THE AIR GASIFICATION OF WOODY BIOMASS FROM SHORT ROTATION FORESTS

Opportunities for small scale biomass-electricity systems

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ABSTRACT

Downdraft gasification of short rotation forestry (SRF) biomass was investigated to identify opportunities for small scale biomass-electricity systems. Case studies were conducted in Kenya to identify these opportunities by (i) defining the energy demand and supply structure to identify markets; (ii) evaluating the biomass resources available; and (iii) identifying the availability of other facilities required for such a system. At the same time, the yield potential of 12 SRF species, planted in Palmerston North, New Zealand in small plots at 3470 stems/ha and harvested after 2, 3, 4 and 5 years was evaluated. Samples were collected from each species to determine their energy properties. Data on tree growth, yield, and biomass properties were used to develop two multi-objective indices - the relative yield index (RYI) and the fuelwood value index (FVI) for evaluating SRF species. Biomass from the 4 year rotation harvest was used as feedstock to fuel a downdraft air gasifier rated 35 kW (electric). Feedstock gasification processes, gas quantity and quality were correlated with the biomass properties to define the characteristics of a good fuelwood species for gasification purposes.

The Kenyan studies highlighted constraints in the energy sector and identified opportunities for new bioenergy technologies. Small scale biomass gasification systems showed potential but suitable sites were restricted to sawmills where processing residues could be used as gasifier feedstock. Field trials of SRF systems were recommended to evaluate tree species over different silvicultural treatments, and to intensify biomass production. A demonstration plant at one of the bigger sawmills was recommended to stimulate interest among investors.

Species yields of the trial plantings in New Zealand in the 12 species assessed ranged from 6 ODt/ha/y for *Alnus glutinosa* to 73 ODt/ha/y for *Eucalyptus globulus* at 5 year rotations. A stocking density trial of *E.saligna* showed that 3,500 stems/ha managed on 4-5 year rotations provided the highest yields. Though these yields may not be achieved in field plantings or in Kenya, the study demonstrated the feasibility and methodology that could be applied.

Like yield, the bioenergy properties varied between species. Higher heating values ranged from 19.6-20.5 MJ/kg for wood, 17.8-20.6 MJ/kg for bark, and 19.5-24.1 MJ/kg for leaves. Gas yields varied between 1.88-2.89 g/g dry wood due mainly to moisture content variations which also affected the composition of the gas. Gas heating values varied from 4.602 to 6.112 MJ/Nm^3, and were considered to be of sufficient quality to fuel internal combustion engines.

Both RYI and FVI showed that yield factors outweighed bioenergy properties when identifying a good fuelwood species. The large differences in yields indicated the benefits that could be achieved by selecting appropriate species for a specific region. Although feedstock properties affected the gasification processes and products, their overall influence was not statistically significant. The inclusion of bark in the feedstock did not adversely affect the suitability of the feedstock.

EXECUTIVE SUMMARY

The energy supply and utilisation structure of many developing countries is constrained. Since the development of national economies is linked to the availability of appropriate energy resources, it is important that alternative energy supplies to fossil fuels that are environmentally friendly, economically sound, and those that will blend with the existing energy supply and utilisation technologies are identified. One such energy option is biomass when converted by thermal gasification for electricity generation. A successful application of this option requires (i) the identification of appropriate biomass energy applications and technologies; (ii) the identification of biomass resources to be supplied on a sustainable basis; (iii) the definition of biomass feedstock quality requirements for the selected technology; and (iv) the determination of the optimum operating conditions for high quality products. These were all covered in this research programme.

A case study was conducted in Kenya to identify the opportunities for modern biomass energy technologies like gasification for small scale biomass-electricity systems. At the same time, field trials of short rotation forestry (SRF) at Massey University, New Zealand were conducted to evaluate a selected range of tree species and silvicultural treatments (based on growth and yield). Samples were collected from each of the species grown under a range of silvicultural treatments and tested in the laboratory to characterise their energy properties. The data on growth, yield, and energy properties obtained were used to develop two multi-objective indices used to evaluate SRF species - the relative yield index (RYI) and the fuelwood value index (FVI). Samples of biomass harvested at the age of four years from nine of the twelve SRF species were processed and used as feedstock in a 35 kW (electric) downdraft gasifier. The gas produced under a controlled set of conditions was analysed and correlated with the laboratory feedstock characteristics to determine any differences in the fuelwood species.

