Using small steam-turbine–generator sets to replace pressure-reducing valves

Thomas S. Ewing and Lynn B. Di Tullio

ABSTRACT: A back-pressure turbine can generate power for as little as 1.2 cents per kilowatt-hour.

KEYWORDS: Cogeneration, electric generators, power generation, rotary generators, steam turbines, turbines, turbogenerators, water.

There are many ways to improve energy efficiency in the typical paper mill. One often-overlooked opportunity for energy savings is the replacement of steam pressure-reducing valves with steam-turbine cogeneration systems. In the right circumstances, mills can use this technology to generate electricity at a cost of US$ 0.012/kW·h by using the steam that they are producing for process loads.

Steam-turbine cogeneration is not new to the paper industry. Virtually all of the large, integrated mills cogenerate electricity. However, despite the industry's awareness of the large cogeneration systems, the smaller opportunities to exploit this technology are often ignored.

Many engineers believe that the smaller systems are not economical, a notion that is disproved by the many systems now operating both inside and outside the paper industry. For example, the district heating utility for St. Paul, MN, recently installed a 900-kW steam-turbine cogeneration system that will supply 95% of the electric load at the utility's main boiler plant. A food-processing plant in California installed a similar system to supply a large percentage of its electric load. Montana State University has installed a 670-kW unit on the campus steam distribution system, and a large chemical company has installed systems at several of its plants. Not all recent installations have been at large facilities. A small wood-processing plant in Vermont is generating 200 kW, and a small paper mill in Massachusetts installed a 400-kW unit. Over the past decade, dozens of similar systems have been installed in nearly every type of facility that uses a significant amount of steam.

None of these plants has "surplus" steam. In every case, they are using their steam twice: first for generating electricity and secondly for process. These facilities are purchasing fuel at the going rate, yet they are still able to produce their own power for about US$ 0.012/kW·h.

Using a back-pressure turbine in a cogeneration application is one of the most efficient ways of producing electricity. Steam-turbine cogeneration is a mature technology. Steam turbines and engines have been used by industry to cogenerate power since before there were electric utilities. While the technology for turbines, generators, and controls has continued to develop, there is very little about this equipment that is not well understood.

Back-pressure turbines

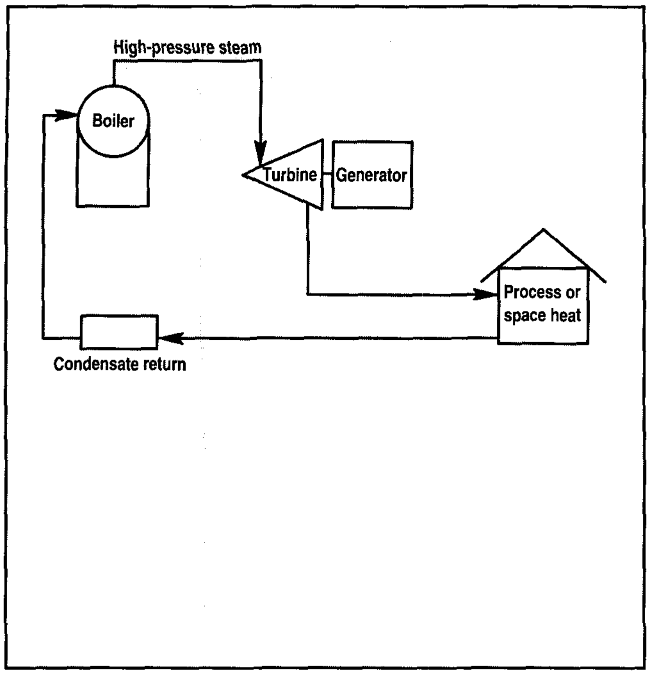
The heart of most steam cogeneration systems under 2000 kW is the single-stage steam turbine. These prime movers are most commonly used as mechanical drives for large pumps, compressors, blowers, and similar equipment. Such turbines are industrial workhorses with a proven record of performance in refinery, petrochemical, and powerhouse applications. In the paper industry, they are commonly used to drive paper machines and to power pumps.

