From workshop proceedings, “The 10-50 Solution: Technologies and Policies for a Low-Carbon Future.”
The Pew Center on Global Climate Change and the National Commission on Energy Policy.

Renewable Energy Options – An Overview

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A Renewables-Intensive Energy Future

Stabilizing future atmospheric carbon dioxide (CO_2) from fossil fuel burning is a Herculean task, requiring continuous and increasing buildup of new carbon-emissions-free power along with improvements in energy conversion efficiency over this century. Renewable energy from the sun, wind, water flows and biomass can provide carbon-emission-free power as long as the sun shines and the earth’s biosphere lives. Prior well documented studies show that a CO_2 -emission-free primary power equivalent of 10 – 30 TW could be needed by 2050 to simultaneously mitigate against the most adverse climate change impacts from global warming and meet the energy needs that would allow for continued global economic growth of 2-3% per year—this being the most likely range in light of presently understood uncertainties (Hoffert et al, 2002; Caldeira et al., 2003). In round numbers, the rate of total global primary commercial energy consumption at the beginning of the century was approximately 12 TW. In other words, some 100 to 300 percent of present-day power might be needed from non-CO_2-emitting sources fifty years hence to significantly slow global warming.

Electricity is a rising fraction of total energy in the United States and worldwide. Producing a significant proportion of electricity in a GHG-emission-free manner is a major challenge. Renewables (mainly solar and wind power) are one path to responding to this challenge. The renewable path is technologically challenging, particularly implementing it in time to significantly slow global warming. But all alternate energy technologies to fossil fuel burning with CO_2 vented to the atmosphere face major hurdles. And if successful, renewables could provide the energy for our civilization sustainably and pollution-free into the indefinite future. This paper explores the potential for a significant scale-up in the use of renewables to produce electricity, with an emphasis on transmission and storage needs and options. Electricity, a clean, high quality energy product, is an increasing fraction of energy end use. For a typical conversion efficiency of 33% to convert primary energy (in chemical and nuclear bonds) to electrical energy with conventional fossil and nuclear fueled power plants and transmission lines, a fully electric economy might need only a third as much electric power as primary power; that is, 3.3 to 10 TW(e)[1], rather than 10 to 30 thermal terawatts, to slow global warming by 2050.[2]

Even so, getting 3.3 to 10 TW(e) electrical power capacity by 2050 from emission-free sources is a huge job, equivalent to building 1.2 to 4 conventional one-thousand megawatt power stations every week for the next fifty years starting immediately. Another way to view the scale-up needed is to consider that generating 3.3 TW (e) from solar cells at the earth’s surface would require an area of roughly 220,000 km^2, equivalent to an array of PV panels 470 km on a side (Hoffert et al., 2002). But all the PV cells shipped from 1982 to 1998 would only cover less than 10 square kilometers. The gap between where we are and where we need to be is so large that it will, in the author's opinion, take efforts on the scale of the Apollo moon program or the Manhattan atomic bomb project to bridge it.

To minimize adverse impacts on biodiversity and human health from pollution and global warming, environmentalists have called for renewable electricity, and hydrogen made with renewable energy, since the "energy crisis" of the 1970s. So far, an insignificant fraction of U.S. and global energy supply comes from renewables. This is measurable in different ways. For example, the cumulative global energy produced by wind power by 1995 was approximately 0.3% of the electrical energy consumed by the United States in one year (Fig. 1, IEA, 2000). Worldwide in 2000, solar, geothermal, wind, combustible renewables, and burning garbage and other wastes collectively only provided 1.6% of electricity production (Malsch, 2003; (firewood burning in traditional societies, and hydropower, near saturation at a few percent of the total, are excluded)). A scale-up of renewable power from 1.6% to 10% or more in a few decades, and then to a major fraction of world energy supply by 2050 will be a major effort. The author argues that it's doable, but unlikely to happen spontaneously through market forces. Policy incentives are needed. The year 2050 is closer in time than the first nuclear reactor built by Fermi's team at the University of Chicago (2 December 1942), and fission today provides less than 5% of primary power. So the critical questions are: "How much power can the United States expect from renewables fifty years from now if we made it a priority?" and "What policies can get us there?"

So far, the U.S. Department of Energy (DOE) hasn't assigned renewable energy a significant role in global warming mitigation. DOE is, however, exploring two other paths: (1) centralized coal-fired power plants producing electricity and/or hydrogen, with carbon sequestered as pressurized CO_2 gas in depleted natural gas reservoirs or deep saline aquifers (the "FutureGen" project); and (2) new generations of nuclear reactors resistant to accidents and weapons proliferation with more sustainable and acceptable fuel cycles (the Gen III and Gen IV fission reactor programs). However, the GHG-emission-free energy challenge is so unprecedented that more technology initiatives are urgently needed. Expert panels and eminent scientists, haven't been very effective historically at predicting technology winners and losers. The most prudent policy is to imaginatively explore multiple approaches to insure that failures (normal in engineering development) aren't catastrophic. This group of authors argues that a new R&D initiative is urgently needed aimed at the technologies needed to generate and support the transmission and use of a significant amount of GHG-emission-free electricity from renewable energy by mid-century.

