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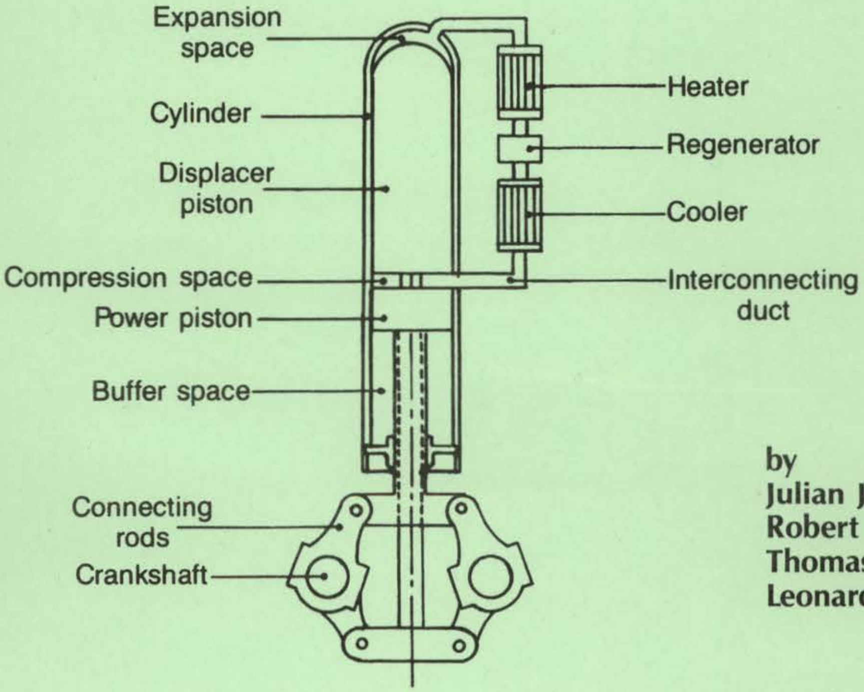
An Overview of Cogeneration Technologies



by
Julian J. Meimban III
Robert L. Govett
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Cover: *A simplified cross section of the Stirling engine.*

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AN OVERVIEW
OF
COGENERATION TECHNOLOGIES

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Preface

The Wood Energy Program in the College of Forestry, Wildlife and Range Sciences encompasses projects related to the use of wood residuals for energy, collection and processing of forest residues, and disposal of wood energy wastes. This paper investigates the use of wood residues for cogeneration of process steam and electricity and presents a general and highly simplified discussion of the characteristics and operations of various topping-cycle and bottoming-cycle technologies for cogeneration. It is intended for readers who have a limited background in the technical aspects of cogeneration technologies. Because the discussion of the technical aspect of cogeneration technologies is kept to a minimum, readers who desire to know more about the technical features of these technologies may wish to refer to the references listed at the end of this report.

What is Cogeneration?

Cogeneration may be defined as the simultaneous but sequential production of processed heat or steam, and electricity, from a single plant versus the more conventional method of producing these products from separate stand-alone plants. The traditional practice is to produce electricity from a stand-alone power plant and to produce process heat or steam from another plant (Office of Technology Assessment 1983). The advantage of the cogeneration process simultaneously producing both electricity and process heat or steam in contrast to separate stand-alone plants is that the cogeneration process is more efficient. With cogeneration, less total energy input is required to produce outputs of electricity and steam or process heat than would be the sum of the energy requirements needed to produce the same output of electricity in a stand-alone plant and to produce separately the same output of process heat or steam in another stand-alone plant.

A simplified explanation of why the higher level of energy efficiency is possible with a cogeneration system may be provided by considering a wood-fueled steam turbine power plant used to produce electricity. Such a plant would typically require about 9500 Btus of energy to produce 1 kWh of electricity. If the plant were burning dry wood fuel, about 1 pound of wood bark or about 1.1 to 1.2 pounds of wood would be required to provide the gross heat of 9500 Btus. However, the equivalent heat in 1 kWh of electricity would be equal to only about 3400 Btus of energy. The difference of about 6000 Btus (or almost two-thirds of the input heat requirement) is not recovered in the form of electricity or another type of product output. This loss includes stack gas heat loss and other conventional heat losses that are difficult to recover. These "non-recoverable" losses represent only about 10 percent to 20 percent of the total energy input of 9500 Btus, for a loss of about 1000 to 2000 Btus. In this example, the stack gas heat loss, other conventional heat loss, and the heat equivalent of the electricity produced all combined account for only about half of the energy input. Cogeneration offers an opportunity to utilize much of the remaining half of the energy input in the form of relatively inexpensive process steam or heat.

A. Stand-alone Plant versus Cogeneration Plant

A typical stand-alone power plant has a boiler, a turbine-generator (or turbo-generator), a condenser, and a cooling tower (Figure 1). The interaction of these pieces of equipment during electricity generation is as follows:

In a condensing-turbine, stand-alone system, the steam that flows through the turbine is condensed immediately as the steam leaves the turbine exhaust. In the condensation process, a powerful vacuum is created as the volume of the steam is dramatically reduced. Steam under high pressure is across the turbine from this vacuum. The steam flows through the turbine, causing the turbine shaft to rotate. This mechanical energy is used to spin an electric generator. The intensity of shaft rotation of the turbine depends on the pressure drop across the turbine and the temperature and the volume of steam flowing through the turbine.

Back-pressure steam leaving the turbine and entering the condenser has a latent heat of vaporization which is released in the condenser. The condenser functions as a heat exchanger, where the latent heat of vaporization is gained by water which flows through the condenser as a cooling medium. This heat is then dissipated from the water through use of a cooling tower or by other means. Being a low-temperature energy (about 125° F), the energy released from the condenser is generally not used. When the steam is condensed, it changes from steam to liquid (condensate), and the condensate is then recirculated to a tank for reuse in the boiler.

The operation of a cogeneration system in a forest products mill (such as a sawmill) is quite different from that of a stand-alone power plant. A simple cogeneration system may not use a condenser to dissipate heat (Figure 2), because a process load, such as the heating of dry kilns, may act as a condenser. This circumstance would describe a non-condensing steam turbine cogeneration

