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Micropower: The Next Electrical Era

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This paper is dedicated to my grandmothers, Virginia Crane Anderson and Susan Gage Dunn: artists, environmentalists, and living proof that good things do indeed come in small packages.

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Introduction

When Wall Street analysts stepped back from the Internet "'99 dot-com rush" to survey potential investments elsewhere in the economy in 2000, they converged on a seemingly unlikely candidate. "Don't look now, but utilities could be one of the hot new investment opportunities," proclaimed *Business Week*. *Venture Capital Journal* was even more bullish, declaring the electricity industry "the next big thing." Much of the attention focused on "micropower" technologies that are smaller than today's typical generators.[1]

Other writers and analysts picked up on these pronouncements, and in the following weeks shares of several companies manufacturing two types of small-scale power generators—fuel cells and solar photovoltaics—shot up, some as much as sevenfold. Even after a subsequent stock market decline, most of these shares remained well above pre-surge levels. Investment banks, meanwhile, scrambled to set up power technology divisions and to court the companies developing these technologies; before long, "venture" funding rounds for the new firms had become oversubscribed.[2]

Thomas Alva Edison would be delighted. The prolific inventor and father of the modern electrical age was well aware of the need to raise large amounts of capital to support his young power-and-lighting company. Impressing money men, in fact, was a major reason for locating his first power station in New York City's Wall Street district in 1882. Just as J. P. Morgan underwrote Edison's 257 Pearl Street station and later projects, today's financiers are beginning to infuse the next generation of power technology startups with levels of investment capital that were unthinkable only a few months ago. Now, as then, the arrival of financial entrepreneurs on the scene marks an important step in the evolution of a new electric power system.[3]

Edison would be excited for another reason as well. Relatively small-scale, localized power was what he had in mind when first installing his electric power-and-lighting systems in the late nineteenth century. Edison envisioned a dynamic, decentralized electricity industry, with dozens of companies generating and delivering power close to where it was to be used, or even putting systems on site in customers' basements. And at first, electric power systems did indeed evolve along these lines, with hundreds of small "central-station" and isolated plants appearing in cities across the Western world. Small-scale power units were particularly popular in factories, which could save money by capturing and reusing their waste heat.[4]

But new technological and institutional developments soon began to point in a different direction. The rise of the steam turbine and the development of alternating current were making it economical to generate larger amounts of electricity and to transmit it over longer distances. The parallel spread of the idea of the power business as a natural monopoly reinforced this trend, as electric utilities embraced the large-scale model, with its "economies of scale," as the best means to generate low-cost power for consumers. Five decades later, however, in the 1980s, the steady trend of bigger plants and plummeting prices came to a sudden end as the industry encountered limits to efficiency gains, environmental problems, rising energy prices, and costly nuclear power projects. By the 1990s the trend had actually reversed, with gas and wind turbines auguring a dramatically different paradigm for energy supply.[5]

As we embark upon the second electrical century, a "triple power shock" of technological, economic, and environmental trends could potentially push the energy system further toward a more small-scale decentralized model. Some see parallels with recent revolutions in the telecommunications industry, which has been transformed by new technology and deregulation, and in the computer industry, which has been completely realigned by the rapid shift from mainframes to personal computers. In any event, these new "micropower" technologies represent a dramatic departure from the status quo.[6]

The solar cells, microturbines, fuel cells, and other devices now beginning to trickle into the commercial power market have capacities as low as 1 kilowatt, one millionth the amount of power generated by a typical nuclear plant. With three quarters of U.S. commercial and residential customers using on average no more than 10 and 1.5 kilowatts, respectively, the new generation of technologies is well matched to the scale of need. During the coming decade, continued technical advances will likely accelerate the downsizing. Small and modular, the new technologies' advantage stems not from economies of scale—building bigger units to lower costs—but from economies of production—producing more units to lower costs.[7]

A related factor in micropower's rise is the shift in the philosophy of power generation—away from the natural monopoly of utilities, and toward open, competitive markets—that is sweeping the globe and revolutionizing an $850 billion industry. As the costs of ever-larger power supply, or "diseconomies of scale," come under greater scrutiny, it appears that, to paraphrase E.F. Schumacher, small may be beneficial. In addition to becoming economical when mass-produced, modular systems can be adjusted to match the scale of demand and installed far more quickly than a central station. Micropower can improve reliability by reducing demands on transmission systems and thus avoid costly investment in new power plants. And smaller systems can facilitate more local control over power use, contributing to economic development within the community and reducing reliance on distant institutions.[8]

Some of the most important benefits may be environmental, as modern micropower systems will generally leave a lighter ecological footprint than the predominantly fossil fuel-based network that is linked to a host of environmentally damaging activities. While many of the old diesel generators currently in use for standby or remote power do produce significant air pollution, newer natural gas-based generators and other systems release between 50 and 100 percent less. In addition to natural gas, these systems can also operate on solar, wind, and other renewable energy flows, with some eventually running directly on hydrogen. And since they are deployed close to where the power is actually used, the waste heat from these generators can be more easily captured for use—leading to total efficiencies of 80–90 percent. Conventional power plants, on the other hand, waste as much as two thirds of the energy they consume.[9]

The reappearance of small-scale electricity comes not a moment too soon in increasingly "digital," or computer-dependent, economies that place a high premium on reliable power. Just as summer heat waves and power outages are revealing the weaknesses of aging grids, the rising role of voltage-sensitive computerized processes throughout modern economies is heightening vulnerability to disruptions of power supply. Many high-tech industries, as well as institutions such as banks and medical centers, are highly dependent on computers and can suffer the loss of millions of dollars and valuable scientific research from a power outage lasting a few hundredths of a second. A more "distributed," or decentralized, network of small systems can reduce this vulnerability, providing a higher quality and greater reliability of power. It may also do so in a less environmentally disruptive manner than the roughly 100 gigawatts of "merchant" power plants—large systems intended to provide back-up for utilities facing shortages—that are now being slated for construction around the globe.[10]

Micropower systems may be most consequential in the developing world, where "power poverty" is becoming as economically and politically unsustainable as power outages are in richer nations. Where power systems do exist in developing countries, they are even more brittle—and polluting—than those in the developed world, causing frequent

blackouts and contributing to major health problems. Meanwhile, a staggering 1.8 billion people, nearly one third of humanity, have been left utterly powerless by the centralized model. Lacking access to modern electricity, they are often forced to rely on dirty, inefficient diesel generators and kerosene lanterns. In these parts of the world, decentralized technologies have enormous potential to bring power to the people, allowing the development of stand-alone village systems and doing away with the need for expensive grid extension. And for a rapidly growing urban base, small-scale systems can substantially reduce the economic and environmental cost of electrical services.[11]

Substantial market barriers to the broad deployment of micropower systems remain, however. Created over three generations with the large central model in mind, a plethora of subsidies for fossil fuel energy—worth at least $120 billion annually—regulations, and other policies render today's power markets essentially blind to the benefits of small-scale systems, making it hard for them to compete. Most monopoly utilities, perceiving downsized systems as a threat to their core business of generating and distributing power, employ tariffs and standards to block their use. While some industrial countries are gradually rewriting their market rules to smooth the way for small-scale power, limited progress may result in a monoculture of merchant and other multi-hundred-megawatt gas turbines that are, judging by conventional market prices, often the least expensive option, but have marginal advantages over the current system. The risk of "lock-in" to the dirtier, less efficient, less reliable, and more expensive twentieth century model is even greater in developing nations, which have a golden opportunity to get these rules right the first time.[12]

Pressures for micropower-friendly market reform are building. A swelling number of small new electric companies—as well as spin-offs of big utilities and energy multinationals—are springing up between Connecticut and Calcutta, ready to put central power stations out of business or to help people turn on the lights for the first time. In addition, as consumers become increasingly able to choose their power suppliers, marketers will have no option but to give customers what they want, and evidence to date suggests they want reliable electricity from clean sources. From the San Francisco Bay Area to Bangladesh, venture capital and microcredit models are being used to finance micropower, helping "startup" companies survive their revenue-losing early years and enabling potential customers to surmount the high first cost of the new technologies.[13]

The most important determinant of how far and how fast such systems emerge may be less technical, regulatory, or financial than institutional. Micropower may represent what management experts call a disruptive technology, one whose potential is greatly underestimated at first but whose eventual popularity topples unprepared companies and takes analysts by surprise. By developing the appropriate micropower "software"—the institutional base of support—businesses, government, and civil society can prepare for such change, and facilitate broader public understanding, acceptance, and use of the new technologies.[14]

It is difficult to gauge how much electricity may come from micropower in 10, 25, or 50 years' time. Historians remind us that technical systems are formed at the intersection of technologies and values. But electric power systems are also cause and effect of social change, and events of recent decades suggest that such change is not always gradual. Indeed, if upheavals in political systems are any guide, structural shifts can occur with surprising speed when people stop taking the dominant paradigm for granted. Not unlike Soviet-style central planning a decade ago, the large-scale electricity model appears to be collapsing under its own economic and ecological weight, creating big opportunities for a little approach.[15]

Coming Full Circuit

Local, personal power may be depicted in industry journals as a twenty-first century idea, but it is also the second time around for a nineteenth century concept. Edison's historic Pearl Street station was a small operation, running on six coal-fired boilers that produced steam to run reciprocating steam (piston-based internal combustion) engines and was designed to serve nearby customers. Operating a direct-current generator, the system sent electricity through underground wires and initially lit up some 400 of his new incandescent lamps, totaling roughly 33 kilowatts, of the 800 Edison had connected to the Drexel-Morgan building, the *New York Times* office, and 40 other establishments within a square-mile area of the Wall Street district.[16]

Edison anticipated a highly dispersed electricity system, with individual businesses generating their own power. His strategy, soon adopted by his competitors, was to build small generators within the area of use and sell electricity and illumination together as a service. By 1882 and 1883, the Edison Electric Illuminating Company had plans under way to diffuse the system to more than a dozen other large cities, among them Chicago, Philadelphia, London, Berlin, and Paris.[17]

At first, Edison's conception aligned with reality. The system was well suited to heavily populated urban areas, and during the next two decades, several thousand central stations (small scale and decentralized by modern standards) generating up to a few megawatts and serving small surrounding areas, were established in the great metropolises of the Western world. Also popular were smaller "isolated" plants, self-contained and sized as low as 100 kilowatts, that formed the bulk of the company's initial business and were used in stock exchanges, factories, department stores, hotels, ranches, cafes, and apartment buildings. By 1886, Edison had installed 58 central stations and 500 isolated lighting plants in the United States, Russia, Chile, and Australia.[18]

By the late 1890s, many small electrical firms were doing a brisk business marketing and building power plants that not only generated power but also provided district heating and reused their waste heat. This became an especially popular option for the basements of downtown businesses and factory buildings. In the early years of the twentieth century, the small systems of industrial firms accounted for more than half the electricity generated in the entire United States. Small isolated systems continued their spread, and their share of U.S. electricity use rose from 50 percent in 1889 to 59 percent in 1907. Many of these self-contained units were connected to central heating systems, feeding back waste heat, or were part of "neighborhood systems" that sold excess current to nearby users.[19]

But the new century was ushering in new views of electricity generation. Businesses were starting to build large centralized power plants in Chicago, Berlin, New York, and other cities. In 1901, the president of the influential Institution of Electrical Engineers announced to the group's members that "larger areas of supply and fewer generating centres in an area are necessities—it is recognized that the secret of economic working is to generate on a large scale and to distribute over a large area at an appropriate high voltage." By 1911, the average size of a power station had grown to 23 megawatts in Berlin and 37 megawatts in Chicago.[20]

Technological changes were one factor in this shift. George Westinghouse and other Edison rivals were experimenting with alternating current, which despite its safety risks was making it conceivable, in conjunction with the newly developed transformer, to transmit electricity over long distances. This was not economically possible with Edison's direct-current technology. At the same time, an engine that had been developed in 1884—the turbine—was being promoted as smaller, lighter, and cheaper than the reciprocating engine. Several European companies had already started to use steam turbines, sized up to 3 megawatts, in the first years of the twentieth century.[21]

Pioneered by former Edison assistant Samuel Insull, a

"grow-and-build" strategy emerged that encouraged increased electricity use to stimulate the installation of large central plants. This had the effect of lowering electricity prices and further driving up use. The new approach became widespread in modernizing nations, and by the 1920s it was seen as the only sensible way to run a utility company. Small-scale systems became, at least for the moment, a "loser in history," as scores of companies obligingly shut down their units and turned to low-cost utility power.[22]

The build-big approach was also furthered by the broad consensus that the generation, transmission, and distribution of electricity should be defined as a "natural monopoly"; one firm supplying all customers in a given area was viewed as the most economical path to electrification. Governments in the United States and overseas began to create monopolies by granting concessions for the sale and distribution of power—while establishing regulations to ensure that the companies did not use their monopoly positions to increase profits or deprive customers of the low prices that resulted from the system's economies of scale. Monopolists were also obligated to provide a secure power supply and offer the same prices to customers in the same class (commercial, residential, or industrial) in order to guarantee cheap, reliable electricity.[23]

Edison anticipated a highly dispersed electricity system, with individual businesses generating their own power.

