Appendix One
Scale Issues

The notes for Appendix 1 appear on page 57 of this pdf.

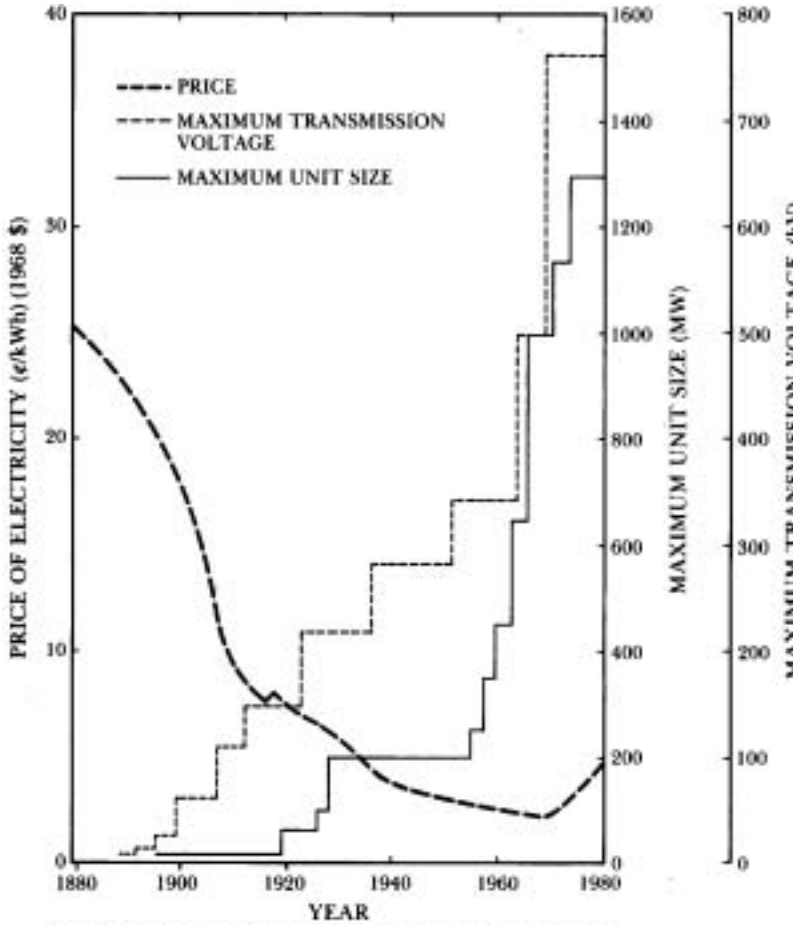
Chapter Fourteen summarized the conclusion that if all relevant economic factors are taken into account, the cost of supplying energy services to relatively dispersed users–that is, to most users–can be minimized by building energy supply systems on a relatively small scale. This appendix outlines the technical basis for that finding.

Electrical supply in the 1970s accounted for two-thirds or more of the capital invested in the U.S. energy sector and in federal energy research and development. (By 1981 it accounted for about a third of the former and over three-fourths of the latter.)[1] Better data on scale effects are available for electric than for other energy systems. For both these reasons, the examples in this appendix are mainly (though not exclusively) electrical, even though this form of energy accounts for only twelve percent of U.S. delivered energy and for eight percent of current U.S. delivered energy needs.[2] Similar arguments apply to other energy forms, to other classes of energy technologies, and probably to at least some ranges of unit size outside the span to which most of the data directly apply.

Doctrinaire belief in economies of scale–the bigger, the cheaper per unit–has long dominated energy investment decisions, especially in the electric utility industry. This belief made the capacity of the largest turbogenerators, for example, double every six and a half years through a size range of over ten thousandfold.[3] Since the total capacity of the electric grid doubled slightly more slowly (about every seven years until the 1970s), this meant that the physical centralization of generating electricity steadily increased.

Indeed, ever since the world's first central power station was commissioned in 1882 at Appleton, Wisconsin, the scale of all kinds of electrical generating and transmission components has grown at a rate which, until the past decade, has been remarkably inexorable and consistent. This trend contributed, until about the 1960s, to real economic savings in the cost of new power stations (Figure A.1.). But as the stations got bigger, they also moved farther from their customers, making grid failures a more

Figure A.1 Evolution of U.S. central electric technology (maximum generator size and maximum transmission voltage) and of average delivered electricity price (1968 dollars)



Source: Economic Regulatory Administration 1981: Figure 2.1.

important source of blackouts than power plant failures and introducing the new types of control and grid–stability problems described in Chapter Ten. In 1900, sixty percent of the nation's electricity was generated on-site. By 1920, the portion had fallen to twenty percent. Today it has bottomed out at approximately four percent and is beginning to rise again as traditional economies of scale reverse themselves.

Figure A.1 illustrates the relentless growth of scale in electrical supply equipment over the past century. The largest generating unit produced an output of only a thirteenth of a megawatt in the earliest days of pressure-staging turbines.[4] By 1903, the

biggest generators produced five megawatts. By 1930, engineering advances had raised the maximum size to two hundred megawatts, where it stayed for more than twenty-five years. It then rose rapidly to about thirteen hundred megawatts by the late 1970s—though, as we shall note below, it is far from clear that the increase from two hundred megawatts was economically worthwhile. Maximum steam pressures, too, rose from two thousand pounds per square inch in the 1940s to over five thousand by the 1960s, then fell back to about two thousand four hundred as it became "clear that some of these technological trends had been extrapolated prematurely."[5] And as generating units became larger, more units were clustered at a single site. This trend led the average size of power plants to increase two-thirds faster, during 1938–57, than the average size of the generating units in those plants.[6]

Maximum transmission voltages also rose more or less exponentially during the hundred-year history of central electrification, from a few kilovolts (thousands of volts) in the 1800s to seven hundred sixty-five kilovolts in the late 1960s. (Experimental lines in the megavolt—million-volt—range are encountering such difficulties that seven hundred sixty-five-kilovolts may represent a saturation level.) The increased voltage offered, at least at first, considerable economies, since electricity "can be transmitted over a seven-hundred-sixty-five-kilovolt line for three hundred miles as effectively as over a one-hundred-thirty-eight-kilovolt line for ten miles."[7] This trend significantly promoted concentration of utility ownership and made possible the siting of power plants hundreds of miles from their loads.

It is widely accepted in the utility industry today that many of these technical developments have gone about as far as present technology permits (and in some cases further). Enormous increases of scale which were pursued more or less blindly—as if the size of anything could keep on doubling indefinitely—are now slackening. But those increases are normally examined only from the narrow standpoint of engineering feasibility for a single plant, not in the broader context of whether they improve the economics of building and operating the *whole* electrical system. In this wider perspective, might not the increases of scale have gone, not just up to, but well beyond an optimal level? An answer to this question may lie in a list of the effects which utilities considered when they ordered ever-larger components and plants—and the more numerous and important effects which they did not consider but should have.

Direct construction costs

Claimed economies of scale in direct construction costs arise mainly from two factors. First, in large projects, the fixed costs—those of setting up a project regardless of its size—become small relative to the variable costs—those which are proportional to size. Total costs per unit of capacity should thus become smaller at large sizes as the fixed costs are diluted. Second, the costs of the materials and labor needed to build anything depend in part on geometrical relationships: for example, the cost of building a vessel depends mainly on its surface area, while its capacity depends mainly on its volume. Since volume increases more rapidly with size than does surface area, a classical rule of

thumb holds that for chemical plants, power stations, and so forth, cost per unit of capacity tends to rise only as approximately the six-tenths power of plant size,[8] so that doubled capacity increases total cost by only about half. But in practice this geometrical saving is mostly exhausted by the time a power plant is as big as a hundred megawatts, and becomes at best trivial above a few hundred megawatts.[9]

Several reasons for this departure from the industry's expectation of unlimited economies of scale can be readily identified. First, a quarter or more of the total construction cost of large projects is the interest paid on construction capital before commissioning. "Economy of scale is nonexistent in interest rates":[10] bankers charge essentially the same interest rate on a large loan as a smaller one, so as interest becomes a larger component of total construction cost, the "scaling exponent" of total cost should rise from six-tenths toward seven- or eight-tenths or more. This reduces the savings from larger sizes. Longer construction times, considered separately below, intensify this effect because interest payments increase both in absolute size and as a fraction of total costs.

Second, building large plants may "involve more complexity, greater precision, smaller margins of error, and new engineering problems" compared to building smaller plants.[11] It may even introduce wholly new designs and requirements. Thus the increase in pressures and temperatures accompanying the modern shift from subcritical to supercritical steam conditions made the specifications on coal plants far more stringent. As nuclear plants became larger, they lost the ability to remove their post-shutdown decay heat passively by natural convection of their cooling water after shutdown. They therefore developed new potential accident modes not characteristic of small plants, requiring new safety analyses and devices to ensure active cooling.

Larger facilities also tend to need more onsite fabrication. This method of construction is costlier and more prone to error than prefabrication of subsystems that can be transported whole to the site. And large plants may require "custom design and custom construction. In these cases," remarks the former Chairman of Con Ed, "a consequent increase in the eighty percent of the plant costs represented by field labor and overhead–most of which are time dependent–make[s] the total cost of a larger plant comparable to an equivalent number of smaller facilities"[12]–that is, it eliminates net economies of scale.

Another implication of this requirement for more or less custom-building large plants is that they cannot benefit significantly from economies of mass production. In contrast, with smaller units "it becomes possible to standardize a design and replicate a large number of identical units." According to a senior official of the [U.S.] General Electric Company, "this opens up the possibility of a new dimension in scale of economy" which "may be of considerable significance."[13] The saving from mass production can so outweigh traditional scale economies in construction that the optimal turbogenerator size would be the *smallest*, not the largest, that can be made for specified steam conditions, opening up "an entirely new and profoundly different avenue for reducing the capital cost of generating capacity."[14]

The possible magnitude of cost savings from mass production can be illustrated by a simple analogy. Mass-produced car engines cost only a few dollars per kilowatt of shaft-power, while the engines that drive power stations cost hundreds of dollars per kilowatt.

Car engines could be made as durable as power-plant prime movers at an extra cost that is very much smaller than their initial cost difference. For equivalent durability, the remaining net saving from mass production would be at least tenfold. This is not to say that the power plants should be replaced with large numbers of car engines; but it does give some idea of the potential savings which custom-built large devices inevitably forego.

The combined result of these phenomena (except perhaps for mass production, which is seldom relevant at the large unit sizes considered) is revealed by an exhaustive statistical analysis of the entire body of U.S. experience with commercial coal and nuclear power stations.[15] For nuclear plants, the scale exponent is not six-tenths as hoped but rather exactly eight-tenths. As a result, the actual cost data show that doubling the size of a nuclear plant reduces its direct construction cost per installed kilowatt by only thirteen percent, rather than by the twenty to thirty percent *assumed* in all industry and government cost studies. (Even the existence of the decline is also statistically less certain than that of most of the other explanatory variables.) As will be mentioned below, construction time also increases with unit size, and the resulting extra interest costs decrease the apparent cost saving of thirteen percent with doubled capacity to only ten percent. While not trivial, a ten percent saving is two or three times smaller than was assumed in the official studies which sought to show that nuclear power is attractive.[16] Those studies, on close examination, proved to be only theoretical; they ignored the real data.

Coal plants show an even smaller economy of scale in construction costs. Although it is normally presumed that doubled size reduces cost per kilowatt by ten to fifteen percent, there is in fact *no* statistically significant correlation between size and cost. At most, there might be (at only eighty-two percent statistical significance) a gross cost saving of three percent–reduced to only two percent net saving by the longer construction time.[17]

Operating costs

The money saved by building a bigger plant may be more than made up by the extra costs of operating it routinely or of repairing it when it fails. The following four categories of scale effects are concerned with running costs. (Later categories consider broader system effects which raise the cost of delivering the energy sent out by the plant, or the cost and risk of financing the project, or the cost of doing separately some other energy task which, in an integrated project design, could be done jointly.)

Although no detailed data are yet available on operating and maintenance costs as a function of unit size, it is clear from operating experience with all kinds of power stations that larger ones tend to have more numerous and complex failure modes, longer downtime, more difficult repairs, higher training and equipment costs for maintenance, higher carrying charges on spare parts inventories, and higher carrying charges on spare parts inventories, and higher unit costs of spare parts made in smaller production runs. Conversely, there "may be a reduction in maintenance personnel [per kilowatt] for smaller units because of their higher reliability"[18] (discussed further below). Large units may be more able to attract and equip the specialized maintenance cadres they require, but may also become disconcertingly more vulnerable to

those cadres' whims, as noted in Chapter Four.

A survey of the general problem of repairing large industrial plants notes that high interest rates have "made it more important than ever to keep plants operating," and the

> high cost of financing inventories has forced manufacturers to live within tight production schedules: any equipment breakdown is bound to anger customers and likely to cost a company business. Yet while costly money has increased the pressure to avoid breakdowns, it has also made them more likely. Many companies believe they are forced to cut corners when building new plants, either by eliminating backup equipment or going without spare capacity. "It used to be that you'd install a spare pump at every critical point in a refinery. You can't afford to do that willy-nilly now," says [a senior officer of a construction firm] …. Moreover, neither equipment manufacturers nor their customers can afford to keep a wide range of spare parts in stock. This is due not only to the high cost of financing the parts, but also to the cost of the parts themselves. Westinghouse Electric Corp. has managed to sell about one hundred spare power-plant turbine-rotors in the past five years by persuading utilities that they can save seven days of costly outage by having parts on hand. But for many utilities the cost of these spares, currently one to seven million dollars, is prohibitive.[19]

Just installing them is a risky and demanding operation: "We're dealing with things that are extremely heavy and yet extremely delicate," said a Con Ed official.[20] Dropping a rotor could cost millions of dollars in an instant.

The logical consequences of these considerations is that big plants tend to have smaller safety margins built in, less redundancy, fewer spare parts, and hence more frequent and serious failures. In contrast, since smaller plants are often simpler than big plants, lower skills and standards of maintenance may suffice; the plants are more comprehensible to their staff; and for technical reasons they often tend to fail more gracefully. All the extra costs of maintenance for larger plants then operate in reverse.

A possible economy of scale in operation is that it may be simpler to arrange delivery of fuel, or conversion from one fuel to another, for a single large plant than for multiple smaller plants. This argument does not apply, however, to comparisons between conventional power stations, which require fuel, and renewable energy sources, which do not.

Availability

A low cost per kilowatt of installed capacity is useless if that capacity is not available to provide energy. Since about eighty percent of the cost of generating nuclear electricity (or about forty percent for coal-fired electricity) is the capital cost of the plant itself, the cost of electricity, even after adding the cost of delivering it, is quite sensitive to the reliability of the plant. Unfortunately, the reliability of large power stations has in fact been generally disappointing. As Robert Mauro of the American Public Power Association remarked,

> …the disappointing availability record of many large units has diminished, if not entirely dissipated [,] the theoretical savings expected from bigness….[It is ironic that] many small … electric utilities, which have been jeered at for operating "obsolete" plants with "tea-kettles," have had fewer problems in maintaining adequate power supply than some larger systems with modern large-scale units.[21]

The reasons for the greater unreliability of large plants are simple and fundamental. A five-hundred-megawatt boiler has approximately ten times as many miles of tubing as a fifty-megawatt boiler, so "a tenfold improvement in quality control is necessary to maintain an equivalent standard of availability for the larger unit."[22] A large turbine has high blade-root stress, often forcing the designer to use exotic alloys with unexpected characteristics: highly skilled turbine designers in several advanced industrial nations have watched their turbines explode because the metal did not behave as hoped. (Giant wind machines show similar stress and vibration problems, making their design complex and costly. As a result, no net economies of scale have yet been demonstrated for wind machines bigger than tens of kilowatts.) A more complex control system runs up against the discouraging mathematics of unreliability (Chapter Thirteen). Even on the scale of such simple components as nuclear pumps and valves, detailed assessments show that larger units are less reliable.[23] In general, the technological evolution needed to meet ever more stringent performance standards exhibits diminishing returns to money and talent invested. Rapid scaling-up often outruns engineering experience, especially in long-lead-time technologies. This is true of all types of engineering.

This combined effect of the greater unreliability of more and bigger components in more complex plants has recently been quantified by analyzing the capacity factor (actual output as a fraction of output if the plant ran at full rated power all the time) of U.S. power plants.[24] For all commercial nuclear reactors through June 1980, the capacity factor averaged sixty-six percent for the twenty-three plants (one hundred seventy-three plant-years) with electrical output capacities under eight hundred megawatts. But for the thirty-nine larger plants (one hundred eighty-eight plant-years), the capacity factor averaged only fifty-four percent–nearly a fifth worse. Sufficient experience is available, according to the nuclear industry, to distinguish statistically the effects of age from those of size. There is now no doubt that if all other variables are held constant, the larger plants are less reliable.[25]

An equally striking correlation between size and unreliability holds for U.S. coal plants.[26] During 1961–73, average unit size increased by seventy-seven percent while capacity performance (a measure of reliability) fell by thirteen percent. Coal plants of between four hundred and eight hundred megawatts were about eight percentage points less available than plants half as big. And for all U.S. coal- and oil-fired power plants during 1967–76, the forced outage rate (fraction of the time the plant was broken down) ranged from a tiny two and a half percent for plants under one hundred megawatts to sixteen percent for plants upwards of eight hundred megawatts,[27] rising proportionately in between.[28] It is partly for this reason that the average size of newly installed coal plants *fell* from about seven hundred megawatts in 1971 to four hundred megawatts in

1978; three hundred megawatts is now common size for new utility orders. The frequent breakdowns of large plants are simply proving to be more than utilities can afford.

Similar experience abounds worldwide. As the Federal Energy Administration was castigating the dismal reliability of large new power plants in the U.S.,[29] similar evidence was already accepted in Europe as showing that a fundamental mistake had been made in investment strategy. A German/British conference in 1973, for example, had already found that poor availability had canceled out the expected economies of scale in coal plants. The larger plants took longer to "mature"–to overcome their "teething troubles"–and never did become as reliable as the smaller units. After four years' operation, availability ranged from about eighty-two percent for sixty-megawatt units (which had already leveled off at their "mature" availability) to only about fifty-two percent for five-hundred-megawatt units, which were still far from maturity. Intermediate sizes fitted this pattern correspondingly.[30]

Reserve margin

The unreliability of large units is worse than appears at first sight. The possibility that a large unit might fail requires the provision of an equally large block of back-up capacity to protect the grid. Conversely, a larger number of smaller units provides better protection because they are not all likely to fail at the same time.[31] Hence the smaller units would need less reserve margin to achieve the same reliability. In other words, "the enhanced reliability contribution of small generating units arises because the failure of a single large unit is more likely than the simultaneous failure of two smaller units equalling the same capacity."[32]

For this reason, several studies of typical interconnected grids show that building several power plants of three or four hundred megawatts each, rather than a single plant of a thousand megawatts, would provide the same level and reliability of service with about a third less new capacity.[33] Thus a thousand megawatts of new nuclear capacity should, in such a grid, be compared in costs and impacts with only about seven hundred megawatts of coal plants, because the latter can come in smaller units. For still smaller units, such as ten-megawatt fuel cells sited at distribution substations, the savings in extra capacity to do the same task may exceed sixty percent because of the added protection from grid failures.[34] (This initial rate of savings diminishes as dispersed sources are successively added to a typical grid.) Conversely, big, "lumpy" units require disproportionately large back-up capacity, especially if they are unreliable or not thoroughly interconnected.[35]

Thermal efficiency

Power plant engineers have devoted immense ingenuity to trying to increase the amount of electricity derived from each unit of fuel. By the 1960s, average thermal efficiencies (the fraction of the fuel's energy that is converted into electricity) had improved from less than twenty-three percent to about thirty-four percent. Part of this progress was achieved simply by making plants bigger: larger scale both permitted more ambitious engineering designs and improved, for example, the ratio of boiler combustion volume to heat-losing surface area. But despite more rigorous engineering and the pure geometric advantages of scale, the average efficiency of U.S. power plants has slightly decreased in recent years. This is partly because larger plants, built in the hope of wringing another few tenths of a percentage point

out of the thermal inefficiency, proved less reliable.[36] Their frequent stopping and starting greatly increased heat losses–having to heat up the boiler and plumbing afresh with each restart–and entailed more operation at partial load, also reducing efficiency.

