Chairmen : N.G. Koumoutsos, M. Agapitos

E. Gyftopoulos
Massachusetts Institute of Technology
Cambridge Massachusetts 02139 and
Thermo Electron Corporation
Waltham Massachusetts 02254 U.S.A.

COGENERATION - RESOURCE RECOVERY

1. OVERVIEW

Cogeneration is the concurrent generation of motive power and process heat or steam (1–6). It saves fuel because either waste energy from a heating process is used for the generation of motive power, or waste energy from a power plant is used for heating applications. Typical fuel savings are illustrated schematically in Figures 1 and 2. For example, the top of Figure 1 shows the fuel consumption – – 2.25 barrels of oil – – of a high temperature heating process requiring 5.4 million British thermal units of net process heat, and the fuel consumption – – 1 barrel of oil – – of a power plant generating 600 kilowatt–hours of electricity. The bottom of the figure shows that the same energy services can be provided by using only 2.25 barrels of oil to fire the high temperature process, and then capturing the waste energy from this process to supply the power plant. Thus, an energy saving of 31 percent is achieved.

Again, the top of Figure 2 shows the fuel consumption – – 1.75 barrels of oil – – of a low–pressure steam boiler that raises 8500 pounds of process steam, and the fuel consumption – – 1 barrel of oil – – required for 600 kilowatt–hours of electricity. The bottom of the figure shows how the same energy services can be provided by using only 2.25 barrels of oil. This energy is used in a boiler to raise high–pressure steam, which in turn flows into a back–pressure turbine. The turbine powers the generator, and supplies low pressure steam to the process. Here, the energy saving is 19 percent.

Cogeneration affords one of the largest opportunities for saving fuel because many common processes have sizeable waste energies suitable for this technology. It encompasses many different energy recovery and energy conversion devices. Some of the energy conversion devices, such as steam turbines and reciprocating diesel and spark–ignition engines, have been in common use for decades. Others, such as turbines with an organic material as a working fluid and thermionic converters, are just now being commercialized or are still undergoing testing. The various conversion technologies currently available and those soon to enter the marketplace provide power system designers and utility mamagers with an unprecedented opportunity to save not only energy but scarce capital as well.

Small-scale congeneration facilities save capital because the equipment is built in a manufacturing plant rather than at the site of the facility, and in a much shorter time than that required for a large central electric power station. This latter feature is an invaluable tool for electric utility planners who have had to predict under conditions of great uncertainty electricity demands a decade before a new large power plant would finally come into service.

Power devices for cogeneration fall into two distinct classes: topping units and bottoming units. Topping units take advantage of the fact that many low-temperature direct-fired processes such as drying, curing, baking, space heating, and washing are thermodynamically inefficient because they consume directly the high-quality energy of high-temperature combustion products for tasks that actually require only low-quality energy. The effectiveness of fuel use in such processes can be increased substantially by first using the high-quality energy of fuel combustion in a diesel engine, gas turbine, or steam turbine to drive an electric generator, and then recovering the exhaust energy of the unit to perform heating tasks needing temperatures of only 70 to 350 °C.

Bottoming units are applicable to high-temperature processes such as the production of metals and ceramics in furnaces and kilns operating at 500 °C and above. Waste energy from such a process is directed to a power conversion device driving an electrical generator. In a typical application, furnace exhaust gas, still containing a large quantity of high-quality energy, is directed to a boiler where steam is generated. The steam drives a turbine-generator engine and produces electricity. The combined system uses about 30 percent less energy than when the furnace heat and electricity are produced separately. Cogeneration by means of waste energy recovery with a bottoming engine is particularly attractive because it produces electricity with no incremental consumption of fuel and often can be installed in existing facilities.

2. TECHNOLOGIES

The major energy conversion technologies used in cogeneration are described briefly in what follows.

Steam Turbines. Steam turbines have been used for both cogeneration and conventional power generation throughout much of this century. In a paper mill, for example, a high–pressure topping turbine extracts part of the energy from a high–pressure steam flow. The remaining energy in the exhaust steam, at pressures of 3 to 15 atmospheres (50 to 200 pounds per square inch), is used to operate paper mill machinery such as digesters, blenders, and dryers. A typical electrical output would be about 50 kilowatt–hours per million kilojoules of steam energy delivered to the mill machinery.

