Industrial Cogeneration of Steam and Power

Gurney P.R., Reid J.A., McCann D. and Sinclair M.

ABSTRACT:-- The evolution of cogeneration, the simultaneous generation of power and process steam, is explained. The current popularity of cogeneration in North America is discussed.

Various cogeneration options are reviewed. Cogeneration matching and economic sizing are discussed. Environment considerations are examined. Cogeneration applications for pulp and paper, industrial and commercial plants are reviewed.

INTRODUCTION

In the past, electricity generation and supply has often been monopoly of large private or government regulated utility companies able to achieve economies of scale in large central plants. Industrial plants were sometimes permitted to produce and sell electrical power surplus to their needs to these utility companies- but usually at a very low and uneconomic rate.

In recent years, some of the apparent advantages of the central utility approach have been re-evaluated in various countries throughout the world and the emphasis on generation by the private sector has increased. This paper explains why and suggests how the pulp and paper industry and other power consumers may respond and benefit through cogeneration.

Where appropriate, modern cogeneration techniques can provide economical, efficient or environmentally acceptable power production. Pulp and paper mills which are more self-sufficient will have improved control over future production costs. Sales of surplus power may create a useful new profit centre and further improve the competitiveness of the pulp and paper industry.

EVOLUTION OF COGENERATION

Cogeneration is defined as the simultaneous or sequential production of two or more forms of useful energy from a single primary fuel source. It is almost always used to refer to the production of electrical power and steam from the same process. In the United Kingdom, cogeneration is known as combined heat and power (CHP).

History

An early example of cogeneration was the district heating systems which exist in many of the world's metropolitan areas. They were developed together with the first electrical utilities. It was good business for developers such as Thomas A. Edison to promote sales of steam from the generating plant. In the United States. utilities with the Edison name sold heat as well as electricity. With cogeneration there were therefore two streams of energy (and two streams of revenue) from a single source. As one might expect, the revenue and profitability of such plants is a direct function of their efficiency.

Once efficiency was neglected, prices became non-competitive and most of these district heating facilities in North America, with some notable exceptions, have languished. However they are still quite common in northern Europe, especially in Scandinavia and Finland.

H.A. Simons Ltd.,
III-Dunsmuir Street, Suite 400
Vancouver, B.C., CANADA

In the pulp and paper industry, cogeneration is not a new concept, having been used for close to 100 years. Early pulp and paper mills, often located far from electrical transmission lines, were obliged to generate their own electricity, often using cogeneration. In some areas of the world where power supplies are unavailable, inadequate or too unreliable to meet industrial requirements, on-site generation is necessary.

In order to understand its relevance today we must understand the "driving forces" which make it attractive and how to "optimize" efficiency and other factors to best suit each application.

Driving Forces

Cogeneration has become popular in North America through the coincidence of four factors:

- The move towards private, independent or non-utility generation (NUG).
- The increasing difficulty and cost of permitting large central power plants: nuclear, coal or hydro.
- Availability of low cost natural gas.
- Developments in gas turbines.

The oil shortages and energy crises in the 1970's les to the re-assessment of the belief that large utilities in North America, with a virtual monopoly in power generation and distribution, are the only approach to power generation.

The United States Federal Government passed the Public Utility Regulatory Policies Act (PURPA) in 1978. This legislation required utilities to purchase power generated by third parties at the utilities' avoided costs, provided that their facilities met certain operating and efficiency requirements. PURPA, along with several other parts of the National Energy act of 1978, provided a major impetus to the current development of cogeneration in the United States.

More recently, a trend towards privatization and de-emphasis of the role of government has occurred worldwide.

Environmental and other opposition to large nuclear, coal-fired and large hydro power plant projects has strengthened. The recent stringent permitting requirements have increased costs, caused delays and have stalled some proposed major projects indefinitely.

Coincidentally, as coal and nuclear power options faced increased costs, in several countries natural gas has become cheaper and more abundant.

Perhaps the most important element in cogeneration evolution has been the progressive development of more powerful, more efficient and economical gas turbines, with high temperature exhaust gas streams and heat recovery steam generators (HRSGs) can be used to generate steam. All or part of this steam may be expanded through a steam turbine for additional power output.

