

ENERGY

A Road Map to U.S. Decarbonization

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Today, 85% of the United States' energy mix comes from carbon-rich fossil fuels: oil, natural gas, and coal (1). With demand increasing worldwide, existing oil reserves could peak within 20 years (2), followed by natural gas and coal. Growing fuel use is increasing CO₂ and CH₄ emissions and the risk of global warming. The United States has responded by sponsoring research into alternative energy (3). However, because research success is not predictable, an effective plan must be based on proven technologies. We propose to switch our economy slowly (over 30 to 50 or more years) to nonfossil energy sources by using proven technologies and available, expandable distribution systems.

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Available Methods

Because all available energy technologies have limitations (see table, above right), a comprehensive plan should include several options:

1. Concentrated solar thermal (CST) energy with storage, a proven technology for electricity generation (4), can provide variable energy, to compensate for fluctuations in demand, for a large fraction of U.S. energy needs.

2. Nuclear energy. New and safer designs, not yet built on a commercial scale, merit construction. The implementation of a large nuclear capacity [1000 gigawatts (GW)] requires study regarding the long-range availability of nuclear fuel and the disposal of accumulated waste. Present nuclear plants are used for base power, only 40% of our electricity needs.

3. Geothermal and hydroelectric plants. However, their total output is limited.

4. Wind. The amount of uncontrollable electricity the grid can accept from this highly variable source is limited.

5. Solar cells. Sunlight is available for only part of the day. Like wind power generators, solar cells lack storage capacity. However, unlike CST, solar cells can be widely distributed.

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Potential for fossil fuel replacement and CO ₂ reduction		
Fossil fuel use	Fossil fuel replaced (%)	CO ₂ emissions reduction (%)
Replaced by electricity from alternative sources		
All coal for electricity	25	33
All natural gas and petroleum for electricity	7	6
All fossil fuels for residential and commercial	13	11
65% of petroleum for transportation	20	21
70% of natural gas used in industry	7	5
Replaced by syngas processes from biomass		
All petroleum + 30% of natural gas used in industry	14	9
35% of petroleum for transportation	12	12
Total	98	97
[Source (4)]		

6. Biomass. The only renewable source of industrial petrochemical feedstocks and fuels for trucks and aviation that cannot be provided by electricity is biomass, but only a limited amount can be grown. Proven technologies for generating syngas by combining carbon oxides (from partial oxidation of biomass) with H₂ (from electrolysis) can currently generate three to four times the product yield obtainable by fermentation (5).

A discussion of decarbonization should also include CO₂ sequestration, a technology available only for new coal power plants (6). This technology depletes valuable fossil fuel resources and is more expensive than CST and nuclear (4). It is doubtful that it will play a major role in the near to midterm future.

Alternative Energy Sources

The magnitude of our energy problem is illustrated in the figure (below); our plan is outlined in the table on page 1244. Electricity from alternative sources could replace all fossil fuel power plants and all residential and commercial uses with available technology and distribution systems, as well as 70% of the natural gas used for industrial furnaces, steam generation, and H₂ production (1, 7).

Of the gasoline used for private cars and light trucks, 80% can be replaced by hybrid cars with plug-in batteries (8), the cheapest way to reduce oil consumption. Railroads driven by electricity could probably assume 50 to 60% of long-distance hauling. Therefore, 72% of the cur-

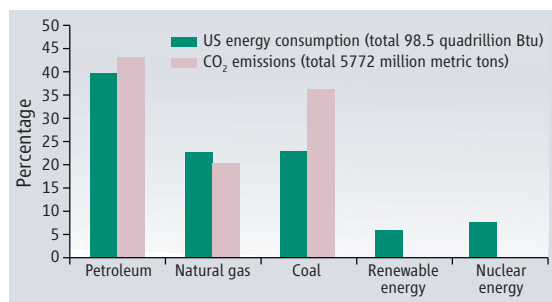
Alternative energy sources could replace 70% of fossil fuels in America within 30 years at a cost of \$200 billion per year.

rent use of fossil fuels can be replaced by electricity from alternative sources and 26% by combined biomass and H₂, whereas 2% cannot be replaced at all.

Concentrated Solar Thermal Energy

CST technology utilizes solar collectors that concentrate solar rays on a heat-transfer fluid able to sustain high temperatures (>800°F) (4) and raise steam for driving turbines. This technology has been demonstrated in a 354-MW modular plant running in the Mojave Desert for the past 20 years (4). On rainy days, the steam power plant consumes fossil fuel, but it could use fuels made from biomass and H₂.