Total electric power consumption in the United States at the end of the 20th century was about 9.0 exajoules(e) per year (WRI, 1998, Table 15.1) equivalent to a mean consumption rate of 0.285 terawatts(e). Since there are about 8760 hours in a year, U.S. electricity consumption can also be expressed as 2,500 terawatt(e)-hours per year. At a plausible growth rate of 3% per year, U.S. demand by mid-century would be some 11,000 terawatt (e)-hours per year. How will this be met? Roger Anderson advances the case for new smart, next-generation, continental-scale electrical networks[3] that efficiently interconnect a wide variety of sources to consumers. These sources would include gas, coal and nuclear generation along with wind, solar, geothermal and other renewables in both centralized (deserts, offshore) and distributed (house, block, community, business, town) facilities. Predominantly wind or solar power electricity systems, whether grid-connected or not, will likely require enough energy storage capacity for days to perhaps a week.

Much can be achieved through expanded use and evolution of existing technologies, but in spite of dramatic cost declines for solar and wind technologies, these generation technologies for the most part remain more costly today than electric generation from fossil fuels, especially in the case of photovoltaics (solar cells). Moreover, large-scale deployment of these technologies depends on critical enabling technologies, particularly in storage and distribution (grid) systems designed to meet key renewable characteristics: intermittency, remote location, and extremely large numbers of generation sources. Addressing the storage, transmission, and distribution needs of renewables will require cost reductions in, and testing of, "smart" grid technologies in pilot and demonstration projects, and significant technological breakthroughs, or will utilize technologies that do not yet exist. Technologies critical to large-scale deployment of renewables need to be invented, mass-produced, commercialized and marketed.

Present Status and Outlook of Renewable Technologies

A long-standing controversy exists in the renewables community over centralized (often remote) versus distributed (often local) power generation. The "best" solution is not yet evident, but it may well involve some combination of the two. Renewables are thin gruel. Their adoption will require innovative and effective technical approaches to deal both with the low average power density and the intermittent nature of solar, wind and geothermal sources. To address low power density, one general approach is to seek sites where the energy flow per unit area is higher than average. However, these sites are not usually located near to where the energy is needed. They might be winds in the Great Plains, or offshore, atop high buildings, even in the intense jet steams of the upper troposphere; relatively intense sunlight might be captured by PV arrays in deserts, in orbit outside Earth's shadow cone, or on the moon. Large-scale use of such distant energy sources will require more intelligent and efficient grid systems.

Managing supply and demand imbalances due to the intermittency of wind and solar power sources can be accomplished by storage and by "net metering," i.e., extracting grid power when local power sources are insufficient, and selling power back to utilities when there is excess. Existing distribution networks can accommodate this so long as renewables are a small fraction of the power flowing through the grid. The precise fraction at which present grids would become overwhelmed isn't well characterized, but it's likely in the range of 5 and 20% from renewables, depending on details. A smarter grid is going to be needed for a significant amount of electric power to come from renewables.

Most homes, buildings, and commercial businesses consume power at kW(e) scales, and yet at present most power is generated at scales of hundreds of MW(e). This mismatch stems from the historical focus on the apparent economies of scale of large power production and transmission. At the household and community scale a fundamental transformation in energy production and use is now possible if we are prepared to invest seriously in distributed power generation *and* intelligent efficient grid systems. Thus, proponents of distributed and remote renewable power alike cite Internet-like models for transmission and storage (Vaitheeswaran, 2003). The present status of generation, storage, and grid technologies is summarized below.

Generation Technologies

Renewable energy generation technologies have experienced dramatic technical and economic advances over the past several decades, and now stand at a point where they are already contributing significantly to energy and electricity production in a number of states, provinces, and nations. Over the next five decades solar and wind energy could provide well over one third of electricity demand, with biomass meeting another 20 percent (Herzog, *et al.*, 2001).

The most cost-effective renewable today is wind, although the best sites are often remote from users or offshore. Wind could supply a major part of U.S. and world electricity requirements were turbines sited at locations with the highest wind intensity. Advanced technology options for wind include siting turbines in high-altitude intense jet streams -- for example, as tethered autogiros where part of the wind energy supports the turbine at altitude; and the balance goes to electric power generation transmitted to the surface. Although wind is more cost-effective in the near term, solar offers a larger resource. Several advanced solar power ideas exploit the fact that the long-term average solar power per unit area is about 8 times higher in space than at earth's surface. Collecting this energy in geostationary orbit or on the Moon, and beaming electric power to the surface with microwave or laser beams, may be cost-effective someday if access to space costs fall sufficiently. These, and other high-risk, high-payoff renewable energy ideas, including advanced biofuels exploiting genetic engineering, should be explored seriously to understand their attributes and potential.

The table below compiled by the California Energy Commission compares approximate present-day costs of several electrical energy sources (CEC, 1996).