Gas turbines have been recognized as economical prime movers for generating plants for at least 25 years. Application was restricted however, due to their preference for clean fuels such as natural gas, which was too expensive or too scarce in the past. When natural gas is available at attractive long-term contract rates a gas trubine plant frequently becomes competitive with, or superior to, all other alternatives, especially in combined cycle format, and even for modest output in the range of 50 to 100 MW.

Efficiency

As noted in reference to early cogeneration systems in the form of district heating, two streams of energy (heat and electricity) are derived from a single source and likewise two streams of revenue. Revenue from the plant is directly related to efficiency. All forms of energy are not of equal value, however, as shown in Figure-1, generally electricity has a much higher value than steam. This should influence the selection in designing a cogeneration system.

In practical terms in North America, the regulatory and tax authorities recognize the difference in energy values and have attempted to develop various formulae to evaluate cogeneration systems

Typical Industrial Energy Costs
(US Dollars / GJ)

ENERGY	CANADA	U.S.A.	INDIA
Electric	7.2-12.0 (2.6-4.2 ¢/kWh)	11.0-26.0 (4.0-9.5 ¢/kWh)	20 (a) (7.4 ¢/kWh)
Fuel	1.5-2.2 (b)	1.6-2.6 (b)	1.75 (c)
Steam	2.2-3.7	2.2-4.4	–

(a) Electricity and fuel prices for India based on a recent paper mill feasibility study in Andhra Pradesh
(b) Based on natural gas
(c) Based on coal

FIGURE-1

Efficiency Formulae
NORMAL ENGINEERING DEFINITION

$$\text{Fuel Charged to Power} = \frac{\text{Total Fuel - Equivalent Fuel Saved}}{\text{Net Power}}$$

where Equivalent Fuel Saved is the Fuel Required to Generate the Steam in a New Fossil Fuel Fired Boiler

PURPA

$$\text{Fuel Charged to Power} = \frac{\text{Total Fuel - 50\% of Steam Energy}}{\text{Net Power}}$$

Required Steam Load to Qualify > 5% of Fuel Input (for gas fuelled projects)

FIGURE-2

which, by definition, produce two streams of energy of different value to the consumer. Figure-2 shows two formulae in North America.

In the United States, a project must attain a target efficiency to become a Qualifying Facility (QF) under the PURPA legislation. The Fuel Changed to Power (FCP) calculation allows only 50% of the steam energy to be deducted as a credit on fossil fuel consumed, thus emphasizing efficient power production rather than steam.

PURPA also requires that steam energy be more than 5% of the fuel energy input, presumably for the same reason, but this is a modest demand.

The basic thrust is similar, i.e., towards higher efficiency utilization of fossil fuels, but the evaluation techniques vary widely. This must be considered in optimizing equipment selection for a cogeneration facility.

COGENERATION OPTIONS

Forms of Cogeneration

Any manufacturing plant requiring a large quantity of medium or low pressure process steam lends itself to cogeneration. Steam generated at higher conditions can be efficiently reduced to the process conditions by converting some of the thermal energy to electrical energy.

In practical terms there are two common forms of cogeneration:

(a) Solid fuel, oil, natural gas or black liquor burning systems generating high pressure steam using a backpressure or extraction backpressure steam turbine-generator to generate power and supplying steam to process.

(b) Gas turbine (or diesel) cycles which provide electrical power and generate steam from their exhaust heat. Such cycles may supply steam directly to process or via a steam turbine in a combined cycle.

Various combinations of the above are also used. Steam from wood residue and liquor burning has been used for many years in the pulp and paper industry to cogenerate. Few mills in the past, however, were self-sufficient based on the power available from these sources. However, modern kraft mills are becoming self-sufficient as the pulping processes become more energy efficient.

Fuels

Solid fuel systems can be competitive if the fuel is priced at realistic levels, which may be negative if the alternative to power and steam generation is expensive tipping or disposal of waste solid fuels. In order to compete with current natural gas prices, most waste fuels including wood residue must be priced at zero or negative to compensate for the higher capital costs of solid fuel burning plants.

Fired in modern boilers with stack emission control devices, wood residue burns cleanly with no sulphur dioxide. It can also be argued that power generation is an environmentally more acceptable approach than open burning or landfill. On-site wood residue production and the common requirement of pulp mills to dispose of byproduct residues from purchased wood chip supplies ensure that wood residues will be a source of energy in the pulp and paper industry for many years.

