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Biomass Energy Background Paper (Yukon Energy Planning Charrette)

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Yukon Energy Planning Charrette - Biomass Energy Background Paper

Introduction

The world derives approximately 12 percent of its energy from biomass. In Canada this figure is approximately 6% or 650 PJ/a. In developing countries biomass is the most important energy source, accounting for about 35 percent of the total energy consumption. In the largest developing countries, China and India, biomass accounts for 19 percent and 42 percent of the primary energy supply respectively. The annual global annual production of biomass totals 220 billion bone dry tonnes, or 4,500 EJ. The theoretically harvestable bioenergy potential is estimated to be 2,900 EJ, of which 270 EJ could be considered technically available on a sustainable basis (IEA/OECD, 2002).

Biomass fuels include items as diverse as residential yard waste, manure, agricultural residues, and dedicated energy crops. In industrialized nations, bioenergy facilities typically use biomass fuels in large industrial cogeneration applications (e.g. pulp and paper production, sugar cane milling). Conversely, developing nations largely rely on biomass for rural cook stoves or small industries. Such applications are relatively inefficient and dirty. Increasing industrialization and household income are driving the economies of developing nations to implement cleaner and more efficient biomass technologies. Environmental concerns may help make biomass an economically competitive fuel. Because biomass fuels are generally less dense, lower in energy content, and more difficult to handle than fossil fuels, they usually do not compare favourably to fossil fuels on an economic basis. However, biomass fuels have several important environmental advantages. Biomass fuels are renewable, and sustainable use is greenhouse gas neutral (biomass combustion releases no more carbon dioxide than absorbed during the plant's growth). Biomass fuels contain little sulphur compared to coal (reduced sulphur dioxide emissions) and have lower combustion temperatures (reduced nitrogen oxide emissions). However, unless biomass is efficiently and cleanly converted to a secondary energy form, the environmental benefits are only partially realized, if at all. For this reason, efficient, modern biomass utilization technologies must be developed to supplant traditional applications.

The modes of energy conversion of biomass are almost as varied as the sources of feedstock. It can be co-fired with pulverized coal in power generation stations, burned in dedicated equipment, gasified to drive a reciprocating engine or turbine, or transformed into higher density solid or liquid fuels. There are however competing uses which must be considered: bedding for livestock, strawboard manufacture, and production of chemicals are examples.

Bioenergy utilization is attracting ever-growing attention. The European Union has large research, development and demonstration programs for bioenergy. There have been several high-profile initiatives in the USA to increase the production of bioenergy and bio-products where the label 'biorefinery' is used to summarize this integrated approach to the development of the biomass resource. This interest can only increase with the recent volatility in conventional fossil fuel prices. There is now a strong economic incentive for energy consumers to find alternative energy sources, bioenergy being a leading contender. Bioenergy can be considered as a renewable energy source that is greenhouse gas neutral, if the biomass is produced in a sustainable manner. Political or public pressure to reduce greenhouse gas emissions, or the economic benefit of carbon credits, can also be driving forces for the increased use of bioenergy. These driving forces will produce more rapid development of technology and increased adoption of bioenergy. Increased adoption can change the markets, infrastructure, regulations and policy environment for bioenergy.

The expected role of biomass in the future energy supply is based on two main considerations:

> i)The development of competitive biomass production, collection, and conversion systems to create biomass-derived fuels that can substitute for fossil fuels in existing energy supply infrastructure without contributing to the build-up of greenhouse gases in the atmosphere. Intermittent renewable sources, such as wind and solar energy, are more challenging to fit into existing distribution and consumption schemes.
>
> ii) The potential resource base is generally considered substantial given the existence of land not required or unsuitable for food production, as well as agricultural food yields that continue to rise faster than population growth. An assessment of potential bioenergy development must first address issues ranging from land-use conflicts with food production to health and environmental problems.

Biomass is often perceived as a fuel of the past because of its low efficiency, high pollution, and associations as being the major third world energy source. Biomass is the fuel most closely associated with energy-related health problems in developing countries. Exposure to particulates from biomass can cause respiratory problems. The collection and transport of biomass can result in increased vehicle and infrastructure use and air-borne emissions. Biomass fuels are bulky and may have high water content. Fuel quality may be unpredictable, and physical handling of the material can be challenging. Also, the chemical composition may vary considerably, which may require pre-treatment in order to meet the requirements for quality and homogeneity of many conversion technologies. For these reasons, biomass pre-treatment (or upgrading) techniques may be necessary to convert raw biomass into easier to handle, denser and more homogeneous (solid (e.g. pellets) or liquid) fuel, in order to reduce supply chain cost and increase the efficiency and reliability of downstream processes. Increasing the energy density of biomass may also be attractive if it is necessary to decouple bioenergy production from its point of use, due to the increasing cost of transport.

A key issue for bioenergy is that its use must be modernized to fit into a sustainable development economy. Conversion of biomass to energy carriers like electricity and transportation fuels will give biomass a commercial value and provide income for local rural economies. In order to achieve this it is essential that biomass markets and the necessary infrastructure are built up, key conversion technologies like integrated gasification combined cycle and advanced fuel production systems for methanol, hydrogen and ethanol are demonstrated and commercialized, and that much more experience is gained with biomass production systems in a wide variety of contexts. Although the actual role of bioenergy will depend on its competitiveness versus fossil fuels and agricultural policies, it seems realistic to expect that the current contribution of bioenergy will increase during this century.

Energy Conversion Technologies

Biomass conversion technologies can be grouped into three categories: Thermochemical, Physicochemical and Biological. A detailed description of the various conversion routes is provided in Annex A.

Thermochemical conversion involves processes by which biomass undergoes chemical reaction induced by high temperature. Four thermochemical routes are combustion, gasification, pyrolysis, and torrefaction which differ mainly in their temperature ranges, heating rate and amount of oxygen present in the reaction.

Physicochemical conversion is used to produce liquid fuels (biodiesel or vegetable oil) from oil crops (rapeseed, soybean, Jatropha, etc.) by oil extraction. Biological routes use living micro-organisms (enzymes, bacteria) to degrade the feedstock and produce liquid and gaseous fuels. Biological routes are numerous, key examples being fermentation from sugar (sugar-cane, sugar-beet, etc.), starch (corn/maize, wheat, etc.) and lignocellulosic (grass, wood, etc.) feedstocks, and anaerobic digestion (mostly from wet biomass).

Electricity conversion technologies can be grouped into two broad categories, based upon their stage of development – Figure 1. Existing technologies, which consist of direct combustion applications, are typically well-established, but tend to be expensive relative to most fossil fuel options, have generally low electricity conversion efficiencies (~25%), and have greater air emissions than most other renewable energy options. Newer, not quite commercial for power generation, technologies include biomass gasification and pyrolysis. Pyrolysis refers to the thermochemical process for converting solid biomass into a liquid fuel (bio-oil). The pyrolitic liquid or bio-oil can be transported and refined into various products. Gasification is a thermal conversion process in the presence of approximately one third the air required for combustion in which the solid biomass is converted to a synthetic gas (syngas) containing high levels of carbon monoxide and hydrogen. Both pyrolysis and gasification are technologies with the potential for higher energy efficiency, improved environmental performance, and potentially more favourable project economics. Both use heat to decompose the biomass into combustible gas and/or liquid, which can potentially be burned in a turbine or internal combustion engine. The major technical issues are the cleaning and consistency of the gas or liquid fuel produced. As with combustion technologies, the behaviour of the different types of biomass and process optimization is important. Gasification is naturally linked to combined cycles, where useful energy is obtained from the gasification cycle and the combustion cycle, with higher conversion efficiency for the energy in the biomass. Other cycles, like the Stirling or Brayton cycles, can be combined with direct combustion systems. Gasification and pyrolysis for electricity generation are, however, still costly in their developmental stages and not yet commercially competitive – Figure 2.

For manures and other materials with very high water content, biogas production may be the most efficient method of energy extraction. An anaerobic digester is used to produce a gas with high methane content. The biogas can be used for heat or to drive an engine for electric power. The residual solids are better suited as fertilizer than the untreated manure.