Table 1

Levelized Electricity Cost at Busbar (¢/kWe-hr) (1996)[4]	
Coal	4.8 -5.5
Gas	3.9 -4.4
Hydro	5.1-11.3
Biomass	5.8-11.6
Nuclear Fission	11.1-14.5
Wind (without federal production tax credit)	4.0-6.0
Wind (with federal production tax credit)	3.3-5.3

Windpower at the busbar is already cost-effective at the best locations, in the 3-5 cents per kilowatt(e)-hour range, and is the world's fastest growing energy source on a percentage basis, at 32% per year growth for the past five years. Globally there was over $7 billion in wind energy investment in 2002 alone, and worldwide capacity is over 31,000 MW. In Denmark and some regions of Spain and Germany, 10 – 25 percent of total annual electricity generated is from wind. Rapid growth of electricity generated by wind is likewise planned by many State governments in the United States. The symbolically important "Freedom Tower" planned for the World Trade Center reconstruction is expected to contain wind turbines in its cable-tensioned upper structure sufficient to generate 20 percent of the building's electricity. Wind turbines have undergone a technological revolution in blade and motor design, and in the size of individual units. Five years ago 750 kW turbines were considered large, but today 1.8 – 3 MW machines are standard in new wind farms, with even larger machines (~ 5 MW) planned for many offshore installations. Innovations have come at such a rate that repowering (replacing/upgrading) existing wind farms installed within the last decade has become the industry norm.

Busbar electricity costs from photovoltaics (PV) are likewise declining. For many new technologies, costs decline with increasing market volume (and increasing time). Shown below as log-log plots for renewable and nonrenewable energy technologies are busbar electricity generation costs in 1990 Eurodollars per kilowatt-hour versus cumulative production in terawatt-hours (IEA, 2000). Numbers in parentheses are cost reductions in recent history from doubling cumulative installed power. When, for example, the size of PV markets doubled, the cost of PV electricity dropped to 65% of its previous value. Present PV levelized electricity costs are in the 15-25 cents per kilowatt(e) range, and continuing to decline.[5] Unit costs of massively scaled-up arrays are projected by the National Renewable Energy Laboratory (NREL) PV Roadmap to be competitive by 2025.

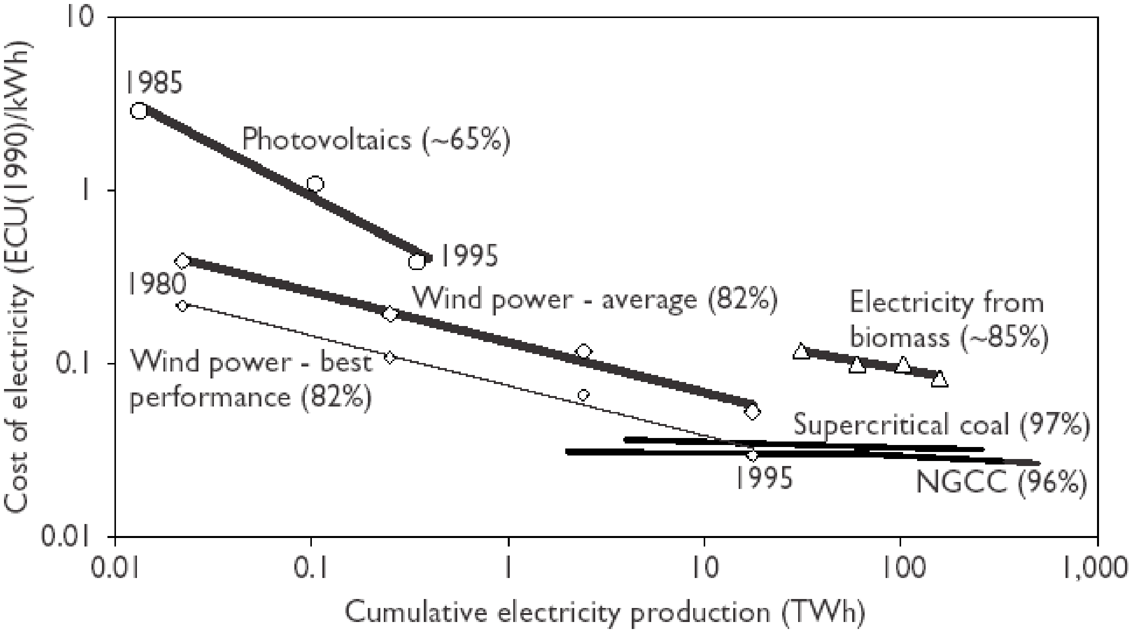

Figure 1. "Learning by Doing." Economies of scale for various electrical energy generating technologies thus far (from IEA, 2000).

Solar PV today relies on semiconductor-grade crystalline-silicon wafers that are expensive to produce compared with energy from fossil fuel sources. Less costly amorphous semiconductors, thin films, organic polymers and "quantum dot" technologies and mass-production manufacturing processes could provide major cost breakthroughs in world markets. These are under intense study. Radically new systems incorporating solar PV (and solar thermal) technologies, including solar power beamed from space, could likewise revolutionize the field by mid-century if they are aggressively pursued now. The potential of PV, and the magnitude of the solar resource, is too great to be deterred by presently high costs.