In Kenya, fuelwood supplies more than 70% of the total national energy requirements. Oil provides 22-26%; coal 1%; and electricity (hydro, thermal, geothermal and imports) 2-4%, being 821 and 672 MW (installed and effective capacity, respectively). Recommendations for the development and use of more renewable energy sources were made based on economic, environmental and feasibility considerations, and favoured sustainable utilisation of biomass

in modern conversion technologies like gasification for electricity production. However, the standing tree stock as assessed on private farms in the densely populated rural areas (0.7-4.6 m^3/household) would be insufficient to supply such technologies for rural areas. The location of such plants is therefore limited to sawmills processing more than 720 t/y of round wood and generating more than 1 t/day of solid residues (including slabs and offcuts but excluding sawdust). This quantity of residues could be supplied to a gasifier to generate on an annual basis more than 0.3 GWh (electric) and almost 0.6 GWh of heat in a co-generation plant. The 73 medium to large scale sawmills in Kenya have the potential to generate more than 100,000 t of solid residues per year with a producer gas potential of 221 x 10^6 normal cubic metres per year (Nm^3/y), equivalent to 24,000 t of oil. This gas could be used to generate up to 76 GWh (electric) plus another 141 GWh of heat per year.

A demonstration plant at any of the 73 sawmills was recommended to illustrate the potential of the technology. Also, field trials were recommended to (i) evaluate a range of high yielding SRF species suited to specific regions; (ii) evaluate a range of silvicultural treatments suited to the production of large quantities of high quality woody biomass; and (iii) intensify woody biomass production to supply gasifier installations in rural communities.

Of the 12 SRF species evaluated in New Zealand, being planted at 3470 stems/ha in small plots and harvested at 3, 4 and 5 year rotations, *Eucalyptus globulus* had the highest yields of 73 oven dry tonnes per hectare per year (ODt/ha/y), while *E.nitens* and *Acacia dealbata* had 59 and 49 ODt/ha/y respectively in the 5 year rotations. The lowest yielding were *Eucalyptus saligna* (< 12 ODt/ha/y); *Salix matsudana* x *alba* (1002), (< 10 ODt/ha/y); *Alnus glutinosa*, (< 6 ODt/ha/y); and *Paulownia tomentosa*, (< 7 ODt/ha/y) in all three rotations. Although the longer rotations had higher yields, the current annual increment (CAI) for most species was decreasing and approaching the mean annual increment (MAI) for the 5 year rotation. This indicated that the plots were nearing the optimum rotation length. In a "Nelder" radial design trial of *E.saligna*, the 4-5 year rotations at a stocking density of about 3500 stem/ha provided the optimum growing conditions for SRF systems in the Manawatu region of New Zealand. Results of the coppicing trial were not conclusive.

A series of biomass properties were recorded - the harvest index, proportion of bark on the stem, basic density, fixed carbon content, extractives content and heating values. These varied significantly between species, and among the tree components tested (wood, bark and leaves). Most properties did not vary significantly with different silvicultural treatments except for the proportion of bark which declined with cutting age, and the wood basic density which increased. Biomass properties did not vary significantly with sampling height up the stem.

Higher heating values (HHV) ranged from 19.6-20.5 MJ/kg for wood, 17.8-20.6 MJ/kg for bark, and 19.5-24.1 MJ/kg for leaves. The highest HHV (20.5 MJ/kg for wood and 20.6 MJ/kg for bark) was obtained from *Pinus radiata*, the only softwood tested. The different properties were correlated indicating that the quality of biomass used as feedstock was defined by most of the properties. Therefore, each property of the potential feedstock must be considered when formulating guidelines for the design of biomass energy conversion equipment.

Multi-objective techniques incorporating measured yields and energy properties for the range of species showed that yield factors outweighed the energy characteristics when identifying a good fuelwood species. The large differences in species yield indicated the large gains in terms of GJ/ha/y to be made by selecting the most appropriate species for a specific region. Assuming that the average yields (27-39 and 41-55 ODt/ha/y of stemwood and total biomass respectively) from the 4 best species over the three rotations would be achievable under Kenyan growing conditions, it was estimated that a gasifier suitable to produce electricity and hot water for a village community would require a minimum of 10 hectares of SRF harvested (2.5 ha/year), to produce about 0.5 t of dry feedstock per day.

