Preprint of an article published in
"The Bridge", National Academy of Engineering
Summer 2003

Microgeneration Technology : Shaping Energy Markets

Robert W. Shaw, Jr.

Robert W. Shaw, Jr., is president of Aretê Corporation.

Over the last few decades, developments in technology have incrementally refined the way energy is produced and delivered to customers. But in fundamental ways the energy system remains much as it was in the 1950s. Nuclear reactor technology has the potential to create a paradigm shift in the electric-generation sector, but because of public concerns about reactor safety and waste disposal, its promise has not been fully realized.

Today technology development supported by government and the private sector that has been under way for decades has begun to yield microgeneration systems that are now available commercially and are beginning to penetrate energy markets. The emergence of microgeneration technologies could lead to paradigm shifts in two key elements of the energy delivery system: distributed generation and hydrogen systems.

Distributed Generation. Based on a number of newly commercial technologies for power generation, such as fuel cells, as well as substantial refinements in traditional, engine-based systems, we can now envisage an electric system in which power is generated very close to the load being served; the generators will be several orders of magnitude smaller (i.e., 10 to 1,000 kW) than traditional utility generation stations of 100 to 1,000 MW. Distributed generation systems will have several advantages over the existing central station / electric grid system:

- high levels of reliability
- modularity that permits incremental additions in capacity
- potentially very low capital cost (on a $ / kW installed basis) as a result of mass production economies (not possible with the central station paradigm)
- the capture of waste heat that can then be used at the site through combined heat and power (CHP) systems
- minimal environmental footprints, particularly in CHP systems
- customer control (not practical in the large, impersonal, and often remote existing system)

Hydrogen Systems. Hydrogen has long been a widely produced, widely consumed commodity in our industrial society. However, its use as a fuel replacing natural gas and oil, although recognized as a possibility, has not been pursued because of the perceived difficulty of establishing a distribution infrastructure. But with advances in technology, distributed generation of hydrogen for use in direct-combustion applications, as well as in fuel cells, will not only be feasible, but will also be increasingly attractive economically.

This article describes some of the developments in technology that are making these two paradigm shifts possible and the most significant barriers to their large-scale market penetration.

Distributed Generation Systems

Emerging technologies for the distributed generation of electric power and related control and system-integration technologies are categorized in Figure 1. In the last decade, substantial technical progress has been made in many of the areas shown in this figure.

The technical developments described briefly below are all leading toward the commercial introduction of small-scale, distributed generation systems that offer customers economical, reliable power generated locally. These systems, which are penetrating markets at levels that were almost unthinkable only a few years ago, are in the vanguard of profound, fundamental changes in the world's electric system.

Fossil-Fuel Microgeneration Technologies

Some of the most interesting developments in this area are in traditional internal-combustion engines, microturbines, Stirling engine systems, and solid-oxide fuel cells.

Widely used in backup power and peaking applications for decades, *internal-combustion engines* have been refined substantially in the last few years to achieve expected lifetimes of up to 50,000 hours in continuous operation, higher efficiencies (now better than 30 percent), and lower emissions of criteria pollutants (low enough so they can be operated in most metropolitan air sheds). European companies have introduced engine systems in the range of 10 to 100 kW with CHP integration that can achieve customer paybacks in one to three years. Prime-power internal-combustion engine systems with CHP have become commonplace in commercial applications (e.g., in multistory city-center office buildings, food processing plants, and retail outlets) in both the United States and Europe. Systems for handling residential loads (5 to 10 kW) are now being introduced in Europe.

In the last three years, *microturbine-based gensets* in the 30 to 200 kW range have been introduced commercially by a number of companies on both sides of the Atlantic and in Japan, often with CHP capability, using the high-grade heat available in the turbine exhaust stream. With technology lineage in aircraft auxiliary turbines and truck turbochargers, microturbines have single-component cores, air bearings, and custom-designed recuperators, as well as very sophisticated power electronics to convert high-frequency (50,000 to 100,000 Hertz) AC power to DC power and then back to line-frequency AC. Efficiencies are improving but are typically less than 30 percent, particularly if compression of the natural gas fuel stream is required. Costs are below $1,000 / kW but still much higher than for internal-combustion engine gensets. Microturbine manufacturers expect that product costs will decline significantly as production volumes increase, simply because of learning curve effects.