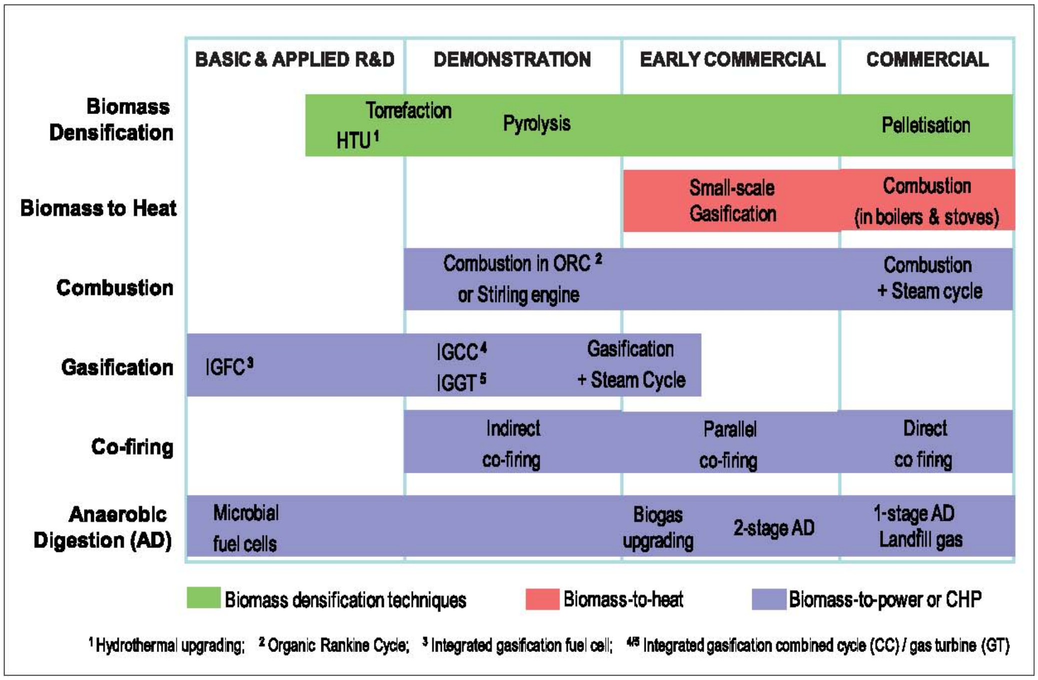


Figure 1. Status of Bioenergy Conversion Technologies (IEA, 2009)

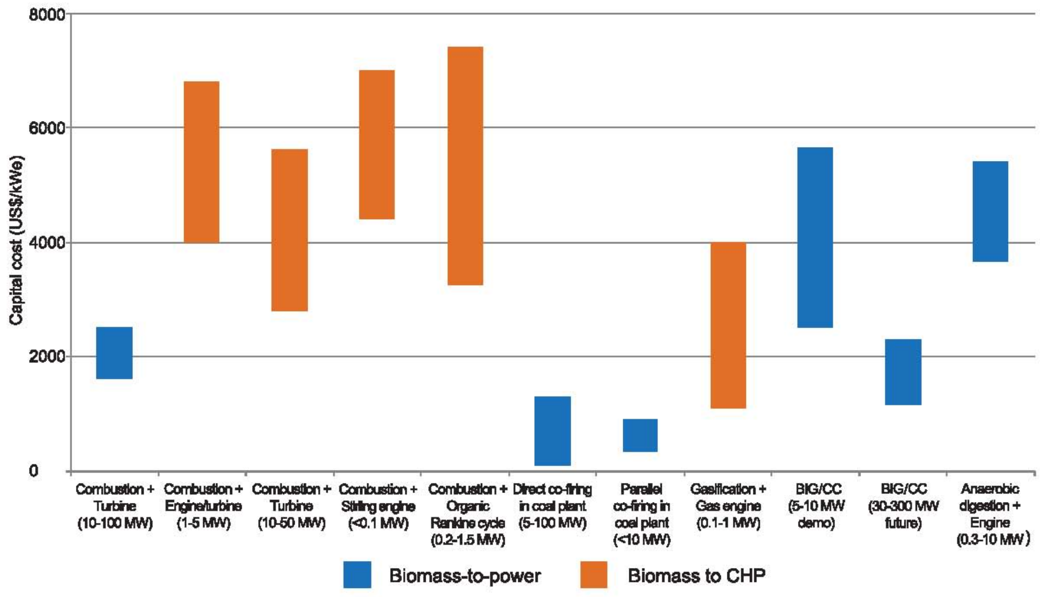
Biomass Combustion

Direct combustion or burning of biomass for heat is the oldest and most common way of converting solid biomass to energy. Because combustion is a straightforward and reasonably well understood process, there exists a wide range of commercial technologies tailored to the characteristics of the biomass and the scale of the application. Technologies include either grate furnaces or fluidized bed combustors which can be coupled to standard steam cycles for electric power generation. Combustion is currently the cheapest and most reliable route to produce power from biomass in stand alone applications.

Even though combustion technologies are fairly well established there are issues which need to be carefully evaluated. The emissions and ash behaviour of particular fuels need to be characterized. Furnaces need to be optimized for the specific biomass fuel mix. High moisture content means that significant fuel energy is used in vapourizing water and hence recovering this latent heat by flue gas condensation can be a significant source of energy.

An increasing number of boilers in the 0.5-10 MWth range are found in industries that consume large amounts of heat and have large volumes of biomass residues at their disposal. The industrial sector is potentially a large market for biomass heating, but it requires tailored solutions that meet the technical requirements of the different industries.

In a fragmented biomass supply market, the cost of purchasing large quantities of biomass may increase sharply as the distance to suppliers (and thereby logistical cost) increases. In this context, the importance of economies of scale for steam-cycle plants has meant that dedicated biomass power plants have generally only proven commercially viable at the larger scale (20-100 MWe) when using low cost feedstocks available in large volumes such as agricultural residues (e.g. straw), or wood residues and black liquor from the pulp and paper industry. However, a growing number of viable smaller scale plants (5-10 MWe) using other type of residues (wood, straw, etc.) are found throughout Europe and North America.



Note: Anaerobic digestion can also be run in CHP mode.

Figure 2. Capital Cost Ranges for Bioenergy Technologies (IEA, 2009)

Waste-to-energy Conversion

Municipal solid waste (MSW) is a highly heterogeneous and usually heavily contaminated feedstock, which calls for robust technologies and rigorous controls over emissions, leading to relatively high costs associated with waste-to-energy facilities. Different technologies are available, and the choice usually depends on the degree of separation of the different MSW fractions. The generally uncompetitive cost at which electricity is generated means that, in the absence of an appropriate waste hierarchy and associated incentives, MSW remains a largely unexploited energy resource despite its significant potential in most countries.

Combined Heat and Power

The principal means to significantly increase the overall efficiency of a power plant (and hence its competitiveness) is to find an economic application for its waste heat. Combined heat and power (CHP) plants, also called cogeneration plants, have typical overall (thermal + electric) efficiencies in the range of 80-90%, provided a good match can be found between heat production and demand. This is commonly the case, for example, in the pulp and paper industry.

Co-generation has been shown to reduce the cost of power production by 40-60% for stand-alone plants in the range of 1-30 MWe. However, for domestic and commercial heating applications, the scale of biomass CHP plants is often limited by the total local heat demand and by its seasonal variation, which can significantly affect economic returns unless absorption cooling is also considered (tri-generation). Even with a proven technology, the economic case for biomass-based district heating depends on a number of complex techno-economic parameters. Today, biomass-based district heating provides a significant share of the heating requirements in some countries (e.g. northern European countries). Although an economic case can be made for appropriatelyscaled district heating networks, the high cost of new heat distribution networks and the difficulty of guaranteeing high overall efficiency are key issues hindering further deployment.

