COMBINED HEAT AND POWER:
EQUIPMENT OPTIONS AND APPLICATION ALTERNATIVES

R. Gordon Bloomquist, Ph.D.
Washington State University Energy Program

ABSTRACT

Combined heat and power (CHP) is the generation of electrical power, mechanical energy, and thermal energy. By fully using the energy available, fuel use efficiency can exceed 80 percent while emissions of air pollutants is significantly decreased. Applications include all forms of industrial processes, commercial and institutional complexes, and single commercial and residential buildings. Generation equipment includes internal combustion engines, combustion turbines, steam turbines, Stirling engines, and fuel cells. Thermal energy is captured through the use of a heat recovery steam generation or, in the case of a steam turbine, extracted at various temperatures and pressures. The thermal energy can be used directly in industrial processes or used for space heating, e.g., district heating. The thermal energy can also be used for cooling. Extracted or generated steam can be used in a steam-driven chiller, absorption, adsorption, or a desiccant system. Storage has also become an important component of many CHP systems and provides increased reliability to both electrical and thermal systems.

INTRODUCTION

Combined Heat and Power (CHP)--alternately referred to as combined cooling, heating, and power (CCHP) and, on a building scale, BCHP, building cooling, heating and power, can be defined as systems that use the same energy source for the simultaneous or sequential generation of electricity or mechanical shaft power (or both) and steam, hot water, chilled water, or other forms of useful thermal energy. CHP systems can provide significant advantages in fuel use efficiency and achieve dramatic reductions in air emissions when compared to conventional generation of electricity where much of the thermal energy is wasted to the environment. CHP systems can result in overall system efficiencies of 60 to 80+ percent compared with the national average of 30+ percent efficiency in conventional thermal electricity plants. In addition, CHP generated electricity on-site avoids transmission and distribution losses, provides high-quality, reliable power, and serves to reinforce the electricity transmission and distribution systems. CHP can also offer cost savings, price stability, and a competitive advantage to those who install it.

Recent advances in technology and a number of emerging technologies are making CHP an increasingly attractive option for applications that range in size from multi-hundred MWe industrial sites to a few tens of kWe for single buildings. Recent advances in generation technologies such as combustion turbines, internal combustion engines, fuel cells, and heat recovery equipment, as well as absorption and adsorption and desiccant cooling technologies, have decreased the cost and improved the performance of CHP systems. Unfortunately, despite increasing interest in CHP, the focus of most projects continues to be on electrical production and electrical generating equipment. The goal of this paper is to provide the reader with not only information relative to the broad range of electricity-generating equipment that is now available or is likely to become available in the foreseeable future, but to introduce in some detail thermal equipment and, in particular, options for cooling.

ELECTRICAL GENERATION EQUIPMENT

Electrical generating equipment now spans the spectrum of desired installed capacity from a few tens of kWe to several hundred MWe. Generating equipment includes: steam turbines; internal combustion engines, including both spark ignition (otto cycle) engines and compression ignition (diesel system) engines; combustion turbines; combined cycle combustion turbines; Stirling engines, and fuel cells.

Steam Turbines

Steam turbines were the first commercially successful thermal electrical generation technology and continue to dominate both utility and industrial electrical generation. Fuel is burned in a boiler to produce steam that drives a steam turbine that in turn drives the generator. Thermal energy can be extracted from the turbine in the form of steam (back-pressure steam turbine) at various pressures, depending upon need, or hot water can be generated from a lower pressure back-pressure extraction point or from the condensing cycle. Because of the nature of the boiler, almost any fuel can be used including, for example, coal, oil, natural gas, propane, biomass including municipal waste, land fill or digester gas, and byproduct fuels. Steam turbines range in size from a few kWe to a 1,000 or more MWe. Cost is fairly low, ranging from $350 to $1,000+ per installed kWe. Steam turbines continue to be applied in numerous industrial applications, and in many district energy applications that serve colleges and universities, military bases, downtown business districts, hospitals, correctional facilities, and airports. In many of these applications, steam production for non-electrical applications is the primary function of the system with a steam turbine being used as a pressure reducing device. This is especially common on many college and university campuses and/or some military installations where, for example, higher pressure steam is reduced to lower pressure (15-200 pounds) before it enters the steam distribution system. Many, if not most of these systems could be upgraded to produce significantly more electricity while still using a very high percentage of the thermal energy available. For example, Washington State University has upwards of 300,000 pounds per hour of peak demand for steam but produces only 2 MW of electricity at the present time. Recent analyses indicate that between 40 and 70 MWe could be produced and still maintain a fuel use efficiency of between 70 and 60 percent.