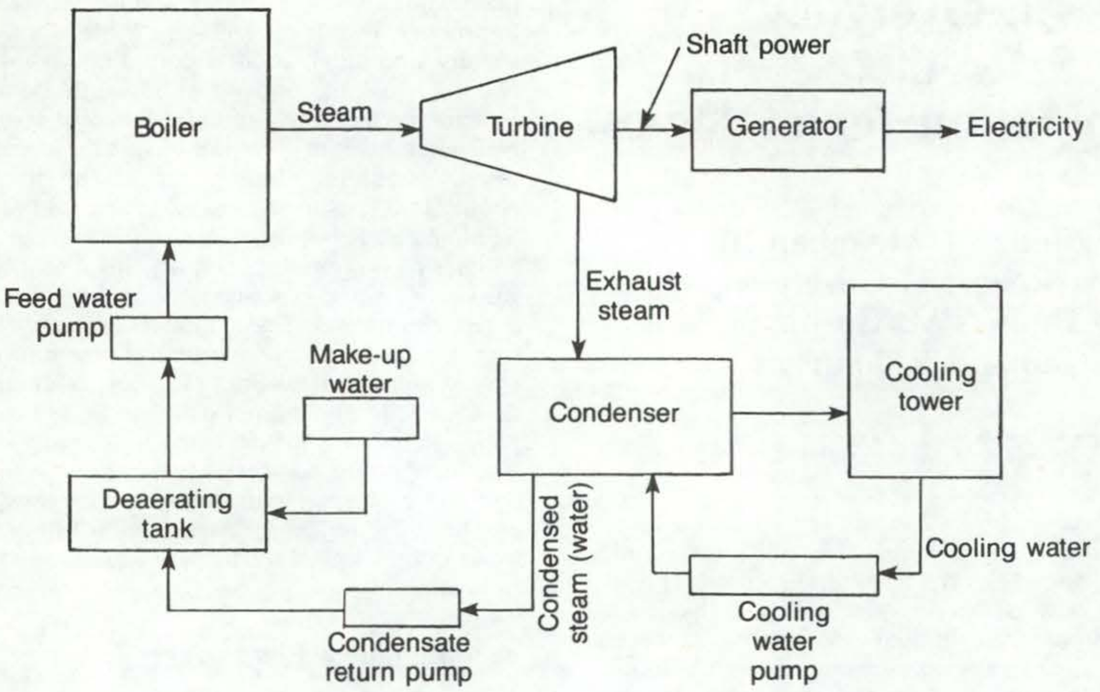


Figure 1. A typical stand-alone steam turbine power plant (simplified).

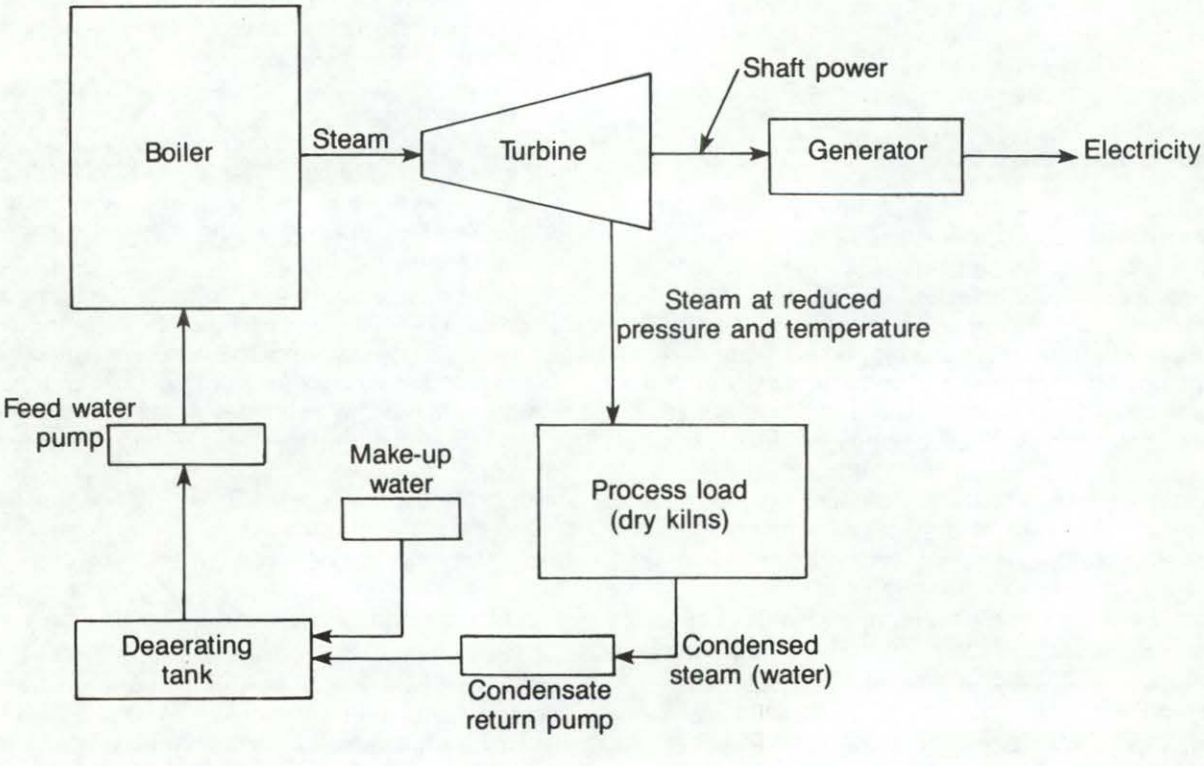


Figure 2. A typical non-condensing steam turbine in a cogeneration system (simplified).

system where process steam demands control the steam flow through the turbine. In such a case, the latent heat of vaporization of the steam is used to dry lumber. In a sawmill, process steam used mainly for lumber drying as well as space heating may be considered as the primary output of the cogeneration system, with generation of electricity as a secondary output. Since the process steam demands of lumber drying control the steam flow through the turbine, electrical output is affected by the process steam demand for lumber drying. Consequently, the electricity production component of the system may not operate at capacity.

To minimize the impact of this constraint, an extraction steam turbine or condensing steam turbine can be used (Figure 3). With a condensing steam turbine, the latent heat of vaporization of the steam can be condensed in a condenser or used in a process steam load such as lumber dry kilns. Process steam at the desired pressure (usually reduced pressure) and temperature is extracted directly from the turbine, while the rest of the steam flows through the turbine and then into the condenser. Work that is ultimately recovered in the form of generated electrical power is performed in the turbine both before and after the extraction of process steam. During conditions of low process steam demand, greater volumes of steam flow through the turbine and higher levels of electrical output are achieved. During conditions of high process steam demand, more steam is removed for the process load and less is allowed to flow all the way through the turbine, resulting in lower levels of electrical output.

Cogeneration has greater overall fuel efficiency than stand-alone systems because the latent heat of vaporization is used rather than being dissipated as "waste heat" in the condenser (Vranizan et al. 1987). Furthermore, the amount of energy needed to produce electricity and process steam from separate plants is greater than the amount of energy required to produce the products from a cogeneration plant (Whiting and Decker 1985). This energy efficiency of cogeneration is illustrated in the following example.