Distributed Generation & Yukon College Biomass Gasifier

Biomass fuels exist in many areas that lack conventional infrastructure, e.g. an electrical supply grid. Many of these sites must use imported fuel oil to generate small-scale power at substantial cost. There is therefore considerable interest in using the local biomass resource (in many cases a residue stream) to generate power. The size of these would typically be in the 250 kWe to 5 MWe range. This is a size range in which the conventional Rankine steam cycle, although technically feasible, is not economically feasible due principally to the need for continuous manned attendance. Efforts underway within the last five years have been aimed at developing "small modular" automated, safe and reliable biomass-fired systems, which can meet these needs. In the lower capacity range, the Stirling Engine (10-100 kWe) and the Organic Rankine Cycle (ORC) (50-2000 kWe) are promising technologies for distributed cogeneration. Currently at the demonstration stage, improvements are still needed, in particular concerning conversion efficiency, reliability, and cost. There are as yet no systems that can approach these criteria. Typical costs for existing systems are in the $4,000-$5,000/kWe range. The consensus is that the current price barrier for these systems is about $3,000/kWe.

Small gasifiers coupled to diesel or gasoline engines (typically for systems of 100-500 kilowatts of electricity with an approximate electrical efficiency of 15-25 percent) are being pursued by a large number of companies worldwide. In fact, the first large (> 2 MW(th)) fluidized bed gasifier installed in Canada was installed over 20 years ago at Yukon College, Whitehorse. Inadequate controls prevented this gasifier from operating properly however the basic design is similar to a number of units currently in operation. The basic principle of power generation via gasification is illustrated in Figure 3.

The limiting factors for power generation from gasification have been high costs and the need for gas cleaning and unmanned control systems. Some crude systems are being applied fairly successfully in rural India and in China and Indonesia. For example, in China at least 20 fluidized bed gasifier/internal combustion engine plants are operating but the engines require shutdown and overhaul every 100 hours due to the contaminants in the syngas. In Europe a few units are operating with some success but they depend on very expensive multi-stage gas cleaning. Gas cleaning and conditioning remains a key requirement for these systems and a facility such as the Yukon College Gasifier would provide a good platform for such research. The heating value of gases that can be turned into electricity at an efficiency of up to 40% lies between 0.5 kWh/m^3 and 34 kWh/m^3, which is well within the range which could be produced by the Yukon College Gasifier. Jenbacher systems apply combustion technologies that have been patented worldwide and achieve guaranteed emission levels below 250 mg/m^3 of NOx and below 300 mg/m^3 of CO when operated with natural gas. The overall energy efficiency of the systems is as high as 88% when operated in cogeneration mode - i.e. simultaneous production of heat and power. For example, the Yukon College Gasifier could produce syngas which after cleaning is used to run an internal combustion engine. The hot exhaust from the engine could then be run through a boiler thus generating hot water to provide space heating. Such a project would be a showcase for advanced energy from biomass.

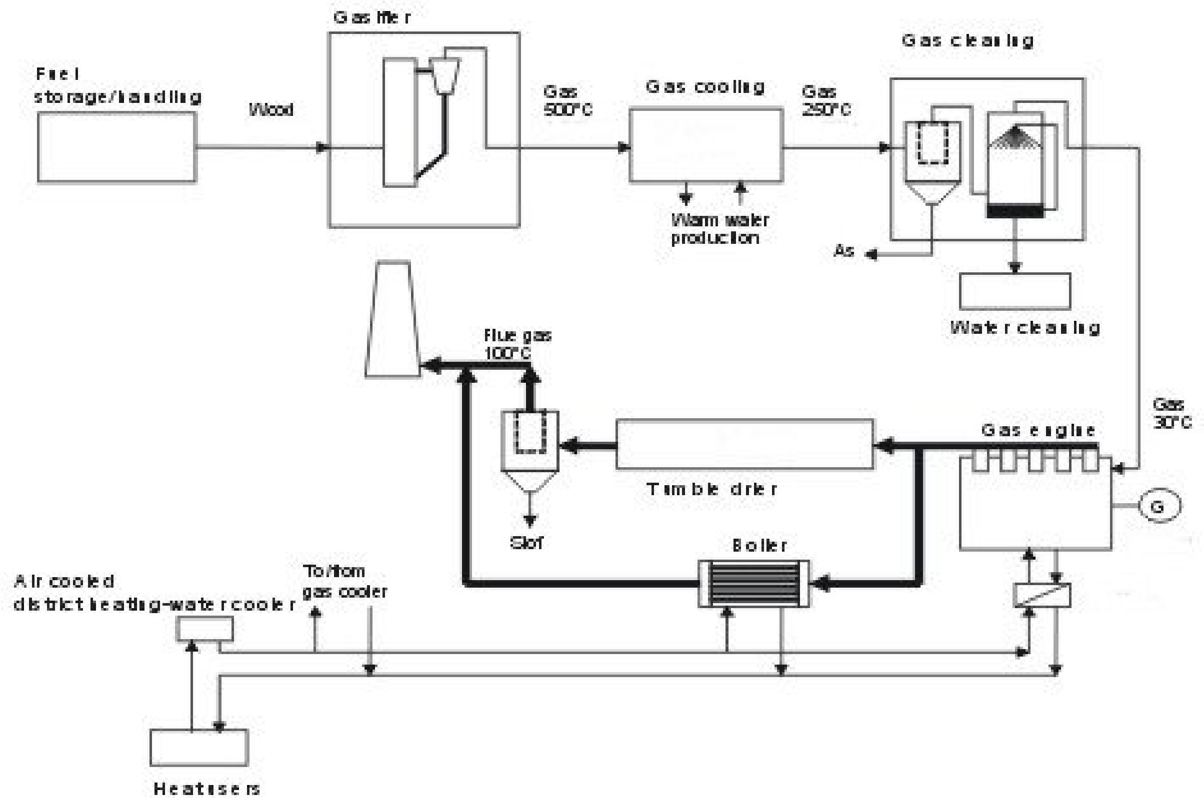


Figure 1 Combined Heat and Power Schematic

Biomass Energy Supply and Sustainability in the Yukon

Canada is a forest nation. Its forests cover 42% of its land mass and represent 10% of the world's forests and more than 30% of the Boreal Forest. Forests play an important role in the economic, social and spiritual well-being of Canadians. The majority of Canada's forests lie within eight ecozones delineated on the basis of the interactions of geological, landscape, soil, vegetation, climate, wildlife, water and human factors.

The Boreal Cordillera ecozone, covering sections of northern British Columbia and the southern Yukon, has a Pacific Maritime influence that moderates temperatures over most of its area. The climate is marked by long, cold winters and short, warm summers. The ecozone is 61% forested. Vegetative cover ranges from closed to open canopy forest. Tree species include white and black spruces, alpine fir, lodgepole pine, trembling aspen, balsam poplar and white birch. The tree line ranges from 1500 metres in the southeast to about 1200 metres in the northwest, where the stands are generally open, and there is almost no lodgepole pine or alpine fir. This ecozone is sparsely populated, with the majority of the population of approximately 32904 (density 0.1) residing in the larger communities of Whitehorse and Dawson. The major economic activity is mining followed by forestry, tourism, and hydroelectric development.

The mean annual increment (MAI) is the average net annual increase in the yield of living trees to a given age, and is calculated by dividing the yield of a stand of trees by its mean age. The MAI is dependent on a number of factors, including climate and elevation, soil conditions and forest management practices. MAI is a measure of the net biomass production of the forest in m^3/(hectare·year). For the Boreal Cordillera, the MAI ranges from 0.69 for poplar (Note: this is conventional poplar trees, not short rotation poplar which is under consideration in parts of Canada as an energy crop) to 1.57 for larch. The values (from Natural Resources Canada / Canadian Forestry Service (CFS) surveys) include 1.30 for spruce, 1.11 for pine, 1.46 for fir, 1.20 for hemlock and 1.17 for birch. In estimating how much forest area would be required for a given amount of energy, after discussions with CFS (Jeff Karau and Derek Sidders, 2008) it was decided that a conservative number would be an MAI of 1.1 for the area around Whitehorse. For comparison purpose, spruce in the Pacific Maritime region have an MAI of 3.8.