Small steam turbines also make excellent generator drives. The best way to take advantage of this technology is to replace pressure-reducing valves (PRV) with small steam turbines. When used in this way, they are commonly referred to as "back-pressure" turbines. Most industrial and institutional steam users produce steam at a higher pressure than is ultimately necessary. At various points in the steam distribution system, the steam is put through a PRV to lower its pressure.

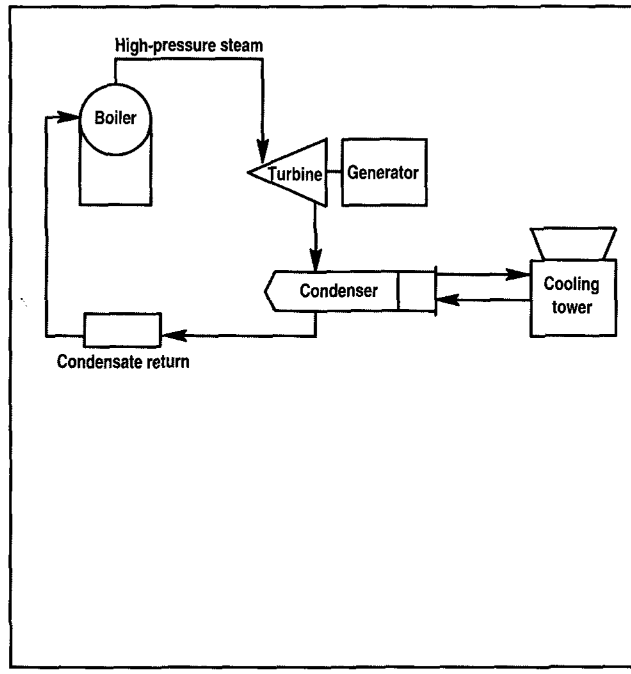
A steam turbine performs the same pressure-reducing function as a PRV and can be used as a direct replacement. Steam enters the turbine

Ewing is president of Ewing Power Systems, Inc., 5 North St., South Deerfield, MA 01373. Di Tullio is a project engineer with Ewing Power Systems, Inc.

1. Back-pressure turbine in cogeneration application. Steam flow through the turbine is controlled by the demand for low-pressure process steam or space-heating steam. Electricity production is determined by steam flow, so more electricity is produced when steam demand is high. All heat not extracted by the turbine is used by the process or heating load.



2. Condensing turbine in straight power generation. Steam flow through the turbine is controlled by electricity demand, since the condenser absorbs all exhaust steam. Turbine exhaust pressure is very low (usually vacuum) to maximize the amount of electricity produced per pound of steam. All heat in the exhaust steam is dissipated in a heat sink, usually a cooling tower.



through an inlet control valve, which is controlled by an external system sensing steam pressure, electric load, or other parameters. The steam then passes through internal nozzles, which direct high-velocity jets of steam toward the turbine rotor. The steam strikes the blades of the rotor, causing it to rotate. After passing through the blades, the steam flows through the turbine exhaust and on to process. The turbine does not consume steam. All the steam entering the turbine leaves through the exhaust. The turbine only reduces the pressure and temperature of the steam.

Figure 1 shows the steam flow in a system with a back-pressure turbine in place to cogenerate electricity. Back-pressure turbine systems are extremely efficient at converting heat to electrical energy. The key to this high efficiency is the fact that energy in the steam flow not used by the turbine remains in the low-pressure-exhaust steam. Except for very minor bearing friction and radiation losses, the turbine only uses as much energy as it converts to mechanical energy. Conversion from mechanical energy to electrical is performed by the generator, which typically operates at 94–96% efficiency. In some systems, there are also speed-reduction-gear losses of about 2%, but back-pressure turbines with induction generators are usually directly driven without a reduction gear.

A complete energy balance for a steam-turbine cogeneration system must also account for other system losses, particularly those in the boiler. Boiler losses occur as the primary fuel is converted to steam and include stack-gas losses, incomplete combustion, heat radiation, and other losses. Modern boilers usually operate at 80–85% efficiency, with some boilers achieving even greater efficiencies. When boiler losses are taken into account, the overall system efficiency of a steam-turbine cogeneration system ranges from 75% to 82%.