By the 1930s, most industrial countries had set up a monopoly utility system based on large-scale power systems. The dominant design of electric power systems was now established: turbine generators, operated by monopolistic utilities overseen by regulatory bodies, and running alternating current from central stations over transmission lines. It may seem obvious today, notes historian Richard Hirsh, but it was neither obvious nor inevitable at the time: "…it is conceivable that the industry could have developed along the lines that Edison had envisaged, with individual businesses generating electricity themselves in decentralized fashion."[24]

Instead, for four decades, technological and institutional developments reinforced the trend toward large power systems, which in turn created remarkable declines in consumer prices. Improvements in the efficiency of steam turbines steadily pushed up the scale of the generation units, whose largest size jumped from 80 megawatts in 1920 to 600 in 1960 and from 600 megawatts in 1960 to 1,400 in 1980. But then, unit scale "hit the wall" of efficiency limits, environmental concerns, energy crises, overcapacity, and multi-billion dollar losses from nuclear power plants, all of which indicated that the bigger-is-better approach entailed certain "diseconomies of scale."[25]

Meanwhile, new policies and technologies were in the process of reversing the decades-long trend toward large-scale power systems, allowing the development of inventions that challenged the natural monopoly of utilities. In the United States, the energy crisis of 1973 had laid the groundwork for legislation that allowed independent power producers access to the electrical grid. By removing barriers to entering the power-generating market, the laws catalyzed major innovations in small-scale technologies.[26]

In his new book, *Power Loss*, Hirsh writes that these rules "proved that large-scale hardware no longer held a stranglehold on low-cost electricity." New types of equipment were brought on line, tapping resources that had for decades been wasted or overlooked. Thousands of wind turbines, averaging between 50 and 300 kilowatts in size, were installed in the state of California. Between 1980 and 1990, U.S. industry's use of waste heat from electricity generation for heating and additional power, known as "cogeneration," nearly quadrupled. Particularly popular were new combined-cycle gas-combustion turbines derived from aircraft jet engines, which were suitable for mass production and ranged in scale from 10 to 90 megawatts. Their use grew dynamically as natural gas prices dropped. The turbines were economical at sizes of 100 megawatts or less and required

much lower initial investment than 1,000-megawatt coal or nuclear power units did.[27]

By demonstrating smaller and cheaper ways to provide electricity, these new technologies, offered by independent producers, began to undermine the justification for monopoly utility control over power generation. During the mid-1980s, support grew for eliminating monopoly regulation and bringing market principles back into the power sector, or restructuring. In the United Kingdom, deregulating the coal industry and opening utilities to competition led to a dramatic increase in the use of combined-cycle gas turbines, whose heightened commercial attractiveness spurred interest in power sector restructuring elsewhere.[28]

Large electricity consumers were particularly intrigued by the shift. Pointing to the cost declines resulting from the restructuring of the airlines and telecommunications industries, they pressed for analogous changes in the power generation sector. Similar changes unfolded in some European nations, Latin America, and the United States. The tide of electricity restructuring was washing up on more and more shores, gradually converting a once staid industry into a free-wheeling, dynamic business.[29]

The gas and wind turbines and cogeneration systems of the 1980s were bellwethers of a trend that would accelerate throughout the 1990s. The average size of a new generating unit in the United States declined from 200 megawatts in the mid-1980s to 100 megawatts in 1992 and to 21 megawatts in 1998, roughly equal to the electrical sizes of the World War I era. Still smaller sizes, down to 10 and even below 5 megawatts—the average size in 1903—were also beginning to emerge. (See Table 1.)[30]

From the perspective of power generation, the last decade of the twentieth century may have had more in common with its first decade than with the 80 years in between. Discovering that they could provide power from cogeneration, wind, and gas systems, independent power producers—as well as some utilities—were revitalizing the concept of generating power at a smaller scale and nearer its ultimate

TABLE 1

Typical Power Plant Scales, United States, 1980–2000

Type	Average scale (kilowatts)
Nuclear plant, 1980	1,100,000
Coal plant, 1985	600,000
Gas turbine, combined-cycle plant, 1990–2000	250,000
Single-cycle gas turbine, 2000	150,000
Industrial cogeneration plant, 2000	50,000
Wind turbine, 2000	1,000
Microturbine, 2000	50
Residential fuel cell, 2000	7
Household solar panel, 2000	3

Source: See endnote 30.

point of use. Writes Hirsh, "In this so-called distributed utility network—somewhat of a throwback to the days of industrial self-generation in the 1900s—consumers reduced their dependence on regulated utilities and derived valuable benefits."[31]

While electric power systems did not evolve uniformly in modern industrial economies, the pattern of events in the United States, and in other nations discussed here, generally held true elsewhere. Over the course of the twentieth century, large-scale electric power systems quickly gained, and then just as quickly lost, momentum as they exploited their economies of scale and subsequently reached limits to them. The bigger-is-better ideology that had become widely accepted within the industry and reached its apex in the 1970s would become so discredited by the end of the 1990s that even utility spokespersons acknowledged that "the era of big

is certainly over." Indeed, a new electrical era had begun, one that was in many respects bringing Edison's original vision back into focus—and acquiring a momentum of its own.[32]

Hot Little Numbers

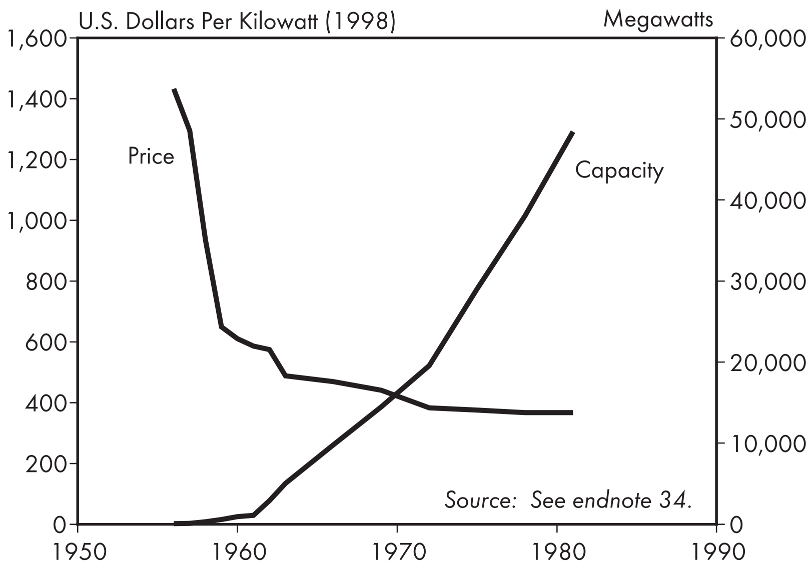
Electricity's downsizing is just getting under way. Advances in metallurgy, synthetic materials, electronics, and other scientific fields are contributing to the rapid development of ever-smaller power technologies. They span a wide array of innovations, ranging from improved internal combustion engines to generators that rely on electrochemical, photoelectric, hydrological, biological, and geological processes.[33]

Micropower technologies remain expensive when compared directly with conventional systems on the narrow basis of installation costs; some can cost up to five times as much to install. As they enter expanding market niches, however, they are expected to move steadily down the "learning" or "experience" curve along which increases in mass production lower technologies' unit costs, making further production expansion economically feasible. Mass production of single-cycle gas turbines, for example, drove down the technology's cost per kilowatt from $1,200 in the mid-1950s to less than $400 by 1981. (See Figure 1.) Today, single-cycle and combined-cycle gas turbines dominate global power markets, with more than 64 gigawatts of engine capacity ordered between mid-1998 and mid-1999—twice the previous 12-month total. Similar curves, well demonstrated with microwave ovens and toasters, can also be expected from the micropower systems, which are suited to mass production.[34]

The definition of micropower technologies applies here to systems of less than 10 megawatts, or 10,000 kilowatts, in size. At this scale, the unit need not be connected directly to high-voltage transmission systems, but can instead be

FIGURE 1

World Gas Turbine Price and Cumulative Installed Capacity, 1956–81



hooked up to low-voltage local distribution systems or installed in commercial and residential buildings. In addition to enabling economies of mass production, which drive down their installation costs, the modularity allows for fast construction: micropower units can be built in factories, transported to their site, and installed in a matter of hours. By contrast, large power plants must be built on site, and construction can take months, years, or even decades.[35]

Leading micropower's move to market are the reciprocating engines, used for decades in trucks, buses, and other off-grid applications. Reciprocating engines currently dominate the roughly 10,000 megawatts of generation units sized at 5 megawatts and below that are installed annually for continuous use, as well as the 14,000 megawatts installed for standby power. According to Cambridge Energy Research Associates, this market is growing at roughly 5 percent per year—closer to 10 percent in Asia.[36]

Running either on diesel fuel or natural gas, reciprocating engines are relatively inexpensive to install, and when waste heat is reused for water or space heating or industrial processes, they can reach efficiencies of 85 percent and above. Several manufacturers have begun mass-producing these engines with installation costs as low as $600 per kilowatt. (See Appendix A for a sampling of reciprocating engine and other micropower companies.) (See Table 2.) Current uses include small commercial and remote applications. Caterpillar, for example, offers 25-kilowatt generators for fast-food restaurants and runs a 500-kilowatt system that provides heat and power to the South Pole Research Facility. Honda, SenerTec, and others are developing residential cogenerating systems of roughly 2 to 5 kilowatts—some with 90 percent efficiencies—which can run air conditioners, though some analysts believe they will be used mainly for standby purposes.[37]

TABLE 2

Combustion-based Micropower Options

	Reciprocating Engine	Microturbine	Stirling Engine
Current size range (kilowatts)	5–10,000	30–200	0.3–25
Electrical efficiency (percent)	20–45	27–30	15–30
Current installed cost (U.S. $ per kilowatt)	$600–$1,000	$600–$1,100	$1,500
Expected installed cost with mass production (U.S. $ per kilowatt)	<$500	$200–$400	$200–$300

Source: See endnote 37.

The worldwide market for reciprocating engines of 10 megawatts and below has been expanding: close to 17,000 megawatts of capacity were added between June 1997 and May 1999. The majority of these new units are diesel fired, although the share of natural gas-fired engines is rising and reached 20 percent in 1999. The proportion of engines used for continuous service, as opposed to standby or peaking purposes, has also grown: it stood at 46 percent in 1999. The 1- to 3.5-megawatt engines are the fastest-growing segment, and the fastest-growing markets are Western Europe and North America, which together placed more than 3,500 orders for 1- to 3.5-megawatt systems between mid-1998 and mid-1999. Orders at this size grew 60 percent in South America but dropped by more than half in Southeast Asia in the wake of the region's economic downturn.[38]

Reciprocating engines do raise concerns, however. "Lean burn" engines and catalytic converters are being adapted to reduce nitrogen oxide and other emissions, which raises their cost. Converting to natural gas or biodiesel also makes these engines more expensive. Companies generally have to use mufflers and soundproofing to reduce their noise. According to one estimate, just servicing the system can amount to as much as one third of the total generation cost.[39]

Reciprocating engines will compete with two types of combustion turbines. Gas turbines derived from jet aircraft engines, popular in the range of several hundred megawatts, are being scaled down to a few hundred kilowatts. More than 500 of them, sized between 1 and 30 megawatts, were shipped worldwide in 1998. But a more radical type of turbine is the turbogenerator or microturbine. Under development for several decades, it has benefited from major military research efforts aimed at figuring ways to use it in cruise missiles. A number of firms—several with aerospace backgrounds—are preparing to bring microturbines to the commercial market, where they expect them to be one of the most competitive distributed applications.[40]

A mix of low- and high-tech elements, microturbines have several advantages over conventional engines.

Composed of a regenerative gas turbine and a single-shaft compressor, the most advanced versions are air cooled, can vary their speed electronically, and—because they have only one moving part—have no gearbox or lubricating oil requirements. Their engine speeds are also very high, ranging from 80,000 to 100,000 rpm. They offer low capital costs with mass production, low maintenance costs, high reliability, high suitability for cogeneration applications, and low nitrogen oxide emission levels. And they are adaptable to a broader array of fuels, such as natural gas and biogas, which makes them viable where piped gas is not available.[41]

The microturbine is expected to compete primarily with reciprocating engines and fuel cells, with initial cost, maintenance requirements, and air quality serving as important factors. At the moment, reciprocating engines hold an edge in terms of efficiency at scales of several hundred kilowatts; but at sizes below 100 kilowatts, microturbines appear to have an initial advantage over the other two systems, particularly when providing heat via cogeneration applications. Other promising uses may be in hybrid systems with fuel cells.[42]

The initial commercial microturbines range in size from 28 to 75 kilowatts, though larger units, above 200 kilowatts, as well as smaller ones are also under development. Elliott's 45-kilowatt cogenerating system, for example, has an overall efficiency of 85 percent. Capstone has shipped several hundred of its 28-kilowatt units at roughly $1,000 per kilowatt after testing runs in restaurants, factories, bakeries, and banks. Working with NiSource, it has installed a cogeneration unit at a Walgreens drugstore in Indiana, and it plans to market the system in the United Kingdom and Japan. Honeywell is commercializing a 75-kilowatt unit, now running in a suburban Chicago McDonald's, and is testing the system in Europe.[43]

Some industry members anticipate rapid growth in use of microturbines as their production is ramped up and costs drop. Capstone president Åke Almgren, who predicts a $1-billion microturbine industry in five years, calculates that an annual production volume of 100,000 units would lower the cost of a 30-kilowatt turbine to $400 per kilowatt. Turbines generating 100 kilowatts would cost just above $200 per kilowatt—less than half the cost of the most economical power plants now being built.[44]

The elder statesman of combustion engines is the Stirling, the namesake of Scottish theologian and engineer Robert Stirling. Invented in 1816 and used quite extensively in the late nineteenth century, the Stirling is externally heated, usually by combustion, to warm a gas that drives either pistons connected to a rotating power shaft (kinematic engines) or oscillating pistons that are supported by mechanical springs and gas bearings (free-piston engines). New piston designs using materials that reduce friction and wear have greatly improved the engine's efficiency and revived its economic viability. Both engine types are being developed by some dozen manufacturers around the world. Targeting the residential cogeneration market, many are packaging Stirlings as electric furnace or boiler replacements.[45]

The advantages of Stirling engines over reciprocating engines include their smaller size, relatively low noise levels, and potentially very low maintenance requirements—free-piston engines can run for more than 50,000 hours without maintenance. They also have comparatively greater potential for low-cost mass production. In addition, Stirlings can be adapted to a variety of combustible materials, including agricultural and forestry residues. Standard Stirling units can run on essentially any heat source above 1,000 degrees Fahrenheit, and are being tested for use with solar thermal parabolic dishes that concentrate the sun's radiation.[46]

Current Stirling engine applications, many for residential cogeneration in Europe, range from 500 watts to 3 kilowatts. While electrical efficiencies are low, overall efficiencies (with cogeneration) can reach up to 85 percent. Whisper Tech of New Zealand is working with a Dutch gas company to test and sell an 800-watt unit in European markets. The unit can be hooked up to a water storage tank, which allows it to supply hot water and run at full capacity even when limited heat is available. Another residential cogeneration unit is being tested by BG Technology of the United Kingdom. Sized at 1 kilowatt and run on natural gas, this Sunpower system is small enough to fit into a kitchen cabinet.[47]

The efficiency of Stirling engines at many scales enables the engine makers to experiment with both larger and smaller units. Sunpower, for example, is also working on biomass-run engines scaled up to 10 kilowatts. The Stirling Technology Company, which sells 350-watt engines for remote and cogenerating uses, is developing off-grid systems scaled at 3 watts that run quietly on woodchips.[48]