Based on the growth rate of 1.1 m^3/(hectare·year) an area of approximately 1 square kilometre would supply, in a sustainable manner, approximately 50 tonnes of wood per year.

In the Yukon there are a number of off-grid communities which rely on diesel generation in the range of 1 MWe. The total off-grid diesel capacity is 8.4 MW and in 2010 these units generated 19.8 GWh of electricity. This represents a capacity factor of approximately 30%. In estimating how much wood and forest area is required to provide these communities with biomass power the following assumptions were made:

- Wood Energy content of 18 MJ/kg
- Efficiency of conversion to electricity 20%
- MAI is 1.1 m^3/(hectare·year)
- Wood availability in mature forest 85 m^3/hectare
- 1 tonne of wood (~ 1 cord) is 2.2 m^3
- 1 square kilometre is 100 hectares

Based on these assumptions an isolated community with a 1 MWe biomass power plant running at 30% capacity would require 2,400 tonnes of wood. In order to collect this much wood an area of 62 hectares would have to be harvested. In order to maintain a sustainable harvest, an area of 48 square kilometres (4800 hectares) would have to be set aside so that growth equals harvest. The following table summarizes the figures for varying capacity factors for a 1 MWe power plant:

1 MWe Plant Capacity, %	Wood Required Tonnes	Annual Harvest Area Hectares	Set-aside Sustainable Forest, km^2
30	2400	62	48
60	4800	124	96
90	7200	186	144

The above table is based on harvesting an existing forest for power production. There are however substantial resources in the Yukon of “dead” forest which could be utilized depending on proximity to the power plant.

In addition to the annual growth of forest, there are two other factors affecting the potential for energy from biomass in the Yukon Territory: forest fires and spruce bark beetle infestations.

A forest fire kills trees and shrubs but often does not consume them; instead, it turns them into dead fuel. Combustion rarely consumes more than 10 to 15 percent of the organic matter, even in stand-replacement fires, and often much less. Consequently, much of the forest remains in the form of live trees, standing dead trees, and logs on the ground. Forest fires typically kill over 1000 square kilometres of forest in the Yukon each year. A considerable amount of biomass is therefore available to be used for energy systems.

The infestation of the mature spruce forests by the spruce bark beetle in the area around Haines Junction (Champagne and Aishihik Traditional Territory) has been epidemic since 1992. The infestation has contributed to a potential fire hazard for communities, increased the risk of catastrophic loss of property, affected visual landscapes, reduced the value of the forest for timber, recreation and tourism and impacted ecosystems. The scale of the infestation is extreme. Based on a forest health survey conducted by the Canadian Forest Service and the Yukon Forest Management Branch the infestation over the last 10 years has expanded its range and now occupies a total area of more than 220,000 hectares in the region. In some of the 18 planning areas in the region, the infestation has killed 100 per cent of the infested stands. This means that a potential area of 2200 square kilometres of dead forest is potentially available for energy use.

There are obviously opportunities to utilize fire and pest-killed trees for a variety of products. The value of these trees generally decreases over time due to factors, such as, checking and decay. However, these factors may be less critical when fire-killed trees are used as a source of biomass for the production of heat energy. The heat content of oven dry material from downed and standing dead western white pine and lodgepole pine has been found to be similar to that for material from green trees. Studies carried out in Colorado on fire-killed trees from three separate years (1996, 2000 and 2002) showed that there was no significant difference between the heating value of living trees and fire-killed trees. Furthermore, the recoverable heat of combustion was higher for trees that had been dead longer, as a result of lower wood moisture content. The moisture content for samples from live trees averaged 77.8 percent, while trees killed after 1, 3 and 7 yeas averaged 39.1, 27.5, and 9.4 percent, respectively.

The exact mechanisms of decay for standing trees is not well understood and requires considerable additional work. These losses were extremely dependent on climatic conditions and for the U.S. have been reported to be from 3.6% per year to 11% per year. For the Yukon would likely be in the lower end of this range. Trees deteriorate continuously after death thereby reducing both recovery volumes and values decrease with the amount of time that dead trees are left standing. The key factors for standing trees killed by fire or pests are ambient moisture and temperature. Water immersion can be used to control wood deterioration over time; however the economics of storing large volumes of wood in water are not compelling.

The biggest value losses in dead trees are associated with handling. Dry, brittle trees are more susceptible to breakage—11% in four-year-dead trees versus 0% in live trees. The processes of falling, skidding, loading, hauling, decking and feeding mills involve handling the wood with large machinery, which result in significant breakage. Secondary problems with handling dead wood include safety concerns as brittle trees can easily break unexpectedly. Dry logs delivered to a sawmill also present difficulties in the processing stage. Debarkers tend to become less efficient when handling dry logs, because the dry fibre is easily damaged. Dry wood requires more energy to saw. Saws and chipper and planer blades blunt faster, in part because of dirt and stones lodged in wood checks. Checks formed due to severe drying of the wood result in splits in logs which open up and reduce board width and length. When checked lumber breaks during processing, pieces can jam sawmill and planer machinery, which leads to downtime and reduced productivity.

Burning wood for energy is often proposed as possible use for pest and fire-killed trees. Although domestic stoves, furnaces and fireplaces can make use of some logs, more promising options involve industrial production of fuel pellets, electricity and heat. Large, commercial-scale wood-pelletization plants already in operation in British Columbia’s beetle-infestation area consume large volumes of residual fibre from other processing facilities. Unfortunately the potential for bioenergy from dead trees depends heavily on costs for production, not technical feasibility. Most literature points to feedstock costs as a critical factor in economic feasibility of biomass-energy production. In British Columbia, current pellet production depends on residual wood fibre delivered at little or no cost to production facilities. However, if direct salvaged beetle-killed lodgepole pine were used to procure wood fibre, costs of pellet production could potentially double or triple. Although there are cost and supply concerns, there are also benefits specific to bio-energy products. Fuel pellets offer several benefits over wood chips and other forms of combustible wood material: they are a stable product and have significant advantages in terms of transportation, storage and handling.

In terms of energy content the following gives a general trend for net energy content with years following tree death. Harvesting in the 3 to 4 year time frame seems optimal for obtaining relatively dry wood which is still “safe and easy” to harvest.

Figure 4. Standing Dead Tree Energy Content

ANNEX A: Biomass Conversion Technologies

(Adapted From Bioenergy – a Sustainable and Reliable Energy Source, IEA Bioenergy EXCO Report: 2009:06)

Biomass-to-Heat Technologies

The direct burning of wood and other solid biomass feedstock for domestic heating and cooking purposes is the oldest and most accessible energy technology used by man, and it is still by far the largest contribution of biomass to global energy supply today. Depending on the socio-economic context and environmental legislation in place, domestic biomass combustion technologies range from very inefficient devices such as open fire places (efficiency ranging from -10% to 10%31) or traditional cooking stoves found primarily in developed countries (efficiency 10-15%), through to very efficient and increasingly popular modern chip-burners, heat storing stoves and pellet-boilers with efficiencies of up to 90%. Advanced biomass boilers can even reach efficiencies of 105-110% (on LHV basis) if flue gas condensation and humidification of combustion air is applied, or if the waste heat is used for absorption cooling.

A range of biomass combustion systems is available for heat production on a larger scale for industrial purposes or district heating. Grate boilers and underfeed stokers are the most common technologies for small- to medium-scale applications (200 kW-20 MW) as these offer low investment and operating costs. Fluidised bed technologies, which became commercial in the 1970s, offer higher thermal efficiency and lower toxic emissions (CO, NOx) than fixed bed approaches due to better control over combustion conditions. Fluidised bed technologies also offer the further advantage of a greater tolerance of moisture content and type of biomass used.

However, fluidised bed technologies have higher capital and operating costs, and require significant economies of scale, so that only larger plants (>20-30 MW) are economically viable. Over 300 fluidised bed installations have been built worldwide to date.

