Biomass Fired – Steam Injected Combustion Turbines (BF-StIC)

Providing renewable energy from gas turbines?

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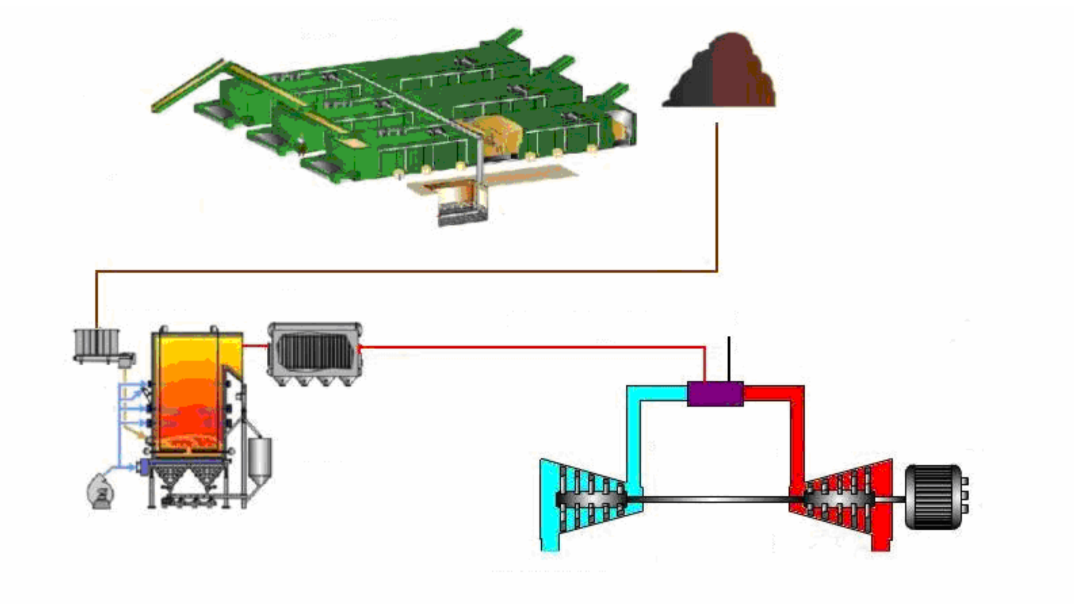
White Paper



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Background

In light of concerns about GHG's, global warming, domestic supply, sustainability and escalating costs associated with fossil fuels, renewable energy (heat, steam and power) is being promoted as one possible solution to these issues.

Renewable energy is often defined as "renewable non-fossil energy sources such as wind, solar, geothermal, wave, tidal, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases.

Furthermore, "biomass" shall mean the biodegradable fraction of products, waste and residues from agriculture (including vegetal and animal substances), forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste (source: EU Directive 2001/77/EC).

At present, the amount of useable power being produced from biomass is still very small relative to the biomass resources available for this use. If there is such a desire to employ biomass power and there are such vast biomass/organic resources available for fueling biomass power plants, why do we not see more use of these biomass resources to produce power?

First, much of this biomass or organic waste is wet (40%-80% MC); which increases transportation costs and drastically reduces its heating value and the efficiency of the energy conversion process in which it will be used. Unfortunately, conventional thermal drying systems (rotary, etc) use fossil fuels themselves, are energy intensive and are expensive to build and operate.

Secondly, biomass power plants typically rely on less efficient boiler/steam turbine technology (Rankine cycle); have a higher installed price per kW; and draw on fuel supplies that are bulkier, less homogeneous, and more difficult to fire and handle than fossil fuels.

As a result, biomass plants are more costly to build and operate than coal, simple or combined cycle or hydroelectric plants which make them less competitive in the power market.

Therefore to effectively capture this underutilized renewable energy resource, new generations of biomass power plants need to be developed that more effectively dry the wet biomass and produce power at heat rates equivalent to coal plants or gas turbines.

To meet this challenge, the author is developing a novel biomass plant design that:

1. First incorporates a biological dryer (Biodryer®) to improve the availability, consistency and heating values of biomass/organic wastes and

2. Secondly converts this improved biomass fuel in a biomass boiler into steam that will be injected into a combustion (gas, oil) turbine as a power augmentation strategy (i.e. incremental power increase).

This new "Biomass Fired-Steam Injected Combustion Turbine" (BF-StIC) thermodynamic cycle utilizes the existing infrastructure of a combustion turbine plant (gas turbines, switchgear, buildings, grid connection, steam injection ports, PPA's, etc) along with standard "off the shelf", well proven equipment (Biodryer®, biomass boilers, steam injection systems, demineralized water, etc) from existing manufacturers to greatly improve the performance, economics and time to market for biomass power plants.