The Stirling cycle has been investigated for many years but has been plagued by difficult engineering problems. In the last five years, several entrepreneurial companies have addressed and solved these persistent problems and have introduced 5 to 50 kW *Stirling engine gensets* commercially. Because the working fluid in Stirling systems is heated via external combustion of fuel, they are very versatile and can run on low-grade synthesis gas, landfill gas, biogas, and even waste heat, as well as concentrated solar radiation. With inherently high efficiency (the first commercial units are in the 30 to 35 percent range, and laboratory demonstrations have shown better than 40 percent) and components producible by traditional automotive engine suppliers, Stirling microgenerators have the potential to be exceptionally attractive economically.

Although *solid-oxide fuel cells (SOFCs)* are not yet available commercially, substantial progress has been made in the last five years on fuel cell couples in which the electrolyte is a ceramic (typically yttrium-stabilized zirconium). Even though difficult technical problems of thermal stability and sealing remain to be solved, precommercial systems are now being demonstrated by a number of companies worldwide. SOFCs operate at high temperature (600 to 1,000ºC), thus offering excellent potential for CHP applications, and have the advantage that they can operate on lightly pre-reformed fossil fuels, instead of the pure hydrogen stream required by polymer-membrane systems. SOFCs have inherently high efficiency (40 percent or better).

Renewable Microgenerators

Intensive efforts devoted to the development of renewable energy systems by governments and the private sector for more than 30 years have begun to yield serious commercial offerings in two areas: wind energy technology and photovoltaics.

Wind energy technology has evolved rapidly in the last two decades, and wind turbines in the range of 500 kW to 3 MW are now deployed commercially around the world in large-scale wind farms. Commercially available wind energy systems produce electric energy at costs that are competitive with electricity generated by conventional power plants and available on the grid. Although in principle wind turbines can be sited individually (and often are at remote locations, such as telecom repeater stations, off-grid cabins, and research stations in Antarctica), they are not suitable for distributed generation in urban areas. Therefore, they will only contribute in a minor way to the paradigm shift.

The most significant technical advances in distributed renewable-energy systems have occurred in *photovoltaics*, the direct generation of electricity via sunlight absorbed by, and exciting electrons in, a semiconductor. Progress on thin-film photovoltaic devices (e.g., using films of semiconductors, such as amorphous silicon, CdTe, and copper-indium-diselenide) has been somewhat disappointing. However, the performance of crystalline silicon, particularly thin-ribbon polycrystalline silicon, continues to improve (12 to 20 percent efficiency). Costs have come down progressively on an 80 percent experience, or "learning," curve. Photovoltaic modules are now available on the world market at less than $3.00/W, and building-integrated photovoltaic systems (e.g., roof tiles, decorative panels, sun shades, and skylights) are being widely installed in grid-connected applications in Europe, Japan, and the United States. Meanwhile, the off-grid market in developing nations and some commercial applications (e.g., obstruction and construction lighting, call boxes, signal lights, and sign lighting), as well as numerous telecom applications, continues to grow.

Annual worldwide production of photovoltaic modules is now in the 500 MW range, and the overall PV market continues to grow at 20-35 percent per year (PV News, 2003; Schmela, 2002). Large producers and small entrepreneurial companies are expanding production capacity rapidly using highly automated manufacturing technology that continues to drive down the cost per watt. Even at today's installed costs of $5 to $6/W, photovoltaics can compete with conventional peaking power in parts of the United States, Western Europe, and Japan. Incentives offered by many governments make the economics even more attractive (Eckhart et al., 2003).

Power Quality and Storage

Technical developments in power quality and storage are too numerous to be discussed adequately here. By way of illustration, superconducting magnet technology developed by the Fermilab for accelerator applications has been adapted to create a small-scale superconducting magnetic energy storage (micro-SMES) device for voltage stabilization and momentary carryover during sags in line voltage. The micro-SMES has been available commercially for several years. Another unique technology now entering the commercial market for telecom backup power is the zinc-air fuel cell, in which tiny pellets of zinc are oxidized on the anode side of a fuel cell with an advanced air cathode to generate electricity when the grid is down. When the line voltage is again available, fresh zinc pellets are regenerated from the oxide in the system.

