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Decarbonization: Achieving near-total energy independence and near-total elimination of greenhouse emissions with available technologies

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Abstract

This paper presents a comprehensive plan for conversion, over a 30–50 year period, to available and affordable technological options that can accomplish the replacement of 98% of US fossil fuel needs and the reduction of 97% of present US CO_2 emissions.

Keywords: Decarbonization; Energy; Greenhouse gases

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1. Introduction

Today, 85% of the energy used in the US comes from carbon-rich fossil fuels: oil, natural gas, and coal [1]. But demand throughout the world is increasing, and there is little doubt that proven reserves of oil will peak sometime in the next 20 years [2]. Eventually, natural gas and coal will also peak. It is not surprising that many leaders in government and technology are calling for replacement of these fossil fuels with alternative energy sources—a process often referred to as decarbonization. Additional motivation for decarbonization of the US energy mix is the danger of global warming, which most scientists now attribute, at least in part, to CO_2 emissions that accompany the use of fossil fuels. To be feasible and affordable, any switch to alternative energy has to be accomplished over a long period, at least 30–50 years. Thus it is urgent that a blueprint and timetable be developed for achieving this goal.

In this paper, we present a plan for the gradual replacement of 98% of total US fossil fuel needs using available and affordable technology, which would also reduce 97% of present total CO_2 emissions. We will show that the direct use of electricity produced from alternative sources can replace 72% of the fossil fuels being consumed. Another 26% can be replaced by hydrocarbons produced from syngas, a mixture of carbon oxides produced by gasifying biomass and hydrogen generated by electrolysis powered by alternative energy sources. Seventy percent of this goal could be achieved over 30 years, and 90% over about 50 years.

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A complementary short-term approach to the problem could be to improve the efficiency of energy use. Thus, for example, gasoline powered vehicles could easily reduce their gasoline consumption by 30–40%. The practical elimination of the CAFÉ laws by the Congress, allowing SUVs and not enforcing the fleet average restriction on fuel economy, increased gasoline consumption undoing all the progress made in this area. Reintroducing them in a tougher form would easily save 30–40% of gasoline consumption, equivalent to 3–4 million barrels of crude oil per day. This can be done without introducing any new technology or alternative fuels as outlined in this paper.

We have limited the scope of this paper to a discussion of technological options. A truly comprehensive plan would also focus on other critical problems, such as priorities and costs, political and economic constraints, regulatory issues, and government-mandated incentives without which the free market is not likely to reduce CO_2 emissions or prepare for a distant, uncertain future. For society, however, the penalty of strongly reduced oil and gas supplies would be catastrophic, unless we prepare in advance for substantial reductions taking place over a long-time period. While research could and should lead to better technologies, and should be continued, we can never be sure which research will lead to useful results. Any effective plan for solving our energy problems over a short timeframe needs to be based on proven, existing technologies. During the Apollo Space Program, President Kennedy expressed this clearly: ‘‘It is too late for research. We will have to do with what we have.’’ In 1970s, a worldwide research effort to produce H_2 from nuclear reactors by thermochemical cycles was terminated with no results after spending approximately $40 billion (2005 dollars) [3]. A further constraint on any such a plan is that new technology should allow for gradual phase-in and preferably should use available distribution systems, which suggests wide use of electricity from alternative sources.

It is encouraging that proven technologies for decarbonizing our energy mix using existing distribution systems already exist. The approach described in this paper is in large part based on electricity from alternative sources, with the prime candidate being concentrating solar power (CSP) with storage. Plants with a total of 354 MWe installed capacity have been operating in California since the late 1980s [4]. This technology has been overlooked until now despite the fact that it probably has a larger potential than all other options. Our paper will compare its capabilities and costs with other available options.

Before costs are considered, however, it must be acknowledged that technologies that achieve decarbonization by replacing power plants and other existing uses of fossil fuels cannot be competitive in the free market without some form of government incentive or subsidy. The only times when this is possible without incentives are when the equipment becomes obsolete, or the technology is no longer competitive, or the fossil fuels costs become too expensive. We will show, however, that for new installations, with specific applications, a variety of alternative technologies are already competitive. Of these, CSP has applications on the broadest scale.

It appears that the free market is unfortunately moving the US towards tolerance for increased CO_2 emissions. Natural gas, hydrogen, and ammonia plants in the US vent about 100 million tons of already separated CO_2 a year into the air [5]. According to Holt [6], an investment of $4.6 billion would be required to separate 100 million tons of CO_2 a year in coal power plants. In recent years, a large fraction of the natural gas-fired, combined-cycle power plants for generating base power have been shut down due to high gas prices and being replaced by conventional coal-fed power plants. Also, petroleum feedstocks are becoming heavier, thus increasing CO_2 emissions per energy generated. It is urgent that we achieve decarbonization by promoting specific applications for proven technologies that are economically attractive. We have shown elsewhere that some large applications of CSP are already economically competitive [7,27].

2. Available methods for decarbonizing energy consumption

Today, only three options are available to help reduce the consumption of fossil fuels:

(1) reduce total energy demands;
(2) switch to alternative energy sources;
(3) convert coal feed to H_2 (if our only aim is to reduce CO_2 emissions) and sequestering the CO_2 simultaneously.

However, all available technologies for alternative energy have limitations, therefore a comprehensive plan should not be based on a single option. Following is a more detailed discussion of the available options for alternative energy.

2.1. Concentrating solar power (CSP)

CSP with storage is a proven technology that is ready for implementation [7]. We will show that it can supply most of the energy needs of the US that can be satisfied by electricity. CSP is already competitive with most technologies currently in use for intermediate loads, which constitute 50% of the country's electricity needs. Furthermore, this technology can be designed to generate large amounts of instantaneously dispatchable, variable electricity to compensate for fluctuations in demand (presently 10% of our electricity needs). In the future, CSP could also be used to compensate for variable inputs from other alternative energy sources, such as wind and solar cells.