For CST, the collectors and storage (90% of the investment) are comparable to the fuel plant for a conventional steam power plant (10% of the investment). By doubling the capacity of the steam power plant, a solar plant designed for 1-kW capacity or 24 kWh/day continuous production (base load) can supply 2 kWh for 12 hours with only a 10% incremental investment or 4 kWh for 6 hours with a 30% incremental investment, by quadrupling the capacity of the steam plant. For coal or nuclear plants, the increase in investment is 100 and 300%, respectively. Investment and electricity costs for CST are given in the table (page 1244) and compared with costs for nuclear and various versions of coal power (6, 9,



U.S. energy sources and CO₂ consumption in 2003. U.S. energy consumption (total, 98.5 quadrillion Btu) (white bars) and CO₂ consumption (total 5772 million metric tons) (black bars). [Source (1)]

Electricity costs for solar thermal compared with conventional energy sources

	Investment (\$/kW installed)	Cost (cents/kWh)		
		Base	Intermediate	Load following
Solar thermal: near term (10)	4000*	8.0†	8.0	10.4‡
Solar thermal: future (10)	3220	6.2†	6.2	8.6‡
Conventional coal power plant (with scrubbers) (6)	1200	4.5§	8.0	13.5
Clean coal (6)	1550	5.6§	10	Cannot supply it
Clean coal (6) (with CO ₂ sequestration)	2000	10–11	14–15	Cannot supply it
Nuclear (9)	2200	6.0§	10–11	Cannot supply it

[Source (4)] *Explanation of estimate (4). †Operated 4900 hours/year. ‡A power plant designed to supply, for each kW installed, 12 kWh/day of variable electricity at instantaneous maximum rate of 4 kWh. §Operated 6500 hours/year. ||Designed for the same load-following capability as in †.

10). CST is not competitive yet with nuclear or coal for continuous production (base load). However, it is more flexible in adjusting to changing needs, potentially switching off in periods of low demand, such as at night (intermediate load). Power can be produced according to demand almost instantaneously (load following), which makes it cheaper than other sources of power. CST is cheaper than new coal power plants with CO₂ sequestration, even for base power.

CST load-following capabilities enable it to be the anchor of an alternative energy grid that can compensate for the variable output of wind and solar cells. An area of the desert Southwest of 15,000 square miles is sufficient to supply 50% of our total present energy requirements (2). The transmission lines of the national grid would have to be 100% larger at a cost of about \$250 billion to \$300 billion (11). The cost of the local distribution lines, independent of the location of the power plants, would add another \$850 billion to \$1000 billion (11). The nationwide power losses in transmission and distribution, with present technology, are less than 7% (1).

Role of Biomass and H₂

Of the fossil fuels we currently use, 28% cannot be replaced by electricity but can be replaced by hydrocarbons produced from biomass in combination with H₂. Efforts now focus on ethanol, but we prefer biomass from less-energy-intensive agriculture such as fast-growing trees, grass, and agricultural waste. Biomass is used to generate syngas to produce methanol or liquid hydrocarbons (12, 13). Available technologies can produce any fuel or petrochemical from these two ingredients. The syngas for these two processes can be made from H₂ and CO or CO₂. H₂ can be generated on location by electrolysis using alternative electricity (14), and the O₂ coproduced can be used to partially oxidize the biomass. This method produces three to four times as many hydro-

carbons as by fermentation to ethanol (5), which is an advantage as there are limits to the amount of biomass that can be grown. In our plan, biomass is converted on location in small plants, and the methanol produced is transported to a biorefinery or to existing petrochemical plants. Further investigation is needed to determine how much biomass can be produced and the optimal technologies for its utilization.

H₂ is not available in nature; energy is required to generate it. Were we to generate sufficient H₂ from natural gas to fuel our cars, we would double our natural gas consumption. To produce H₂ from alternative sources (by electrolysis) is an expensive process. As the direct use of electricity is cheaper by a factor of 3, our plan minimizes the use of H₂ to uses for which electricity cannot be substituted. We eliminate the problems of safety and transportation (14) by generating H₂ on location and converting it on site in a controlled industrial environment to conventional hydrocarbons.

Conclusions

Except for H₂, all the technologies we consider could become competitive with crude oil at \$70 per barrel. Our main objective, however, should be to implement the best technology for eliminating dependency on fossil fuels rather than to compete with coal or cheap oil. Investment in demonstration plants and in large-scale implementations will be required.

Approximate cost estimates (4, 7) to replace 70% of our fossil fuel use (including most coal) are about \$170 to \$200 billion per year over 30 years. At current levels of CO₂ emission, a tax of \$45 to \$50 per ton of CO₂ would pay for the whole investment and provide incentives for implementing renewable technologies (5).

We must start now, as our country does not have the resources to complete this switch within a few years. The United States must create long-range incentives (such as a CO₂ tax or tax credits) large enough to

induce companies and utilities to implement proven technologies and to provide the required infrastructure. A successful U.S. program can set an example for the rest of the world, as many of the key technologies are well suited to developing countries. Once the technologies are established on a large scale and are mass-produced, these costs should go down by a factor of 2, making them competitive and reducing the need for subsidies. The required increase in the electric distribution system poses problems, such as obtaining rights of way for new distribution lines, that only the federal government can handle. There are political hurdles, but we believe they can be overcome.

References and Notes

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Supporting Online Material

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