The biomass energy sector is also undergoing a significant transformation. Biofuels can be carbon-neutral if produced sustainably on energy plantations. For example, grasses and softwoods from managed energy farms can be burned alone or in combination with other fuels, or gasified and then co-mingled with other fuels such as natural gas. Efficient combustion of solid biomass is now practiced extensively in a number of countries such as Sweden where biofuels are expected to meet 20 percent of electricity demand by 2010 (Johansson, et al. 2002). Advances in biomass gasification that permit fuel substitution between natural gas and biofuels are now yielding commercial designs at kW to MW scales. Biomass can also be used as a source of hydrogen, which could play a critical enabling role in GHG reduction efforts because of its ability to serve as an energy carrier for both stationary and vehicle-based power. Unfortunately, and exacerbated by the low efficiency of photosynthesis (~ 1%), biofuels compete for land with carbon sequestration through forest conservation, with human agriculture, and with preservation of biodiversity. We need to understand these land-use trade-offs better and to explore advanced ideas like plants genetically engineered to be more efficient fuels, perhaps even producing hydrogen directly.

The Grid

At present, the grid is not even equipped to deal with the large increases in electricity traffic and congestion stimulated by the long-distance demands of power trading and restructuring of U.S. electricity markets. Slow response times of mechanical switches, lack of automated analysis of problems, and inability to "see the whole grid", are contributing to a noticeable increase in grid failures. These problems have caused a dramatic increase in blackouts and brownouts since 1998. They will propagate cascading grid failures more and more frequently unless we migrate to a new "smarter" grid control system because decision speeds increasingly are becoming too fast for humans to manage. In order to be able to utilize massive amounts of renewable energy sources -- accommodating centralized, large-scale, as well as smaller, distributed, home, business and community generation—it is necessary to first modernize the grid by installing digital controls, electronic switches, and higher capacity transmission lines. The management of the grid will require digital control, automated analysis of problems, and automatic switching capabilities more familiar to the Internet (like the routers sold by Cisco that break messages into packets and send them over several different routes to relieve congestion, only to reassemble them at the destination into your next e-mail). In short, the present U.S. electric grid will not work on any scale – local, state, national or international—at the higher loads and more diverse generation sources required in the future.

Storage

Most renewable energy sources are intermittent, variable, and unpredictable. Large-scale storage of electricity to accommodate the erratic nature of green power sources will be required. Electricity is not usually stored *per se*. Energy storage technologies instead convert electricity to other energy forms (gravitational, pneumatic, kinetic, or chemical). The lowest cost energy storage technologies avoid most of the cost of energy storage capacity by relying on natural geologic formations to store energy in elevated water or compressed air, the cheapest substances known. Unfortunately the scale and location-specific nature of energy storage in natural formations is likely to render it of limited benefit to small-scale distributed renewables. Available pumped hydro and compressed air energy storage (CAES) capacities could prove small in relation to the overall amount of future global renewable electricity—and attendant storage requirements—necessary for massive reductions in greenhouse gases. If energy storage in existing natural formations turns out to be insufficient, then man-made energy storage systems will be needed to support massive deployment of intermittent renewables.

Among man-made energy storage systems, the most well known is the battery. Batteries are very modular and are therefore technically well suited to use with small-scale distributed renewables. The chief difficulty of battery technology is short life which, given their capital cost can make storing electricity in batteries at least as expensive as generating electricity. Additionally, in the context of deep GHG reductions, the sheer scale of raw material needed for batteries (billions of tonnes) would likely outstrip the known reserves of common battery materials (lead, nickel, cadmium), further increasing battery cost. Such huge quantities of battery materials might also need to be recycled nearly indefinitely to minimize disposal issues and environmental impacts.

An emerging alternative to batteries is the high-speed flywheel. Flywheels store kinetic energy in a cylindrical or ringed mass, spinning at very high speeds (~10,000-20,000 rpm). Key issues for flywheels are safety and cost. Addressing the safety of deploying millions of flywheels would likely require underground use and/or stringent containment designed to withstand high-speed (~ 1000 miles per hour) fragments from a broken flywheel. This will likely place a lower limit on flywheel system capital costs. Performance has improved dramatically over the last two decades with progress in ultra-high strength composite materials. If future developments reduce the cost of ultra-high strength materials, flywheels will be substantially more attractive. Currently, flywheels are just beginning commercialization for high-value uninterruptible power applications. If they become economic in a renewables context, flywheels are likely to be best employed for routinely (i.e., daily) storing small amounts of energy delivered at high power for short times (1-2 hours),[6] or perhaps to smooth out peaks in power demand into and out of a much larger battery storage system (improving battery life).

Predominantly solar or wind power systems will likely require energy storage for days to approximately a week. If so, conversion of electricity to chemical energy is potentially attractive since chemicals are inexpensive to store. The most attractive chemical for this process is likely to be hydrogen (H_2). A predominantly renewable electricity supply could be combined synergistically with a future H_2 transportation sector. Co-production of electricity and H_2 fuel would enable massive deployment of intermittent electric generation by making efficient use of otherwise almost unavoidable excess generation during some time periods. Hydrogen storage onboard vehicles, be it in high-pressure gas, cryogenic or metal hydride tanks, is a major technological challenge to be solved before hydrogen cars can become widely accepted in the market. However, if this problem is solved satisfactorily, enough H_2 could be stored in the H_2 infrastructure and/or onboard H_2 vehicles to buffer H_2 demand on the time scale of days.[7]