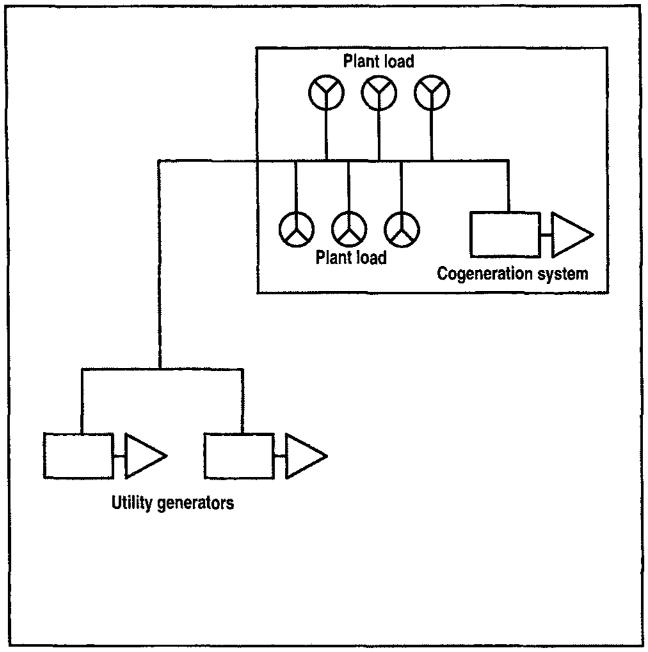
This means that cogeneration with a back-pressure turbine is perhaps the most thermally efficient way to produce electricity. This efficiency also results in very low operating costs, with electricity typically being produced for about US$ 0.012/kW·h. (See appendix at the end of this article.) However, this high efficiency and low cost is obtained only if all the exhaust steam is used for some productive purpose.

Back-pressure vs. condensing turbines

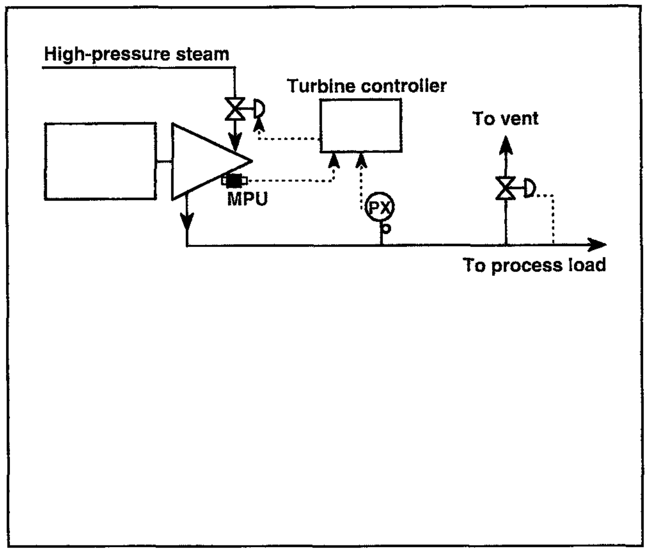
The back-pressure turbines discussed here are quite different from the condensing turbines that are the mainstay of nearly every electric utility in the world and which are commonly used in large pulp mills.

A condensing turbine reduces the pressure of the steam just as a back-pressure turbine does. However, the exhaust pressure is usually very low, well below atmospheric pressure, and as close to an absolute vacuum as the condenser cooling system will permit. Vacuum exhaust pressure enables much more of the energy to be squeezed out of the steam by the tur-

3. Cogenerating in parallel with the utility. In parallel operation, both utility generators and in-plant cogeneration generators are connected to the plant load. As cogeneration system output changes, the amount of power supplied by the utility also changes, so the plant electrical load is always met. The cogeneration system is governed by the plant's low-pressure-steam demand rather than electric demand, thus greatly improving efficiency.