Internal Combustion Engines

There are three types of internal combustion engines commonly used in CHP applications: industrial gas engines, automotive-derived gas engines, and diesel engines. Sizes start at about 25 kWe output and can exceed 10 MWe. Multiple engines can be applied in larger systems with the additional benefit of increased availability.

The most popular fuel for internal combustion engines-based CHP systems is natural gas and is usually used in a spark ignition gas engine that can be of either an automotive derivative or an industrial type.

Diesel engines are also widely used and may be diesel/gas duel fuel. Internal combustion engines can usually be installed for a cost of between $300 and $900 per installed kWe.

Industrial Engines

Industrial engines are heavy, rugged, stationary types that have been developed for the purpose of providing reliable power with very low maintenance costs. They are built with large bearing surface areas for low wear and are constructed for ease of maintenance. Both spark ignition and diesel types are available. Output generally ranges from 150 to 200 kWe, but some units are available up to several MWe. They are ideal for applications where reliability is paramount as in areas where grid electricity is not available. Life expectancy can exceed 50,000 hours.

Automotive-Derived Engines

Automotive-derived engines are widely used in CHP applications up to approximately 200 kWe. These engines are based on de-rated and modified truck engines converted to run on natural gas and/or propane. Engine life, when measured against that of its automotive parent, is extended as is the interval between servicing. This is achieved primarily by running the unit at a constant speed (generally under 1,500 rpm) under steady state conditions. Engine life is, however, shorter than is the case with industrial engines and ranges from 20,000 to 30,000 hours prior to a major engine overhaul, but with a longer lifetime for larger units.

Diesel Engines

Diesel engines are available in sizes ranging up to 10 to 15 MWe and are particularly well-suited to baseload operation. Medium speed (500-600 rpm) super/turbo-charged compression ignition engines having an electrical output of 5 to 15 MWe are ideally suited to many CHP applications. A turbo-charged engine produces higher exhaust temperature over the load range and gives higher efficiency under part load conditions than a normally-aspirated engine.

The heat rejected to exhaust and jacket is almost constant between full load and half load, and the power generation efficiencies are also more constant at peak load. As with other internal combustion engines, heat can be recovered from the exhaust gases, engine jacket cooling water, the lubricating oil cooler, and, if super-charged or turbo-charged, from the air inter-cooler. This increases the overall efficiency from 36 to 38 percent for generation only to as high as 90 percent if all the heat rejection sources are collected to a secondary circuit distributing heat at no more than 90ºC. Heat recovery is maximized if the return water is low enough to recover heat from the turbo-charger after-cooler. Supplementary firing can be utilized to give flexibility in operating mode and unscheduled operation.

Internal combustion engines up to about 10 MWe are ideally suited to CHP and are often preferable to a gas turbine plant provided that the return temperature from the thermal distribution system is low enough to maximize heat recovery. Because of this low temperature, hot water systems (<120ºC) are the logical choice for distribution. Large diesel engine CHP systems are commonly found in smaller colleges and universities, hospitals, correctional facilities, and in industrial applications where the availability of large amounts of steam is not a major consideration.

A fairly unique, but highly replicable application of a large compression ignition engine system in a CHP application is in Fredricshavn, Denmark. The engine drives a large water-source heat pump that is used to extract heat from the city's sewage effluent system. The heat from the heat pump, together with heat recovered from the engine, is provided to the city's district energy system. The engine also drives a generator coupled to the same shaft as the heat pump providing electricity to the sewage treatment facility.