2.2. Nuclear energy

New, safer designs have been developed, but they are unproven, as none have yet been built on a commercial scale. To become the major alternative energy source, 1000 GWe nuclear energy plants would have to be built. Implementation of this large nuclear capacity would require further study as to the long-range availability of nuclear fuel and the disposal of accumulated waste on a global scale. As other countries may follow our lead, nuclear energy capacity must be expanded with caution because of the danger of nuclear weapons proliferation.

2.3. Hydroelectric power

This is an excellent energy source with a little environmental impact. Although hydropower has limited total output, its contribution could be increased if the restrictions sought or imposed by some animal protection groups were eased. While it is regrettable, we may come to a point where we have to decide that the protection of some animal species is less important than the survival of our civilization.

2.4. Geothermal energy

Similar to hydropower, geothermal is an excellent energy source with little environmental impact. Studies are presently in progress to determine the potential contributions of geothermal energy to a non-fossil energy mix and its related costs [8].

2.5. Wind energy

Wind is already a competitive energy source that is growing steadily. Its limitation is that the availability and speed of wind can vary greatly, but the amount of variable energy input that the electricity grid can accept—without compensating for the fluctuations—is limited, therefore wind energy requires a backup. CSP could provide the compensation and stabilization that a large-scale use of wind energy would require.

2.6. Solar cells

At present, solar cells are too expensive for large-scale implementation, but this should change with further research. Solar cells, like wind, lack affordable storage. Also, unlike wind, sunlight is only available for part of the day, making photovoltaic energy even more variable than wind energy. On the bright side, solar cells can be placed throughout the country, while CSP is limited to desert areas. If solar cells could be produced cheaply, they could become part of an advanced grid, stabilized by CSP plants with large storage capacity. Until further research leads to the removal of these limitations, their total contribution will be limited.

2.7. Biomass

Biomass is the only alternative energy source that can create liquid fuels for aviation and trucks, and petrochemical feedstocks for industry. But, as the amount of biomass that can be grown is limited, biomass will not be able to provide more than about 10% of the total energy presently used. However, by gasifying biomass and combining it with H_2 produced from alternative energy sources to form syngas, three to four times the product yield obtainable by fermentation could be generated (see the Appendix). The products obtained could supply the many types of hydrocarbons that cannot be replaced by electricity.

Many discussions on decarbonization also include CO_2 sequestration, a technology only available for new coal power plants [6]. Strictly speaking, however, this technology does not contribute to the decarbonization of our energy mix, as it still depletes valuable fossil fuel resources. Furthermore, as we will show later, CO_2 sequestration is more expensive than CSP and nuclear energy. It is, therefore, doubtful that it will play a major role in the near- to mid-term future.

3. Decarbonization using electricity from alternative energy sources

Before we can estimate the full potential impact of CSP on the decarbonization of the US energy mix, we must first determine the fraction of our fossil fuel use that can be replaced by electricity generated from alternative sources currently available. Table 1 and Fig. 1 summarize total US energy consumption and provide a detailed breakdown of the current use of fossil fuels [1]. CO_2 emissions caused by the various uses of fossil fuels are shown in Table 2 and Fig. 2 [1].

From Table 1 we note that coal-fired power plants contribute to 24% of total fossil fuels consumption (which cause 33% of total CO_2 emissions, Table 2). Power plants using natural gas and oil represent 8% of total fossil fuels use (7% of total CO_2 emissions, Table 2). All these power plants fueled by fossil fuels could be replaced by electricity from alternative sources.

As natural gas and oil emit much less CO_2 per kWh, the most cost-efficient way to reduce CO_2 would be to replace all existing coal-powered plants by building 300 GWe of alternative energy power plants [1], such as CSP plants with storage or coal power plants with CO_2 sequestration. Present plans for CO_2 sequestration are based on building new power plants as well as pipelines for the final disposal of the CO_2. We will show that CSP plants with storage cost less to build per kW capacity than coal-fired plants with CO_2 sequestration. Nevertheless, both technologies should be considered for the significant potential advantages of each. On the other hand, because replacing all power plants is very expensive, if the only goal is CO_2 sequestration, CO_2 scrubbers for existing power plants merit a second look. Replacing electricity generated from oil and gas would require another 120 GWe of electricity from alternative sources [1].

Other uses for fossil fuels that are relatively easy to replace with electricity include all residential and commercial non-electric energy use, 12% of the total use for fossil fuels (Table 1), which generate 10% of all CO_2 emissions (Table 2). The distribution system and technology needed to implement this changeover are

Table 1
US energy consumption by sector and source (quadrillion Btu, 2005)

	Residential	Commercial	Industrial	Transportation	Electricity	Total
Petroleum[a]	1.450	0.723	9.706	27.280	1.235	40.394
Natural Gas[a]	4.930	3.182	8.064	0.625	6.015	22.816
Coal[a]	0.008	0.086	1.954	0	20.737	22.785
Renewable energy	0.487	0.119	1.885	0.345	3.568	6.475
Nuclear energy	0	0	0	0	8.160	8.160
Total						100.630

Source: [1].

