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Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies

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Humanity already possesses the fundamental scientific, technical, and industrial know-how to solve the carbon and climate problem for the next half-century. A portfolio of technologies now exists to meet the world's energy needs over the next 50 years and limit atmospheric CO_2 to a trajectory that avoids a doubling of the preindustrial concentration. Every element in this portfolio has passed beyond the laboratory bench and demonstration project; many are already implemented somewhere at full industrial scale. Although no element is a credible candidate for doing the entire job (or even half the job) by itself, the portfolio as a whole is large enough that not every element has to be used.

The debate in the current literature about stabilizing atmospheric CO_2 at less than a doubling of the preindustrial concentration has led to needless confusion about current options for mitigation. On one side, the Intergovernmental Panel on Climate Change (IPCC) has claimed that "technologies that exist in operation or pilot stage today" are sufficient to follow a less-than-doubling trajectory "over the next hundred years or more" [(*1*), p. 8]. On the other side, a recent review in *Science* asserts that the IPCC claim demonstrates "misperceptions of technological readiness" and calls for "revolutionary changes" in mitigation technology, such as fusion, space-based solar electricity, and artificial photosynthesis (*2*). We agree that fundamental research is vital to develop the revolutionary mitigation strategies needed in the second half of this century and beyond. But it is important not to become beguiled by the possibility of revolutionary technology. Humanity can solve the carbon and climate problem in the first half of this century simply by scaling up what we already know how to do.

What Do We Mean by "Solving the Carbon and Climate Problem for the Next Half-Century"?

Proposals to limit atmospheric CO_2 to a concentration that would prevent most damaging climate change have focused on a goal of 500 ± 50 parts per million (ppm), or less than double the preindustrial concentration of 280 ppm (*3*–*7*). The current concentration is ~375 ppm. The CO_2 emissions reductions necessary to achieve any such target depend on the emissions judged likely to occur in the absence of a focus on carbon [called a business-as-usual (BAU) trajectory], the quantitative details of the stabilization target, and the future behavior of natural sinks for atmospheric CO_2 (i.e., the oceans and terrestrial biosphere). We focus exclusively on CO_2, because it is the dominant anthropogenic greenhouse gas; industrial-scale mitigation options also exist for subordinate gases, such as methane and N_2O.

Very roughly, stabilization at 500 ppm requires that emissions be held near the present level of 7 billion tons of carbon per year (GtC/year) for the next 50 years, even though they are currently on course to more than double (Fig. 1A). The next 50 years is a sensible horizon from several perspectives. It is the length of a career, the lifetime of a power plant, and an interval for which the technology is close enough to envision. The calculations behind Fig. 1A are explained in Section 1 of the supporting online material (SOM) text. The BAU and stabilization emissions in Fig. 1A are near the center of the cloud of variation in the large published literature (*8*).

The Stabilization Triangle

We idealize the 50-year emissions reductions as a perfect triangle in Fig. 1B. Stabilization is represented by a "flat" trajectory of fossil fuel emissions at 7 GtC/year, and BAU is represented by a straight-line "ramp" trajectory rising to 14 GtC/year in 2054. The "stabilization triangle," located between the flat trajectory and BAU, removes exactly one-third of BAU emissions.

To keep the focus on technologies that have the potential to produce a material difference by 2054, we divide the stabilization triangle into seven equal "wedges." A wedge represents an activity that reduces emissions to the atmosphere that starts at zero today and increases linearly until it accounts for 1 GtC/year of reduced carbon emissions in 50 years. It thus represents a cumulative total of 25 GtC of reduced emissions over 50 years. In this paper, to "solve the carbon and climate problem over the next half-century" means to deploy the technologies and/or lifestyle changes necessary to fill all seven wedges of the stabilization triangle.

Stabilization at any level requires that net emissions do not simply remain constant, but eventually drop to zero. For example, in one simple model (*9*) that begins with the stabilization triangle but looks beyond 2054, 500-ppm stabilization is achieved by 50 years of flat emissions, followed by a linear decline of about two-thirds in the following 50 years, and a very slow decline thereafter that matches the declining ocean sink. To develop the revolutionary technologies required for such large emissions reductions in the second half of the century, enhanced research and development would have to begin immediately.