Gas Turbines

Gas turbines are the fastest-growing technology in the CHP arena. Advances in everything from micro turbines, mini turbines, and up through the large frame units, have made gas turbines the technology of choice for everything from small commercial installations, e.g., 30 to 60 kWe, to major industrial applications, e.g., 50 to 300+ kWe, in the pulp and paper, wood products, petroleum, chemical, and steel industries. A gas turbine is a heat engine that uses a high-temperature, high-pressure gas as the working fluid. Part of the heat supplied by the gas is converted directly into the mechanical work of rotation. In most cases, the hot gases from operating a gas turbine are obtained by combustion of a fuel in air. Thus the name combustion turbine. After passing through the turbine, the exhaust gas at 350+ to 500ºC is routed to a heat recovery steam generation (HRSG) where the heat is recovered. The steam produced may be routed to a steam turbine to generator additional electricity (a combined cycle system) or the steam and/or hot water can be used for industrial purposes or to supply a district energy system directly or converted to cooling through absorption for provision of cooling. Gas turbines and waste heat recovery boilers compete against internal combustion engines in small scale CHP applications, i.e., <15 MWe, and against steam and combined-cycle units in large scale applications.

Micro Turbines

Micro turbines are one of the latest technologies to hit the CHP market place and appear to have a very promising future for small to medium-sized commercial and industrial facilities, institutions, and multi-unit residential complexes. Units generally range in size from 25 to 200 kWe, but some manufacturers are evaluating niche markets up to 1 MWe. Microturbines appear to be very attractive in such applications due to high reliability, low emissions, especially NO_X, high potential for waste heat recovery, quiet operation, ease of installation, fuel flexibility, and automated operation. However, efficiency is relatively low for electrical only applications, e.g., <28 percent, but when coupled with waste heat recovery and even cooling operations, fuel use efficiency can easily exceed 75 percent. Cost is also a factor with the present cost per installed kWe exceeding $1,250. However, with increased production, costs are expected to fall substantially, and manufacturers are targeting an installed cost of $350 to $800/kWe installed. Installation of multiple units to meet large capacity demand increases reliability and availability to critical facilities such as law and justice centers, hospitals, banks, etc. Microturbines can also provide back-up power or peak shaving.

Z 7Small Gas Turbines

Small gas turbines hold only a relatively small percentage of the market in the 1 to 10 MWe range (15-25%)(4) and 33 to 50 percent of the market between 10 to 20 MWe in relationship to their chief competition, internal combustion engines. Electrical efficiency for small gas turbines range from 23 percent (LHV) for the small units to about 30 percent (LHV) for a unit of 7 MWe. However, with heat recovery, overall efficiency can exceed 75 percent(4). One major advantage of gas turbines in this size range is that some companies will provide a packaged integrated unit including the turbine, synchronous generator, combustion air filtration system, exhaust, fuel system, turbine controls and alarms, and electrical switch gear, as well as highway-transportable trailer and an acoustic enclosure. Packages are factory tested and are delivered ready to operate. The heat-recovery steam generators (HRSG) are standard design to match with the individual turbines(4). Installed cost is <$1,000/kWe and may be closer to $500/installed kWe for larger units. Applications include industrial facilities, airports, colleges and universities, etc., where a requirement for high-temperature steam makes internal combustion engines with their low-temperature thermal output less applicable.

Large Gas Turbines

Large gas turbines ranging in size from ca 15 MWe to well in excess of 250 MWe have dominated the electric utility, independent power, and industrial CHP industries for the past several years. Advancements in technology that have enhanced the efficiency of both aeroderivative and frame units, and abundant supplies of inexpensive natural gas have both contributed to making large gas turbines the technology of choice. Although many of the installations are simple cycle or combined cycle plants without thermal applications, many are also used in both industrial and large institutional CHP systems. While some combined cycle plants approach 60 percent efficiency, 70 to 80 percent efficiency is common in CHP applications. Cost per installed kWe is highly variable and appears to depend upon both size of the installation, difficulty of integrating into the existing infrastructure, and degree of flexibility required by the thermal host. While several industrial applications in the 80 to 500 MWe range all came in at from $500 to $600+/installed kWe, a number of institutional projects ranged from approximately $1,000 to a high of $1,700/installed kWe.

EMERGING GENERATION TECHNOLOGIES

Fuel Cells

Fuel cells are one of the exciting emerging technologies that is likely to play a major role in future CHP application. They generate electricity through an electrochemical process in which the fuel is converted to electricity, producing almost no air emissions. Fuel cells work with the movement of ions across the electrolyte when air and fuel (hydrogen) are supplied. The oxygen in the air is ionized at the cathode and oxygen ions flow through the electrolyte to the anode where the fuel (hydrogen) is oxidized to water. In the process, electrons are released and, if the anode and cathode are connected to an electrical circuit, the flow of electrons produces DC current. The reaction continues so long as fuel and air are supplied to the cell(1). Heat is a byproduct of the chemical reaction and can be recovered in much the same way as with combustion-based systems. There are three main components: a hydrogen reformer that extracts hydrogen from a fuel source, e.g., natural gas, methane, etc.; a fuel cell stack where the electrochemical process generates DC power; and an inverter that converts DC output to AC power.