[a] Total fossil fuels consumption = 85.995

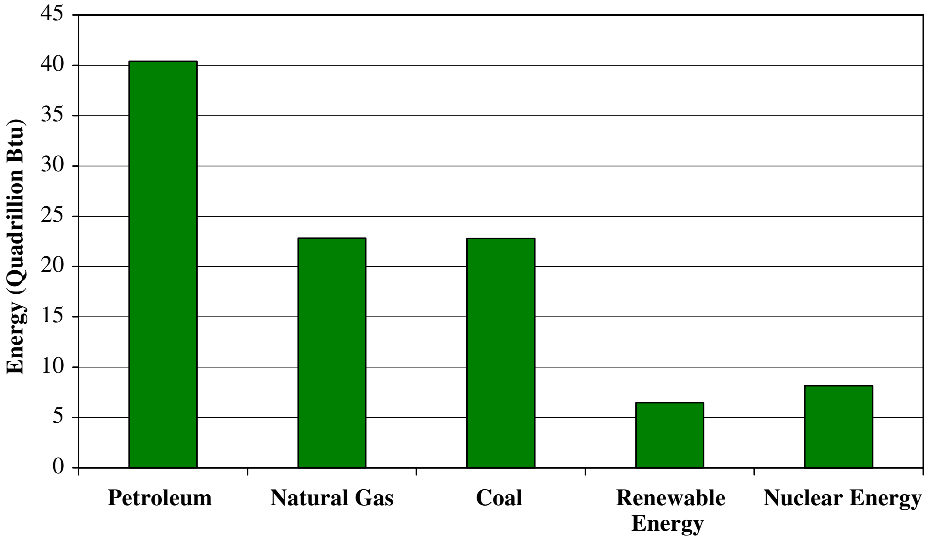

Fig. 1. US energy consumption by source (2005). *Source*: [1].

Table 2
US CO_2 emissions by sector and source (million metric tons, 2005)

	Residential	Commercial	Industrial	Transportation	Electricity	Total	Total (%)
Petroleum	105	55	431	1922	100	2613	44.1
Natural gas	262	166	400	32	319	1179	19.9
Coal	1	8	185	0	1944	2138	36.0
Total						5930	100

Source: [1].

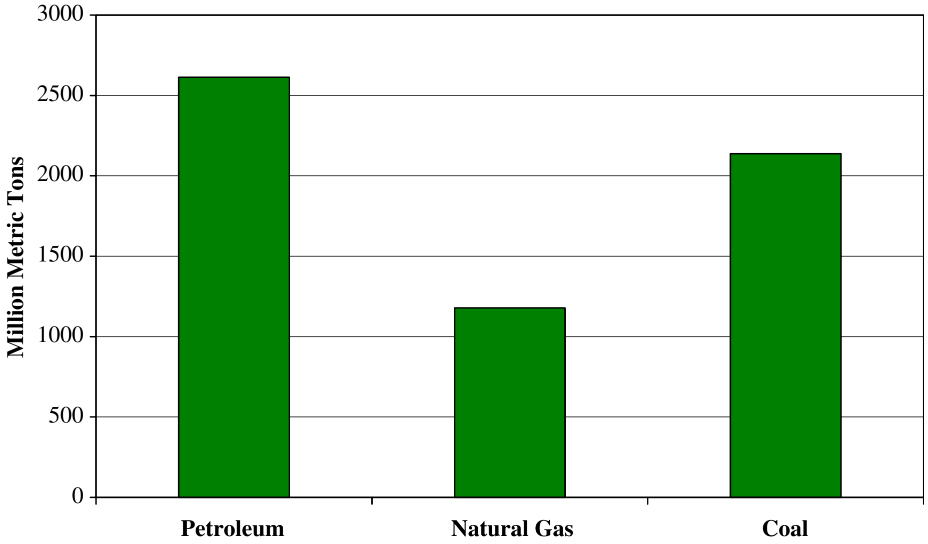

Fig. 2. US CO_2 emissions by sources (2005). *Source* [1].

already available. Furthermore, for these applications, direct use of electricity can meet most needs much more efficiently than using fossil fuels. For example, in many situations heat pumps are more efficient than conventional heating systems.

Petroleum constitutes 40% of our energy mix [1]. The petroleum we use for commercial, residential, and power generation (8% of total petroleum, already counted above) would be easy to replace by using electricity obtained from alternative energy sources (Table 1).

The primary use of petroleum (almost 70%) is for transportation (Table 1), and a large part of this petroleum could be shifted to alternative fuels. Specifically, 80% of the gasoline presently used for private cars and light trucks (about 60% of oil used for transportation [9]), can be replaced by hybrid cars with plug-in batteries. Using electricity instead of gasoline is probably the cheapest and most politically attractive way to reduce oil consumption and is comparable today with $40 per barrel for crude oil. In addition, railroads powered by electricity could take on much of the hauling now handled by heavy trucks, which would probably shift 60% of the oil used for big trucks (29% of oil used for transportation [9]), but exact figures require more studies to evaluate the costs involved. Both contributions could save 21% of total fossil fuels (Table 1), which is 44% of total US petroleum consumption, or 65% of the oil used for transportation [7].

Shifting the heavy use of transportation fossil fuels to electricity would be an attractive solution that would be easier to achieve than replacing coal power plants. Unlike coal power plants, which last about 50 years, cars are replaced much more frequently. Second, our dependence on imported fossil fuels would be reduced substantially (petroleum accounts for almost 90% of our energy import [1]). Reducing oil consumption has attracted much wider support than CO_2 reduction because dependence on imported oil and its erratic price fluctuations have strongly negative political and economic implications. Furthermore, fossil-fuels resources are being depleted at a growing rate worldwide, and it would be wise to prepare for a non-fossil energy mix before peaking occurs. Replacing 65% of the petroleum used for transportation with electricity from alternative sources would also decrease CO_2 emissions by 21% (Table 2).

Regarding the use of natural gas, all residential, commercial, and power generation uses can be replaced by electricity generated from alternative sources. Industry uses 35% of natural gas (10% of total fossil fuels used), but we have no breakdown of specific uses. Based on Shinnar's experience, at least 70% is used for internal power and steam generation, furnaces (such as in distillation), and H_2 production. All these uses (7% of total fossil fuels, which generates 5% CO_2 emissions) could be switched to electricity that comes from alternative sources. The only use that is not switchable is for chemical feedstocks, approximately 30% of industrial gas use or 3% of total fossil fuels.

Finally, direct industrial use of coal, 2% of total fossil fuels, cannot be switched at all.