Production costs of biomass-based heating systems vary widely with size and fuel cost. Heat production costs in pellet boilers in the range 5-100 kW range from 8 to 99 Euro/ GJ, with an average of 26 Euro/GJ – about competitive with fossil resources. A mere 4-6% cost reduction is expected through to 2030 (at a constant fuel price) by increasing lifetime and efficiency. Combustion of wood chips for district heating is more commonly applied than pellet burners. These can have higher investment costs but lower fuel prices.

Further R&D on combustion technologies will focus mainly on increasing thermal efficiency, and the need to develop small-scale technologies that can burn biomass other than wood (e.g. energy crops, tree residues, etc.). Also, as the combustion process per se is associated with toxic emissions of volatile compounds (in particular NOx and particulates), continuous effort is needed to further reduce these harmful emissions in order to meet increasingly stricter emission regulations. This is particularly the case for biomass fuels rich in nitrogen and ash. Small-scale combustion units are of special concern, as they need simple and affordable solutions. Finally, questions remain regarding the most environmentally sound and affordable manner for processing ash from contaminated biomass sources in the context of increasingly strict landfill regulations.

Biomass Combustion-to-Power Technologies

The heat produced by direct combustion in boilers can be used to produce electricity in a separated steam turbine or engine. Overall electrical efficiency is limited by the relatively low efficiency of the steam cycle. The efficiency of electrical generation alone typically ranges from about 10% for small CHP plants (<1 MWe steam-engine) up to close to 40% (electricity only mode) for >50 MWe steam-turbine combined with the most advanced fluidised bed combustion technology. The rest of the energy from the combustion (60-90% of the energy contained in the feedstock) is lost into the air or water as waste heat.

The main way to increase the overall efficiency of a power plant (and hence its competitiveness) significantly is to use this heat. By making use of waste heat, combined heat and power (CHP), or cogeneration, plants have typical overall efficiencies in the range 80-90% provided a good match can be found between heat production and demand. However, recycling the waste heat has a slightly detrimental impact on the efficiency of the power production, which is a few percentage points lower in CHP plants than in power-only plants.

Economies of scale are very important. Investment cost is about 3,500 Euro/kWe for a 5 MWe plant, but drops to about 2,000 Euro/kWe for a 25 MWe plant. Until recently, dedicated biomass power plants have only proved competitive when using large quantities of free waste that had to be disposed of, such as MSW, black liquor from the pulp and paper industry and agriculture residues such as bagasse. However, a growing number of viable smaller scale plants using other type of residues (forestry, straw, etc.) are found throughout Europe and North America. Co-generation has been shown to reduce the cost of power production by 40-60% for stand-alone plants in the range 1-30 MWe. However, the scale of biomass CHP plants is often limited by the total local heat demand and by its seasonal variation, which can significantly affect economic returns unless absorption cooling is also considered.

As an alternative to conventional steam plants in the range 0.5-2 MWe, the Organic Rankine Cycle (ORC) engine33 can offer technical and economic advantages (e.g. lower process temperature, low operating cost, and the potential to use a thermal oil boiler instead of a more expensive high temperature-proof steam boiler). The gross efficiency of ORC engines can reach 17%. However, the net efficiency can be significantly lower due to the relatively high power consumption of ORC units. Although ORC is a well-proven technology (e.g. in geothermal applications), only a few ORC plants operate on biomass at this stage (e.g. Switzerland, Austria, the Netherlands). Work is still needed to improve efficiency and reliability, and to reduce costs.

In the lower capacity range (10 -100 kWe), the Stirling engine is a promising technology for domestic cogeneration. Currently at the demonstration stage (e.g. in Denmark, Germany, UK, Switzerland, Austria, and New Zealand), improvements are still needed, in particular to improve the current 12-20% conversion efficiency.

Biomass Gasification Technologies

Gasification occurs when biomass is heated under sub-stochiometric combustion conditions. This results in the production of a combustible gas mixture (called producer gas or syngas) rich in carbon monoxide (CO) and hydrogen (H2), which has an energy content of 5-20 MJ/Nm3 (depending on biomass and whether gasification is conducted with air, oxygen, or indirect heating), that is, roughly 10-45% of the heating value of natural gas.

Gasification was originally developed in the early 19th century to produce town gas from coal for lighting and cooking, before it was supplanted by natural gas and electricity. Wood gasification-based engines called gasogene were also used to power vehicles in Europe and elsewhere during the fuel shortage of World War II. Gasification regained interest in the early 1980s and has undergone significant RD&D both in Europe and North America, with several competing reactor designs and gas cleaning processes.

Gasification is a highly versatile process. Virtually any biomass feedstock can be converted into syngas with a very high carbon conversion and thermal efficiency of 85-90%. Furthermore, syngas is an intermediate product that offers a large range of possible secondary conversion and final energy uses. Heat application of gasification is mainly confined to countries with emerging economies. Hundreds of small and medium size biomass gasifiers (< 1 MWth) are, for example, being deployed mainly for heat applications in China, India, and South-East Asia with attractive pay-backs. These gasifiers are operated intermittently and may not conform to the environmental guidelines generally practiced in OECD countries. Their reliability and lifespan in continuous operation may be an issue.

Raw syngas can also be cleaned of its particulates and condensable hydrocarbons and burnt in an internal combustion gas engine, which offers electrical efficiency in the range 22-35%, that is, slightly higher than for steam engines used in conjunction with biomass combustion. Higher electrical efficiencies are reached if the syngas is combusted in gas turbines (up to 40% efficiency), or in gas and steam turbine combined cycles (up to 42%). Due to their high conversion efficiencies, these technologies offer greater CO2 emission reduction potential than direct combustion-based approaches. However, these pathways rely on pressurised operations which have not yet been adequately demonstrated at large-scale. The first pressurised (1.8 to 2.5 MPa) biomass integrated gasification combined cycle (BIG/CC) plant running on 100% biomass (9 MWth and 6 MWe plant based on wood and straw) has been successfully demonstrated in Sweden since 1995 and technical issues (process integration, tar formation, real-time process monitoring, etc.) appear to have been overcome. However, other projects have not succeeded (e.g. the ARBRE project in the UK) due to inadequate support to resolve process shakedown and system integration issues.

The syngas can be converted to hydrogen-rich gas or pure hydrogen that could be electrochemically converted in fuel cells to produce electricity. The integrated gasification fuel cell (IGFC) technology is expected to yield high electrical efficiencies – 50 to 55%. However, significantly more RD&D is needed to develop, demonstrate, and commercialise IGFC systems in the near future.

Instead of being directly combusted for heat and power, the syngas can be further processed into a methane-rich gas called substitute or synthetic natural gas (SNG), the composition of which makes it suitable for blending in the natural gas network, thus offering enhanced flexibility as to the final use. The syngas can also be converted into a liquid fuel (e.g. Fischer Tropsch or FT-diesel, DME, methanol, or mixed alcohols) using different methods employing the proven catalytic conversion process.

Gasification of coal and oil residues has been used for decades at industrial scale for strategic reasons (e.g. Sasol plants in South Africa). Biomass gasification technologies struggle for market entry due to limited plant capacities because of the cost of collection and transportation of biomass to central energy conversion plants. For this reason, out of the ~5.25 GWe of existing global IGCC plant capacity in 2006, only 0.15 GWe run on biomass fuel, mostly in the EU with a negligible capacity in North America and Asia.

Further support and development of certain biomass gasification processes is required to address and resolve issues related to sensitivity to feedstock quality and moisture content, reliability of feedstock feeding systems into the reactors, gas clean-up (tar formation, process monitoring, and tar, alkali, chloride, ammonia, etc. removal), and process scale-up with first-of-a-kind plants. Due to inadequate opportunities to replicate commercial applications, it is difficult to obtain performance and reliability guarantees from many technology developers, which poses a financial risk to investors. The evolving lignocellulosic and other biofuel processes, including algal fuels, do not convert the entire feedstock to the desired products and leave behind a significant portion of carbonaceous matter that could be effectively utilised in closely integrated biomass gasification processes, to improve overall process performance. It is noteworthy that for many countries, demand for electricity may be comparable to security of supply of transportation fuels in importance. With adequate incentives, biomass gasification offers prospects for the market entry of distributed power generation to meet future needs. Whatever form biomass gasification may evolve into, it should play a critical role in building a ‘bridge’ for sustainable energy for the future.