Cool Electrons

Like their combustion-based counterparts, the more revolutionary micropower systems—which rely on natural physical and chemical processes, are free of moving parts, and emit zero or few pollutants—are old concepts revitalized by technical advances. In 1839, British physicist William Grove found that hydrogen and oxygen could be combined to generate electricity. But fuel cells did not move beyond the laboratory until the mid-1960s, when lightweight but expensive versions were deployed as power sources for U.S. manned space missions. Further improvements have made fuel cells viable for use in powering automobiles, homes, laptop computers, and cellular phones. Researchers around the globe are working feverishly to turn them into a competitive power source.[49]

Fuel cells consist of electrochemical devices that combine hydrogen and oxygen to produce electricity and water. Installation costs remain high, as many current models are hand built by electrochemists and require platinum to catalyze the necessary reactions. (See Table 3.) But the past decade has yielded designs that could lead to far lower costs at a wider range of scales. One type, the phosphoric acid fuel cell (PAFC), is already commercially available. Considerable

TABLE 3

Non-Combustion-based Micropower Options

	Fuel Cell	Solar Cell	Wind Turbine
Size range (kilowatts)	<1–10,000	<1–1,000	<1–3,000
Electrical efficiency (percent)	35–50	–	–
Current installed cost (U.S. $ per kilowatt)	$2,000–$3,500	$5,000–$10,000	$900–$1,000
Expected installed cost with mass production (U.S. $ per kilowatt)	$100–$300	$1,000–$2,000	$500

Source: See endnote 50.

attention is also being given to the proton exchange membrane (PEM) cell, which has been demonstrated in a few locations and is nearing commercialization, with factories to mass-produce them now being built. Other types under development are solid oxide and molten carbonate fuel cells.[50]

Fuel cells have numerous advantages over combustion generators. The first commercial fuel cells derive their hydrogen from natural gas through the use of a reformer, producing nitrogen oxides and carbon dioxide in lower quantities than combustion engines. Virtually soundless, they are ideal in places like libraries, office buildings, and hospitals where noise is a concern. Later models may use hydrogen directly, leaving only water as a byproduct. Their lack of moving parts, meanwhile, minimizes maintenance needs.[51]

In the transportation sector, fuel cells still face formidable competition with the internal combustion engine (ICE). However, technical gains are improving the odds: in the last 15 years, researchers at national laboratories, universities, and companies such as Canada-based Ballard Power Systems have achieved a 30-fold reduction in the platinum requirements of PEM cells. Ballard fuel cell stacks with greater power and efficiency than the ICE at the same weight and volume have been tested in buses in Vancouver and Chicago.[52]

Such demonstrations have caught the attention of major automakers, all of whom now have fuel cell programs. Over the next three years, the California Fuel Cell Partnership, a collaboration of car and fuel cell manufacturers, oil companies, and government agencies, plans to test 50 demonstration cars and buses. DaimlerChrysler, which is collaborating with Ballard and Ford to develop fuel cells, plans to begin selling buses in Europe in 2002 and to have 40,000 passenger cars commercially available by 2004. General Motors has also adopted the 2004 goal, while Honda and Toyota have set a 2003 target.[53]

At the same time, companies and research labs in eight industrial nations have ambitious stationary fuel cell programs. Some are starting to yield commercial uses for cogeneration of heat and power at industrial sites, backup power, wastewater treatment, and "green" technology and design facilities. The focus for stationary applications has evolved in recent years. While in the past, utilities tested large experimental fuel cell systems ranging from 2 to 11 megawatts, most manufacturers today are devoting more attention to smaller systems in the range of 5 to 500 kilowatts. They expect systems of 50 kilowatts and below to be used in basements and backyards of homes, shops, small businesses, hotels, apartment buildings, and factories; larger ones running up to several hundred kilowatts would power commercial buildings and other enterprises.[54]

As in vehicles, stationary fuel cell use has been limited by high costs—well above the $500–$1,000 per kilowatt of the gas-fired combustion turbine commonly used by utilities. Some analysts believe, however, that with further design and manufacturing improvements their various advantages could make these fuel cells viable in a large number of applications when prices reach $1,500 per kilowatt. A seven-kilowatt Plug Power unit was installed in the garage of a ranch-style house in June 1998 in Latham, New York; the dishwasher-sized system supplies the house's entire power needs during all but peak periods. GE MicroGeneration, a Plug Power-General Electric joint venture, plans to market this system and others sized up to 35 kilowatts to residences and small businesses worldwide beginning in 2001. Others developing residential systems include Northwest Power Systems, Avista, and Ballard, which is working with Japanese firms Ebara and Tokyo Gas to adapt its fuel cells to that nation's housing market.[55]

Larger systems for industrial and commercial use are approaching readiness, with several hundred 200-kilowatt PAFC units from firms like ONSI (now International Fuel Cells) operating in the United States and Japan, and with units of up to 500 kilowatts under development by many others. An estimated 85 organizations are researching or developing stationary PEM systems. Ballard plans to start selling 250-kilowatt systems, sufficient to run a medical or business center, in 2001 with multiple units linked up as needed. Fuel cell developers are also exploring combinations with gas turbines to boost efficiency. Siemens Westinghouse is working on a 220-kilowatt solid oxide fuel cell/microturbine system with an electrical efficiency of about 57 percent.[56]

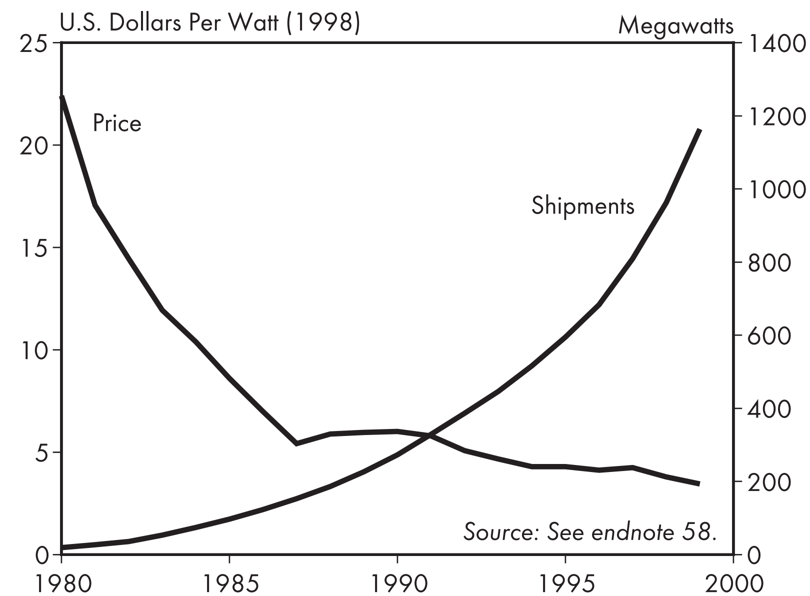
Other players are focusing on appliance-sized or smaller systems. Matsushita is developing 1.5- to 3 kilowatt cells; Sanyo is working on 1- to 2-kilowatt units; and H Power, which is emphasizing backup power, telecommunications, and transport applications (such as retrofitting road signs), is selling units in the 35- to 500-watt range. Fuel cells could also eventually supplant batteries in portable electronics, perhaps allowing cellular phones that run on standby for months, or laptops that operate for over 100 hours without needing to be recharged. Some experts believe that miniature fuel cells will displace batteries sooner than their larger versions will overtake the ICE: the former can tap several times more energy at a lower price and weight. They can also be refueled quickly, whereas batteries require lengthy recharging.[57]

Also descending from space to Earth is the solar photovoltaic (PV) cell, the world's second-fastest-growing energy source. PV cells employ the "photoelectric effect" discovered by Edward Becquerel in 1839, using semiconductor chips to create electric current. Utilized first in a host of off-grid applications where grid-based power was too costly or inaccessible—communications satellites, navigational buoys, highway roadsigns, handheld calculators—solar cells are now beginning to enter the grid-connected market in residences and on commercial rooftops thanks to a fourfold cost decline since 1980. (See Figure 2.) Marketed by firms like BP Solarex, Astropower, and Kyocera, these are typically 2- to 5-kilowatt systems, which can suffice to meet a residential household's needs.[58]

Other niches where PVs are emerging include solar shingles and window-glass-integrated systems, which have

FIGURE 2

World Photovoltaic Price and Cumulative Shipments, 1980–99



the potential to become cost-effective building materials; municipal buildings and transit stations; and “brownfields,” or abandoned urban factories where land is inexpensive. But larger markets for PVs will require further cost declines. The accounting firm KPMG estimates that a large-scale production factory that annually manufactures 500 megawatts of PV modules—more than twice current world production—could achieve a 60–80 percent reduction in price, making PVs competitive for small-scale users.[59]

The PV market is currently dominated by three technologies. Single-crystal silicon cells are the leading type, followed by polycrystalline silicon cells; together, the two generate at least 80 percent of global sales. Thin-film amorphous silicon cells, which account for roughly 16 percent of sales, are generally less efficient than crystalline cells but are believed by some experts to have the most potential for future manufacturing cost declines.[60]

The governments of several countries, including Germany, Japan, and the United States, have launched nationwide solar roof programs that offer financial and technical support to interested individuals and businesses. In Japan, roughly 50 megawatts of rooftop systems have been installed on some 30,000 homes—including more than 9,000 in 1999 alone. Innovative efforts to promote PV use are also materializing in the developing world, often supported by governments and international agencies.[61]

Wind power is the world’s fastest-growing energy source, boasting a 24 percent average annual growth rate in the 1990s. Generally consisting of three-bladed devices that capture the wind’s kinetic energy, today’s systems employ fiberglass technologies, advanced electronics, and aerodynamic engineering. In contrast to the other technologies, turbine scales are increasing: the most popular models today range from 600 to 1,000 kilowatts, while a number of 2- to 3-megawatt versions are on or near the market or nearly ready for sale.[62]

Although many grid-connected projects consist of wind “farms” or “parks”—large aggregations of windmills or turbines—the turbines are more dispersed in Germany and Denmark, two of the world’s leading users. There, most turbines are sited individually or in clusters of two or three, are connected directly to local distribution systems, and are owned by farmers or farmers’ cooperatives. In Germany, wind power accounts for 2 percent of total electricity; the share is between 10 and 15 percent in some northern regions. Wind’s portion is 7 percent in Denmark, where firms like Vestas and Bonus have made the nation the world’s leading turbine exporter.[63]

The cost gap between wind and conventional power continues to close. According to the U.S. Department of Energy, wind power is now directly competitive with new gas-fired plants in some regions. In windy areas such as the inland plains of North America and China, distributed systems can meet electricity needs and augment rural incomes. Several European nations and companies are moving aggressively to tap the even larger offshore wind resource; Royal Dutch Shell is planning projects in the North and Baltic seas. A recent report by Germanischer Lloyd and Garrad Hassan estimates that along the coastal regions of these two seas, out to a depth of 30 meters, enough wind potential exists to meet the continent’s entire electricity needs.[64]

The cost gap between wind and conventional power continues to close.

Another study, from the Forum on Energy and Development, estimates that wind power could supply 10 percent of global electricity by 2020 if recent growth rates are sustained. However, this would require that annual investments reach $78 billion in 2020, or 40 percent of annual investments in all electric generating capacity in the 1990s.[65]

Small-scale applications of other renewable energy technologies may also increase, though probably less dynamically than solar and wind. Small geothermal projects, now in use in the United States, Iceland, New Zealand, Asia, and Latin America, can displace diesel generators in remote rural regions. Microhydro systems at scales down to 50 watts are becoming prominent in Nepal, Peru, Bhutan, and in some parts of Europe and the United States. Small wave and tidal systems are expected to become commercial over the next decade. Biomass gasifiers as small as 100 kilowatts, combined with diesel and gas generators, are in use in rural India, China, and Indonesia to convert crop waste. Supplemented by others, these small-scale technologies will contribute to a more downsized, decentralized, and diversified power system.[66]

Is Smaller Cleaner?

Like many future classics, the thin volume published in 1973 by a former chief economist of the British National Coal Board initially created controversy. E.F. Schumacher's *Small Is Beautiful* urged society to "leave behind its obsession with megasystems of production and distribution," which he found "overorganized" and destructive, both to the human spirit and to the planet. Schumacher's principles of economics rested on the use of "methods and equipment which are cheap enough to be accessible to virtually everyone; suitable for small-scale application; and compatible with man's need for creativity"—to build a relationship between humanity and nature that could be made more permanent.[67]

An energy variation on this argument was made in *Foreign Affairs* in October 1976 by an analyst named Amory Lovins. In "Energy Strategy: The Road Not Taken?" Lovins applied the question of scale to the power system, criticizing the historical approach of supplying energy in excessive amounts and in an inefficient manner; at the highest quality possible, whether or not high quality was needed; and at a scale of between one and 100 million times the actual use. Challenging the "bigger-is-cheaper" concept, his article posed a question that remains relevant today: do small power systems, made appropriate to the scale needed, have economic benefits that large centralized power systems do not?[68]

Nearly a quarter century later, Lovins and Rocky Mountain Institute (RMI) colleague André Lehmann are still asking this question, pointing out that they count roughly 75 benefits from using power at a scale closer to the amount needed. Their forthcoming book, *Small Is Profitable*, shows that three quarters of U.S. residential customers use electricity at an average rate as low as one millionth the size of a conventional power plant, avoiding the latter's "diseconomies of scale." (See Table 4.) Including all of these benefits in comparisons of power sources, they argue, could make wind farms more economical than natural gas-fired combined-cycle plants, and bring PVs into the range of broad cost effectiveness. (See Table 5 for a synthesis.)[69]

Earlier, concentrated fossil fuel resources may have been a logical choice for centralized, large-scale generation based on thermal combustion. Increased electricity demand spurred the aggressive extraction, processing, distribution, and use of fossil fuels and the construction of large nuclear and hydroelectric facilities. The discovery and exploitation of new reserves in turn lowered costs, increased demand, and enabled faster power supply expansion. This symbiotic relationship resulted in a 1,000-fold increase in electricity use and a 20-fold increase in fossil fuel burning between 1900 and 2000; between 1950 and 2000, hydropower capacity increased nearly 16-fold, and that of nuclear power from zero to nearly 345,000 megawatts.[70]

Electricity's environmental impacts, which once mainly affected local communities, became regional and global as well. Tied to fossil fuel mining, extraction and combustion, nuclear fission, and the construction of massive hydroelectric dams, the large-scale generation, transmission, and distribution of electricity is currently among the most ecologically disruptive of all human activities. Environmental impacts from central power transmission and distribution involve extensive land use requirements and visual blight. Impacts related to power generation are even more pervasive.[71]

Fossil fuel-based electricity is linked to several air pollutants—particulates, sulfur dioxide (SO_2), nitrogen oxides

TABLE 4

Scales of Selected Electricity Use and Supply, United States

Use	Approximate Scale (kilowatts)
Portable radio	.0001
Cellular phone	.001
Portable computer	.01
Desktop computer	.1
Household average	1–1.5
Commercial customer average	10
Passenger car engine average	25–50
Supermarket	100
Medium-sized office building	1,000
Medium-to-large factory	1–10,000
Peak use of largest buildings	100,000
Peak use of largest industries	1–10,000,000
Supply	
One central thermal power plant	1,000,000
Large power plant cluster	10,000,000

Source: See endnote 69.