The incremental power generated from this BF-StIC process could be eligible as "renewable energy" as the steam produced for injection into the combustion turbine which creates this additional power comes from a renewable resource - biomass fuel (similar to cofiring biomass with coal scenario).

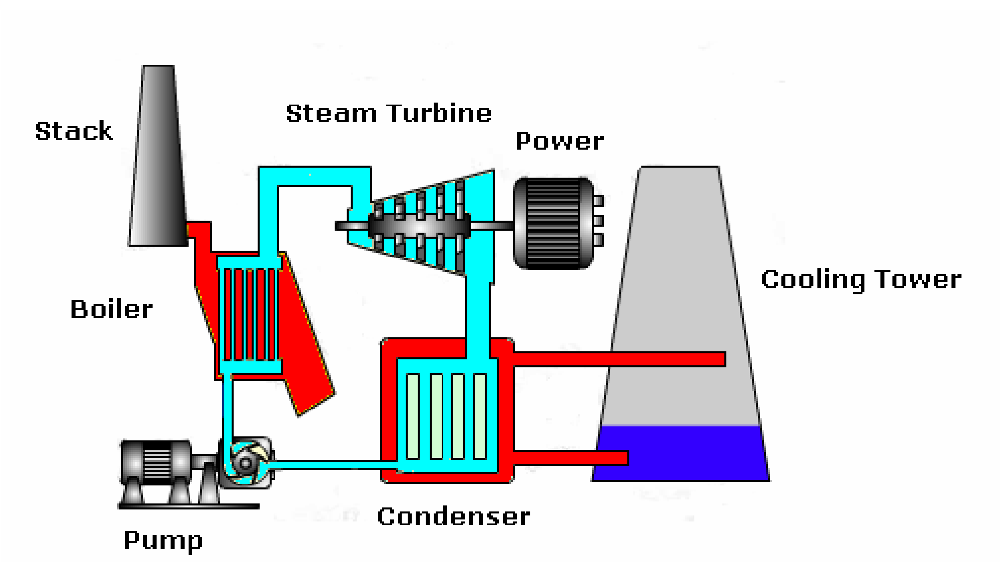
Therefore, by providing viable and cost effective solutions which address both the drying of the biomass and improvements in heat rates, it is hoped that more utilities and developers will consider using biomass to meet their renewable energy targets and business strategies.

Biomass Power Plants

Power from biomass is a proven commercial electricity generation option in the United States, Canada and Europe. For example, in the United States there was about 9,733 megawatts (MW) in 2002 of installed capacity. In terms of renewable electricity in the US, biomass is only surpassed by hydro power.

Most of today's biomass power plants are direct-fired systems that are similar to most fossil-fuel fired power plants and use the basic Rankine steam cycle (Figure 1) to produce electricity.

Figure 1: Biomass Power Plants – Direct Combustion (Rankine Cycle)



The biomass fuel is burned in a boiler to produce high-pressure steam. This steam is introduced into a steam turbine, where it flows over a series of aerodynamic turbine blades, causing the turbine to rotate. The turbine is connected to an electric generator, so as the steam flow causes the turbine to rotate, the electric generator turns and electricity is produced.

While steam generation technology is very dependable and proven, its efficiency is limited. Biomass power boilers are typically in the 20-50 MW range and operate with plant efficiencies of 20% – 24% (i.e. 14770 – 17936 kJ/kWh heat rates).

Dryers and more severe steam turbine cycle conditions (higher pressure, higher temperature and reheat) can help improve these efficiencies to almost 34% (Renewable Energy Technology Characterizations, December 1997, Direct Fired Biomass, DOE Report). In addition, new biomass gasification plants are operating at slightly higher efficiencies than traditional direct combustion.

Coal plants on the other hand operate at even higher efficiencies (28%-38%) or heat rates (9496 – 12660 kJ/kWh) than direct combustion or gasification based biomass power plants.

Therefore, an effective option to building a new direct fired or gasification biomass power plant is to co-fire the biomass in an existing coal plant. Co-firing involves substituting biomass for a portion (up to 15%) of coal in an existing power plant furnace. This is one of the most economic near-term options for introducing new biomass power generation.

Because much of the existing power plant equipment can be used without major modifications, co-firing is far less expensive than building a new biomass power plant. Compared to the coal it replaces, biomass reduces sulfur dioxide (SO_2), nitrogen oxides (NOx), mercury and other air emissions. After "tuning" the boiler for peak performance, there is little or no loss in efficiency from adding biomass. This allows the energy in biomass to be converted to electricity with the higher efficiency of a modern coal-fired power plant.

However, where coal plant generation is limited or non-existent, cofiring biomass with coal is not an option.

Therefore, it would be prudent if other types of existing generating assets could also be modified or retrofitted so that engineers and developers could take advantage of their existing infrastructure, fuel switching capability and improved heat rates to cost effectively convert biomass into renewable energy.