Anaerobic Digestion Technologies

Anaerobic digestion is the biological degradation of biodegradable organic matter under exclusion of oxygen/air conditions. The main product of anaerobic digestion is biogas, a gas mixture of methane (the main component of natural gas) and carbon dioxide (CO2). The biogas produced can either be cleaned for on-site use in heat and power generation units or be separated from the carbon dioxide, compressed and injected into the natural gas network for use in heat or electricity generation elsewhere or as a transport fuel.

Anaerobic digestion applies to almost any biodegradable waste materials such as grass clippings, leftover food, sewage, animal waste, or industrial waste. Anaerobic digesters can also be fed with specially grown energy crops to boost biodegradable content and hence increase biogas production. However, lignin can not be degraded by anaerobic digestion, which makes woody biomass not suited for this conversion route.

Both dry and wet processing are well-established technologies, have a good track record and have been proven at a commercial scale. Anaerobic digestion is happening both in centralised plants (typically for the treatment of sludges in waste water treatment plants or landfill gas recovery facilities close to urban areas) and in small and distributed biodigester units, usually in rural areas on farms or even in small households where mostly manure and agricultural wastes are being digested. Anaerobic digestion is also part of the mechanical biological treatment of municipal solid waste (MSW), where the waste is sorted into refuse derived fuels going into waste-to-energy plants (combustion), while the organic fraction undergoes anaerobic digestion.

There are two main classes of proven technologies that differ in their process temperatures. Thermophilic digestion (50-70°C) systems offer faster throughput and better pathogen and virus reduction than mesophilic processing (25-40°C), but require more expensive technology and a higher degree of hands-on operation and monitoring. Thermophilic units are thus mostly used for centralised production. Most such plants are found in Switzerland and to a smaller extent in Sweden. China is by far the biggest biogas producer and user in the world, with around 18 million farm households using biogas (about 7 million Nm3 per year) and about 3,500 medium to large-scale digester units (about 250 million Nm3 per year). In Europe, Germany is the leading country with some 3700 units in operation corresponding to some 1270 MWe total capacity installed in 2007 (mostly small cogeneration units running on agricultural residues) generating 8.9 TWh of electricity annually. This success is mostly explained by the support provided by the feed-in tariff targeted to farm-scale systems. The Danish centralised AD plants are also a technical success and are more cost-efficient than the German plants thanks to economies of scale.

The economic viability of biodigesters is highly sensitive to unit size and feedstock price. Small-scale plants are often uneconomic, but centralised digestion may be limited because of the distances over which manure has to be transported, which increases both the price of feedstock and the biosecurity issues in the case of manure handling. Also, the rural context of farm-based biogas digestion is often associated with difficulty in selling the surplus process heat and high cost of grid connection in remote areas. Finally, the anaerobic digestion process cannot easily accommodate changes in feedstock properties and thus requires significant technical know-how and commitment to operate effectively. Failure rate has been very high in the past decades, with a detrimental impact on the economic viability of these units, due to the complexity of design and operation. German manufacturers largely overcame this issue with simpler designs and good technical support.

Biomass Upgrading Technologies

There are numerous possible pre-treatment techniques ranging from well-established mechanical techniques that consist of simply chopping, chipping or milling the raw feedstock into ready to use material for subsequent conversion, to less well upgrading techniques that also increase the energy density of the biomass. Pelletisation, torrefaction and pyrolysis technologies are such examples.

Pelletisation and briquetting

Pellets are small wood-based cylinders 6-12 mm in diameter and 10-30 mm in length. They are produced by compressing wood sawdust through a die. The high pressure of the press causes the temperature of the wood to increase greatly which causes the lignin content of the wood to form a glue that binds the pellet together as it cools.

Pellets have quality standards in Europe (CEN, DIN) that guarantee a moisture content below 10% (against 20%-25% for commercial wood chips), a uniform density and hence calorific value irrespective of the wood used, as well as strict physical and chemical characteristics. Pellets can be made from virtually any type of woody feedstock, as well as from herbaceous biomass, fruit biomass, and peat. However, the use of such alternative feedstocks might result in pellets with ash or contaminant contents that do not comply with the above standards.

Pelletising is an efficient energy densification technique as pellets typically have a bulk density of 650 kg/m3, that is some 3.3 times higher than industrial softwood chips. Moreover, due to their very low water content, pellets also have a high net calorific value (or lower heating value) of about 19 MJ/kg. This property alone can make it economically viable for material to be pelletised to reduce transport and storage costs. In Sweden for instance, where pellets are primarily used to substitute for coal in large power plants, pellets are manufactured from sawdust at the sawmill, before being transported to the power plant where they are milled before combustion.

Pellets thus have the great advantage over other woody feedstocks of being a homogeneous, dense, and easy to handle solid fuel, which explains its increasing popularity both at domestic and industrial scale. However, pellets are hygroscopic, i.e. they tend to absorb moisture during transport and storage, which can cause them to revert to sawdust with increased moisture content.

Pellets have become a common fuel in developed countries. Some 442 pellet producers were identified worldwide in 2007, spread throughout Europe, Russia and North America. Quality standards are increasingly contributing to the development of international trade in pellets. Canada produced close to 1.5 million tonnes of pellets in 2007, most of which were exported to Europe. Since pellets are mostly produced from sawdust, which is a co-product of sawmilling, the volume of pellets produced may depend on the volume of timber consumed in the wood industry. The recent housing crisis in the USA, resulting in fewer houses being built and hence less timber consumed, has been interpreted as a possible cause of the sawdust shortage. In Canada, on the other hand, large amount of wood unsuitable for the processing industry has been available for pelletising due to the massive destruction of the forest by the pine beetle.

In Europe, average production cost of wood pellets is estimated to be in the range 50-80 Euro/tonne, compared to $60-84/tonne in Canada. The competitiveness of wood pellets with alternative fossil options differs from country to country depending on the tax system and market price of pellets. The latter ranged roughly from 120 to 270 Euro/ tonne in 2007 in the 17 European countries that use pellets, where the lower limit corresponds to industrial volumes for co-firing applications, and the upper limit is small volumes for household boilers. Market price to the final customer was around 184 Euro/tonne in Germany at the end of 2007 (after climbing above 250 Euro/tonne in 2006), which makes pellets much cheaper (~4 Euro cents/ kWh) than heating oil and gas. There is no apparent correlation yet between the pellet price and oil price.

Further research is still necessary to increase the stability and resistance to abrasion of pellets, as well as to reduce the dust emission during handling in domestic applications.

Pyrolysis

Pyrolysis is the thermal decomposition of biomass occurring in the absence of oxygen (anaerobic environment) that produces a solid (charcoal), a liquid (pyrolysis oil or bio-oil) and a product gas. The respective fraction of these three co-products depends on the operating temperature and on the residence time of the hot vapour used in the process. Moderate temperatures (around 500°C) and short residence time (around 1 second) used in so-called fast pyrolysis (or flash pyrolysis) are optimal conditions for maximising the production of the liquid fraction (up to 75% of the output energy content).

The production of wood charcoal using slow pyrolysis (also known as carbonisation) has been used for centuries throughout the world (e.g. in traditional stoves in developing countries, in barbecues in Western countries, as well as in industry such as the Brazilian steel industry). However, it is only in the last 30 years that fast pyrolysis has been given extensive development effort because liquid fuels are generally easier (and thus cheaper) to handle, store and transport than solid biomass. In spite of considerable experience gained over the last decades, fast pyrolysis is still in its demonstration stage. Although fast pyrolysis units are used in niche applications such as the production of food flavourings, only a few successful demonstration units have been realised for bioenergy (e.g. in Finland and Canada), and both economic and technical challenges must be resolved before commercialisation is feasible. Bio-oil could either be burnt directly for power in CHP applications (in boilers, stationary engines and turbines, co-firing), or upgraded to transport fuel.