(NO_x), ozone, and carbon monoxide—that contribute to human respiratory ailments. U.S. utility power plants, which rely on coal for 56 percent of their electricity, account for 64 percent of national SO_2 emissions and 26 percent of NO_x emissions, as well as 33 percent of mercury emissions—which accumulate in aquatic species and, among other things, endanger fetal development via the food chain. SO_2 and NO_x also cause acid deposition, impairing natural ecosystems, buildings, and crops. In addition, nitrogen contributes to eutrophication of waterbodies. In the form of nitrous oxide, it is also a greenhouse gas.[72]

TABLE 5

Eight Hidden Benefits of Micropower

Benefit	Description
Modularity	By adding or removing units, micropower system size can be adjusted to match demand.
Short lead time	Small-scale power can be planned, sited, and built more quickly than larger systems, reducing the risks of overshooting demand, longer construction periods, and technological obsolescence.
Fuel diversity and reduced price volatility	Micropower's more diverse, renewables-based mix of energy sources lessens exposure to fossil fuel price fluctuations.
"Load-growth insurance" and load matching	Some types of small-scale power, such as cogeneration and end-use efficiency, expand with growing loads; the flow of other resources, like solar and wind, can correlate closely with electricity demand.
Reliability and resilience	Small plants are unlikely to all fail simultaneously; they have shorter outages, are easier to repair, and are more geographically dispersed.
Avoided plant and grid constuction, and losses	Small-scale power can displace construction of new plants, reduce grid losses, and delay or avoid adding new grid capacity or connections.
Local and community choice and control	Micropower provides local choice and control and the option of relying on local fuels and spurring community economic development.
Avoided emissions and other environmental impacts	Small-scale power generally emits lower amounts of particulates, sulfur dioxide and nitrogen oxides, heavy metals and carbon dioxide, and has a lower cumulative environmental impact on land and water supply and quality.

Source: See endnote 69.

The rate of global warming in the past century, which scientists agree is at least partially human induced, is projected to triple or quadruple over the next 100 years, causing a range of impacts, including sea level rise, more frequent and intense extreme weather events, flooding coastal lowlands, and shrinking freshwater supplies. Carbon dioxide (CO_2) is the most important greenhouse gas, and electricity generation is the largest single source of global carbon emissions, accounting for more than one third of the roughly 6 billion tons emitted annually. All fossil fuel combustion emits carbon, though coal releases 29 percent more than oil and 80 percent more than natural gas per unit of energy.[73]

Power generation also imposes environmental burdens on land, water, and wildlife. Coal mining removes forest cover, contributes to soil erosion, and blocks stream flow, and increasingly it entails mountaintop removal. It also displaces poor populations, as do large-scale hydropower projects. Uranium mining releases radioactive gas, dust, and seepage from piles of waste rock. Both forms of mining create acidic mine drainage and discharge substantial amounts of heated water that cause long-term damage to aquatic ecosystems.[74]

In the case of wildlife impacts, a comparison between large-scale and micropower options is useful. The cooling systems of thermal and nuclear power plants can trap and kill fish. Large hydroelectric dams can directly cause fish fatalities or block migration patterns, leading to substantial population declines: U.S. dams are primarily responsible for a reduction in Pacific Northwest salmon from 16 million to 300,000 wild fish per year. Single events can also have an impact: the Exxon Valdez oil spill killed between 90,000 and 270,000 seabirds. Documented bird deaths related to wind turbines, by contrast, have been confined to less than 200 during the late 1980s, and the problem has since been addressed by careful siting and other practices.[75]

Solid waste and heavy metals provide additional environmental criteria for comparing micropower and larger systems. Two PV technologies, cadmium telluride and cooper indium diselenide, use semiconductors that employ heavy metals instead of silicon; but toxic cadmium and selenium releases are small and can be further reduced by improved fabrication, construction, and recycling procedures. While waste from biomass is not toxic, the flue gas and solid waste from coal plants contain high levels of arsenic, cadmium, and other toxic heavy metals.[76]

Large-scale power generation can pose radiation threats. In addition to the danger of catastrophic accidents, radioactive elements from nuclear fission increase the risk of cancer, damage organs, and affect cell development. Nuclear waste from irradiated fuel rods can also cause cancer or genetic damage and has prompted the creation of costly underground repositories. Nuclear reactors release low levels of radioactivity and lower-level waste that require expensive disposal and storage. Even coal-fired plants release some background radiation.[77]

Energy use can involve many processes, from mining and transportation to combustion and cleanup, and "life-cycle" assessments that take all these stages into account help gauge a power source's total environmental impact. Particularly relevant are the life-cycle air and climate impacts from coal, the fuel accounting for a 40 percent share of global electricity—and shares of 73, 75, and 95 percent in India, China, and South Africa, respectively. (See Table 6.) Producing and using limestone to remove sulfur from coal combustion, for example, releases more particulates than federal standards allow for U.S. coal plants. It is also the largest source of coal-related carbon emissions other than combustion, with emissions more than double those for transporting the fuel.[78]

Life-cycle analysis of micropower systems is also revealing. Solar PV has the highest life-cycle emissions among non-combustion options mostly because of the energy needed to make silicon, but they are much lower than those of combustion-based systems. The life-cycle impacts of reciprocating engines will depend on whether old, diesel-based or modern, natural gas-based systems are used; those from fuel

TABLE 6

World Electricity Generation, by Energy Source, 1980 and 1998

	1980		1998	
Source	Gigawatts	Share of Total Capacity (percent)	Gigawatts	Share of Total Capacity (percent)
Coal	635	32.7	1,260	40.2
Natural gas	169	8.7	495	15.8
Oil	540	27.8	311	9.9
Hydropower	459	23.7	678	21.6
Nuclear power	134	6.9	359	11.5
Renewables[1]	4	0.2	30	1.0
Total	1,941	100	3,133	100

[1]Includes biomass.
Source: See endnote 78.

cells will depend on the source of the hydrogen and the efficiency of the system. CO_2, NO_x, and volatile organic compounds will be released by reformers that derive hydrogen from natural gas in some fuel cells, but these levels can be halved if waste heat is reused. In the long term, fuel cells may run on hydrogen derived from biomass or from water using solar or wind energy, which would almost eliminate life-cycle greenhouse gas emissions.[79]

In general, the natural gas and renewable energy sources expected to run modern micropower systems are likely to have lower life-cycle emissions than the current mix. Combustion-based micropower systems using waste heat can attain overall efficiencies of 80 to 90 percent, as compared with overall efficiencies of 30–60 percent for a coal-fired power plant or 45–80 percent for a large natural gas-fired turbine. If they rely on cogeneration and cleaner fuels—either renewable flows or the cleanest of the fossil fuels, natural gas—micropower technologies also have 50 to 100 percent fewer emissions, on a per-kilowatt basis, of particulates, nitrogen and sulfur oxides, mercury, and carbon dioxide.[80]

Micropower's carbon-saving benefits could be sizable. Studies indicate that the United States could cut power plant carbon emissions by half or more by meeting new demand with microturbines, renewable energy, and fuel cells. In the developing world, where half of new power generation over the next 20 years is projected to be built, comprising some $1.7 trillion in capital investments, power sector carbon emissions are projected to triple under a business-as-usual scenario. RAND Corporation reports suggest that widescale adoption of distributed power could help lower this trajectory by as much as 42 percent. These steps would also cut emissions of sulfur oxides by as much as 72 percent and nitrogen oxides by up to 46 percent, while lowering electricity prices by as much as 5 percent.[81]

The ecological benefits of micropower are worth comparing with those of the large, centralized combined-cycle natural gas turbines, most sized between 100 and 1,000 megawatts, that account for the bulk of new power generation globally—88 percent of new orders in the United States. When transmission and distribution losses are taken into account, large turbines offer only marginal efficiency and emissions improvements over the best steam turbine, and considerably less improvement than micropower options. Furthermore, many of these turbines are being packaged as 400- to 900-megawatt merchant power plants designed to run part-time and sell power to utilities when high demand raises prices. Although some 100 gigawatts of merchant plants are planned worldwide, almost 80 of them in the United States, they have been difficult to finance and have faced grass roots opposition due to concerns about noise, air pollution, and impacts on farmland and pristine areas. The need to weigh the comparative environmental benefits of micropower and merchant plants is likely to increase as societies struggle to meet changing and growing power needs.[82]

Running the Digital Economy

In February 2000, the prestigious U.S. National Academy of Engineering released its ranking of the top 20 engineering achievements of the 20th century. Topping the list was electrification, or, more precisely, "the vast networks of electricity that power the developed world" and the innovations that made them possible. Electricity, the release read, "...runs the smallest electric appliances in homes and offices, the mammoth computers that control power grids and telecommunications systems, and the machinery that produces consumer goods...it is hard to imagine our lives without it."[83]

Yet life without electricity had been a costly if temporary reality the previous summer, as a string of power disturbances and outages disrupted the lives of millions of people and thousands of businesses across the United States. Heat-related power equipment failures in New York City led to a 19-hour blackout of 200,000 residents of Washington Heights and ruined refrigeration-dependent cancer and AIDS research experiments at Columbia Presbyterian Medical Center. Power demand during a heat wave in Chicago caused three outages that left 100,000 customers without power and cut off 2,300 businesses and the entire Board of Trade one mid-week afternoon.[84]

In April 2000, Energy Secretary Richardson announced that the threat of blackouts would be even greater in the coming summer, noting, "We're worried as a nation, despite a hugely booming economy, about problems in our electricity grid." His department had just released a study warning that increased electricity usage and an aging infrastructure were stressing the system to the point of disrupting service; the report recommended on-site systems as one way to help utilities meet growing power demand. Utilities responded that they had made new investments and would be ready for the hot weather. But the Electric Power Research Institute, which estimates that power outages and fluctuations already cost the economy up to $30 billion annually in lost production, argues that the electricity system is in its worst condition since 1965.[85]

Even as it is celebrated as a pinnacle of 20th century engineering, the modern electricity network is revealing vulnerabilities that call into question its ability to meet the needs of 21st century society. The 1999 power equipment failures highlighted several decades of utility underinvestment in local distribution relative to generation. "The outages revealed a number of weaknesses...in the system," explained David Helwig, a senior vice president at Commonwealth Edison in Chicago. But the issue is not about generating enough power so much as being able to deliver it.[86]

In the modern world, the main threat to power reliability is the disruption of local supply, usually from weather damage to distribution lines or overloading of lines due to excessive demand. Distribution system failures account for 95 percent of the electricity outages in the United States. While heat waves can cause power demand from air conditioning to overwhelm electricity distribution systems, other weather extremes such as floods, ice storms, and hurricanes can knock down lines and cause widespread outages. In December 1999, a quarter of France's grid network was impaired by the nation's worst storm in a decade, leaving nearly 3 million people without electricity.[87]

The weakness of local distribution systems points not merely to the need to spend more on upgrading power lines and transformers, but also to the value of small generators that, by producing power within the local system, can lighten loads on distribution equipment. U.S. transmission and distribution expenditures have exceeded those of generation since 1994, and now stand at more than $10 billion annually. According to a report prepared for the Energy Foundation, between $800 million and $2.5 billion of these expenses could be profitably diverted to small-scale generators and improved energy efficiency given the financial benefits of avoiding power outages and spending more on grid upgrades.[88]

At the same time that old equipment and strained transmission networks are casting doubt on the reliability of large, centralized power systems, modern society's growing dependence on digital, computerized processes is beginning to heighten the need for high-quality, reliable power. With the rise of computerized transactions and manufacturing, users are more susceptible to momentary voltage fluctuations or outages. In the past, such "glitches" were less important, causing lights and motors to dim or slow but not to fail. But greater reliance on computers demands voltage stability; computer networks cannot withstand disruptions longer than eight thousandths of a second, a timespan that utilities do not consider long enough to be categorized a failure. For businesses that already cite electricity as a critical lifeline service, growing use of "e-commerce" will increase the need for reliable power.[89]

Particularly at risk from unreliable power are computers at the heart of the financial system. If they shut down even for a moment, data can be lost and millions of dollars of transactions involving loans, credit cards, and automatic teller machines forgone. In 1997 a brief disruption of electrical supply—a mere "power flicker" to the local utility—caused a widespread crash of the computer system responsible for virtually all of the major transactions of the First National Bank of Omaha. The bank, which estimates that a one-hour power outage costs it $6 million, has now invested in a high-reliability system from Sure Power, consisting of four phosphoric acid fuel cells backed up by two flywheels and two diesel generators. The fuel cells supply 800 kilowatts of power to the data center's mainframe, and run at "six 9s," or 99.9999 percent availability. The system also reduces carbon emissions by 45 percent and other air pollutants by 95 percent relative to grid power.[90]

Not only banks, but supermarkets, restaurants, insurance companies, hospitals, and factories are all beginning to look to micropower to avoid costly interruptions in their electricity supply. In Anchorage, Alaska, the U.S. Postal Service is running five fuel cells that protect its automatic mail-processing system against grid power outages. In New

York City, Central Park police have installed a fuel cell and cut themselves from the aging grid; a new skyscraper at Four Times Square employs two fuel cells that provide supplemental power and maintain vital operations in the event of a blackout. Micropower is especially valuable for high-tech industries such as computer chips, semiconductors, pharmaceuticals, chemicals, and biotechnology, which rely on computerized manufacturing applications, and are vulnerable to slight power interruptions. The byproducts of micropower can be useful resources: computer chip manufacturing plants may employ fuel cells, Stirlings, or microturbines as a source of hot distilled water as well as reliable power.[91]

