC), is an important part of greenhouse gas (GHG) emission reduction strategies, due to higher efficiency and a reduced need for fuels in comparison to stand-alone systems.

Electricity production can be fuelled by solid, liquid or gaseous biofuels, with the biggest fraction of biopower today being produced using solid biofuel [1, 5, 7].

Pellets are another form of modern bioenergy source. Pellet is a term used for a small particle of cylindrical form produced by compressing an original material. At present, pellets are mainly produced from wood residues, though the volume of pellets produced from agricultural by-products such as straw, husks of sunflower seeds and stalks and corn leaves etc. are increasing. A key advantage of pellets compared to unprocessed biomass is the high density and high energy content per unit volume [6, 7]. The combined yearly capacity of the mills when plants under construction or planned are considered is likely to be above 42 million tonnes [5]. The current production (in 2014) was 27 million tonnes and North America and Europe accounted for 97% of all the production volumes [1, 2, 5, 6, 7].

The goal of CO2 emissions reductions and the subsequent renewable energy incentives have led some power plant operators to broaden their fuel palette to include various carbonneutral biomass fuels. Co-firing of fossil fuels and various types of biomass is a mature technology and is currently being successfully practiced globally [1, 5]. With technological advances, many limitations associated with it have been overcome. Many coal-fired plants have been converted or retrofitted to accommodate co-firing with limited impact on efficiency, operations or lifespan [6]. However, there is much more to co-firing than simply adding a secondary fuel. Boiler technology and design remain critical issues when evaluating the maximum share of

biomass that can be used without compromising boiler performance (output, efficiency, and power-to-heat ratio) or the lifetime of the boiler components [7].
Direct co-firing is the most straightforward, most commonly applied and lowest-cost concept for partially replacing coal or other solid fossil fuels with biomass. In direct co-firing, biomass and coal are burned together in the same furnace using the same or separate fuel handling and feeding equipment, depending on the biomass, targeted biomass share and site-specific characteristics. The share of biomass that can be successfully employed in direct co-firing is modest and the type of biomass is limited mostly to pellet-type fuels. With torrefied biomass, however, higher shares are expected, up to tens of percentages. Three different main configurations can be distinguished for direct co-firing: the first option is to mix the biomass and coal and co-mill them in the same mill. With typical fuels this is restricted to fairly low cofiring shares of typically 5–10% and specific biomass types. In the second option, the biomass is pulverised in dedicated mills and is injected in the coal powder stream somewhere between coal mills and burners. This enables higher co-firing shares and wider selection of acceptable fuels but necessitates investments. In the third option, dedicated burners for biomass are also installed allowing burners to be optimised for both fuels independently but increasing the investment costs further [1, 2, 7, 10-14]

3. Environmental impacts of biomass combustion

Because of its ability to limit climate change from energy production, biomass is widely considered to be a major potential fuel and renewable resource for the future [15-22]. Biomass power plants must be evaluated on the basis of their capacity to satisfy both local and regional needs for thermal and electrical energy, and while this evaluation leads to the consideration of the plants contribution to reducing GHG emissions and climate change, at the same time, its effects on local environmental quality must be considered [23]. In the current context of greenhouse gases emissions reduction, small and medium sized combined heat and power biomass plants with an installed rated electrical power up to 5 MW represent a good opportunity to exploit cheap and/or locally available biomass. While the positive effect of biomass use from a CO2 balance is relatively straightforward [24, 25], biomass combustion releases other pollutants resulting from both complete (for SOx) and incomplete combustion (for NOx). The concentrations of these pollutants being strictly regulated, pollutants emissions control measures have to be put in place either by avoiding their creation (primary measures) or by removing them form the flue gases (secondary measures) [26].

Modern biomass combustion power plants are often zero discharge for waste water or reduce waste-water discharges to levels that are accommodated within the local municipal sewer system. Water supply and water quality are, however, critical issues for plant siting and operations, and most boiler facilities include a water treatment plant to produce high-purity water for the boiler. The largest fraction of solid waste is typically the bottom and fly ashes from the furnace and emission control equipment. With the exception of metals-contaminated feedstock, such as some urban and industrial wastes, ash often has value in secondary markets, such as land application as agricultural fertilizer, as admixtures for concrete, and in the steel-making industry [27-33]. Air emissions generally constitute the largest environmental concern for most combustion systems and have become a principal inhibitor to expanded development in many regions with poor air quality due to the high cost of stringent emission control or emission offsets. Smoke emissions from uncontrolled fires and stoves have long been recognized as major contributors to human respiratory and other disease. Increasing use of small biomass combustion systems for distributed power generation will similarly be of concern for increased risk of exposure to pollutant emissions among other environmental factors, such as noise, odors, and fugitive emissions. Despite these concerns, progress has been made in reducing emissions from combustion systems and improving emissions measurement and monitoring. Environmental issues in biomass combustion, including emission control devices, are reviewed in greater detail by van Loo and Koppejan [27].