In summary, using existing technologies it is feasible to replace 72% of present fossil fuel usage by substituting electricity from alternative sources (Table 3, and Fig. 3). This shift would also reduce CO_2

Table 3
Potential for fossil fuels replacement and CO_2 reduction by electricity from alternative sources

Fossil fuel use	Fossil fuel replaced (%)	CO_2 emissions reduction (%)
(a) *Potential for fossil fuels replacement and CO_2 reduction by electricity from alternative sources*		
All coal for electricity	24	33
All natural gas and petroleum for electricity	8	7
All natural gas + coal + petroleum for residential and commercial	12	10
Sixty-five percent of petroleum used in transportation	21	21
Seventy percent of industrial natural gas (used for power and steam generation, furnaces and H_2 production)	7	5
Total	72	76
(b) *Potential for fossil fuels replacement and CO_2 reduction by syngas processes*		
All petroleum in industry	11	7
Thirty-five percent of petroleum used in transportation	11	11
Thirty percent of industrial natural gas (used for chemical feedstocks)	3	2
All natural gas used in transportation	1	1
Total	26	21

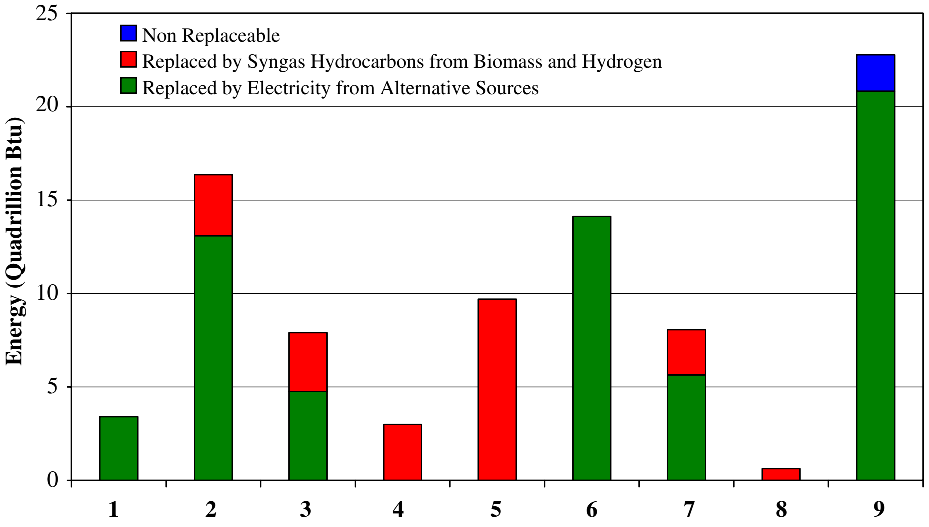

Fig. 3. Potential replacement of the US fossil fuels by alternative energy. Key: (1) Petroleum used in Residential + Commercial + Power Generation; (2) Gasoline; (3) Diesel; (4) Jet Fuel; (5) Petroleum used in Industry; (6) Natural Gas used in Residential + Commercial + Power Generation; (7) Natural Gas used in Industry; (8) Natural Gas used in Transportation; (9) Coal.

emissions by 76% (Table 3). In Section 6, we discuss how to replace another 26% (2% of coal used in industry is not replaceable), also shown in Fig. 3.

4. Concentrating solar power with storage

A more detailed technical discussion of CSP with storage can be found in another recent paper by Shinnar and Citro [7]. However, our main objective here is to assess the potential of CSP technology for decarbonizing the US energy mix, so only the relevant points of the previous work will be summarized here.

CSP technology utilizes solar collectors of the parabolic-trough type to concentrate solar rays on receiver tubes positioned on the focal line of the reflectors (Fig. 4). The heat is absorbed by the receiver tubes and transferred to a fluid that flows within the receiver tubes and is able to reach and sustain extremely high temperatures (>800 °F) [7]. The heat collected in the hot fluid can then be used directly to generate steam to drive turbines in electricity-generating plants. Alternatively, the hot fluid (and its energy content) can be stored as sensible heat in large underground ponds. Later, the stored energy can be fed to the steam power plant instantaneously to meet variable electricity needs. This technology has been amply demonstrated in a 354 MWe modular plant (consisting of nine CSP units), which has been running in the Mojave Desert since the late 1980s (Appendix A in [7]).

CSP has been evaluated in two reports prepared by the National Research Council (NRC) [10,11], both of which conclude that CSP is unlikely to become competitive with conventional coal power. While this conclusion may be correct, the reports missed two important points:

- CSP with storage is the only alternative energy source (other than nuclear energy) that can supply all the nation's energy needs [7]. All other alternative energies have severe inherent limitations.
- Given the capital costs projected currently, CSP may not be competitive with coal or nuclear energy for base power [7]. However, as explained in Section 5, it can become competitive with all other conventional sources because of its capacity for storing heat [7]. Indeed, it can supply 60% of the requirements of the US electric grid, intermediate and peak load, at an acceptable cost.

4.1. The importance of variable loads in generating electricity

Most comparisons of alternative energy costs, including the two evaluations by NRC [10,11], compare the costs of base load, which is 40% of total electricity consumption [12]. But, for base load, CSP is presently more