With a stand-alone electrical generation plant, the equivalent of 1 barrel of oil is needed to produce 600 kWh. With a stand-alone steam plant, a low-temperature industrial-process steam boiler needs an oil-equivalent energy input of about 2.25 barrels to produce 8500

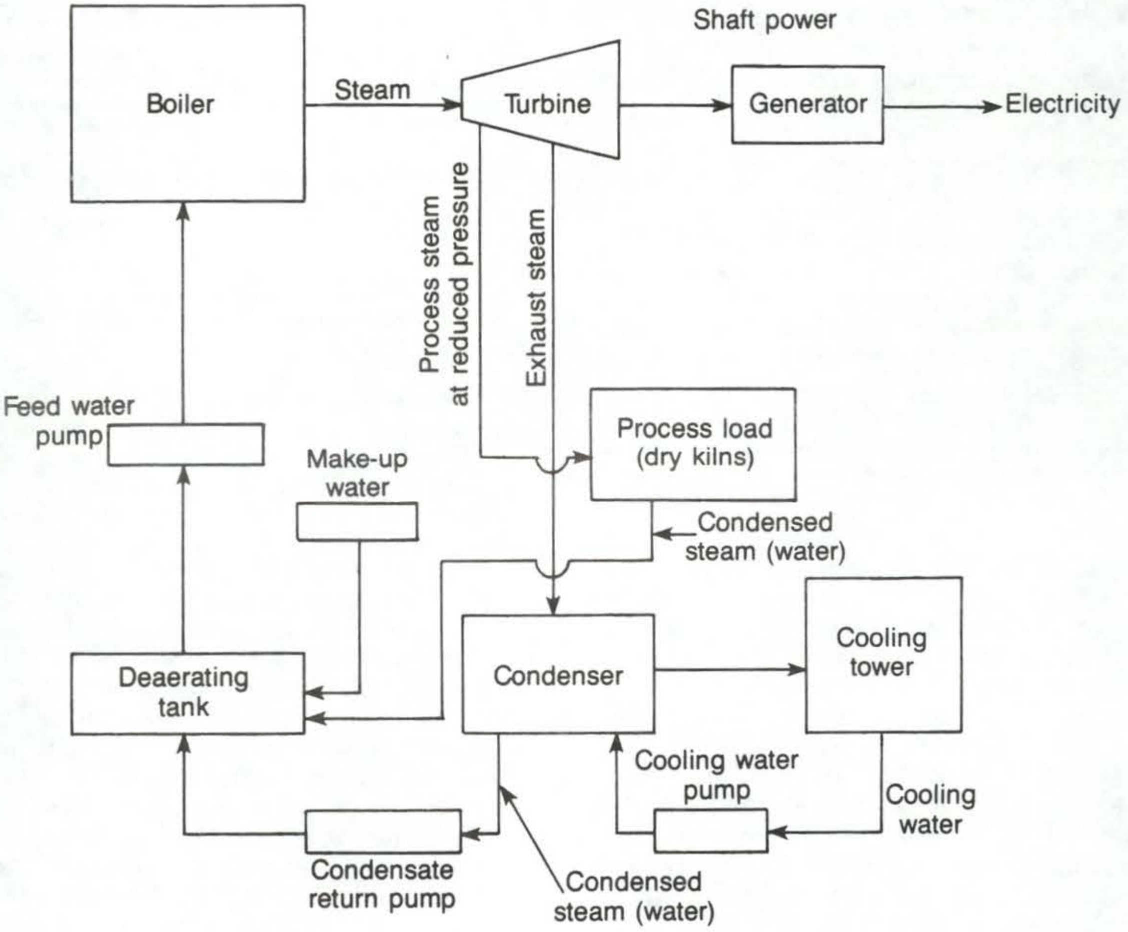


Figure 3. Condensing steam turbine in a cogeneration system.

pounds of process steam. On the other hand, a cogeneration plant needs only about 2.75 barrels of oil to produce 600 kWh of electricity and 8500 pounds of process steam. Therefore, there would be a saving of ½ barrel of oil if both electricity and process steam are cogenerated rather than produced in separate stand-alone plants (Office of Technology Assessment 1983).

The energy efficiency of cogeneration will not always justify a cogeneration system as being superior to separate stand-alone systems. Additional items which must be considered in an analysis of a cogeneration opportunity include the relative value of electricity being generated, the size, type and nature of the process steam load, and the risk and returns projected for a cogeneration system investment versus other investment alternatives. A cogeneration system will in many circumstances have a payback period and rate of return that may be acceptable to a utility company, yet represent a commitment which may be unacceptable to a manufacturing company that could utilize the process steam. Also, the scale of a cogeneration plant appropriate to a manufacturing company that could utilize the process steam may be quite small as a single block of power to be purchased by a utility. If a cogeneration plant is to be owned and operated by a manufacturing company whose prior experience with boiler operation is low-pressure systems for process steam, a far higher level of technical knowledge and proficiency may be required in the operation of high-pressure boilers and steam turbines than may be found in the existing workforce.

B. Cogeneration Technologies

Cogeneration systems can be broadly classified into topping-cycle or bottoming-cycle. In a topping-cycle system, the steam is used first for electricity production, and the by-product steam is captured as process steam for kiln drying, water heating, or space heating and cooling. In a bottoming-cycle system, the high temperature steam is used first for industrial processes such as in steel furnaces, glass kilns, or aluminum furnaces, and the by-product heat is used for electricity production (Butler 1984, Office of Technology Assessment 1983).

1. Topping Cycles

Commercially available topping-cycle cogeneration systems include steam turbine, open-cycle gas turbine, closed-cycle gas turbine, combined gas turbine/steam turbine, and diesel engine systems (Hu 1985, Office of Technology Assessment 1983). These systems may be sized up to 100-MW capacity, except for diesel engine systems, which may be sized up to 30-MW capacity (Office of Technology Assessment 1983). Fuel cell and Stirling engine systems are emerging technologies, still in developmental stages for large-scale applications.

a. Steam turbine—Steam turbines are the primary systems for cogenerating electricity and process steam (Office of Technology Assessment 1983, Technology Application Laboratory of the Georgia Institute of Technology Engineering Experiment Station 1984). They can accommodate a wide variety of fuels such as wood, coal, natural gas, and solid wastes. They can be categorized into non-condensing (Figure 2) or condensing (Figure 3). In a condensing system, a valve is used to extract process steam from the turbine. Because the steam is condensed at the exhaust of the turbine, process steam at required pressure must be extracted before the steam leaves the exhaust. In the non-condensing system, there is no extraction valve and process steam comes directly from the turbine exhaust. The turbine, in producing power, acts as pressure reducer. Types of steam turbines suitable for industrial cogeneration are presented in Table 1.

Table 1. Types of steam turbines for industrial cogeneration.

Turbine Type	Application
1. Single Automatic Extraction (condensing)	Supplies process steam at one pressure level, meets variations in electrical load
2. Double Automatic Extraction (condensing)	Supplies process steam at two pressure levels, meets variations in electrical load
3. Back Pressure (non-condensing)	Turbine exhaust meets process steam demand, electricity generation directly related to steam flow
4. Single Automatic Extraction (non-condensing)	Supplies process steam at two pressure levels, electricity generation directly related to steam flow
5. Double Automatic Extraction (non-condensing)	Supplies process steam at three pressure levels, electricity generation directly related to steam flow

Source: The Technology Application Laboratory of the Georgia Institute of Technology Engineering Experiment Station 1984.