Primary pollutants formed during biomass combustion include PM, CO, HCs, oxides of nitrogen (NOx, principally NO and NO2), and oxides of sulfur (SOx, principally as SO2). Other acid gases, such as HCl, accompany the use of halogenated feedstock, such as MSW and straw. Elevated halogen concentrations can also lead to the formation and emission of hazardous air pollutants in addition to accelerated corrosion in the combustion system of particular concern for chlorinated fuels is the formation of dioxins and furans, especially with waste fuels, although new emission standards for WTE facilities have greatly reduced dioxin contamination from this source [24, 25]. The presence of heavy metals, such as lead, cadmium, selenium, and zinc, in the fuel leads to their concentration in ash, sometimes to levels above the hazardous waste thresholds as measured by the toxicity characteristic leaching procedure and related methods [28, 29]. Heavy metals can be present in high concentration in certain urban and refuse-derived fuels, especially if treated or painted woods are present [19, 29]. Control of heavy metals is generally by fuel selection to exclude contaminated feedstock, unless the facility is specifically designed and permitted for such use.

3.1. Nitrogen emissions

The actual levels of emissions in the flue gases depend on the equipment itself, the fuel used and, to a very great extent on how they are operated. Recent figures from the Austrian testing agency (BLT) showed the vast majority of those tested could achieve levels of 120 mg/MJ or below, with most of these 100 mg/MJ or below. At partial output these levels can fall, but efficiency is lower too and particulate emissions can rise. Typical figures for good modern gas boilers tend to fall around 5-20 mg/MJ, oil boilers at perhaps 50-70 mg/MJ and coal boilers higher still. Relatively high nitrogen content fuels, such as sapwood, will tend to push fuel NOx up, while heartwood will help keep it down, and careful control of combustion temperature, especially if using dry fuel, such as waste wood, can help to keep thermal NOx down. These are areas where there are relatively low background levels as a result of relatively low density of housing and especially traffic, where natural dispersion will ensure that NOx levels at ground level will be largely unaffected. To put these emission values into context, data from the National Atmospheric Emissions Inventory give figures for NOx emissions from diesel cars of 440-530 mg/km when hot. This is an average figure, so while some cars will be better, others will be much worse. In addition to this, the cold start emissions will be an additional 270 mg per trip. A short 10 mile trip to the local supermarket would result in 14,350 mg NOx emissions. This would be the equivalent of running a 10 kW biomass boiler with NOx emissions of 150 mg/MJ for over 2.5 hours. These emissions from vehicles will of course be at ground level, while those from a boiler will be emitted from the flue at much higher level, allowing considerable dispersion and dilution, considerably reducing further the actual concentration at head height [29-31].

3.2. Sulfur emissions

Emissions of sulfur oxides are associated with sulfur in the fuel unless some other source of sulfur is available, such as H2S in a cofired waste or process gas stream. Sulfur oxides are respiratory irritants and their effects are enhanced in the presence of PM due to transport deep within the lung. Both sulfur and nitrogen oxides contribute to acid precipitation. In addition to sulfur oxides, some sulfur remains in the ash or is deposited in the furnace. Some may also be released as salts or H2S. SOx emissions can be reduced through dry or wet scrubbing. Removal of sulfur upstream of post-combustion catalysts is important to avoid catalyst fouling and deactivation. Inadequate sulfur control has been a consistent problem with engines burning digester or landfill gas and using catalytic after-treatment of combustion gases for NOx control [31]. Limestone or dolomite injection in fluidized bed combustors has been a primary control measure for SOx, in addition to reducing fireside fouling from sulfates in boilers [30-32].

3.3. Particulate emissions

Particulate emissions from burning natural gas tend to be extremely low, typically less than 1 mg/MJ. Boilers burning light fuel oil might have emissions around 5 mg/MJ, while those burning heavy fuel oil might be around 50 mg/MJ and coal might be 120 mg/MJ upwards, and significantly higher for larger and older equipment. Modern, high efficiency biomass boilers operating at full output might produce total particulate emissions (predominantly PM2.5) in the range 10-70 mg/MJ range. The BLT results showed that well over half of those tested achieved 20 mg/MJ or less, and from Phase 2 of the RHI there will be a limit of 30 mg/MJ for all biomass boilers seeking RHI support. Incorrect operation however, can increase these figures significantly. On the other hand, open fires and some old or poor quality log stoves will produce massively more. However the use of high efficiency modern filters, such as ceramic filters can ensure that particulate emissions are kept extremely low (<1 mg/m3 in the flue gas) at all times. As the optimum scale for wood boilers is that of district heating and large, multi occupancy sites, these abatement technologies are economically viable. Usage of best available technology in terms of both combustion equipment and abatement technology can ensure that emissions are no worse than typical oil technology [32].