The deployment of pyrolysis technology still faces technical and economic challenges. A key challenge remains the improvement of the quality and consistency of the pyrolysis oil in terms of moisture content, contaminants, corrosiveness and viscosity, as well as in terms of stability, as bio-oil tends to degrade and separate over time. Reactor design and bio-oil upgrading techniques can address these technical challenges but are expensive. Also, current bio-oil production technology is not very selective, resulting in a bio-oil composed of more than 300 chemicals. These prove mostly incompatible with the upgrading of bio-oil into transport biofuels, which require precise, highly selective composition. New techniques for increasing the control of bio-oil composition are thus required to make this technology more attractive. Among the technological advances needed are better characterisation of the thermal reactions and greater understanding of how catalysts can be incorporated into the reaction environment to produce the preferred bio-oil compositions. There are also technical challenges relating to scale-up, particularly concerning heat transfer which is crucial in this technology.

The by-products of fast pyrolysis are mainly char and a product gas, which can typically be recycled (burnt) in the process to produce the heat necessary for the conversion process. Alternatively, applications for the char including soil amendment, use as combustion fuel (possibly added to the pyrolysis oil in co-firing applications), or gasifier feedstock have been proposed but not yet extensively studied.

While bio-oil has a calorific value of about 17.5 MJ/kg, which is comparable to that of pellets, its energy density is about 20-30 GJ/m3 – about twice that of pellets and 4-5 times that of torrefied biomass (but still only half that of diesel oil). This gives pyrolysis a competitive advantage over pelletisation and torrefaction in terms of transport cost. However, this advantage is not sufficient to offset the higher cost of bio-oil. Investment costs have been calculated in the range 1900-4200 Euro/kWth for 25 MW plants, while production costs (excluding feedstock cost) are estimated to be 50-100% higher than those of pelletisation or torrefaction plants.

Torrefaction

Torrefaction is a thermal process that involves slowly heating the biomass at 200-300°C in the absence of oxygen. This degrades the biomass into a completely dry coal-like product that has lost the fibrous structure of the original biomass, hence significantly improving its grindability, as well as net calorific value (19-23 MJ/kg) and energy density. Torrefaction can be a highly efficient means of densification, with torrefied products retaining some 92% of the original feedstock energy.

In addition, torrefaction transforms hygroscopic feedstocks into a hydrophobic material. This represents a significant advantage over traditional dried biomass such as pellets, since torrefied feedstock can be transported over long distances and stored outside without absorbing any moisture, hence without seeing its calorific value drop.

Although torrefaction is an old technique, it is not commercially available as a means of pre-treating biomass for biomass-to-energy production chains. Although torrefied biomass can be produced from a wide variety of biomass while yielding similar product properties, this upgrading technique is mostly applied to wood. Torrefied wood can be subsequently pelletised, which could reduce logistics cost by as much as 50% as compared to traditional pellets, This is expected to compensate largely for their higher production cost (approximately 10% higher).

ANNEX B:

CASE STUDY: McNeil Generating Station - Utility-scale biomass-fired power plant

Background

Information for this case study was collected from John Irving (Irving, 1993, 2002), Burlington Electric Department (2003) and a site visit to the plant. Built in the 1950s, the Moran power station, owned and operated by Burlington Electric was still providing most of the power to the city of Burlington, Vermont in the 1970s. Generating power via three 10MW stoker coal-fired units, the power station and emissions controls were in need of upgrading and at the same time the city power requirements were increasing. As the local utility set out to evaluate methods of providing adequate generating capacity to the city, resulting studies found that wood would be the fuel of choice based on local availability, reliability, cost-effectiveness, pollution and public acceptance. Using such a fuel could also prove beneficial for the local economy as jobs could be created in Vermont and fuel harvested locally.

As the biomass fuel supply network had to be proven reliable and financially viable prior to committing to such a project, it was decided in 1977 that Unit 1 of the Moran power station would be modified for wood chip co-firing. Unit 2 was converted in 1979 in the light of the success of the first unit's conversion. In 1978 a bond issue was passed at 71% by the voters for the construction of the McNeil Generating Station. Construction started in 1981 and in April 1983 the main power boiler was hydrotested. By October of that same year the electrostatic precipitator and steel structure building were almost completed. In January 1984 the turbine generator set was operational and commercial operation of the McNeil Generating Station began on June 1984.

In addition to being completed ahead of schedule, the station was built $13 million under budget for a total cost of $67 million.

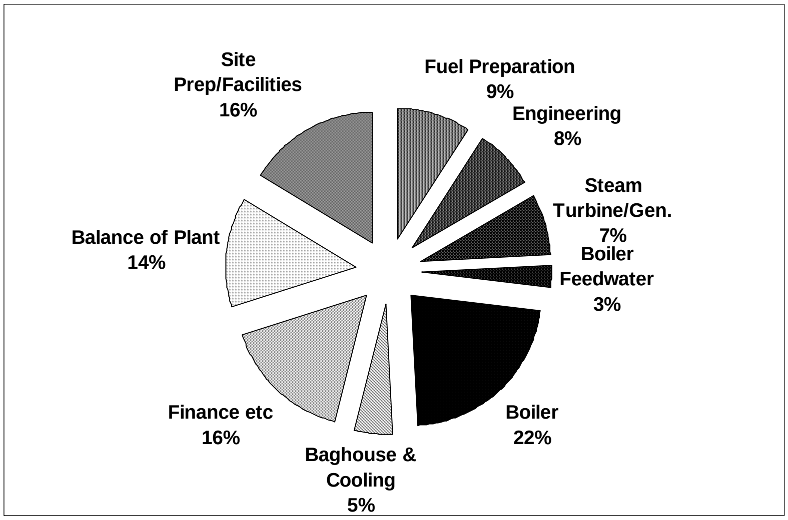


Figure 2. Capital Cost Breakdown for McNeil Generating Station

Boiler and Turbine Specifications

The McNeil Generating plant was commissioned in June 1984. The boiler, provided by Zurn Industries, is a two drum, top supported Sterling unit with water wall cooling. As the boiler was originally designed with pulverized coal firing capabilities, three burners had been installed for startup using oil, with the possibility of adding another three burners if the demand required it. The heat input using the existing three burners is 250 MBTU/hr or 73 MWth. The boiler is fired predominantly using wood waste but occasionally using natural gas when required or when economics are favorable. Net power output for the facility is 50 MWe consuming 76 tons per hour of wood waste. The boiler is equipped with two traveling grates and when exclusively fed wood at 55% moisture, it can produce up to 480,000 lb/hr of 1275 psig steam at 950°F (218,000 kg/hr, 86.7 atm, 510°C).

Electricity is generated by a Brown Boveri Corporation 59.4 MW steam turbine. At maximum capacity, 348,000 lb/hr (158,000 kg/hr) of 1275 psig (86.7 atm) steam is required. The turbine set is mated to a 3600 rpm generator rated at 60,037 MVA. It should be noted that this plant uses only one turbine generator for electricity production. Power generating stations typically have a pair of turbines installed: one for base load power and a second one (usually of lower output) for peak power generation. The Brown Boveri in this case was designed specifically for the McNeil Station, keeping in mind it would undergo frequent cycling. Plant efficiency ranged from 24.2 to 24.9% (HHV) over the years 1995 to 1998.

Biomass Reception / Fuel Preparation

Fuel preparation is performed essentially offsite. Whole tree chips - from low quality trees and harvest residues - account for 70% of the feed. The trees or residues originate in majority from privately owned land and are chipped at the harvest site; these wastes are then trucked to the McNeil station or to a railcar loading site in Swanton, VT (56 km from Burlington and 13km from the Canadian border).