4. Emergency power generation capability. Back-pressure steam turbines can be configured to provide stand-alone power to a plant in cases of utility outage. A synchronous generator and switchgear controls are required, as well as some additional piping. During a utility outage, steam flow through the turbine is governed by electrical demand rather than low-pressure steam load. If electrical demand requires a greater steam flow than is needed to meet process steam loads, the system must be able to vent excess steam automatically. When electrical demand is low, process loads can be satisfied by using the bypass PRV to supplement turbine flow. MPU = magnetic pickup; PX = pressure transmitter.



bine, but it also means that the steam cannot be used for any other productive purpose. Steam pressure and temperature are far too low. **Figure 2** shows the steam flow in a system with a condensing turbine for power generation.

An important advantage of condensing turbine systems is that electrical output is not limited by process steam use. While back-pressure turbines can only generate power in proportion to the demand for low-pressure steam, the condenser in a condensing turbine system forms an essentially infinite heat sink (relative to the turbine steam capacity), so electric demand can be the governing parameter rather than steam demand.

The high inlet pressure and low exhaust pressures typical of utility power plants help boost efficiency, but even the best condensing turbine systems can only achieve total system efficiencies of 30–40%, less than half the overall efficiency of a back-pressure turbine. Utilities are forced to use the lower-efficiency condensing cycle because there are no low-pressure process steam loads large enough to absorb the millions of pounds of steam per hour produced by utility plants.

Interestingly, the very advantage of each system also forms its limitation. Back-pressure turbines are very efficient because the exhaust steam is used for some other productive purpose, but this same characteristic limits their output. Condensing turbines can produce as much power as required regardless of exhaust-steam demands, but they suffer a loss in efficiency because the exhaust steam cannot be utilized.

Assessing cogeneration feasibility

Steam-turbine cogeneration can be an extraordinarily good energy-conservation investment in the right application. However, it is not practical in many applications, usually because insufficient steam flow or steam pressure drops make the system uneconomical. Analysis of economic feasibility is particularly critical because, like most energy-conservation investments, a cogeneration system is not required for production. It can only be sold to management on the basis of payback.

Estimating power production

The first piece of information to be determined is how much power can be produced. This will determine how much electricity can be produced and how much money can be saved.

Design power output is a function of the steam flow and the pressure drop through the turbine. Turbine power output can be estimated in several ways:

- Mollier chart
- Table of theoretical steam rates
- Performance estimates from a turbine vendor.

The Mollier chart is one way of roughly estimating turbine performance under virtually any steam conditions. The chart shows the isentropic energy drop from the inlet steam conditions to the exhaust conditions and enables the user to estimate the total potential energy available. A theoretical steam rate table shows the same information in tabular form, which lists the theoretical amount of energy available when steam is reduced from one temperature and pressure to another.* **Table I** shows actual steam rates for typical steam conditions, including generator and gear reducer losses. When using a Mollier chart or a steam rate table, assume that a single-stage back-pressure turbine will be able to convert 40–60% of the theoretical energy available into electricity. The remaining 60–40% of the theoretically available energy remains in the steam.

While a Mollier chart or steam rate table can be used as a quick reference, neither is particularly accurate. The actual turbine–generator performance is affected by many factors, such as turbine wheel diameter, speed, partial-load performance requirements, and other factors. Furthermore, capital cost considerations may dictate use of a less-than-ideal turbine design. The only really accurate way to account for all of these factors is to obtain performance estimates from a turbine–generator supplier.

Once performance has been determined, electricity cost savings can be estimated. Annual power production can be estimated if good records of steam use are available, since turbine performance is a function of steam flow.

I. Typical steam rates for single-stage turbines, lb/kW·h

Turbine inlet	*Turbine exhaust pressure* *50 psig*	*40 psig*	*30 psig*	*15 psig*
600 psig/650°F	35.4	30.4	26.8	25.1
400 psig/550°F	45.5	37.6	33.1	29.4
300 psig/ D&S*	59.8	48.1	39.7	35.6
250 psig, D&S	67.1	53.7	43.9	36.6
150 psig, D&S	99.2	68.7	53.6	44.0
125 psig, D&S	122.9	79.9	58.3	46.6

Generating potential is determined by dividing available steam flow by given steam rate. Single-stage turbines can handle inlet steam up to 875 psig at 825°F and are capable of exhaust pressures as high as 300 psig. Notice that the power available increases as exhaust pressure decreases.

*Dry and saturated.

