Distributed Energy

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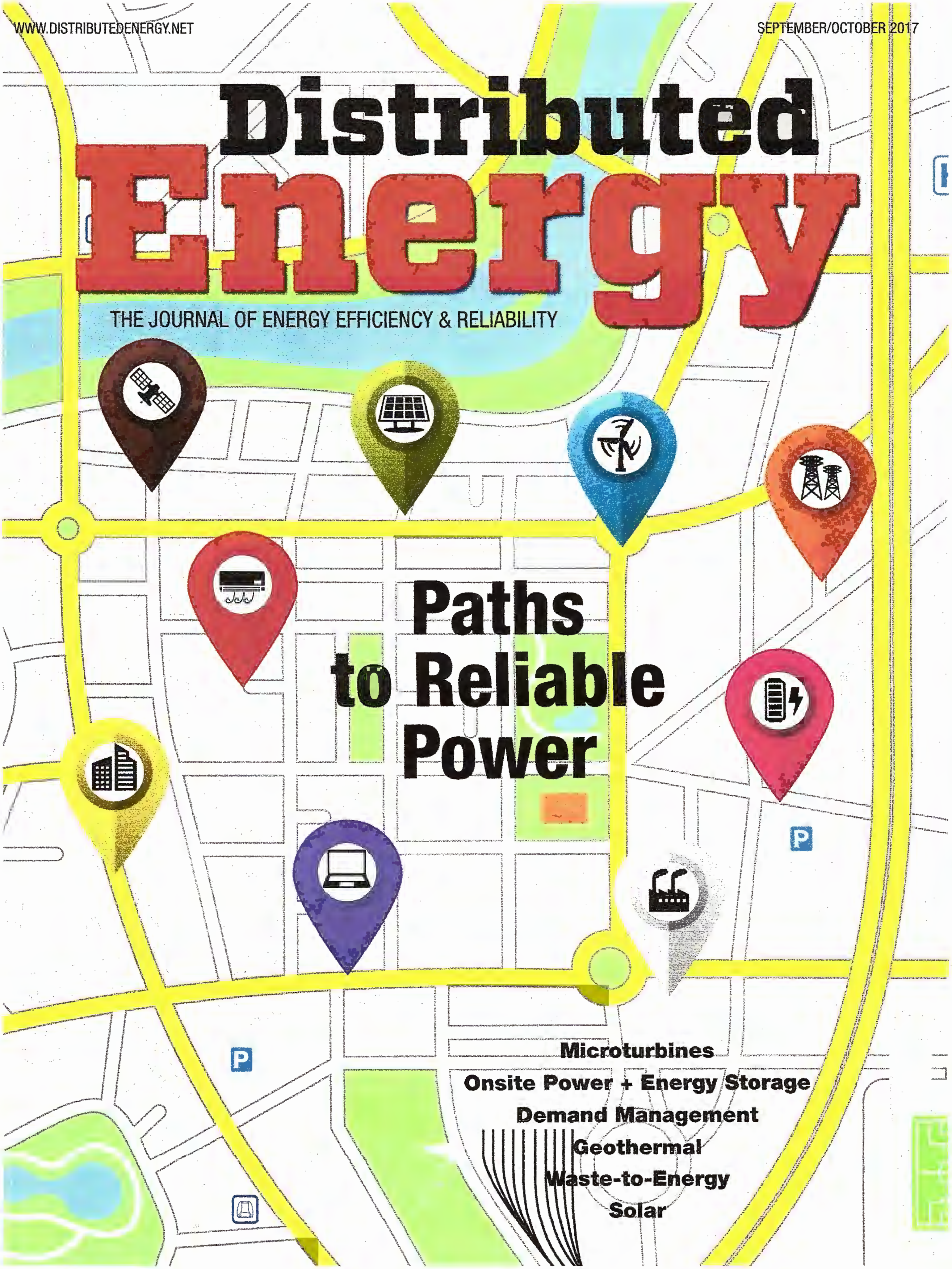