It is reasonable to ask whether a distributed power network would be more capable than the existing system of meeting the need for more reliable, higher-quality electricity. For many decades, utility engineers argued that centralized control of the system was necessary to maintain the reliability of the grid. Allowing millions of customers to operate their generators, they contended, would endanger the flow of current they had been entrusted to provide.[92]

Many analysts now argue the contrary: that an electric power system in which control is more decentralized may prove more reliable and better able to respond to weather extremes and fluctuations in demand. Some see electric power systems exhibiting a "bio-logic": evolving more along the lines of biological systems, such as ecosystems or the human body, that run not with a rigid, centralized hierarchy but with a decentralized series of feedback loops. Just as the brain does not need to track every bodily process—breathing, blood pumping, for example—for the system to function, power networks need not have a point through which all information flows.[93]

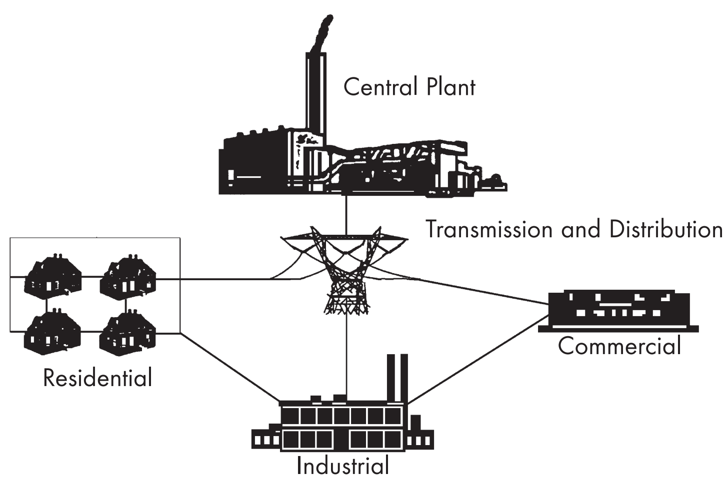
There are a number of ways in which innovations in telecommunications, power electronics, microelectronics, and storage systems might make a micropower-based network more reliable. Some utilities already employ telecommunications to start and run engines at customer sites when they are needed to support the grid. This type of "central dispatch" control of dispersed devices is common for water heaters, air conditioners, and on-site backup generators.[94]

Meanwhile, advanced power electronics like miniaturized chips, wires, and sensors are improving the ability to invert electrical flows from direct current to alternating current (or vice versa) at a reasonable cost. Most digital demands, moreover, are for direct-current power, which is offered by many micropower options. And new electronics make it easier to synchronize small direct-current generators with a grid tied to alternating-current transmission. The electronics also make it possible to isolate the system if the grid fails, allowing utility workers to repair power lines and transformers with little danger.[95]

At present, communications and power technologies are converging toward what some call an "intelligent" digital grid that can respond instantaneously to problems and run more efficiently than current mega-systems. The outcome may be a more "omni-directional" grid, a departure from the standard one-way street between central plant and

FIGURE 3

Schematic of a Centralized Power System



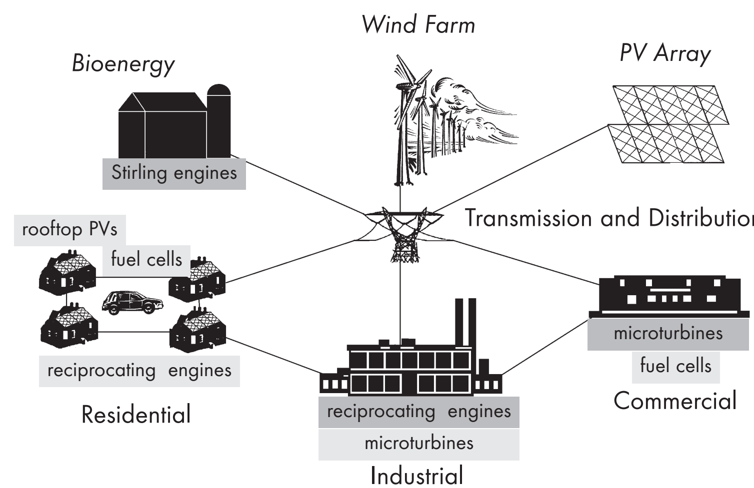
Source: See endnote 96.

end user. (See Figures 3 and 4.) This way, the owner of a refrigerator with the right communications and control equipment could, for a small reduction in the monthly bill, allow a utility to shut it down when overall demand is high. Similarly, a utility's computer can trigger a consumer's fuel cell to turn on when needed to supply the neighborhood's electricity. Some observers, pointing out that generating one's own power creates a clearer incentive not to waste it, see the role of the electricity meter itself changing or disappearing as local systems encourage greater efficiency.[96]

Computer-based software may also benefit micropower. Companies could, for example, communicate with and sell various "grades" of electrical current to customers seeking different levels of power reliability. A hospital could buy high-grade, or ultra-reliable, power for its emergency room and lower-grade power for its vending machines. A number of power-quality and "e-energy" companies are now emerging that use energy management software to let power companies control output from generators by way of the Web.

FIGURE 4

Schematic of a Distributed Power System



Source: See endnote 96.

While computers and the Internet may increase electricity demand, they could also displace more energy-intensive activities, and further save energy by selectively employing more efficient small-scale generators.[97]

Finally, storage technologies can improve micropower reliability by enabling greater use of power from intermittent renewable energy flows. Flywheels, batteries, and supercapacitors are among the devices under development and entering commercialization. Eventually, hydrogen may be produced through the splitting of water by renewable energy-derived electricity. Some analysts foresee a hydrogen delivery system emerging quickly with the proliferation of fuel cell cars, much as the ICE cars drove demand for oil. While the networks of micropower, hydrogen, and natural gas will need to be coordinated, the end result may be a system that is more reliable—and more compatible with the information age—than its predecessor.[98]

Electrifying the Powerless

A country renowned for marathon runners is setting a fast pace for the adoption of a new technology. Until the late 1980s, solar electrification in Kenya and other parts of East Africa was limited to affluent households and a handful of donor projects. Little in the way of government or international agency subsidies or support was provided, and the national Rural Electrification Program had connected less than 2 percent of rural households to the power grid. But falling PV costs and the efforts of private and volunteer organizations to provide communities with information and training fostered a vibrant commercial market with dozens of homegrown assembly, sales, installation, and maintenance companies.[99]

Today, Kenya boasts the largest per capita PV penetration rate in the world, with more than 100,000 systems sold, and sales averaging 20,000 modules per year. More than

200,000 Kenyans are being served with solar systems that are mostly 10 to 14 watts in size. PV market growth is outpacing grid connections under the official program, as rural electricians and Nairobi-based entrepreneurs and equipment suppliers compete vigorously. Providing a cheap, reliable alternative to kerosene, the program is also attracting lower-income people who have been waiting indefinitely for grid extension. Kenyan marketers now receive World Bank support, and efforts are being made to replicate Kenya's solar success elsewhere in the developing world.[100]

For all the remarkable generation-cost declines it achieved during the last century, the central, large-scale electrical model has yet to become cheap enough to reach 1.8 billion people living in rural parts of the developing world. Government rural electrification programs have provided grid electricity to more than 1.3 billion in developing nations since 1970, bringing the total to nearly 2 billion with access to power. (See Table 7.) But the majority of connections have occurred in or near urban areas, and in Asia and sub-Saharan Africa, the rate of electrification has not kept up with population growth.[101]

If China's electrification program is excluded, the share of rural people worldwide without power, 33 percent, has remained the same since 1980. In many regions, the extension of the electrical grid, which is typically the only approach considered, has been regarded as too expensive, costing as much as $10,000 per kilometer. Nor does village access necessarily mean household access: 80 percent of India's villages are electrified but a far smaller percentage of homes have power. Consequently, a number of nations have sizable rural-urban disparities in access to power. (See Table 8.)[102]

This inequity in electrical access creates several problems. It is highly detrimental to the health, standards of living, and future economic prospects of the rural poor, forcing them either to do without lighting and power or to rely on kerosene lanterns and diesel generators. It also poses the risk of social unrest. The issue of rural power is thus rising on the agenda of developing-nation decisionmakers who must con-

TABLE 7

Urban and Rural Access to Electricity, Developing Countries, by Region, 1970 and 1990

	Urban		Rural	
Region	1970	1990	1970	1990
	(percent)			
North Africa and Middle East	65	81	14	35
Latin America and Caribbean	67	82	15	40
Sub-Saharan Africa	28	38	4	8
South Asia	39	53	12	25
East Asia and Pacific	51	82	25	45
All Developing Countries	52	76	18	33
Total Served (millions)	320	1,100	340	820

Source: See endnote 101.

sider the possibility that millions of people will migrate to overcrowded cities in search of modern electrical services. "Power poverty" is becoming as unsustainable in the South as power outages are in the North.[103]

Where electric power systems do exist, they are even more brittle than in industrial nations. Transmission and distribution losses equal roughly 20 percent of power demand in India and Sri Lanka, more than 30 percent in Bangladesh and Nigeria, and over 50 percent in Benin and Haiti. In addition to placing a heavy burden on the environment, these systems impose a financial drain on government budgets, owing to their long lead times and inefficiency: infrastructure costs can represent as much as 40 percent of capital expenditures on new power capacity. For such regions, adding small-scale systems near the places where power is to be used often makes the most economic and ecological sense. In India, power unreliability has led industries to invest in on-site generation, which now accounts for 12 percent of national capacity.[104]

Traditionally, rural electrification programs have focused on connecting villages and other remote regions to

TABLE 8

Household Electricity Access, Selected Developing Countries[1]

	Percentage of Households with Electricity	
Country	Rural	Urban
Cote d'Ivoire	12.7	73.1
Ghana	4.3	61.7
South Africa	27.2	74.6
Ecuador	74.8	97.4
Jamaica	69.3	86.1
Nicaragua	33.1	92.3
Panama	48.7	98.1
Nepal	8.9	88.6
Pakistan	58.3	94.6
Vietnam	38.8	87.9

[1]Surveys conducted from 1988 to 1997.

Source: See endnote 102.

a national grid owned and operated by a public utility. Where grid electrification is too expensive, generators run by diesel or biogas are commonly used. Thousands of decentralized, isolated diesel generators now serve villages and towns in countries like Ghana, Bolivia, Yemen, and Pakistan. These relatively inefficient generators carry high maintenance and fuel costs, frequently requiring the trucking of spare parts and fuels. Meanwhile, hundreds of millions of people without diesel generators spend roughly $20 billion each year on ad hoc solutions like kerosene lamps, candles, open fires, and batteries in regions that have some of the world's largest indigenous renewable energy resources.[105]

The imperatives of economy and convenience increasingly make off-grid microhydro, solar PV, and small wind power systems attractive choices for rural electrification. In terms of technical performance, economic competitiveness, and reliability, these systems also compare favorably with the cost of extending transmission lines to unserved areas in many parts of the developing world. This is especially true in remote and island regions. The off-grid systems also offer a viable alternative for a range of critical village tasks, such as ice making; water desalination, purification, and pumping; and the operation of rural schools, police stations, and health clinics. They can, in addition, be used individually in homes or serve tens or hundreds of users through village "minigrids."[106]

The sustainable small-scale power options include retrofitting diesel generators to use biomass and other fuels, using diesel/wind hybrids, or using biomass in Stirling engines. Village-scale microturbines burning gasified biomass can reduce the unhealthful use of biomass for cooking, on which 2 billion people remain dependent. Excess corn stalks can be "trigenerated" by gasifying the corn to generate heat for district heating, cooking gas, and electricity, and the excess power can be sold to the utility grid and delivered to other villages. These options are particularly attractive in remote regions or small islands where imports are expensive. Microhydro systems can provide timely and reliable rural power, provided the water is stored in upper reservoirs. China alone has about 60,000 small hydropower stations, totaling roughly 17,000 megawatts or one fifth of overall rural electricity use.[107]

Existing small-scale applications provide a glimpse of their potential. (See Table 9.) Solar home systems now serve more than half a million households in China, the Dominican Republic, India, Indonesia, Kenya, Mexico, South Africa, and Zimbabwe. Wind power has begun to spread in China's Inner Mongolia region and in several Indian provinces.[108]

These rapid advances suggest that rural and urban regions of the developing world may "leapfrog" to the new downsized power technologies, much as some have moved directly to cell phones and beepers, bypassing the stationary systems and their expensive distribution networks. Where power lines are unlikely, so are phone lines; small-scale systems are thus well suited to powering radios, televisions, and computers. Nongovernmental organizations (NGOs) are working to promote solar-powered telecenters in west central India and Uganda. The Solar Electric Light Fund is attempting to link solar-powered computers in South African schools via satellite to the Internet.[109]

TABLE 9

Small-Scale Power Applications, Selected Developing Countries

China	Over 150,000 small-scale wind turbines operating; more than 500,000 people served.
	More than 200,000 solar home systems installed.
Dominican Republic	Over 9,000 solar home systems installed.
India	An estimated 1,095 megawatts of wind power capacity installed.
	More than 70,000 solar home systems installed.
Indonesia	Over 20,000 solar home systems installed.
Kenya	More than 100,000 solar PV systems installed (over 200,000 people served).
Mexico	Over 40,000 solar home systems installed.
South Africa	An estimated 50,000 solar PV systems in place, including in 1,300 rural schools, 400 rural health clinics, and 2,000–4,000 water-pumping systems; more than 84,000 PV modules ordered for wireless rural phone systems.
Zimbabwe	13,000 solar systems installed in rural homes, schools, and clinics; 70 local design and installation companies in business.

Source: See endnote 108.