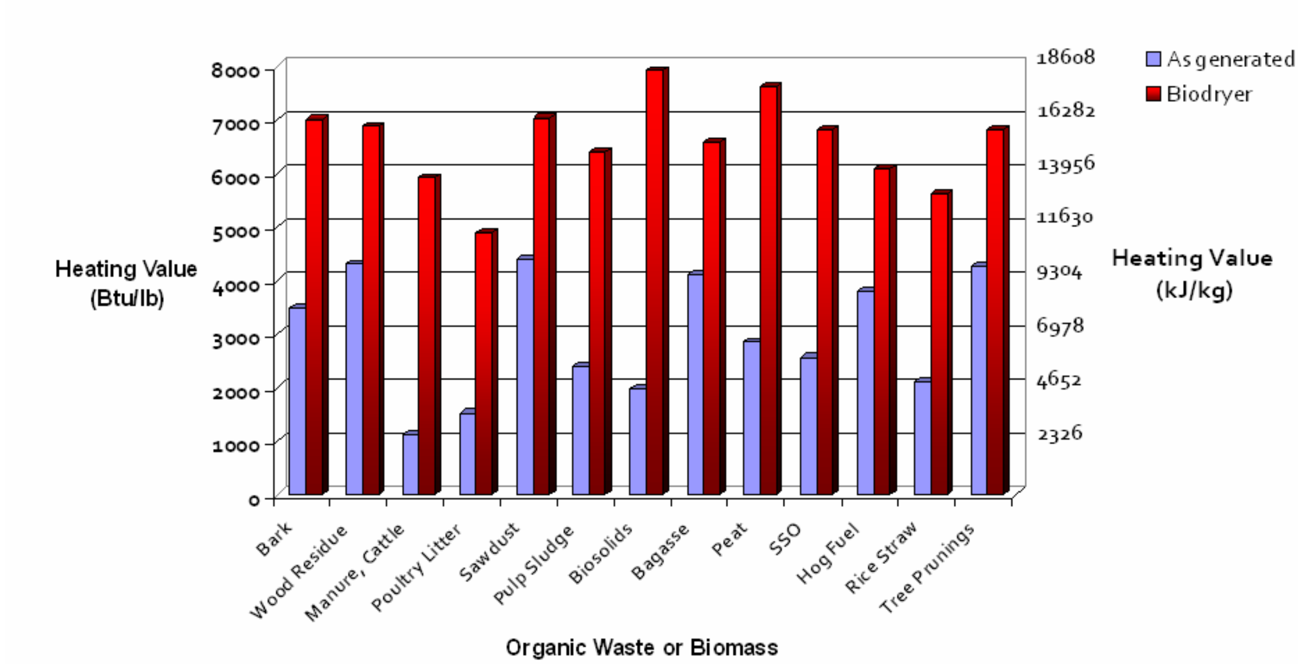
For example, in places like California where renewable energy (especially biomass) is now a major focus, it is gas turbines that presently provide much of their power needs. Imagine the impact on the State's renewable energy production if their existing gas turbines could all be modified to produce renewable energy from biomass.

Biological Dryers (Biodryer®)

Earlier we mentioned that much of the organic waste or biomass that is produced today is a wet material. Unfortunately, this wet biomass has low calorific value (kJ/kg, Btu/lb) and reduces the efficiency of the boiler in which it is burned.

Figure 2 shows the heating value of various organic wastes and biomass resources as they are typically generated and after biologically drying to 20% moisture content (%MC).

Figure 2: Affect of moisture content on heating values of organic waste and biomass



For example, sewage sludge or biosolids typically contains about 80% moisture and therefore has a heating value of around 4605 kJ/kg (1980 Btu/lb). In comparison, drying the biosolids to 20% MC would increase the heating value of the biosolids to 18421 kJ/kg (7920 Btu/lb).

Biomass can effectively be used to replace fossil fuels for most applications if a suitable feedstock can be found at reasonable cost. The critical issues for most industrial requirements are the cost of fuel, quality of heat needed to perform the process task and the state (solid, liquid or gas) of the biomass fuel.

If biomass can be produced from organic waste feedstock that would otherwise go to landfill, then the tipping fees ($30-$100/tonne) generated from processing this waste into a fuel can help to keep the cost of the biomass end product competitive to traditional fossil fuels.

Biomass at 50-percent moisture typically has an adiabatic flame temperature of about 1350–1400°C compared with about 1950°C for natural gas and over 2000°C for fuel oil. Under these conditions, biomass may have difficulty in completely replacing fossil fuel use.

However, if dried to 20-percent moisture, biomass has an adiabatic flame temperature of approximately 1830°C, making it suitable for a wider range of applications.

