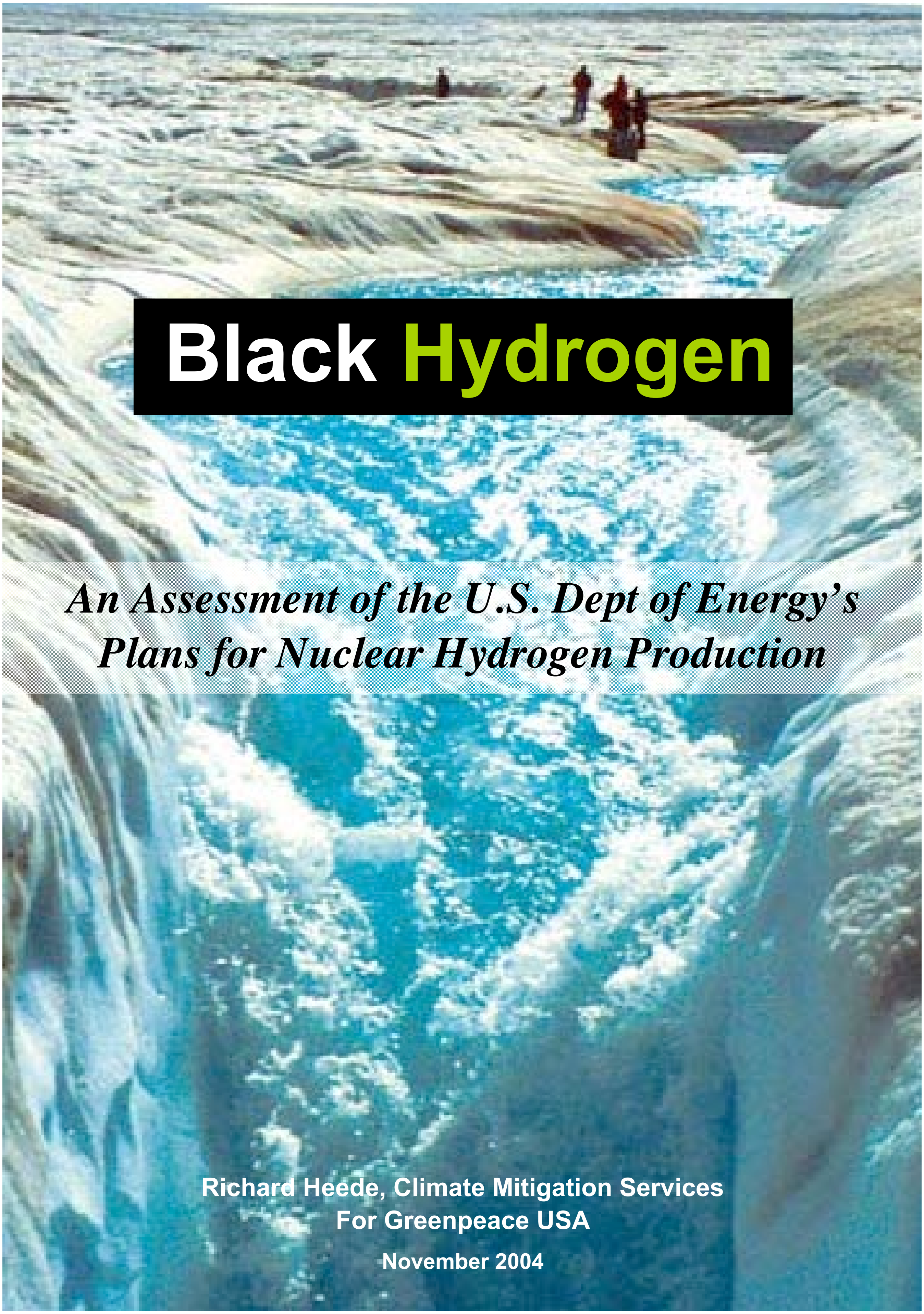

Black Hydrogen

An Assessment of the U.S. Dept of Energy's Plans for Nuclear Hydrogen Production

Richard Heede, Climate Mitigation Services
For Greenpeace USA

November 2004

Note on units: we have used metric units throughout, except for a few mentions of gallons (of gasoline, for example) and miles (1.609 km). See Appendix A for conversions and hydrogen facts. Tonnes = metric tons (1.102 short tons). MtH_2 = million tonnes of hydrogen. The energy content of hydrogen is typically taken at its Lower Heating Value.