Hydrogen Systems Technology

The basic technologies for producing hydrogen via the reforming of fossil fuels or via the electrolysis of water have long been known. Industrial scale-steam-methane reformers (SMRs) are ubiquitous in the chemical and petrochemical processing industries. Indeed, hydrogen is one of the most widely produced commodities in the world economy (Heydorn and Zuanich, 1998). The challenge, addressed by numerous companies in the last few years, is to reduce the scale of hydrogen production systems while maintaining reasonable product cost.

Distributed Electrolysis

Technology developments in both proton-exchange membrane (PEM) electrolysis and alkaline electrolyte (KOH)-based electrolyzers have led to the commercial introduction of systems capable of producing 50 to 5,000 scf/hour of pure (99.99+) hydrogen gas via water electrolysis. At bulk power costs (<3 cents/kWh), these electrolyzers can produce hydrogen at prices competitive with hydrogen transported as a compressed gas in tube trailers, or cryogenically as liquid H_2. Applications include generator cooling, semiconductor processing, and hydrogenation of food products. When hydrogen vehicles are introduced commercially, these electrolyzers could also be used to refuel them, even at individual residences.

Small-Scale Reforming

Downsizing industrial-scale reformers has never been proven economical, but several entrepreneurial companies have achieved excellent results in the last few years with novel reactor designs and unique catalysts that enable distributed production of H_2 at costs competitive with much larger systems. Commercial introduction of these small-scale (2,000 scf/hour) SMRs is just beginning in industrial applications. These systems are also ideally suited for siting at "gas stations" for hydrogen-vehicle refueling.

Proton-Exchange Membrane Fuel Cells

Enormous effort in the last decade has gone into the development of proton exchange membrane (PEM) fuel cell stacks and systems. Not only has membrane technology advanced, but significant advances have also been made in lifetime, efficiency, and cost reduction of PEM fuel cell systems. Despite this progress, PEM technology has proven to be much more difficult to perfect and is still more expensive than many had expected. To date, there has been no large-scale commercial introduction of PEM fuel cells for stationary or automotive applications.

Hydrogen Storage

The major advance in hydrogen storage has been the improvement in compressed-gas storage tanks. Using carbon-fiber technology to strengthen aluminum tanks, pressures of 5,000 psi are now routinely achieved, and 10,000 psi tanks are under development. Work also continues on various metallic and nonmetallic hydrides, as well as on carbon nanotubes, as storage materials; some early versions of small-scale hydride storage systems are available commercially. Although acceptable volumetric energy density for hydrogen storage is still a challenge, thanks to technical progress on several fronts it is of much less concern than it was even a few years ago.

Hydrogen-Fueled Vehicles

The idea of a hydrogen-fueled vehicle fleet has captured the public imagination because it has the potential to reduce criteria pollutants dramatically and could ultimately lead to a fully sustainable transportation energy system based on the renewable generation of hydrogen. Because of the technical and economic challenges of introducing PEM fuel cell-powered vehicles, automakers have deferred the large-scale introduction of PEM-based fleets (although two Japanese automakers recently introduced fuel-cell vehicles in limited numbers in California). However, several automakers are looking into hybrid vehicles in which the internal-combustion engine would be operated with hydrogen as a fuel. Now that the distributed generation of hydrogen is technically available at reasonable prices, the hydrogen-hybrid vehicle may be a way to introduce hydrogen as an automotive fuel. Eventually, this might lead to the development of a hydrogen fuel infrastructure even before the cost of PEM fuel cell technology is brought down to an economical level.

Market Entry

Essentially all of the new energy technologies discussed in this article are "disruptive technologies" (Bower and Christensen, 1995; Christensen, 2000). As Figure 2 shows, disruptive technologies often enter the market with significant performance disadvantages (e.g., cost, efficiency, lifetime), but by serving niche markets in which they are competitive, they gain experience, improve performance, and eventually surpass the performance of established technologies, even though mainstream technologies may also improve in performance over time..