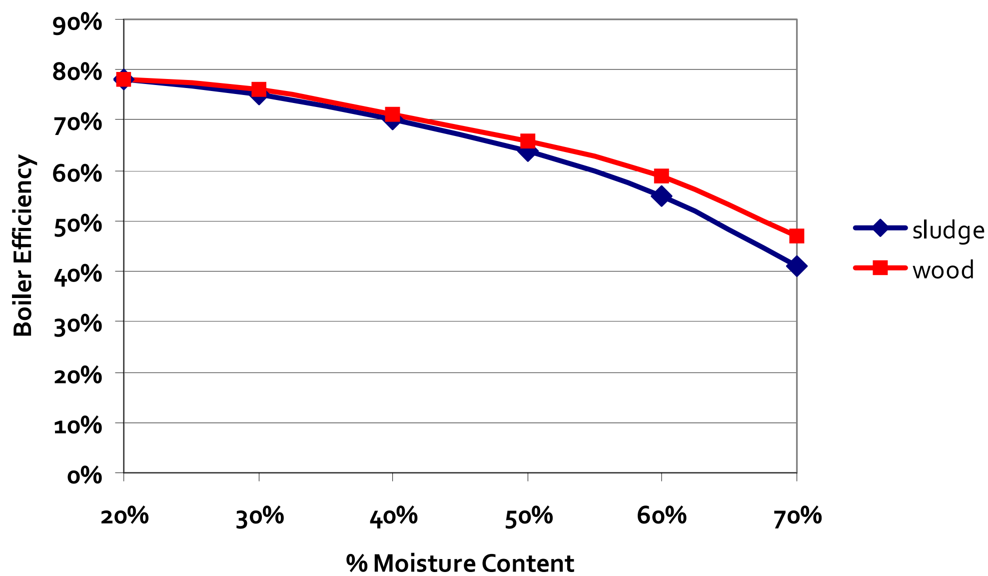
In terms of understanding how the moisture content of the biomass affects boiler efficiency and power plant heat rates, let's look at a typical boiler efficiency curve at a paper mill plant.

Burning wood waste at 60% moisture content is a very inefficient (only 60% efficiency) way of converting this biomass fuel into energy (steam).

Much of the energy contained in the dry wood waste is simply used to evaporate (970 Btu/lb, 2257 kJ/kg) the water present in the fuel and provides no useful work in the energy conversion process.

In comparison, drying the wood waste to 20% moisture content increases the boiler efficiency to almost 80% (Source: Energy Cost Reduction In the Pulp & Paper Industry, November 1999, Paprican)

Figure 2: Affect of Biomass Moisture Content on Boiler Efficiency



A Biodryer® utilizes the "free" heat (exothermic reaction) produced during this aerobic process to help dry the biomass or organic waste. This accelerated biological oxidation process is brought about by naturally occurring microorganisms, which consume oxygen and produce the heat required for the drying of the biomass:

$$(C_6H_{10}O_4)_x \quad + \quad 6.5O_2 \quad = \quad (C_6H_{10}O_4)_{x-1} \quad + \quad 6CO_2 \quad + \quad 5H_2O \quad + \quad \text{Heat}$$

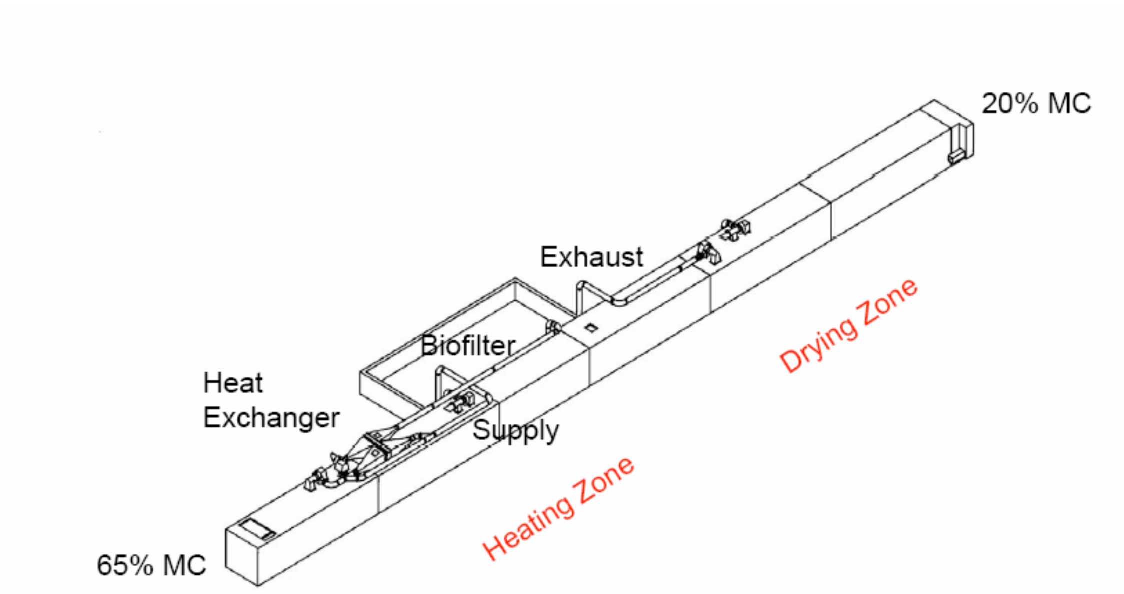
Organic Waste Oxygen Biomass Carbon Dioxide Water 17,500 kJ/mole