There are several types of fuel cells including PEM, proton exchanger membrane; PAFC, phosphoric acid; SOFC, solid oxide; and MCFC, molten carbonate. PEM and PAFC operate at relatively low operating temperatures, e.g., <200ºC, while MCFC and SOFC operate at much higher temperatures: 600 to 650ºC and 800 to 1,000ºC, respectively. Although MCFC and SOFC operate at much higher temperatures, a great deal of the heat is often used in the fuel reforming process and is not available to meet on-site thermal applications. Of the four, the phosphoric acid fuel cell is the only one to have entered the commercial CHP market. The others are still in various stages of development and demonstration.

The biggest advantage that fuel cells offer are reduced air emissions and, in particular, criteria pollutants; high electrical efficiency (35 - 60%); and high availability. Cost is, however, a major concern and although phosphoric acid fuel cells have been available commercially for several years, the cost per installed kWe is still ca $3,500. Demonstration projects with molten carbonate fuel cells are in excess of $15,000 per installed kWe. Manufacturers are, however, convinced that the cost of fuel cells can be reduced to $1,500 or less per installed kWe, making them competitive with other technologies. Today's manufacturers have concentrated on units from a few kWe to 1-2 MWe output, but larger units may become available at some point in the future and, of course, multiple fuel cells could be integrated into a single system.

Today, the 200 kWe ONSI phosphoric acid fuel cell is the only commercially available system for CHP application. The ONSI skid-mounted containerized package unit is capable of producing electricity at ca 40 percent (LHV) and thermal energy with a total overall system efficiency of 80 percent. When fitted with an optimal double-walled heat exchanger, this ONSI unit can produce 350,000 Btu/hour of 121ºC hot water and 350,000 Btu/hour of 60ºC hot water.

Hybrid fuel cell systems are also being seriously looked at and include the coupling of a fuel cell with a gas turbine. By coupling a high-temperature (molten carbonate or solid oxide) fuel cell to a gas turbine, it is possible to produce electric power at an efficiency that is higher than would be possible with either technology alone. It is estimated that an electrical efficiency as high as 65 to 75 percent may be achievable.

Fuel cells appear to be ideally suited to applications where highest possible reliability is a major consideration. To date, many applications involve installation where the economic consequences of power interruption can be catastrophic or where security of operation is paramount. For this reason, bank, credit card processing facilities, law and justice centers, hospitals, sewage treatment facilities, and military installations are all prime marketing targets.

Stirling Engines

Stirling engines are another technology that continues to receive considerable attention by developers, but most of the emphasis has been on very small applications of less than ca 0.5 kWe to 25 kWe aimed primarily at the residential and small commercial markets.

The Stirling engine, being an external combustion machine, has a number of advantages over a small, internal combustion engine in terms of reliability and performance, and ultimately should cost somewhere between the spark and compression ignition internal combustion engine(3). In some applications, a 3 kWe Stirling engine achieved a 95 percent overall conversion efficiency.

Stirling engines fall into two general categories: kinematic and free-piston engines. In kinematic engines, the pistons that move the working fluid through the thermodynamic cycle are connected to rods and crank shafts. Power is available in the form of rotary motion of the crank shaft, typically connected to a generator. The free-piston machine, on the other hand, operates on the same thermodynamic cycle, but the rotary motion is replaced by linear oscillation. The pistons move through their cycle connected to a linear alternator, so the system moves only along a single axis. Support is provided by planar springs and clearance gaps are maintained by gas bearings(4).

One of the most attractive features of the Stirling engine is that it can run on any number of heat sources including natural gas; landfill gas; digester gas; coal bed methane; light crude oil; diesel, kerosene; gasoline; fuel oil; waste heat from furnaces, boilers, and combustion turbines; and even solar thermal energy. They can also tolerate much dirtier, contaminated, and unrefined fuels than can be used in an internal combustion engine or a combustion turbine since the fuel is burned outside the cylinder. There are also major environmental advantages including very low emissions because the fuel can be combusted more fully, waste heat can be economically captured increasing fuel use efficiency, and they operate extremely quietly.