Capital costs

Unlike internal-combustion-engine-based cogeneration or other technologies, the capital cost of a single-stage steam turbine is not highly dependent upon system size. Utility switchgear requirements, the length of piping and wiring runs, and the type of generator can affect cost as much as system output. The cost for the turbine, steam controls, switchgear, and other components are almost the same for a 500-kW machine as for a 1000-kW unit.

Complete systems in the 100–1500-kW range, including turbine, generator, electrical interface switchgear, controls, and engineering, usually cost between US$ 80,000 and US$ 300,000, with costs per kilowatt ranging from US$ 150 to US$ 700. Steam piping, electrical wiring, and other installation costs can total as much as the equipment itself.

Operation and maintenance costs

Operating and maintenance costs for a steam-turbine–generator set are usually very low. There is the cost of incremental fuel to produce additional steam (see appendix at the end of this article), and there are maintenance costs.

Single-stage turbines are well known for their low maintenance requirements because of their mechanical simplicity. A turbine is essentially a wheel spinning between two bearings. There are no reciprocating parts, and there is no combustion occurring in the turbine. It is generally fair to assume about 2–3 worker days per year for lubrication, parts replacement, and other maintenance. In addition, steam-turbine–generator sets are designed for a 20-year minimum service life. The low operating and maintenance costs of these machines is confirmed by operating experience with the mechanical drive turbines serving the paper industry.

Electrical considerations

In small steam-turbine cogeneration systems, the generator is usually interconnected with the plant electrical system so that both the utility and the cogeneration system simultaneously feed the complete plant load. **Figure 3** illustrates a system cogenerating in parallel with the utility. As more power is produced by the turbine, less is purchased from the utility. This is in contrast to stand-alone systems, where the generator is tied to specific electrical loads that are isolated from the utility.

Parallel operation is preferred because it allows turbine output to be controlled by steam demand rather than being limited by the demand of a particular load. This maximizes turbine operating efficiency and increases the total power output. In a stand-alone system, the turbine output must be limited to exactly match electrical demands of a particular load.

Another advantage of parallel operation is that the generator can be tied into the plant electrical system at any point where there is sufficient conductor capacity. It is not necessary to bring the generator output back to the main service entrance. The gen-

*Spencer, R.C., Rossettie, P.G., and McClintock, R.B., Theoretical Steam Rate Tables, American Society of Mechanical Engineers, New York, 1969.

Cost of producing electricity

Figure 5 shows the energy flow for a system with a pressure-reducing valve. **Figure 6** shows the energy flow for the same system with a 542-kW back-pressure turbine in place. The cost of generating electricity is obtained by determining the amount of energy extracted by the turbine and then calculating the cost of that heat.

The amount of energy extracted by the turbine is obtained as follows:

Turbine energy = generator output/generator efficiency

Using the example in Fig. 6,

Turbine energy = 542 kW/0.95
= 570 kW·h/h

Kilowatt-hours are converted to Btu to facilitate the cost calculation.

570 kW·h/h × 3413 Btu/kW·h
= 1,945,410 Btu/h

With the energy consumed by the turbine expressed in units of Btu per hour, the cost of the extra fuel needed to generate this heat can be calculated. Assuming natural gas at a cost of US$ 2.75 per million Btu and a boiler efficiency of 82%, the steam cost per million Btu is:

Steam cost per million Btu
= US$ 2.75/0.82
= US$ 3.35

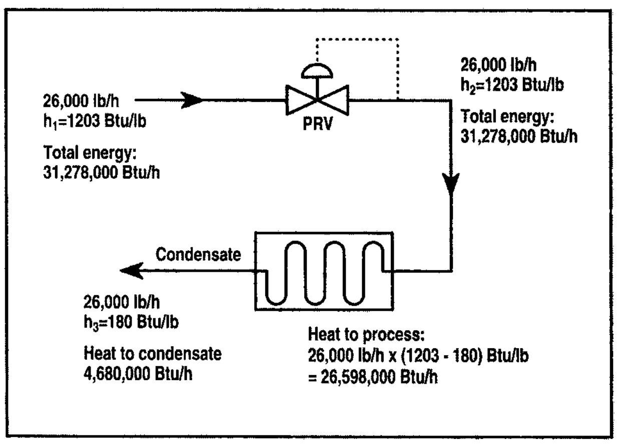
At a steam cost of US$ 3.35 per million Btu and an hourly consumption of 1,945,410 Btu, the hourly fuel cost for generating electricity is:

US$ 3.35/1,000,000 Btu
× 1,945,410 Btu/h
= US$ 6.52/h

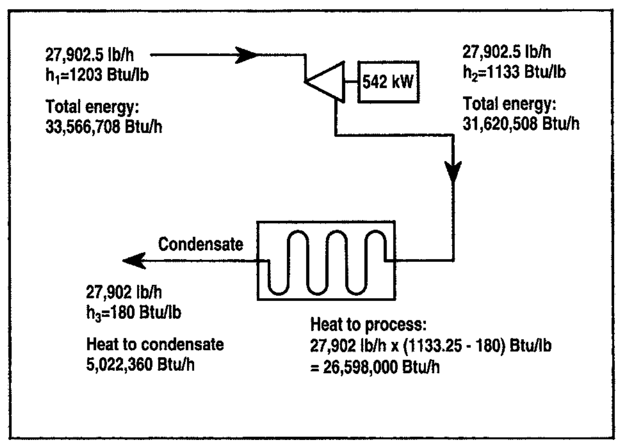
With the hourly cost of fuel known, the unit cost of the fuel used to generate electricity can be calculated.

(US$ 6.52/h)/(542 kW·h/h)
= US$ 0.012 per kW·h

5. System energy flows with a pressure-reducing valve



6. System energy flows with a steam turbine



erator can be interconnected at any nearby distribution panel. Power not used by the local load will travel back through the distribution lines to the rest of the plant.

Parallel operation of the generator also provides greater security, since the utility is instantaneously available to meet all electrical loads if the cogeneration system should go off-line.

Induction and synchronous generators

Generators are available in two designs: induction and synchronous. The two types differ in how they are excited. Induction generators, which are essentially induction motors rotated overspeed by the turbine, are excited by the utility system to which they are interconnected. If the utility system fails, an induction generator cannot operate. Synchronous generators are excited by their own exciter and can be operated in isolation from the utility or in parallel with it.

For most small steam-turbine applications, the induction generator is a better choice. Operation is easier because synchronizing—the process of matching the voltage and frequency of the generator to the voltage and frequency of the utility—is not required. There is no need for a synchroscope, synch-check relay, or automatic synchronizing equipment, allowing the use of less-expensive switchgear.

The fact that induction generators cannot operate without utility excitation also reduces the need for the switchgear to protect the utility. One of the primary concerns that utilities have with cogeneration systems is making sure that the cogenerator will not feed a line they are repairing. Under certain circumstances, synchronous generators can inadvertently feed a utility distribution system fault and create a serious safety hazard for workers trying to repair those lines. Induction generators, in contrast, cannot operate without utility excitation and are therefore safer for the utility and require less protective switchgear.

Despite the increased complexity and cost of synchronous systems, they do have one overriding advantage: Synchronous generator systems can be operated as emergency backup generators, since they have their own source of excitation and do not require utility interconnection to operate. **Figure 4** illustrates the steam flow for a synchronous generator used for emergency power generation.

If saving money and improving energy efficiency are the reasons for installing a cogeneration system, then an induction generator is usually a better choice. If the unit is also to function as an emergency generator or in a stand-alone application, then a synchronous generator must be used.

Summary

Steam-turbine cogeneration is a well-proven, viable energy-conservation technology. Industry is now using hundreds, perhaps thousands, of steam pressure-reducing valves that could be replaced with turbines. The current availability of packaged turbine–generator systems makes them easy to implement, and they can be used to replace pressure-reducing valves in applications with steam flows as low as 4000 lb/h. Based on current prices for gas and oil, these systems can produce electricity for US$ 0.01–0.02/kW·h. System costs range from US$ 200 to US$ 800 per kilowatt of capacity, and simple system paybacks between one and three years are common. TJ

Received for review June 24, 1991.

Accepted March 23, 1992.

Presented at the TAPPI 1991 Engineering Conference.