Some factors influence the selection of a condensing or non-condensing steam turbine. If process steam requirements are more important than electricity, and process steam requirements are not highly variable, a non-condensing turbine system may be appropriate. Since steam flow is directly related to electricity output, a normal condition of high steam flow corresponds to high electricity production and an abnormal condition of low steam flow would correspond to a low level of electricity production. The advantage of a non-condensing system is that it is a simplified system that does not need the condenser and cooling tower required for a condensing turbine system and, therefore, should have lower investment and maintenance costs. The disadvantage of non-condensing turbines is that the system cannot accommodate variable electrical load and process steam demands, and, consequently, is less flexible than a condensing turbine system. This disadvantage would be least important where process steam demands are reasonably steady and are set at a level near the capacity of the system.

If variable electrical and process steam demands are anticipated, a condensing turbine is recommended. In a condensing turbine, process steam is extracted from the turbine before it flows all the way through the turbine and is condensed. Electricity can be generated when steam flows either to the extraction valve or to the condenser (Figure 2). If demands for process steam increase, larger volumes of process steam are extracted and, assuming a constant level of steam generated by the boiler, less steam flows all the way through the turbine. During periods of no demand for process steam, steam flow can still be directed through the turbine and to the condenser. Consequently, the condensing turbine system is much more flexible than the non-condensing turbine, because it provides the opportunity to generate high levels of electricity where there is little or no demand for process steam.

In a condensing turbine system, some electricity can be generated even in a condition where the entire steam flow is extracted as process steam (100% extraction), but more electricity can be generated if steam is allowed to flow all the way through the turbine. Maximum levels of simultaneous process steam extraction and electrical power generation are achieved with adequate boiler capacity to generate the required steam flow. This is graphically depicted in a steam performance map as shown in Figure 4. Line A-F-B represents an extreme condition when all steam is extracted and no steam flows to the condenser. This corresponds to high process steam demand and relatively low electrical power demand and/or steam supply limitations. Line A-C represents the other extreme condition when all steam flows to the condenser and corresponds to no demand for process steam. The area bounded by line A-B-E-C represents variable combinations of electricity and steam outputs. Point E represents a condition where process steam demand is at a high level and extraction of steam is roughly equivalent to extraction at Point B, but additional steam flow has been provided to permit a peak level of electrical power generation.

Although condensing turbines are more (operationally) flexible than non-condensing turbines, condensing turbines are limited to larger sizes and are more expensive. It is rare to find condensing turbines smaller than 5-MW capacity because smaller-sized turbines of this type are difficult to manufacture and operate economically. As previously mentioned, the condensing system requires a condenser and cooling tower and also requires a more complicated and typically more expensive turbine-generator than is required in a non-condensing system. Consequently, a condensing turbine system is usually far more expensive than a non-condensing turbine system (Technology Application Laboratory of the Georgia Institute of Technology Engineering Experiment Station 1984).

b. Open-cycle gas turbine—Open-cycle gas turbine systems may be simple (Figure 5) or regenerative (Figure 6). In both types, air from the atmosphere is compressed, heated to required turbine inlet temperature in the combustion chamber, and then expanded through the turbine. In a regenerative turbine, the low-pressure hot gases from the turbine are used to preheat the input air (input air is high-pressure air discharged from the compressor) in the regenerator. In a simple system, the low-pressure hot gases from the turbine are not recirculated in the system.

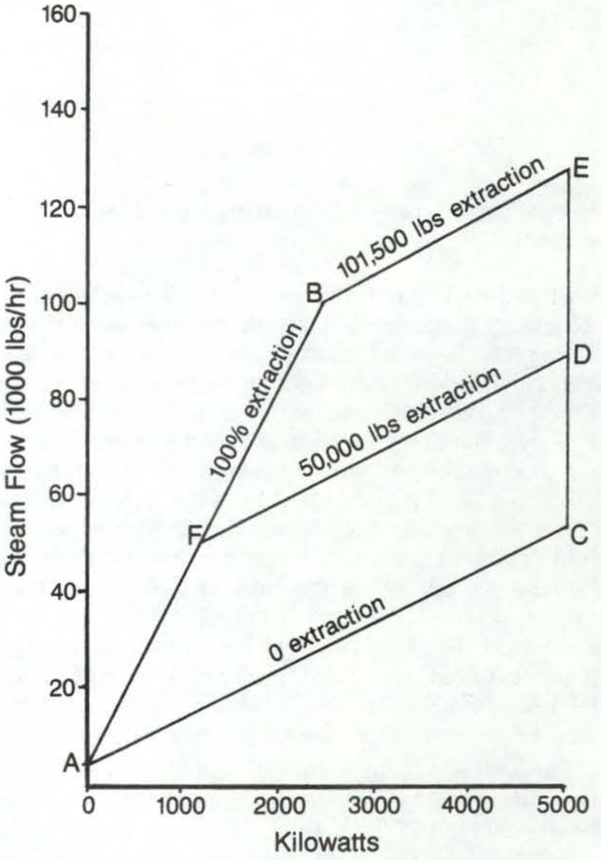


Figure 4. Steam performance map (Source: The Technology Application Laboratory of the Georgia Institute of Technology Engineering Experiment Station 1984).

Open-cycle gas turbines cannot directly burn solid fuels (such as wood or coal) without first liquefying or gasifying them. When such gaseous and liquid fuels are used, they need to be cleaned of impurities because some products of combustion may damage or corrode the turbine blades. Since the turbine blades are exposed to the products of combustion, open-cycle turbines that burn liquid fuel require about three times more maintenance than steam turbines and are generally expected to last 15 to 25 years in operation.

Poor maintenance, use of liquid fuel, or intermittent operation can lower the service life of open-cycle gas turbines. Technical and economic constraints currently exist with design of turbines durable enough to handle wood-derived gaseous or liquid fuel and/or with the design of equipment to suitably clean such fuel for use in conventional turbines. This presently restricts the use of wood fuel in open-cycle gas turbines.

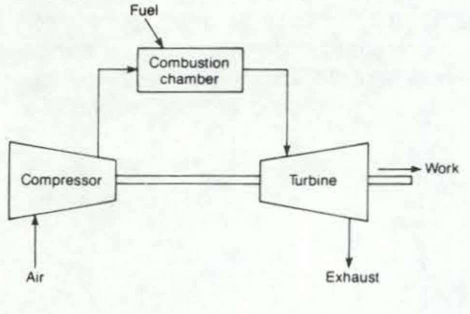


Figure 5. Simple open-cycle (Source: Office of Technology Assessment 1983).

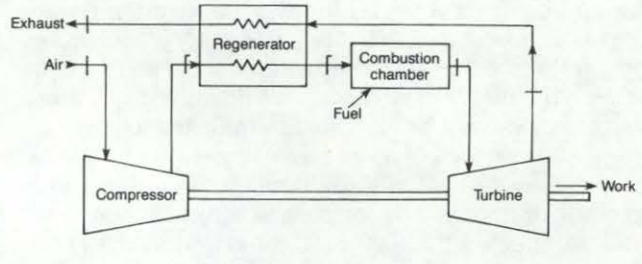


Figure 6. Regenerative open-cycle (Source: Office of Technology Assessment 1983.