Paths to Reliable Power

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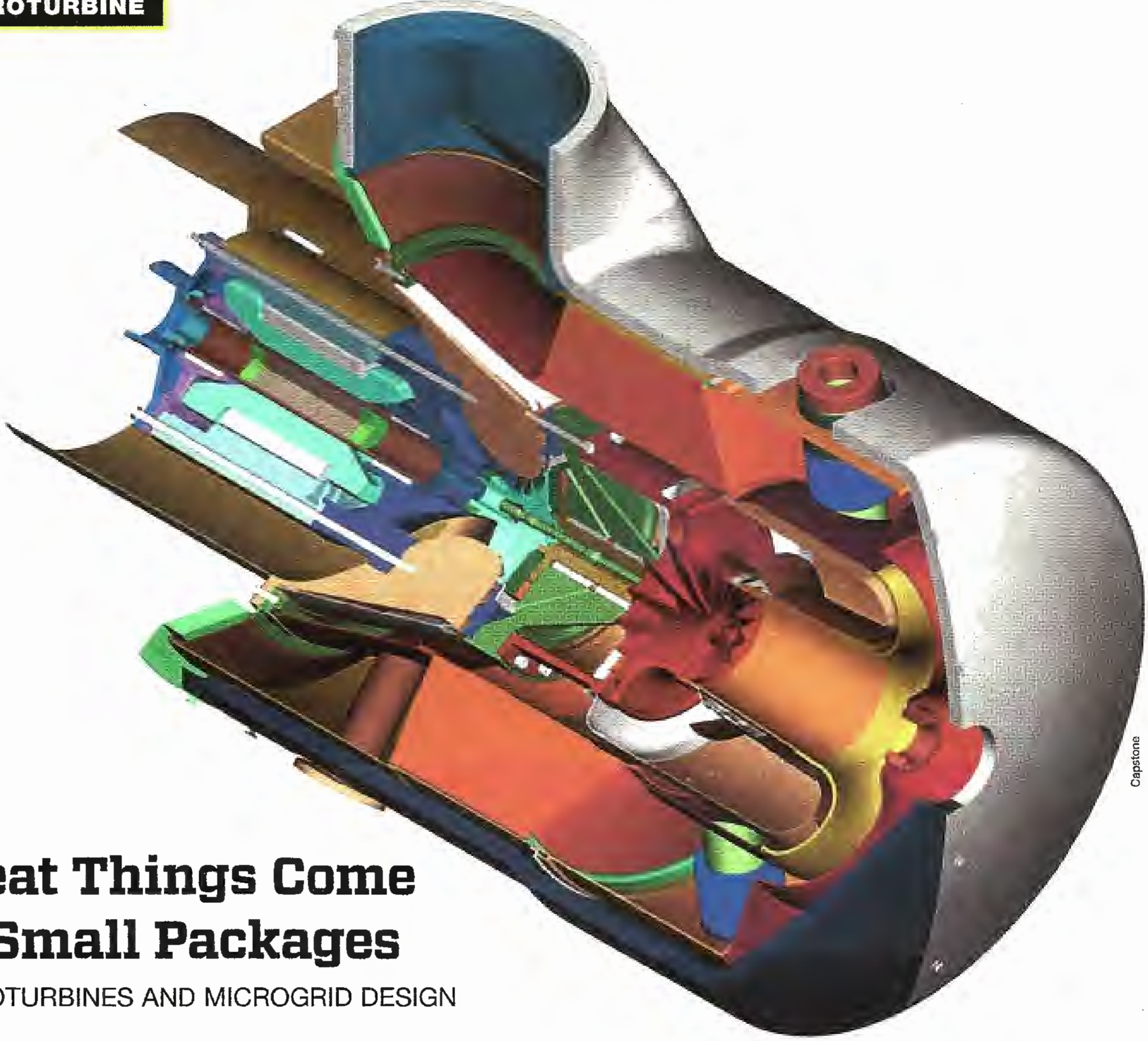


Great Things Come in Small Packages

MICROTURBINES AND MICROGRID DESIGN

BY DANIEL P. DUFFY

The famous saying "smaller is better" is not necessarily true. A more accurate statement would be that "appropriate scale is better." This brings us to the use of microturbines and their appropriate applications. Micro turbines are not actually tiny; they are still relatively large and powerful machines. But compared to industrial and commercial scale turbines they are small, compact, and very useful for confined space applications. They are also applicable for small-scale utility power applications such as individual businesses, residential buildings, small industrial facilities, college campuses, and microgrids. It is this last application that microturbines are finding their latest and fastest growing use, and their most wide spread application.