The processes and products of downdraft air gasification were influenced by (i) gasification temperature (ii) the equivalence ratio (ER) defined by the quantity of air used; and (iii) the feedstock moisture content. High temperatures (above 1000°C) produced larger quantities of gas with high heating values. The ER values of 0.195-0.328 (with an average of 0.250) were less than the optimum value of 0.275 and indicated that air flow was not optimum for most runs, resulting in insufficient gasification reactions (tending towards pyrolysis), and lower gas yields. High feedstock moisture contents reduced the reaction temperatures; altered the optimum temperature profiles; reduced the available feedstock substrate through hydrolysis, thereby reducing the quantity of gas achievable; and produced a gas with high moisture content, high CO_2 and N_2

content, but reduced CO and CH_4 content with consequently lower heating value. Although feedstock properties affected the gasification processes and products, their overall influence was not statistically significant. Similarly, the inclusion of bark in the feedstock did not adversely affect the suitability of the feedstock when compared to samples without bark.

Downdraft air gasification of biomass produced 1.88-2.89 grams of gas per gram of feedstock (equivalent to 2.1-3.0 m^3/kg of dry feedstock). The gas composition varied but typically contained 51-62% nitrogen; 19-26% carbon monoxide; 8-13% hydrogen; 7.5-10.6% carbon dioxide; and 1.8-2.5% methane. The gas heating value varied from 4.602 to 6.112 MJ/Nm^3, and the heating value of the stoichiometric gas-air mixture ranged from 2.241 to 2.524 MJ/Nm^3 for air dry and oven dry feedstocks. The gas composition and heating values were considered to be of sufficient quality to fuel internal combustion engines.

The quantity of solid residues (and ash particulates) produced was not sensitive to the species or feedstock properties, reaction temperature, equivalence ratio (air supply) or the feedstock moisture content. The quantity of liquid residues (condensate) generated being 20-80 g/kg of dry gas from air dry feedstock and oven dry feedstock decreased with increasing gasification temperatures and increased with increasing feedstock moisture contents. The quantity of condensate was however not sensitive to the species or to the equivalence ratio. The pH, COD, electrical conductivity and turbidity of the condensate showed that it would be unsafe to dispose of the residue into water-ways or onto land without pre-disposal treatment. An initial step would be to filter the residue through the solid residues collected from both the ash port and from the cyclone.

The study demonstrated methodologies for (i) identifying and evaluating opportunities for biomass to electricity systems in developing countries, and in isolated remote regions of developed countries; and (ii) evaluating SRF species for fuelwood requirements using multi-objective indices - the relative yield index (RYI) and the fuelwood value index (FVI). The methodologies may be applied to other regions of the world. In particular, the indices could be used to evaluate SRF species grown under Kenyan conditions. The species which performed well under the Manawatu conditions, (*E.globulus*, *E.nitens*, *A.dealbata* and *E.ovata*), and others which are known to grow well under tropical conditions should be evaluated alongside high yielding local species.

Commercial gasifiers need to be compared and one selected for a demonstration to stimulate the concept in Kenya. A financial and economic evaluation of the demonstration plant would not necessarily indicate the true economic and environmental values of the venture as a learning process will be involved. However, given that the project would be in the experimental / demonstration stages, it would enable a full cost - benefit analysis to be undertaken to provide useful data which would be accurate enough to be used when comparing electricity generation from SRF crops and sawmill residues with other electricity generating technologies such as traditional fossil fuel fired power plants, or even photovoltaic, solar, wind, or diesel generator sets.

DEDICATION

This Thesis is dedicated to my mother, posthumously,

The Late

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MAMA PAULINE MUHONJA KINGIRI

†

You got so close, yet

(i) a few weeks shy of realising your own work

(ii) many years shy of reaping the full benefits of your long, hard and painful struggle

(iii) capable of much more, had you had the opportunities you gave us

"......the long hours of sleep after finishing school will never have the meaning you meant".

Gona vulahi

Nyasaye nakulumikiyi
bulikasaganili mwigulu

†

May the almighty God rest her soul in eternal peace

†

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