3.4. Heavy metals

Hg is strongly released to the flue gas during combustion and can be classified as a highly volatile element together with Cl, F, and Se [33]. Some Hg removal occurs during the control of other species, such as SOx and NOx, and Hg can be strongly concentrated in fly ash, but for fuels containing higher concentrations of Hg, active control such as activated carbon injection as a sorbent may be required [34]. Water leaching of the feedstock to remove alkali metals and chlorine does not appear to alter Hg mobility in biomass. Other less volatile metals, such as copper and zinc, are enriched in slag and bottom ash, while cadmium, selenium, and more volatile elements vaporize in the combustion zone, condense downstream on fine particles, and are either captured in flyash or escape to the atmosphere. Lead and chromium exhibit enrichment factors of three or more inincinerator bottom ash [36], but are also enriched in flyash [37].

3.5. Radioactive species

naturally occurring radionuclidesfound in soil, artificial radionuclides occur in wood and other biomass as a result of deposition from atmospheric testing of nuclear weapons, the Chernobyl nuclear reactor accident, and other radioactive contamination [38, 39]. Wood samples collected in Croatia after the Chernobyl accident contained levels of 137Cs, 214Bi, and 40K in the range 1.6–37.3 Bq kg-1 1, 0.2–27.1 Bq kg-1, and 21.5–437.1 Bq kg-1 respectively (1 Bq=1 nuclear decay/s=2.7x10-11 Ci) [34]. Both 214Bi and 40K are naturally occurring and so are always found in biomass, 214Bi being a decay product of uranium contained in soil and 40 K a natural isotope of potassium in the environment. 137 Cs is an artificial isotope and indicative of radioactive contamination. Combustion results in enrichment in ash as radionuclides evaporate and recondense on flyash particles [40].

3.6. Greenhouse gas emissions

The use of diesel fuel, gasoline, natural gas, coal-fired electricity, and other fossil-based energy in the production, harvesting, processing, and conversion of biomass is not offset when biomass is grown on a purely replacement basis [2]. An additional amount of biomass would need to be grown and the carbon sequestered to offset the fossil carbon release from biomass handling. CH4, N2O, and other pollutants released during biomass production and conversion also have larger GWPs than CO2. Combustion of biomass, therefore, results in an imbalance in greenhouse gas emission and uptake. The large displacement of fossil-derived CO2 through the substitution of biomass in well-controlled systems, however, still results in a substantial decrease in net greenhouse gas emissions [40]. Advanced biomass conversion technologies reduce the emission of CO2 per unit of product energy by increasing efficiency and reducing the fuel consumption. For biomass utilization to be effective in managing atmospheric CO2, it must be produced on a renewable and sustainable basis, including indirect effects associated with global marketmediated impacts. Carbon capture and storage, currently under development for use with fossil fuels, and a number of other techniques to sequester carbon have the potential to achieve a net reduction in atmospheric carbon when applied to sustainable biomass conversion systems. Achieving substantially lower levels of pollutant emissions and realizing potential carbon benefits remain important objectives for biomass combustion research and development [40].

4. Conclusions

Biomass has been successful in many developed countries and to a certain extent, some developing countries as well. Countries with high share of renewables also have a high share of biomass in their energy mix. Bioenergy has enabled countries in a gradual decarbonisation of the energy system and reduced dependency on fossil fuels. The sustainable use of forestry and forest products has led them to be World leaders in renewables. Countries like Brazil are becoming independent of oil by increasing their blending of biofuels in the transportation sector. This transition has been possible because of effective policies such as carbon taxes, blending mandates and investments in research and development.

These policies have been driven by strong support from the universities, associations and companies. Apart from various environmental benefits, the use of bioenergy has enormous socio economic benefits as well. Bioenergy employs thousands of people globally along the complete value chain. The increased use of bioenergy will generate more jobs, provide added income to farmers and strengthen the local economies.

The health and safety of women and children is interlinked with bioenergy. Improving equipment efficiencies and supply chain management will improve the living conditions and enable women to be involved in income generating work. On the other hand, Biomass incinerators produce hundreds of tons of nitrogen oxides (NOx) and volatile organic compounds (VOCs) two ingredients of the ground-level ozone dangerous to human respiratory health and the environment. Biomass burning also produces tons of fine particulate matter (PM), a pollutant associated with asthma, heart disease, and cancer for which no safe level is known.

Acknowledgment

The authors acknowledged to prof. Dr. Kamil Kaygusuz for his valuable suggestions for accomplished to this study.

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