Technology and Policy Paths Forward and Barriers

Research & Development

The United States hasn't had a pro-active research, development, demonstration, and deployment policy for renewable energy since the 1970s when Middle East oil cutoffs and OPEC price hikes were existential realities. Initiatives from that period include the Public Utility Regulatory Policy Act of 1978 (PURPA) mandating that electric utilities buy energy from independent generators (Grubb and Meyer, 1993). Cost-effective wind farms at the Altamont Pass near Livermore, California, a legacy of that period, would likely be nonexistent without PURPA and tax subsidies initiated by then Governor Jerry Brown. The DOE National Renewable Energy Laboratory (NREL) is potentially a key player in an expanded role for renewables. However, and despite important work on wind turbines, geothermal energy, PV, solar thermal, biomass and hydrogen, NREL so far is working on renewables mainly for niche markets. Absent U.S. federal incentives, policies supportive of renewable energy are coming mainly at the state level in the United States and from Europe (Hassol and Udall, 2003).

Research and development (R & D) is critically needed in each technology area discussed above. This should include large-scale demonstrations of system viability and shakedowns in operational environments to accelerate commercialization by lessening risks to investors of new technologies. Generation technologies require R & D for cost reductions and efficiency increases; grid technologies need R & D to reduce costs, in addition to testing sites for integrated operation of a smarter, digitally controlled, high-speed, “internet” type system. Storage technologies need R & D both to reduce costs and to increase the efficiency of renewable generation through integration with transportation sector energy needs. A critical failing in current U.S. R & D is the fickle and intermittent nature of renewable energy research and development support. Many R & D programs have exhibited roller-coaster funding cycles, at times doing more harm than good to the sustained development and deployment of specific technologies (Margolis and Kammen, 1999). At the same time, the R & D portfolios we have adopted for many renewable energy technologies have been tremendously risk-averse—and hence potential benefit-averse.

Research, development and demonstration programs designed to achieve a massive scale-up of renewable power from approximately 1% presently to 10% or more in a few decades to a major fraction of market share by century’s end are urgently needed. The need for a revolutionary change in the U.S. and global energy system to implement the goals of UN Framework Climate Change is accepted (in principle) by DOE and by the present administration—despite withdrawal of the United States from the Kyoto Protocol. In a December 11, 2003 letter to the *New York Times*, John H. Marburger III, President Bush’s Science Advisor, and Director of the White House Office of Science and Technology Policy, said:

> Although we believe that the Kyoto Protocol on climate change is flawed because its targets are arbitrary and expensive, the United States is demonstrating leadership and commitment on multilateral efforts . . . Investment in carbon sequestration, hydrogen fuel cycle technology, next-generation nuclear fission, fusion energy and energy-related biotechnology is an absolutely indispensable

precondition for an economy with dramatically reduced greenhouse gas emissions.

This group of authors supports these efforts. However, for reasons discussed in detail above, we urge that a “Third Stream” in renewable energy be included in the U.S. Climate Change Technology Program along side existing R&D streams in (1) hydrogen from coal with carbon sequestered and (2) advanced nuclear reactors. It is critical to explore the role advanced renewable energy technologies could play in time to slow global warming. The following specific program elements are excellent starting-points:

(1) **Continental and global-scale systems analysis of electricity and hydrogen transmission and storage and distribution systems**. This is in the spirit of "systems integrations" studies in the aerospace industry. Most energy technology research is focused on devices, but we need to explore physical limits and opportunities for global energy systems. A relevant principle of systems analysis is that optimizing a component of a complex system doesn't necessarily optimize the system as a whole. This idea needs to be applied to analysis of large-scale energy systems, for example, to explore the relative advantages and disadvantages of distributed generation versus long distance power transmission on a large scale.

(2) **"Smart" and low-loss electrical grids**. Electrical networks in the U.S. and Europe are going to be reconstructed or upgraded in any event in the wake of recent power outages. We should take this opportunity to see how they can be made user-friendly to renewable power sources. This needs to be studied now, to prevent foreclosing a major role for renewable electricity in the future. Reducing the electrical resistivity of such grids with high-temperature superconductors or carbon nanotubes is one element of this; computerized load management is another. Energy storage is important enough to have a program of its own.

(3) **Electrical and hydrogen chemical energy storage**. Buffering the energy produced by solar and wind is a critical issue for renewables to become cost effective at a large scale. The level of storage needed is massive, and could be the most expensive and technically challenging part of the system.

(4) **Advanced biomass**. Conventional biofuels aren't going to produce much emission-free power because the efficiency of photosynthesis is low (leading to large land use) and significant energy and nutrient inputs are needed. In principle, genetically engineered plants could, for example, produce hydrogen.

(5) **Space solar power**. Here is a real opportunity for DOE to get into a sustainable emission-free energy source with enormous potential. Beginning 40 years ago or more, DOE bet on controlled fusion power, a technology that looked doable. Using fusion in a controlled way to make electricity turned out to be

> much harder than anticipated. In principle, space solar power (SSP) can capture the sun’s power more efficiently that terrestrial collectors, and moreover do the same job as fusion power plants—supply baseload electric power in arbitrarily large amounts anywhere on Earth. The United States has spent peanuts on this technology compared to tens of billions on fusion power. Arguably, we would be much further down the path to sustainable electric power had we pursued SSP at comparable funding levels. We have a second chance to explore this path now.