Thus in Britain, among stations of the same size (five-hundred megawatts), thermal efficiency ranged from twenty-three or twenty-four percent for plants with a capacity factor of only five or ten percent (out of order nearly all the time) to thirty-four or thirty-five percent for relatively reliable plants (capacity factors over sixty percent).[37] For all plants upwards of four hundred fifty megawatts in output capacity, the correlation was equally stong[38]–lower reliability meant lower thermal efficiency. Based only on availability, thermal efficiency, maintenance cost, lead time, and direct capital cost, the optimal size for such a plant was calculated to be between two hundred and three hundred megawatts. The British electrical authorities, however, adopted five hundred megawatts as the standard size. Because these larger plants proved to be less reliable and less efficient than smaller ones, the choice of an excessive standard size led to a sixteen percent overbuilding of U.K. generating capacity[39]–a mistake costing more than ten billion dollars.

U.S. data confirm that bigger or newer power stations are, on the whole, no more efficient than smaller or older ones.[40] The ten most efficient power plants operated in 1974, for example, had thermal efficiencies around thirty-seven to thirty-nine percent. They ranged in size from two hundred thirty-eight to nine hundred fifty megawatts, and in vintage from 1958 to 1970. The quintupling of the size of the largest plants during 1958–74, and all the technological progress of those sixteen years, did not improve thermal efficiency.

The same lesson applies in many other energy systems. For example, efficiency (and energy cost) bear no necessary relation to unit scale or degree of centralization in most technologies for generating electricity from high-temperature solar heat[41] or even in machines that capture energy from the wind. With these technologies as with conventional power stations, bigger is not necessarily more efficient, and may cost more, too.

Waste-heat integration

Using fuel to raise steam to drive turbines to generate electricity inevitably loses about three-fifths or more of the fuel's energy in the form of warm water used to cool the steam condenser. But this heat need not be wasted, as it normally is in U.S. power stations. Instead, it can be used to heat buildings or greenhouses via a combined-heat-and-power station. Such an integrated "total-energy system" can raise to eighty percent or more the efficiency with which useful work is extracted from the fuel, saving money correspondingly. This can be done particularly well on a small scale because it is more difficult to transport low-temperature heat for long distances than electricity.

Neighborhood- or building-scale total-energy systems are especially attractive.[42] Devices which use small engines to generate electricity and provide heat for a building and its domestic water supply are commercially available. Some achieve about ninety percent overall efficiency,[43] use standard automotive engines burning a wide range of liquid or gaseous fuels, and are suitable for a single apartment house.[44] The current price of a typical total energy system such as a Fiat TOTEM™ is about ten thousand dollars for an output capacity of fifteen kilowatts of electricity plus thirty-eight kilowatts of heat[45]–easily

competitive with centralized supplies, despite the limited engine lifetime. Fuel cells, which convert fuels directly into electricity plus heat without fumes, noise, or moving parts, can be similarly economical. Models now being field-tested by the Gas Research Institute are expected to achieve overall efficiencies from eighty to ninety-five percent.

Total-energy systems can distribute waste heat at the scale not only of a building or neighborhood but even of a whole city. This is commonly done in Europe, and especially in the Soviet Union and Scandinavia. District heating, for example, warms forty percent of all Danish households. Sweden, widely regarded as the leader in district heating technology, is halfway through a ten-year program of converting all cities of over one hundred thousand people to district heating (Stockholm will take twice as long). The conversion process involves both technical and institutional innovations. The former include highly insulated flexible pipes which can be laid rather cheaply to carry pressurized hot water throughout large areas, even at low suburban housing densities. (Steam systems are usually considered obsolete.) Many Swedish boilers for district heating can burn a wide range of fuels, including municipal wastes or wood chips. Cheap back-up boilers are commonly provided to ensure reliable service, and there is usually redundant water-pumping capacity. An experimental boiler at Enköping, Sweden uses fluidized-bed combustion to burn virtually any combustible material efficiently and cleanly.

Not content with present fuel flexibility, the Swedish District Heating Association even recommends that new district heating systems be so designed that they can later be easily converted to solar district heating. Several solar district heating systems are in operation or under construction, mainly in Scandinavia.[46] Geothermal district heating systems are already operating in parts of Lassen County and elsewhere in California, in Boise, Idaho, and in Klamath Falls, Oregon (which also uses the hot water for air conditioning and industrial process heat).[47] Three Minnesota towns and the city of St. Paul are currently installing modern fossil-fueled district heating systems.

Not surprisingly, most modern power stations are too big to take advantage of district heating opportunities. A thousand-megawatt power station produces about two thousand megawatts of warm water–far too much to use conveniently. The largest readily manageable combined-heat-and-power systems operating in Sweden are only half this size, serving the heat and power needs of a city of one hundred thousand; and that system took seventeen years to build up. Considerably smaller systems, typically tens of megawatts and downwards, offer more flexibility, are faster to build, and need less back-up to ensure reliability.

Another kind of integration between electrical and heating systems is industrial "cogeneration"–making electricity in a factory as a byproduct of heat or steam that is already being used for an industrial process. The most common way to do this is to use a slightly higher temperature than normal, use it to drive a steam or gas turbine, then use the exhaust heat (still quite hot) for the industrial process. Such cogenerated electricity can cost about half as much in capital investment and use half as much fuel as would be the case if the same amounts of electricity and process heat were made seperately.[48] In effect, cogeneration replaces two separate boilers–one at the factory and another at the power plant–with a single unit that costs little more to build and operate.[49] Not just a third but about three-fourths of the energy in the fuel can then be harnessed. Further

byproducts can include air conditioning and desalination.[50] The proprietor of cogeneration equipment also gains a reliable power source that can work in isolation–an advantage that the publishers of the computer-intensive *Los Angeles Times* found irresistable.[51] California alone expects to have over six thousand megawatts of cogeneration capacity by 1990[52]–about a third as much as currently operates in the United States. One team of four California engineers recently identified a hundred megawatts of attractive cogeneration projects embracing virtually every sector of industry, yet generally small enough to have escaped prior notice. Some inventors believe that cogeneration may be attractive even on as small a scale as a home furnace, using a tiny gas or steam turbine to produce household electricity and then distributing the waste heat.[53]

Many forms of system integration besides the use of waste heat are feasible and economically very attractive at small scale. This important advantage of decentralized systems is described more fully in Chapter Sixteen.

Transmission and distribution costs

If an energy-supplying device is much larger and more concentrated than its customers, its energy must be distributed to them through a costly network. The costs and losses of that distribution are a diseconomy of excessive scale.

The extent of this mismatch is illustrated by U.S. private electric utilities in 1965–71.[54] Their demand was very diffuse: it averaged only three hundredths of a watt per square meter of land area–up to tenfold more or less in extreme cases. The density of demand by nonindustrial users was only half this great–only about a twelve-thousandth of the average density of solar energy on the earth. In contrast, a thousand-megawatt power plant which (with its coal depot or nuclear exclusion area) occupies an area of several square miles represents a source whose power density is about a thousand watts per square meter, the same as bright sunlight at noon–some thirty thousand times as great as the average density of demand. Therefore, to spread out the highly concentrated electricity to its relatively dispersed users, it must be hauled an average of about two hundred miles or more. Even in the denser European grid, this distance is typically around sixty miles. That is, to reach enough customers to be able to use the output of a single modern power plant often entails covering a large area with a transmission and distribution network. This is expensive.

In 1972, the last year for which a detailed analysis is available, the cost of building and maintaining that grid accounted for about seventy percent of the cost of delivered U.S. elcetricity[55]–more than twice the cost of generation. That is, only thirty percent of what we paid for electricity in 1972 actually bought electricity; the rest paid for getting it from the plant to us. Similarly, natural gas systems are so concentrated that in 1976, transmission and distribution accounted for sixty-five percent of the delivered gas price; wellhead gas accounted for only twenty-nine percent.[56]

In recent years, galloping escalation in the cost of energy plants has shifted these ratios. By 1980, for example, U.S. private electric utilities were spending sixty-nine percent of their total investment on generation and twenty-six percent on the grid, compared with fifty percent for generation and forty-seven percent for the grid eleven years

earlier.[57] But the grid also loses nine percent of the electricity sent through it, and the cost of operating and maintaining the grid (currently four billion dollars a year) is probably even greater than the capital charge for all the transmission lines.[58] Thus even the 1980 investment pattern suggests that about a third of the price of electricity from newly ordered plants will be for delivering it, not for generating it. This is a significant diseconomy of large scale in central generation. Clearly, both costs and losses could be greatly reduced by better matching the scale of supply to that of end use.

Several studies have tried to estimate how much money is saved by putting smaller generators near the users so that less grid investment is needed. Five studies with widely varying assumptions found "dispersion credits" ranging from eight dollars to one hundred sixty-five dollars per kilowatt of dispersed generating capacity.[59] (The latter figure is roughly what a kilowatt of generating capacity cost ten years ago.) However, none of these studies counted the saving from eliminating underground cables, which are used in most new primary distribution circuits and can cost ten to forty times as much as overhead lines. The actual saving is therefore even larger.

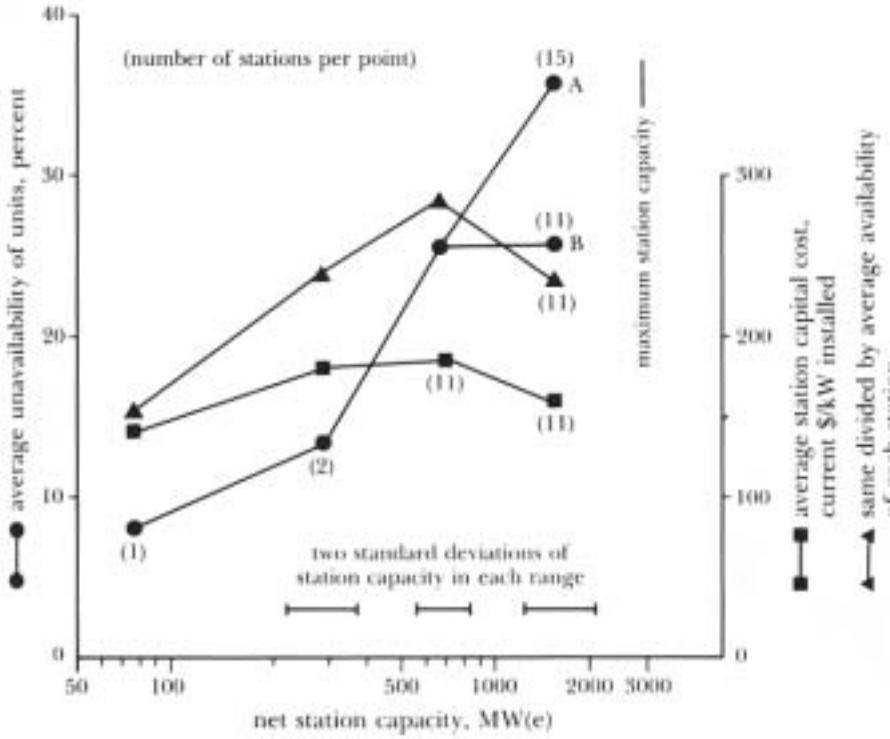
Several of the same studies allowed a credit for more reliable service. This arises because a source sited at the substation, or even closer to end users, protects them from transmission failures–the main cause of blackouts–and can thus improve reliability ten- or twentyfold.[60] This is in addition to any gain in reliability from the possible use of a different generating source that is inherently more dependable than a central station.

Construction time and indirect costs

As cost of money and escalation of real capital cost take a larger share of total construction costs–due to the interrelated increase of capital intensity, scale, technical complexity, perceived impacts,[61] and lead times–total economies of scale decline because only physical, not financial, quantities become cheaper with size.[62] But the reality appears to be worse than that. There is some evidence that for very large units, economies of scale in capital cost per installed kilowatt actually become negative. Figure A.2, for example, shows this effect for a sample consisting of half of the thermal power stations commissioned in the United States in a two-year period during 1972–74. Plots of the capital cost per kilowatt of installed generating capacity (squares) or per kilowatt available to be sent out (triangles) as a function of unit size reveal that unit capital cost in this sample is less for a small plant than for a very large one–just the opposite of the usual economies-of-scale theory.

A possible explanation for this unexpected result arises from differences in construction times as a function of scale.[63] Although it might seem intuitively that doubling the size of a plant will double its construction time, utilities have traditionally expected any increase in construction time to be negligible. The actual data, however, show that doubling the size of a nuclear plant in fact increases its construction time by twenty-eight percent, or of a coal plant, by thirteen percent, simply because of the sheer volume of materials and labor whose use must be coordinated.[64] (These increases refer only to actual construction time, not licensing. There is no statistically significant correlation between licensing duration and reactor cost.[65]) Two Los Alamos researchers, who also consider the

Figure A.2 Average unavailability and specific capital cost vs. unit size in a nearly even-aged sample of twenty-nine thermal power stations



SOURCE: Data from *Electrical World* 1975, replotted in Lovins 1977b:92.

NOTE: The sample includes seventeen or eighteen coal-fired, two or four nuclear, three gas-fired, two gas- or oil-fired (dual-fuel), and one or two oil-fired stations-a total of twenty-nine plants, built in every region except New England. Point A on the graph is from the original source's graph; point B is from its tabular data, which omit the [apparently high] unavailability of four very large plants included in the graph. The right-hand triangular point is calculated using the lower value (B). Komanoff's (1981) smallest reactor has a capacity of four hundred fifty-seven megawatts–between the second and third groups in the graph–so his finding of a positive economy of scale is not inconsistent with the graph, which shows a reversal of the sign only for plants below about a hundred megawatts. Electrical World's corresponding data for 1980 (Friedlander 1982:76–77) are consistent with the graph for 1974, but the numbers and types of stations in the 1980 survey provide sparse data for the lower size ranges.

process of siting and licensing, find even stronger scale effects on construction time.[66]

Although all parties to utility construction projects tend to blame each other for delays, it is indisputable that the complexity of large projects is at the heart of the difficulty. The Federal Power Commission reported that during 1967–76, utilities themselves cited vendor-related problems (late delivery, unacceptable quality, etc.) as being responsible for thirty-seven percent of their plant delays; poor site labor productivity

and other labor-related problems for thirty-four percent; regulatory problems for thirteen percent; utility-related problems (chiefly finance) for nine percent; and bad weather, legal challenges, and all other causes for eight percent.[67] The more ambitious the project, the more important all these problems become and the greater the delays.

Longer construction times increase the indirect costs of construction in at least seven ways, some of which are difficult to quantify but all of which can be important. Longer lead time

- increases exposure to real cost escalation;[68]
- increases the absolute and fractional burden of interest payments during construction;[69]
- makes the utility's cash flow less favorable, reduces the self-financing ratio, increases the debt/equity ratio, reduces the interest coverage ratios, and generally increases the utility's financial risk and hence its cost of money in the capital marketplace;[70]
- increases the project's exposure to regulatory changes during construction[71] and to technological progress that can alter the design criteria or even make the project obsolete;
- may increase the incentive (and bargaining power) of some construction unions to demand very high wages, or to stretch out construction still further, or both (as occurred on the Trans-Alaska Pipeline);
- may arise from siting problems provoked by the large scale and hence the more obtrusive impacts of the plant[72] (this may in turn lead utilities to try to maximize installed capacity per site, making the project so big and problematical that the plant becomes a worse neighbor than it should have been, so the next site becomes much more difficult and time-consuming to find, and so on exponentially); and
- exposes the builders to high financial risk because of uncertainty. This last point deserves further discussion.

"The greater time lags required in planning [and building] giant plants mean that forecasts [of demand for them] have to be made further ahead, with correspondingly greater uncertainty; therefore the level of spare capacity to be installed to achieve a specified level of security of supply must also increase."[73] Longer lead time increases both the uncertainty of demand forecasts and the penalty per unit of uncertainty. Some analysts have tried to show that the financial penalty for underbuilding is greater than the penalty for overbuilding;[74] but their recommendations—to overbuild baseload plants—are actually artifacts of flaws in their models.[75] More sophisticated simulations show on the contrary that (at least for utilities which do not carry unfinished plants in their rate base) if demand is uncertain, the low-financial-risk strategy is deliberately to underbuild large, long-lead-time plants.[76] There are three reasons for this:

- it costs less to use short-lead-time stopgap plants more than expected (even gas turbines burning petroleum distillate) than it does to pay the carrying charges on giant power stations that are standing idle:
- short-lead-time plants have a shorter forecasting horizon and hence a greater certainty of being needed; and
- short-lead-time plants can be built modularly in smaller blocks,[77] responding more closely to short-term perceptions of need and straining a utility's financing ability far less.

> That is, adding a plant to a hundred similar small ones rather than to two similar big ones causes an incremental capitalization burden of one percent, not thirty-three percent.

These qualities all reduce the financial risk and therefore the utility's cost of money.[78] Therefore, as a *Business Week* article remarked, "Utilities are becoming wary of projects with long lead times; by the time the plant is finished, demand could be much lower than expected. If you're wrong with a big one, you're really wrong…. Uncertainty over demand is the main reason for the appeal of small plants.[79]

Control of residuals

It is often claimed that centralization simplifies control of residuals, such as air pollutants released by burning coal. But this is not obvious in view of the many counter arguments:

- Smaller scale may reduce the total load of residuals by permitting the use of combined-heat-and-power plants or of inherently more flexible and benign processes (for example, fluidized-bed combustion of coal, now commercially available at thermal capacities of tens or hundreds of megawatts but not of thousands of megawatts).
- Smaller scale lowers both the risk and the cost of failure in individual pollution controlled installations: less will get out than in the case of failure at a large plant, and there is less fiscal incentive to bypass a defective scrubber than if the alternative were shutting down a major power station.
- Smaller scale in certain kinds of installations makes it possible to turn residuals from pollutants into useful nutrients and byproducts as in the case of ethanol stillage.[80]
- Smaller scale, by siting the plant near its users, also gives them a direct incentive to insist that it run cleanly and quietly–as is illustrated by the German block-heating plant cited in Chapter Sixteen.[81] Conversely, when a large plant is rurally sited, often because politically stronger urban residents do not want it near themselves, agrarian politicians are often impotent to enforce environmental standards in the face of its overwhelming economic power. The result is often inequity, giving rise to tensions and perhaps to violence.[82]

Other issues of scale economies

Large plants may make it easier to use and finance the best technologies currently available. On the other hand, smaller plants with shorter lead times may, at each stage during rapid technological evolution, have less capital sunk in inflexible infrastructure, and may reflect a shorter institutional time constant for getting and acting on new information. Thus less capital is sunk at one time in any particular technology that may soon become obsolete, and a larger fraction of capacity at any time will use up-to-date designs.