"Valley Beyond," 102x126cm, Tania Dibbs, www.taniadibbs.com

Cover image of enhanced Greenland ice melt falling into a Moulin by Roger Braithwaite, University of Manchester; image used without permission due to hefty reproduction fee charged for an image taken whilst on a publicly-financed expedition (this image from Hansen, 2004; also in *Science* 12Jul02).

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Dedicated to my daughter Shana Breeze for her boundless enthusiasm, wisdom, and compassion.

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Summary, Analysis, & Recommendations

"People and nations behave wisely—once they have exhausted all other alternatives" —Abba Eban.

The vision of a pollution-free hydrogen economy has emerged as a public issue amid deepening U.S. dependence on soon-to-peak global oil supplies, rising oil prices, and growing unease over energy security issues. Seeing an opportunity to lower oil imports and boost the use of domestic energy resources, President Bush highlighted America's transition to a hydrogen economy in his 2003 State of the Union address by telling the nation that "the first car driven by a child born today could be powered by hydrogen, and pollution-free." In one swift and well-received stroke, the Bush Administration simultaneously supported the carbon and nuclear lobbies *and* pacified the environmental community. The U.S. Dept of Energy (DOE) was charged with outlining the hydrogen transition and did so through a series of roadmap and RD&D workshops in 2002-2003. DOE's hydrogen research budgets were sharply increased. Congress, seldom known to dither in the face of lucrative boondoggles, also re-shaped the National Energy Bill into what Senator McCain called "The Leave No Lobbyist Behind Act" and whose $24 billion cost promised acute trichinosis in Washington.[1] The Bill's hydrogen titles and DOE's research have supported aggressive development of multiple hydrogen production options, end-use equipment, storage media, and related issues such as safety codes and public education.

The central concern of this report is that hydrogen's advantages may be sullied by the manner in which hydrogen is produced and delivered. The Bush Administration's preference, based on its budgetary priorities, is to keep hydrogen a "black" energy carrier: centralized, vulnerable, costly, environmentally damaging, and controlled by incumbent industries. Still, there are good reasons to believe that black hydrogen will be out-competed by more sensible and sustainable options. The electricity sector is shifting from centralized generation to distributed generation coupled to end-use efficiency, and the hydrogen infrastructure is likely to follow a similar pattern toward decentralized, resilient, decarbonized, cleaner, cheaper, and nimbler systems. The question is whether the Administration and the U.S. Dept of Energy will get with the green hydrogen program or stay in the black.

Concerned that a critical opportunity to clean and transform the nation's energy systems might be hijacked by the incumbent carbon and nuclear industries and thus mismanage a fundamental shift toward energy sustainability, Greenpeace USA commissioned this report from Climate Mitigation Services to describe the many hydrogen production pathways, assess the potential of producing hydrogen using renewable energy, outline the principles of sustainable hydrogen production, trace DOE's policy and budgetary priorities, and, in particular, evaluate the rationale and weaknesses of the Nuclear Hydrogen Initiative. Is it true, for example, that nuclear reactors can reliably, cheaply, and safely produce hydrogen for the emerging hydrogen economy, as proposed by DOE, the nuclear industry, and even some "greens"? Is 'atoms for sustainability' a promising solution, and should environmental NGOs reconsider opposing all things nuclear?