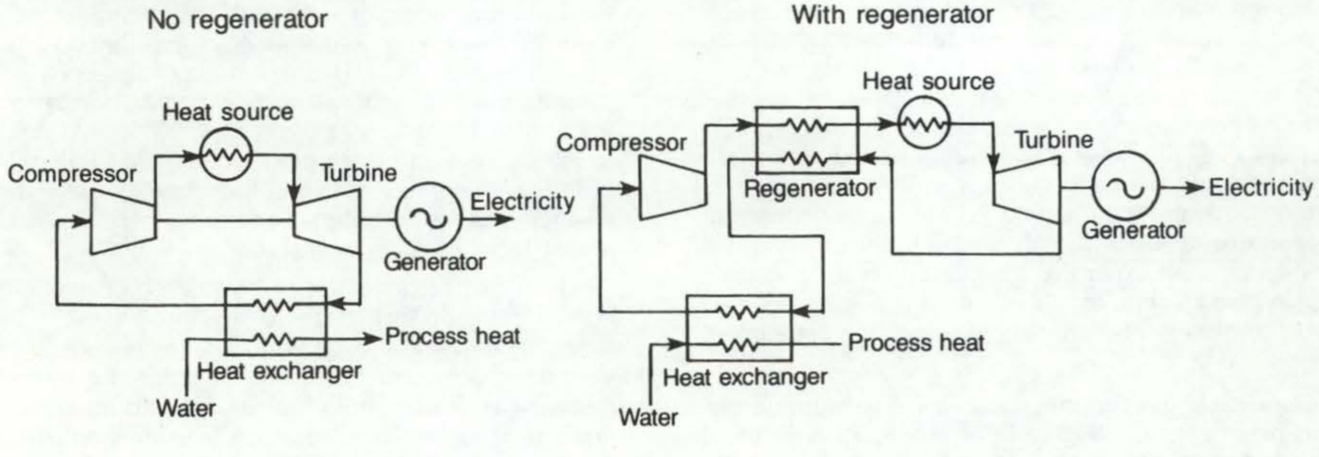
c. Closed-cycle gas turbine—A closed-cycle gas turbine consists of a compressor, a turbine-generator set, a heat source (combustion chamber), and a heat exchanger (Figure 7). A working fluid (usually helium or air) is used as a medium to carry heat from the heat source to the turbine by circulating the fluid into the system. Because it is a closed-cycle system, virtually any gas could serve as a working fluid (Office of Technology Assessment 1983). When the working fluid leaves the turbine exhaust, the fluid circulates back to the compressor and then back to the heat source. Before the working fluid enters the compressor, however, the fluid is cooled; in the process heat is released. The heat released becomes available for use as process heat (Hu 1985). In the regenerative system, the heat from the working fluid leaving the turbine is used to preheat the working fluid from the compressor.

In a closed-cycle system, both the working fluid and the turbine are separated from the combustion chamber (heat source), and thus are separated from the products of combustion. Therefore, the turbine blades are not subjected to the corrosive impact of combustion products. Consequently, closed-cycle systems generally require less maintenance than open-cycle systems. Unlike open-cycle systems, closed-cycle systems can directly burn solid fuels (such as coal and wood) as well as gaseous fuels (Office of Technology Assessment 1983).

d. Combined-cycle—In this system (Figure 8), a topping-cycle and a bottoming-cycle operating at different temperatures are linked together to form a larger interconnected system. The topping-cycle operating at a higher temperature rejects heat that is recovered and used in a bottoming-cycle operating at a lower temperature.

In Figure 8, the top portion is a gas turbine topping-cycle, to which a steam turbine bottoming-cycle is connected. A two-pressure-level heat exchanger (or heat recovery system) links the two cycles. To improve overall conversion efficiency and produce additional power, the heat recovery boiler (in which waste heat of the topping-cycle is captured) is usually also fired by an external fuel (Office of Technology Assessment 1983, Hu 1985).

e. Diesel engine—The first diesel engines were designed for automobiles and propulsion engines. Cogeneration systems using diesel engines (Figure 9) are topping-cycle systems. Major components of a typical diesel engine cogenerator are an engine, a generator, and a heat recovery unit. Since a diesel engine is an internal combustion engine cooled by water, the heated water can be used


No regenerator

With regenerator

Figure 7. Closed-cycle with and without regeneration (Source: Office of Technology Assessment 1983).