Small plants may be perceived as so benign, and fit so well onto existing sites near users (such as the sites of old municipal power stations), that they have few siting problems: they offer far greater siting flexibility than large plants,[83] and this in turn saves

transmission costs and losses, increases the scope for total-energy systems, and encourages the use of inherently superior sites.[84]

A social or psychological perspective suggests many further scale effects.[85] Some, like users' perceptions of dependency or oligopoly, are beyond the scope of this work.[86] Others are of a more technical character. For example, large technologies tend to submerge, but small ones to emphasize, individual responsibility and initiative. This may improve the quality of work and decisions. Furthermore, large technologies, as the physicist Freeman Dyson has remarked, are "less fun to do and too big to play with."[87] They are so complex and expensive that their design is fixed by committees, not changeable by a single technologist with a better idea. The kind of fundamental innovation which evolved cheaper and more effective energy systems in the past has often depended on the technologies' accessibility to a multitude of tinkerers.[88] (This emerges clearly from the relative speed of innovation in large vs. small wind machines or in mainframe vs. microcomputers.) The ability of a single person to understand a technology and make a basic contribution to it is of fundamental importance: there is, so far as we know, nothing in the universe so powerful as four billion minds wrapping around a problem. It is for this reason that many of the most exciting solar developments, as noted earlier, are the work of individuals, often without the trappings and inertias of "big science."

The scale of an energy system can also change its basic physics and its potential performance in ways that are rather subtle and unexpected. For example, several analyses have found that solar district heating should be able to cut the delivered price of active solar heat roughly in half.[89] There are good physical reasons for this:[90]

- A large water tank, shared between tens or hundreds of dwellings, provides (compared to the small tank in a single house) a large ratio of volume to surface area, hence low heat losses.
- The large tank has a favorable ratio of variable to fixed costs, and it is relatively cheap to increase the size of an already large tank.
- One can therefore afford to use a big enough tank to provide true seasonal (summer-to-winter) heat storage.
- This in turn provides a full summer load, improving annual collector efficiency.
- The large tank also permits further efficiency gains by separating the storage volume into different zones with the hottest water near the center and the coolest near the periphery: this improves collector performance and further reduces heat losses from storage.
- With true seasonal storage, collectors can face east or west with relatively little penalty, rather than only towards the Equator, so such a system would be more flexible to site, especially in a city.

The net result of all these effects is a marked cost reduction–probably to a level well below the oil prices of the mid-1970s.[91] Incorporation of solar ponds or ice ponds[92] or both[93] would cut costs still further, and would incorporate energy collection and energy storage into the same device.

This example illustrates how sensitively optimal scale depends on technological con-

cept and on the proposed use. (It will certainly depend, for example, on how much heat the buildings require and on the local climate.) It may well turn out that active solar heating is cheaper at some intermediate scale than at the scale of a single house or a whole city. And it may also very well turn out that active solar heat at any scale is uncompetitive with simpler, smaller measures to make buildings more heat-tight and to increase their passive solar gain. The question of optimal scale for a particular device is therefore not the only important question to ask; one must also determine whether that sort of device is worth building at all.

Finally, to make this analysis of scale issues at all tractable, it has excluded such questions as the appropriate organizational scale of energy systems. (For example, solar district heating may be technically cheaper than single-building active solar heating, yet cost more in practice because of the greater social costs of organizing a joint project among many people.) The organizational patterns of the energy system are a vast and important subject. It is important for some purposes, for example, to know that of the roughly three and a half thousand U.S. electric utilities, the largest ten own about twenty-five percent of the total capacity, the largest thirty own fifty percent, and the largest hundred own eighty percent.[94] (The concentration before the Great Depression was even greater: in 1932, eight holding companies produced three-quarters of America's electricity, although several of them then went bankrupt as sales declined.[95]) The quintupling of the size of steam-electric generating stations during 1950–75 submerged the authority of localities, states, and even individual utilities themselves beneath that of regional power pools.[96] But although the nature and scale of utility ownership, control, and regulation undoubtedly affects somehow the economics of the hundred-billion-dollar-a-year utility industry, no effort has been made here to determine how. This analysis also neglects the sociopolitical effects of scale (many of which were mentioned in previous chapters), because while they are undoubtedly important–some would say dominant–in the way the United States actually makes public policy decisions about energy, nobody knows how to quantify those effects.

What is the net result?

This appendix has listed ten broad classes, and nearly fifty specific types, of competing effects of scale on the economics of energy systems. Large scale affects direct construction costs through the ratio of fixed to variable costs, geometrical factors, construction techniques, technical requirements and complexity, and scope for mass production of components. Some of these effects are economically favorable, at least at first, while others tend to be adverse. Scale alters operating costs in many ways and probably in both directions. Large scale affects (generally adversely) technical reliability, reserve needs, opportunities for thermal and other types of system integration, and distribution costs and losses. Scale and concomitant effects (notably availability) can affect thermal efficiency. And large scale is intricately (and generally adversely) related to construction time and, via at least seven pathways, to ultimate cost.

Clearly, then, it is not good enough to look only at one or two economies of scale–such as a saving on the direct construction cost of a power plant per kilowatt–and

ignore the nearly fifty diseconomies identified here. Yet it is by such defective reasoning that America has come to rely on huge and brittle energy technologies. The same habit of thought has led many energy technologists to assume that smaller technologies, lacking those economies of scale, must be uneconomic. Yet on the contrary, it is partly by avoiding the diseconomies of large scale that many small energy technologies are in fact able to compete economically with conventional large technologies as is demonstrated in the next two appendices.

The dispute over the economics of scale would be easier to settle if one could cite a careful economic comparison between big and small technologies which focused solely on scale as the key variable. Unfortunately, small systems also tend to differ from big ones in many respects other than scale: they may, for example, be total-energy or renewable systems, and these fundamental differences tend to submerge the importance of their different scale. There is, however, a detailed analysis by two Los Alamos scientists which shows how scale alone can give an economic advantage to the smaller of two otherwise identical systems–big versus very big coal-fired power plants.[97] That analysis is only peripheral to the broader case developed here. Whereas Part Three of this book is concerned mainly with small technologies, the Los Alamos study deals only with two different sizes of a technology which are both many thousands of times larger than any small technologies. The importance of the example lies rather in showing that by considering eight scale effects rather than only one, the conventional wisdom of the utility industry (very big power stations are cheaper per kilowatt than big ones) can be reversed.

The Los Alamos scientists' calculation used empirical cost and performance data to compare coal-fired power station projects in two different sizes: four plants each generating seven hundred fifty megawatts; and nine plants, each only a third as large. Because the larger plants are less reliable and can "drop out" more capacity at once, they would need a third more total capacity to do the same job. This puts the larger plants at an initial disadvantage. In addition, the smaller plants would save money by being nineteen percent more reliable, by taking five years to build instead of nine, and by having a forced outage rate fifty-nine percent lower than the big plants. The money saved by these advantages would more than make up for smaller plants' economic disadvantages: fifteen percent worse thermal efficiency, eleven percent higher capital cost per kilowatt, and slightly higher costs for coal transportation and electricity transmission. Balancing all these effects, the total cost (discounted to present value) of building the smaller plants would be less than that of the larger plants by one percent in operating costs, seventeen percent in construction costs, and six percent in total lifetime electricity price. The smaller plants would thus save electricity consumers a total (in 1977 value) of two hundred twenty-seven million dollars compared to the bigger plants.

The Los Alamos calculation is especially impressive because it finds an advantage for smaller plants–within the size range in which economies of scale are supposedly best known to operate–even though it leaves out approximately forty diseconomies of large scale identified earlier in this appendix. Its assumptions, too, consistently favor the larger plants. For example, it supposes that in practice, the hoped-for gains in thermal efficiency at larger scale will not be reversed by higher forced outage rates. It assumes

economies of scale in construction four times as large as those (if any) actually observed for all U.S. coal plants. It ignores the likelihood that the better cash flow associated with shorter lead time would reduce the utility's effective cost of money. It does not account for possible reductions in grid costs and losses from siting the smaller plants closer to the users. Most importantly, it does not count the potentially very large savings that could be achieved through district heating or other forms of system integration–opportunities that could completely change the design and purpose of the project if the plants were, say, two hundred fifty kilowatts rather than a thousand times larger. Yet despite its narrow focus, the study finds that taking a few competing diseconomies into account gives the smaller plants a cost advantage larger than many on which utilities now base their investment choices.

The evidence cited earlier for additional advantages of much smaller scale, and especially for total-energy systems and other forms of system integration (treated in Chapter Sixteen), suggests that a much stronger economic case could be made for making the plants even smaller and more local than the case study assumes. And in the case of renewable sources–which tend to have greater integration opportunities, which can generally be sited directly at the point of use so as virtually to eliminate grid costs and losses, and which have no cost of fuel delivery–the economic advantages of small scale, for uses of normal (relatively low) density, should be even greater.

By now, in short, the evidence of compensatory diseconomies of large scale which favor smaller technologies is so overwhelming that no rational decision-maker can ignore it. However these many competing effects are balanced, it is difficult to imagine a way–save in the most centralized applications, such as operating a giant smelter–that they can yield lower net costs of delivered energy services at very large scale than at moderate, and often quite small, scale. Thus the relatively small, dispersed modules of energy supply required for a genuinely resilient energy system do not appear to be incompatible with reasonable cost, and may indeed be one of the simplest ways of achieving it.

The notes for Appendix 2 appear on page 59 of this pdf.

Appendix Two

Technical Progress in Appropriate Renewable Sources

The state of the art in inherently resilient energy sources has been treated in detail in recent primers for lay audiences,[1] for scientists,[2] and for policy-makers.[3] It is not possible in a book of this length to do justice to those fundamentals. Rather, this appendix highlights some recent technological advances, not described in earlier chapters, which seem especially promising for making the U.S. energy system less vulnerable.

Heat

Passive solar design Passive solar techniques–capturing and storing solar energy in the fabric of the building itself–are now known to be the best buy (after, and in combination with, efficiency improvements) for space-heating both new buildings and retrofits. Passive devices requiring no pumps can also heat domestic water cheaply (Appendix Three). Sophisticated design tools[4] and packaged design kits have been tailored for use in many climates.[5] These now permit the performance of any combination of passive elements in any climate to be accurately simulated and optimized on a hand calculator. In general, passive design has turned out to be simpler and more effective than expected. Annual national and international passive solar conferences have refined and propagated these techniques with remarkable speed. Successful passive solar houses are now being built or retrofitted[6] at a rate of hundreds of thousands per year, even in the least favorable solar climates.[7]

New materials New materials with unusual properties are becoming available for both passive and active solar use. Transparent insulation and heat-reflecting glazings (including Heat Mirror,) are now in commercial production. An experimental glass-plastic-argon glazing with an R-value of nineteen–as good an insulator as nearly two and a half inches of foam–has been developed in Germany. Some new plastic-film glazing materials, such as 3M's Flexigard,, transmit better than window glass at visible wavelengths, are nearly opaque in the infrared, and show no signs of degradation after twelve years' weathering in bright sun.[8]

Solar plastics Tough, highly durable plastic films have been proposed by T.B. Taylor and developed by Brookhaven National Laboratory as materials for active solar collectors at least ten times cheaper than conventional ones. Such collectors have for several years been sold in Switzerland,[9] and could easily be site-assembled just as plastic-film greenhouses are now. (Stockpiling appropriate films and instructions could indeed be an important element of any solar mobilization.) Active solar collectors molded from up to four different polymers, each suited to its task, are now being sold. Micropolished reflective films are proving highly resistant to weathering and are starting to reduce dramatically the price of concentrating collectors.

Simple concentrating collectors So diverse are the designs of active solar collectors–now being made by more than three hundred fifty U.S. companies–that it is not yet clear whether flat-plate or concentrating collectors are superior for supplying heat below the boiling point of water. The Office of Technology Assessment found that the cheapest collector on the 1977 market (other than rollable plastic mats and other unconventional designs, some of which are quite effective) was a concentrating parabolic trough.[10] Very simple automatic tracking mechanisms have been developed. They can be quite reliable, as attested by the performance of military and airport radar trackers. Robert Stromberg of Sandia National Laboratory, who has sold thousands of sets of plans for a homemade concentrator of the type used on his own house, argues with some justification that even in a climate as cloudy as Boston, the extra efficiency of a concentrating collector when exposed to direct sunlight can more than make up for its inability to capture the diffuse light which may be at too low an intensity to reach the flat plate's operating threshold. This argument has particular merit for photovoltaic cogeneration systems (described below). Moreover, compound parabolic (Winston) collectors can achieve concentrations of several suns–in some cases approaching ten suns–without needing to track the sun at all, or with only a few adjustments of their orientation each year. Such collectors can combine the advantages of concentration in direct sunlight with respectable performance as flat-plate collectors on cloudy or hazy days, and can be cheaply mass-produced from molded plastic.

Selective surfaces A response to the argument for concentrating collectors is that in a cloudy climate, "conventional" flat plates–those with a flat-black absorbing surface–are the wrong choice. A "selective" surface, which absorbs visible wavelengths well but radiates infrared badly, is far preferable. A surface which absorbs visible light about five times as well as it emits infrared (a "selectivity" of five) can be made simply by brushing a lampblack-water slurry on a metal absorber plate and letting it dry to a thickness which removes the metallic luster but is still gray, not black. A selectivity around eight to ten can be achieved by many kinds of electrochemical coating processes and some special paints. Adhesive selective foils (such as SunSponge®) can boost even the performance of Trombe walls–passive, glazed masonry walls–by about a third, more cheaply than equivalent night insulation.

For about thirty cents per square foot, a selectivity-eight foil can be applied, perhaps by stretching it over a slightly convex absorber, to an active collector. This simple modifi-

cation produces remarkable results. Since the diffusely scattered light on a cloudy day, although somewhat reduced in intensity, is still energy of extremely high quality–its effective color temperature is over five thousand degrees Fahrenheit–a selective surface, suitably insulated, will attain very high equilibrium temperatures. Thus a single-glazed selectivity-eight collector–a selectivity achieved in many commercial U.S. and Japanese flat-plate collectors–has been demonstrated to heat domestic water by a highly satisfactory fifty-four Fahrenheit degrees–that is, to a final temperature well over a hundred degrees–with forty-five percent efficiency on a cloudy winter day in Hamburg.[11] (The total solar radiation per square foot was equivalent to a fifth of the level obtained on a clear summer day at noon. Raising this to three-tenths increased the efficiency to fifty-seven percent.)

Higher selectivity would make the collector even less sensitive to cloudiness. A selectivity in excess of fifty can be obtained by sputtering thin films using well established high-vacuum techniques similar to but less demanding than those used in coating optical lenses. A selectivity–fifty surface in a hard vacuum will serve a process heat load at upwards of a thousand degrees Fahrenheit on a cloudy winter day in Juneau. If the liquid-metal coolant in such an absorber should stop flowing the metal absorber plate would probably melt.

Medium-concentration-ratio collectors In contrast, only direct sunlight can be used to operate conventional collectors. Commercial line-focus systems, of which more than a million square feet were made in the U.S. in 1980, go up to about five hundred degrees Fahrenheit, and sold in 1980 for about thirty or forty dollars per installed square foot[12]–a price competitive with oil today, and certainly with new synfuels or electricity (Appendix Three). Point-focusing dish collectors can achieve higher temperatures. General Electric prototype dishes twenty-three feet in diameter recently supplied heat at seven hundred fifty degrees Fahrenheit with seventy-one percent collection efficiency.[13] (That temperature is adequate to supply essentially all the process heat needed by the food, paper, and chemical industries, plus most of the needs of oil refining.) Point-focus systems for loads up to about fifteen hundred degrees Fahrenheit are beginning to enter the market at attractive prices. For example, Power Kinetics Corporation, of Troy, New York, offers for thirty-seven thousand dollars an eight-hundred-sixty-square-foot dish with a peak output capacity of fifty-nine kilowatts and a measured efficiency of seventy-four to seventy-nine percent. It is calculated to pay for itself by saving oil in the Northeast within three to ten years[14]–similar to the economies estimated in the Solar Energy Research Institute's "conservative" mass-production case shown in Table A.2 in Appendix Three, and competitive today with most fuels in most parts of the United States. Another dish has heated gas to twenty-two hundred degrees Fahrenheit steadily, twenty-six hundred maximum.[15]

High-concentration-ratio collectors Large dish concentrators can achieve concentration ratios up to about a thousand suns–enough to vaporize any material. For achieving very high temperatures, however, it is more common (though not yet proven to be cheaper) to focus sunlight on central receivers by using large fields of tracking mirrors (heliostats). Such systems, now under development in many countries, can achieve essentially any concentration ratio. One Italian firm sells small heliostat fields.[16] Heliostats operate megawatt-range

solar power plants in Japan, Spain, and France. Southern California Edison Company proposes to build by 1988 a hundred-megawatt solar peaking unit instead of oil-burning gas turbines. Edison believes that modest heliostat production–about a hundred megawatts of electrical capacity per year for five to seven years–would make such solar-thermal systems economic for repowering oil-fired plants in the Southwest.[17] The biggest application of heliostat technology, however, will probably be in high-temperature direct process heat. In that market it will have some stiff competition from lower-technology solar collectors. As an example of what can be achieved even with devices simple enough for a tinkerer to make at home, one dish concentrator built by Doug Wood in the cloudy Olympic Peninsula of Washington State provides forty kilowatts of steam at a new-materials cost less than half the cost of heat from burning 1981 world oil in an eighty-percent-efficient boiler. Even a commercial replica of this simple dish (made of sections of pipe and cheap sections of mirrored glass) would compete handily with today's oil prices (Appendix Three).[18]

Solar ponds Among the most rapidly emerging solar technologies during 1980–82 has been the solar pond–a passive device for cheaply supplying heat year-round, day and night. Although there are several types of solar pond, the most common is a hole in the ground with an impervious liner, filled with concentrated brine–various kinds of salts can be used–and preferably with a darkened bottom. Both direct and diffuse solar radiation heat up the bottom of the pond, but because the hotter water there dissolves more salt and is thus denser, convective heat transfer to the surface is suppressed. (The proper geometry can enable the salt to form a self-stabilizing gradient of optical bending power which helps to concentrate light on the bottom.) A layer of fresh water on top, which stays fairly well segregated, acts as a transparent insulator. Other forms of translucent insulation can also be added. A simple heat exchanger, such as some pipes near the bottom, can extract heat at nearly the boiling point: solar ponds in sunny areas can boil by late summer, as a pond near Albuquerque did in 1980. The large thermal mass of the pond provides built-in heat storage, although it may take some months to come up to its full working temperature. Good ponds convert twenty to thirty percent of the total solar radiation into usable heat. They may cost fifty cents to a dollar per square foot if salt is available onsite, as near many mines and factories; three dollars or more per square foot if the hole, liner, and salt must be specially provided.

Solar ponds were originally expected to work only in desert climates, but the successful operation of a nearly half-acre pond by the City of Miamisburg, Ohio since 1978 has dispelled that notion. Even with ice on the surface, the bottom temperature in the cold spell of February 1978 was still eighty-three degrees Fahrenheit. The total cost, mostly for eleven hundred tons of salt and for the liner, was three dollars twenty cents a square foot. Maintenance cost is very small. The delivered heat price, as noted in Appendix Three, is just over nine dollars per million BTUs.[19] That is equivalent to burning seventy-five-cent-a-gallon oil (hard to find these days) in a seventy-percent-efficient free furnace, or to running a baseboard heater with electricity costing three and a tenth cents per kilowatt-hour (about half the national average residential price). Recent reports indicate that the heat was stored for two or three months rather than for six, and

thus did not quite match the load, but a larger or better-lined pond would provide longer storage. Other pond projects, including some to provide district heating, are being pursued in cloudy northern climates.[20]

Solar pond research and demonstrations being pursued by the CalTech Jet Propulsion Laboratory, Los Alamos National Laboratory, California Energy Commission, Southern California Edison Company, and others should lead in the next few years to the sort of "cookbook" understanding of pond design already obtained for passive solar techniques. Solar ponds are a robust, nearly invulnerable heat source: even an event which disturbed the salt gradient and reduced collection efficiency would still leave weeks' worth of recoverable heat.