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[1] Statement of Senator McCain on The Energy Bill, 19Nov03: "Adding to this feast, this bill also contains the other white meat. Of course, I am referring to pork. I fear for the passage of a 1,200-page, pork-laden bill. The outbreak of Washington trichinosis will be so severe we will be forced to have a field office for the Centers for Disease Control right next to the Capitol. I am not saying this will not generate some energy, not at all. It will fill the coffers of oil and gas corporations, propel corporate interests, and boost the deficit into the stratosphere." mccain.senate.gov/index.cfm?fuseaction=Newscenter.ViewPork&Content_id=1187

Summary

Hydrogen combustion results in a remarkable oxide: H_2O, water, the cleanest exhaust imaginable. Yet the hydrogen economy will *not* cleanse the environment or reduce emissions of carbon dioxide *unless* hydrogen is produced from clean energy sources. Hydrogen does not occur naturally; it can't be dug up in a magic mine. It has to be produced through human ingenuity and technology. Today hydrogen is primarily used to refine and sweeten oil, in fertilizer production, and even in foods. Nearly half of the world's annual production of 48 million tonnes of hydrogen is produced by steam reforming of natural gas (chiefly methane, CH_4). The most significant environmental challenge to producing hydrogen from fossil fuels is the co-production of large amounts of carbon dioxide, all the more so from coal and tar sands and heavy oils than from lighter liquids and gases with higher hydrogen to carbon ratios. All fossil fuels contain varying percentages of hydrogen, thus it can also be produced from petroleum and from heavy oils and tar sands, as well as from coal. The U.S. has the largest coal reserves (~250 billion tonnes).

Coal is typically 4.7-6.3 percent hydrogen by weight. Technologies to separate the hydrogen are fairly well advanced, though the coal must be mined and transported before it enters an energy-intensive multi-stage gasification process where the hydrogen is separated from the carbon, sulfur, and other contaminants common to all coal types. If fossil fuels are to become significant long-term hydrogen sources, it will necessitate the capture, injection, and reliable storage of the carbon dioxide in geologic reservoirs for several hundred years. This appears technically and economically feasible but must be studied, monitored, and verified; fears that the public will equate carbon storage with nuclear waste concerns are probably exaggerated. To further this objective, Congress is funding DOE's $920-million proof-of-concept "clean coal" facility that aims to demonstrate affordable electricity generation plus hydrogen production with the capture and storage of 80-90 percent of the carbon dioxide. Making use of U.S.'s vast coal resources may require the capture and storage of a *billion* or more tonnes of CO_2 annually by 2050.

Fortunately, cleaner alternatives exist. Biomass resources can be gasified and the hydrogen removed. Other biological and bio-mimetic hydrogen production pathways are being studied, such as eukaryotic green algae. Solar heat can thermo-chemically dissociate hydrogen from water or boost the efficiency of hydrogen recovery from fossil fuels, and solar radiation can catalytically crack water into hydrogen. Electricity from wind, photovoltaic, hydroelectricity, tides, waves, ocean or river currents, or geothermal power can produce clean hydrogen at service stations through electrolysis. However, some of America's largest and cheapest renewable sources are currently stranded by a lack of access to existing wire and/or pipeline grids.

All preparation of fuels requires energy input, whether it's cutting firewood, refining gasoline, or generating electricity. So, too, for hydrogen, whether we use today's electrolyzers that are 60 to 73 percent efficient in converting electricity into hydrogen (not including the conversion and T&D losses in generating and delivering the electricity) or renewable or fossil hydrocarbon sources. Society readily makes the choice to invest energy and capital for the purposes of convenience, new uses, deliverability, and cleanliness, as we do in favoring electricity and absorb the roughly 60 to 70 percent loss when coal is consumed in power plants and delivered to customers. Fossil fuel use is typically a dirty process from beginning to end: routine oil leaks, tanker accidents, water pollution, mountain top removal, uranium wastes, unsightly power lines, fly ash, acid rain, particulate pollution, smog, upper respiratory diseases, sullied buildings, social injustices, community and ecosystem disruption, and oil wars are among the consequences we

bear for the many benefits of using energy. Energy production and use impact the environment to some degree, including renewable energy and hydrogen. Persistent environmental pressures lead, albeit too slowly, to regulations, improved corporate performance, and the implementation of cleaner energy options. Since hydrogen produces warm water and electricity when used in fuel cells—as will happen soon enough in hydrogen fuel cell vehicles from scooters to submarines but soonest and most significantly in light- and heavy-duty vehicles—the hydrogen economy meshes nicely with the inexorable U.S. and global trend toward lower-carbon energy supplies (see Fig 2, p. 6). While this trend boosts the likelihood of a hydrogen economy, it is neither inevitable nor necessarily as clean and carbon-free as it must be to survive in the 21st Century.