The modern gas turbine can usually accept distillate fuel. However, the fuel of choice in North America is natural gas, where it is available at a competitive price. Natural gas burns to produce much less carbon dioxide than coal or oil, and it produces almost no sulphur dioxide or particulate. Nitrous oxide emissions can also be limited to low levels at an acceptable cost.

In the future, integrated coal gasification and generation (ICGG) technology with high efficiency gas turbine cycles may make coal a competitor. Currently it competes with natural gas only if the cost of the latter increases to around $ 3.7/GJ or double its current price.

Power/Steam Ratio

The most important difference between the traditional cogeneration and the gas turbine approach is in the different relative amounts of steam and electrical power which they produce.

The traditional-back pressure steam (BP) turbine system has a very high efficiency, greater than a modern gas-turbine based system. However, it suffers from the disadvantage that it produces limited power per unit of steam flow supplied to the process. Typically it generates only about 1 kW per 15-30 lb/hr of steam flow (refer to Figure-3).

If more power is needed from such a cogeneration system, extra steam must be produced over and above the process requirements and this steam will have to be condensed (see Figure-4). This allows the ratio of power to steam to increase to 1 kW per 5-12 lb/hr but the extra power is produced at low efficiency due to heat being rejected in the condenser.

As noted previously, the value of electrical power is many times that of steam on an equivalent energy basis. For this reason, many cogeneration systems are based on gas turbines (see Figure-5).