The Biodryer® is a double-walled insulated tunnel (stainless steel interior, pre-engineered building siding exterior) with an integral heat recovery system and computer processor to control the heat produced when this organic based biomass decomposes (Heat Zone). With this accelerated aerobic drying process, moisture, temperature, oxygen, carbon to nitrogen ratios (C:N) and porosity are all controlled within ideal ranges for maximum microbial and drying activity

The Biodryer® (Figure 2) is divided into two distinct zones (Heat, Drying), which are separated by spinners. The Heating Zone is where the biological oxidation and resulting exothermic reaction takes place.

In the Heating Zone, typical biomass temperatures will increase from 55°C after 24 hours to 80°C after 7 days. In addition, the moisture content of the biomass will decrease from about 65% to 40%. At 40% MC, the biological oxidation process drastically slows down as moisture is necessary to support the metabolic processes of the microbes.

Figure 2: Biodryer Process for Drying Wet Biomass or Organic Waste



A heat recovery system captures the heat produced in the Heating Zone and transfers this heat into the air stream of the Drying Zone for improved drying performance.

The biomass moisture content is reduced from 40% to about 20% (or setpoint condition) during the next 7 days in the Drying Zone to meet the client's specific biofuel requirements. Due to the low moisture levels in the Drying Zone, the biological oxidation process has practically stopped.

The biomass material is further aerated by mechanical means (spinners) before entering the Drying Zone to ensure that there are no anaerobic pockets in the biomass and more uniform drying is provided.

Therefore, the Biodryer® is able to precisely control temperatures and moisture levels within the biomass while limiting the biological oxidation process to only 7 days. This unique design results in minimal carbon loss (CO_2) and ash production, which translates into improved biofuel quality and calorific value.

The Biodryer® can dry high moisture content organic waste streams like those found in pulp or fibre sludge, MSW, Source Separated Organics (SSO), manures, bagasse, peat or biosolids to 80% solids (i.e. 20% MC) or better, without the combustion of fossil fuels and at a fraction of the energy and O&M costs associated with conventional thermal dryers (rotary, flash, steam).

In addition, since the Biodryer® is not a "combustion based" drying process, SCR's, scrubbers and similar pollution control systems are not required and air permitting is a much simpler process.

Biodryer Tunnels

Heat Exchanger

Unloading Trays

To learn more about the patented Biodryer® technology please go to Wright Tech Systems Inc's website at www.wrighttech.ca

Combustion Turbines

Gas turbines or combustion turbines (CT) typically operate on natural gas or oil and therefore in the past renewable energy options have typically been limited or non-existent.

For example, in the past the typical strategies for using biomass in gas turbine applications were to either gasify the biomass or to convert it into pyrolysis oil. The biomass-derived gas or oil would then be mixed with compressed air in a combustion chamber and ignited.

Contaminants and their ability to foul and corrode the turbine blades are a critical concern when using biomass fuels. For this reason, along with other cost related and technical issues there are currently no commercial operations using these technologies on biomass fuels. The longest demonstration in Sweden operated for almost a decade in the 1990s before technical issues caused the project to be discontinued. Recently, in Canada, a demonstration project has started at a pyrolysis plant using pyrolysis oil to fuel a specially designed gas turbine.

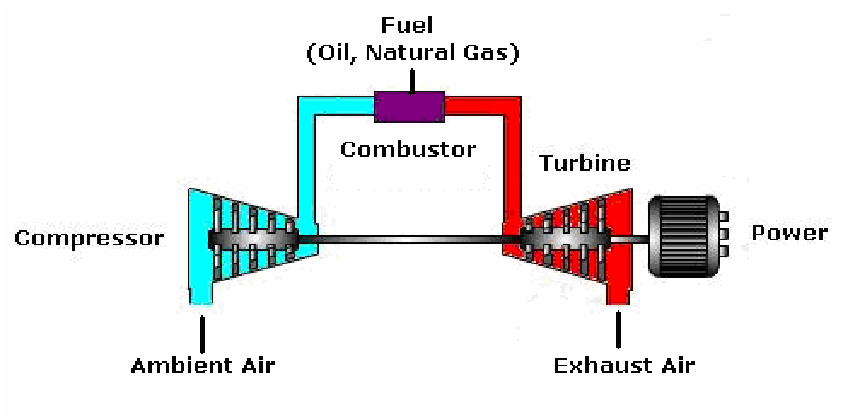
To understand how we might be able to use biomass in a more standard way in a gas turbine application, let's start by looking at how gas turbines operate and then explore how we can apply a common power augmentation technology known as "steam injection" to the process.

