VIEWPOINT

A Realizable Renewable Energy Future

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The ability of renewable resources to provide all of society's energy needs is shown by using the United States as an example. Various renewable systems are presented, and the issues of energy payback, carbon dioxide abatement, and energy storage are addressed. Pathways for renewable hydrogen generation are shown, and the implementation of hydrogen technologies into the energy infrastructure is presented. The question is asked, Should money and energy be spent on carbon dioxide sequestration, or should renewable resources be implemented instead.

Interest in renewable energy has depended on the perceived risks of using fossil fuels. During the energy crisis of the mid-1970s, the perceived risk of running out of conventional fossil fuels led to crash programs in developing renewable sources and energy conservation measures, including higher vehicle fuel economy and energy-efficient buildings and homes. These programs were scaled back as supply once again met demand. In the 1980s, the risks associated with pollution spurred work to avoid or remedy environmental damage from fossil fuel extraction, processing, and transport and led to measures to burn fossil fuels more cleanly (the catalytic converter is a product of this movement). The United States's dealings with these risks were akin to the analogy of a smoker who, having perceived the risk of heart disease, takes up running—but continues to smoke. More recently, the risks associated with CO_2 emissions and global warming have again spurred interest in renewable energy. However, we cannot continue to burn fossil fuels and somehow sequester the produced CO_2 efficiently enough to actually address global warming, as the processes of concentrating and burying or transforming the CO_2 are themselves energy intensive; as in the above analogy, there is no activity that can clean our lungs while we are still smoking. Although CO_2 sequestration, where it is generated near depleted gas fields and aquifers or used for tertiary recovery, can be done at low cost, building pipelines to transfer CO_2 to sequestration sites can quickly become an expensive endeavor. Pipeline costs can range from $1 million to $2 million per kilometer. The safety of CO_2 sequestration has also not been fully addressed. Should a CO_2 sequestration reservoir break and the CO_2 make it to the surface, it would effectively displace O_2, because CO_2 is heavier than air.

Thus, if global warming issues require us to quit our fossil fuel use, are there in fact practical renewable alternatives? More generally, is there a sustainable energy system that can supply a growing population with energy without destroying the environment within which it is used, providing energy for the present without compromising the ability of future generations to meet their needs (*1*)?

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Feasibility

The United States is the largest user of energy in the world (~50% of total consumption), and any change in global energy use would require a change in U.S. production and consumption of energy. Is it then actually feasible to supply all of the U.S. energy needs from renewable energy? The major renewable energy systems include photovoltaics (PVs) (or solar cells), solar thermal (electric and thermal), wind, biomass (plants and trees), hydroelectric, ocean, and geothermal (*2*). Solar cells, perhaps the most recognizable solar energy converters, directly convert the sun's energy to electricity with no moving parts, whereas solar thermal systems generate heat, and range from the simple solar hot-water heating system to the multimegawatt power plant outside of Barstow, California. Wind energy represents the nearest term cost-competitive renewable energy source. Produced by the heating of Earth, wind as an energy resource is possible over the entire United States and presents a dual-use technology: The land can still be used for farming, ranching, and forestry. Biomass power ranges from burning wood chips in power plants to burning biogas from waste treatment plants to the generation of methanol and ethanol, which can be used as fuels. The ocean is Earth's largest collector of solar energy, and ocean thermal platforms have a large potential for electricity generation.

Figure 1 shows the ability of PV technology alone to provide all of the energy needs of the United States. This calculation assumes a 10% solar-to-electrical system efficiency and the use of fixed flat-plate collectors; tracking to follow the sun would lower the area required. A square ~161 km (~100 miles) on a side would, during 1 year, produce the energy equivalent to that used annually in the entire United States (*3*). Although 25,921 km^2 (10,000 square miles) is a large area, it is less than one-quarter of the area that this country has covered with roads and streets. If wind is added to the energy mix, this area for PV is reduced (in fact, the United States also contains enough usable wind resources to produce all of the electricity used by the nation); if geothermal energy is added, the PV area is even smaller, and if hydroelectric energy is added, the area is again smaller. The point is clear—we can gather more than enough renewable energy to power our society.