In a district heating installation, waste energy from a power plant is fed, either in the form of low–pressure steam or hot water, to a network that supplies the heating needs of a city or a residential and commercial complex of buildings.

Low–pressure steam turbines are used as bottoming units. They recover waste energy from relatively high–temperature exhaust gases of a process by means of a waste–heat boiler, or from the spent steam of intermediate–temperature industrial processes.

Steam topping and bottoming turbines are feasible from about 2 megawatts up to several hundred megawatts with presently available hardware. Capital and installation costs for such units range from about $1000 to $2000 per kilowatt, depending upon system size, waste energy temperature, type of fuel, and specific interface requirements and site constraints for the cogeneration system.

For district heating applications, the capital and installation costs are dictated by the type of plant under consideration and the costs of the district heating network.

Diesel Engines. Diesel engines are applicable as topping units of cogeneration systems when a high ratio of electrical output to process heat is required – up to 400 kilowatt–hours per million kilojoules of heat delivered to the process. Process steam and hot water are produced by recovery boilers coupled to the exhaust stack and to the cooling water of the engine. Systems from as little as 100 kilowatts to several thousand kilowatts can be built. However, these systems are based upon medium–speed and high–speed diesel engines, the type generally used in trucks, construction equipment, and rail locomotives. Such engines are limited to the burning of high–grade distillate petroleum, a product that is likely to be expensive and often in short supply in years to come.

A more versatile diesel engine for topping large cogeneration systems, from several thousand kilowatts up to about 30,000 kilowatts, is the large slow–speed, two–stroke diesel engine. This engine, often used for propulsion of large ships, is capable of burning very–low–grade fuels such as high–sulfur crude or heavy residual oil. Recent experiments have shown that it may even be capable of burning a powdered coal–water slurry. System costs, including heat recovery boilers, range from about $1200 to $1800 per kilowatt.

Combustion Gas Turbines. Combustion gas turbines are well suited as topping units for large–scale systems, particularly where natural gas or clean burning byproduct fuels such as refinery gas are available. Gas turbine systems offer low capital cost, about $500–$1000 per kilowatt, particularly in large systems of 10 to 150 megawatts. Also, the high exhaust gas temperature of gas turbines permits their integration with a great variety of industrial processes

Spark–Ignition Engines. Spark–ignition engines that burn natural gas can also be used as topping units. A relatively new concept for achieving very low capital cost is based upon derated automobile engines converted for use in prepackaged cogeneration modules. One module generates about 60 kilowatts of electricity and about 500,000 kilojoules per hour of process heat in the form of low–pressure steam and hot water. One to ten modules could be used in applications such as shopping centers, hospitals, apartment buildings, and light industrial sites, to supply all on–site electrical and process heat needs.

Other modules are rated at 200 kilowatts, and 600 kilowatts of electricity, and proportionately higher thermal outputs, including relatively high pressure steam. For example, a natural–gas, turbocharged internal combustion engine, coupled with an electric generator and a twin–helical screw steam compressor can generate between 480 and 650 kilowatts of electricity, and between 1400 and 1700 kilograms per hour of high pressure process steam at about 10 atmospheres. Prior to the introduction of the screw compressor, cogenerators requiring high–pressure process steam were forced to use combustion turbines rather than reciprocating engines which yield much higher electrical output efficiency.

Organic Rankine Turbines. An organic Rankine turbine is an advanced type of bottoming unit (7). It uses an organic material as a working fluid and is capable of recovering efficiently the energy from low–temperature (150 to 600 °C) waste streams.

It can be built in a wide range of sizes, from as small as 50 kilowatts to 30,000 kilowatts or more. Output per unit of waste energy input will generally be 20 to 30 percent greater than that obtainable with steam–turbine bottoming units. Commercialization of organic Rankine turbines is just beginning.

The various technologies described above provide the basis for virtually all cogeneration systems. Other technologies now in the research and development stage, such as thermionic converters and Stirling cycle engines, may also play a role in future cogeneration systems.