Figure B2. McNeil Railcar Unloading Facility and Urban Wood Waste Pile

Sawdust and chips from local sawmills constitute approximately 25% of the plant's fuel input while the remaining 5% comes from the Burlington community as urban contaminant free (untreated) wood wastes such as wood trimmings or shipping pallets.

There was concern that traffic in Burlington and neighboring Winooski would pose a problem if most of the McNeil's station wood requirements were to be provided by truck. At full load, the plant's fuel consumption is 76 tons per hour; since a wood truck can typically haul 25 tons of wood, it was necessary for 3 trucks per hour to dump their content at the facility versus one railroad car that can carry above 75 tons. To address this issue the Vermont Public Service Board ruled that 75% of the wood delivered to McNeil be shipped by rail. The Burlington Electric Department agreed to this measure even though a rise of 20% in fuel transportation would be encountered.

The Swanton station serves as a remote wood yard where material transiting to the McNeil Station is stored before being loaded into the 21 gondola railroad cars. The cars have been designed to facilitate unloading of bulk biomass in a loose state but are quite difficult to empty when it has been packed by vibration in transport, and especially by snow and ice in winter months. In those months the cars can take anywhere from twenty minutes to a few hours to empty in the worst cases. The material is unloaded through 7 doors at the bottom of each car, each actuated manually.

Fuel arriving by rail is dumped at the rail trestle located at one end of the wood yard where front loaders move the new arrival and amass it into piles. Fuel piles are used on a first-in first-out basis to prevent inventory fermentation. This is motivated by the control of odors due to the proximity of housing near the plant and also by control of fires in the stockpile. The fuel is then loaded onto a conveyor belt system where material is sorted via magnetic separation and disc screen. Grinding reduces oversized material. The conveyor belts are ribbed to increase traction when wood is frozen during winter months. The material is then fed to surge bins (to regulate fuel flow) and then to stoker augers that meter the fuel to the boiler.

Environmental - Air Pollution Control

The plant is equipped with a bank of cyclones of 50 inch (1.27 m) diameter manufactured by GEESI, and a nine-field weighed wire electrostatic precipitator. Approximately 65% of the fly ash is collected in the cyclones and 25% in the electrostatic precipitator. The bottom ash amounts to 10%. The combined particulate removal efficiency is about 99.9% with particulate emissions typically around 0.0007 grains/dscf at 12% O_2.

Associated with the handling of fuel, dust was a concern for the McNeil Generating Station's residential neighbors. As trains emptied their load at the elevated trestle, dust was picked up by the wind and carried some distance. As more sawdust became available in Vermont, due in great part to the decline of farming, more was transported by railroad thus increasing the occurrences of fugitive dust during unloading. This was partially resolved by adding windscreens, dust screens and tree plantings, and also by improving conveyor belt cleaners. Wind direction and speed was taken into consideration when unloading railcars and was avoided during adverse conditions. A private engineering firm and state air quality regulators assessed the plant's particulate emissions to be within established standards. While the wood dust is only a minor constituent of the city dust the neighboring population is concerned by the quantity as wood dust can easily be identified due to its particle size. The McNeil Generating Station stack emissions are 1/10th the emissions limit for the Vermont state and 1/100th of the US federal regulations.

Environmental - Water Pollution Control

Two options were considered for cooling water: it could be pumped from Lake Champlain located less that 1.6 km away or a cooling tower could be erected on the premises. The latter was chosen based on environmental considerations and a Hamon-Research Cottrell product was used, capable of 44,000 gpm (166,558 lpm) at an ambient wet-bulb temperature of 22°C. Located 120 meters from the generating station, four wells supply the necessary cooling water and once treated it is discharged into the Winooski River 300 m to the east. To ensure the least impact on aquatic fauna and flora, the wastewater is monitored for pH, temperature, flow and metals. Its quality reentering the ecosystem must be equal or better than drinking water.

Product / Residue Recovery and Disposal

Ash is the only residue from the operation of the McNeil plant. Bottom ash is mixed with water and removed by augers at the traveling grate level. Water is used in this process to facilitate the removal of the ash by creating sludge and at the same time act as an airlock between the augers and furnace. The annual ash production is 5000 tons and it is temporarily stored outside on a concrete pad. Fly ash is mixed with agricultural grade powdered limestone and used as soil conditioner for farmlands. Bottom ash is mixed with limestone rock and used as base for road construction.

Fuel Characteristics

Most of the fuel requirements for the generating station are met by the purchase of fuel. Approximately 66% of the purchased wood comes from Vermont with the balance from New York, Quebec, New Hampshire and occasionally Massachusetts. Hardwood makes up 60% of the feed versus softwood. The distance of delivery source, the type of waste and transport method, influences transport economics. For instance it was estimated that shipping fuel to the Swanton station by truck to then have it shipped to the McNeil plant by railroad was 17-20% more expensive than transporting the wood by truck directly to the generating station. Prices have ranged from 10 $US to 23 $US per ton delivered which is the equivalent to 20 $US to 46 $US per dry ton or 1.20 $US-2.70 $US/MJ.

Strict environmental guidelines have been established by the State of Vermont and the Burlington Electric Department regarding the harvesting of wood for the McNeil station. These stipulate that an environmental assessment must be performed on an area that is being considered for tree harvesting. The impacts of such a harvest must be minimized while optimizing re-growth potential. The harvest plans must be reviewed by one of the four McNeil staff foresters then approved by the state and a forester monitors each harvest operation. Clear cutting is limited to areas where a new crop of trees needs to be established or to improve wildlife habitat. The allowed area to be clear cut is limited to 25 acres (101,171 square meters) in these cases. The station accepts wood waste from land being cleared for development, agriculture or tree planting. Fuel suppliers must comply to strict with those strict environmental standards. With an estimated 50% of Vermont’s forest inventory composed of wood material with no potential to manufacture goods the US Forest Service calculates the usable biomass for whole tree chip harvesting at 1 million tons per year in Northern Vermont only. This is twice the quantity of fuel required by the McNeil plant at 85% load. The remaining wood waste supply comes from a waste wood recycling facility. It was established in 1990 by the City of Burlington on the site of the McNeil Generating Station and all residents of the Chittenden County are allowed to bring in their tree trimmings, leaves or other urban waste wood instead of using the landfill. The only restriction is that the wastes must be untreated. The facility has received 5,000 tons/year from 1993 to 1998. In 1998 the supply increased to 20,000 tons due to the ice storm that hit in January of that year.

Natural gas capability was added to the plant in 1989 with the addition of 3 burners to the original design. The boiler can be fired at maximum capacity (50MW) using natural gas and 15MW using No.2 oil. As the natural gas prices were quite high in the mid-1990's the plant used almost exclusively wood.

Capital, Operational and Maintenance Costs

Construction costs for the McNeil Generating Station were 67 million $US in 1984. This can be expressed as 1340 $US/kW compared to the adjusted value of 2080 $US/kW in 1998 dollars. The interest rate on the bond, which financed BED’s 50% share of the plant in the 1980’s, was 12%. The bonds have been refinanced 3 times since, incurring high costs. Employment and expenditures are given in Tables B1 and B2.

Table B1. McNeil Plant Related Employment in March 2002

Sector	**Jobs**
Power plant operation	40
Home office support	4
Forest management	4
Harvesting and processing	36
Wood transportation	35
Support services	11
TOTAL	130

Most of the spending the McNeil station has done was in the local area around Burlington.

Table 2. McNeil Plant Cumulative Expenditures (1984 to 2000)

Expenditure	**$US**
Payroll	31,481,650
Property Taxes	155,091,58
Sales Taxes	873,708
Rail Transportation	117,161,47
Local Contractors	109,503,00
Wood Fuel Purchases	718,904,78
Total	142,421,441

These figures do not include the expenditures for the plant construction nor for the $US30 million gasification project, built onsite at the McNeil Generating Station. As of 1998 the operation and maintenance costs for the plant were of 4 million $US/year, including 1 million $US/year for property taxes. These costs yield approximately 2.6 ¢/kWh when calculated over the plant output of 155 million kWh/year.