Policies designed to stabilize at 500 ppm would inevitably be renegotiated periodically to take into account the results of research and development, experience with specific wedges, and revised estimates of the size of the stabilization triangle. But not filling the stabilization triangle will put 500-ppm stabilization out of reach. In that same simple model (*9*), 50 years of BAU emissions followed by 50 years of a flat trajectory at 14 GtC/year leads to more than a tripling of the preindustrial concentration.

It is important to understand that each of the seven wedges represents an effort beyond what would occur under BAU. Our BAU simply continues the 1.5% annual carbon emissions growth of the past 30 years. This historic trend in emissions has been accompanied by 2% growth in primary energy consumption and 3% growth in gross world product (GWP) (Section 1 of SOM text). If carbon emissions were to grow 2% per year, then ~10 wedges would be needed instead of 7, and if carbon emissions were to grow at 3% per year, then ~18 wedges would be required (Section 1 of SOM text). Thus, a continuation of the historical rate of decarbonization of the fuel mix prevents the need for three additional wedges, and ongoing improvements in energy efficiency prevent the need for eight additional wedges. Most readers will reject at least one of the wedges listed here, believing that the corresponding deployment is certain to occur in BAU, but readers will disagree about which to reject on such grounds. On the other hand, our list of mitigation options is not exhaustive.

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What Current Options Could Be Scaled Up to Produce at Least One Wedge?

Wedges can be achieved from energy efficiency, from the decarbonization of the supply of electricity and fuels (by means of fuel shifting, carbon capture and storage, nuclear energy, and renewable energy), and from biological storage in forests and agricultural soils. Below, we discuss 15 different examples of options that are already deployed at an industrial scale and that could be scaled up further to produce at least one wedge (summarized in Table 1). Although several options could be scaled up to two or more wedges, we doubt that any could fill the stabilization triangle, or even half of it, alone.

Because the same BAU carbon emissions cannot be displaced twice, achieving one wedge often interacts with achieving another. The more the electricity system becomes decarbonized, for example, the less the available savings from greater efficiency of electricity use, and vice versa. Interactions among wedges are discussed in the SOM text. Also, our focus is not on costs. In general, the achievement of a wedge will require some price trajectory for carbon, the details of which depend on many assumptions, including future fuels prices, public acceptance, and cost reductions by means of learning. Instead, our analysis is intended to complement the comprehensive but complex "integrated assessments" (*1*) of carbon mitigation by letting the full-scale examples that are already in the marketplace make a simple case for technological readiness.

Category I: Efficiency and Conservation

Improvements in efficiency and conservation probably offer the greatest potential to provide wedges. For example, in 2002, the United States announced the goal of decreasing its carbon intensity (carbon emissions per unit GDP) by 18% over the next decade, a decrease of 1.96% per year. An entire wedge would be created if the United States were to reset its carbon intensity goal to a decrease of 2.11% per year and extend it to 50 years, and if every country were to follow suit by adding the same 0.15% per year increment to its own carbon intensity goal. However, efficiency and conservation options are less tangible than those from the other categories. Improvements in energy efficiency will come from literally hundreds of innovations that range from new catalysts and chemical processes, to more efficient lighting and insulation for buildings, to the growth of the service economy and telecommuting. Here, we provide four of many possible comparisons of greater and less efficiency in 2054. (See references and details in Section 2 of the SOM text.)

Option 1: Improved fuel economy. Suppose that in 2054, 2 billion cars (roughly four times as many as today) average 10,000 miles per year (as they do today). One wedge would be achieved if, instead of averaging 30 miles per gallon (mpg) on conventional fuel, cars in 2054 averaged 60 mpg, with fuel type and distance traveled unchanged.

Option 2: Reduced reliance on cars. A wedge would also be achieved if the average fuel economy of the 2 billion 2054 cars were 30 mpg, but the annual distance traveled were 5000 miles instead of 10,000 miles.

Option 3: More efficient buildings. According to a 1996 study by the IPCC, a wedge is the difference between pursuing and not pursuing "known and established approaches" to energy-efficient space heating and cooling, water heating, lighting, and refrigeration in residential and commercial buildings. These approaches reduce mid-century emissions from buildings by about one-fourth. About half of potential savings are in the buildings in developing countries (*1*).