Basic Turbine Operation

A turbine is a machine that translates chemical energy into heat energy, then into kinetic energy, then into mechanical energy, and finally into electrical energy. Physically, it consists of a housing that contains a rotating axle fitted with angled vanes. A working fluid or gas (water, steam, a gas such as CO2, or simple air) impacts the vanes at it flows through the turbine causing the axle to rotate. As it rotates, it spins an attached wheel or rotor.

The chemical energy consists of the potential energy sequestered in the chemical bonds of the fuel (coal, oil, natural gas, or nuclear reactor core) used to heat or create the working fluid that spins the turbine. Igniting the fuel (or making the nuclear fuel go critical) generates the heat energy released by the chemical reaction. This heat energy is used to expand the working fluid (turning water into steam, for example), creating the kinetic energy that causes the fluid to flow through the turbines. This, in turn, generates mechanical energy in the form of a spinning axle and rotor. And lastly, the bundled coils of wire in the spinning rotor spin in a magnetic field, creating electrical current and electrical energy.

Turbines can vary in size from the relatively small microturbines mentioned above to huge hydro-electrical power dam turbines. Their power output can vary greatly as well with microturbines generating power in the 25 kW to 500 kW range and up. Standby backup generators produce lesser amounts of electrical energy. At the other end of the power spectrum are the hydroelectric dams whose power output ranges from 2,080 MW generated by the Hoover Dam (the world's first large-scale hydroelectric dam) to the recently completed Three Gorges Dam with its 22,500 MW capacity. Large or small, all turbines operate in accordance with the Euler Turbine Equation:

$$\mathbf{T} = \mathbf{rho} * \mathbf{Q} * (\mathbf{r}_{in} * \mathbf{V}_{in} - \mathbf{r}_{out} * \mathbf{V}_{out})$$
$$\mathbf{P} = \mathbf{w} * \mathbf{T}$$

Where:

- Q = fluid flow rate
- rho = fluid density
- q = fluid flow velocity
- beta = incidence angle
- V = tangential fluid velocity, V = q cos(beta)
- r = turbine radius (r in and r out)
- w = turbine rotational speed (RPM)
- T = torque
- P = power output

A gas generator consists of the following components connected by a drive shaft: compressor module, fuel injection ports, combustor unit, and the actual turbine. Similar in operation to that of a jet engine, a turbine intakes air into a compressor module where the air is compressed and then mixed with fuel (typically natural gas). The fuel and compressed air mixture is then ignited to create an expanding mass of rushing hot air. The hot gas passes through the turbine, impacting on, and spinning, the blades. This applied force rotates the axle drive shaft and generates electricity. The connection of the drive shaft to the generator shaft is accomplished either directly or via a gear box. The gear box allows for a variance of the electrical frequency between 50 hertz and 60 hertz. Given the high operating temperature of the hot gas (2,200 to 2,900°F) the blades are cooled with air flow introduced via small openings.

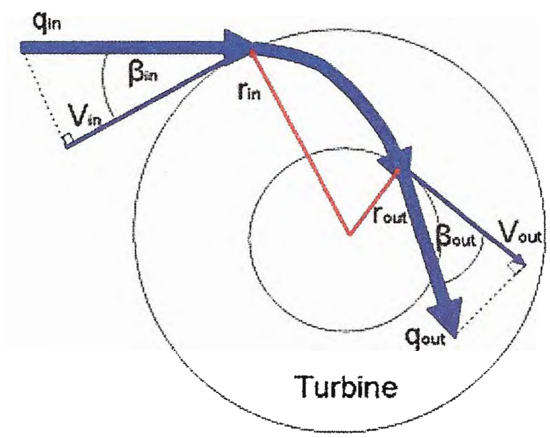
Turbines can achieve superior operating efficiencies with a combined cycle system. A gas turbine can generate an additional 50% more electricity by recapturing its waste heat. The hot gasses that pass through the turbine and spin the vanes are typically vented out the other end. In a combined cycle system, the waste heat is captured by the heat exchanger. This heat is then used to flash steam to run a second steam turbine and a second operational cycle. Afterwards, the steam is condensed back into water, recycled, and use again as steam to run the second generator.