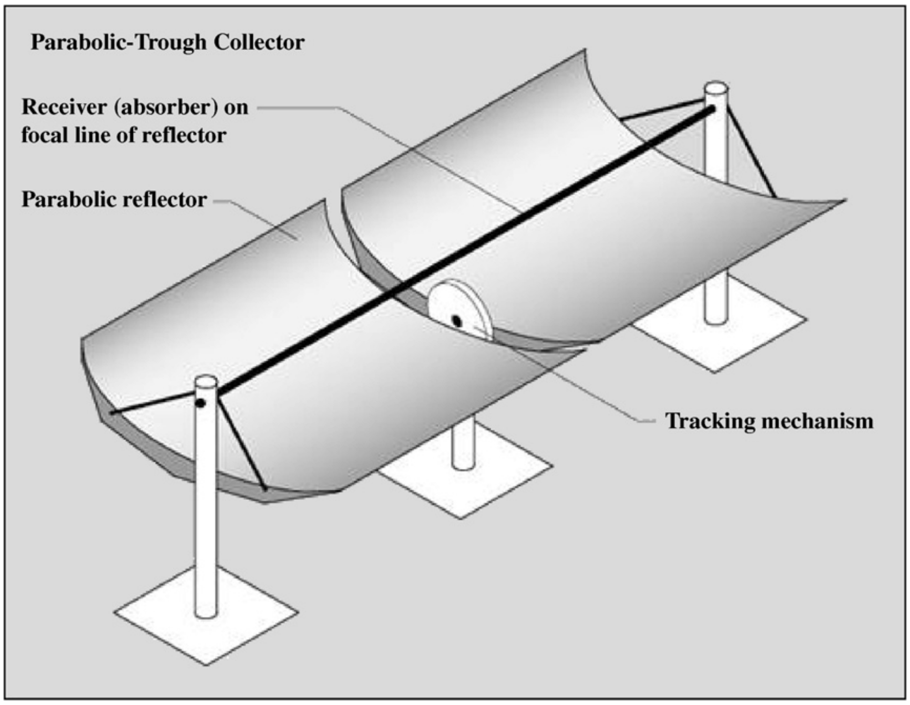

Fig. 4. Schematic of parabolic trough collectors. *Source* [26].

expensive than conventional coal power plants and nuclear power plants. However, when we consider the other 60% of the load, intermediate and peak electricity, the comparison changes completely and, as shown below, CSP becomes attractive even at present prices. Similarly, gas turbines are only competitive for peak loads (400 h a year).

The effect of operating power plants for just a fraction of time adds to capital-related costs. Capital costs are a major portion of the total cost of electricity from nuclear and coal power plants. Although the penalty for natural gas plants would be smaller, they are not included in our comparison as the cost of natural gas has increased five-fold in the last 10 years and the current shortage of gas does not allow for large expansion.

CSP has a unique feature: the collection and storage devices (90% of the investment [7]) are comparable to the fuel plant for a conventional steam power plant. By doubling the capacity of the steam power plant (10% of the investment) a solar plant designed with collectors and storage for 1 kW capacity base load (24 kWh/day) can supply 2 kWh for 12 h with only a 10% incremental investment, or 4 kWh for 6 h 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. Despite the fact that initially the capital investment for CSP plants is double that of coal and nuclear plants, their cost-effective design for intermediate and peak loads, plus their lower maintenance costs and ‘‘zero’’ fuel costs, make them competitive even today [7].

Furthermore, CSP technology could be integrated with wind and solar cells to provide an output for the electric grid that is reliable and controllable in order to offset strong variations in demand and large fluctuations in input from environmental sources. Thus, beside its enormous potential to become the main energy source of the future, CSP with storage is also the energy source of choice whenever large instantaneous control capabilities are required—an essential need in a decarbonized economy.

4.2. *Estimated costs for CSP*

The cost estimates for CSP were taken from a recent report by the consulting firm of Sargent and Lundy [13] commissioned by the US DOE and reviewed by the NRC [11]. In our earlier writing on estimates [7], we compared published data for CSP plants with both nuclear and various coal technologies. It is important to emphasize that the estimate for CSP technology by Sargent and Lundy is based on available technology and a conventional approach to building power plants. However, their estimate misses two critical factors:

- With a much larger market and increased competition, costs will be significantly reduced. For example, LNG plants and combined-cycle power plants leveled out at half the initial predicted cost.
- Additionally, those authors did not take into account that, with a large market, solar collectors (70% of cost [13]) could be designed for mass production, which would drastically reduce their cost.

However, CSP is already sufficiently competitive for many existing large-scale needs to initiate the creation of this market. Ultimately, CSP plants could become the cheapest source of alternative energy and of electric power in general.

A comparison of the costs of base power, intermediate power, and load following appears in Table 4. From this table we note that for base power, CSP is competitive only with future coal power plants with sequestered CO_2. On the other hand, for variable loads (60% of US electricity demand) CSP is already competitive. Furthermore, an increased large-scale use would drop the cost, making CSP also competitive for base loads.

As the desert areas in the US are all in the southwest, the Pacific grid will need to be connected to the national grid so that CSP can serve the entire country. Fortunately, the distances to be spanned are not prohibitively large, but planning on a national scale will be required. The transmission lines of the national grid would have to be enlarged by 100%, at an approximate cost of $250–300 billion [14]. The cost of distribution lines would add another $850–1000 billion [14]; however, distribution cost is independent of the location of the power plants. The nationwide power losses for transmission and distribution, with present technology, are less than 7% [1].

4.3. Compensating for variable power inputs and demand fluctuations on the grid

Until recently, the only problem of variable power requirements for the grid was due to variations in consumer demand. However, when switching to non-fossil energy economy, wind and solar cells will become sources of fluctuation in power inputs into the electric grid as their ability to generate electricity changes with weather conditions and time; furthermore, they lack a capacity for affordable storage. Fortunately, CSP plants are uniquely suited for large-scale load following. Therefore, such plants could make it possible to create an advanced grid that integrates nuclear, wind, and solar cell technologies because CSP can quickly and reliably compensate for variations in demand and fluctuations in power inputs into the grid.

Table 4
Electricity costs for CSP compared to coal and nuclear

	Investment ($/kW installed)	Base (cents/kWh)	Intermediate (cents/kWh)	Load following (cents/kWh)
CSP–near term [13]	4000[a]	8.0[b]	8.0	10.4[d]
CSP–future [13]	3220	6.2[b]	6.2	8.6[d]
Conventional coal power plant (with scrubbers) [6]	1200	4.5[c]	8.0	13.5[e]
Clean coal [6]	1550	5.6[c]	10	Cannot supply it
Clean coal [6] (with CO_2 sequestration)	2000	10–11	14–15	Cannot supply it
Nuclear [25]	2200	6.0[c]	10–11	Cannot supply it

Notes:

[a] The estimate was obtained as follows: near-term estimate in [4]: 4816 $/kW installed, 20% scalable with exponential scale-up factor of 0.6 saves 540 $/kW installed, 8 parallel trains built simultaneously should save 10–20% of the non-scalable part of the plant, for a saving of 380–760 $/kW installed.