For example, microturbine generators entered the market with cost and performance disadvantages when compared to the electric grid. Initially they have most successfully addressed marketswhere they had a unique advantage, such as on-site power generation in oil fields where flare gas is used as a fuel. As production quantities increase, microturbines can be expected to work their way down the experience curve on cost, and performance will improve as a result of technical improvements based on field experience. Thus over time, they will be able to compete in the mainstream market.

Photovoltaic devices provide another illustration. Introduced early in the space program, they were, and remain, extremely expensive devices when used in space applications. As refinements in device and production technology have been made over time and as unit volumes have increased, costs have come down and efficiency has improved. Photovoltaic systems can now address a broader market, and photovoltaic-generated electricity is now competitive with conventionally generated peak power in many markets. Further reductions in module cost (to the range of $2.00/W), which are clearly achievable, will open up even larger markets and, in turn, will make the technology even more competitive with central station generation.

It is important to recognize that distributed generation technologies must compete against the cost of delivered power at the load, not just against the cost of central generation at the bus bar. Transmission and distribution (T&D) costs (including capital, as well as operating costs, such as tree trimming, transformer replacement, and resistance loss) can be two to three times the cost of bulk power. Unfortunately, in the United States maintenance and upgrades to the power grid have sometimes been less than adequate. As a result, the power grid has a reliability risk that may be unacceptable to end-users with critical electrical loads, which, because they require advanced electronics controls, are often vulnerable to even minor voltage sags, as well as to outages of any duration.

Furthermore, as a result of social and regulatory decisions made over time, the actual cost of providing electric service to certain customers (e.g., remote/rural homes or villages) may be far higher than a utility can charge. In these situations, distributed generation may be economically attractive to the utility that is currently serving customers in those locations.

The kinds of entry markets in which distributed generation systems may build "beachhead" positions (to use Geoffrey Moore's terminology [1999]) are indicated in Figure 3. Distributed systems have already made a substantial penetration into the worldwide power market. A recent survey by the World Alliance for Decentralized Energy indicates that penetration is 7 percent of generation worldwide and as high as 30 to 50 percent in some countries (Brown, 2002). Over time, these percentages are likely to increase significantly, and distributed-generation systems will become more attractive economically and demonstrate exceptional reliability; the central station / T&D grid model of electricity supply will gradually be displaced.

The established paradigm of a petroleum-based transportation system will also come under attack by hydrogen over time. The issue of how to establish a hydrogen infrastructure has been hotly debated, and no simple solution has emerged. One model considered likely is that fleets will convert to hydrogen-fueled vehicles, perhaps the hydrogen-hybrid vehicle discussed earlier. In an alternative model, the dual-fuel hybrid, existing hybrid vehicles would be outfitted with a small compressed-gas hydrogen tank with a 100-mile range; longer range requirements would be met by the existing gasoline tank (Shaw, 2002a,b). With this model, hydrogen fueling stations could be installed in city centers only (perhaps initially in only two or three cities), thus avoiding the need to equip all of the (approximately) 100,000 U.S. gas stations with hydrogen fueling capability at one time. As the fleet size increased, hydrogen fueling would expand outward from the city center, and to more cities over time. This model is similar to conventional market-entry strategies for consumer products. Incentives, such as convenient "green" parking spaces and access to HOV lanes, could be provided for early adopters of dual-fuel hybrids.

No matter which approach to the creation of a widespread hydrogen infrastructure is adopted, there is little doubt that distributed generation of hydrogen will be a key component, with small-scale SMRs being the choice where natural gas is available and electrolyzers where it is not. These technologies are available today and, therefore, can facilitate earlier-than-expected development of the hydrogen infrastructure.