More important than the area required to supply this amount of energy is the way in which the electricity is generated. If we look at solar irradiance data (how much sunshine is available per day), we see that the sun only shines in that area for an annual average of ~6 hours/day (*4*). One of the major drawbacks to many forms of renewable energy is their intermittency, which I will discuss in more detail below.

Paybacks and Costs

A persistent belief is that renewable resources require more energy in their manufacture than they produce in their lifetime; however, actual calculations show a very rapid payback. For example, the energy payback for current PV systems has been calculated to range from 3 to 4 years, depending on the type of PV panel (thin-film technology or multicrystalline silicon, respectively). This energy payback time includes the energy costs for processing the semiconductor and assembling a module, frame, and support structure (*5*–*8*) and is expected to be reduced to 1 to 2 years as manufacturing techniques improve. Wind energy has an even faster payback of 3 to 4 months (*9*). During their lifetime (30 years for PV and 20 years for wind), these technologies not only pay back the original energy investment, but also the emissions produced from their own manufacture.

The CO_2 savings from displacing fossil fuels with PVs depend on the regional fossil fuel mix and the solar irradiance; values range from 270 g of CO_2/kilowatt-hour (kWh) to $>$1050 g of CO_2/kWh. Other pollutants are avoided, including NO_x, SO_2, and particulates. With the average value of 662 g of CO_2/kWh and an average of 5.5 hours of sunlight per day, a 1-kWh PV panel would give a yearly CO_2 savings of 1330 kg. The

CO_2 payback time from avoided emissions also depends on the local energy mix and the panel efficiency. Assuming an energy cost for a crystalline silicon panel of 600 kWh/m^2 (*5*) and the average of 662 g of CO_2/kWh, the manufacture of a 1-m^2 panel produces ~400 kg of CO_2. If we assume 10% efficiency and a solar irradiance of 1 kW/m^2, it takes 10 m^2 of collector to produce 1 kW. Manufacturing 10-m^2 panels produces 4000 kg of CO_2, which is paid back in avoided emissions at 1330 kg/year for a total time of 3 years. Higher efficiencies lower both the energy and CO_2 payback time, as do manufacturing techniques that are more energy efficient. From this, one can easily envision a renewable energy breeder plant, a manufacturing plant that completely relies on renewable energy for the manufacture of additional renewable energy resources.

An Infrastructure Roadmap

Two pathways can lead to a renewable-based energy infrastructure while reducing CO_2 emissions and oil imports. One pathway focuses on the U.S. electricity-producing sector and the other on the U.S. transportation sector.

Any renewable energy system that produces electrons should be connected to the infrastructure to directly reduce the CO_2 emissions from current fossil fuel generation and to avoid construction of additional fossil fuel power plants. PV, of course, comes very close to matching the early afternoon peak in energy use. There is some debate as to how much intermittent power the infrastructure can accept, but even 10% would constitute a large amount of renewable energy.

Intermittency and H_2 Use

The missing links required for a sustainable energy system are an energy storage scheme (a way to store the renewable energy for times when it is not being generated) and an energy carrier (something to replace gasoline and other fossil-derived energy carriers). Energy storage technologies include H_2, batteries, flywheels, superconductivity, ultracapacitors, pumped hydro, and compressed gas. The most versatile energy storage system and the best energy carrier is H_2.

Hydrogen can replace fossil fuels as the energy carrier for transportation and electrical generation when renewable energy is not available. Because H_2 is transportable by gas pipelines or can be generated on site, any system that requires an energy carrier can use H_2. The conversion of the chemical energy of H_2 to electrical energy by a fuel cell (*10*) produces only water as waste.

Currently, H_2 is manufactured in large quantities from steam reforming of natural gas. However, H_2 can be generated by solar energy. Figure 2 shows a number of pathways by which solar energy can be used to generate H_2. Thermolysis, the direct splitting of water at high temperatures, suffers from the rapid back reaction of H_2 and O_2 at these temperatures, preventing this pathway from being a viable approach. Thermal cycles, in which O_2 and H_2 are generated in separate steps, are well known, and although these were initially developed to use the waste heat from a nuclear reactor, some have been adapted for solar concentrator systems. The conversion of biomass to H_2, although fairly straightforward, has a low conversion efficiency from sunlight to H_2, and any system designed to generate substantial amounts of H_2 must be rather large. Nonetheless, if the biomass used is a waste by-product, then this is perhaps the least expensive of the H_2 generation technologies. Wind energy and PV systems coupled to electrolyzers (*11*) are perhaps the most versatile of the approaches and are likely to be the major H_2 producers of the future. These systems are commercially available but are very expensive.