What Makes Microturbines So Different? (It's Not Just Their Size)

Microturbines are commercially available power generators with a range from 25 kW to 500 kW. They usually use natural gas, hydrogen, propane, gasoline, or diesel as a fuel source. Given their small size (about the size of a refrigerator) and superior efficiency, their rate of pollution exhaust is relatively low, with NOx emission less than 9 ppm. They can also be configured to increase overall operational efficiency via cogeneration. This is performed by a recuperator (a sheet metal heat exchanger) which captures waste heat and uses it to improve the efficiency of the compressor stage. Typically, the hot exhaust is used to heat water to temperatures ranging from 125°F to 175°F (50°C to 80°C). Originally used as turbochargers for ground vehicles, and as auxiliary power units for aircraft, their use has expanded to fill a much-needed operational niche. Being roughly the size of a refrigerator, microturbines are typically used in applications where size constraints are as important as flexibility of operations.

The various types of microprocessors on the market are defined by the arrangement of their components. There are several different types of configurations: bearing configuration (oil or air), inter-cooled and reheat systems, split-shaft for machine drive applications, recuperated CHP, or simple unrecuperated single-cycle, single-shaft, or two-shaft. Rotation speed for most microturbines is typically more than 40,000 rpms with typical design speeds of 90,000 RPMs to 120,000 rpms. Cycle turbines are simple to operate, have lower capital costs, and lower operating and maintenance costs, but have lower efficiencies of only 15%. Though more expensive to run, recuperated systems can achieve up to 85% fuel efficiency from the recapture of waste heat. The materials used in their construction are also unique with extensive use of heat resistant ceramics.

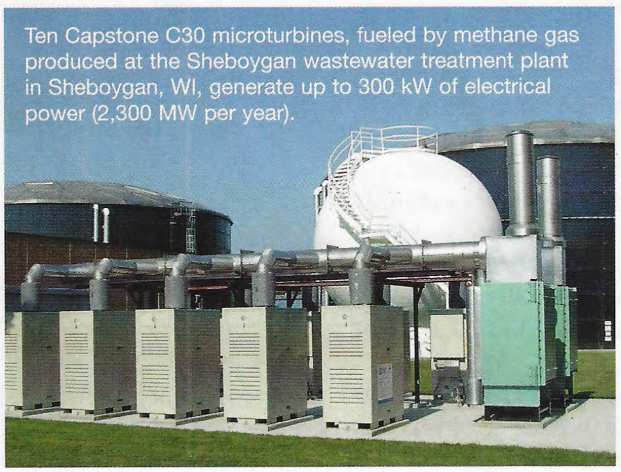
Euler's Turbine Equation



Microturbine Applications and the Advantages of Utilizing Microturbines

There are several unique operational characteristics of microturbines. They are especially useful in distributed generation situations as stand-alone power sources. These can be both as emergency backup power supplies and in remote onsite applications far removed from power grids. Given that they are the last resort for power users, they have to provide quality reliable electrical power to manage surges and dips in the general power supply, complete cut off of the grid power system, and all sorts of disruptions due to weather or equipment failure. Though most obviously used during power outages, microturbines are mostly used for peak shaving to reduce grid dependence when power usage spikes. Consumers located at the remote edges of the grid can also benefit from local microturbines that boost power to compensate for distance from the main power source. Microturbines also lend themselves to ultra-efficient combined heat and power (CHP) application, which re-utilize waste heat for thermal operations. Lastly, microturbines can often be the low-cost alternative when produced locally for facilities and customers.

Microturbines have both strengths and weaknesses that the system designer has to take into account. Microturbines have easier maintenance and less expensive repairs (with longer intervals between maintenance events) since they utilize fewer moving parts. Most systems have maintenance intervals targeted between 5,000 to 8,000 hours, with an industry standard of one maintenance cycle per year. They have a compact size that utilizes minimal volume, making them suitable for small space availability applications. Their light weight allows for installation in structures that do not require excessively strong structural foundations. They can utilize waste fuels or alternate fuels and produce lower emissions. They generate fewer vibrations and less noise, reducing the need for foundation reinforcement and active noise abatement measures. Visually, the use of microturbines can result in superior aesthetics. They remove the need for overhead power lines and massive power towers.