As a general principle, energy production and efficiency goals and openness to promising new ideas, not specific programmatic or technological subsidies, should guide the long-term direction of renewable energy R&D. One possibility is to create a DARPA-like organization whose program managers are charged with developing to technical maturity potentially revolutionary ideas, whatever it takes. DARPA (Defense Advanced Research Projects Agency) has a track record of doing this, having funded among many other technologies the Internet and supercomputers. Comparable efforts such as the modernization of, and renewable access to, national electricity grids are needed within DOE.

The Near Term (Now to 2025)

At present a Renewable Portfolio Standard (RPS)[8] is the most effective mechanism to bring renewable energy generation technologies to market. In the near term an RPS is an innovative and critically important measure because it utilizes a transparent regulatory policy to open markets for clean energy technologies. If a given energy technology has a 1 percent or smaller market share, its economics are dominated by a niche application, or by a specific regulatory provision. By contrast, roughly a 10 percent market share is one that is, for many technologies, one of economic competitiveness. The threshold to move from niche to mainstream is thus likely somewhere between 1 and 10 percent. An RPS provides one clear mechanism to move these promising but marginalized technologies to the point where they can compete in the broader marketplace. At present wind is the cheapest form of renewable energy in many locations, so care needs to be exercised to open markets to a range of renewables, as in Nevada where the RPS includes a specific set-aside for solar energy. Allowing regional differentiation could also be a significant benefit, so that biomass-rich regions such as the Southeast or Midwest could adopt initial set-asides for biomass-based renewable fuels. Related measures are introducing carbon credits into energy markets, and ‘feebates.’ Credits based on units of clean, carbon-free energy produced would allow trading in markets where low-or no-carbon energy sales and use are rewarded. ‘Feebates’ are an attractive and under-used policy measure where a technology is rewarded with a rebate when it meets a specified standard, and taxed when it falls below this level.

Another immediate policy option is the mechanism that many researchers consider to be the most effective and economically efficient tool at our disposal: pollution fees. There is nearly universal agreement that the prices of fossil fuels far fall short of their social and environmental cost. The introduction of taxes to reflect these costs – which could readily be made revenue-neutral through compensating reductions in income tax – would be an efficient way to encourage cleaner forms of energy generation. A carbon tax of $10/ton – which would result in gasoline prices still far less than we see in parts of Europe today – could encourage a wave of clean energy research and market implementation.

In many respects the greatest hurdle that must be addressed to take advantage of the opportunities for small-scale renewables generation and concomitant efficiency improvements is the role of utilities. In most areas the present utilities see few attractive revenue opportunities through encouraging greater efficiency. In particular, distributed generation appears to be a simple loss of revenue to electric utilities. R&D programs, subsidies, and other incentives for local, clean generation merely steal or divert customers. Thus at present the U.S. utilities correctly see little benefit, and great expense, in investing in the infrastructure needed to make distributed power generation and use the norm.

Moreover, regulators do not allow utilities to recover the costs of purchasing some of the equipment critical to renewables through consumer electricity rates. Both significant storage capacity and new "power controllers" are needed. New power controllers would allow a dual power system, in which higher quality, more reliable power can be delivered at an added cost only to those consumers that need it, while lower-quality, less reliable, less expensive power could be delivered to the rest of us. Supplying and charging higher rates for high-quality power would provide added revenue, revenue needed to attract the private capital necessary to upgrade the long-distance transmission system so that it can accommodate vast new wind and solar "farms." Presently, we all get the same high-quality, expensive power (99.999 percent of the time it is within a strict range of voltage and frequency, referred to as "five 9's" in the power business). Identifying opportunities for utilities to profit from clean, local, power production is one area critically in need of attention.

Grid system test beds *must* be in operation within 10 years if we are to meet the power needs of the continent 20 to 30 years out. Such test beds would combine promising new technologies. Designing a smart grid is difficult to do if individual technologies are deployed in isolation. The grid cannot be experimented with "live." We must be certain that the grid is capable of handling each new technology *before* it is deployed. It is not an option to connect new gadgets directly to the grid, and accidentally cause massive, cascading blackouts. The problem with creating such national test beds is that electric utilities have among the lowest R&D expenditures of all companies (Lerner, 2003). The federal government must recognize the electric grid as vital to our prosperity and national security and support the creation of several test beds to experiment with deploying new smart grid technologies on a large scale and in an integrated way. Such an effort, dedicated to modernization of the electricity grid, is needed within the DOE.

The Mid Term (2025 to 2050)

The U.S. electric grid will almost certainly be upgraded in the coming decades to address the dramatic increase in blackouts and brownouts in recent years (Lerner, 2003). But hasty decisions to "beef up" the hub and spoke networks which now form the base of the U.S. electric grid and which are unsuited to decentralized and distant sources could be hard to change after infrastructure investments are "sunk". Restructuring the grid needs to be done from a long-term strategic perspective. As upgrades proceed, it is important not to foreclose "smart" grid systems, systems that can deal with variable and unpredictable loads from renewables in addition to more traditional power sources. Upgrades should be designed to accommodate long distances (continental scales and beyond), high-voltage AC and DC transmission lines as well as local, distributed generation and storage. A "lean engineered" electric power system, one that will improve efficiency of transmission and distributions system by 50 percent or more is needed. The grid should incorporate computer control systems to simulate and dispatch imperfect loads, deliver "five 9's" of quality power only when and where it is needed, and accept renewable power without the need to build enormous new distribution and transmission capacity (Anderson, et al., 2004). The estimated price of this upgrade is in the $100 billion range.