Nuclear reactors have been proposed as sources of heat or electricity for hydrogen production. While current reactor types can produce hydrogen through electrolysis (as can all electricity sources), new reactors are being designed to produce the high temperatures required for thermo-chemical dissociation of water into hydrogen and oxygen. Several nuclear reactor and hydrogen production pathways are being studied, including the use of different catalysts, hybrids, "hot" electrolysis, modular reactors, coolants, and so on. The U.S. Dept of Energy, its nuclear industry partners, and several foreign governments are collaborating on new reactor designs with strict construction cost criteria, improved operating efficiencies (≥48 percent), inherently safe to operate, proliferation resistant, and which may ease the nuclear waste burden. An investment of several billion dollars in RD&D on six Next Generation Nuclear Plant (aka Gen-IV) designs is proposed, with two high-temperature reactors of greatest utility for hydrogen production. DOE has launched the Nuclear Hydrogen Initiative with proposed initial funding of $1.14 billion (plus "such sums as are necessary") over FY2004-08 to demonstrate the viability of nuclear hydrogen production. The size of the nuclear hydrogen enterprise is daunting: 241 to 444 GW of nuclear capacity is required to supply the hydrogen needed for the U.S. transportation sector.[2] Using the MIT study's cost estimates, this means an investment of $0.62 to $1.1 trillion (see pages 26, 29).

Our analysis of the costs and vulnerabilities of nuclear reactors for electricity generation or hydrogen production highlights several shortcomings (see pages 26-32):

- New nuclear will remain a high-cost and highly vulnerable source of electricity and/or hydrogen.
- The competition to new nuclear is not old nuclear, it's electric efficiency, advanced natural gas turbines, distributed generation, and wind power, all of which are cheaper, faster, more modular, security-enhancing, and safer.
- The competition to centralized, unsafe, and expensive nuclear hydrogen is not lower-cost nuclear hydrogen but distributed, faster, cheaper, and safer hydrogen production and delivery pathways.
- Nuclearization is an uncompetitive way to reduce emissions of carbon dioxide by displacing coal-fired electricity or by producing hydrogen to displace transportation fuel.
- Uranium reserves are inadequate to run large-scale nuclearization, whether it's the 4,000-reactor climate-safe world of the enthusiasts or a slower build-up to global hydrogen production; uranium reserves are adequate, however, to supply a gradual expansion of nuclear capacity through 2050.
- Safe disposal of nuclear wastes is far from resolved, and the Faustian bargain to safely keep radioactive wastes out of the biosphere for thousands of generations remains in effect.
- The transportation of radioactive wastes and weapons-grade plutonium remains an unacceptable vulnerability, even before the threat of terrorists targeting the waste-transportation infrastructure.
- Peaceful uses of nuclear materials, technology, and know-how opens the lid to Pandora's box of proliferation of radiological materials, designs, or weapons into the wrong hands, too often leading to international blackmail and global insecurity of the first order, now potentially even brought by jihadists wishing our destruction.

[2] U.S. nuclear capacity totaled 98.6 GW in 2002. Chiefly for hydrogen production based on projected demand in the 2040-2050 timeframe. Estimate excludes replacement of future decommissioned nuclear power plants. Hydrogen demand: see pp. 17-18.

- Reactor designs may not prove inherently, passively, or "walk-away" safe, and reactor vendors are hoping NRC regulators will license reactors without containment domes and other crushingly expensive safety features that seriously compromise nuclear economics.
- Nuclear thermo-chemical hydrogen production is a complex technology much farther from commercialization than other hydrogen production pathways.
- Even if reactors can be cost-effectively built, safe to operate, with an invulnerable fuel cycle, and proliferation proof—the technology still suffers from unacceptable risks. In a new jihadist world, reactor complexes, waste storage pools, and other concentrations of radioactive materials should not be pre-positioned around American cities as convenient targets for patient enemies to attack.
- The Nuclear Regulatory Commission and the nuclear utilities cannot assure adequate protection of America's 103 existing reactors, much less guarantee the invulnerability of the hundreds of new reactors envisioned by the nuclear hydrogen and nuclear climate-mitigation enthusiasts.
- Renewal of Government-guaranteed Price-Anderson liability protection (which S.2095 proposes to extend through 2023) catches the nuclear industry simultaneously assuring public safety *and* seeking deep public pockets as backing for unavailable private-sector accident insurance.
- Even the largely pro-nuclear MIT report acknowledges that "[w]e have not found, and based on current knowledge do not believe it is realistic to expect, that there are new reactor and fuel cycle technologies that simultaneously overcome the problems of cost, safety, waste, and proliferation."
- Solving fewer than all of these problems is taking the nation down the wrong path.