The photolysis systems combine the two separate steps of electrical generation and electrolysis into a single system. These direct conversion systems include photoelectrolysis and photobiological systems and are based on the fact that visible light has a sufficient amount of energy to split water (*12*).

Transportation

Fuel cell vehicles have the possibility of being highly efficient, reaching an equivalent fuel economy of over 42 kilometers/liter (100 miles/gallon), with performance and range equivalent to current vehicles (*13*). Additionally, when fueled with H_2 generated from renewable resources, these vehicles have no emissions. However, there is a catch—a H_2-fueling infrastructure does not exist. Manufacturers do not want to build a vehicle that cannot be easily refueled, and energy companies do not want to build an infrastructure that has limited or no use.

There appear to be two pathways to addressing these issues. The one currently receiving the greatest funding is a fuel cell vehicle that uses an on-board chemical process plant to reform (convert) gasoline or other liquid fuel to H_2. Miniaturizing reformers for small-scale intermittent operation appears to be unreliable, however. Although this approach would allow the continued use of the current energy infrastructure, it does not move us toward a necessary, more environmentally sound H_2 economy.

H_2 as the energy carrier is a much better approach. On-board H_2 would allow a vehicle to maximize the energy-efficient aspects of fuel cells and the environmental attributes of H_2. The near-term approach would be to build stationary reformers at current compressed natural gas filling stations. Because it would run continuously, putting the same small-scale reformer on the ground would spread the cost over a larger number of consumers and would minimize development costs (*14*). Initially, the H_2 would be used in

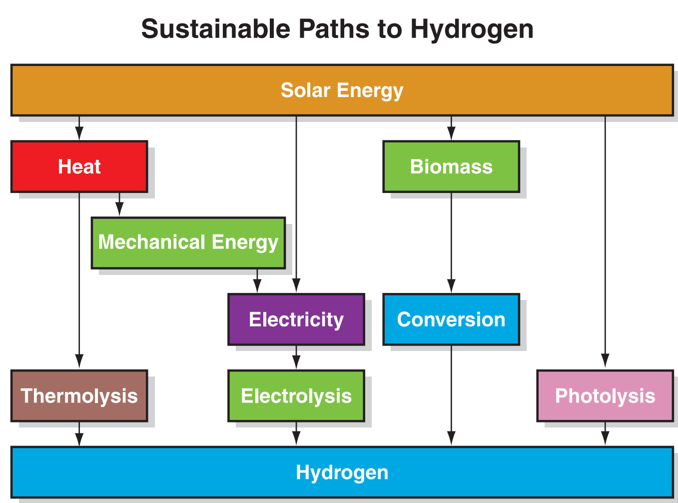

Fig. 1 (above). Calculated area required for a PV system to produce the entire U.S. yearly electrical needs. **Fig. 2 (right).** Sustainable pathways from solar energy to H_2.

modified internal combustion engines. Although not "pollution free," the exhaust from a H_2 internal combustion engine would be much cleaner than that from gasoline engines. This engine technology is already well developed, and the entire automotive industry would not have to retool to build these more environmentally sound vehicles. This approach minimizes the risk to the consumer and allows a H_2 infrastructure that deals with safety issues to be built simultaneously with the development of fuel cells. Markets that can afford the higher initial costs for new technologies would be used to develop commercial applications of fuel cells. These markets include buses, mining vehicles, buildings, and distributed and remote stand-alone power systems. Fuel cell vehicles would be available when the costs of fuel cells come down to an acceptable amount for automotive applications. Again, one can easily show that renewable energy can supply all of the H_2 necessary for cars (*15*).