Ten Capstone C30 microturbines, fueled by methane gas produced at the Sheboygan wastewater treatment plant in Sheboygan, WI, generate up to 300 kW of electrical power (2,300 MW per year).

On the negative side, microturbines have a relatively low operational fuel efficiency, that is, they tend to generate fewer kWh per gallon of fuel. They also experience power losses when operating in environments with higher ambient temperatures or at high elevations.

Indirect advantages are also incurred from the use of microturbines. By shaving peak demand, they can lower demand charges. Their use in marginal grid systems can provide improved quality by avoiding localized surges and brown outs while evening out loads. Conversely, they can increase the potential for upstream transmission line overloads. They can avoid the need for extensive power line construction, or if power lines are necessary, they can expedite transmission line upgrades. The modular nature of microturbines allows for efficient allocation of capital resources. In general, the addition of microturbines to the power supply mix makes for a system with superior operational flexibility and reliability.

The economics and cost effectiveness of microturbines depend on several factors. Capital costs for installation and start up (hardware, instrumentation, software, training, etc.) can range from $700 to $1,100 per kW. As the market for these systems matures and expands, future costs are anticipated to fall to less than $650 per kW. The labor associated with the physical installation can add an additional 30 to 50% to the total cost, though this can change significantly with location. Add-ons such as heat recovery mechanisms for CHP systems can add a further $75 to $350 per kW. Operating and maintenance costs can run between $0.005 to $0.016 per kWh (at 8,760 hours per year, this is equivalent to $44 per kW to $140 per kW annually).

A relatively new use of microturbine systems is their utilization in transportation applications. Bus, truck, and even automotive manufacturers are eyeing microturbines as fuel-efficient, relatively lightweight power plants, suitable for hybrid electric vehicles. Research continues in this area as it does to improve microturbine performance with regard to flexible fuel use, in combination with fuel cells and fly wheels for energy storage and heat cogeneration.

Microturbines and Microgrids

Microgrids are small-scale power distribution networks operating over a limited geographical area and providing power to a limited number of users. Microgrids can operate in conjunction with regional utility power grids, independently of utility grids, or in complete isolation from other power sources. Microgrids have been increasing in number due to the expanded use of alternative and renewable power sources such as wind and solar. Microgrids also allow for easier use and integration of alternate power sources.

But above all else, microgrids provide resiliency and flexibility. This resiliency is especially useful in the face of hurricanes, tornadoes, wind storms, and super storms like Hurricane Katrina. Being less extensive, microgrids tend to survive these storms better than larger, more vulnerable grids and can be repaired and put back online faster. While the main regional utility is still knocked out, a microgrid can still be serving its customers. It's this need for resiliency that has prompted the expanded use of microgrids across the country. Their emergency use is not just confined to the private sector to serve the needs of a small customer base (such as a retail shopping mall, office building, college campus, or specific commercial and industrial facilities). Of particular importance are critical facilities such as hospitals, police stations, sanitary sewer treatment facilities, and stormwater flood control pump systems.

These systems usually form individual "islands" of electrical service within the overall regional power grid—a situation that can cause potential safety issues to repair crews trying to restore power to the main grid after a blackout. Certain local governments (such as the state of Connecticut) have been integrating a number of local microgrids into their main power grid. To further promote the spread of microgrids, the Department of Energy (DOE) has established a grant fund of over $7 million to fund microgrid design and engineering efforts.

The flexibility provided by microgrids is in answer to the spread of distributed and renewable energy sources. These are not necessarily the same thing. A wind turbine farm or solar cell array can be local, and thus, a distributed energy source, or large enough to provide a utility-scale regional power supply. Microturbines that require natural gas for fuel are not considered to be a renewable energy source (however, they can be designed to utilize alternate renewable fuel sources such as biogas). Distributed energy itself is not a renewable concept *per se.* Distributed energy systems go back to small town power supplies or the dedicated independent power sources used to supply energy to mills and factories.

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Microgrids rely on a wide variety of power sources. Though not strictly electrical in nature, central heating plants that utilize recovered waste heat from generator operations can be considered to be a form of distributed energy system. In this set up, the waste heat can be utilized to indirectly heat water with a heat exchange and provide direct heat via underground steam pipes connected to several buildings at once. Regional cooling systems can be co-located with regional heating systems, utilizing the collected waste heat as a source of energy.