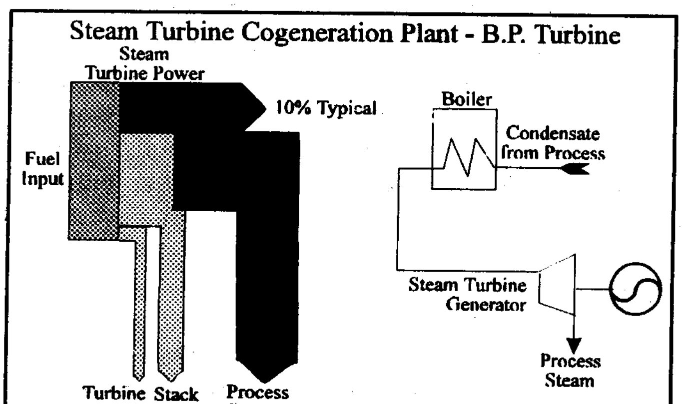


FIGURE-3

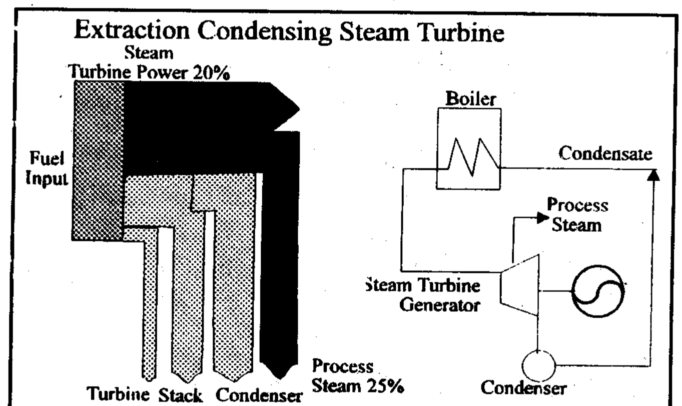


FIGURE-4

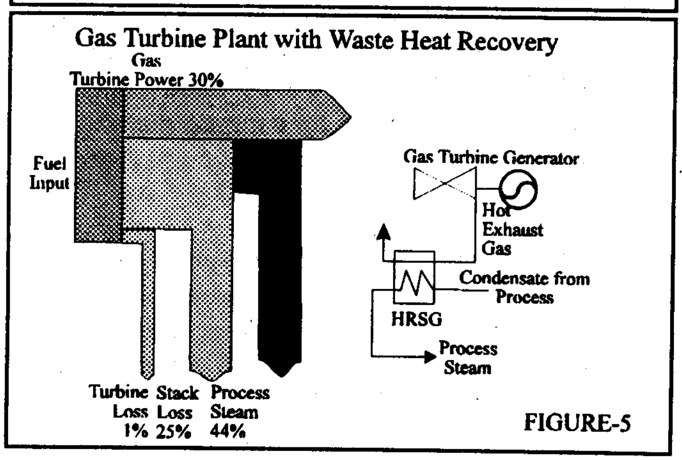


FIGURE-5

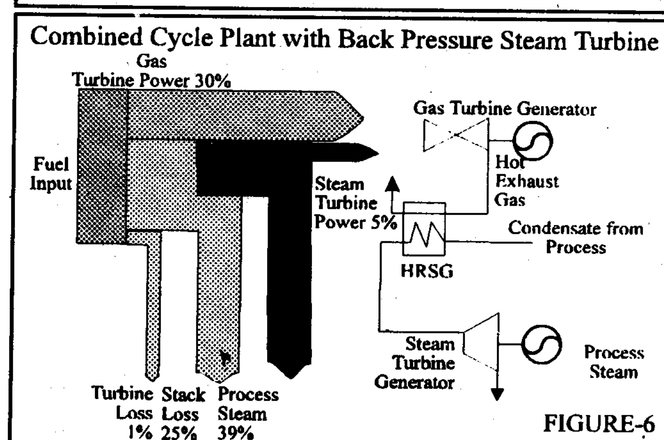


FIGURE-6

This allows electrical energy to be produced at the rate of 1 kW per 1-5 lb/hr of steam.

It should be noted that the efficiencies used in the figures presented here are based on the higher heating value (HHV) of fuel. Gas turbine manufacturers usually express efficiencies based on the lower heating value (LHV), hence showing larger values for the same unit. The gas turbine HHV efficiencies shown in the various figures are quite conservative.

The most basic system utilizes steam produced in a heat recovery steam generator passing directly to process. If steam is generated at somewhat higher pressure, it can generate power by expansion in a backpressure turbine before going to process. This is a "combined cycle" (see Figure-6). Finally, power to steam ratio is further increased by condensing some of the steam (see Figure-7). Again the condensing is done at a low efficiency.

The plant configuration chosen for a specific pulp and paper mill or other industrial or institutional application will be dictated by the specific relationships between heat or steam needs and power required. Before considering specific case histories, it is worthwhile reviewing the types of gas turbines available and their characteristics.

Gas Turbines

Most large industrial cogeneration projects currently favour industrial or heavy duty gas turbines. Such units are optimized for combined cycle use, with moderate pressure ratios (12-15) and high

Combined Cycle Plant with Extraction Condensing Steam Turbine

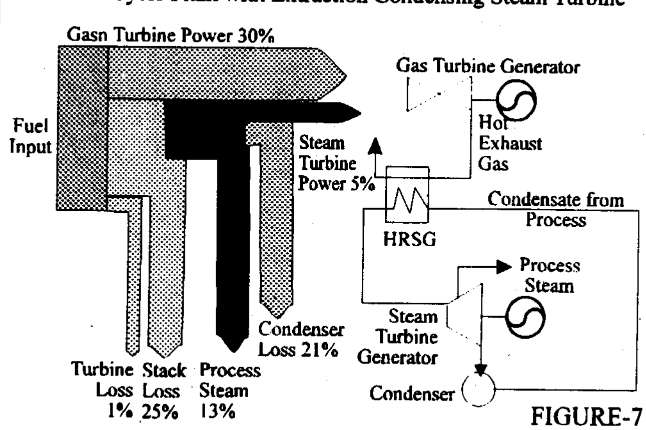


FIGURE-7

exhaust gas temperatures. Industrial units produce about 5 lb/h of low pressure steam per kW to 3.5 lb/h of high pressure steam per kW. In combined cycle, using a backpressure steam turbine, the steam/power ratio may go as low as 3 lb/h per kW without any condensing.

Aero-derivative units are generally optimized for high specific power (for aircraft take off). Such units have a high pressure ratio and low exhaust gas temperature. They produce less steam flow relative to the industrial type; for a modern aero-derivative unit as little as 2.5 lb/h per kW in simple cycle and below 2 lb/h per kW in combined cycle.