Ice Ponds Another and in some ways even more exciting development, seasonal storage ice ponds,[21] can store winter coolth through the summer, offering reliable air-conditioning at a tenth of the usual energy cost. T.B. Taylor has demonstrated that high-density ice can be formed on a chilly winter day in Princeton, New Jersey, simply by spraying water from a garden hose into a hole in the ground. Insulated by straw (or more elaborate materials), such a block of ice can supply thirty-two-degree meltwater for chilling a building right through the summer. (A large building using this principle is now under construction in Princeton with funding by an energy-conscious insurance company, Prudential.) A combination of ice ponds with solar ponds,[22] taking advantage of the economies of seasonal storage noted in Appendix One,[23] can provide heating, cooling, and–via a low-temperature heat engine–electricity at prices which look very attractive today.

Vehicular liquid fuels

Enough liquid fuels can be sustainably produced from farm and forestry wastes (not special crops) to run an efficient vehicle fleet.[24] (Biomass-derived chemical feedstocks also show considerable promise.)[25] The sustainable use of biomass wastes will require careful management and integration with basic reforms of cultural practice which should be undertaken in any case to protect soil fertility–now eroding faster than during the Dust Bowl.[26]

Primers on biomass liquids have been published elsewhere.[27] The main types of liquid fuels available from biomass include pyrolysis "oil" made by heating woody substances with little air; such "oil" slurried with char produced in the same process; diesel fuel or gasoline refined from pyrolysis "oil"; methanol; ethanol; butanol; and blends of various alcohols. These can be burned neat or blended with oil-based fuels; Gasohol,, for example, is a blend of ten percent anhydrous ethanol with ninety percent gasoline. Other liquids also show promise: for example, alcohols and inedible vegetable oils can be reacted in a simple solar-heated catalytic device to form esters which are reportedly superior to oil-based diesel fuel.[28]

Use in vehicles Some of these fuels are usable directly in unmodified car engines; others need minor modification which costs up to several hundred dollars for retrofit or nothing at the factory.[29] (These modifications must, however, be properly done; inadequate atten-

tion to such details as making fuel-system gaskets insoluble in alcohols and preventing alcohols from becoming contaminated by water has led to well-publicized problems in Brazil's ethanol fuel program.) The range of some fuel-engine combinations can be extended by changing the engine design: alcohols, for example, burn well in spark-ignited diesels with proper lubrication. The high compression ratios obtainable from such designs can enable alcohols, especially methanol, to burn much more efficiently than gasoline–one of the reasons why methanol has long been used as a premium fuel by racing drivers.

It would enhance energy preparedness if car makers routinely used methanol-proof components in fuel systems, and provided carburetors with a switch for easy conversion between gasoline, gasoline/alcohol blends, and pure alcohol. (At least one U.S. automaker has reportedly developed such a device.) Brazilian automakers owned by Ford, General Motors, Chrysler, and Volkswagen are already making pure-ethanol cars and converting about ninety thousand gasoline cars to ethanol each year.[30] Despite some teething troubles, Brazil's program is expanding. In California, some cars are being commercially converted to burn neat methanol (cheaper and cleaner than gasoline), with the conversion cost being almost entirely covered by the renewable energy tax credit.

Dispersed ethanol production Excellent manuals on commercial ethanol production from crops are available,[31] though analogous guides are not yet available for other, more promising, feedstocks, processes, and products. Extensive grassroots training programs in ethanol still construction and operation are provided by a wide range of groups, especially in the Midwest.[32] Given that knowledge, a still big enough to fuel a car can be built from commonly available materials in a few days and operated from almost any sugary or starchy feedstock. Although this approach, using traditional still designs, is not energy-efficient, it does provide a premium fuel from what may otherwise be waste materials. Small- and medium-sized ethanol plants of more formal design also offer interesting advantages for integration into farm operations[33] and are attracting special interest as a community economic development tool at small Black colleges.[34]

Whether ethanol is produced in small stills or (preferably) a wider range of fuels is produced by more efficient methods from non-crop feedstocks (especially cellulosic wastes), the potential contribution from many small plants, both routinely and in an emergency, could be very large. As an analogy, in the United States today about eleven million cows, in herds averaging sixty cows each, produce fifteen billion gallons of milk per year. That is about a fifth as many gallons as the gasoline used annually by American cars, or about the same as the number of gallons that those cars would use if they were cost-effectively efficient (Chapter Fifteen). Yet much of that milk "is efficiently supplied by small-scale decentralized operations"[35]–at far lower cost than if all the milk were produced, say, in a few giant dairy farms in Texas and then shipped around the country. Likewise, "the average stripper well produces about two and eight-tenths barrels of oil per day, which is about one-seventh of one-thousandth of a percent of what we consume in oil every day, …but…the cumulative effect of all our stripper wells [is]…twenty-one percent of continental oil [extraction]."[36]

A special advantage of alcohol or other liquid-fuel production from farm and forestry

wastes is that it would tend to be concentrated in the mainly agricultural, rural areas which have disproportionate, highly dispersed needs for mobility fuels[37] These regions are at the end of conventional supply lines: some North Dakota farmers today must drive hundreds of miles to get to a gas station, making it hardly worthwhile to fill up. But without adequate fuel, those rural areas cannot grow food for export to the cities. Of the two and a half quadrillion BTUs used in American agriculture in 1978, about ninety-three percent was oil and gas.[38] Most of that ran farm equipment and dried crops. In a shortage, and especially in a war, farms could no longer compete in the marketplace for very costly mobility fuels–especially if agricultural exports had also been interrupted, making grain prices plummet at the very time when oil prices were skyrocketing, probably to several dollars a gallon. In these dire circumstances, farmers could continue to feed the nation only if they had the means to convert crop wastes (and perhaps even surplus grains at a pinch) into alcohol fuels. It is for this reason that Admiral Moorer, former Chairman of the Joint Chiefs of Staff, noted "the valuable contribution of a highly dispersed, self-contained liquid fuel production system to serve the vast U.S. farming community in developing the strategic defenses of the United States."[39]

Other biomass-to-liquids alternatives Many people think only of corn-based ethanol when biomass liquids are mentioned. A million tons of corn did in fact provide about one hundred of the hundred and five million gallons of fuel alcohol made in 1980.[40] If earlier federal commitments had been honored, grain ethanol plants producing nearly six hundred million gallons per year would have been built by the end of 1982.[41] But corn ethanol is far from the only important feedstock, process, or product, and–especially with the inefficient, oil- or gas-fired stills commonly used–is among the least attractive. Other processes, notably thermochemical ones, have better economies and at least equal technical simplicity.[42]

Feedstocks for pyrolysates or alcohols abound, even in urban areas: just the pure, separated tree material sent each day to Los Angeles County landfills, not counting mixed truckloads, is four to eight thousand tons, with an energy content of the order of a thousand megawatts. At a nominal conversion efficiency of seventy percent, a thousand megawatts (thermal) of tree wastes would yield fuel equivalent to nearly half a million gallons of gasoline per day–enough to drive a sixty-mpg car more than ten miles per day for every household in the county. Sacramento is spending three and a half million dollars to build a fluidized-bed gasifier, expected to repay that cost within six years, which will consume twenty thousand tons per year of tree, lawn, and garden trimmings–a third of the City's total trimmings now sent to landfill. On completion in late 1982, the gasifier is to provide sixteen megawatts of heat at eighty-five percent efficiency, replacing half the natural gas now used in the boilers that heat and cool the Capitol and seventeen large state office buildings.[43] Similarly, Gold Kist, Inc. expects a three-year payback for the four-million-dollar boiler installed in 1981 at its soybean processing plant, and fired with peanut hulls and pecan shells. Diamond/Sunsweet, formerly having to dispose of a hundred tons of walnut shells per day, is now getting a three-year payback by burning them in a four-and-a-half-megawatt cogeneration plant. And the

Boeing Company's huge production complex in Everett, Washington is building a plant which will burn cartons and other factory wastes to raise steam for space-heating and powering manufacturing processes.[44]

Most parts of the United States have some similarly rich source of biomass wastes whose premium use, in general, is not combustion for heat or electricity, but rather conversion to mobility fuels. The cotton-gin trash currently burned or dumped in Texas is enough to run every vehicle in Texas at present efficiencies. The distressed grain in an average year in Nebraska would fuel a tenth of the cars in Nebraska at sixty mpg. At that efficiency, the straw burned in the fields of France or Denmark each year would fuel every car in those countries. Feedstocks range from walnut shells and rice straw in California to peach pits in Georgia and apple pomace (left after squeezing cider) in Pennsylvania. None of these wastes by itself is nationally significant. But numerous small, localized terms, of which the largest is logging wastes, add up to quite enough to fuel, even with expanded travel, the entire American transport system if it is run at cost-effective levels of efficiency.[45]

Appendix Three shows that some of the processes available today can provide liquid fuels from biomass wastes at prices competitive with oil products. Some other processes and feedstocks are not quite competitive with today's oil, though they are much cheaper than the synthetic fuels which are proposed (with huge federal subsidies) to be made from coal or oil shale. To bring the full range of bioconversion processes from promising pilot-scale tests to competitive market availability will require three main types of technical developments. The first, most important, and least supported is reform in farming and forestry practice to make these activities sustainable by protecting soil fertility while at the same time providing residues for fuel conversion.[46] This is an intricate biological, social, and economic question which no federal program addresses; but without it, Americans will not long remain able to feed themselves.

The second need is rapidly being met: the final product engineering and wide deployment of improved processes to ferment sugars or starches into ethanol. For example, a few years ago it took fifty to a hundred thousand BTUs to distill a gallon of ethanol to one hundred ninety proof. Today some commercial processes use twenty-five thousand BTUs to go all the way to dried (anhydrous) ethanol,[47] and the best demonstrated processes have reduced this to only eight or ten thousand BTUs, using advanced distillation or critical-fluid processes.[48] Innovative water-alcohol separation processes include freezing (New England applejack and Appalachian moonshine were long fortified by leaving the kegs out to freeze), chemical extractants, hydrophobic plastics, cellulosic adsorbants,[49] and–just emerging–synthetic membranes.[50] Good process efficiencies, in mass yield from feedstock to alcohol, are now typically forty-six to forty-eight percent for glucose fermentation to ethanol–some ninety to ninety-five percent of the theoretical limit on efficiency. These processes are likely to become widely available at all scales over the next few years.

The third and technically most exciting line of development is the evolution of new processes (or refinement of old ones–acid hydrolysis has been in use for over a century) to convert cellulosic wastes, the most versatile and abundant kind, into alcohols. Acid hydrolysis can break down cellulose to glucose with virtually complete yields, providing a mass yield of over forty percent from cellulose to ethanol.[51] Cellulose and hemi-

cellulose can also be converted directly into ethanol by special bacteria at mass yields of better than twenty-five percent[52]—a figure that is being improved upon.

Thermochemical processes Thermochemical processes can yield methanol by the routine catalytic "shift reaction"[53] of steam with synthesis gas (a hydrogen/carbon-monoxide mixture produced by oxygen gasification of biomass). Using modified coal-conversion technology, which is not optimal for biomass, the efficiency of the whole process is about forty to forty-eight percent, or about as good as the main processes for making synthetic fuels from coal.[54] A new downdraft gasifier has increased the methanol yield to an astonishing eighty-three percent, while another gasifier design can directly produce gasoline.[55] Pyrolytic "oil" production has at least a fifty percent conversion efficiency[56]—typically sixty to eighty percent including the slurried char, even in small plants that can fit on the back of a pickup truck and go to where a pile of logging wastes, mill sawdust, or other feedstock happens to be available.[57]

Most thermochemical processes are better suited to producing methanol than ethanol. As mentioned earlier, methanol has long been considered a premium fuel for its high performance, cleanliness, and safety; in high-compression-ratio car (say, fourteen or more to one), it burns so efficiently that even though it contains only half as much energy per gallon as gasoline, it can supply only a fifth to a quarter fewer miles per gallon. Methanol/ethanol/tert-butanol blends and other combinations of several types of alcohol can be even more advantageous.[58] Since cellulosic feedstocks are the most widespread and the easiest to convert and use efficiently in small, dispersed plants using low technology, the emerging cellulosic conversion processes seem particularly advantageous for building a nearly invulnerable national capability for dispersed, sustainable liquid fuel production.

Gaseous fuels for road vehicles As still another option, cars can burn gaseous hydrocarbons with little modification except in the fuel tanks. Although hydrogen-burning cars are still fairly rare, other gaseous fuels are becoming quite popular. Canada has a program of conversion to compressed natural gas (CNG), at a capital cost of about seventeen hundred dollars per car for retrofits or at most a few hundred dollars at the factory. Although the limited gas capacity of the steel gas bottles reduces the range of the cars to about forty-five miles per standard welding-gas-sized tank, the bottles can be kept in the trunk without taking up all the luggage space, and the normal gasoline tank can be kept connected to the fuel line too. Thus the car can remain dual-fueled, enjoying both the long range of gasoline and the reduced engine wear, lower emissions, and lower costs of CNG (especially in urban driving). Upwards of twenty thousand American and a quarter-million Italian drivers have already switched to CNG. They usually refill their gas bottles in a few seconds at compressor stations (many of which are at gasoline filling stations). Methane suitable for CNG cars can also be made from biomass wastes and compressed on the farm. Congress recently passed a Methane Transportation, Research, Development and Demonstration Act to encourage CNG applications.

Another alternative vehicular fuel now gaining ground is LPG (Chapter Eight)—chiefly propane stored as a pressurized liquid and vaporized on demand by a small heat

exchanger warmed by the vehicle's exhaust. About three million LPG carburetors have been sold in the U.S. since 1969, and the rate of conversions is rapidly increasing as fuel costs and taxes rise. Renault and Peugeot sell LPG production cars.[59] Ford offers a 1982 propane model in production Granadas and Cougars.[60] Many fleet operations already use LPG. The fuel tank is arguably more dangerous than a gasoline tank in a crash, though the safety experience so far is not bad. With CNG–already gaseous rather than liquid, and contained within half-inch steel tank walls–no tank ruptures have been reported in one hundred eighty rear-end collisions.

A million portable wood gasifiers ran European cars during World War II. Extensive data are available on their design and performance.[61] Although they take about an hour a day to fuel and care for, and consume about twenty-two pounds of dry wood per gallon gasoline equivalent, they are such a robust substitute in heavily wooded regions that Sweden is considering stockpiling gasifiers in case of severe gasoline shortage. Direct-combustion Stirling engines may also be attractive.[62] The Boat Division of Chalmers in Sweden has even burned wood flour directly in diesel engines. Wood itself (and sawdust, peat, etc.) is easy to store, ship, and handle in pelletized form: one version, Woodex™, is cleaner than coal, at least as cheap, and made by at least twelve plants in seven states.

Electricity

The most commonly discussed renewable electrical sources are microhydroelectricity, wind electricity, and photovoltaics (solar cells). (Others, such as solar cogeneration in dish concentrators supplying industrial process heat, or electric-only "power towers" using large fields of heliostats, will not be treated here.) Wind and small hydro can also be used for pumping water or heat, for direct mechanical drive, for compressing storable air to run machines, or even for refrigeration.[63] At least one small hydro operation in upstate New York is also reported to be using its surplus off-peak output to electrolyze water; the resulting hydrogen, a premium gaseous fuel, could of course be stored under pressure or in solid hydrides and used to operate clean vehicles at high efficiency. Surplus electricity from solar cells or other sources could be similarly used. Although pure-electric cars cannot compete in principle with very efficient fueled cars, some of those, such as series hybrids, lend themselves to partial operation by cheap solar cells (perhaps installed on the car itself) or other renewables.

Low-temperature solar thermal electric systems A little-known option may, in favorable sites, be the cheapest known source of new baseload electricity: a solar pond with a low-temperature heat engine, especially if it works into an ice pond as suggested by T.B. Taylor. The large heat capacity of the pond would provide weeks or, in large ponds, many months of built-in storage. Israel has operated a hundred-fifty-kilowatt-electric solar pond/Rankine-engine combination of this type since 1979. There are plans to expand this to five megawatts, at a cost of about two thousand dollars per electric kilowatt, in 1983. Israel also plans two thousand megawatts (the equivalent of two giant power stations) in floating solar ponds in the Dead Sea by 2000, and projects that a proposed Southern California Edison Company plant in the Salton Sea–officially projected to generate elec-

tricity at about seven to ten cents per kilowatt-hour (competitive with central coal or nuclear plants)—could actually be built to run at four to seven cents a kilowatt hour.

Small hydro Small hydro—variously defined as less than one-tenth, five, or twenty-five megawatts per site—is being intensively exploited by entrepreneurs.[64] Many of these projects merely revive older ones that had fallen into disrepair. By 1976–77,[65] innumerable small dams, including over ten thousand in New England alone, had been abandoned: just in the past twenty years, more than three thousand working hydroelectric plants totalling some three thousand megawatts had been taken out of service, considered a nuisance by utilities that preferred to manage a few big plants instead. (Many existing large dams were also left with empty turbine bays.[66]) The National Hydroelectric Power Study by the Army Corps of Engineers has identified still more opportunities, but has tended to ignore many of the best ones, such as canal locks.

There are more than fifty thousand dams over twenty-five feet high, plus many which have a lower head but are still potential power sites (heads as low as five feet,[67] or essentially zero-head run-of-the-river sites, can be used). Some of these sites are environmentally or institutionally unsuitable,[68] but many others can be refurbished and some developed from scratch without doing much harm. The technologies are generally straightforward and highly cost-effective.[69] A do-it-yourself manual and several excellent periodicals are available.[70]

The rate of progress in installing small hydro equipment is hard to measure because many utilities seem to underreport their hydro projects. For example, Pacific Gas & Electric and Southern California Edison reported one hundred seventy megawatts of hydro in the January 1981 Electrical World survey of capacity additions underway, but the California Energy Commission's staff report on the proposed Allen-Warner Valley coal project lists, for these two companies respectively, seven hundred seventy and eleven hundred fifty megawatts of hydropower as "reasonably expected to occur" and about fifteen hundred and seven hundred fifty megawatts as "additional, but not counted." Thus those two companies' hydro projects already underway, most of them with permits filed for, total eighteen hundred fifty-seven megawatts—over ten times what the Electrical World survey, the utility industry's standard source, reflects.[71]

A further barrier is that the Federal Energy Regulatory Commission is inundated with license applications: twenty-six hundred applications averaging eight megawatts each were submitted in the two years ended July 1981[72] (including some applications apparently filed by a few companies that intend to sit on them or resell them at "scalper's" profits). In that one month alone, the Commission issued more small hydro permits than it used to do in a whole year; but it also received new applications at a rate averaging ten per day, so the backlog grew.

Despite these impediments, the impact of small hydro is already substantial in some areas.[73] Nationally, over the next few decades small hydro should approach the same total capacity as existing large-scale hydroelectricity, but far more evenly distributed around the country. New York State alone envisages two to three thousand megawatts of small hydro by the mid-1990s, the equivalent of three or four major power stations.[74]

Similar programs are underway abroad, even in countries noted for their devotion to large hydroelectric plants: Sweden, for example, plans to have built two hundred and fifty small plants by 1982, while New Zealand has sixty and plans to build more.[75]

Small hydro should be speeded by new companies providing a "no-hassle" turn-key development service, such as Energenics Systems, Inc. Among the new hardware, too, is a range of Chinese turbines designed by American engineers a half-century ago and ruggedly built for export at prices well below those of American and European manufacturers. China, as mentioned in Chapter Seven, now gets more than seven thousand megawatts from over ninety thousand local microhydro sets (few of them grid-connected[76]) ranging from six hundred to a hundred thousand watts, and usually with heads of only zero to sixteen feet. This adds up to at least a third of all Chinese electricity outside the cities,[77] and powers much of the dispersed light industry–an important element of Chinese civil defense planning.