Research and Development Issues

The key to the above infrastructure scenario is energy storage. Because the energy storage system is likely to be very dependent on the local environment, there needs to be a capability for matching the energy storage system with the energy generation system. Pumped hydro, for example, is perhaps the least expensive large-scale energy storage system but is very site specific. Hydrogen storage systems are particularly important. Hydrogen stored as compressed gas or as a hydride works well for stationary applications; however, H_2 storage for transportation is problematic because of its low volumetric density. Some automakers (for example, BMW and DaimlerChrysler) are looking at liquid H_2, but one must pay a heavy energy penalty to liquefy it. Advanced automotive concepts that reduce weight and resistance (*16*) are very important because they reduce the amount of fuel necessary. Nonetheless, research is necessary on the development of compressed gas tanks made of lightweight advanced composites and on new H_2 absorbents such as carbon nanotubes.

For the PV industry, increasing module efficiency to 15% is critical, especially for thin-film technologies that are less expensive to manufacture. For the crystalline solar cell industry, refining plants must be built to produce solar-grade silicon. Currently, the crystalline silicon industry uses microelectronic silicon scrap as feedstock. That feedstock will soon be exhausted as demand increases and the microelectronics industry becomes better at recycling their scrap. Inexpensive systems that concentrate sunlight could minimize the costs and manufacturing demands of PV material and greatly increase our capability of producing electricity from PVs (*17*).

Two key components of this scenario that require additional research and development are fuel cells and electrolyzers, key components in the load-leveling scheme of renewable energy (electrolysis and H_2 storage) fuel cells. These electrochemical systems have been studied for over a century and yet have some distance to go before they can be brought into the energy infrastructure mainstream. The cost of electrolyzers and fuel cells will be critical. Electrolyzers currently cost about \$3000/kW, and for large-scale use, they should be less than \$200/kW. Fuel cells are even more expensive, and for automotive applications, they need to be less than \$50/kW.

Conclusion

The question for our time is whether governments should subsidize building, manufacturing, and implementing renewable energy technologies, or should governments instead develop and build CO_2 sequestration technologies. By developing and implementing renewable energy technologies and manufacturing capabilities, we would build a sustainable energy infrastructure to carry us well into the next millennium. We should embark upon this path with all due speed.