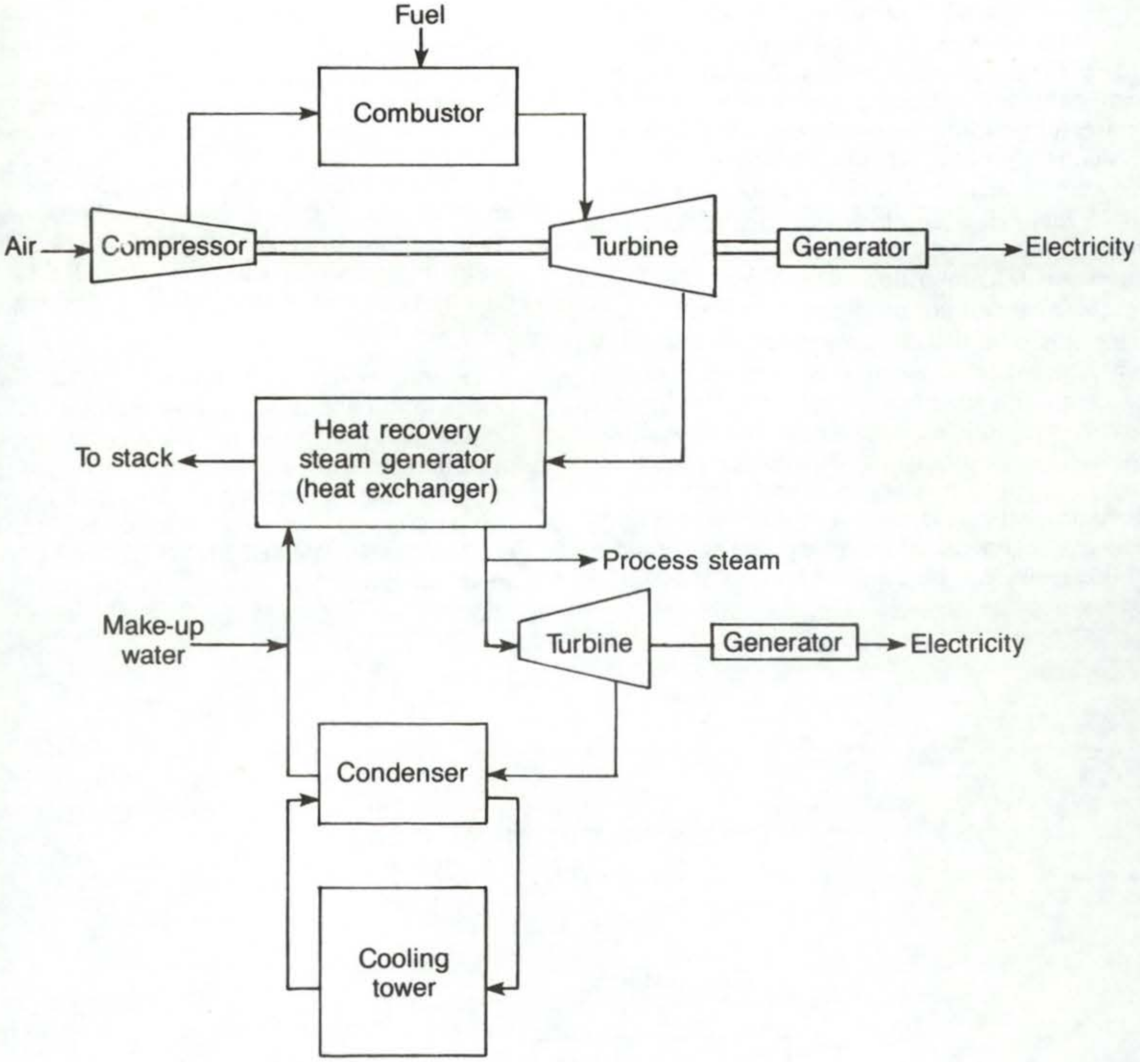


Figure 8. Combined cycle (Source: Hu 1985).

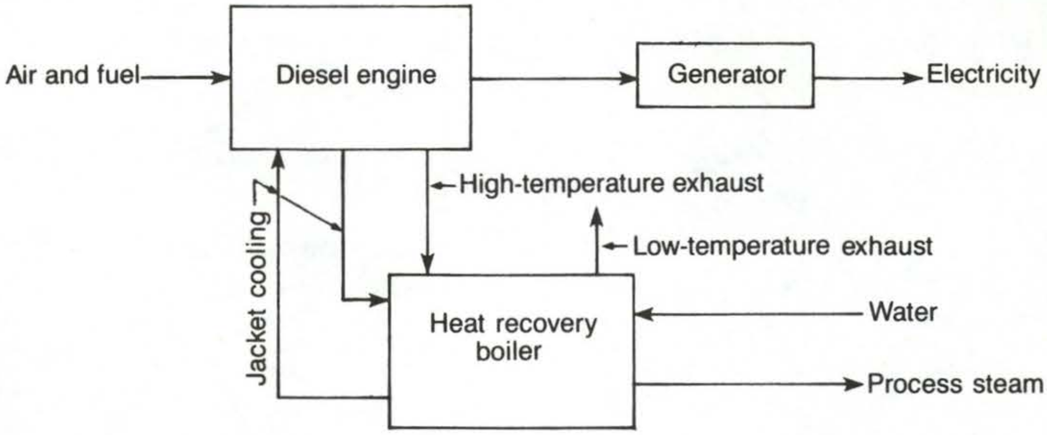


Figure 9. Diesel engine (Source: Office of Technology Assessment 1983).

directly for processes (Office of Technology Assessment 1983). It is possible to power a diesel engine and other types of internal combustion engines with wood fuel by using a small gasification unit. Such technology was developed and employed a half-century ago on a limited basis, but is currently not practical or economically justifiable except in very limited circumstances.

f. Fuel cell—A fuel cell is an electrochemical device that converts the chemical energy of a fuel into electricity with no intermediate combustion cycle (Figure 10). Electricity and process steam are produced as follows.

Hydrogen (the typical fuel) is injected into the anode (a negatively charged pole) where electrons are freed by catalytic reaction. This leaves hydrogen ions. The hydrogen ions are then conducted (through an electrolyte) toward the cathode (a positively charged pole), where they combine with oxygen to produce heat and water. Electricity is generated when electrons and the electrolyte react, while steam is generated when heat and water are produced. The steam can be used for process steam in a cogeneration system.

A fuel cell model using phosphoric acid as the electrolyte, uses hydrogen processed (by a device called a reformer) from hydrocarbon obtained from oil or gas wells. Oxygen is extracted directly from the surrounding air.

The electricity produced by a fuel cell is direct current, the type of current used by battery-powered equipment. Since many types of electrical equipment run on alternating current, an inverter is needed to convert the direct current into a utility-grade alternating current (Holusha 1989).

Properties that make fuel cells suitable for industrial cogeneration are: modular construction, automatic start-up and shut-down, low pollutant emissions, and quiet operation. In addition, individual cells can be assembled in series to form different voltages, and these assemblies can be connected in parallel to form different power levels (such as 40 kW to 25 MW) (Office of Technology Assessment 1983).

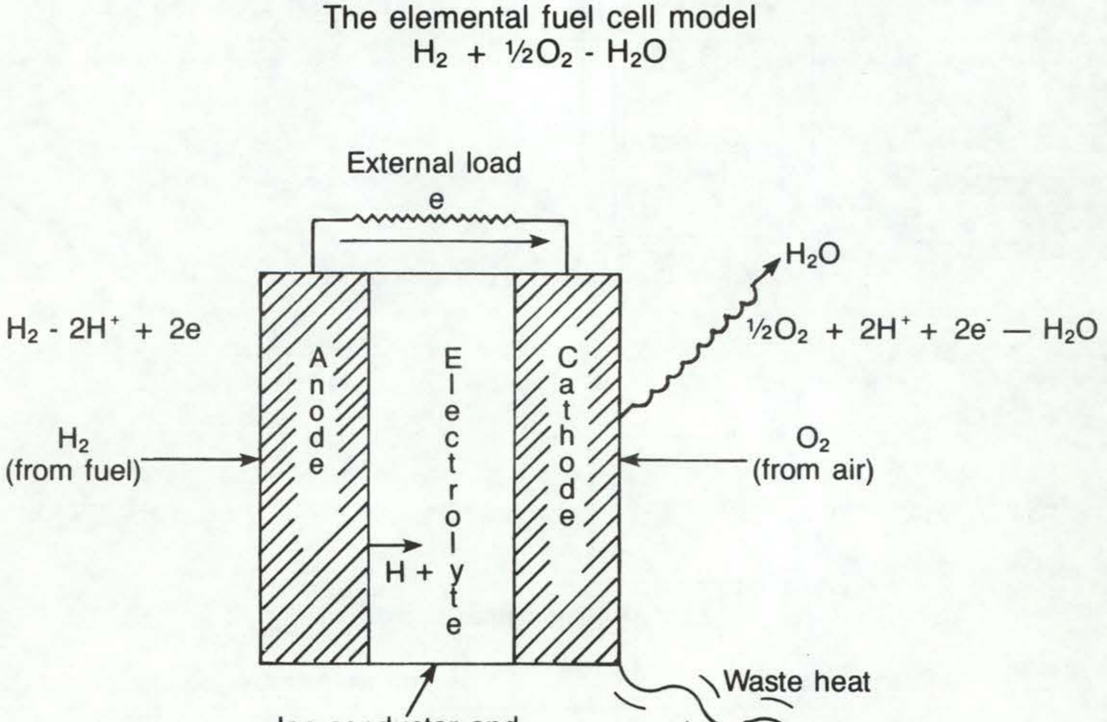


Figure 10. Fuel cell (Source: Office of Technology Assessment 1983).