Gas turbines are essentially composed of three major components: compressor, combustor, and power turbine. In the compressor section, ambient air is drawn in and compressed up to 30 times ambient pressure and directed to the combustor section where fuel is introduced, ignited, and burned.

The gas-turbine operates on the principle of the Brayton cycle (Figure 2), where compressed air is mixed with fuel (typically oil or natural gas) and burned under constant pressure conditions. The resulting hot gas is allowed to expand through a turbine to perform work.

More than 50 percent of the shaft horsepower is needed to drive the internal compressor and the balance of recovered shaft horsepower is available to provide power.

Figure 2: Gas Turbine Simple Cycle (Brayton)



The simple cycle is the most basic operating cycle of gas turbines with plant efficiencies ranging from about 30 to 40 percent (8968-11606 kJ/kWh).

A combined cycle gas turbine is a gas turbine with a Heat Recovery Steam Generator (HRSG) designed to capture waste heat from the gas turbine exhaust and convert it to steam for additional power production. The gas turbine drives an electric generator, and the steam from the HRSG drives a steam turbine which also drives an electric generator.

A supplementary-fired boiler can be used to increase the steam production. The thermal efficiency of a combined cycle gas turbine is between 38 percent and 60 percent (5908 – 9496 kJ/kWh).

Gas turbines are rated at ISO conditions (15°C/60% Rh ambient air and sea level). Therefore any increases in one of the above decrease the performance and output of all combustion turbines, regardless of manufacturer.

This is especially critical in summer months (ambient air is 26-38°C), when power is needed the most and energy prices have a tendency to be at their highest.

The CT's in simple cycle and combined cycle power plants output can be as much as 25% - 30% less than the manufacturer's (GE, Siemens, Westinghouse, Alstom, Solar, etc) ratings at ISO conditions.

This loss in power output can be explained by the fact that power output of a gas turbine is directly proportional to and limited by the mass flow rate of compressed air from the air compressor that provides high-pressure air to the combustion chamber of the gas turbine.

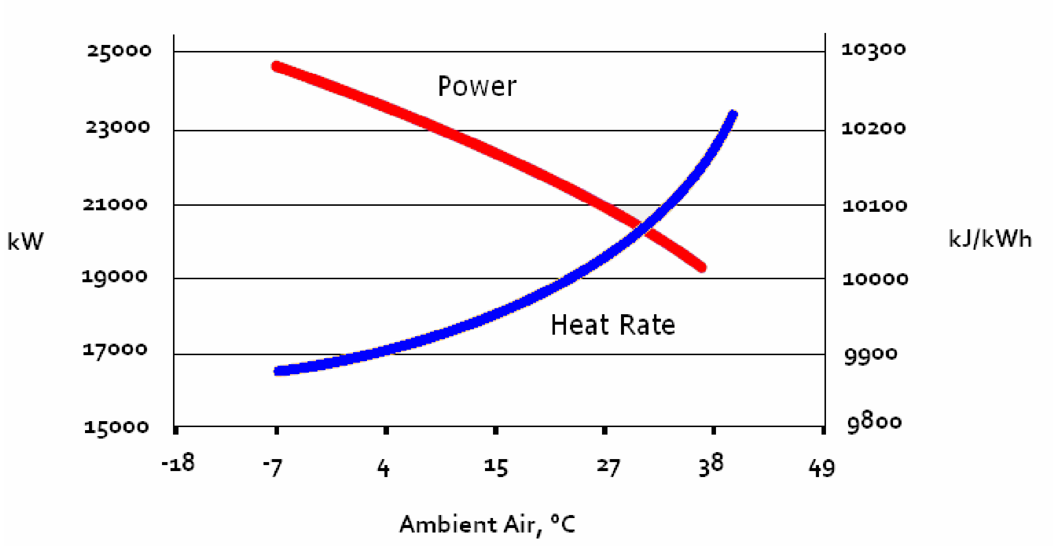
Gas turbines operate with a constant volume of air flow, but the power they generate is determined by the mass flow of air. As a result, the denser that the air is when it flows through the turbine, the greater that the output power will be.

Warm air is less dense than cold air, and therefore gives a lower power output. In addition, warm air is harder to compress than cold air, thus requiring greater work from the compressor, leaving less net available shaft energy.

The affect that warmer air has on CT performance is illustrated in the following performance curves (Figure 3) for a General Electric LM2500 gas turbine (aeroderivative).