Option 4: Improved power plant efficiency. In 2000, coal power plants, operating on average at 32% efficiency, produced about one-fourth of all carbon emissions: 1.7 GtC/year out of 6.2 GtC/year. A wedge would be created if twice today's quantity of coal-based electricity in 2054 were produced at 60% instead of 40% efficiency.

Category II: Decarbonization of Electricity and Fuels

(See references and details in Section 3 of the SOM text.)

Option 5: Substituting natural gas for coal. Carbon emissions per unit of electricity are about half as large from natural gas power plants as from coal plants. Assume that the capacity factor of the average baseload coal plant in 2054 has increased to 90% and that its efficiency has improved to 50%. Because 700 GW of such plants emit carbon at a rate of 1 GtC/year, a wedge would be achieved by displacing 1400 GW of baseload coal with baseload gas by 2054. The power shifted to gas for this wedge is four times as large as the total current gas-based power.

Option 6: Storage of carbon captured in power plants. Carbon capture and storage (CCS) technology prevents about 90% of the fossil carbon from reaching the atmosphere, so a wedge would be provided by the installation of CCS at 800 GW of baseload coal plants by 2054 or 1600 GW of baseload natural gas plants. The most likely approach

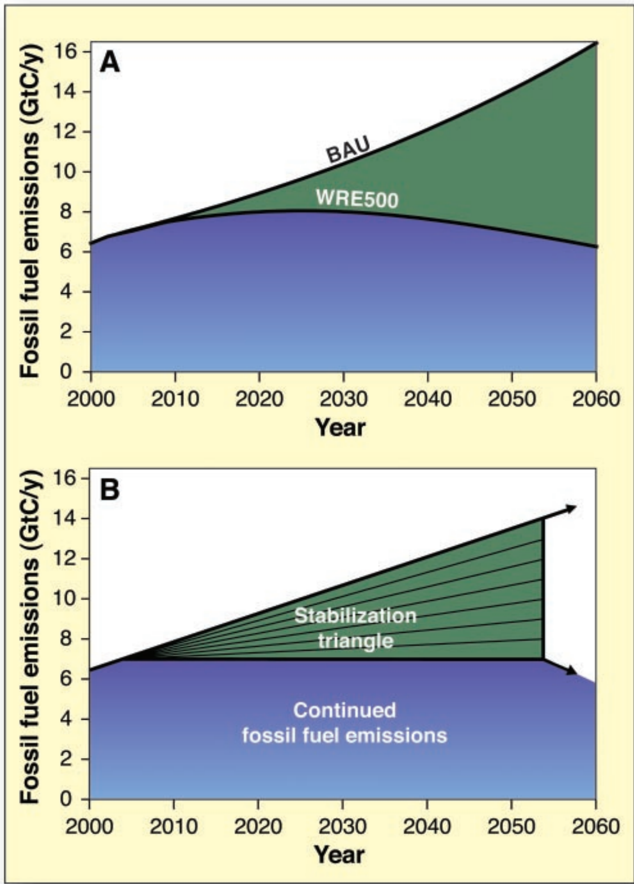

Fig. 1. (**A**) The top curve is a representative BAU emissions path for global carbon emissions as CO_2 from fossil fuel combustion and cement manufacture: 1.5% per year growth starting from 7.0 GtC/year in 2004. The bottom curve is a CO_2 emissions path consistent with atmospheric CO_2 stabilization at 500 ppm by 2125 akin to the Wigley, Richels, and Edmonds (WRE) family of stabilization curves described in (*11*), modified as described in Section 1 of the SOM text. The bottom curve assumes an ocean uptake calculated with the High-Latitude Exchange Interior Diffusion Advection (HILDA) ocean model (*12*) and a constant net land uptake of 0.5 GtC/year (Section 1 of the SOM text). The area between the two curves represents the avoided carbon emissions required for stabilization. (**B**) Idealization of (A): A stabilization triangle of avoided emissions (green) and allowed emissions (blue). The allowed emissions are fixed at 7 GtC/year beginning in 2004. The stabilization triangle is divided into seven wedges, each of which reaches 1 GtC/year in 2054. With linear growth, the total avoided emissions per wedge is 25 GtC, and the total area of the stabilization triangle is 175 GtC. The arrow at the bottom right of the stabilization triangle points downward to emphasize that fossil fuel emissions must decline substantially below 7 GtC/year after 2054 to achieve stabilization at 500 ppm.