Windpower Windpower has the disadvantage (compared to flat-plate photovoltaics) of moving parts, but the considerable advantage of being able, in decent sites, to collect a great deal of energy from a relatively small machine. A machine which extracts only thirty percent of the power in the wind–reasonable performance for a good design without fancy equipment (tipvanes, shrouds, variable pitch, etc.)–can extract nearly twice as much power from a square yard of area swept through an eighteen-mile-per-hour wind as a square yard of ten-percent-efficient solar cells can extract in bright sunlight.[78] Furthermore, the average U.S. sunlight (direct plus diffuse) averaged over the day and year is only a sixth as strong as bright noon sunlight on a clear day, whereas strong winds can blow at any time, and tend to be especially common in cloudy winter weather. Accordingly, a simple wind machine in a good site, such as many parts of New England, the Great Plains, or the Pacific coasts and islands, can capture mechanical work very cheaply.

A few examples give the flavor of the machines now commercially available and of those now being tooled up for series production. Designs like the very simple one mentioned on page 232 in Chapter Fourteen are now on the market and will become much cheaper when mass production supplants model-shop operations.[79] Even with hand production of only twenty per month, each with a peak capacity of only one kilowatt, those Bergey machines sold in 1981 for twenty-five hundred dollars FOB factory (five hundred more for a synchronous inverter). In a windy site on the Great Plains, such a machine can produce electricity at prices as low as five to eight cents per kilowatt-hour. Professor Otto Smith, a Berkeley engineer, has made at home, for fifteen hundred dollars (1980 value), a seventeen-and-a-half-kilowatt (at thirty-eight mph) Chalk-wheel turbine, looking like a giant bicycle wheel, which he estimates could be commercially produced for sixty-seven hundred dollars, or under four hundred dollars per peak kilowatt[80]–an excellent bargain. (The electrical output capacity of wind machines is normally rated at a particular speed, generally lower than Smith's figure, and the cost of that capacity is expressed per kilowatt peak [kWp] at that rated speed.) The Borre sail-wing design[81] is on the market in an eighteen-kilowatt version for about six hundred fifty to six hundred ninety dollars per peak kilowatt,[82] producing power in good sites at

about five cents per kilowatt-hour. Machines made by U.S. Windpower of Burlington, Massachusetts, and designed around commonly available, mass-produced components, are selling (complete except tower, FOB factory, 1981) for six hundred ten to seven hundred dollars per peak kilowatt in the twenty-five- and thirty-seven-kilowatt sizes (models CA and CB respectively).[83] A refined prototype can probably be made for about half that much.[84] The late Terry Mehrkam of Hamburg, Pennsylvania recently built a very large (one-megawatt) machine for a local factory at a total labor-and-materials cost of four hundred twenty-five dollars per installed kilowatt–roughly half the expected mass production cost of the more complex megawatt-range machines developed by government programs with aerospace companies.

The roughly sixty U.S. manufacturers of small machines are listed in indices published by Wind Power Digest, the American Wind Energy Association, and the Rockwell International wind test program at Rocky Flats. (There are also many manufacturers abroad, including more than two dozen in Denmark alone.) Basic guides to selecting wind machines[85] and their sites[86] are bringing the technology into common currency. New "wind prospecting" methods include satellite observation of inversion-layer breakups (University of Alaska) and detailed computer simulation of windflow over digitized terrain (Lawrence Livermore Laboratory). Although one might suppose that an art as ancient as wind machines has already had all possible technical refinements, basic improvements continue, especially in blade aerodynamics and designs for applications other than electric generation. For example, the Wind Baron Corporation (Phoenix, Arizona) reports that its design, by using adjustable weights to counterbalance the water column, can pump up groundwater from three hundred feet down in winds as low as five mph–a speed which occurs ninety percent of the time over ninety-four percent of earth's surface.

Large-scale commercial wind projects are springing up. Southern California Edison Company has agreed to buy the output from eighty-two megawatts offered by entrepreneurs and is negotiating for several hundred more–over twice its target for the year 2000. A three-hundred-fifty-megawatt project by Windfarm™ of San Francisco, contracted in January 1982 for construction during 1983–89 thirty miles northeast of that city, is to cost over seven hundred million dollars and serve four hundred fifty thousand people. It is to supply nearly a billion kilowatt-hours per year at a real price of three and a half cents per kilowatt-hour[87]–probably less than half the likely incremental cost which California utilities face if they order a coal or nuclear plant. Another company, U.S. Windpower, is currently installing an array of two hundred machines, each with a peak capacity of fifty kilowatts; in all, the company seeks to have six hundred such machines supplying ninety million kilowatt-hours per year by mid-1983. The same firm built twenty machines of fifty kilowatts in New Hampshire within five months of first contacting the site owner, and hooked them to the grid in late 1980 in a mutually profitable symbiosis.[88] This is about twenty-five times as fast as central-station capacity can be built–clearly a way both to reduce utilities' forecasting and financial risks (Appendix One) and to replace power plants in an emergency.

The Hawaiian Electric Company has offered to buy eight and a half percent of its electricity from wind machines starting in 1985. This could be supplied by building

twenty large machines at a site (Kahuku Point, Oahu) with twenty-mph minimum winds eighty percent of the time. Plans to finance such a project collapsed in 1982, but the opportunity remains. At least one California city has an operating municipal windpower utility.[89] The Bonneville Power Administration is operating three multi-megawatt wind machines on its grid in the Columbia River Gorge in Washington State. A private entrepreneur reportedly built more than a hundred sailwing gyromills of twenty-five to thirty kilowatts each, priced at eighteen thousand dollars, to run a bleach plant in Dalhart, Texas.[90] Other private projects abound.

Interest in windpower is rapidly rising abroad as well. The Dutch government, for example, is expected to approve a plan for eleven hundred wind machines each providing about three megawatts and all generating, in conjunction with lagoon pumped storage, about nine billion kilowatt-hours per year, or about twelve percent of projected national electricity demand in the year 2000.[91] The Dutch wind array would be completed one-third at a time (by 1990, 1995, and 2000), at a cost of about nineteen hundred million dollars, or just over two cents per kilowatt-hour–a fifth of typical European electricity prices today.

Photovoltaics Photovoltaics are extremely durable, reliable, and simple to use:[92] when placed in the sun, they produce direct current, needing no maintenance unless they have a tracking concentrator. There is no chemical reaction inside them: nothing decays, discharges, or is consumed, or given off. These qualities have long commended them for such applications as powering buoys, highway signs, Forest Service towers, microwave relay stations, and remote military bases (part of the rationale for proposed Defense Department purchases[93]). Indeed, solar cells are considered a strategic device whose export is restricted by law.

As with transistors in the 1950s and 1960s and integrated circuits in the 1970s, the cost of solar cells has been falling dramatically. Even conventional, first-generation cells (silicon wafers cut from cylindrical single crystals melt–grown by the Czochralski process) have shown a steep price drop. Czochralski silicon array prices fell from about thirty dollars per peak watt in late 1976 to seven to ten dollars per peak watt in 1979–80. (Photovoltaics are rated in peak watts [Wp] of direct-current output in full sunlight of one thousand watts per square meter.) Such single-crystal silicon cells are now made and sold in many countries: Brazil will even begin exporting them in 1982. There is a consensus among the managers of the very competently run federal photovoltaics program that implementing proven technologies for producing such cells in a more automated fashion, without the thirty-odd hand operations now needed, can reduce the array price to about two dollars and eighty cents per peak watt (in 1980 dollars) by late 1982, corresponding to an installed whole-system price of about six to thirteen dollars per peak watt for flat-plate systems.[94] This is already a sufficiently interesting price that Citicorp has announced plans to install photovoltaics on the slanting roof of its New York City headquarters; the Sacramento Municipal Utility District plans a hundred-megawatt array next to the Rancho Seco nuclear plant; and the European Economic Community in November 1980 authorized the construction of approximately twenty photovoltaic pilot plants in Europe, ranging from thirty to three hundred peak kilowatts.[95]

It is highly likely that several of the second-generation processes already demonstrated and in advanced commercial development–silicon web or ribbon growth, coarse polycrystalline silicon, amorphous silicon films (which can be very cheaply vacuum-deposited on anything, including plastic films), or other materials–will achieve, on or ahead of schedule, the Department of Energy's 1986 array-price goal of seventy cents (1980 dollars) per peak watt, corresponding to a whole-system price of a dollar sixty to two dollars and sixty cents per peak watt and to electricity prices comparable to or lower than those from a newly ordered central power station.

American firms recently invested about two hundred million dollars in photovoltaic risk capital in a year and a half.[96] Solarex, a pioneering firm in Rockville, Maryland, plans by late 1982 to be operating an advanced and automated silicon wafer plant entirely powered by cells which it produces (which should settle the spurious net-energy question once and for all). Westinghouse, Mobil-Tyco, and others report progress with advanced processes for making fairly cheap single-crystal silicon in large amounts. Several American firms have announced the development of amply efficient amorphous materials which they expect to market by about 1985 at about seventy cents per peak watt or less. One such material, developed by AMETEK,[97] can be applied by a simple wet-chemical process similar to electroplating; is already about eight percent efficient; has a materials cost of forty cents per peak watt; and may be applied to the absorber plate of an AMETEK flat-plate solar heat collector to produce electricity as a byproduct. Collector glazings can also be used as nonfocusing concentrators by dispersing a fluorescent dye in the glazing material so that the fluorescence is internally reflected to a photovoltaic strip along one unsilvered edge: a small cell area could thus produce byproduct electricity.

Some of these cheaper designs may be delayed in coming to market by the 1981 cancellation of federal funding for the higher-risk, second-generation cells. A more serious concern is that the longer-term competitive edge in photovoltaics will probably shift to other countries. In Japan, for example, Sanyo has already invested fifty million dollars in a factory for commercial production of amorphous silicon cells.[98]

It is not yet clear how the recent cuts in federal funding for photovoltaics will affect the timetable for achieving the Department of Energy's goal of seventy-cent-a-peak-watt arrays by 1986. If American firms miss that date, however, it will be only by a few years; and foreign competitors are likely to be ahead of schedule. It is therefore important to note that, according to detailed economic calculations, this confidently expected 1986 price–which assumes no further technological breakthroughs–will permit solar-cell electricity to compete on utility grids in most of the United States.[99] (Solar-cell power without a cogeneration heat credit would probably, however, be unable to compete with electricity from wind and small hydro in good sites.) Accordingly, the Department of Energy's Solar Photovoltaics Energy Advisory Committee stated in February 1981 that, due to a combination of rapid technical advances, PURPA buyback provisions (which help to create a competitive market in generation), and higher marginal cost estimates for conventional sources, it is likely that central station photovoltaics will compete around 1986.[100] This means that well-designed cogeneration versions should have become competitive around 1980–81 on a residential scale and in the late 1970s on a community scale.[101] In seeming

confirmation, many small firms are now springing up to offer packaged photovoltaic cogeneration systems, which concentrate sunlight on a small cell area and capture the waste heat for domestic use. Such a system is reportedly being installed in a San Diego hotel[102]; another)a costly federal demonstration) is operating in a Kauai hospital.

Many photovoltaic experts expect that by the late 1980s, it will probably be fairly common for new houses (and some old ones) to be net exporters of electricity. Already, using only the relatively expensive single-crystal silicon wafers, at least hundreds of houses had installed stand-alone photovoltaic systems with battery storage by the end of 1981.[103] By 1982, thousands of photovoltaic houses were operating in the U.S., of which the greatest concentrations occur in certain remote parts of California. The California Energy Commission expects photovoltaics to supply eleven percent of the state's peak electrical demand by the year 2000.[104]

New technical developments, now in the "breakthrough-a-month" stage, may indeed outdo even these prognoses in helping devices to move rapidly from laboratory achievements to mass-marketed products. Conscious of the need to make photovoltaics easy for builders and homeowners to use, General Electric is developing photovoltaic shingles which would cost little more than normal shingles but produce electricity too. They would be hooked up by nailing them onto the roof. Texas Instruments is developing a clever photovoltaic-hydrogen system with onsite hydrogen storage and a fuel cell. Technical developments in this field are moving, as is the way of semiconductors, too quickly even to report. This adds urgency to the need to plan for the long-term shape of renewable source integration into the power grid (Chapter Sixteen). The photovoltaics revolution is indeed already upon us. We should start getting used to the idea and figuring out how best to use these rugged, almost invulnerable devices to increase the resilience of national electrical supply.

Interconnection with the electric grid

There are many possible ways to connect dispersed renewable sources of electricity to the grid.[105] Which is the best method depends in part on which type of electricity the source generates. Fuel cells, solar cells, or special types of shaft-driven devices make direct current, whose flow is steadily in one direction. Batteries, the most commonly available electrical storage device, can be charged with, and when discharged provide, direct current. So far so good: direct current, with proper wiring, is a safe, simple, and robust way to deliver electricity throughout a building. Once delivered, direct current can operate incandescent lights and certain types of motors. Direct current at the proper voltage is also required by electronic circuitry and some industrial processes such as electroplating. Today, direct current for these purposes is often obtained by "rectifying" alternating current from the grid, then smoothing out its "ripple" to a semblance of a constant flow. Thus almost any electronic device–a television or stereo, for example–contains a rather bulky, heavy, and costly power supply to convert line-voltage alternating current to low-voltage direct current. If this were no longer necessary–if direct current were supplied to start with–a good deal of money, weight, and copper could be

saved, provided that the equipment manufacturer offered a direct-current option. This is already the case with many types of appliances which are already available in direct-current versions (typically at twelve or twenty-four volts) for marine use and for recreational vehicles. Before rural electrification, thirty-two volt direct-current appliances, such as washing machines, were also commonly sold for use on farms with direct-current wind systems and battery banks. This type of market is now re-emerging.

Historically, a main reason for standardizing the power grid to use alternating current was that it can be readily changed from one voltage to another by using a transformer (an iron core wound with two coils having different numbers of turns). That reason, however, is no longer valid, since modern solid-state circuits can convert one direct-current voltage to another very efficiently. Other new circuitry can operate ordinary alternating-current motors (which tend to be cheaper) on direct current over varying loads with better-than-normal efficiency. These conversion devices broaden the opportunities for using direct, without having to replace all of one's appliances.

Inverters Alternatively, or additionally, direct current can be converted into alternating current by a device called an "inverter." Old inverters used rotating motor-generator sets, but most today use solid-state switching electronics. Small inverters, such as are used to operate normal alternating-current appliances from the direct current available in a car or boat, are widely available. Larger ones, less commonly available, enable a house wired for direct current to interconnect synchronously with the alternating-current grid. Alternatively, the house itself can remain wired for, and operate its appliances on, alternating current, but connect the internal wiring via an inverter to its own solar cells or other local sources of direct current (typically via a battery bank or other storage device). A household source of direct current can thus connect to alternating-current appliances, to the grid, or both.

There are several kinds of inverters with different electrical properties, complexity, price, and reliability.[106] Some particularly useful inverters are sold in Japan, for example by Hitachi: they use a microcomputer to make a ninety-nine-percent-plus pure sine wave which changes in a fraction of a cycle to respond to the size and reactance of the load. The Sandia National Laboratory experts who design inverters for the firing circuits of atomic bombs have also been applying their skills to devising simple and reliable inverters for renewable energy sources. Most of the inverters now on the market were designed for use with wind machines, and do not operate as well with solar cells. Solar cell companies and special "packaged-system" consultants, however, are starting to provide complete combinations of compatible components–all the way from cells through inverters and other control equipment to end-use devices. Though this type of "balance-of-system" requirement is still the weakest point in solar-cell equipment, the available range of efficient, versatile inverters, compatible with a wide range of sources and uses, is likely to increase rapidly in the next few years as solar cells become more economic and widespread.

An inverter which connects a direct-current supply to the alternating-current grid must of course be synchronized with the grid. Some inverters take their cue from the grid itself but cannot work without it; some process the line voltage through a microcomputer for greater responsiveness; some maintain roughly the right frequency on

their own even if disconnected from the grid; and some rely on radio signals for synchronization. Among the relatively old and unsophisticated designs in common use with wind machines today, the "line-excited" inverters are the most common.

Alternating current Alternating current can by directly generated by any source of shaftpower, using an ordinary generator.[107] There are two main types. A "synchronous" generator, the type used in nearly all large power plants, must have its shaft turned at a constant speed–thirty-six hundred revolutions per minute, divided by the number of pole pairs in the generator–if it is to produce sixty-cycle output. It can operate, and supply local loads, in isolation from the grid, but will not produce the correct frequency unless property regulated (which is quite easy to do). It cannot be connected to the grid at all unless its speed, voltage, and phase are first matched to those of the grid: otherwise, both the generator and utility equipment could be seriously damaged.

A simpler and somewhat cheaper type of generator is simply an induction motor turned around backwards. An induction motor connected to the grid will turn at a particular speed determined by the voltage fed into it. If, instead, the motor's shaft is turned–for example, by a wind turbine–slightly faster that it would run of its own accord, then instead of consuming power from the grid, it feeds power back into the grid ("induction backfeed"). An induction generator can be connected to the grid at any speed down to and including zero. It is in general more "forgiving," especially of irregularities in the pattern of voltage and current, than a synchronous generator.

Induction generators Many people assume that induction generators cannot start up by themselves ("self-excite") when disconnected from the grid, or when connected to a grid that is not energized–for example, during a blackout. This feature is indeed often relied upon to ensure the safety of people repairing power lines. But in fact, many induction generators use series capacitors to compensate for their inductance and ensure the correct relationship between voltage and current. If those capacitors are sited near the generator, it can in some circumstances "self-excite" in isolation. Ordinarily, it would then generate at a frequency and voltage different from its normal output, and this could damage certain end-use devices connected to it. A "spike" of high voltage can be limited in duration, but not in intensity, by overvoltage relays, since it occurs very rapidly. For this reason, the interconnection criteria of (for example) the Southern California Edison Company state that where self-excitation is possible,

> special service arrangements will be required such as two-line loop service or subtransmission service in order to avoid the induction generator['s] becoming isolated with small amounts of load [which could cause voltages high enough to burn out the load devices]. In many cases, the addition expense for such special load service methods may outweigh the cost savings associated with induction generators.[108]

Such criteria, in practical effect, require that if induction generators are used, they be used in such a way that they cannot function at all without the grid. Their ability to serve an isolated local load is therefore outlawed.

Induction generators' outwardly disagreeable ability to self-excite with their own

compensating capacitors, however, can be turned to advantage. By deliberately providing enough capacitors near the generator to self-excite it, then switching those capacitors (typically with fast-acting thyristor controls) to stabilize the voltage and frequency generated, it is possible to obtain the constant output conditions of a synchronous generator with a simpler, more rugged, and probably cheaper induction generator whose voltage/current relationship is almost ideally matched to the grid. (Isolation relays could ensure the safety of utility personnel.) Induction generators have long been used in some remote hydroelectric sites–the North of Scotland Electricity Generating Board, for example, has approximately twenty-seven megawatts of them on its thirty-three-kilovolt grid,[109] and Southern California Edison Company itself has operated one (apparently without capacitors) since 1951[110]–but the concept of controlling with switched capacitors is apparently new,[111] having been practiced, for example, in 1980 and 1981 installations by the Metropolitan Water District of Southern California.[112] The concept appears useful even in large central-station generators.[113] Applied to smaller, more dispersed sources, it has the subtle advantage that induction generators are far less likely than synchronous generators to be damaged by harmonics and switching transients which arrive through the grid. Thus, with modern control circuitry, induction generators can go a way towards solving, at reasonable cost, the dilemma posed in Chapter Sixteen–how to protect both the utility's and the end user's equipment while remaining able to supply local loads in an emergency. The use of such systems, however, will probably require utilities to rethink their restrictions on dispersed self-excitable induction generators.