Within twenty to thirty years, a high temperature superconductor/liquid hydrogen (HTS/LH_2) super energy highway recently proposed by EPRI and DOE might provide the clean and green energy in both electrical and chemical forms to power urban transportation and electricity needs simultaneously. This "Super Grid" could employ a high-capacity, superconducting power transmission cable cooled within a liquid hydrogen pipeline—the liquid H_2 in the pipe doing double duty as superconductor coolant and energy-carrier. It should in this time frame also be possible to produce solar cells with installed costs of around $1000 per peak kilowatt(e).

The Long Term (2050 and beyond)

The projected electricity demand worldwide is huge. In the United States alone, generating a major fraction of the 10 to 15 thousand terawatt(e)-hours per year projected for 2050 with solar and wind power is an enormous challenge. The gap between where we are and where we want to be is so large that it will take R & D efforts on the scale of the Apollo moon program or the Manhattan atomic bomb project to bridge it. This grand transformation will also require policy incentives, large-scale investment, mass production and innovative marketing. Still, our panel finds no physical limits, no "showstoppers" preventing renewables in principle from becoming major primary power sources.

The history of technology is replete with seemingly "far out" ideas that changed the world. But the track record of "expert predictions' of where specific technologies will go on century time scales is not encouraging. Consequently the most prudent policy is to imaginatively explore multiple approaches. The "Willie Sutton Principle"—robbing banks because that's where the money is concentrated—argues for going where and when renewable power is most available, even to very remote or centralized capital-intensive sources if they are cost-effective. Buckminster Fuller proposed a continent- and time zone-spanning global grid that could wheel solar electricity from the sunlit hemisphere of Earth to the night side, before the discovery of high temperature superconductivity that could enable it. Radically new technologies like collecting wind power from the jet stream, or ocean power from the thermocline,[9] or solar power from geostationary orbit or the Moon, could play a major roles fifty years from now.

In any case, solar cells are likely to be a lot less expensive by 2050. Amorphous thin-film alternatives hold promise, as do organic cells, with the potential for unprecedented low cost – well below $0.50 per peak watt. An alternate vision for renewable energy is distributed generation: each rooftop covered with cheap solar cells, each building complex or neighborhood with its own fuel cells and hydrogen storage.

The march of discovery and technological innovation goes on, a process the United States has been leading so far. Continuing this leadership will require a greater commitment to R&D and to science and technology education in the increasingly globalized world economy. We're living now off our prior investments. The potentially revolutionary discovery of high-temperature superconductive materials several decades back has ramifications for renewable energy that are still working themselves out. More recently, Rick Smalley's discovery of a new form of carbon, carbon nanotubes, is a wild card that, like personal computers and the Internet, could enable renewable energy in ways largely undreamt of today. Nano-scale transmission wires, called quantum wires (QW), might revolutionize the grid. The electrical conductivity of QW is higher than copper at one sixth the weight, and QW is twice as strong as steel. A grid made up of such transmission wires would have no line losses or weather dependencies, eliminating the need for massive emergency generating capacity. QW, perhaps spun into non-corrosive polypropylene-like rope, might be buried "forever" with no fear of corrosion and no need for shielding of any kind.

There have been those with upbeat technological visions since the Industrial Age, and we admit to being among them. But the future—as Arthur C. Clarke observed—is not what it used to be. As it evolves, we have an opportunity to shape it adaptively. There will be lags between cause and effect, and the window of opportunity to slow global warming may be limited. The challenge for *Homo sapiens* is implementing energy policies now that will foster the global environment we want for our grandchildren.

Conclusions

Where should The United States be in 50 years? This group of authors argues here that a major fraction of electricity can and should come from renewable energy. The more the better, but as a practical matter anything over 20 percent – twenty times more than today—will be useful in slowing global warming. An ambitious but desirable interim goal for climate change stabilization is 10 to 30 terawatts of CO_2-emission free primary power worldwide: one-third from fossil fuel with sequestration, one-third from advanced nuclear and one-third from renewables by 2050, with the U.S. amount perhaps 15% of the total. To get there we must start immediately to:

- Develop an appropriate R&D effort, likely on the scale of the Apollo Moon program or the Manhattan atomic bomb project or greater. Consider a DARPA-like program management model with a mandate to advance technology significantly beyond the state-of-the-art, to bring new options into the market place, and to fund a broad spectrum of researchers. This program would add a "third stream" to DOE's present two paths for reducing GHG emissions (carbon capture and sequestration, and a new generation of nuclear reactors).
- Get test-beds for smart transmission and distribution systems up and running.
- Expand the use of regulatory mechanisms, such as RPS, which serve to increase the market share for existing renewable-generation technologies, to bring costs down and to make renewables competitive with other technologies.
- Begin to insure that renewable electricity generation technologies are developed in coordination with building and transportation technologies (particularly the use of H_2 as a transportation fuel) with a view to finding synergistic opportunities including meeting renewable energy storage needs in the most efficient manner.
- Create a new generation of engineers and scientists, attracting top students to these fields through fellowships and scholarships.