South Africa has big small-scale plans of its own. Since 1994, the national utility Eskom has electrified 1.8 million rural homes through a grid extension campaign. Electricity costs, however, have been high, forcing many to revert to biomass during the winter. Meanwhile, 1 to 2 million households are too far from existing grids to be reached by the program. While PV systems have been widely installed in schools, rural health clinics, and wireless telephone systems, a large-scale solar home program had not been attempted until recently.[110]

In early 1999, then-President Nelson Mandela announced a rural electrification program to install 350,000 solar PV systems in remote rural areas. Seven private consortia are being considered for concessions in separate districts, where they are to develop rural energy utilities; the first two have been identified, with Eskom partnering with Shell Renewables and BP Solarex, respectively. The 1999 Eskom-Shell joint venture is aimed at installing 50,000 home PV systems over the next three years in areas where grid extension is not feasible. Using a public subsidy, rural utilities will adopt a fee-for-service approach to make small systems for lights, radio, and TV accessible to even the poorest homes along with cooking and heating.[111]

It is unclear, though, whether the new utilities will become self-sustaining. Investors may be reluctant to support off-grid electrification if there is a risk that the aggressive grid expansion program will later undermine it. The off-grid utilities will also need to sign legal contracts with the local authorities responsible for providing the people with electricity services in order to share the public subsidy. And a new regulatory framework has yet to be established to ensure that the national home solar system standard is being met and that rural utilities will be compensated in case their investments are overtaken by grid extension. As the South Africans are discovering, conventional markets often discriminate against small-scale power.[112]

Rewiring the Market Rules

The Great Depression of 1929 may have wiped out Samuel Insull's sprawling Chicago-based empire of utility holdings, but his legacy lived on for decades in the rules of electric power markets. Although the state-granted monopoly

promoted by Insull and others in the early twentieth century is now beginning to be dismantled, a slew of subsidies, regulations, and policies remain that reinforce large central-station power and inhibit the use of smaller systems. As Walt Patterson of the Royal Institute of International Affairs writes in his 1999 book, *Transforming Electricity*, "all too often . . . inherently decentralized technologies find themselves 'playing away', on the home terrain of the centralized system and according to its rules." Creating a fair playing field for micropower is a prerequisite for its spread.[113]

The "home rules" begin with the $120 billion in annual subsidies for fossil fuel and nuclear energy. Another key market barrier to small-scale generators is that they are not reimbursed for the grid support and environmental benefits they provide. (See Table 10.) The European Commission estimates the value of distributed solar power in Italy at more than 10 cents per kilowatt-hour—half from generating the solar power, and half from added reliability and grid support. Such values typically go unrecognized in the market, deterring micropower development.[114]

One solution to this "market access" problem is to reform the tariff and regulatory system. The electricity "in-feed" tariffs established in Denmark, Germany, and Spain, which have already spurred wind power use, require utilities to purchase wind-energy-derived electricity at prices ranging from 7 to 10 cents per kilowatt-hour. In March 2000, the German Parliament reformed its feed-law, continuing its strong support for wind and providing a generous 47-cent per kilowatt-hour payment for solar PV generators.[115]

Although its operating costs are much lower, micropower also has higher initial costs than conventional systems. One way to reduce these costs is to allow system owners to use their excess power to offset purchases from the grid, paying for the net amount used. This is the approach of the Japanese solar roof program, which permits customers to sell excess PV-generated power back to the electrical grid at the retail price, which runs as high as 23 cents per kilowatt-hour. In the United States, 30 states have adopted "net

TABLE 10

Eight Barriers to Micropower

- Higher initial capital costs
- Ownership rules
- Customers not rewarded for relieving peak load
- Impacts on local reliability ignored
- Unfair standby charges, exit fees, transition costs
- Burdensome interconnection requirements
- Discriminatory permitting, fire, building, and other codes
- Inequitable emissions policies

Source: See endnote 114.

metering" programs that permit PV system owners to run their meters backwards.[116]

As policies like net metering become more common, it will be important to standardize the requirements that exist for safely and reliably interconnecting power systems with the distribution grid. In many regions, utilities impose a melange of complicated requirements that typically increase the cost of installing a small-scale system by several thousand dollars. Many of these standards, furthermore, vary from utility to utility, making it difficult for a manufacturer to plan for a regional or national market. In January 2000, the Institute of Electrical and Electronics Engineers approved standards designed to simplify the process for PV interconnection with the grid.[117]

Complex power purchase agreements and discriminatory charges pose other barriers to fair competition. Local utilities often require small-scale system owners to sign lengthy agreements that are designed for systems in the range of hundreds of megawatts and thus deter installation. Utilities also commonly impose stranded-asset charges—which compensate utilities for uneconomic plants that regulators approved prior to competition—exit fees, and stand-by charges that, combined with requirements for utility grid interconnection, could as much as double the cost of small-scale power.[118]

Distribution utilities, which remain regulated monopolies under the current restructuring, often erect roadblocks to micropower because regulators generally tie profits to the amount of electricity delivered, making small-scale generation on the customer side of the meter a perceived threat. But these steps could ultimately hurt utilities by leading to "wire-cutting" as frustrated users find they can get less expensive, more reliable power by installing generators off the grid. To give distribution utilities an incentive to support micropower, regulators can cap revenues from power delivery and offer credits for improving reliability. Policymakers can also smooth the way for small-scale systems by setting cost limits on fees and charges for users, or even waiving them, and by establishing time limits for the approval of new micropower generators.[119]

Other policies to support a micropower system involve the standardization or elimination of siting and permitting requirements and emissions regulations that were established when small-scale power was not an option. Micropower is not accounted for in the building, electrical, and safety regulations in most industrial nations; local code and zoning officials tend to be unfamiliar with the technology. Homeowner associations concerned about lower property values often retain restrictions on modifications such as solar roofing well after developments have been completed. Land use planning and zoning laws favor the right to build over the "solar access" of neighboring property owners. Environmental regulations do not fully credit the pollution-reduction gains of small-scale systems, and sometimes exempt their older, dirtier competitors. These are problems that can be addressed through clear performance standards.[120]

Joseph Iannucci of Distributed Utility Associates identifies 10 "market accelerators" for micropower, concluding that if electric utilities do not take the lead in promoting distributed power, then customers—supported by aggressive new companies—will. (See Table 11.) This may already be occurring. Responding to surveys indicating strong consumer interest in paying small premiums, companies and utilities in Australia, Finland, Germany, the Netherlands, Sweden, the United Kingdom, and the United States are offering "green power" derived partly from solar, wind, and other clean energy sources. While sales have been limited, the potential has prompted BP Amoco and other investors to announce in May 2000 that they would invest $100 million in one of the leading marketers, GreenMountain.com. In California, the Sacramento Municipal Utility District has mounted nearly 500 systems on the roofs of homes of "PV Pioneers" who either pay small "green fees" of about $4 per month or buy the system at a discount and take part in net metering.[121]

Electricity restructuring presents an opportunity to address micropower's market barriers. If the thicket of regu-

TABLE 11

Ten Micropower Market Accelerators

- Simplified interconnection standards
- Modest or unpredictable growth in electricity demand
- Aggressive gas, energy service, and micropower vendors
- More efficient electricity pricing schemes
- Saturation of electric transmission and distribution systems
- Siting difficulties for new central generation plants and transmission and distribution lines
- Streamlined, standardized permitting procedures
- Electricity customer dissatisfaction with central power
- Technological improvement
- Demand for green energy

Source: See endnote 121.

latory barriers is cleared and incentives are installed, a more competitive market for power generation may encourage a more small-scale and decentralized system. Beyond market access policies, net metering, and standardized interconnection and siting requirements, governments can use tax incentives, public R&D, and renewable energy standards to support micropower development and use. In addition, government procurement can speed up the "virtuous cycle" of falling costs and increasing production, much as U.S. government purchase and use of semiconductors played a critical part in spurring growth of the Internet. The closing of loopholes that exempt the oldest, dirtiest plants from environmental regulations would, furthermore, allow small-scale systems to displace existing capacity more quickly.[122]

Developing nations have a unique opportunity to get these market supports right the first time, avoiding at the outset the adoption of rules that favor and lock in a dirtier, less efficient system. By including or requiring the inclusion of the cost of power delivery—not just generation—in investment decisions and power generation bids, policymakers can ensure that tomorrow's markets will not be biased toward yesterday's electricity model. This approach will also reduce emissions and could spur dynamic growth in emerging industries, as has happened with wind turbines in India. Kenya's PV market, meanwhile, shows the importance of performance standards for the new technologies and the ability to attract a range of commercial interests. Also vital are policies that support independent power producers and limit or remove taxes and tariffs on clean energy.[123]

Back in the industrial world, stakeholders in a micropower system are organizing politically and pressing for the overhaul of market rules that discriminate against small-scale power. The California Alliance for Distributed Energy Resources, for instance, has prodded the state's Public Utilities Commission to examine distributed generation issues. The Distributed Power Coalition of America, which has 69 members, advocates a range of policies to address micropower in national restructuring legislation: standardized interconnection rules, streamlined permitting standards, net metering requirements, new tax code provisions, and reduced stranded-asset charges for users. Unlike Insull and his contemporaries, who pushed for consolidation and monopoly, these networks advocate decentralization and fair competition in the power business.[124]

Finding Financing

Although utility stocks have long been considered stable and unexciting, suitable for "widows and orphans," those belonging to a handful of power industry newcomers behaved out of character in the first months of the new millennium. Stock in Plug Power, which had opened at $15 per share the previous November, leapt from the low $20s to a high of $156 before dropping close to $50 by mid-May. Shares in Ballard jumped from the $20s to nearly $145 before dipping into the $70s. Astropower, Spire, and Energy Conversion Devices also experienced stock gyrations, with most staying well above pre-surge levels. Ballard raised large amounts of capital through a secondary offering, while those that had not yet gone public found themselves the friendly focus of investment bankers.[125]

The recent investor interest in micropower companies indicates a deeper trend, paralleling that described in *Networks of Power*, Thomas Hughes's survey of the development of electric power systems in Western society between 1880 and 1930. Initially, "inventor-entrepreneurs" like Edison were the key actors, presiding over the creation and early application of their innovations. Later on, other entrepreneurs—"manager-entrepreneurs" and "financier-entrepreneurs"—such as J. P. Morgan began to take center stage as the problems blocking the growth of the new system became more managerial and financial. Inventors and engineers still played an important role in the evolution of the system, but were complemented by players experienced in the complexities of organization and financing.[126]

The new electric power system appears to be evolving in the same way. Echoing Hughes, equity analyst Hugh Holman explains that "one reason we take a more optimistic view toward the future of energy technology is that we see a new breed of entrepreneur appearing in the power industry—the financial, versus the techie, entrepreneur….Thus, from day one, the financial entrepreneur brings rigor to the management of a technology startup and has an eye on the financial end game, the exit strategy." Holman lists a growing number of investment funds, both venture capital and those funding companies at a later stage, that specifically target business opportunities created by energy deregulation, as well as venture funds that include energy-related investments in their diversified portfolios. (See Appendix B.)[127]

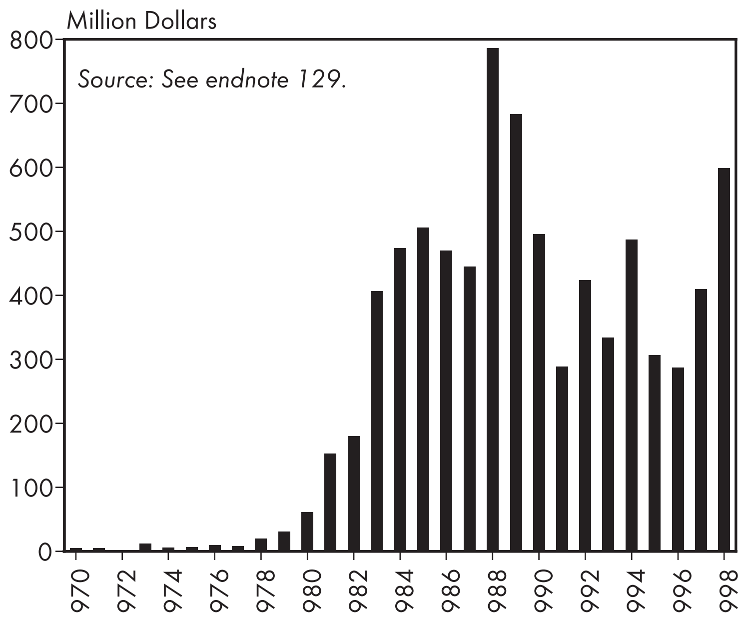
For small, less-established high-technology firms that often lack initial access to capital markets, venture capital funds can provide essential seed finance, experienced advice, and access to managers with business skills to balance those of the more technically inclined entrepreneurs. The United States has the most highly developed venture capital market, with hundreds of funds reviewing thousands of financing proposals each year. Although the first fund was started in Boston in 1946, the model was copied and improved upon on the West Coast, where it has driven the Silicon Valley information technology revolution and the biotechnology revolution that originated in San Francisco. As restructuring picks up in the United States, with 24 states now starting to open their power generation to competition, energy-focused venture firms are appearing.[128]

One prominent firm, San Francisco-based Nth Power Technologies, has invested its first $65 million and is raising another $75–$100 million. Current investments include micropower technology suppliers as well as firms that focus on providing power quality. Nth Power's investors are utilities—among them Pacificorp, Sierra Pacific, and Electricité de France—that see these technologies as a marketing tool for attracting customers in a competitive market. Founding partner Maurice Gunderson views the utility industry as sitting roughly where the telecommunications industry sat in 1982, when court rulings and laws were opening the door to a decentralized future but investment capital had not yet flooded the market. (See Figures 5 and 6.) He expects energy venture capital investments to reach $500 million in the next five years, as more utilities recognize that the new market is likely to be small scale and run by many startups: "We're only at the beginning of the growth curve."[129]

Robert Shaw of Aretê Corporation, a pioneer in energy venture investments, concurs that the power sector is "hot" among investors. Pointing to the early-2000 stock surges and the "IPO fever" among financiers hoping to launch initial public offerings for private startups, Shaw cites growing con-