Unusual frequencies Whichever type of alternating-current generator is used, it need not operate at sixty cycles per second if it is not connected to the grid at the time. This expands still further the number of ways in which renewable sources can generate electricity. Many alternating-current motors can, within limits, tolerate a "wild" frequency from a unregulated generator, though synchronous clock motors will of course run at the wrong speed.[114] Some devices normally operated on alternating current are quite indifferent to frequency–incandescent lights, for example. Fluorescent lights normally operate at more or less sixty cycles per second but do not require an exact frequency match. As a further complication, some new types of high-efficiency fluorescent lights operate at much higher frequencies: hence the high-pitched whine from portable camping lanterns. Indeed, to save power and weight (high-frequency transformers and motors contain less metal), aircraft often operate on four hundred cycles per second or more. Thus sixty-cycle alternating current and direct current are not necessarily the only two interesting options. The only restrictions is that whatever is connected to the grid must be synchronized and at sixty cycles.

If, as appears likely, solar cells become important sources of dispersed supply, it appears that the near-monopoly of alternating current in end-use devices and in local wiring may be broken. A challenge facing electrical engineers and renewable energy designers is to devise the most flexible possible ingredients for an inter-compatible system–from end-use devices to patterns and hardware for household wiring to inverters and (if any) utility interconnections–that will both save the customer money and pre-

serve, for that customer and for the grid, the potential resiliency benefits of essentially uninterruptable sources. The case of the induction generator, described above, offers hope that these goals may prove mutually compatible. But above all, the present procedure–setting interconnection and wiring requirements purely out of habit without even considering resilience–must be changed before unconsidered standards, emerging de facto, sacrifice the security gains that the resilient technologies could have offered.

Summary

Five years ago, analysts who suspected that appropriate renewable energy sources might well offer cost-effective ways to replace dwindling fossil fuels tended to be dismissed as enthusiasts. Technologists conditioned by dismal experience with complex, large-scale energy systems told them that it would take decades just to develop renewable sources from a laboratory curiosity to a useful commercial form, and many decades more to disseminate them throughout society. But since then, despite the normal quota of trial and error, actual developments in the field have produced more, better, and cheaper renewable options than anyone thought possible. Experience has also shown that the expected decades of research and engineering could be–indeed, in many cases have been–telescoped into a few years, because the devices were so simple and small that each generation took only days or months to build and test, not ten years.

In many cases, adequate and cost-effective renewable sources sufficient to provide for most or all of the needs of a major sector are already on the market. In some cases, such technologies are available but not yet optimized: processes are in use (for example, for certain cellulose-to-alcohol conversions or high-temperature uses) which work and which can compete but which are likely to be markedly improved in the next few years. And in other cases, such as solar cells, technologies which are now cost-effective only in certain uses or places are virtually certain to become generally economical very quickly–sooner than a centralized plant could be built–as processes now being perfected in many countries move into intensive production. This book, in concluding that today's best renewable sources are economic and ample, does not assume such future progress: but the new developments are very likely to happen anyhow, and it is only prudent to get ready for them and seek to capture their security benefits.

The pace of development is continuing to accelerate so quickly that any snapshot of the state of the art, including this one, is bound to be out-of-date before the ink is dry. But already, so many solid technological achievements have been reported that many renewable energy experts suspect that they had guessed wrong about what their main problem would be over the next five to ten years. The problem they had feared was that there might not be enough attractive renewable sources to meet the needs of an advanced industrial economy. The problem they are actually encountering, however, is that there are too many. The range of choice is so wide, and so quickly expanding, that the hardest part of many renewable energy projects is deciding which of many inviting opportunities to grasp first. A wider appreciation of how those opportunities can reduce energy vulnerability can only speed up this process.

The notes for Appendix 3 appear on page 61 of this pdf.

Appendix Three

Economic Assessment of Appropriate Renewable Sources

Comparing the calculated costs of energy services delivered by renewable and nonrenewable sources (or by renewables vs. Each other or vs. Efficiency improvements) is an easy process to describe but a very difficult one to do properly. In principle, the economic value of renewables depends both on the price of the energy they deliver and on the price of the energy they replace. Both are highly uncertain. Both can be evaluated only with reference to a particular energy service delivered to a final user. Market price reflects some "internal" costs but excludes others ("externalities"), such as unregulated forms of pollution, vulnerability, or other costs paid by neighbors or by society as a whole, not specifically by the buyer (Chapter Sixteen). While a complete cost comparison should include these factors, this appendix considers only internal costs that are private to the purchaser/operator of the energy device. This biases the results in favor of the centralized, nonrenewable technologies, because they tend to have larger external costs than appropriate renewable sources do.

Renewable energy systems have no fuel cost (except for the feedstock to bioconversion systems and, perhaps, water rights for some hydro). If well designed and built, they also tend to have low operating and maintenance (O&M) costs. (Long-term economic performance can be quite sensitive to those costs.) The price of energy from renewable sources thus depends mainly on:

- their initial capital cost. This depends strongly on
  - the simplicity, cleverness, and durability of design. These can vary enormously and may bear no relation to the designer's formal credentials: indeed, highly qualified designers may produce the most gratuitously complex designs.
  - the marketing structure. A "packaged" flat-plate solar collector system whose price is marked up three or four times–by the manufacturer, wholesaler, retailer, and installer (if different from the retailer)–can end up costing its user several times as much as an otherwise identical "site-assembled" system with one mark-up.[1] Most analyses assume only the "packaged" method.
  - how efficiently the delivered energy is used. This affects, as the Saskatchewan Conservation House example in Chapter Fifteen showed, the size of the renewable system (which can

be reduced by tenfold), its performance, and its complexity (as in the replacement of a heat distribution system by natural convection). Such synergisms can be examined only on a micro design level.

These effects can together change unit prices by factors ranging from *ten to perhaps a thousand*.

- the cost of financing them over their lifetimes. This depends on
  - real interest rates, which depend on perceived risk and should therefore be lower for many renewables[2]—but may not be in practice if the lending agency is unfamiliar with technology.
  - working capital requirements. These are related to capital intensity by construction time, payback time, and shape of cash flow, and again should be more favorable for soft technologies.[3]
  - projected operating lifetime, which may be difficult to estimate. (Some wind machines and flat-plate solar collectors have worked well for decades with little or no maintenance. Badly built, they could have failed in a few months or years. Some designs are much more forgiving of mistakes and environmental insults than others.)
- the amount of energy supplied annually. This depends on
  - quality of design, construction, operations, and maintenance.
  - patterns of energy use. A mismatch between supply and demand patterns could leave some demand unmet or lead to the "dumping" of surplus supply (such as unneeded waste heat in the summer).
  - variations in weather and climate.
  - appropriateness of design to local conditions and use patterns. Some large corporations have been unable to compete in the solar collector market with some small business, not only because the latter had better innovation and lower overhead, but also because they could achieve better performance by matching designs to local weather, building styles, and so forth—rather than making a "cookie-cutter" product which is designed for a hypothetical average house and is therefore suboptimized for any actual particular house.
- the amount and type of storage required, if any. This depends on the three factors just listed and on the nature and degree of integration with other renewable or nonrenewable sources (Chapter Sixteen).

This may seem, and it is, more complex than one might have expected. To make matters worse, the price of competing nonrenewable energy is equally imponderable. It depends mainly on

- general and sector-specific inflation in the cost of goods, services, and money, both during construction and afterwards for the project's operating lifetime.
- the relationship between historic and marginal capital costs. (The latter have generally exceeded the former since about 1970.)
- the difficulty of obtaining fuels from ever more remote and awkward places.
- the economic and political policies of fuel-exporting countries interacting with a complex world market and with unforeseeable political exigencies.

- national and local policies regarding trade, legal structures, inflation control, employment, environment, and a host of other factors.
- the degree of technical reliability and resilience desired.
- tax and accounting conventions, tariff structures, and subsidies. Subsidies to the U.S. energy system total over two hundred fifty-two billion 1978 dollars historically.[4] Those to nuclear power alone suffice to cut the cost of nuclear electricity, as seen by consumers, about in half.[5] Tax and price subsidies are currently continuing at a rate approaching one hundred billion dollars per year[6]–enough to reduce average energy prices by over a third and nuclear electricity prices by more than a half again.[7] Direct tax subsidies currently favor supply over efficiency by eight to one and hard over soft technologies by between ten and twenty to one.
- salvage values. (For nuclear facilities and wastes these are negative–that is, the plant will cost money to decommission–but of unknown size.)

Renewable/nonrenewable comparisons are further complicated by the following problems:

- great variation in price quotations even for one product in one market. Identical gas-fired water heaters in identical Southern California apartments differ by a factor of two in retail price and by nearly a factor of three in installed price. Price scatter is larger in solar markets, which are less mature and have more diverse product lines and marketing structures.
- extremely rapid technical change, especially for renewables, much of it outside official programs and traditional information channels.
- uncertainty about how far, or how, to internalize important externalities (many of which are considered in Chapter Sixteen).
- what depletion value to put on nonrenewable fuels and other resources. Their cost was traditionally assumed to be only the cost of mining them, as if that mining did not make their future replacement cost more.
- the many imponderable (e.g., psychological and political) factors which help to determine how far and how fast different available technologies can be put into use.
- economies and diseconomies of scale (Appendix One).
- the inability of most simulation models used by energy policy analysts to cope properly with diverse, relatively dispersed renewable sources or with their nontraditional processes of market penetration (Chapter Fourteen). Models attuned to centralized and nonrenewable technologies tend to give results that favor those technologies.
- the need to match any renewable source to its climate, site, applications, and users, in order to achieve best performance at least cost.
- the difficulty of comparing the storage and back-up requirements of complete energy systems containing renewable or nonrenewable components, to achieve a given level of reliability to final users, when there is not a fully satisfactory reliability theory for either type of system, let alone for both in combination.

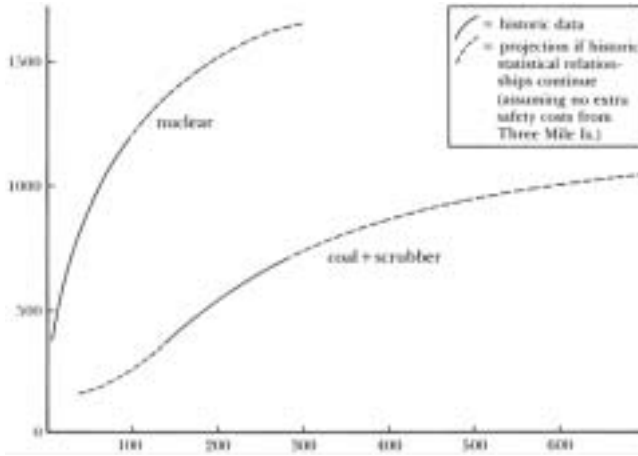
- the potential for total-energy systems which provide electricity and heat (and perhaps liquid fuels) and other types of hybrids (Chapter Sixteen and Appendix One).
- the opportunities offered by many renewable sources (but only rarely by nonrenewables) for sharing functions and costs through integration into shelter, food, water, or other systems (Chapter Sixteen). Such opportunities, however, can be identified only by a highly localized and disaggregated analysis which goes beyond the energy sector itself.
- the sensitivity of economic comparisons to minor changes in accounting for inflation, "leveling" varying costs over the life of a project, discounting the future, and so on. Small, seemingly innocuous changes in real discount rate are a commonly used method of reversing the outcome of renewable/nonrenewable comparisons.

In view of these complications, it is not surprising that virtually no renewable/nonrenewable cost comparison will prove satisfactory to everyone. Experts often disagree about basic data by factors of severalfold, depending on their familiarity with recent developments and willingness to accept an example of what exists as an "existence proof" for what can be done more widely. They differ in their assessment of the state of the art or the applicability of certain methodologies. They do not accept other experts' views on how far particular case studies are more widely applicable. Thus a large number of energy experts, laid end to end, will probably never reach a conclusion about the economies of renewable sources. The only recourse is to make assumptions and data sources explicit enough so that the cost calculations are transparent, scrutable, and easily compared.

It must also not be expected that the unit cost of any technology can be represented by a single number. How much a thing costs depends on how many of them you want. Economic theory indeed requires that each technology (or aggregate of different technologies) be subject to a "supply curve" in which unit price rises with increasing supply. That this is the case for conventional utility power plants, owing to a complex series of political-regulatory relationships reflecting a social desire to hold constant the perceived social costs of expanding coal and nuclear sectors, is nicely illustrated in Figure A.3. It plots as supply curves the data obtained by a detailed statistical analysis of historic costs,[8] which explains ninety-two percent of the observed variation in the real cost per installed net electric kilowatt for forty-six nuclear plants and sixty-eight percent for one hundred sixteen coal-fired plants.

Renewable sources too have supply-curve costs rather than point costs, though the shape of the curve will differ from one technology to another. For example, solar heat collectors which are small enough to fit onto a building usually cost less than those which need extra land, and those so small that they can be integrated into the structure of a building cost still less. How big a collector is needed depends on how efficient the building is. Likewise, if biomass fuels are efficiently used, not much will be needed, so the feedstock can be wastes which are cheap (or which may even have a negative cost because converting them to fuel saves a disposal cost). Less efficient use, hence higher demand, may require the use of more expensive feedstocks such as grains; higher demands many

Figure A.3 Plant construction cost (1979 steam-plant dollars per net electric kilowatt of installed capacity, without interest during construction)

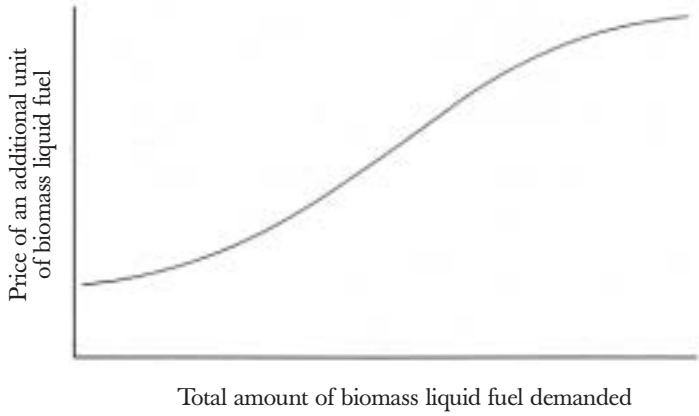


Thousands of megawatts of net electric capacity (of each type of plant) built or being built

entail the growth of special "fuel crops"; higher still, irrigation for that purpose. This raises costs as can be illustrated by the schematic sketch in Figure A.4 (not meant to be exact, since complete data do not yet exist). Buying efficient vehicles–because their efficiency costs less than fuel–means that the nation needs substantially less fuel; therefore it is relatively cheap (near the lower left corner of the graph). Underinvesting in efficiency requires the nation to buy a large amount of fuel which rapidly becomes expensive (near the upper right corner of the graph). Most studies assume the latter and hence find that biomass fuels are costly. This book, however, is concerned with a more nearly optimal economic balance between investments in energy supply and in energy productivity, represented by the "market clearing price" at which the supply and demand curves cross in equilibrium. This example illustrates why, even though the price estimates for renewable sources are discussed below as points or narrow ranges, each estimate is only part of a supply curve which cannot be analyzed independently of competition between increased energy supply and increased efficiency.

Despite all generic uncertainties of renewable/nonrenewable cost comparisons, four broad principles can often simplify economic choices. First, investment decisions should be based not on projected small differences of marginal cost (which are often well within the uncertainty of the data) but rather on how sensitive those costs will be to changes in key variables such as oil price. Basing decisions on sensitivities enables on to "play Safe" in an uncertain world. In general, the variations of greatest policy interest, such as high world oil prices or high inflation, tend to improve the competitive position of renewables still further. Yet soft technologies do not (as the data below will show) need such assumptions for their attractiveness, since they can generally compete with present

Figure A.4 Illustrating schematic supply curve for biomass liquid fuels.



oil prices with considerable room to spare.

Second, differences of internal cost may be less important to many nations than differences not captured in that cost–implications for resilience and self-reliance, employment, equity, balance of trade, and so forth.[9] Third, in general, the real costs of fossil and nuclear energy are likely to rise and those of most renewable sources to fall. The relative speeds of change in both cases are the subject of great uncertainty and dispute, although the directions of change are empirically undeniable and the fundamental reasons for those changes are all but certain to persist.

And finally, renewable sources in general offer far greater scope than nonrenwables for simple, low-technology adaptations suitable for local construction with limited skills and common materials. Such simplified versions cost far less than those normally analyzed; they are more analogous to the improvisations commonly made by individuals at a grassroots level. It is difficult to capture the enormous range of costs reported for such self-help projects, especially those done by low-income people who do not cost their own labor or who do cooperative projects. But in general the real costs to the users are far less–even orders of magnitude less–than for conventional, industrially supplied hardware, and the performance is often broadly comparable and sometimes better. This important point is explored under "Simplified versions" in Chapter Sixteen.

Subject to these caveats and uncertainties–the last, the immense range of technical complexity and costs over which many renewable options can be built, being perhaps the most difficult to analyze–illuminating comparisons of renewable/nonrenewable economics are in fact possible. Dispassionate evaluations yield a result which, though it seemed surprising a few years ago, is now becoming widely accepted: that if one chooses good designs and shops carefully for the best buys, many renewable energy systems already offer a pronounced economic advantage over present fuels, and virtually all appropriate renewables are cheaper than the incremental cost of nonrenewable, centralized supply technologies. The renewables' advantage is generally increased by doing the

still cheaper efficiency improvements first. This economic ranking of marginal sources–efficiency improvements cheapest, then appropriate renewables, then nonrenewables (synfuels and power plants)[10]–holds true even if one ignores (as this book does) all external costs and benefits not currently reflected in market prices, including differences in vulnerability or resilience. If those important nonmarket considerations were included, the results would favor efficiency and renewables by an even more lopsided margin.

A responsible analysis of renewable energy economics, however, must be internally consistent. Data derived by different analysts often cannot be directly compared because they use different assumptions and accounting conventions. This appendix therefore uses consistent conventions. Furthermore, to ensure that the results are robust and cannot be overturned by minor changes in the assumptions, those assumptions are consistently weighed in the sense least favorable to the conclusions. An earlier comparison of this type, for example, assumed:[11]

- no real cost escalation for any source after ordering in 1976 (whereas in fact the capital cost of nonrenewable technologies continues to escalate steeply, while that of most renewables is declining);
- generously low prices for nonrenewable systems;[12]
- no cheap designs (such as passive solar systems, solar ponds, community-scale or roof-integrated collectors, collectors made of such materials as plastic films or extrusions, other low-technology designs and devices);
- the same fixed charge rate (which converts an initial capital cost into an annual capital charge against output) for renewable as for nonrenewable systems, making no allowance for the renewables' more favorable cash flow due to shorter lead time and faster payback time;[13]
- a high fixed charge rate[14] for both systems (this discriminates against those with a high ratio of capital to operating costs, such as renewables, whose operating cost is virtually nil);
- for heating applications, an unrealistically efficient heat pump (two hundred fifty percent efficient even on the coldest day) operated by baseload (rather than average or peaking) electricity; and
- subsidies included for hard technologies but excluded for efficiency improvements and soft technologies.

Such multiple "conservatisms" help to ensure that the severalfold price advantage shown for the soft technologies over their nonrenewable, centralized competitors is not an artifact of arguable assumptions but a firmly defensible conclusion–one on which many analyses have lately converged.[15] Most of the same conservatisms are preserved in the present analysis. Although a few simplified designs are included to reflect more fully the wide range of technical complexity among systems actually being bought in the marketplace, the economic advantage found for soft technologies generally does not depend on these simplified versions; it is merely stronger in their case. As in the earlier analysis, subsidized nonrenewable systems are compared in price with unsubsidized renewable systems, to emphasize the advantage which the latter actually display.