Each type has applications for which it is better suited than the other; the aero-derivative for peaking, variable speed operation such as compressor drives and cogeneration applications below 40 MW or requiring little process steam; the industrial for base load and cogeneration applications above 40 MW. There are few areas or ratings at which the two types compete.

All of these steam/power ratios ignore the effect of steam injection, because like condensing, injection does not utilize the latent heat of the steam. This is discussed later.

COGENERATION MATCHING

Cogeneration requires that the steam produced from the gas turbine exhaust gas be used in a process. Where all the steam is used, the process or steam host is said to be "thermally matched" to the gas turbine (GT). Such a match provides optimum efficiency in traditional terms (usable energy as a proportion of energy input). However, economic optimization and the need for operational flexibility require other approaches.

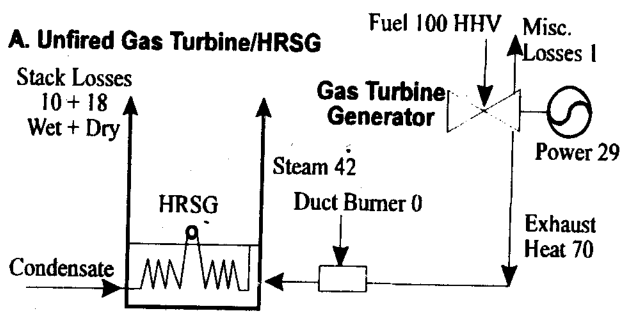
Several useful devices allow improved matching of the basic gas turbine combined cycle with the plant or mill demand.

(1) Condensing Turbine - Where system power output and process steam are fairly evenly matched but steam demand may drop seasonally or intermittently (due to, downtime or upset conditions for example), the excess steam can be passed through the condenser section

of the turbine, generating increased power. If this assists the utility to meet a seasonal peak such as air conditioning demand, etc., the surplus power may be sold profitably.

(2) Supplementary Firing - The use of duct firing upstream of the heat recovery steam generator adds great flexibility to the operation of a cogeneration cycle with variable steam load, especially if the condensing option is unavailable. Additional steam, up to double the normal heat recovery steam generator output on gas turbine exhaust gases alone, may be generated by this means. Duct firing and condensing simultaneously is not efficient but may be economic to provide variable output if fuel prices are low.

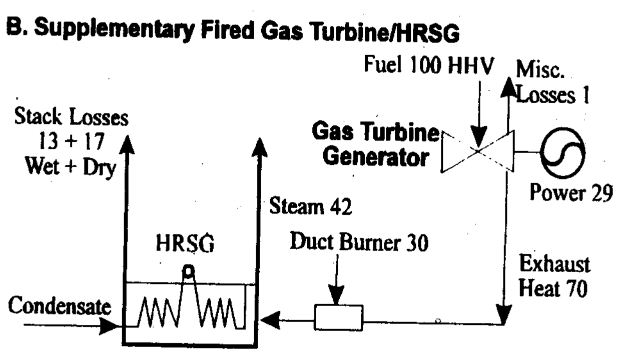
Typical Energy Balances and Fuel Charged to Power Ratios for Different Cogeneration Systems



$$FCP = \frac{(100-42/0.84) \times 3412}{29} = 5883 \text{ BTU/kW hr}$$

FIGURE-8

Typical Energy Balances and Fuel Charged to Power Ratios for Different Cogeneration Systems



$$FCP = \frac{(130-70/0.84) \times 3412}{29} = 5490 \text{ BTU/kW hr}$$

FIGURE-9

(3) Steam Injection - Steam injection can offer increased output and a lower cost alternative to condensing for surplus steam.

In the STIG (steam injected gas turbine), steam from the heat recovery steam generator is injected into the gas turbine to produce additional power. This capability to produce increased power could be economical for plants which operate on a five-day week.

(4) Peaking Ability- A gas turbine's peaking ability can be used to meet short-term electrical and thermal demands. The peaking margin can vary from 10% on industrial units to 25% on the aero-derivative type.