[b] Operated 4900 h/year.

[c] Operated 6500 h/year.

[d] A power plant designed to supply, for each kWe installed, 12 kWh a day of variable electricity at instantaneous maximum rate of 4 kWh.

[e] Designed for the same load following capability as in (d).

The actual composition of the advanced grid (i.e., which alternative energy sources will compose it and in what percentage) and the potential contribution of CSP to the grid generating capacity require further studies. It is encouraging to realize, however, that the available US desert area is sufficient to generate several times our current total energy needs [7]. Thus, we have the technology to supply all our future electricity needs from alternative sources at a reasonable cost. Moreover, if we start now, the switch from fossil fuels to electricity from alternative sources can be done gradually.

5. Potential contributions of CSP and electricity from alternative sources

In the preceding section we showed that CSP could serve as a viable source of electricity. It is also the only available source of alternative electricity that, like nuclear energy, can support a major share of the nation's electric energy needs. Although we advocate a more diversified approach, we also note that there is sufficient sunlit area in the US to supply several times all of our energy needs [7]. On the other hand, the total power that could be generated from all other proven alternative energy sources, such as hydroelectric, geothermal, wind, and solar cells, is limited. Furthermore, CSP can become the mainstay of an advanced grid (the control of such a grid would be different from the present one, but the theoretical tools for designing it are available). Therefore, CSP merits a more thorough evaluation. Several large demonstration plants (250–400 MWe) with adequate storage capacity should be subsidized by the federal government—similar to what was provided to launch nuclear power—to help prove that CSP can be useful to industry at an acceptable cost. This paper focuses on an existing version of CSP [4]. Other proposed designs should also be evaluated, but only those with sufficient storage would have a large impact.

Although possible, full decarbonization of energy resources in the US economy could take from 30 to 50 years to be accomplished. Therefore, implementation cannot wait until either global warming has reached an unacceptable level or oil and natural gas sources have peaked, as then it will be too late. The cheapest way to initiate decarbonization is by building new CSP plants and slowly enlarging our national electric grid with alternative energy until we double or triple our total electricity generating capacity. We must start now.

At this point, we would underscore that just because alternative technologies are already available does not mean the US should stop the research into new and better ideas. To the contrary, a detailed plan for the development of available technologies, as outlined above, could serve as a yardstick for evaluating new research proposals and achievements.

Our discussion of the advanced grid did not include coal power plants with CO_2 sequestration because, although they may create no CO_2 emissions, they do not address the need to decarbonize the US energy mix. Coal reserves are finite and should be preserved as a chemical resource for the long term. Furthermore, new coal plants with CO_2 sequestration have a higher electricity cost than any other power source, and are designed to produce base power, not intermediate or variable power, and therefore are not suitable for stabilizing the grid.

In Section 3 we showed that, on a Btu basis, a 72% decarbonization of the energy mix could be achieved gradually by generating electricity from alternative sources using available, affordable technology. In Section 6, we consider how decarbonized energy can be developed to meet the balance of US needs.

6. The role of H_2 and biomass in the decarbonization of the US energy mix

Many resources have recently been put into programs that aim to develop H_2 as a main energy source. However, H_2 is an energy carrier, not an energy source, as it is not available in nature and energy is required to generate it. If produced from fossil fuels, such as natural gas and coal, H_2 would not contribute to decarbonization. Also, if natural gas was used to generate sufficient H_2 to fuel cars, the total consumption of natural gas would double—and it is already in short supply. Producing H_2 from coal would introduce a difficult switching problem, since H_2 cannot be produced at a gas station and an extensive transport system would be required.

If H_2 is going to be produced from alternative sources, the only available method is by electrolysis, an expensive process. Other ways to produce H_2 from alternative sources, e.g., the photoelectrochemical and photochemical decomposition of water, have not yet been developed, but merit research. A recent NRC report concluded that an H_2 economy requires further research and is not ready for implementation [15], which places H_2 beyond the scope of our discussion.

For as long as H_2 must be made by electrolysis, then it is clearly preferable to use electricity directly whenever possible. It would cost approximately as much for energy needs that use electricity as it would cost to use oil and gas. Therefore the direct use of electricity from alternative sources should be maximized in the near future. As noted previously, however, about 28% of fossil fuels use cannot be replaced with the direct use of electricity or with the direct use of H_2; that is, we cannot substitute electricity or H_2 for petrochemical feedstocks or airplane fuel. As will be discussed below, H_2 can play a different, important role in the development of hydrocarbons from alternative sources.

We have the technology to synthesize virtually any known hydrocarbon from syngas (a mixture of H_2, CO and CO_2) either via methanol or via Fischer–Tropsch intermediates [16,17], which can be made to react by using shape-selective catalysts [18,19]. The H_2 needed for both these processes can be obtained from electrolysis. The source of the carbon oxides is less obvious. If the carbon oxides were generated by combusting fossil fuels, we would continue to create the same CO_2 emissions as before, so this is not a valuable solution. It also has been suggested that CO_2 can be separated from air, but this is not practical. In fact, 22 lb mol of CO_2 would be required per equivalent barrel of crude produced (at a theoretical 100% efficiency). Since the concentration of CO_2 in the air is only 0.0365%, it would require 60,000 lb mol of air (or 22 million SCF) to separate the CO_2 necessary to produce one barrel of oil. The non-feasibility of such an approach becomes obvious if we consider that for a 50,000 barrel/day plant (a common size for the US, which uses about 20 million barrel/day of crude oil [1]), the volume of air that would have to pass through the CO_2 scrubber (or extractor) is equal to the volume of air required to combust enough coal to fuel about 600 GWe coal-powered plants (twice the total capacity of all coal power plants presently installed in the US [1]).