has two steps: (i) precombustion capture of CO_2, in which hydrogen and CO_2 are produced and the hydrogen is then burned to produce electricity, followed by (ii) geologic storage, in which the waste CO_2 is injected into subsurface geologic reservoirs. Hydrogen production from fossil fuels is already a very large business. Globally, hydrogen plants consume about 2% of primary energy and emit 0.1 GtC/year of CO_2. The capture part of a wedge of CCS electricity would thus require only a tenfold expansion of plants resembling today's large hydrogen plants over the next 50 years.

The scale of the storage part of this wedge can be expressed as a multiple of the scale of current enhanced oil recovery, or current seasonal storage of natural gas, or the first geological storage demonstration project. Today, about 0.01 GtC/year of carbon as CO_2 is injected into geologic reservoirs to spur enhanced oil recovery, so a wedge of geologic storage requires that CO_2 injection be scaled up by a factor of 100 over the next 50 years. To smooth out seasonal demand in the United States, the natural gas industry annually draws roughly 4000 billion standard cubic feet (Bscf) into and out of geologic storage, and a carbon flow of 1 GtC/year (whether as methane or CO_2) is a flow of 69,000 Bscf/year (190 Bscf per day), so a wedge would be a flow to storage 15 and 20 times as large as the current flow. Norway's Sleipner project in the North Sea strips CO_2 from natural gas offshore and reinjects 0.3 million tons of carbon a year (MtC/year) into a non–fossil-fuel–bearing formation, so a wedge would be 3500 Sleipner-sized projects (or fewer, larger projects) over the next 50 years.

A worldwide effort is under way to assess the capacity available for multicentury storage and to assess risks of leaks large enough to endanger human or environmental health.

Option 7: Storage of carbon captured in hydrogen plants. The hydrogen resulting from precombustion capture of CO_2 can be sent offsite to displace the consumption of conventional fuels rather than being consumed onsite to produce electricity. The capture part of a wedge

Table 1. Potential wedges: Strategies available to reduce the carbon emission rate in 2054 by 1 GtC/year or to reduce carbon emissions from 2004 to 2054 by 25 GtC.

Option	Effort by 2054 for one wedge, relative to 14 GtC/year BAU	Comments, issues
	Energy efficiency and conservation	
Economy-wide carbon-intensity reduction (emissions/$GDP)	Increase reduction by additional 0.15% per year (e.g., increase U.S. goal of 1.96% reduction per year to 2.11% per year)	Can be tuned by carbon policy
1. Efficient vehicles	Increase fuel economy for 2 billion cars from 30 to 60 mpg	Car size, power
2. Reduced use of vehicles	Decrease car travel for 2 billion 30-mpg cars from 10,000 to 5000 miles per year	Urban design, mass transit, telecommuting
3. Efficient buildings	Cut carbon emissions by one-fourth in buildings and appliances projected for 2054	Weak incentives
4. Efficient baseload coal plants	Produce twice today's coal power output at 60% instead of 40% efficiency (compared with 32% today)	Advanced high-temperature materials
	Fuel shift	
5. Gas baseload power for coal baseload power	Replace 1400 GW 50%-efficient coal plants with gas plants (four times the current production of gas-based power)	Competing demands for natural gas
	CO_2 Capture and Storage (CCS)	
6. Capture CO_2 at baseload power plant	Introduce CCS at 800 GW coal or 1600 GW natural gas (compared with 1060 GW coal in 1999)	Technology already in use for H_2 production
7. Capture CO_2 at H_2 plant	Introduce CCS at plants producing 250 MtH_2/year from coal or 500 MtH_2/year from natural gas (compared with 40 MtH_2/year today from all sources)	H_2 safety, infrastructure
8. Capture CO_2 at coal-to-synfuels plant	Introduce CCS at synfuels plants producing 30 million barrels a day from coal (200 times Sasol), if half of feedstock carbon is available for capture	Increased CO_2 emissions, if synfuels are produced without CCS
Geological storage	Create 3500 Sleipners	Durable storage, successful permitting
	Nuclear fission	
9. Nuclear power for coal power	Add 700 GW (twice the current capacity)	Nuclear proliferation, terrorism, waste
	Renewable electricity and fuels	
10. Wind power for coal power	Add 2 million 1-MW-peak windmills (50 times the current capacity) "occupying" 30 × 10^6 ha, on land or offshore	Multiple uses of land because windmills are widely spaced
11. PV power for coal power	Add 2000 GW-peak PV (700 times the current capacity) on 2 × 10^6 ha	PV production cost
12. Wind H_2 in fuel-cell car for gasoline in hybrid car	Add 4 million 1-MW-peak windmills (100 times the current capacity)	H_2 safety, infrastructure
13. Biomass fuel for fossil fuel	Add 100 times the current Brazil or U.S. ethanol production, with the use of 250 × 10^6 ha (one-sixth of world cropland)	Biodiversity, competing land use
	Forests and agricultural soils	
14. Reduced deforestation, plus reforestation, afforestation, and new plantations.	Decrease tropical deforestation to zero instead of 0.5 GtC/year, and establish 300 Mha of new tree plantations (twice the current rate)	Land demands of agriculture, benefits to biodiversity from reduced deforestation
15. Conservation tillage	Apply to all cropland (10 times the current usage)	Reversibility, verification