It will also be critical to:

1. Find ways to make renewable and distributed generation financially attractive to utilities.
2. Obtain government or private market financing to supplement the extremely low R&D funding available within the electricity industry.
3. Avoid hasty decisions to beef up hub-and-spoke networks unsuited to decentralized and distant sources. The results of such decisions could be hard to change after infrastructure investments are "sunk" and it is important not to foreclose smart grids with sophisticated computerized load management.
4. Insure that support for renewable programs is steady and continuous

Twenty to thirty years out the United States should be targeting at least 10% of electric power from renewable energy sources:

- Build the next generation, smart electricity transmission and distribution system, possibly a "super grid" which would integrate the H_2 and electricity distribution systems with superconducting power transmission cables cooled within a liquid hydrogen pipeline.

- Install equipment that will allow a dual system so that high-quality power (e.g. “five 9’s” of reliability) can be supplied only where and when it is needed, enabling users of high-quality power to be charged appropriate rates, and lower-grade power can be supplied to the vast majority of users at lower rates.
- Have renewable generation technologies become cost-competitive not just in niche markets but also widely across regions and at scales ranging from buildings through communities and large centralized plants and linked into a “smart” transmission and distribution system.
- Build up storage capacity either through integrating transportation and electricity systems or through storage technologies developed in the R & D program.

By 2050 at least 20 percent of power should come from GHG emission-free renewable sources:

- Low-cost renewable generation technologies utilizing the entire spectrum of resources: solar, wind, ocean, biomass, etc.
- New breakthrough approaches developed from technologies presently in early research states or as yet not dreamed of: bio-converters, solar power beamed from space, global power grids wheeling electricity from one side of the earth to the other, transmission wires based on nano-technology, a fully integrated, transportation and power generation system.

Getting there will require substantial R & D investments in renewable energy technologies—investments not yet being made at the required scale and focus. This work would be done by national labs, universities and industry, and could perhaps be part of the U.S. Climate Change Technology Program (CCTP). Research tasks would include continental and global-scale systems analysis of electricity and hydrogen transmission and storage and distribution systems, smart and low-loss electrical grids, (3) electrical and hydrogen chemical energy storage, advanced biomass and space solar power. Achieving this goal “…requires the recognition that, although regulation can play a role, the fossil fuel greenhouse effect is an energy problem that cannot be simply regulated away.” (Hoffert et al., 2002). In the words of U. S. Energy Secretary Spencer Abraham (2003):

> We can set targets and timetables for reducing emissions by certain percentages by certain dates. …. We will also need to develop the revolutionary technologies to make these reductions happen. That means creating the kinds of technologies that do not simply refine current energy systems, but actually transform the way we produce and consume energy. When those technologies are developed, we will all exceed our targets.

The job of the science and engineering communities now is to develop strategic technology research programs capable of “transforming the way we produce and consume energy.”

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[1] Units of power and work used here are: 1 W (watt)= 1 J/s (joule per second); 1 EJ (exajoule) = 10^{18} J; 1 TW (terawatt) = 10^{12} W; 1 EJ/yr (exajoule per year) = 0.0317 TW (terawatts) = 278 TW-hr/yr (terawatt-hours per year). Watts and joules from burning chemical (i.e. fossil) and nuclear fuel are unsubscripted. However, we use "(e)" to denote work and power in electricity.

[2] This somewhat underestimates electric power needed, since space heating, for example, normally consumes as many electric as thermal watts because the energy is dissipated as heat.

[3] The present grid is primarily a "hub-and-spoke" system, with generation facilities and their attendant transmission and distribution systems originally built to serve local regions. These "hubs-and-spokes" have been partially brought together into three "interconnects," one serving the eastern two-thirds of the United States and Canada, one serving most of Texas and one serving most of the rest of the Canada and the United States.

[4] Electricity cost at busbar is the average cost of generation including capital investment amortization, operating costs, and fuel over the plant lifetime. Busbar costs do not include transmission and storage costs.

[5] For distributed solar and wind power, busbar costs may not provide the most useful comparison with conventional power sources because distributed solar and wind avoid transmission and distribution costs which must be added to busbar costs in the case of conventional power supply.

[6] Flywheels are not suited to long-term storage because momentum, on which they are based, is lost over time.

[7] When wind or sunshine were low, higher H_2 prices might temporarily reduce H_2 demand from vehicles. Later, when solar and wind electricity supplies returned to higher levels, accumulated demand for H_2 fuel could be met and H_2 prices could drop.

[8] A Renewable Portfolio Standard specifies that a certain amount of electricity must come from renewable energy. In some states, utilities may comply with an RPS through the use of renewable energy credits.

[9] A thermocline is a layer which separates regions of water that are of different temperatures within large bodies of water. Presently available technologies such as such as Ocean Thermal Energy Conversion (OTEC) take advantage of this temperature gradient to make electricity. See http://www.nrel.gov/otec/what.html.