Stirling engines have significant application potential for use in oil and gas refineries, on off-shore oil drilling and production platforms, at sewage treatment plants, restaurants, laundries, hotels, and nursing homes.

Because to date almost all Stirling engines have been part of production development and demonstration exercises, little data on operation experiences or cost is available

STORAGE

There is an increasing emphasis and concern about reliability and power quality. Many high tech firms are requiring seven, eight, and even nine nines of electrical system reliability, and high tech commercial as well as industrial complexes require technologies to condition the power against voltage spikes and surges—the so-called clean nines. For many high tech firms, the cost of down time can exceed several million dollars per hour. Although CHP can provide an increased level of reliability, in order to reach reliability in the high nines, as well as provide clean power, compressed air storage, fly wheels, motor generators, and batteries, are all finding increased applications and must be looked at as technologies designed to complement CHP systems where highest possible reliability and/or power quality are a must.

HEAT RECOVERY

For combined heat and power applications, various amounts of heat or thermal energy may be extracted or recovered from the engine, turbine, or fuel cell for heating and/or cooling purposes, depending upon the technology employed. With a back pressure steam turbine, steam may be extracted directly from the turbine at a single or at multiple pressure. In the case of a condensing turbine, thermal energy may be recovered as part of the condensing cycle.

With internal combustion engines, combustion turbines, fuel cells, and Stirling engines, thermal energy is recovered through the use of heat exchangers or a heat recovery steam generator (HRSG) designed to recover thermal energy at specified temperatures and flow rates to meet the objective of the heating and/or cooling applications. An important consideration is that as the required temperature increases the quantity of energy available at the temperature decreases. In order to maximize heat recovery, it may be desirable or even necessary to use multiple heat exchangers capable of recovering thermal energy at two or more temperature levels. Although heat recovery systems are usually designed to provide steam for industrial processes or to feed district energy networks, thermal energy in the form of hot water may be a viable alternative for many heating applications. For example, in district energy applications in Europe, hot water is the preferred heat transfer medium and dominates the district energy industry. The recovery of steam or high-temperature hot water is necessary for cooling applications.

Many heat recovery systems incorporate supplemental firing in order to boost steam temperature and pressure as a means of meeting peak thermal demand, as in the case of a district energy application. Supplemental firing also allows for the thermal demand to be met in cases where the engine or turbine is unavailable.

Thermal Storage

Thermal storage may also be an attractive addition to a heat recovery system. Such systems may be designed for diurnal or seasonal storage. Water is by far the most common diurnal storage medium, and is an integral component of many hot water-based district heating systems in Scandinavia and Europe where the primary purpose is to help meet peak demand. Water is also used as the storage medium for seasonal storage systems and although few such systems have been implemented, they would appear to have significant potential where large amounts of waste heat are available from industrial sources or from a CHP facility where there is little opportunity or need for thermal use during the summer months.

Other diurnal storage mediums include oil/rock and molten salt. Both can be used to store significant amounts of heat at high temperature for use for either thermal applications, including steam generation or for additional electrical generation. Solar Two, for example, uses molten salt to level out electrical generation from the experimental solar thermal facility.

There are two primary reasons for implementing thermal storage in conjunction with CHP. The first is to minimize fuel use in peaking boilers and the second is to enable the CHP plant to maximize electricity revenues.

In the case of extraction/condensing steam turbines, the thermal storage is used to supply heat during periods when the electricity price is high, allowing the turbine to run at maximum power without extraction. With gas turbines or internal combustion engines, the surplus heat is stored for use at night when electricity prices make it uneconomic to run the CHP plant.

COOLING TECHNOLOGIES

The thermal energy available from CHP systems can often be used to provide cooling at a significant cost advantage compared to using that same thermal energy for heating. While use of thermal energy for heating most often replaces coal, oil, or natural gas, the use of the same thermal energy for cooling generally replaces much higher value and cost electricity.

Steam-driven chillers have found considerable use in many applications where steam is underutilized during the cooling period. This is especially true of institutional complexes, e.g., colleges and universities, hospitals, correctional facilities, etc. In many such applications, the production of chilled water with steam-driven chillers not only reduces electrical demand but frees up additional kilowatts for sale during peak price periods.