Today, hydrogen is produced for internal refinery uses at a cost of ~$0.78 per kg, or considerably less than prevailing gasoline retail prices (a kg of hydrogen and a gallon of gasoline contain the same amount of energy). The difference is due to the cost of delivery: hydrogen delivery is very costly, and expensive infrastructure will have to be made to deliver bulk hydrogen to market, whereas the gasoline delivery infrastructure has already been installed (although not cheap: an estimated $37 billion in new capital is invested annually in the U.S. to bring gasoline to market). Hydrogen supply is likely to grow gradually, first at nodes to supply fleet and highway vehicles, then increasingly by steam methane reformers at filling stations strategically dispersed and sized for the expanding demand. Residential hydrogen appliances may also play an early role, as may be the use of 20-40 kW fuel cell vehicles to generate electricity while idle at home or at work. Future hydrogen demand may eventually justify investment in large distribution pipeline networks from centralized hydrogen production plants such as coal or nuclear facilities.

Centralized hydrogen production may be out-competed by better alternatives, however. *All* of the nation's transportation-sector hydrogen demand can be met by capturing a fraction of America's enormous wind resource potential. Solar electricity and solar-concentrated heat offer numerous promising pathways. Biomass materials from farms, forestry operations, and other sources of organic wastes can supply a sizeable fraction of projected hydrogen demand. Other renewable energy, hybrid, biological, and bio-mimetic hydrogen production pathways are being studied. Hydrogen can also be produced from water through electrolysis of H_2O into its constituent hydrogen and oxygen using either clean renewable power or carbon-intensive grid power, or, if the nuclear industry succeeds, low-carbon nuclear electricity. Which path should we take?

Analysis & opinion

The majority of American citizens support clean energy and real action on global warming. The Bush Administration offers a rosy smoke screen that promises clean hydrogen vehicles but at the unspoken expense of keeping America beholden to dirty and/or insecure ways to centrally produce and deliver hydrogen to market. This is to be achieved with billion-dollar taxpayer-supported incentives to mature and profitable incumbent industries intended to leverage

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enormous private-sector capital into, we conclude, undesirable ways to produce and deliver hydrogen. The opportunity costs of these pathways are even greater: foregone investment in energy efficiency, missed opportunities to profitably reduce U.S. greenhouse gas emissions, rising energy costs, increased energy vulnerabilities, and a hydrogen transition delayed.

The DOE is faithfully following the Administration's policy objectives with respect to hydrogen production and the ancillary clean coal, carbon capture and storage (CCS), FutureGen, Nuclear Hydrogen, Next Generation Nuclear, and related initiatives. DOE's recent private-sector grants for renewable hydrogen production and delivery show the agency's broad investment portfolio in a good light.[3] Support for these programs, however, is miniscule compared to support for carbon- and nuclear-based hydrogen production. Meanwhile, pork-addled Congressional supporters of both parties have wasted no time heaping money into the corporate welfare trough for solutions most likely doomed to failure in the market place. (The following critique is not directed at the thousands of dedicated scientists, engineers, and managers at DOE's research laboratories, but at decision-makers within DOE, the Bush Administration, and Congress.)