would require the installation of CCS, by 2054, at coal plants producing 250 MtH_2/year, or at natural gas plants producing 500 MtH_2/year. The former is six times the current rate of hydrogen production. The storage part of this option is the same as in Option 6.

Option 8: Storage of carbon captured in synfuels plants. Looming over carbon management in 2054 is the possibility of large-scale production of synthetic fuel (synfuel) from coal. Carbon emissions, however, need not exceed those associated with fuel refined from crude oil if synfuels production is accompanied by CCS. Assuming that half of the carbon entering a 2054 synfuels plant leaves as fuel but the other half can be captured as CO_2, the capture part of a wedge in 2054 would be the difference between capturing and venting the CO_2 from coal synfuels plants producing 30 million barrels of synfuels per day. (The flow of carbon in 24 million barrels per day of crude oil is 1 GtC/year; we assume the same value for the flow in synfuels and allow for imperfect capture.) Currently, the Sasol plants in South Africa, the world's largest synfuels facility, produce 165,000 barrels per day from coal. Thus, a wedge requires 200 Sasol-scale coal-to-synfuels facilities with CCS in 2054. The storage part of this option is again the same as in Option 6.

Option 9: Nuclear fission. On the basis of the Option 5 estimates, a wedge of nuclear electricity would displace 700 GW of efficient baseload coal capacity in 2054. This would require 700 GW of nuclear power with the same 90% capacity factor assumed for the coal plants, or about twice the nuclear capacity currently deployed. The global pace of nuclear power plant construction from 1975 to 1990 would yield a wedge, if it continued for 50 years (*10*). Substantial expansion in nuclear power requires restoration of public confidence in safety and waste disposal, and international security agreements governing uranium enrichment and plutonium recycling.

Option 10: Wind electricity. We account for the intermittent output of windmills by equating 3 GW of nominal peak capacity (3 GW_p) with 1 GW of baseload capacity. Thus, a wedge of wind electricity would require the deployment of 2000 GW_p that displaces coal electricity in 2054 (or 2 million 1-MW_p wind turbines). Installed wind capacity has been growing at about 30% per year for more than 10 years and is currently about 40 GW_p. A wedge of wind electricity would thus require 50 times today's deployment. The wind turbines would "occupy" about 30 million hectares (about 3% of the area of the United States), some on land and some offshore. Because windmills are widely spaced, land with windmills can have multiple uses.

Option 11: Photovoltaic electricity. Similar to a wedge of wind electricity, a wedge from photovoltaic (PV) electricity would require 2000 GW_p of installed capacity that displaces coal electricity in 2054. Although only 3 GW_p of PV are currently installed, PV electricity has been growing at a rate of 30% per year. A wedge of PV electricity would require 700 times today's deployment, and about 2 million hectares of land in 2054, or 2 to 3 m^2 per person.