Tables A.1 though A.4 compare the delivered price of an energy form or service in each of four service categories: heat below the boiling point of water (thirty-five percent of U.S. delivered energy needs); heat above that temperature (twenty-three percent); vehicular liquid fuels (thirty-four percent); and electricity (eight percent). The measured or calculated prices shown are documented in the tables, using a wide variety of sources, but care has been taken to normalize the results to the same assumptions so they are comparable. While this comparison cannot be definitive, it does support the broad conclusion that soft technologies are cheaper than competing hard technologies, summarized below in each sector. For consistent comparison, all prices are normalized to the same units; constant 1980 dollars per million BTUs (or, approximately, per billion joules) of energy–heat, liquids, or electricity–delivered to the final user. With a few noted exceptions, all the cost calculations use the same fixed charge rate: ten percent per year in real terms, or ten percent plus the assumed inflation rate in nominal (current dollar) terms. Thus a device with a capital cost of one thousand dollars per kilowatt is assumed to incur each year a capital charge of one hundred dollars per kilowatt. The sum of that charge plus any operating costs equals the total cost of providing the energy. The fixed charge rate used here has been chosen to be comparable to or slightly greater than that used by most energy companies today in their own cost calculations.

Table A.1 shows that low-temperature heat provided by burning today's fuels in a seventy-percent-efficient furnace (better than many) will cost, with the very temporary exception of natural gas pending its decontrol, around fifteen dollars per million BTUs, or about twice as much as (subsidized) average 1981 electricity used in an extremely efficient heat pump. Synthetic gas from coal is no better. Electricity from a newly ordered nuclear (or coal) central station is about the same or worse–in round numbers, twenty-five dollars per million BTUs if used in resistance heaters, or perhaps as little as ten dollars if used in a super-efficient heat pump.

In contrast, efficiency improvements cost typically zero to three dollars per million BTUs saved–at most five dollars among the measures shown, the full achievement of which should keep the nation well provided with savings opportunities for the next decade or two. Passive solar measures are similarly cheap. With careful shopping, active solar space and water heating for a single house (generally costlier than a multifamily dwelling or a neighborhood-scale system) is in the range of eight to ten dollars per million BTUs, competing with deregulated fuels and power today. The real price of conventional packaged active systems is widely expected to continue falling by two to three percent per year,16 and some simplified designs shown in Table A.1, whether do-it-yourself or commercial, have already dropped prices even faster, empirically achieving about four to six dollars per million BTUs even with commercial fabrication. The empirical cost (nine dollars per million BTUs) of heat from a municipally operated solar pond in Ohio (Appendix Two) also competes with oil or electric resistance heat at today's prices, and competes even with electric or gas heat pumps at their marginal prices. Community solar heating systems,17 using conventional collectors or solar ponds, can drop heat prices down into the range of passive solar or the costlier efficiency improvements–about four to six dollars per million BTUs. For provid-

Table A.1 Illustrative delivered prices, in 1980 dollars, for heat below two hundred twelve degrees Fahrenheit. The prices shown reflect the effect of subsidies only for the hard technologies (save in te one solar case shown in parentheses).

Technology	Remarks	Source	1980 $ per million BTUs
HARD TECHNOLOGIES:	*subsidized fuel & power prices for comparison*		
Oct. 1980 controlled natural gas	*70%-efficient free furnace*	*SERI 1981:II:96*	4.0
#2 heating oil @ $1.10/gallon	*70%-efficient free furnace*	*Green 1980*	13.7
propane @ 80¢/gallon	*70%-efficient free furnace*	*Green 1980*	13.4
electricity @ 5.5¢/kW-h	*free resistance heater*		16.1
same (Jan.1981 av. resid. Price)	*$250/kWe, 250%-efficient heat pump, 1% O&M*		6.8
Alaskan gas	*70%-efficient free furnace, 1% O&M*	*Linden 1981:37*	16.6
marginal syngas (first generation)	*same*	*same*	12.3–16.6
same (second generation)	*same*	*same*	11.5–5.2
same (second generation)	*$300/kWt input, 130%-eff. heat pump, 2% O&M*	*Ross & Williams 1981:306*	11.5–13.6
marginal nucl. Elec. @8.4¢/kWh	*free resistance heater*	*see Table A.4*	24.7
same	*electric heat pump as above*	*see Table A.4*	10.3
EFFICIENCY IMPROVEMENTS:	*3%/y real discount rate, 10-year time horizon*	*SERI 1981:11*	
retrofitted direct-fueled houses	*save over 50% of heat*	*:12-13*	2.7
same	*save over 75% of heat*	*same*	5.0
retrofitted elec.-heated houses	*save over 50% of heat*	*same*	5.0
retrofitted commercial buildings	*save over 35% of space conditioning*	*:70*	1.3–2.2
superinsulated new houses	*save over 90% of heat*	*Leger & Dutt 1979; Shick, Shurcliff 1980*	negative
same	*save ca. 100% of heat*	*see Chapter Fifteen*	ca. 0–1.1

SOLAR TECHNOLOGIES:			
passive house retrofit (empirical)	*"best buys" examples*	*SERI 1981:II:94, 204-5*	1.5–2.2
same	*"average" (DIY & Solar I)*	*same*	3.5–7.8
active house retrofit (empirical)	*"best buys" examples*	*same*	8.2
same	*"average" (DIY & Solar I)*	*same*	9.5
1980 commercial water heater	*typical packaged system, no tax credit*	*:186-7*	9.4–32.5
(same)	*(same with 40% tax credit)*	*(same)*	(5.6–20.4)
1990 same, expected	*no tax credit*	*:186-7, 175*	5.0–25.5
ca. 1982 Teagan water heater	*simple design*	Popular Sci. *1981a*	ca. *6–7*
1980 breadbox water heater	*batch; 10-year lifetime*	*Green 1980; see also Shapiro 1980*	2.2–6.2
1981 breadbox water heater	*batch; CETA-installed & $85 complete*	*Fisk 1979*	2.7
1978 sit-assembled air collector system	*see also SERI 1981:II:172, Godolphin 1981 Shapiro 1980*	*Green 1980; Worcester Poly. 1978*	
1990-2000 low-cost collector program goals	*average installed hot-water system (projected)*	*SERI 1981:II:177*	5.3
1980 inflatable greenhouse	*10-year horizon, 8 /kW-h fan*	Solar Flashes *1980*	ca. 0.6
1980 solar pond	*Miamisburg, Ohio municipal operation built from scratch*	Soft Energy Notes *4(1):18-20 (1981)*	9.2
same if it were bigger	*estimated from empirical data*		8.0
community solar systems, flat-plate	*calculated*	*Schurr* et al. 199: *Ch. 11*	3.8–6.4
same, concentrator	*calculated*	*same*	5.1
wood @ $0-90/cord	*20 million BTUs/cord, 50%-efficient stove*	*Green 1980*	7.0–9.0

ing heat, therefore, well-designed and presently available renewable sources are clearly the best buy after efficiency improvements.

Table A.2 shows a similar result. Synthetic gas burned in an industrial boiler to provide process that will deliver even costlier heat (twelve dollars per million BTUs) than residual oil at market prices does now (nine dollars), though still cheaper than marginal electricity (twenty-five dollars). Even expensive wood wastes can deliver the same clean heat via commercially available gasifiers18 for three or four dollars, or more cheaply (if perhaps less conveniently) via direct combustion. Simple solar concentrators at temperatures adequate for nearly all industries other than ceramics/bricks/glass and primary metals (which need higher concentrations or indirect forms of solar energy)19 now deliver heat at prices competitive with syngas or OPEC oil or both. It is for that reason that an Israeli-American entrepreneur can make a profit by offering to supply a specified fraction (normally fifteen to thirty percent) of any factory's steam needs for twenty years at a price ten percent below what the factory now pays. He simply builds parabolic trough collectors, sells their steam, and pockets the ample difference. By late 1981, such schemes were under construction at three textile mills, involving over two hundred thousand square feet of collectors which, over the twenty-year contract period, will save the equivalent of over one billion cubit feet of natural gas.20

Homemade concentrating collectors (costing only materials, not labor) can achieve two dollars per million BTUs even in cloudy areas–remarkable bargain. As the prototype commercial concentrators now on the market are replaced by mass-produced models,21 their heat prices over the next few years should fall to about three to six dollars per million BTUs–well below present oil prices–through normal scaling-up of what are now model-shop operations. As noted in Appendix Two, several solar process heat systems in their initial production runs were already selling for prices comparable to those listed in the "conservative" projection in Table A.2–prices competitive with oil anywhere (especially in Europe),22 and with most domestic fuels in most parts of the United States today. The only fossil fuel that can probably compete with the best solar concentrators today is coal in areas that have a good distribution infrastructure. The *average* coal price today (which conceals wide variations), with a clean and efficient boiler, can undercut almost any commercial solar concentrator (but not, as Table A.3 shows homemade ones). As the average coal price rises above twenty dollars per barrel equivalent (about eighty dollars a ton, compared to the present thirty-odd) over the next two decades, commercial solar process heat costs will fall. The two costs should cross sometime during 1982-85 in much of the United States and by 1990 in virtually all parts.

Table A.3 shows that many renewable liquid fuels–especially those from thermochemical processes fed with farm or forestry wastes–are likewise cheaper than synthetic fuels. This is partly because woody materials have much more favorable chemical reaction kinetics than coal: they break down faster, at lower temperatures, with little or no tar formation, and they contain virtually no corrosive sulfur. Both the energy and the capital requirements are accordingly lower, and the yields generally higher, than for equivalent coal liquefaction. Some renewable liquids, especially those

Table A.2 Illustrative delivered prices, in 1980 dollars, for heat above two hundred twelve degrees Fahrenheit. The prices shown reflect the effect of subsidies only for the hard technologies.

Technology	Remarks	Source	1980 $ per million BTUs
HARD TECHNOLOGIES:	subsidized fuel & power prices for comparison		
1980 average coal	70%-efficient free boiler, 3% O&M	Linden 1981:32	2.5
2000 average coal (DOE est.)	same	same	5.9
$40/barrel residual oil	80%-efficient free boiler, 2% O&M		8.7
syngas (first generation)	same; delivery cost $1 per million BTUs	Linden 1981:37	8.9–12.8
#2 fuel oil from coal syncrude	same; delivery & marketing 77c/million BTUs	same	12.5–13.7
marginal nuclear electricity	8.4c/kW-h, free resistance furnace	see Table A.4	24.7
SOLAR PROCESS HEAT:			
30'-dia. parabolic dish built by Doug Wood (Fox Island WA)	new-materials-only cost; average U.S. site would have 50% greater insolation	Soft Energy Notes 2:97 (Dec. 1979)	2.2
mass-produced Fresnels including storage @$1/GJ	$2.6–5.3/sq ft+installation (semiempirical prices), U.S. av. Insolation, 63% eff.	Ross & Williams 1981: 331; OTA 1978	
1980 handmade parabolic troughs including storage @ $1/GJ	$45/sq ft, 60% efficient in climatic range equivalent to New Mexico to New Hampshire	SERI 1981:II: 623, 630	64–12.5
mass-produced collector goals	"conservative" (same range)–commercial 1981	:634	3.7–6.9
same	"expected" (same range)–mild 1980s estimate	same	3.2–5.6
same	"optimistic" (same range)	same	2.3–3.8
570° F Winston collector including storage @ 50¢/GJ	$17.7/sq ft calculated installed price, U.S. av. Insolation, 4% eff., 2% O&M	Grimmer & Herr 1977	
Sandia 1985 projection	up to 600 F; well above best 1981 prices	Energy Insider 1980a	10.
OTHER RENEWABLE SOURCES:			
wood @ $20/green ton, 65% eff.	different fixed charge rate than this table	Hewett et al. 1981:150	
same, gasified	same	same	3.6
retrofitted wood gasifier 80%-efficient free boiler, 2% O&M	30%/y nominal fixed charge rate; $30/dry ton;	OTA 1980:II:138	3.4
same	different fixed charge rate; $20/dry ton	SERI 1979:I:29	3.8
manure biogas	500 cu ft active volume; same boiler	OTA 1981:99	7.8

Table A.3 Illustrative delivered prices, in 1980 dollars, for vehicular liquid fuels. All tax credits excluded except the present subsidies to nonrenewables. All BTUs counted as equal in value (thus underestimating the value of fuel alcohols in appropriate blends and engines in which they can do more work per BTU than petroleum-based fuels).

Technology	Remarks	Source	1980 $ per million BTUs
HARD TECHNOLOGIES:	*subsidized fuel & power prices for comparison*		
1980 untaxed regular gasoline	*regional price range*	*Linden 1981:39*	7.2–8.0
1980 taxed regular gasoline	*$1.35/U.S. gallon*		11.2
gasoline from shale oil	*$12.50/bbl marketing & distribution mark-up*	*same*	10.4–12.4
same	*same; likewise omits recent cost overruns*	*OTA 1980a*	12.3–13.3
gasoline from coal	*same*	*Linden 1981:39*	12.4–13.4
#2 diesel oil from shale oil	*same*	*same*	9.2–10.2
#2 diesel oil from coal	*same*	*same*	11.2–12.2
EFFICIENCY IMPROVEMENTS:			
efficient light vehicles	*see Chapter Fifteen*	*see Chapter Fifteen*	under 3.5
THERMOCHEMICAL BIOCONVERSION:			
portable pyrolyzer	*free, half-wet sawdust; sei-empirical*	*Tatom* et al. *1976*	1.0–1.4
pyrolysis "oil" from muni. wastes	*empirical*	*Benemann 1977*	6.0
same from wood & cellulosic wastes	*empirical*	*Green 1980*	6.9–12.6
methanol from all sources	*empirical; mostly from wood*	*SERI 1981:II:591*	ca. 16
methanol from muni. wastes	*empirical and calculated*	*Green 1980*	3.9–8.1
methanol from forestry wastes	*hybrid Canadian processes; estimated*	*InterGroup 1978*	ca. 10–13
methanol from wood, $20/green ton	*large scale (2000 tons/day); different fixed charge rate than this table*	*Hewett* et al. *1981:150*	4.1
methanol from wood, oxygen-gasified	*$10-30/dry ton; calculated*	*OTA 1980:II:173*	11.5–22.8
BACTERIAL & ENZYMATIC BIOCONVERSION:			
homemade ethanol from wastes	*empirical; no crop or labor cost*	*Amer. Homegrown Fuel*	5.7
ethanol from wood & cellulosic wastes @ $11.25/dry ton	*enzymatic; estimated from lab results*	*Pye & Humphrey 1979*	
ethanol from grains (empirical)	*conventional large-scale distillation*	*OTA 1980:II:165*	11.3–15.7
same	*same, wet milling*	*Flaim & Hertzmark 1981:99*	*14.9–16.0*
same	*same, various processes*	*SERI 1980a:84*	15.8
ethanol from cellulosic wastes	*same; projected*	*OTA 1980:II:173*	12.2–17.0
ethanol from lignocellulose	*Emert process; projected*	*SERI 1981:II:581*	ca. 16
same	*other processes in development; projected*		ca. 6–10

emphasized by current policy, are slightly costlier per BTU than present gasoline prices if they are inefficiently produced or made from specially grown crops. But a comparison of cost per BTU does not count the credit due to fuel alcohols for burning (in properly designed engines) more cleanly and efficiently than oil. A recent methanol-powered cross-country flight in a light aircraft by former Astronaut Gordon Cooper and by President Reagan's former pilot23 not only dramatized methanol's potential for greatly improving the airlines' parlous finances; it also demonstrated that in piston engines at altitudes above about ten thousand feet, methanol is more powerful per gallon than aviation fuel, even though it has only about half as many BTUs per gallon. Its advantage in low-altitude cars, though less, is still enough to tip many of the close comparisons in Table A.3 in favor of fuel alcohols.

Finally, Table A.4 shows that a wide range of renewal sources–small hydro, wind, wimple solar-thermal engines, even some photovoltaic cogeneration systems–can deliver electricity at about two to six cents per kilowatt-hour. This competes handily with the delivered price from newly ordered central power stations (in the vicinity of eight cents or more in most areas: Southern California Edison Company estimates about twelve centers or more). Many of the presently available renewables also compete with the present average (rolled-in) price seen by the consumer, or with the roughly equivalent fuel and operating cost *alone* for oil-fired stations (typically from five to seven cents or more). Virtually any of the renewables would be attractive today in high-price areas, such as New York City (where in late 1980 the regular taxed price was fifteen cents per kilowatt-hour–twenty-five cents at peak periods), Alaskan villages and remote military bases (typically upwards of forty cents), and rural areas of developing countries (thirty to ninety cents).

Table 4.A confirms that well-designed smaller technologies ten dot delivery cheaper electricity than the centralized ones (Appendix One). It also illustrates the great diversity of options available for cost-effectively generating renewable electricity. Although it is sometimes claimed that solar energy, while an effective source of heat, cannot economically make electricity, Table A.4 shows that on the contrary there is an embarrassing surplus of ways to do so, without even counting solar cells. Photovoltaic prices, as noted in Appendix Two, are dropping so quickly that the Department of Energy now expects them, even in central-station applications, to compete with average grid prices by 1986 using demonstrated technologies;24 but microhydro and wind, and perhaps other renewable sources, have *already* achieved this with hardware now on the market. The same cannot be said of the centralized solar electric systems–multi-megawatt wind machines, power towers, ocean-thermal-electric conversion, centralized biomass plantations to fuel thermal power plants, solar power satellites, and so on. (Unfortunately, it has been these centralized technologies that have received most of the federal solar budget for the past decade.) For comparison, there is not even a credible prospect of *ever* competing with appropriate renewables via the nuclear fusion program, the second-biggest component of the federal energy budget,25 nor (as Tablet A.4 shows) via fission.

In summary, in every category of end-use need (heat, vehicular liquid fuels, and electricity), there are already several varieties of dispersed renewable sources which compete handily with present fuel and power prices–let alone with the far higher

Table A.4 Illustrative delivered prices, in 1980 dollars, for electricity. The prices shown reflect the effect of subsidies only for the hard technologies. Electricity prices converted to heat prices at 3413 BTUs per kilowatt-hour of electricity.