In their present stage of development, fuel cells are an expensive technology for producing electricity in large quantities. Developers estimated that early commercial models may cost from $1,500 to $2,000 per kW, or about $22 million for an 11-MW plant. To be competitive with conventional power plants, the cost must be reduced to $800 to $1,000 per kW (Holusha 1989).

g. Stirling engine—In a Stirling engine (figure 11), power that turns a crankshaft is generated when a gas (such as hydrogen or helium) entrapped in a piston is alternately expanded and compressed. In this cycle, a pressure differential is created. Because the pressure during the expanding step is much greater than the pressure during the compression step, power is produced. Stirling engines were originally investigated for automobiles and development was focused on smaller sizes (3 to 100-kW). Development of larger sizes (1 to 1.5-MW) is still in the experimental stage.

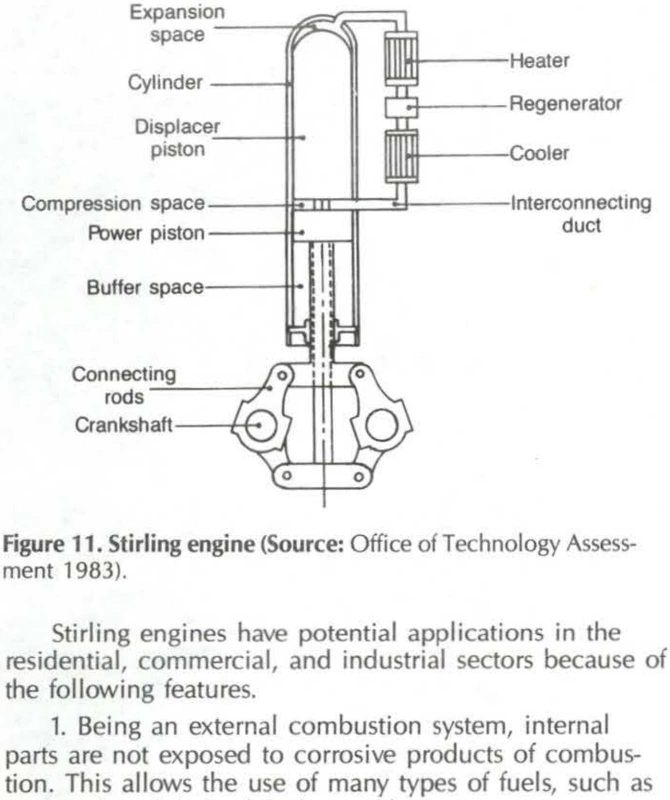


Figure 11. Stirling engine (Source: Office of Technology Assessment 1983).

Stirling engines have potential applications in the residential, commercial, and industrial sectors because of the following features.

1. Being an external combustion system, internal parts are not exposed to corrosive products of combustion. This allows the use of many types of fuels, such as coal and coal-derived fuels, wood, etc.

2. Fuels can be changed without the need of engine adjustments and operation interruption. Thus no power is lost nor efficiency lowered.

3. Stirling engines have far greater efficiency than other available cogeneration systems. Their waste heat is one of the lowest among cogenerators.

2. Bottoming Cycles

Bottoming-cycle systems first extract process heat (usually in the form of high-pressure-temperature process steam) and then use the steam exhausted (e.g., from an industrial process) to generate electricity. The following conditions favor the use of a bottoming-cycle cogeneration system: high-temperature exhaust steam, continuous operation (or a high load factor), high in-plant need of electric or shaft power, and exhaust steam free of corrosive materials. A bottoming-cycle system is most applicable in industries such as metallurgical (aluminum, copper, and steel), graphite, nonmetallic (cement and glass), and intermediate and finished metallurgical processes (forging and casting).

Bottoming-cycle cogeneration technologies include: steam turbine (applicable for large, high-temperature, and continuous operations), gas turbine (applicable for high-temperature and a wide-range-of-power-output uses), and Rankine-cycle turbine (applicable for small and low-temperature uses). The steam turbine used in bottoming-cycle is smaller than the steam turbine used in combined-cycle because in bottoming-cycle the available quantity of waste heat is limited.

a. Steam Rankine-cycle—Rankine-cycle bottoming systems can be a steam or organic cycle. In a steam Rankine cycle (Figure 12), steam from a heat recovery boiler is used to drive a steam turbine which generates electricity and high- and low-temperature waste heat. The high-temperature waste heat is diverted for process use or fed back to the boiler. The low-temperature waste heat is allowed to escape into the air.

b. Organic Rankine-cycle—In an organic Rankine cycle (Figure 13), an organic fluid (such as toluene) is evaporated at high pressure, and the vapor is expanded into a turbine to produce mechanical energy. The vapor is later recondensed for process use or reinjected into the heat recovery boiler. Because organic fluids vaporize at a low temperature, an organic Rankine cycle is suited when only low-temperature heat sources (200 - 600° F) are available. The ability of Rankine cycles to use low-temperature heat allows them to use many forms of energy, such as solar, geothermal, hot engine, and industrial waste heat.

3. Wood-fired Cogeneration Technologies

Other features of the topping-cycle and bottoming-cycle cogeneration technologies presented are shown in Table 2. Of the cogeneration technologies presented, only the steam-turbine, closed-cycle gas turbine, and Stirling engine can be fired directly with wood fuel. Closed-cycle gas turbines are not commercially available in the U.S., but are widely used in Europe (Office of Technology Assessment 1983). Open-cycle gas turbines, combined gas turbine/steam turbines, and diesel systems (all are topping cycles) can accept only clean wood-fuel-derived gases and liquids. Although wood-fired boiler technologies allow the electricity generating capacity of wood-fired cogeneration systems of up to 100 to 150-MW, the availability of wood fuel and its transportation costs may limit the maximum practical commercial capacity to 50-MW or less (Resources Agency of California 1981).

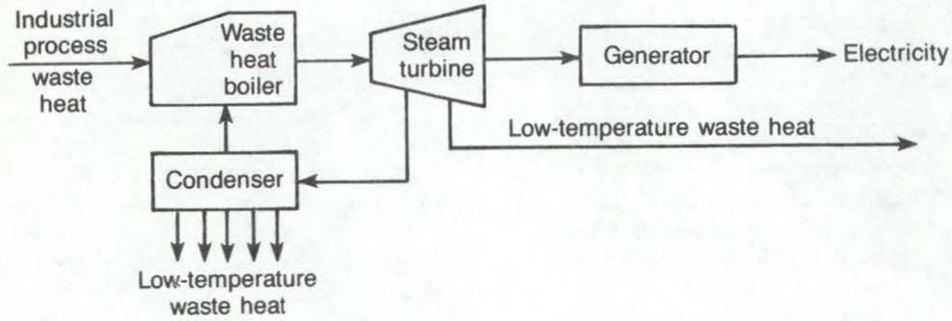


Figure 12. **Steam Rankine-cycle bottoming (Source:** Office of Technology Assessment 1983).