For example, a LM2500 will only produce about 19 MW when the air temperature is 38°C instead of 22 MW when the air temperature is 15°C (ISO conditions).

Figure 3: Gas Turbine Performance Curves (LM2500)



Heavy Duty (E, F class, etc) gas turbines have similar power and heat rate curves. For example the GE7FA is rated at about 171 MW at 15°C (ISO). However, when ambient temperatures increase to 33°C, the power output of the GE7FA drops to about 150 MW.

Therefore, although gas turbines are more efficient than direct combustion (Rankine cycle) plants at converting fuel to electricity (heat rates), they cannot utilize solid biomass fuel directly and their plant performance is greatly affected by ambient air conditions and altitude.

However, biomass fuel can be used indirectly to produce steam that can be injected into the gas turbine to not only create additional power but also improve the system heat rate and address the impact that ambient conditions have on gas turbine performance (especially during peak periods).

Steam Injection of Combustion Turbines

Steam injection for power augmentation and NOx control has been an available option for GE gas turbines since the early 1970's. Other manufacturers such as Siemens, Westinghouse, Alstom, Rolls-Royce, Hitachi and Solar gas turbines are designed or can be upgraded for steam injection as well.

Steam injection increases power output on a gas turbine because the injection increases both the turbine mass flow and the energy extraction by the turbine.

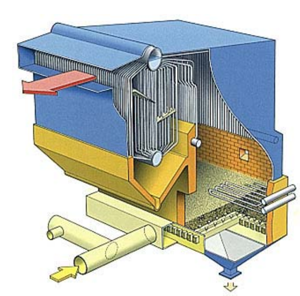
The latter is possible because the heat capacity of steam is almost twice that of normal combustion products. Thus the enthalpy change of steam for a given temperature drop is about double that of air or combustion gas.

In the steam injection cycle, steam is typically produced in a HRSG or OTSG (Once Through Steam Generator) and then is injected into the gas turbine. A steam injection system offers a fully flexible operating cycle, since the amount of steam injected can vary with load requirements and steam availability.

However, the steam does not have to come from a HRSG or OTSG. It could just as easily come from a standard biomass-fired boiler from such well known manufacturers as Alstom, McBurney, Siemens, EPI, Takuma, Hurst, Babcock & Wilcox, Wärtsilä and others.

Hurst

Wärtsilä



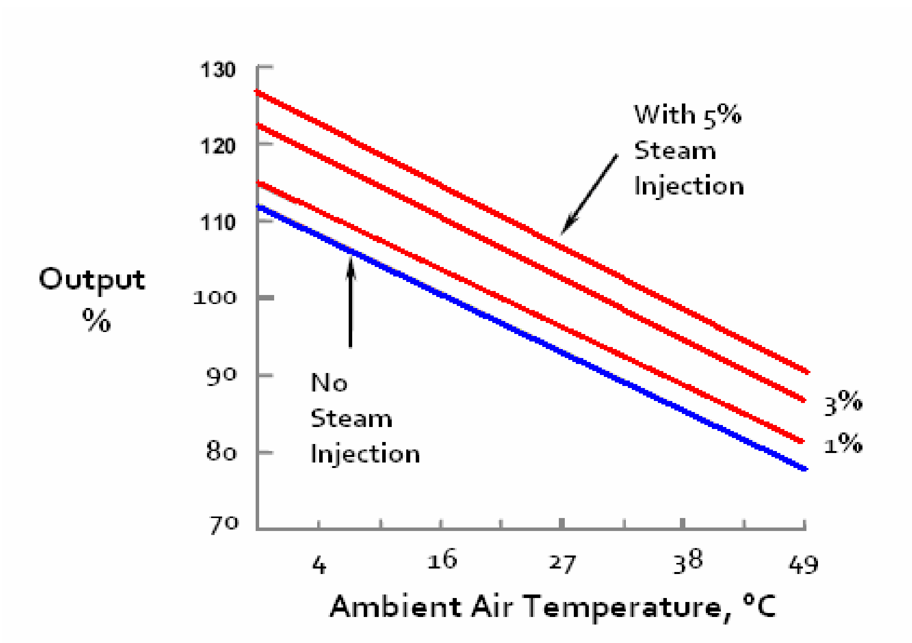
Takuma

These biomass boiler manufacturers provide well proven, engineered, cost effective and energy efficient packages complete with pollution control systems designed to meet the most stringent air emission standards.

Steam must contain 28°C (50°F) superheat and be at pressures comparable to fuel gas pressures. Also, steam can be injected with the gas turbine operating from 50% power to full load.

To preserve the design surge margin, gas turbine manufacturers often limit the amount of steam that will be permitted to be injected to 5 percent of inlet air flow at base load. GE is presently studying the dynamics of increasing the amount of steam that can be injected to 9 percent. Figure 4 shows the effect of steam injection on power output for a GE MS7001EA gas turbine.