Option 12: Renewable hydrogen. Renewable electricity can produce carbon-free hydrogen for vehicle fuel by the electrolysis of water. The hydrogen produced by 4 million 1-MW_p windmills in 2054, if used in high-efficiency fuel-cell cars, would achieve a wedge of displaced gasoline or diesel fuel. Compared with Option 10, this is twice as many 1-MW_p windmills as would be required to produce the electricity that achieves a wedge by displacing high-efficiency baseload coal. This interesting factor-of-two carbon-saving advantage of wind-electricity over wind-hydrogen is still larger if the coal plant is less efficient or the fuel-cell vehicle is less spectacular.

Option 13: Biofuels. Fossil-carbon fuels can also be replaced by biofuels such as ethanol. A wedge of biofuel would be achieved by the production of about 34 million barrels per day of ethanol in 2054 that could displace gasoline, provided the ethanol itself were fossil-carbon free. This ethanol production rate would be about 50 times larger than today's global production rate, almost all of which can be attributed to Brazilian sugarcane and United States corn. An ethanol wedge would require 250 million hectares committed to high-yield (15 dry tons/hectare) plantations by 2054, an area equal to about one-sixth of the world's cropland. An even larger area would be required to the extent that the biofuels require fossil-carbon inputs. Because land suitable for annually harvested biofuels crops is also often suitable for conventional agriculture, biofuels production could compromise agricultural productivity.

Category III: Natural Sinks

Although the literature on biological sequestration includes a diverse array of options and some very large estimates of the global potential, here we restrict our attention to the pair of options that are already implemented at large scale and that could be scaled up to a wedge or more without a lot of new research. (See Section 4 of the SOM text for references and details.)

Option 14: Forest management. Conservative assumptions lead to the conclusion that at least one wedge would be available from reduced tropical deforestation and the management of temperate and tropical forests. At least one half-wedge would be created if the current rate of clear-cutting of primary tropical forest were reduced to zero over 50 years instead of being halved. A second half-wedge would be created by reforesting or afforesting approximately 250 million hectares in the tropics or 400 million hectares in the temperate zone (current areas of tropical and temperate forests are 1500 and 700 million hectares, respectively). A third half-wedge would be created by establishing approximately 300 million hectares of plantations on nonforested land.

Option 15: Agricultural soils management. When forest or natural grassland is converted to cropland, up to one-half of the soil carbon is lost, primarily because annual tilling increases the rate of decomposition by aerating undecomposed organic matter. About 55 GtC, or two wedges' worth, has been lost historically in this way. Practices such as conservation tillage (e.g., seeds are drilled into the soil without plowing), the use of cover crops, and erosion control can reverse the losses. By 1995, conservation tillage practices had been adopted on 110 million hectares of the world's 1600 million hectares of cropland. If conservation tillage could be extended to all cropland, accompanied by a verification program that enforces the adoption of soil conservation practices that actually work as advertised, a good case could be made for the IPCC's estimate that an additional half to one wedge could be stored in this way.

Conclusions

In confronting the problem of greenhouse warming, the choice today is between action and delay. Here, we presented a part of the case for action by identifying a set of options that have the capacity to provide the seven stabilization wedges and solve the climate problem for the next half-century. None of the options is a pipe dream or an unproven idea. Today, one can buy electricity from a wind turbine, PV array, gas turbine, or nuclear power plant. One can buy hydrogen produced with the chemistry of carbon capture, biofuel to power one's car, and hundreds of devices that improve energy efficiency. One can visit tropical forests where clear-cutting has ceased, farms practicing conservation tillage, and facilities that inject carbon into geologic reservoirs. Every one of these options is already implemented at an industrial scale and could be scaled up further over 50 years to provide at least one wedge.

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Supporting Online Material
www.sciencemag.org/cgi/content/full/305/5686/968/DC1
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VIEWPOINT

Sustainable Hydrogen Production

John A. Turner

Identifying and building a sustainable energy system are perhaps two of the most critical issues that today's society must address. Replacing our current energy carrier mix with a sustainable fuel is one of the key pieces in that system. Hydrogen as an energy carrier, primarily derived from water, can address issues of sustainability, environmental emissions, and energy security. Issues relating to hydrogen production pathways are addressed here. Future energy systems require money and energy to build. Given that the United States has a finite supply of both, hard decisions must be made about the path forward, and this path must be followed with a sustained and focused effort.