FIGURE 5

Venture Capital Investment, U.S. Telecommunications Industry, 1970–98



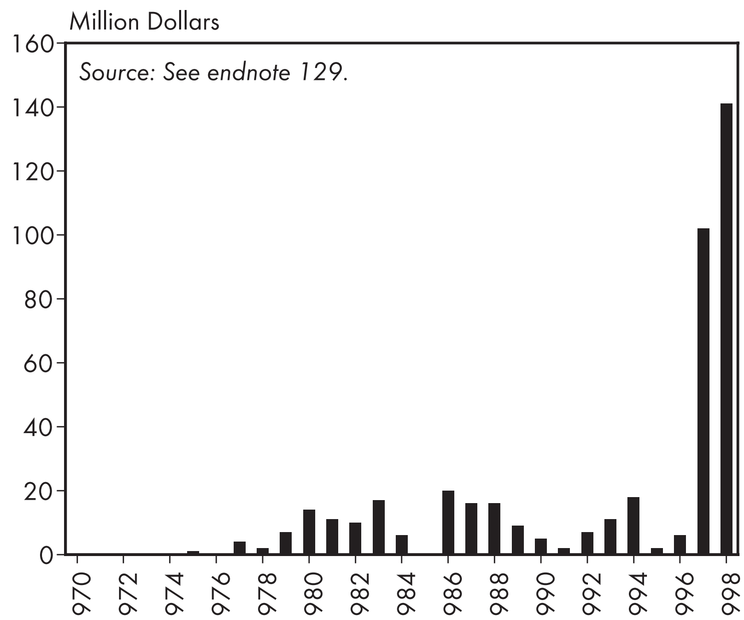
sciousness of the importance of highly reliable power for the new Internet economy as a main reason for this sea change in attitude. A widening circle of Wall Street analysts shares his view: Judy Sack of Morgan Stanley Dean Witter believes that "micro-generation . . . will have decimated the electric distribution monopoly" by the middle of this decade.[130]

Micropower is already attracting the interest of computer industry executives. Capstone's computer industry investors include Compaq founder Ben Rosen and Microsoft founder Bill Gates, who also holds a 5 percent share of Avista. Microsoft President Steve Ballmer counts "the explosion of power available to operate systems" among the main contributors to future changes in Internet infrastructure.[131]

Micropower venture funds are also appearing overseas

FIGURE 6

Venture Capital Investment, U.S. Electric Power Industry, 1970–98



in Europe and Australia. Hakan Blomqvist of Arbustum Invest believes the alternative energy market will take off within five years. In 1999, his and two other Swedish firms purchased Nordic Windpower, which has developed a two-bladed offshore windmill that the investors believe has major growth potential.[132]

While micropower companies focusing on the grid-connected, industrial-nation market are beginning to attract private investment, the off-grid, developing-nation market faces a different sort of financing challenge: the technology is already cost-effective, but people cannot afford it. Consequently, micropower is beginning to benefit from the "microcredit" approaches that have evolved over the last two decades to meet the special needs of the poor. The Bangladeshi Grameen Shakti, a renewable energy affiliate of the non-profit Grameen Bank, provides small loans to the poor to help them handle the initial cost of purchasing solar and wind power systems: PV system buyers receive loans of about $500 for up to three years, paying for 15 percent of the system cost as a down payment. Focusing on isolated and neglected communities, the program has to date installed more than 1,000 solar home systems. The microcredit strategy has also proven effective in installing 10,000 PV systems in Zimbabwe, 20,000 systems in Indonesia, and more than 1,000 systems in Sri Lanka.[133]

One factor in the success of Grameen Shakti has been support from the Small and Medium Scale Enterprise (SME) Programme of the World Bank's private sector arm, the International Finance Corporation (IFC). This enabled Grameen Shakti to lengthen credit periods from one to three years, increasing interest in the program. The SME program, which beyond Bangladesh has supported the installation of some 3,500 PV systems in the Dominican Republic and Vietnam, is one of several joint IFC/Global Environment Facility (GEF) projects to provide firms with business financing and advice. (See Table 12.)[134]

Noting successful PV commercialization efforts in China, Indonesia, Kenya, and Zimbabwe that have not relied

TABLE 12

World Bank Group Initiatives—Micropower Projects and Startups in Developing Countries

Initiative	Funding (million dollars)	Objective
Photovoltaic Market Transformation Initiative (GEF/IFC)	$90–$120	Finance commercial solar home system business ventures in India, Kenya, and Morocco through competitive bidding procedures.
Renewable Energy and Energy Efficiency Fund (GEF/IFC)	$100–$200	Catalyze and finance investments in PV, wind, microhydro, biogas, and geothermal projects for off-grid and utility markets in developing and transitional economies.
Small and Medium Scale Enterprise Programme (GEF/IFC)	$1.58	Finance commercial solar home system business ventures in Bangladesh, Dominican Republic, and Vietnam.
Global Solar Development Corporation (GEF/IFC)	$50	Finance PV-related businesses and provide technical assistance and business services (managed by Triodos Bank).
Total	$241–$372	
Co-investment with Softbank in Internet startups, February 2000.	$500	

Source: See endnote 134.

on direct donor assistance, some observers are doubtful that large international institutions will be able to attract sizable private sector cash flows. Others are concerned that multilateral funding of small-scale power will inject hundreds of millions of dollars and create expectations of instant returns, or take the approach of a social service rather than that of a socially responsible business. Criticizing the Bank's project-by-project efforts as piecemeal, President James Wolfensohn has called for "systemic change" to make renewables (and possibly other distributed power) a major element of bringing electricity to the nearly 2 billion people without power.[135]

One such change might be for the Bank and other multilateral financiers to establish dedicated venture funds for micropower startups in developing countries. Using the "patient capital" approach of venture capitalists, the funds would build sustainable micropower markets by nurturing indigenous companies rather than specific projects or technologies. The World Bank could aggregate (and expand to other small-scale technologies) its existing solar and wind business ventures into a single fund.[136]

Such a fund might be patterned after the Bank's recently established $500 million venture fund with the Japanese firm Softbank to finance Internet startups in developing nations, with the aim of closing the "digital divide." Just as it is drawing on Softbank's Internet startup expertise, the Bank could seek out private investment partners with experience in financing micropower startups in the industrial world. Combining the Bank's contacts and experience in host nations and the startup savvy of micropower venture capitalists, this approach could attract far more funding than would otherwise be devoted to addressing "power poverty"—arguably a prerequisite to narrowing disparities in access to communication technologies.[137]

Other public and private sources can also be tapped. In the United States, 13 states will have roughly $2 billion from consumer surcharges over the next decade that they can use to remove market barriers to clean energy and lower its

finance costs. Some insurers are exploring "electrofinance": rolling the cost of a building-based solar or wind system into a commercial or residential loan or mortgage, as is often done for home appliances.[138]

The emergence of venture capital and microcredit for financing micropower is encouraging, given the track record of these relatively new approaches in spurring technological innovation and improving the access of the poor to new services. But these financial flows, while growing substantially from a small base, are a fraction of the roughly $200 billion invested annually in the global power sector in the 1990s, much of it for large central generation. The rate of future progress, furthermore, will hinge on the extent to which these technologies' benefits are better valued in the marketplace. As private investors awaken to their commercial potential, and public investors to their societal benefits, resistance to micropower-friendly market reform may well weaken. But getting people to see small-scale power as a financial opportunity, rather than a risk, is only one of many institutional challenges confronting the new technologies.[139]

Developing Micropower "Software"

In 1995, two Harvard Business School professors published an article that soon attracted considerable attention. Joseph Bower and Clayton Christensen explored a range of "disruptive technologies"—radial tires, small copiers, personal computers—that leading companies neglected and customers virtually ignored at first. To the surprise of many people, these technologies did gain small footholds in niche markets, and then suddenly grew at steep trajectories, leading to technical improvements that enabled them to eventually meet the needs of mainstream customers. Companies at the top—Goodyear, Xerox, and IBM—were overtaken as small, hungry organizations anticipated demand for these innovations.[140]

The reason established companies were blindsided, according to Bower and Christensen, is that they followed conventional criteria to ask whether these new technologies could outperform existing technologies rather than asking whether they could meet new market needs more effectively. Standard market research can be misleading: Polaroid's president was informed by his marketers, who did not see the uses of instant photography, that only 100,000 of his instant cameras would ever be sold. Instead, millions were eventually bought.[141]

Micropower displays many of the characteristics of a disruptive technology. It has important attributes that are not fully valued in today's marketplace, but it is nevertheless gaining footholds and growing at a quickening pace. And small, hungry companies that anticipate its future use are threatening to upset the market dominance of monopoly utilities. Many companies and analysts still evaluate micropower by conventional criteria rather than by its ability to meet new market demands. Thus they make conservative market projections for small-scale systems and expose themselves to the risk of being caught flatfooted.[142]

Indeed, even as micropower moves from research and development to factory and market, many electric utility executives and industry analysts are skeptical as to whether small-scale, mass-produced generators can provide a viable alternative to large central power plants. Edison, similarly, encountered skepticism from those who doubted electric lamps could replace gas lighting, and resistance from those who perceived his invention as an economic threat. Gas lighting companies tried to block construction of the Pearl Street station, arguing to politicians that severe job losses would result. Some workers even sneaked into the inventor's shop on the night of the demonstration of his invention with the intent of sabotaging the equipment and publicizing its failure. The early waves of micropower installations may not face direct sabotage, but they are likely to encounter intense scrutiny and criticism from some quarters.[143]

One argument leveled against micropower is that the devices are too small to make a major contribution toward

meeting the electricity needs of a modern economy. However, this claim does not stand up against several simple calculations. The power rating, or maximum engine capacity, of the average American car is 124 kilowatts; thus the U.S. auto industry's annual production of roughly 6 million cars provides some 744 gigawatts of capacity. This amount is comparable to the country's 1998 total installed capacity of 776 gigawatts. The existing U.S. car and truck fleet, meanwhile, represents more than 200 million reliable, self-generating power plants with a capital cost less than one tenth that of a large central generator.[144]

Current market assessments suggest that a substantial amount of micropower use is coming in the near term. The business research group Allied Business Intelligence projects a U.S. fuel cell market of $10 billion by 2010, totaling more than 10 gigawatts and driven primarily by power reliability and quality needs. Market studies by the Electric Power Research Institute and other groups suggest that by then micropower could provide between 5 and 40 percent of annual new capacity in the United States, depending on how the details of restructuring are worked out. The European Union, which aims to double its renewable energy use by 2010, projects that 60 percent of this potential may be met by small-scale power. Like the first Polaroid surveys, however, these projections may underestimate the true potential.[145]

The timing and extent of micropower deployment will depend not only on the "hardware"—the technological and financial basis—but also on the "software": the institutional capacity for fostering greater public understanding, acceptance, and use of the systems. To many businesses, governments, NGOs, and education and research organizations—for decades accustomed to manufacturing, supporting, and studying large-scale central power—radically downsized electricity represents disruptive change. But as the conventional model reveals itself to be economically, politically, and environmentally unsustainable, these stakeholders may recognize their interest in helping micropower become established. This broader institutional support could create a wider constituency for the new technologies, catalyzing the positive feedback of technology, capital flow, and policy change that brought unprecedented innovation within the telecommunications industry. Here as well, the result could be better customer service at a lower cost.[146]

Greater dialogue among regulators, micropower advocates, and distribution companies can help build micropower markets. By collectively identifying benefits of small-scale power as well as barriers that stand in their way and then developing supportive policies, these groups can build demand for these systems. While some utilities may not support micropower without external prodding, and could continue to take defensive steps to slow its spread, a growing number do see the business opportunities and are willing to work with other groups to determine how the new technologies can meet their needs. Chicago's Commonwealth Edison, for example, is collaborating with community and environmental groups to explore ways to deploy small-scale power on a neighborhood-by-neighborhood basis.[147]

Indeed, new business models may evolve around the new micropower technologies, just as the vertically integrated utility developed in tandem with central-station power. Lest they repeat the mistakes of IBM, utilities and firms currently vested in large-scale power face the management challenge of "cannibalizing" themselves: creating businesses that may eventually displace their existing core operations. Former AlliedSignal President Tony Prophet frames the varied responses of utilities to this challenge this way: "At every point of evolutionary change, the survivors always adapt. Some of the dinosaurs turned into mammals. The others became fossils."[148]

The test for government agencies, meanwhile, will be to mainstream micropower into operations. A U.S. National Research Council study has recommended that the Department of Energy create a dedicated office to deal with distributed power systems that will define their benefits to national interests, coordinate standards to open markets, and address the institutional barriers they face. The agency

has formed a Distributed Energy Resources Task Force to begin this coordination. The agency is also working with universities and industry to help promote small-scale systems in places like research parks.[149]

International collaboration and research cost sharing between and among governments and industry could spur small-scale power. The U.S. President's Committee of Advisors on Science and Technology projects a $10 trillion worldwide energy market over the next 20 years, much of which could be captured by farsighted companies drawing on appropriate governmental backing. The panel observes that European and Japanese wind and solar firms have received considerable public support for exporting their technologies, which has enabled them to grab market share from American counterparts.[150]

Indeed, new business models may evolve around the new micropower technologies.

Beyond export markets and technological leadership, the prospect of reduced oil import dependence, air pollution, nuclear safety risks, and climate disruption provide additional justification for promoting micropower systems globally. The U.S. government is supporting the California-based Nautilus Institute's installation of three small wind turbines in power-deprived, famine-stricken rural North Korea, in part to lessen bilateral tensions over nuclear proliferation. The Kyoto Protocol's Clean Development Mechanism is another avenue through which near-commercial micropower technologies might be funneled—serving "Northern" climate commitments and "Southern" development objectives while driving down the cost of the new systems.[151]

Governments and NGOs face the formidable responsibility of raising public awareness of micropower's benefits and its financing options. The London-based group Intermediate Technology, for example, has published a guide for development organizations on the financing of renewable energy projects; and the National Renewable Energy

Laboratory (NREL) has produced consumer's guides on buying solar electric systems. Training homeowners on installation, maintenance, and repair of the systems is another step: one factor in the success of China's Inner Mongolia wind program has been the use of printed instructions that are accessible to the herdsmen. NGOs can also provide key information to businesses that may value micropower's reliability "niche" but are unfamiliar with the technology. The Clean Energy Group, for instance, is helping Harvard Medical School explore the use of fuel cells for its teaching and laboratory sites.[152]

Greater information sharing among government officials, NGOs, academics, utilities, and companies can facilitate micropower's spread. Whether in East Asia or Europe, efforts to replicate successful programs elsewhere are frequently limited by lack of institutional support and access to information. The World Bank and NREL annually cosponsor Village Power conferences where policymakers and nongovernmental, and industry representatives share experiences and ideas related to small-scale system applications in developing nations. Solar, wind, and other trade associations provide similar fora to discuss efforts to promote clean energy.[153]

A major educational challenge is to advance the field of interdisciplinary, small-scale, decentralized energy studies, which has in the past suffered from institutional neglect and even active discrimination. Daniel Kammen of the University of California at Berkeley observes that "scholarly attention to the problems of small-scale and decentralized energy systems is notable primarily for its absence." What work does exist, furthermore, focuses more on the technology and less on the social context in which the innovation is adapted and adopted. Kammen points to interdisciplinary fields such as forestry, geography, and agricultural economics that have overcome similar biases, and recommends the introduction of programs organized around subject areas such as energy engineering, business and energy, and the political economy of energy. In 1999 Berkeley launched a Renewable and Appropriate Energy Laboratory to conduct

interdisciplinary research and fieldwork into the infrastructure base needed to commercialize and support particular energy systems in local contexts in both developing and industrial nations.[154]

While the relative paucity of research groups addressing small-scale, decentralized energy systems is a major institutional hurdle, the gap is starting to fill. (See Appendix C for a sampling.) The Renewable Energy Policy Project issues a steady stream of briefs and reports comparing, for instance, the renewable energy policies of industrial-nation governments or framing rural solar electrification as a climate protection strategy. NREL's Renewables for Sustainable Village Power program provides an Internet discussion group and web database of project descriptions, conference proceedings, and papers. The Intergovernmental Panel on Climate Change has released a special report on the transfer of climate-friendly technologies, recommending that governments create an "enabling" environment for their private capital support. The report's case studies on experiences in Kenya and other developing countries provide valuable insights into the promise and problems of diffusing small-scale power.[155]

The institutional—and ultimately political—base of support for micropower that is developed today will heavily influence what kind of systems will be in place a half century hence. Conventional electric power plants have lifetimes of 30 to 50 years, which could mean a costly lock-in to outdated, inefficient, and dirtier technologies. The past century's cultural preference for the large central-station paradigm, moreover, is not likely to disappear immediately. As recent history has taught us, however, systems can collapse quickly when they lose social and economic legitimacy. In any event, supportive institutions and policies put in place now can yield major benefits in the immediate future as well as decades down the road.[156]

How might Edison have viewed micropower's prospects? In his later years, he told friends Henry Ford and Harvey Firestone, "I'd put my money on the sun and solar energy.