Absorption and adsorption chillers as well as desiccant dehumidification equipment provide other alternative technologies for thermally-based cooling.

Absorption Systems

Absorption systems utilize the ability of liquids or salts to absorb the vapour of the working fluids. In absorption systems, compression of the working fluid is achieved thermally in a solution circuit which consists of an absorber, a solution pump, a generator, and one expansion valve. Low-pressure vapour for the evaporation is absorbed in the absorber. This process generates heat. The solution is pumped to high pressure and then enters the generator where the working fluid is boiled off with an external heat supply at a high temperature. The working fluid (vapour) is condensed in the condenser while the weak solution is returned to the absorber via the expansion valve. The most common working pairs are NH_3/water and water/LiBr(5).

Widespread application is primarily in large commercial buildings and institutions such as colleges and universities, hospitals, etc. Units are available for a few kW to 9,000+ kW.

Both single and double effect units are readily available. Triple effect units are also available, but less common. Double and triple effect units require higher temperature than single effect units which operate effectively at temperatures at or above 120°C(5).

Work is, however, progressing on low-temperature adsorption units that work in the 55 to 100°C range. These units using a silica gel/water system could significantly expand the use of adsorption technology(2).

DESICANT DEHUMIDIFICATION SYSTEM

Actively regenerated desiccant dehumidification systems increase moisture removal, as well as provide for independent temperatures and humidity control. A desiccant material naturally attracts moisture from gasses and liquids. This material becomes saturated as moisture is absorbed, but when heated the desiccant dries out, or regenerates, and can be used again. Conventional solid desiccants include silica gel, activated alumina, lithium chloride salt and molecular sieves. Titanium silicate and synthetic polymers are new solid desiccant materials designed to be more effective for cooling aplications. In most systems, a wheel containing desiccants continuously dehumidifies outside air entering the cooling unit. The desiccant is then regenerated. Such systems not only remove moisture effectively but at the same time reduce electricity use and lower elctricity peak demand. This is especially true when heat recovered from a CHP system is used to reactivate the desiccant material. A desiccant system can also supplement a conventional air-conditioning system. The desiccant removes the humidity load while the evaporator of the air conditioner lowers the air temperature.

One of the principal factors in the commercialization of desiccant technology is a growing requirement for improved air quality. It is estimated that poor air quality directly results, on an annual basis, in $1 billion in medical costs and $60 billion in employee sick leave and lost productivity. In addition, indoor air quality litigation increases every year; these lawsuits have commanded hefty settlements. Businesses as well as building owners are now faced with the responsibility of adhering to even more stringent standards related to providing a safe work environment. Increasing ventilation and reducing moisture improves the perceived air quality and the productivity of office workers while decreasing sick building symptoms. Desiccant technology can play a key role in achieving better air quality, and at the same time play a significant role in reducing energy demand. Desiccant technology could also play a role in the replacement of today's chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) vapor compression systems.

Thermal Storage

Thermal storage has become an integral component of many cooling systems. Storage takes the form of water, brine, ice slurry, ice, or eutectic salt. Storage may be full or partial, and provides a cost-effective means to meet peak cooling demand.

Storage has also become a key component of many combustion turbine systems with the chilled water or ice storage being used for cooling incoming air, thus increasing electrical generation capacity.

When storage is integrated into the overall design of a building and not simply an element of the HVAC system, it can result in significant reduction in overall cost while at the same time allowing for additional leaseable space.

SUMMARY

Combined heat and power systems are becoming an increasingly attractive means of providing on-site power, meeting thermal requirements, increasing reliability, and improving overall fuel use efficiency. Advancements in conventional equipment and the commercialization of emerging generation technologies has provided a broad range of equipment types and sizes designed to meet the needs of commercial, institutional, and industrial facilities of all sizes.

Thermally-activated chilling, often coupled with thermal storage, further increases the benefits of CHP by decreasing peak demand or by allowing increased power production during peak demand periods.

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ABOUT THE AUTHOR

R. Gordon Bloomquist is an internationally-known district energy specialist, dealing with geothermal, CHP, and various other forms of district energy. He has been with the Washington State University Energy Program since 1979 as the Principal Investigator for the district energy and geothermal programs. If you would like to reach Dr. Bloomquist, his phone number is (360) 956-2016, his fax number is (360) 956-2030, and his e-mail address is bloomquistr@energy.wsu.edu.