References and Notes

1. World's Commission on Environment and Development, *Our Common Future* (*The Bruntland Report*) (Oxford Univ. Press, New York, 1987).
2. More details on renewable energy systems are available from the National Renewable Energy Laboratory (NREL) at http://www.nrel.gov/ceb.html
3. For an estimate of the land area needed for PV panels, the following information is necessary (R. L. Hulstrom, personal communication). Flat-plate PV collector modules are typically placed so that they cover one-half of the available land; 1 m^2 of PV panels requires 2 m^2 of available land. In 1997, the total U.S. annual electricity demand was $\sim 3.2 \times 10^{12}$ kWh [Energy Information Administration, *Report No. DOE/EIA-0383(99)* (U.S. Department of Energy, Washington, DC, 1999)]. The average solar resource per year for southwest Nevada is 2300 kWh/m^2. If we assume 10% net plant efficiency (current technology), then solar resources per year would provide 230 kWh/m^2. Therefore, the total area needed is $(3.2 \times 10^{12}$ kWh/year)/(230 kWh/m^2 per year) $= 1.39 \times 10^{10}$ m^2 of collector area, which requires 2.78×10^{10} m^2 ($\sim$10,900 square miles) of land area. A system efficiency of 15% would reduce the area to 1.9×10^{10} m^2 (7200 square miles). Although we have used Nevada for this calculation, PV panels can be placed across the entire United States. The U.S. average solar irradiance per year is 1800 kWh/m^2. Implementation would involve 1.6- to 16-km^2 (1– to 10–square mile) "energy farms," along with the rooftops of homes and businesses and over parking lots.
4. For solar radiation data and wind resources, see http://rredc.nrel.gov/solar/ and http://rredc.nrel.gov/wind/, respectively.
5. E. Alsema, *Report BNL-52557* (Brookhaven National Laboratory, Upton, NY, 1998).
6. K. Kato, A. Murata, K. Sakuta, *Report No. 97072* (Utrecht University, Utrecht, Netherlands, 1977), appendix B-8.
7. R. Dones and R. Frischknecht, *ibid.*, appendix B-9.
8. W. Palz and H. Zibetta, *Int. J. Sol. Energy* **10**, 211 (1991).
9. See P. Gipe, *Wind Energy Wkly. No. 521* (1992) (available at http://www.awea.org/faq/bal.html) and S. Krohn, Ed., *Wind Power Note 16* (Danish Wind Turbine Manufacturers Association, Copenhagen, 5 December 1997) (available at http://www.windpower.dk/publ/enbal.pdf).
10. A fuel cell is a device that takes chemical energy and, without combustion, directly converts the fuel to electricity (see http://education.lanl.gov/resources/fuelcells). High-efficiency fuel cell technologies are well known; perhaps the best known current application is the use of fuel cells to power the space shuttle.
11. An electrolyzer is a device that uses electricity to break water into H_2 and O_2. Although commercial electrolyzers are very expensive and primarily used in industry to produce high-purity H_2, companies are working to bring the costs down and to develop small inexpensive systems that are suitable for individual use.
12. The thermodynamic potential for splitting water into H_2 and O_2 at 25°C is 1.23 V. Adding overvoltage losses and some energy to drive the reaction at a reasonable rate, one comes to a voltage of $\sim$1.6 to 1.8 V for water decomposition. In fact, current commercial electrolyzers operate between 1.7 and 1.9 V. Translating an energy of 1.9 eV into a corresponding wavelength of light, one comes to 650 nm, which is in the lower energy red portion of the visible spectra. This means that the entire visible spectrum of light has sufficient energy to split water into H_2 and O_2. The key for these direct conversion systems is to find a light-harvesting system and a catalyst that can efficiently collect the energy and immediately direct it toward the water-splitting reaction. [See O. Khaselev and J. A. Turner, *Science* **280**, 425 (1998).]
13. J. Ogden, T. Kreutz, M. Steinbugler, *Technical Paper No. 982500* (Society of Automotive Engineers, Warrendale, PA, 1998).
14. In a car, an on-board reformer would operate at its designed peak power <1% of the time, and each individual vehicle owner would bear the full cost of the reformer (and the risks associated with its operation). Yet, if you took that same on-board reformer off the car, set it up on the curb, and run it continuously, it could supply 110 vehicles/day. Increasing the size of the reformer so it could service 1000 vehicles/day further decreases the individual cost per vehicle. [See C. E. Thomas, B. D. James, F. D. Lomax Jr., I. F. Kuhn Jr., *Report No. NREL/CP-570-25315* (NREL, Golden, CO, 1998) (available at www.erem.doe.gov/hydrogen/pdfs/25315o.pdf).]
15. For an estimate of the land area needed for H_2 production for transportation by PV electrolysis, the following information is needed [J. Odgen, *Report No. NREL/CP-470-5777* (NREL, Golden, CO, 1993).] We will assume an advanced fuel cell–powered car using pure H_2, with an equivalent fuel economy of 45 km/liter (106 miles/gallon), driven an average of 17,699 km/year (11,000 miles/year). That car will consume 13.7 GJ of H_2/year. If the entire U.S. fleet of $\sim$200,000,000 cars was made up of fuel cell–powered cars, it would require 2.74×10^9 GJ of H_2/year. There is a solar resource in Nevada of 2300 kWh/m^2 per year (*4*). Again assuming a system (solar-to-electrical) efficiency of 10%, an electrolysis efficiency of 77% (lower heating valve and an electrolysis voltage of 1.6 V), and a coupling efficiency between the PV system and the electrolyzers of 93%, we can produce 2300 kWh/m^2 per year $\times$ 0.1 $\times$ 0.93 $\times$ 0.77 = 165 kWh/m^2 per year of H_2. For a conversion of kilowatt-hours of H_2 to gigajoules of H_2, 165 kWh/m^2 per year = 0.589 GJ/m^2 per year. Therefore, the collector area needed is $(2.74 \times 10^9$ GJ of H_2/year)/(0.589 GJ/m^2 per year) $= 4.65 \times 10^9$ m^2 of collector area, which requires 9.3×10^9 m^2 ($\sim$3600 square miles) of land area.
16. For an example of advanced automotive concepts, see http://www.hypercar.com
17. If we take a PV manufacturing plant that is producing 10 MW of PV/year and add an inexpensive optical concentrator capable of 1000× concentration, that plant would produce the equivalent of 10,000 MW of PV/year.