In its most elementary form, a thermionic converter (8) consists of one electrode connected to a high–temperature energy source (about 1700 ^{o}C), a second electrode connected to a low–temperature energy sink (about 500 ^{o}C) and separated from the first by an intervening evacuated space, and leads connecting the two electrodes to an electrical load. Electrons boil off the hot electrode by the process of thermionic emission, condense on the colder electrode, and return to the hot electrode via the load. Thermionic converters may eventually be used as topping units for gas turbines and high–temperature industrial furnaces.

3. TYPICAL APPLICATIONS

Cogeneration has been practiced for many decades. The advent of the energy crisis in the 1970's rekindled the interest in cost–effective, energy–saving technologies, in general, and cogeneration in particular. A few examples of recent additions to the U.S. cogeneration capacity are as follows.

A number of units have been developed, and are owned and operated by Applied Energy Services. One of these is a $280 million petroleum coke–fired facility in Houston, Texas, designed and constructed by Bechtel Power Corporation. Its electrical rating is 140 megawatts, and its thermal output is 15 short tons of process steam per hour. The electricity is sold to the Houston Light and Power Company, and the steam to the local ARCO refinery which also supplies the petroleum coke. The plant began commercial operations in July 1986.

Another unit is a $116 million coal–fired plant purchased from ARCO, and refurbished by Bechtel. It is located in Monaca, Pennsylvania. It generates 121 megawatts of electricity, and 43 short tons of process steam per hour. The electricity is sold to West Penn Power, and the steam to ARCO Chemical. The plant became operational in July 1987.

A third plant will be commissioned in the summer of 1988. It is a $120 million gas–turbine project in Newhall, California, designed and constructed by Brown Boveri Corporation. It generates about 100 megawatts of electricity sold to Southern California Edison, and 125 short tons of process steam per hour supplied to local oil leases and other steam users.

Many smaller cogeneration plants have been designed and built by Thermo Electron Corporation.

One is a diesel cogeneration system at the Hoffman–La Roche chemical plant in Belvidere, New Jersey. It generates 23 megawatts of electricity, and can also produce 80 short tons of process steam and 130 short tons of hot water per hour. It supplies all the electrical and thermal needs of the chemical plant, and excess electricity is sold to the local utility. The plant began commercial operation in December 1982. It saves the equivalent of 200,000 barrels of oil per year, and achieves an overall energy use of 87 percent.

Another is a diesel steam turbine, combined–cycle power plant for the Sebring Utilities Commission in Sebring, Florida, that became operational in May 1983. It produces 38 megawatts of electricity from two low speed diesel engines manufactured by Sulzer, and an additional 3.2 megawatts from a dual–pressure, steam–turbine heat–recovery system designed and manufactured by Peter Brotherhood, Ltd., a subsidiary of Thermo Electron Corporation.

A third example is an installation at the downtown Government Center in Dade County, Florida. This cogeneration unit began operation in December 1986. All of the electrical power, air–conditioning, and hot water needs of the Center are met by a $30 million combined–cycle cogeneration system supplied on a turnkey basis by Thermo Electron. The prime mover is a dual–fuel 22 megawatt turbine generator, normally operating on natural gas. Turbine exhaust gases generate steam in a dual–pressure heat–recovery boiler that drives a 10 megawatt dual–pressure steam turbine generator. Low–pressure steam from the boiler is directed to an absorption chiller that provides 5,200 tons of air conditioning and 300 gallons of hot water per minute. When less air conditioning is required, the low–pressure steam is supplied to the low–pressure stages of the turbine to generate additional electricity. At maximum chiller demand, the overall fuel utilization is 75 percent.