Figure 4: Steam Injection Performance for a MS7001EA



(Source: GE Power Systems GER-3567H)

Therefore, the 5 percent steam flow will increase power output by approximately 17.5 percent. The steam-to-fuel ratio is about 2.5:1 at a steam injection rate of 5 percent of air flow.

The incremental power produced by the steam injected into the gas turbine will exceed the power produced by the same steam conditions when used in a direct combustion biomass power plant operating in a Rankine cycle.

In addition, the incremental heat rate at which this power is produced will also be at a lower heat rate than the gas turbine's standard heat rate in simple cycle.

Following is a chart on other GE Heavy Duty Gas Turbines and the affect that steam injection has on power output and heat rates.

Figure 5: Steam Injection Performance for GE Heavy Duty Gas Turbines

Model	Steam Injection (%)	Increase in Output Power (%)	Decrease in Heat Rate (%)
MS3002J	5	19.0	-9.0
MS5001R	5	15.2	-6.5
MS5001P	5	13.2	-4.6
MS5002B	5	16.0	-7.5
MS6001	5	15.0	-5.0
MS7001B	5	17.0	-6.0
MS7001E	5	15.0	-5.0
MS7001E	9	29.6	-8.1
MS9001B	5	17.0	-6.0
MS9001E	5	15.0	-5.0

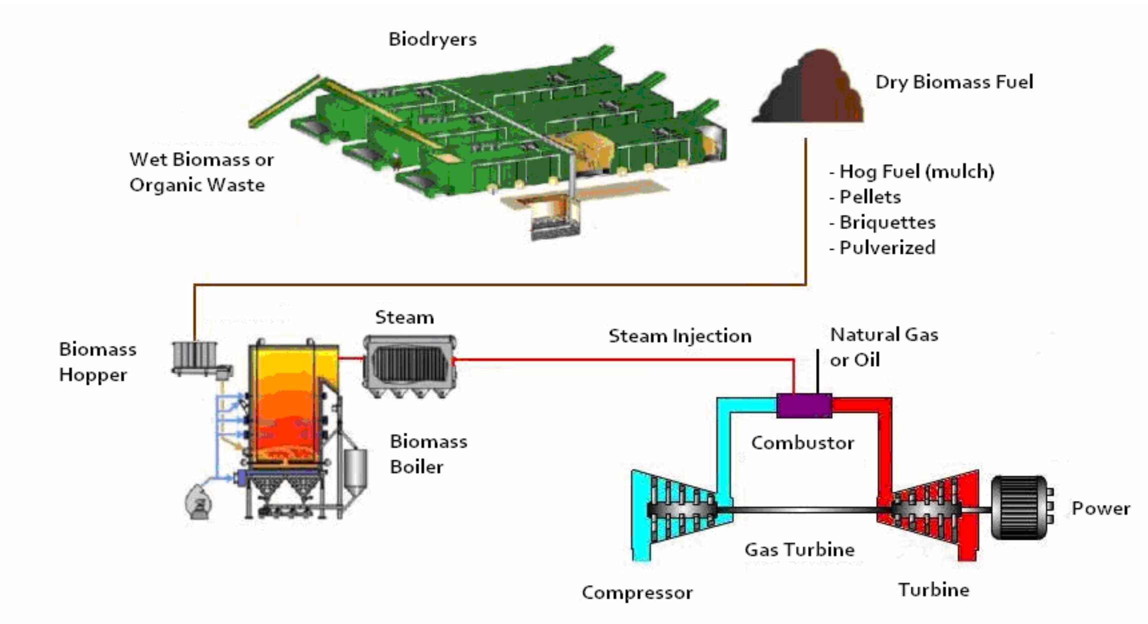
(Source: GE Power Systems GER-3571H)

BF-StIC

A typical BF-StIC process is shown in Figure 6; where wet organic waste is biologically dried to create a higher value biomass which will then fuel a biomass boiler to create steam which will then be injected into a gas turbine to generate additional power.

This augmented power could be considered as "renewable energy from biomass" and thus eligible for the appropriate renewable energy and environmental credits.

Figure 6: BF-StIC renewable energy based strategy



Given that the gas turbine is an existing power plant asset and all the above equipment are standard "off the shelf" systems, then the capital cost of this strategy should be very competitive to traditional direct fired or gasification biomass power plants.

In addition to improved heat rates and performance, the time and cost to site, permit and build should also be an improvement over traditional methods of biomass power production.

Therefore, the author is currently looking for engineering firms, developers, utilities and gas turbine manufacturers whom might be interested in pursuing this strategy further in order to finalize designs, cost models and for a possible test site. The author can be contacted at russ.blades@wrighttech.ca