What a source of power! I hope we don't have to wait till oil and coal run out before we tackle that. I wish I had more years left!" Edison did not live to see the late twentieth century emergence of solar and other forms of small-scale power, which he likely would have fused with his late nineteenth century vision of localized systems. That is an experiment for us to tackle today—hopefully with some of the inventiveness and zest that characterized the wizard of electricity.[157]

Appendices

Appendix A: *Sampling of Micropower Developers and Vendors*

Reciprocating engines

Alstom Engines	*www.engines.ind.alstom.com*
Caterpillar	*www.cat.com*
Cooper Energy Services	*www.cooperenergy.com*
Cummins Energy Company	*www.cummins.com*
Detroit Diesel	*www.detroitdiesel.com*
Honda	*www.honda.com*
Jenbacher Energiesysteme AG	*www.jenbacher.com*
Kohler Generators	*www.kohlergenerators.com*
MAN B&W Diesel	*www.manbw.dk*
SenerTec	*www.senertec.de*
Wartsila Diesel	*www.wartsila-nsd.com*
Waukesha Engine	*www.waukeshaengine.com*

Microturbines

AeroVironment	*www.aerovironment.com*
Capstone Turbine Corp.	*www.capstoneturbine.com*
Elliott Energy Systems	
GE Power Systems	*www.ge.com*
Honeywell Power Systems (AlliedSignal)	*www.honeywell.com*
Ingersoll-Rand Energy Systems	*www.ingersoll-rand.com/energysystems*
Solo Energy Corp.	
Turbec AB	
Williams Distributed Power Services	*www.williamsgen.com*

Stirling Engines

BG Technology	*www.bgtech.co.uk*
SIG Swiss Industrial Company	*www.sig-group.com*
Sigma Elektroteknisk A.S.	*www.sigma-el.com*

Solo Kleinmotoren GmbH	*www.solo-germany.com*
Stirling Technology Company	*www.stirlingtech.com*
Stirling Technology, Inc.	*www.stirling-tech.com*
Sunpower, Inc.	*www.sunpower.com*
Tamin Enterprises	*www.tamin.com*
Whisper Tech Ltd.	*www.whispertech.co.nz*

Fuel Cells

Avista Labs	*www.avistalabs.com*
Ballard Power Systems	*www.ballard.com*
Dais Analytic	*www.daisanalytic.com*
DCH Technology	*www.dch-technology.com*
FuelCell Energy, Inc.	*www.fce.com*
GE MicroGeneration	*www.gemicrogen.com*
H Power Corp.	*www.hpower.com*
IdaTech (Northwest Power Systems)	*www.idatech.com*
International Fuel Cells (United Technologies)	*www.internationalfuelcells.com*
Matsushita Electric Industry	*www.mei.co.jp*
NuPower (Energy Partners, Inc.)	*www.energypartners.org*
Plug Power	*www.plugpower.com*
Proton Energy Systems	*www.protonenergy.com*
Sanyo	*www.sanyo.co.jp*
Siemens Westinghouse	*www.spcf.siemens.com*
Sure Power	*www.hi-availability.com*

Solar Photovoltaics

ASE Americas	*www.asepv.com*
AstroPower	*www.astropower.com*
BP Solarex	*www.solarex.com*
Ebara Solar	*www.ebara.co.jp*
Energy Conversion Devices, Inc.	*www.ovonic.com*
Eurosolare	*www.eurosolare.com*
Evergreen Solar	*www.evergreensolar.com*
Kyocera	*www.kyocera.com*
Photowatt International	*www.photowatt.com*

Sharp Corporation	*www.sharp-usa.com*
Shell Renewables	*www.shell.com*
Siemens Solar	*www.siemenssolar.com*
Solar Electric Light Company	*www.selco-intl.com*
Solartech India	*www.solartech.com*
Spire Corporation	*www.spirecorp.com*

Wind Turbines

Bergey WindPower	*www.bergey.com*
Bonus Energy A/S	*www.bonus.dk*
Desarrollos	
Dewind Technik	*www.dewind.de*
Ecotecnia	*www.icaen.es/icaendee/ent/ecotecn.htm*
Enercon	*www.enercon.de*
Enron Wind Corp.	*www.wind.enron.com*
Gamesa Eolica	*www.gamesa.es*
Made	
Mitsubishi Heavy Industries	*www.mhi.co.jp*
NEG Micon	*www.neg-micon.dk*
Nordex	*www.nordex.dk*
Nordic Windpower	*www.nwp.se*
Vestas Wind Systems A/S	*www.vestas.com*

Appendix B: *Sampling of Micropower-related Venture Capital and Other Funds*

Fund (location)	Current Fund	Micropower-related Investments
Aretê Corporation (U.S.)		
Utech Funds	$95 million invested	Utility-related technologies, including fuel cells and solar PV
Micro-Generation Technology Fund *www.arete-microgen.com*	$40 million	Microgeneration technologies and storage systems

Fund (location)	Current Fund	Micropower-related Investments
Clean Energy Fund (Bermuda) *www.cleanenergyfund.org*	$100 million being raised	Project finance for renewable power projects
Clean Power Investments SCA (U.S.)	$28 million	Clean power assets in Europe
EnerTech Capital Partners (U.S.) *www.enertechcapital.com*	$50 million invested $150 million being raised	Micropower and utility-serving Internet, software, and telecommunications technologies
Fuel Cell Venture Capital Fund (U.S.) *www.FuelCellVentureCapitalGroup.com*	n/a	Hydrogen and fuel cell infrastructure technologies
New Energy Partners (U.S.) *www.newenergypartners.com*	$15 million	Hydrogen-powered fuel cell firms less than two years away from commercialization
Nth Power Technologies (U.S.) *www.nthfund.com*	$65 million invested $75–100 million being raised	Microturbine, solar PV, hydrogen, and fuel cell-related technologies

Fund (location)	Current Fund	Micropower-related Investments
Renewable Energy Equity Fund (Australia)	$18 million	R&D companies preparing to commmercialize renewable energy technologies
SAM Group Sustainability Private Equity Fund (Switzerland) *www.sam-group.com*	$93 million being raised (total)	Sustainable energy, resource, and agriculture investments, including micropower
Triodos (Netherlands) *www.triodos.com*	$60 million (total)	Wind Fund supporting U.K. wind projects; Solar Investment Fund providing microcredit to intermediaries in developing countries
Vtz (Germany) *www.vtz.ch*	n/a	Renewable energy companies in Europe and U.S.

Appendix C: *Sampling of Micropower-related Research and Advocacy Groups*

Developing countries

Governmental and University-based

- Blair Research Institute (Harare, Zimbabwe): *www.healthnet.org/afronets/blair.htm*
- Energy and Development Research Center, University of Cape Town (South Africa): *www.edrc.uct.ac.za*

- Ethiopia Energy Studies and Research Center (Addis Ababa)
- India Renewable Energy Development Agency Ltd. (New Delhi): *solstice.crest.org/renewables/ireda*
- Research and Development Unit, Appropriate Technology Section (Maseru, Lesotho)
- South African Council for Scientific and Industrial Research (Pretoria): *www.csir.co.za*

Multinational and Regional

- Asia Alternative Energy Program, World Bank: *www.worldbank.org/astae/index.htm*
- Energy Sector Management Assistance Program, World Bank: *www.worldbank.org/html/fpd/esmap*
- Global Environment Facility: *www.gefweb.org*
- Intergovernmental Panel on Climate Change: *www.ipcc.ch*
- Sustainable Markets for Sustainable Energy, Inter-American Development Bank: *www.iad.org/sds*

Nongovernmental

- ADESOL (Solar Energy Development Association, Dominican Republic): *rds.org.hn/docs/membresia/directorio/per-ong/adesol.htm*
- African Center for Technology Studies (Nairobi, Kenya): *www.acts.or.ke*
- Bariloche Foundation (Buenos Aires, Argentina): *www.bariloche.com.ar/fb*
- Biomass Users Network (Zimbabwe and Brazil)
- Center for Appropriate Rural Technologies (Mysore, India): *www.oneworld.org/cart*
- Center for Energy Research and Development, Obafemi Awolowo University (Niger, Nigeria)
- Centre for Science and Environment (New Delhi, India): *www.cseindia.org*
- China Energy Research Institute (Beijing)
- Chinese Academy of Sciences, Energy Division, (Beijing): *www.newenergy.org.cn*

- ENDA (Environment et Developpement du Tiers-Monde) Programme Energie (Dakar, Senegal)
- Energy Alternatives Africa (Nairobi, Kenya)
- Grameen Shakti (Dhaka, Bangladesh): *www.grameen-info.org*
- Green Africa Network (Nairobi, Kenya): *members.spree.com/greenafrica*
- International Energy Initiative (Bangalore, India): *www.climatenetwork.org/candir/candir54.html*
- International Institute for Energy Conservation (Bangkok, Thailand): *www.cerf.org/iiec/offices/asia.htm*
- Kenya Energy and Environmental Organization (Nairobi)
- Korea Energy Economics Institute (Seoul): *www.keei.re.kr/eng-html*
- Nimbkar Agricultural Research Institute (Maharashtra, India): *nariphaltan.virtualave.net*
- Quinghai New Energy Research Institute (Quinghai, China)
- Tata Energy Research Institute (New Delhi, India): *www.teriin.org*
- US-Mexico Foundation for Science (Mexico City): *www.fumec.org.mx*

Industrial countries

Governmental

- Battelle Advanced International Studies Unit (Washington, DC): *www.pnl.gov/aisu*
- California Energy Commission (Sacramento, CA): *www.energy.ca.gov*
- Distributed Power Program, U.S. Department of Energy (Washington, DC): *www.eren.doe.gov/distributedpower*
- International Development Research Center (Ottawa, Canada): *www.idrc.ca*
- Lawrence Berkeley National Laboratory (Berkeley, CA): *www.lbl.gov*
- National Renewable Energy Laboratory (Golden, CO): *www.nrel.gov*

- Sandia National Laboratory (Albuquerque, NM): *www.ca.sandia.gov*

Nongovernmental

- California Alliance for Distributed Energy Resources (Sacramento): *www.cader.org*
- Clean Energy Group (Montpelier, VT): *www.cleanegroup.org*
- Consumer Energy Council of America Research Foundation (Washington, DC): *www.cecarf.org*
- David Suzuki Foundation (Vancouver, Canada): *www.davidsuzuki.org*
- Distributed Power Coalition of America (Washington, DC): *www.dpc.org*
- E Source (Boulder, CO): *www.esource.com*
- Electric Power Research Institute (Palo Alto, CA): *www.epri.com*
- Enersol (Somerville, MA): *www.enersol.org*
- Intermediate Technology Development Group (Rugby, U.K.): *www.itdg.org.pe*
- National Rural Electric Cooperative Association (Arlington, VA): *www.nreca.org*
- Natural Resources Defense Council (New York, NY): *www.nrdc.org*
- Northeast-Midwest Institute (Washington, DC): *www.nemw.org*
- RAND Corporation (Washington, DC): *www.rand.org*
- Renewable Energy Policy Project (Washington, DC): *www.repp.org*
- Rocky Mountain Institute (Snowmass, CO): *www.rmi.org*
- Royal Institute of International Affairs (London, U.K.): *www.riia.org*
- Solar Electric Light Fund (Washington, DC): *www.self.org*
- Solar Energy International (Golden, CO): *www.solarenergy.org*

- Stockholm Environment Institute (Stockholm, Sweden): *www.sei.org*
- Worldwatch Institute (Washington, DC): *www.worldwatch.org*

University-based

- Belfer Center for Science and International Affairs, Harvard University (Cambridge, MA): *ksgwww.harvard.edu/bcsia*
- Center for Energy and Environmental Policy, University of Delaware (Newark): *www.udel.edu/ceep/ceephom1.htm*
- Center for Energy and Environmental Studies, Princeton University (Princeton, NJ): *www.princeton.edu/~cees*
- Department of Electric Power Engineering, Royal Institute of Technology (Stockholm, Sweden): *www.ekc.kth.se*
- Energy and Resources Group, University of California (Berkeley): *socrates.berkeley.edu/erg*
- Harvard Electricity Policy Group, Center for Business and Government, Harvard University (Cambridge, MA): *ksgwww.harvard.edu/cbg*
- Institute of Transportation Studies, University of California (Davis): *www.engr.ucdavis.edu/~its/header.htm*
- Renewable Energy Institute, University of Oldenburg (Germany): *www.uni-oldenburg.de/uni/prosengl.htm*

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