Cogeneration modules of 60 to 600 kilowatts are manufactured by Tecogen, a majority–owned subsidiary of Thermo Electron Corporation. Modules have been installed and are being operated for a great variety of uses. A sixty kilowatt unit has been installed in each of the following sites: an athletic club in Escondido, an athletic club in San Juan Creek, the Capistrano by the Sea Hospital and Clinic, and a Ramada Inn, all in Southern California. The annual savings in each of these installations are between $20,000 and $30,000, and the payback period is between two and three years. Six Tecogen modules, 60 kilowatts each, are operating on the campus of Albion College in Michigan since December 1984. They provide electricity, hot water for showers, space heating, and swimming pool heating. Also, a four Telogen system, rated at 240 kilowatts, is installed at a 215,000 square foot building complex in North Haven, Connecticut. The system satisfies the electricity, hot water, and heating and cooling requirements of the buildings.

A 200–kilowatt gas–fueled Tecogen module is providing electricity, space heating, and hot water to a Sheraton Hotel in Danvers Massachusetts. A duplicate unit is operating at OK Towel and Uniform Supply, a commercial laundry in Elizabeth, New Jersey. Two 500 kilowatt units have been installed by New England Electric System at a paper mill and a tool manufacturing plant, both in Massachusetts.

4. CLOSURE

Cogeneration is an effective means for controlling energy costs in a broad spectrum of industrial, commercial, and residential applications. Packaged cogeneration units can also be of value to a utility. They provide a fast–response option to capacity expansion by means of which the utility can avoid the costly occurrence of overcapacity that has plagued the industry over the past decade.

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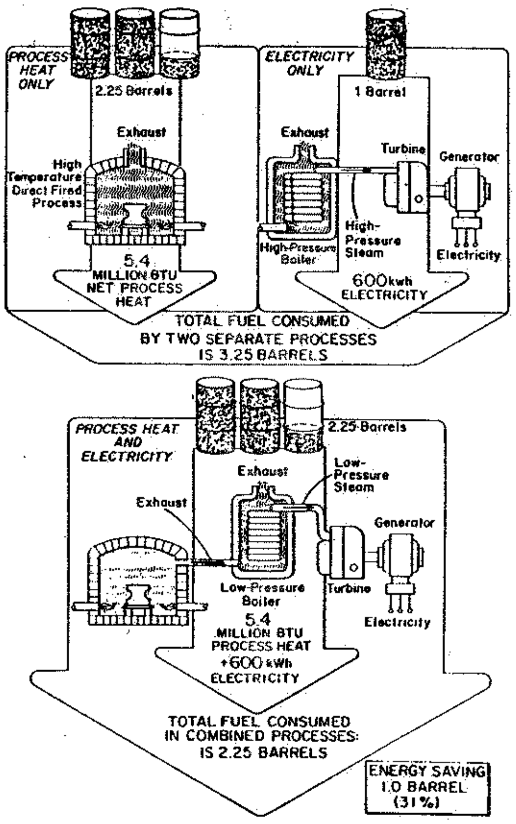

Figure 1

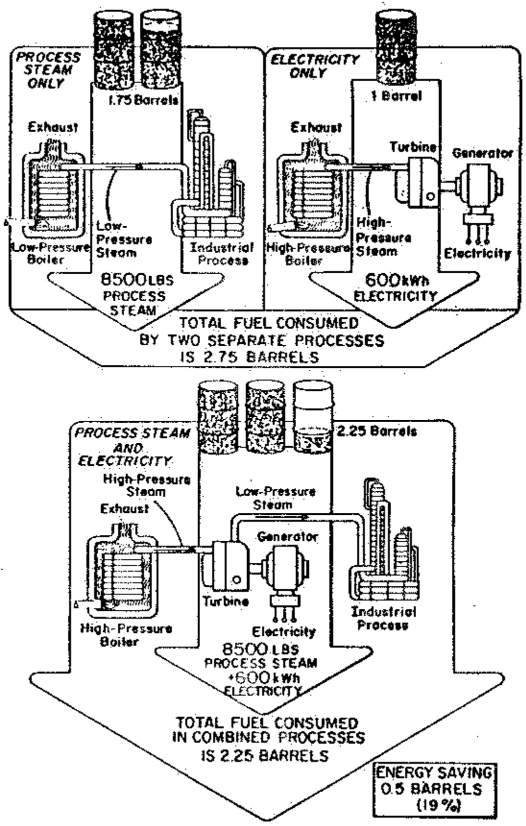

Figure 2