The only way to obtain carbon oxides from renewable sources is from the gasification or combustion of biomass with oxygen. We refer here to fast-growing, non-energy-intensive biomass, which does not compete with food production, such as fast-growing willows and poplars, shrubs, and grass, as well as agricultural waste. The technology for gasification of biomass is available, as gasifying biomass is very similar to the gasification of peat or lignite (for example, in the Winkler or the DOW gasifiers [20]). The role of H_2 in biomass utilization is based on the underlying chemistry. See the Appendix for a brief discussion of the underlying chemistry.

7. Summary

We have shown that 98% of our economy could be decarbonized solely by using available, proven technologies. Seventy-two percent can be replaced by electricity from alternative sources and 26% by syngas processes (the carbon oxides for the syngas being produced by the gasification of biomass, and the H_2 by electricity from alternative sources). Although this is more expensive than cheap oil or coal without pollution control, it is still affordable. Replacing 98% of fossil fuels would also reduce 97% of CO_2 emissions, 76% by using electricity from alternative sources and 21% by syngas processes.

We focused here on what could be done with existing technology, and showed that we have the technology to create a viable economy that does not depend on fossil fuels. A reasonable goal would be to replace 70% of fossil fuels in 30 years and 90% in 50 years, which would extend our oil and gas reserves and reduce CO_2 emissions.

We also showed that CSP could play a significant role in such a program and could anchor an advanced grid that integrates a variety of alternative energy sources. The US is fortunate to have all the resources and desert area needed to supply several times its total energy needs. Further development of these technologies, and their implementation on a large scale, would provide a model for the world, especially for developing nations. As the problems inherent in such a plan are not solely technical, the free market cannot be expected to invest in CO_2 reduction or to fund an uncertain future, especially if there is no law restricting CO_2 emissions. It is clear that government planning and support will be needed in order to achieve these goals. It is encouraging to know, however, that the tools needed to decarbonize the US economy are available at an affordable cost, if the country has the will to use them.

The first step would be a wide-ranging discussion and formulation of a detailed plan and timetable for implementation. This plan should also include an in-depth evaluation of the different technologies, including approximate cost estimates, not only for the technologies, but also the costs related to their introduction (enlargement of the grid, replacement of equipment, etc.). The starting point should be applications that are already competitive, or nearly competitive, today.

To replace 70% of our fossil fuel use (including most coal) would cost approximately \$6 trillion for the technology and \$1.5 trillion for transmission lines, distribution lines, and infrastructure, or about \$250 billion/year over 30 years [7,27]—definitely an affordable cost if the country wants to do it. To put this figure in perspective, it might be helpful to consider that in 2006 the US has had a negative trade balance of oil and natural gas of about \$300 billion [21]. Furthermore, all these investments would stimulate the American economy. We also showed that while the technologies presented here cannot compete with cheap coal power plants when there are no restrictions on CO_2 emissions, it competes well, even for electricity base load, when the cost of sequestering the CO_2 is taken into account.

One way to finance the switch from fossil fuels to alternative energy sources would be to establish a fund to subsidize renewable technologies by introducing a fee on CO_2 emissions. At current levels of CO_2 emissions, a fee of \$65/ton CO_2 would pay for the entire investment. However, the fund does not have to pay for the whole investment, a smaller fee could provide an initial incentive.

The \$65/ton CO_2 fee was computed as follows: at present the US emits about 6000 million metric tons of CO_2 a year. If the plan were implemented, after 70% replacement in 30 years the emissions would be 1800 million metric tons. The average emissions over this 30-year period would be 3900 million metric tons. If the total investment cost of \$250 billion a year is divided by the yearly average emission, we arrive at the \$65/ton CO_2 fee. As this is a time average, the fund collected will be more in the beginning and less at the end.

This example is, of course, not the only option available, but it shows a possible solution and gives an idea of the order of magnitude involved. However, we must start now, as the US does not have the human and industrial resources to complete this switch within a few years. Also, the US must create long-range incentives (e.g., tax credits) large enough to induce major companies and utilities to implement proven technologies and provide the required infrastructure. We have limited our discussion solely to available technologies. We believe that the political hurdles to their implementation can be overcome, but this is outside the scope of our paper.

We want to point out that there is another important problem that must be taken into account in planning the conversion to non-fossil fuels: an urgent need to reduce oil and natural gas imports, a need also addressed in the proposed plan. Some of the present approaches, like building more coal power plants without CO_2 sequestration (20 GWe, emitting 140 million tons CO_2 a year, are under construction) as well as substituting tar sands for crude, do not take into account the necessity to reduce CO_2 emissions. Producing gasoline or diesel from coal, without CO_2 sequestration, would increase CO_2 emissions by a factor of 2.5 compared to producing them from crude. Thus, a comprehensive plan addressing both the long-term problem of dwindling fossil fuels reserves and the near-term problem of global warming, is made even more difficult by the immediate need to achieve energy independence by reducing oil and gas imports. Luckily, all three problems share the same solution: switch to alternative energy sources. It is therefore essential to complete and implement as soon as possible such a comprehensive plan.

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Appendix A

The role of H_2 in the utilization of biomass

The production of all hydrocarbons, including fuels from syngas, is based on the overall reactions:

$$nCO + 2nH_2 \rightarrow (CH_2)n + nH_2O, \tag{1}$$

$$nCO_2 + 3nH_2 \rightarrow (CH_2)n + 2nH_2O. \tag{2}$$

Reactions (1) and (2) occur during the Fischer–Tropsch process, which is preferable for producing diesel and jet fuel. Each of the two overall reactions above can also occur in two steps with methanol as an intermediate. This is the preferred route for producing gasoline and most chemicals [18,19].