Removing Barriers

A major shift in an industrial paradigm will always encounter resistance from established interests. Despite the attractive economics of distributed generation in many applications, electric utilities often regard it as a threat. They argue that using the grid as a backup to distributed systems would "strand" (make uneconomical) existing utility assets that were approved through the regulatory process. In some cases, utilities advocate economic penalties for customers who disconnect from the grid or use it as a backup. Some jurisdictions have taken a proactive position in support of distributed generation, including adopting "net metering" provisions that allow small-scale generators to sell excess power back into the grid. But even in supportive jurisdictions, utilities have often adopted a go-slow approach that makes implementation of distributed generation difficult.

A reasonable concern voiced by utilities is so-called "islanding"—when the grid is down, if grid-connected distributed-generation systems send current into the grid, they can create a safety hazard for line workers. The recent adoption of the IEEE standard covering interconnection for distributed systems should help ease this concern (COSPP, 2003), but some utilities continue to apply their own standards or simply stonewall interconnection entirely. With more experience, many concerns about distributed generation will be addressed by rigorous engineering methods and will fade from view. The fundamental question of the right to interconnect will have to be addressed through restructuring legislation at the state or federal level.

As for the hydrogen infrastructure, the paradigm shift will occur when all of the interested players sense that the economics are acceptable and that the market demand is there. Virtually all of the major oil and automobile companies are actively involved in developing and testing hydrogen-generation systems and vehicle power plants using hydrogen (both fuel cells and internal-combustion engines). Governments throughout the world have shown their support for the transition to hydrogen by funding technology development and by resolutely supporting air quality standards that make cleaner vehicles essential. At some point, there will be a shift equivalent to a phase change in physical systems, and the pieces will line up to bring the hydrogen infrastructure into being. As Seth Dunn has pointed out, "Structural change can occur with surprising speed when people stop taking the dominant paradigm for granted" (Dunn, 2000, 2001).

Conclusion

Efforts to develop distributed generation and hydrogen-production systems in the last decade and more have begun to pay off commercially with the entry into energy markets of products that provide economical, reliable power generation at small scale and distributed systems for the production of hydrogen at customer locations. As these new technology-driven products continue to penetrate their respective markets, major shifts in the established way these markets operate will inevitably follow.

References

Bower, J.L., and C.M. Christensen. 1995. Disruptive technologies: catching the wave. Harvard Business Review 73(1): 43–53.

Brown, M. 2002. Onwards from 7%: new survey quantifies decentralized energy worldwide. Cogeneration and On-Site Power Production 3(6): 25–29.

Christensen, C.M. 2000. The Innovator's Dilemma: When Technologies Cause Great Firms to Fail. New York: HarperCollins.

Dunn, S. 2000. MicroPower: The Next Electrical Era. WorldWatch Paper 151, p. 10. Washington, D.C.: Worldwatch Institute.

Dunn. S. 2001. Hydrogen Futures: Toward A Sustainable Energy System. WorldWatch Paper 157. Washington, D.C.: Worldwatch Institute.

Eckhart, M.T., J.L. Stone, and K. Rutledge. 2003. Financing the PV growth. In Handbook of Photovoltaic Science and Engineering, A. Luque and S. Hegedus, editors. New York: John Wiley & Sons, Inc. Forthcoming.

Cogeneration and On-Site Power Production , 2003. 4(1): 10.

Heydorn, B., and J. Zuanich. 1998. CEH Product Review: Hydrogen. Prepared under the auspices of the Chemical Economics Handbook. Menlo Park, Calif.: SRI International

Moore, G.A. 1999. Crossing the Chasm: Marketing and Selling High-Tech Products to Mainstream Customers. New York: HarperCollins.

Maycock, P.D.. 2003. PV News 22(3): **1**Schmela, M. 2002. Beyond expectations: market survey on world cell production in 2001. Photon International Issue 3: 38–42.

Shaw, R.W., Jr. 2002a. Investing in Hydrogen Technologies. Presented at Globe 2002 Conference, Vancouver, British Columbia, March 2002.

Shaw, R.W., Jr. 2002b. The Hydrogen Infrastructure: Making It Happen. Presented at Montreux Energy's Hydrogen Infrastructure Investment Roundtable, Chantilly, Virginia, November 2002.