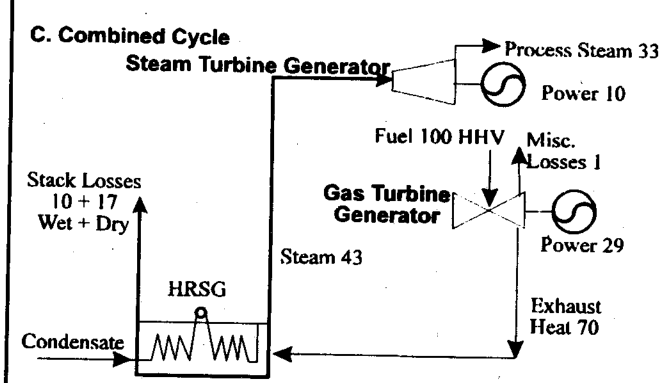
The energy balances (Figures-8, 9 and 10) show the value of the duct burner in matching and the improvement in efficiency or Fuel Charged to Power with the combined cycle approach.

ECONOMIC SIZING

Since there is scope to produce and sell electricity and/or steam from cogeneration plants optimization of the relative electrical and steam outputs is critical if the investment is to be profitable.

Many utilities have attempted to balance power supply and demand, both by encouraging consumers to use high efficiency equipment, e.g., motors, drives, etc., and by offering better rates for power sold to

Typical Energy Balances and Fuel Charged to Power Ratios for Different Cogeneration Systems



$$FCP = \frac{(100-33/0.84) \times 3412}{(29 + 10)} = 5311 \text{ BTU/kW hr}$$

FIGURE-10

them. Utilities requiring additional capacity may now buy power from cogenerators at competitive rates. The improved rates have encouraged both industrial consumers and developers to invest in cogeneration.

ENVIRONMENTAL CONSIDERATIONS

The main environmental considerations associated with gas turbine operation are noise and nitrous oxide emissions.

Sound attenuation usually presents no great technical problems with inlet air silencers and acoustic enclosures. The degree of silencing relates to the capital cost invested.

Various levels of nitrous oxide reduction are possible. Injection of water into the combustion chambers reduces nitrous oxide to about 42 ppm_{VD} levels. High quality demineralized water is required for this purpose. Similarly, steam injection can give nitrous oxide emissions in the order of 25 ppm_{VD}. Medium to high steam pressures, dependent upon the gas turbine's compression ratio, are required and again reasonably high water quality is required. With both water and steam injection, the gas turbine generator's output power is enhanced as discussed in the previous section of this paper.

In North America some local authorities are requiring even lower levels of nitrous oxide emission-down to around 6 ppm_{VD}. This can be achieved by selective catalytic reduction (SCR) equipment, but generally the catalyst has a limited operating temperature range which reduces the effectiveness of the SCR when variable load of the gas turbine and waste heat boiler is necessary.

Most gas turbine manufacturers are offering low nitrous oxide combustors which currently can achieve nitrous oxide emissions down to 9 ppm_{VD}. This is often called dry low nitrous oxide (DLN) combustion since neither water nor steam injection is required.

COGENERATION APPLICATIONS

Pulp and Paper

Because of their large process steam flow requirements, typically at pressures of 150 psig and 50 psig, kraft mills are good candidates for cogeneration. Steam in excess of the recovery boiler (RB) capability is often required and even with an additional power boiler (PB) to dispose of wood residue, sludge and non-condensible gases (NCG), a gas turbine generator and heat recovery steam generator may be used to augment the steam supply and make the mill more self-sufficient in power.

In the case shown in Figure-11, the traditional BP steam turbine generator producing about 25 MW is augmented by a gas turbine generator and heat recovery steam generator producing 130,000 lb/hr or 600 psig steam and 42 MW of electricity, making the mill almost completely self-sufficient.