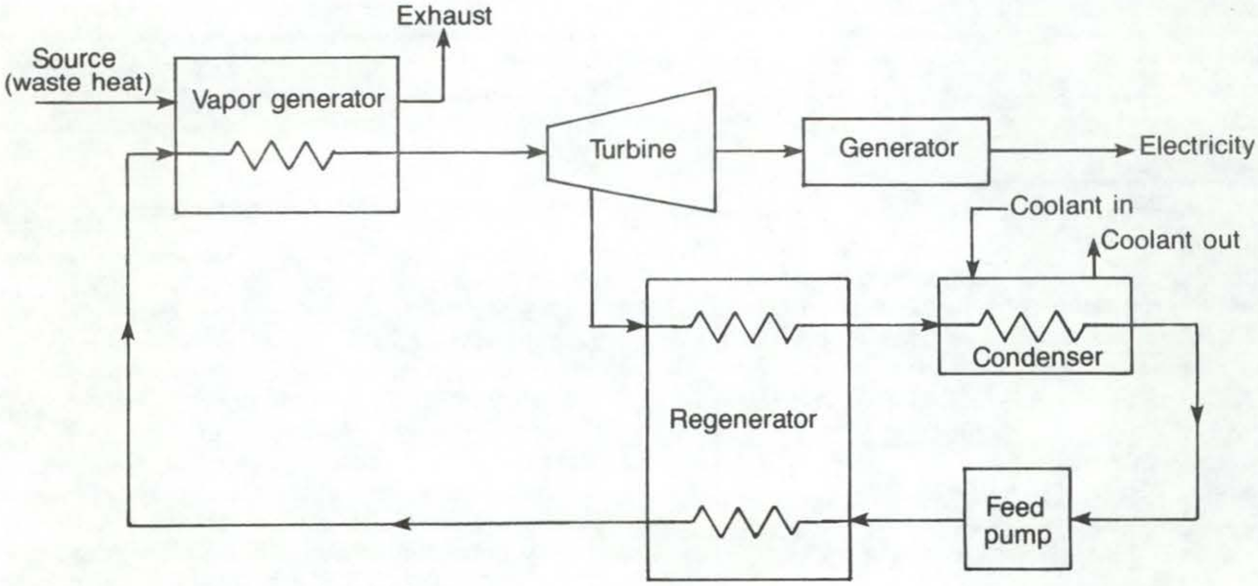


Figure 13. **Organic Rankine-cycle bottoming (Source:** Office of Technology Assessment 1983).

Table 2. Other features of cogeneration technologies.

Technology	Unit Size	Fuel Used	Average Annual Availability (%)	Total Heat Rate[1] (Btu/kWh)
A. Steam turbine topping	500 kW-100 MW	Natural gas, distillate, residual, coal, wood, solid waste/coal-or biomass-derived gases and liquids	90-95	12200-24000
B. Open-cycle gas turbine topping	100 kW-100 MW	Natural gas, distillate, treated residual/coal- or biomass-derived gases and liquids	90-95	9750-14200
C. Closed-cycle gas turbine topping	500 kW-100 MW	Externally fired—can use most fuels	90-95	9750-11400
D. Combined gas turbine/steam turbine topping	4 MW-100 MW	Natural gas, distillate, residual/coal- or biomass-derived gases and liquids	77-85	8000-10000
E. Diesel topping	75 kW-30 MW	Natural gas, distillate, treated residual/coal- or biomass derived gases and liquids, slurry or powdered coals	80-90	8300-10300
F. Rankine-cycle bottoming:				
Steam	500 kW-10 MW	Waste heat	90	17000-34100
Organic	2 kW-2 MW	Waste heat	80-90	17000-34100
G. Fuel cell topping	40 kW-25 MW	Hydrogen, distillate/coal	90-92	7500-9300
H. Stirling engine topping	3-100 kW (expect 1.5 MW by 1990)	Externally fired—can use most fuels	Not known—expected to be similar to gas turbines/diesels	8300-9750

Technology	Net Heat Rate[2] (Btu/kWh)	Construction Leadtime (years)	Expected lifetime (years)	Cogeneration Applicability
A. Steam turbine topping	4500-6000	1-3	25-35	Most commonly used cogeneration technology. Generally used in industry and utility application. Best suited for where electric/thermal ratio is low.
B. Open-cycle gas turbine topping	5500-6500	0.75-2	20 for natural gas 15 for distillate	Potential for use in residential, commercial, and industrial sectors if fuel is available and cost effective.
C. Closed-cycle gas turbine topping	5400-6500	2-5	20	Best suited for large-scale utility and industrial applications. Potential for coal use is excellent.
D. Combined gas turbine/steam turbine topping	5000-6000	2-3	15-25	Most attractive where power needs are high and process steam needs are low. Used in large industrial applications such as steel, chemical, and petroleum refining industries.

Table 2 (cont'd). Other features of cogeneration technologies.

Technology	Net Heat Rate[2] (Btu/kWh)	Construction Leadtime (years)	Expected lifetime (years)	Cogeneration Applicability
E. Diesel topping	6000-7500	0.75-2.5	15-25	Reliable and available. Can be used in hospitals, apartment complexes, shopping centers, hotels, and industrial centers if fuel is available and cost effective, and if can meet environmental requirements.
F. Rankine-cycle bottoming: Steam	NA	1-3	20	Industrial and utility use almost exclusively. Although efficiency is low, since it runs on waste heat, no additional fuel is consumed. Can reduce overall fuel use.
Organic	NA	1-2	20	Same benefits/limitations as steam Rankine bottoming except that it can use lower-grade waste heat. Organic Rankine bottoming is one of the few engines that can use heat in 200 F to 600 F range.
G. Fuel cell topping	4300-5500	1-2	10-15	Modular nature, low emissions, excellent part-load characteristics for utility load following as well as applications in commercial and industrial sectors.
H. Stirling engine topping	5500-6500	2-5	20	High efficiency and fuel flexibility contribute to a large range of applications (residential, commercial, and industrial).

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[1] Total heat rate (Btu/kWh) refers to the "total amount of fuel (in Btu) required to produce one kWh of electricity, with no credit given for the use of 'waste heat'" (Office of Technology Assessment 1983).

[2] Net heat rate (Btu/kWh) refers to the "fuel required to produce electricity, beyond what would be needed to produce a given quantity of thermal energy in separate facility (e.g., a boiler)" (Office of Technology Assessment 1983). It refers to the incremental amount of fuel required to generate one kWh of electricity (Hu 1985).

Electricity-to-steam ratio refers to the "relative proportions of electricity and thermal energy produced by a cogenerator" (Office of Technology Assessment 1983).

Source: Condensed from Office of Technology Assessment 1983.

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