Potential sources of energy for microgrids include both renewable energy (wind, geothermal, and solar), varying in size up to commercial-scale, and microturbines much smaller than those providing power to the main grid. Though often designed to burn alternate biofuels, microturbines generally run on natural gas. Since gas is easily transportable via pipelines, this allows for flexibility in construction and operation. Much of the appeal of microgrids is their small, convenient size. This allows for installation in cramped and confined areas where available space is limited, but a gas pipeline can still be easily installed.

One other source of energy for a microgrid is an emergency backup electrical storage battery, though inverters are necessary to convert the direct current (DC) from the battery to the alternating current (AC) utilized by the grid.

Microgrid power "islands" are connected to the main power grid at what is referred to as a "point of common coupling" (PCC). This device regulates voltage at the connection point to ensure that voltages in the microgrid are in sync with voltage in the main power grid. Should excessive voltage occur in the main grid, or if the main grid is hit with a blackout and its voltage drops to zero, the PCC will trigger a circuit breaker that then isolates the two grids. Once isolated, the microgrid can continue to provide electrical service to its customers. After power is restored to the main power grid, the microgrid operation can reset its connection.

Major Suppliers

Capstone Microturbine is a worldwide leader in clean technology and manufacturer of microturbines with products supported by over 100 patents. The company's comprehensive line of green energy microturbines are scalable from 30 kW to 30 MW and can operate on a variety of gaseous or liquid fuels including: natural gas, associated gas, LPG/propane, flare gas, landfill gas, digester gas, diesel, aviation fuel, and kerosene. Fuel sources include landfills, wastewater treatment facilities, food processing facilities, and agricultural waste (a.k.a. "green waste"). Use of microturbines at a municipal solid waste landfill allows for use of the extracted landfill gas rather than just flaring it away as a nuisance and safety threat. The Capstone Renewable line of microturbines is designed to operate on gas from organic waste sources.

At the small end of Capstone's product line is their C30 microturbine. Rated at 30 kW, the C30 operates with efficiencies of up to 26% for electrical, and 90% for CHP applications. The current is carried by three-phase, four-wire technology at voltages between 400 to 480 V, at a frequency of 50 or 60 hertz. Physically it is quite compact, measuring only 30- by 60- by 70-inches with a weight of only 891 to 1,271 pounds. Combustion exhaust gas flows at a rate of 0.68 lbm per second with post ignition temperatures of 530°F.

In contrast, their large scale C1000S microturbine operates with a rating of 1,000 kW at an electrical efficiency of 33% (up to 90% with CHP configurations), with similar voltages and operating frequencies at the smaller C30. It is also several times larger than the C30 with dimensions of 117- by 360- by 114-inches and operating weights ranging from 37,700 to 20,650 pounds. Its combusted gas exhaust flows at a temperature of 535°F and a flow rate of 14.7 lbm per second.

Princeton Power Systems is a designer of microturbine and microgrid systems, as well as solar energy, battery storage, and microgrid control systems. Their system designs can be found in island applications. According to Darren Hammel of Princeton Power, "Our company is involved in solar, battery storage, and microgrid controls . . . which in most cases are really an alternate solution to microturbines. Most of the places we've seen microturbines are on island applications, where we would typically say a solar and battery system is less expensive and more appropriate—as long as you have the space and capital to pay for the equipment. So, my expertise is more around these types of solutions, and these are what our company produces and installs." Their staff of engineers provides applications engineering, system design, testing and certification, and product evaluation services. They have installed a number of microgrids across the country for all kinds of critical facilities including prisons and emergency response centers.

Their suite of microgrid controls meet all applicable safety standards and are listed to UL1741. To maintain these high safety standards, Princeton employs a full-fledged certified testing lab. This lab is used to certify high-power and high-voltage electronics to various third-party standards, including UL 1741, IEEE 1547, CSA, CEC, and EN standards. Furthermore, their system design incorporates both safety and efficiency in next-generation renewable energy systems. These systems incorporate energy storage, grid support, communications, controls, and microgrid capabilities and incorporate their expertise in testing and inter-operational requirements. DE

Daniel P. Duffy, P.E., writes on topics of energy and the environment.