G.T. Combined Cycle (Self-sufficient/ Power Export

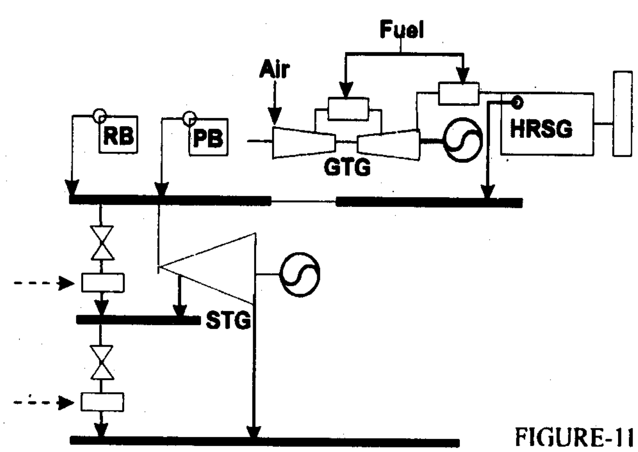


FIGURE-11

McMahon Gas Treatment Plant

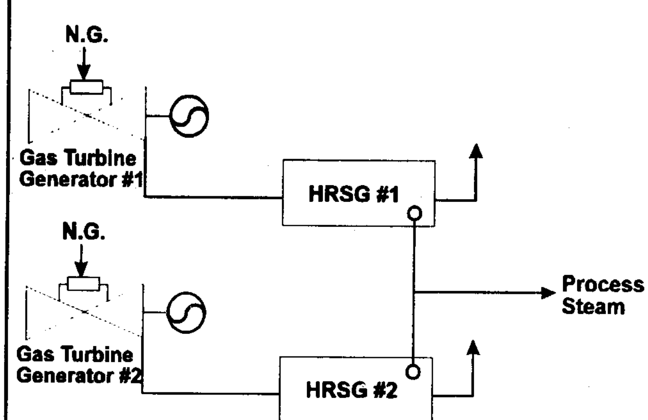


FIGURE-12

Similarly a tissue mill utilizing a gas turbine generator and heat recovery steam generator and one waste wood boiler can produce process steam more economically by generating power from natural gas and steam from the turbine exhaust gases. The biomass boiler is retained to handle wood residue and sludge. Depending on the mill/developer preference the gas turbine generator is selected for 20 MW (self-sufficient) or 40 MW (export of power), with supplementary fuel firing to meet seasonal steam demand. There is no steam turbine generator due to the modest power requirement and matched steam load.

Mechanical pulping mills are normally thermally self-sufficient since reboilers are used to generate low quality steam from the refiners. However, such mills are major power consumers. The high electrical output of combined cycle plant can satisfy this demand and ease the associated problems for the supplying utility.

Paper mills, like kraft mills, have even higher steam demands due to the paper machine and dryer requirements. Integrated mills may have rather less steam requirement per ton of pulp due to the absence of the pulp dryer but newsprint applications often have the high power demand of the thermal mechanical pulp (TMP) facility. Development of this demand may be very attractive to the utility and to the mill/developer due to the size of the cogeneration facility which can be justified (100-150 MW) and the efficiency which can be achieved with a combined cycle gas turbine plant.

The degree to which cogeneration can be utilized depends largely on the mill specifics; relative demand for steam and power, availability of residue or natural gas fuel at economic rates, etc. Each case must be evaluated individually to optimize the cogeneration approach. The pulp and paper industry, as a large steam and power user, is well placed to profit from an equity position in a power company set up to develop cogeneration.

Induatrial and Commercial Plants

Gas turbine based cogeneration is being applied to many industrial and commercial plants. The applications are either combined or simple cycle gas turbine generator plus heat recovery steam generator configurations. One example is Westcoast Energy's Gas Treatment Plant at McMahon near Fort St. John, British Columbia, Canada, see Figure-12. Existing boilers serving the large steam needs are being replaced by gas turbines and waste heat boilers to cogenerate about 100 MW of electricity and 500,000 lb/hour of process steam.

Cogeneration is also finding its place in institutional and commercial installations. Several universities are utilizing or studying electrical generation while satisfying the campus heating and cooling system demands. A small gas turbine generator and waste heat boiler is often appropriate - perhaps in combined cycle with a steam turbine generator set. Heat is provided in the form of steam or, in more modern systems, hot water. Heat exchangers may be used to protect the high quality of water in the boiler/ steam turbine system. Absorption chillers are often used for cooling systems. This maintains thermal demand on the system over the year. An interesting challange of these applications is that the thermal and electrical demands tend to increase steadily with time. This necessitates careful study to optimize the size and arrangement of the cogeneration for maximum economic benefit.

CONCLUSIONS

Cogeneration has already established itself as a significant part of power generation in North America. It is also becoming more popular in other countries. It is particularly relevant to the pulp and paper industry. This industry has traditionally used backpressure steam turbine generators but gas turbine generators in a combined cycle arrangement are becoming important especially for TMP mills.