In his 2003 State of the Union Address, U.S. President Bush proposed "$1.2 billion in research funding so that America can lead the world in developing clean, hydrogen-powered automobiles." Since that time, articles both pro and con have buffeted the whole concept. The hydrogen economy (*1*) is not a new idea. In 1874, Jules Verne, recognizing the finite supply of coal and the possibilities of hydrogen derived from water electrolysis, made the comment that "water will be the coal of the future" (*2*). Rudolf Erren in the 1930s suggested using hydrogen produced from water electrolysis as a transportation fuel (*3*). His goal was to reduce automotive emissions and oil imports into England. Similarly, Francis Bacon suggested using hydrogen as an energy storage system (*4*). The vision of using energy from electricity and electrolysis to generate hydrogen from water for transportation and energy storage to reduce environmental emissions and provide energy security is compelling, but as yet remains unrealized.

If one assumes a full build-out of a hydrogen economy, the amount of hydrogen needed just for U.S. transportation needs would be about 150 million tons per year (*5*). One must question the efficacy of producing, storing, and distributing that much hydrogen. Because energy is required to extract hydrogen from either water or biomass so that it can be used as an energy carrier, if the United States chooses a hydrogen-based future it needs to think carefully about how much energy we need and where it is going to come from. In addition, sustainability must be a hallmark of any proposed future infrastructure. What energy-producing technologies can be envisioned that will last for millennia, and just how many people can they support (*6–8*)?

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Technologies for Hydrogen Production

Hydrogen can be generated from water, biomass, natural gas, or (after gasification) coal. Today, hydrogen is mainly produced from natural gas via steam methane reforming, and although this process can sustain an initial foray into the hydrogen economy, it represents only a modest reduction in vehicle emissions as compared to emissions from current hybrid vehicles, and ultimately only exchanges oil imports for natural gas imports. It is clearly not sustainable.

Coal gasification could produce considerable amounts of hydrogen and electricity merely because of the large size of available coal deposits (*9*). Additionally, because of its relatively low cost, it is often cited as the best resource for economically producing large quantities of hydrogen. However, the energy required for the necessary sequestration of CO_2 would increase the rate at which coal reserves are depleted; converting the vehicle fleet to electric vehicles and generating that electricity from "clean coal" or making hydrogen as a possible energy carrier would accelerate that depletion. Couple that to a modest economic growth rate of ~1%, and U.S. 250-year coal reserves drop to 75 years or so (*6*), which is not at all sustainable. That leaves solar-derived, wind, nuclear, and geothermal energy as major resources for sustainable hydrogen production. The hydrogen production pathways from these resources include electrolysis of water, thermal chemical cycles using heat, and biomass processing (using a variety of technologies ranging from reforming to fermentation).

Biomass processing techniques can benefit greatly from the wealth of research that has been carried out over the years on refining and converting liquid and gaseous fossil fuels. Some of these processes require considerable amounts of hydrogen, and many of these fossil-derived processes can be adapted for use with a large variety of biomass-derived feedstocks. Biomass can easily be converted into a number of liquid fuels, including methanol, ethanol, biodiesel, and pyrolysis oil, which could be transported and used to generate hydrogen on site. For the high-biomass-yield processes, such as corn to ethanol, hydrogen is required in the form of ammonia for fertilizer. Although biomass is clearly (and necessarily) sustainable, it cannot supply hydrogen in the amounts required. It remains to be seen, in a world that is both food-limited and carbon-constrained, whether the best use of biomass is for food, as a chemical feedstock, or as an energy source.

Because the direct thermal splitting of water requires temperatures of >2000°C and produces a rapidly recombining mixture of hydrogen and oxygen (*10*), a number of thermal chemical cycles have been identified that can use lower temperatures and produce hydrogen and oxygen in separate steps. The one that has received the greatest attention involves sulfuric acid (H_2SO_4) at 850°C and hydrogen iodide (HI) at 450°C (*11*). The next generation of fission reactors includes designs that can provide the necessary heat; however, a number of critical material properties must be satisfied to meet the required stability under the operating conditions of HI