Technology	Remarks	Source	1980 $ per million BTU's
HARD TECHNOLOGIES:	*subsidized fuel & power prices for comparison*		
Jan. 1981 av. U.S. residential price	*5.5¢/kW-h*		16.1
New York City 1980 av. Taxed price	*15.3¢/kW-h (peak rate 24.9 /kW-h)*	*Russell 1981*	44.8 (72.6)
marginal price: light-water reactor commissioned 1988 (8.4¢/kW-h)	*GNP deflator applied to earlier calculation done at 12%/y real fixed charge rate*	*Lovins 1977b, 1978a, 1979a, 1981c*	24.
same recalculated: 7.6¢ with 1979 ordering, ca. 8.6¢ with 1981 ordering; same methodology	*updated data on reactor, decommissioning, fuel-cycle, and O&M costs; updated grid & fuel-cycle facility costs*	*Komanoff 1981: Bechtel (Lovins 1979a: nn20,21); 199–80 GNP deflator*	22.
marginal nuclear electricity price (GNP-deflated from 1982)	*Southern California Edison Co. levelized life-cycle cost estimate (12¢ in 1982 $)*	*F.A. McCrackin, personal communication, 1 Dec. '81*	29.
EFFICIENCY IMPROVEMENTS:			
typically 0–1.5¢/kW-h	*see Chapter Fifteen*	*SERI 1981; Lovins 1982*	0.4.4
SMALL HYDRO	*2–8 /kW-h; highly site-specific*	*SERI 1981:II:958*	*5.9–23.4*
WIND MACHINES:			
10-KwP Millville, 13 mph @ 40', calculated from empirical data assuming mass produc. (5.1¢/kW-h	*privately owned, 1% O&M, no extra grid or land costs; innovative installation & 95% learning curve would yield 3.4¢/kW-h*	*SERI 1981:II:191*	14.
best small comm'l models, 1980–81	*empirical ca. 4–6¢/kW-h in excellent sites*	*see Chapter Sixteen*	11.7–17.6
1-MWp Mehrkam machine, empirical	*0.3 capacity factor, 2% O&M*	*see Chapter Sixteen*	4.8

2.5-MWp Boeing Mod II high-tech, 0.3 capacity factor, $15,000/y O&M (delivers @ 4.6¢/kW-h)	*projected 100th-unit price ($809/kWp inst'led +10% contingency); $85/kWp land; $100/kWp grid; 4% grid losses*	*SERI 1981:II:935–9, GNP deflator*	13.0
Mod II machines in Columbia Gorge, $1720/kWp, 1981	*preliminary empirical busbar price (ca. 4 / kW-h) plus ca. 2¢ for grid+losses*		ca.18
SOLAR-THERMAL-ELECTRIC:			
homemade 30' dish/steam engine (generates @ 3.2¢/kW-h)	*new-materials-only cost; average U.S. site would have 50% greater insolation*	Soft Energy Notes *2:97 (dec. 1979)*	9.3
high-tech power tower (7.4¢/kW-h)	*Phoenix; $7.9/sq ft heliostats, projected*	Solar Therman Rpt. *1981*	21.7
same, dish design (ca. 16¢/kW-h)	*1985, no cogeneration credit*	*SERI 1981:II:943*	46.9
same, 1990 projection (5.2¢/kW-h)	*25,000/y production rate*	Ibid.	15.2
PHOTOVOLTAIC:			
communicy cogeneration, heat credit, municipal utility ownership	*$15/Wp array, 18% eff. @ 20°C; $7.4–12.6/ sq ft; diesel back-up; 1976–80 GNP deflator*	*Ross & Williams 1981:170–179*	
best 1981 components, cogen., 4 Wt/ We, heat credit $13.7/million BTUs	*$14/Wp system including 3-sun Winston concentrator; Phoenix/Seattle climatic range*	*Henry Kelly, pers com., 1981; calculated*	
Martin-Marietta Fresnel concentrator	*1981 technology @ 50 Mwe order; offered price*	*Maycock 1981:42*	
1986 Flat-plate DOE goal or AMETEK estimate; no cogeneration	*$1.6–2.2/Wp system; utility buyback @ 50% of average price; delivers @ 5.9–8.1¢/kW-h*	*Russell 1981:DOE 1980a; JPL 1980; AMETEK 1979*	17.
1990 flat-plate (11¢/kW-h)	*conservative So. Cal. Edison Co. Estimate*	*Ca. Energy Comm. 1980a:176*	32.2

replacement prices which new power plants, synfuel plants, frontier oil and gas systems, or other such systems would incur. In each category there are also new renewable energy processes and devices which can be confidently expected to progress over the next few years from pilot-scale engineering to fully commercial products, and which will widen still further their price advantage over centralized, nonrenewable energy sources. Even ignoring these imminent developments, just the economically attractive renewable options already on the market are so numerous and diverse that claims that renewable energy is uneconomic are increasingly confined to the uninformed

* Notes for chapters 1–17 appear at the end of the pdf for Parts I–III

Notes

Notes to Appendix One

1 The three-fourths figure is for Fiscal Year 1982 (ERAB 1981b:17). The proposed fraction for FY1983 is considerably higher – perhaps the highest in the world. Meanwhile instead of increasing to about thirty-nine billion dollars as expected, total investment in the U.S. electric utility industry fell in 1981 to the mid-twenties of billions of dollars, and appears to be continuing to fall.

2 Lovins 1977b.

3 Marchetti 1975.

4 Messing et al. 1979:3.

5 Ibid.

6 Ibid.:17.

7 Congressional Research Service 1979:12.

8 Comtois 1977.

9 Huethner 1973; Messing et al. 1979:204–206.

10 Comtois 1977:52.

11 Messing et al. 1979:206.

12 Quoted ibid.

13 Fisher 1979:10.

14 Ibid.:12.

15 Komanoff 1981.

16 Ibid.:200.

17 Ibid.:220.

18 Fisher 1979:10.

19 Petzinger 1981.

20 Ibid.

21 Messing et al. 1979:209.

22 *Electrical Times* 1975.

23 Procaccia 1975; see also Knox 1977.

24 Komanoff 1981.

25 Ibid.:248.

26 Ibid.:253–257.

27 Ford & Flaim 1979:35.

28 Anson 1977.

29 *Weekly Energy Report* 1975.

30 *Electrical Times* 1973.

31 Ouwens 1977.

32 Economic Regulatory Administration 1981:7–4ff.

33 E.g., Kahn 1977; Wisconsin PSC 1977.

34 Peschon 1976. The exact value depends on details of the grid.

35 Peschon et al. have calculated (personal communication, 1978), for example, that for a loss-of-load probability of one day in ten years–the normal U.S. standard for grid reliability–and a forced outage rate of four percent, generating units equivalent to two percent of the peak load require reserves of only five percent of the peak load; units providing ten percent require about an eleven-percent reserve; units providing twenty percent need about twenty-three percent; and units providing fifty percent need about sixty-five percent. That is, the bigger and "lumpier" the unit, the bigger–disproportionately–its reserve requirements. This becomes much worse with a higher forced outage rate, say fifteen percent: the reserve requirements at the same unit sizes then become respectively about twenty-two, forty-three, sixty-two, and one hundred fifty percent. In fact, forced outage rates of fifteen percent or more are quite com-

mon for large power plants. For isolated grids, see Galloway & Kirchmayer 1958.

36 *Electrical World* 1975.

37 *Electrical Times* 1973.

38 Abdulkarim & Lucas 1977:226.

39 Abdulkarim & Lucas 1977.

40 Messing et al. 1979:10, 14.

41 E.g., Caputo 1977; OTA 1978.

42 Hein 1979.

43 Energy & Defense Project 1980:167–169.

44 Landsbaum 1981.

45 *Popular Science* 1981.

46 Margen 1980; Gleason 1981, 1981a, 1981b. The largest, being built in Uppsala, is to use a hundred thousand metric tons of seasonal water storage in a rock cavern (BFR 1980). Solar district heating could provide four billion kilowatt-hours of heat to Sweden annually by 1990. The Self-Reliance District Heating Group (1717 18th St. NW, Washington DC 20009) provides access to these and similar technological developments.

47 University of Arizona 1981:VI–16; Tomasi et al. 1981:61; Megida 1981.

48 Williams 1978. Payback times of a few years have been reported (Klock 1982). OTA will publish a cogeneration study during 1982.

49 Williams 1978; Klock 1982; Machalaba 1979.

50 *Diesel & Gas Turbine Progress* 1973.

51 Larue 1981.

52 Ibid. The California Energy Commission provides excellent publications.

53 *Los Angeles Times* 1981aa; Larue 1981.

54 Baughman & Bottaro 1976.

55 Ibid.

56 AGA 1977.

57 Economic Regulatory Administration 1980:Exec. Summ.:9; 1980 data from Edison Electric Institute.

58 Baughman & Bottaro (1976) show explicitly that this was true in 1972. Costs have escalated about as fast since then for operation and maintenance of the grid as for building it.

59 Systems Control 1980:Summ.:43–44. Bell (1981:4764) cites eighty-seven to one hundred fifty dollars' credit per kilowatt of dispersed fuel cells, but omits the waste heat credit, which could be worth many hundreds of dollars.

60 To procure the greatest benefit, the dispersed source should be as close as possible to the user, since an estimated eighty-five to ninety-five percent of outages are due to failures in distribution, not in the bulk generation/transmission system (Systems Control 1980:Rpt.:5.47; Systems Control 3–7; cf. Economic Regulatory Administration 1981:4–10).

61 Komanoff 1981.

62 Comtois 1977.

63 As Peter Bradford notes (personal communication, 7 January 1982), this effect has a long and curious history. The financier J.P. Morgan felt that Thomas Edison was mistaken in proposing to build the Pearl Street Generating Station in New York City. Construction, Morgan believed, would take too long, idling capital which could be more profitable used building smaller, decentralized generators in individual buildings. Later, as new markets and alternating-current technology switched the economics in Edison's favor, Morgan changed sides in forming the General Electric Company (from which Edison was brought out). Ironically, today's economics are again reversing the trend and so hurting General Electric's sales of larger power plants.

64 Komanoff 1981:208–209, 224.

65 Mooz 1978, 1979; Komanoff 1981:205. This finding has bee consistently ignored by those anxious to "streamline" nuclear licensing.

66 Ford & Flaim 1979.

67 Messing et al. 1979:207. The Nuclear Regulatory Commission concurs.

68 Komanoff 1981; Mooz 1978, 1979.

69 Comtois 1977.

70 Kahn & Schutz 1978; Wiegner 1977.

71 Komanoff 1981.

72 Ford & Flaim 1979. The feedback loop was pointed out by H.R. Holt.

73 Cantley 1979.

74 Cazalet et al. 1978; Stover et al. 1978.

75 Ford 1978; Ford & Yabroff 1978; Lovins 1981.

76 Ford & Yabroff 1978; Ford 1978, 1979a; Boyd & Thompson 1978; Ford & Polyzou 1981.

77 Hoag & Terasawa 1981.

78 Kahn 1978:333ff; Lovins 1981, 1982.

79 *Business Week* 1980.

80 Carioca, Arora & Kahn 1982.

81 Hein 1979.

82 Gerlach 1979; Gerlach & Radcliffe 1979; Casper & Wellstone 1981.

83 Fisher 1979:10.

84 Some instances of siting problems with

small units have been reported, such as a total-energy system for the Harvard Medical School and wind machines in Cape Cod and in Riverside County, California. In general, these problems have arisen from failure to let the local community participate in decisions.

85 Carioca, Arora, & Kahn 1982.

86 Lovins 1977b.

87 Dyson 1979:104–106; personal communication 1979.

88 This does not imply that end users *need* to be tinkerers. Recognizing that many do not wish to be, this analysis assumed technologies that are at least as convenient, reliable, and "hands-off" as the centralized systems in use today.

89 Hollands & Orgill 1977; OTA 1978.

90 Lovins 1978:492.

91 Hollands & Orgill 1977.

92 McPhee 1981a.

93 Taylor & Taylor 1981.

94 Economic Regulatory Administration 1980:Ex. Summ.:8.

95 Congressional Research Service 1979:11.

96 Morris 1981:114.

97 Ford & Flaim 1979.

Notes to Appendix Two

1 E.g., Energy & Defense Project 1980.

2 Sørensen 1979; Simmons 1981; Lovins 1978.

3 Metz & Hammond 1981; SERI 1981; *Soft Energy Notes*.

4 Department of Energy 1980.

5 E.g., California Energy Commission 1980.

6 Reif 1981.

7 E.g., Maine Office of Energy Resources 1980; Woychick 1981.

8 King 1979; Kensil 1981.

9 Ener-Nat 1979.

10 OTA 1978.

11 Raetz 1979, 1979a.

12 Simmons 1981:11.

13 *Sunworld* 1980.

14 Barden 1981. By mid-1981, ten U.S. dish designs were in detailed engineering development, of which three were ready for production (ibid.).

15 *Solar Thermal Report* 1981a.

16 Ansaldo (Genoa), cited in OTA 1978.

17 F.A. McCrackin, personal communication, 1 December 1981.

18 *Soft Energy Notes* 4(1):18–20 and personal communications, 1979–81.

19 Wittenberg & Harris 1980; Nielsen 1980.

20 Bessell 1981.

21 McPhee 1981a.

22 Taylor & Taylor 1981.

23 Hollands & Orgill 1977; Lovins 1978:492; OTA 1978.

24 SERI 1981; OTA 1980.

25 Lipinsky 1981; Palsson et al. 1981.

26 Jackson 1980.

27 SERI 1981; OTA 1980; Energy & Defense Project 1980; Lovins & Lovins 1981.

28 J.D.B. Carioca & H.A. Arora, University of Ceará, personal communication, November 1981.

29 OTA 1980:II:201ff.

30 Cals (undated).

31 SERI 1980, 1980a.

32 *Energy Consumer* 1980.

33 Patterson 1980.

34 Billingsley 1980.

35 Hobson 1980.

36 Hallberg 1981.

37 Hallberg 1980.

38 Flaim & Hertzmark 1981:89n.

39 Holmberg 1981.

40 ERAB 1981a:28.

41 Ibid.:31.

42 Illustrating the potential for simplicity John Tatom PE (4074 Ridge Road, Smyrna GA 30080) has designed effective pyrolyzers for developing countries, made of old oil drums, rocks, and pieces of pipe.

43 *Energy Task Force Newsletter* 1981.

44 These three cases are described respectively by Deans 1981, Murnane 1980, and Murnane 1981a, and were called to our attention by Alec Jenkins.

45 SERI 1981; OTA 1980. Such a transport system would use about five or six quadrillion BTUs of liquid fuels per year, compared with the present eighteen.

46 Lovins & Lovins 1981; Jackson 1980.

47 Flaim & Hertzmark 1981:94; BioSynthetics 1981.

48 Ferchack & Pye 1981. For a summary of recent developments, including pilot processes using below four thousand BTU/gallon, see

Pacific Northwest Laboratory 1981.
49 Ladisch et al. 1978.
50 Ferchack & Pye 1981.
51 Ladisch et al. 1978; *Biotechnology Newswatch* 1981.
52 Wang et al. 1979.
53 SERI 1981:II:583ff.
54 OTA 1980.
55 SERI 1981:II:585; Simmons 1981:27.
56 Lindström 1979.
57 Tatom et al. 1976; Hewett et al. 1981:147.
58 Tom Reed (SERI) personal communications, 1980–81.
59 *Los Angeles Times* 1981ee.
60 Jedlicka 1982. LNG cars have also attracted some interest (and safety concerns). Another, more exotic cryogenic possibility that may be interesting is to fuel a car with liquid air; the temperature difference between it and ambient would operate a heat engine.
61 Ingenjörsvetenskapsakademien 1950; Datta & Dutt 1981.
62 Ortegren 1981.
63 Franklin 1980. This is a pressing need in many developing countries.
64 McPhee 1981; Shenon 1981.
65 Congressional Research Service 1978:48–128.
66 Ibid.:129–136.
67 Schneider Corp. 1980.
68 Franklin Pierce Energy Law Center.
69 Energy & Defense Project 1980:178–184; SERI 1981.
70 The manual is Alward et al. 1979. The California Office of Appropriate Technology publishes a guide to federal and state programs, *Small-Scale Hydro*; the California Department of Water Resources supplies a newsletter, *Small Hydro News*; and the Idaho National Engineering Laboratory publishes the *Small Hydro Bulletin*.
71 Jim Harding (FOE), personal communication, 19 May 1981.
72 Ron Corso (FERC), personal communication, 4 August 1981.
73 McPhee 1981.
74 Dionne 1981.
75 Gouraud 1981.
76 Energy & Defense Project 1980:178.
77 Smil 1981. The figure was formerly over two-thirds (Lovins 1977b:124). Taylor (1981a) gives an excellent account of the program.
78 Sørensen 1979a:6.
79 Most wind machines now on the market are handmade, with tooling costs spread over production runs of tens to hundreds. Small and medium-sized wind machines, however, lend themselves to mass production of the kind now practiced in appliance and car manufacturing. Karl Bergey, personal communications, 1980–81; Bergey 1981.
80 Lovins 1978:496.
81 Ibid.
82 Carter 1978.
83 Stoddard 1981.
84 Ibid. Stoddard was U.S. Windpower's chief designer.
85 Park 1981. See also the listing in California Energy Commission 1981b.
86 Wegley et al. 1978.
87 Frank 1981.
88 Graves 1981.
89 Tomasi et al. 1981:65.
90 *Energy Research Reports* 1979.
91 *Business Week* 1981a.
92 Maycock & Stirewalt 1981; Watts et al. 1981; Smith 1981.
93 Congressional Research Service 1978:223–274.
94 JPL 1980; Smith 1981.
95 Friedman 1981; Treble 1980.
96 Friedman 1981.
97 AMETEK 1979; personal communications, 1981.
98 Maycock 1981.
99 Russell 1981.
100 Adler 1981.
101 Ross & Williams (1981) present strong arguments to this effect.
102 Larue 1981.
103 McNary 1981.
104 Tomasi et al. 1981:69.
105 Systems control 1980, 1980b; Cox 1981; Smith 1979; Watts et al. 1981.
106 Smith 1979; Cox 1981; Watts et al. 1981.
107 Systems Control 1980:5–16ff.
108 Southern California Edison Company 1981:5.
109 Hodges 1981:3.
110 Ibid.
111 de Mello & Hannett 1981. We are indebted to E.R. Baugh PE for bringing the concept and references to our attention.

112 Hodges 1981:4–5.

113 de Mello & Hannett 1981.

114 In an era of cheap digital electronics, it no longer makes sense to use the grid as a universal clock. Yet large turbogenerators requiring extremely stringent standards of frequency and phase stability are locking us into a grid of clocklike precision for decades to come. This may make interface with large numbers of dispersed renewable sources more difficult, and certainly imposes extra costs for little benefit. (If "stiffer" frequency and phase stability were needed in a renewable-based grid, one solution might be to insert motor-generator sets with large flywheels: angular momentum is cheap.) Similar considerations apply to voltage stability and to reliability. For example, present standards of grid reliability certainly exceed an economically worthwhile value (Telson 1975). Rather than giving everyone maximal reliability, it would be cheaper for customers needing it to get it from local storage or standby capacity, as telephone exchanges, hospitals, etc. do now, while others get–at reduced cost–slightly less reliable supplies. This would improve still further the economics of intermittent renewable sources (Kahn 1978:338ff).

Notes to Appendix Three

1 Worcester Polytechnic Institute 1978; Godolphin 1981.

2 Kahn et al. 1980.

3 Ibid.

4 Cone et al. 1980.

5 Bowring 1980; Omang 1981.

6 Lovins 1981a.

7 Chapman 1979.

8 Komanoff 1981.

9 Quantifying these externalities rigorously, however, may not be possible. The serious theoretical and practical obstacles to such calculations are beyond the scope of this book but have been surveyed elsewhere: Lovins 1977; Junger 1976; Council for Science and Society 1979.

10 E.g., Stobaugh & Yergin 1979.

11 Lovins 1978.

12 Lovins 1978a, 1979a; Nash 1979.

13 Kahn et al. 1980.

14 The rate used in Lovins (1978) was twelve percent a year in real terms–chosen to be several percentage points higher than was justified by the actual cost of capital in 1978, in order to discriminate against renewables. The rate is not nearly so unrealistic, however, in the light of actual 1981–82 market conditions (Lovins 1981c).

15 E.g., Stobaugh & Yergin 1979; Southern California Edison Co. 1980; SERI 1981.

16 SERI 1981:II:1975. This considers, of course, only technological costs, not the effects of tax credits.

17 Gleason 1981, 1981a; Taylor & Taylor 1981; Hollands & Orgill 1977.

18 OTA 1980:II:154–55; SERI 1979. Direct combustion, as noted earlier, is another option being taken seriously: in new sales of solid-fueled industrial boilers, wood ranks only slightly behind coal as the main fuel.

19 This is discussed in the context of the steel industry by Lovins et al. 1982.

20 The company is LUZ International, which is based in California but sells equipment made mainly in Israel (and installed about fifty thousand square feet of parabolic troughs there in 1981 under similar arrangements): Pospisil 1981.

21 This is starting to happen: *Solar Thermal Report* 1981b.

22 Caputo 1981 confirms that solar process heat is economic there.

23 Cooper & Paynter 1981.

24 Adler 1981; Maycock 1981; Russell 1981.

25 The Reagan Administration's budget proposals for Fiscal Year 1983 include eight hundred thirty million dollars for civilian nuclear power, four hundred forty-five million for magnetic fusion (not counting inertial-confinement fusion, which is in the military budget), seventy-three million for solar, and nineteen million for efficiency.

Index

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