Most biomass has the chemical composition $Cn(H_2O)m$ and contains H_2 only in the form of water. Just as in coal liquefaction, the H_2 for syngas is formed from CO by the shift reaction:

$$CO + H_2O \rightarrow CO_2 + H_2, \tag{3}$$

which can occur either in the gasifier or in a separate shift reactor. As reaction (1) requires two moles H_2 per mole CO, at least two moles of CO (reaction (3)) must be shifted for each mole of CH_2 produced, ending up with one-third of the carbon in the product and the rest as CO_2. If H_2 is added from alternative sources, all the CO and CO_2 formed can be converted during the gasification to CH_2, thus tripling the useful product. In addition, the shift reactor and the CO_2 removal are saved.

We estimate that biomass could provide 10% of total US energy needs. By adding H_2, the yield could be tripled to 30%, enough to meet all those energy requirements for which electricity cannot be substituted directly (26% of total fossil fuels used, as estimated in Section 3, which also reduce CO_2 emissions by another 21%, breakdowns are given in Table 3). If we could generate H_2 by electrolysis on site, the oxygen could be used for gasification. Biomass gasification via methanol intermediate, without H_2 addition, is so similar to the industrial process that uses sub-bituminous coal that it should cost no more. While adding H_2 would half the cost of the production process, the H_2 itself is more expensive.

At present, H_2 can be produced by electrolysis at a cost of \$30/MMBtu [22] or about \$160 per barrel of gasoline (a barrel of gasoline is approximately 5.2 MMBtu). An important research project would be to reduce the cost of H_2 produced from alternative energy sources [15].

In our plan, biomass is converted on location in small plants, and the intermediate methanol produced is transported to a bio-refinery or to existing petrochemical plants. Further investigation is needed to determine more precisely how much biomass can be produced and the optimal technologies for its utilization.

In Appendix B, we show that with our method it is possible to produce, from any biomass, three to four times more hydrocarbons than by fermentation to ethanol, a major advantage because the amount of biomass that can be grown is limited.

Appendix B

Comparing biomass gasification and biomass fermentation in terms of yield of hydrocarbons

In our calculations, we assumed that the typical composition of hydrocarbons is $(CH_2)n$. The estimates for the potential yield of hydrocarbons from biomass gasification are obtained by using the biomass elemental composition given in Table 5a and assuming an efficiency of 95% for the gasification conversion, regardless what form the carbon is in (cellulose, hemicellulose, lignin, protein, etc.).

On the other hand, the estimates for biomass fermentation are based on the biomass composition given in Table 5b and the ethanol yield given in Table 5c. The efficiencies for the hemicellulose and cellulose hydrolysis conversions, and the ethanol yields are given in Table 5c, while the efficiencies for the glucose-to-ethanol and pentose-to-ethanol conversions are given in the notes of Table 5c.

Table 5a
Biomass elemental composition

Feedstock	Biomass composition (% dry matter)			
	Carbon	Hydrogen	Oxygen	Other
Alfalfa stem	47.2	6.0	38.2	8.6
Corn stover	44.8	5.7	41.4	8.1
Sugarcane bagasse	48.6	5.9	42.8	2.7
Oak wood	49.5	6.0	44.5	—

Source [23].

Table 5b
Biomass composition

Feedstock	Biomass composition (% dry matter)					
	Hemicellulose	Cellulose	Lignin	Protein	Ash	Other
Alfalfa stem	12	34	9	11	7	27
Corn stover	25	38	15	4	3	15
Sugarcane bagasse	19	38	22	4	3	14
Oak wood	19	44	23	<1	<1	13

Source [24].

Table 5c
Ethanol yield from biomass

Feedstock	Hemicellulose to xylose hydrolysis efficiency (%)	Cellulose to glucose hydrolysis efficiency (%)	Ethanol yield (l/ton)	Ethanol yield (kg/ton)
Alfalfa stem	96	88	228	182
Corn stover	92	90	298	238
Sugarcane bagasse	90	86	267	214
Oak wood	88	79	278	222

Source [24].
Notes:

- Estimated maximum potential yield, no present process exists able to achieve these yields.
- Glucose to ethanol conversion: 95% (24).
- Xylose to ethanol conversion: 60% (24).
- For each of the four cases we take as a basis 1 metric ton of biomass, and calculate the amount of CH_2 produced from both gasification and fermentation, which is the base for the comparison.

Table 5d
Ratio between hydrocarbons yields from biomass gasification and biomass fermentation

Feedstock	Gasification hydrocarbons yield (kg CH_2)	Fermentation hydrocarbons yield (kg CH_2)	Ratio
Alfalfa stem	523	110	4.8
Corn stover	549	135	4.1
Sugarcane bagasse	497	145	3.4
Oak wood	539	130	4.1

Finally, we assume the efficiency of the ethanol to hydrocarbons conversion to be practically 100%.

1 Ton Alfalfa Stem.

Gasification:
472 kg of C (Table 5a) ⇒ this number is multiplied by 14/12 (molecular weight of CH_2/molecular weight of C) and by 0.95 (gasification conversion efficiency) ⇒ 523 kg of CH_2.

Fermentation:
182 kg C_2H_5OH (Table 5c) ⇒ this number is multiplied by 24/46 (molecular weight of 2 moles C/molecular weight of C_2H_5OH) ⇒ 95 kg of C ⇒ this number is multiplied by 14/12 (molecular weight of CH_2/molecular weight of C) ⇒ 110 kg of CH_2.

Ratio (gasification product yield)/(fermentation product yield) $= 523/110 = 4.8$.

Similarly, we can calculate this ratio also for oak wood, corn stover, and sugarcane bagasse. The results are summarized in Table 5d. For all types of biomass, the hydrocarbon yield obtained by gasification is always three to four times larger than the equivalent yield obtained by fermentation.

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