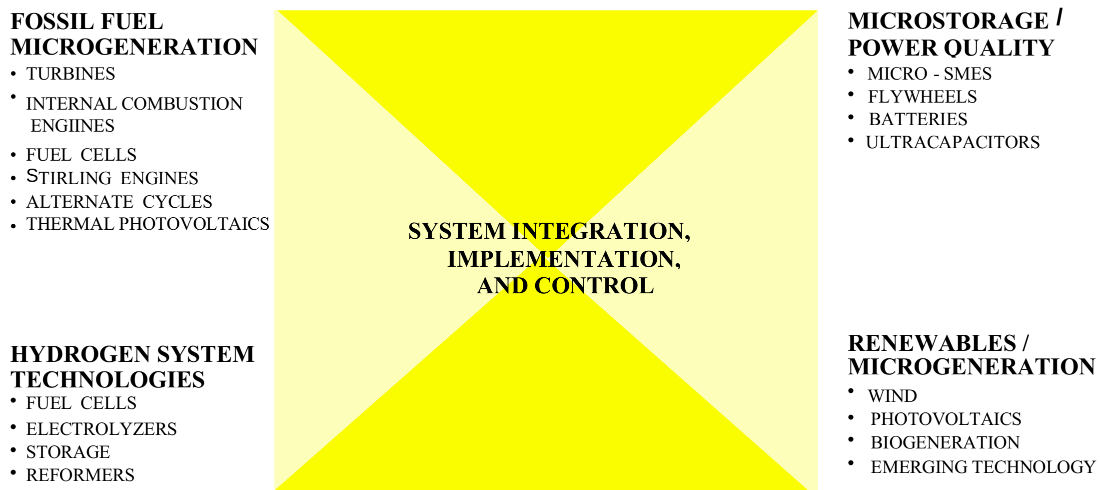

FIGURE 1 Categorization scheme for microgeneration technologies.

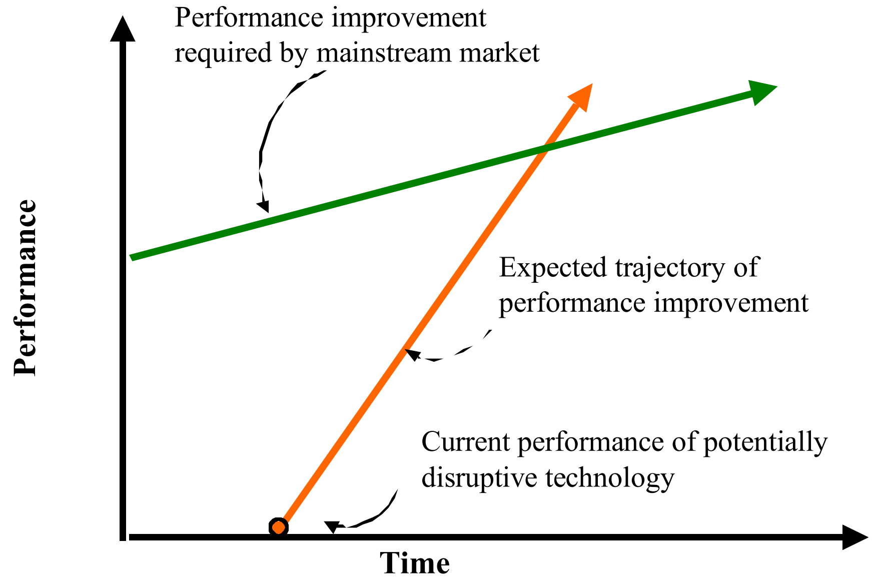

FIGURE 2 Performance trajectories for mainstream and disruptive technologies.
Source: Bower and Christensen, 1995.

- Remote, non-grid-connected markets
  - Telecom
  - Village power
  - Mobile power (boats, RVs)
  - Portable power
  - Standby power
- High-cost, grid-connected market niches
  - Rural villages
  - Undeveloped areas
  - Peak power
  - Voltage stabilization
- Intermediate-cost, grid-connected mainstream markets
  - Engine sets / CHP at commercial loads
  - Grid-connected standby units
  - Grid disconnection situations

FIGURE 3 Entry market niches for distributed-generation technologies.