Massive subsidies or regulatory preferences for large, centralized, capital-intensive and supply-oriented energy solutions are nothing new in Washington. It is pervasive to both parties and illuminates a "group-think" aspect that runs strongly counter to American strengths. To wit, with a focus on hydrogen, energy, and climate issues:

- **Technology:** The prevailing Administration view is one of deep mistrust of both technology and, paradoxically, reduced federal manipulation of the energy market—all while touting hydrogen vehicles, clean coal, and carbon sequestration technologies. When it comes to innovation and technology, the Administration simply cannot comprehend the speed, effectiveness, and scale with which smart leadership, re-tooled policies, off-the-shelf technology, and an economically rational best-buys-first approach can solve otherwise intractable energy and climate problems.
- **Hard path:** in its RD&D plans, the Administration selectively favors dirty, costly, and insecure hydrogen production pathways over the sustainable pathways the hydrogen transition ultimately promises. These go beyond favors to campaign contributors: they illustrate a reliance on narrow expertise and an incumbent-industry approach to "solutions" that often forge deeper problems. Durable solutions require input from a broader spectrum than is typically acceptable to the cabal's members. Examples of this intransigence include the beliefs that energy efficiency doesn't really exist (or it would have been bought already), renewables are immature and can't solve real-world problems, efficiency is for weenies, and 'heavy energy use is a reflection of economic strength.'
- **Environment:** the Bush Administration makes the environment the enemy of economic progress and fails to comprehend the proven profits and demonstrable benefits—both to our economy and our national security—of environmental stewardship. This perception is built into the Administration's hydrogen or climate posture plans.
- **Job creation:** it is almost curious that the job-creation potential of renewable energy and end-use efficiency (as opposed to the typically job-destroying advances in coal mining and oil extraction industries) has not caught the attention of policy-makers. Curious, until one remembers that money trickles *up*. RD&D dollars are heavily invested in capital-intensive energy solutions that favor big business as opposed to job-creating least-cost energy efficiency and renewable energy options. We are not against business, small or large: we do favor fair competition and best buys.
- **Fair competition:** renewable energy is deemed "immature" and policies are promulgated to help ensure the situation doesn't evolve to threaten the stranglehold that incumbent industries have on America's future. Evolve it does, of course, and technical and cost improvements have made several renewable technologies competitive against fossil and nuclear options. Even troglodyte industries evolve, and the smartest energy companies *lead* on climate mitigation and winning approaches to hydrogen production and delivery.
- **Orwellian initiatives:** Clear Skies Initiative, Healthy Forests Initiative, "tax relief," "pollution-free hydrogen," and the Patriot Act are salient examples of the Administration's double-speak.

[3] DOE has recently granted $5.4 million to improve reliability and cost of small methane and alcohol reformers, $2.6 million for research on carbon molecular sieves (simplifying hydrogen via biomass or hydrocarbon gasification), and several million for the design and construction of a solar-powered electrolytic hydrogen service station.

- **Governance I:** Government is not the problem; poor governance is. The Bush Administration's aversion to climate leadership is contrary to our economic interests. The notions that effective climate mitigation has to be wildly expensive and that clean hydrogen production has to be hijacked by reactor vendors and coal companies are counter-productive.
- **Governance II:** Government should steer, not row. The federal government has the opportunity to steer the nation toward sustainable hydrogen production and many other technological leapfrogs that promise to reduce emissions and oil imports while strongly benefiting the economy, global security, and environmental health. Government leadership is urgently needed to envision and implement fundamental changes in how this nation produces and consumes energy, lest we end up where we are now headed: investing trillions into dead-end hydrogen pathways.
- **Governance III** / ideas that hold us back: "That's a big 'No' said Press Secretary Ari Fleischer in early 2001, in response to being asked if the President will ask Americans to use less energy. "The President believes that it's an American way of life, that it should be the goal of policy makers to protect the American way of life. The American way of life is a blessed one … The President considers Americans' heavy use of energy a reflection of the strength of our economy, of the way of life that the American people have come to enjoy."[4] Few in Government appreciate the nation's potential to maintain its standard of living using dramatically less energy.

Impending climate change is appropriately viewed as a threat to U.S. and global security. The transition to the hydrogen economy *will* reduce emissions of greenhouse gases *if* the hydrogen is produced primarily from zero-carbon renewable sources or most of the carbon from hydrocarbon sources is reliably sequestered. Contrary to industry publicity, nuclear power is a high-cost way to displace oil with hydrogen. If DOE's vision is poised to lead the nation down the black hydrogen path, what's a reasonable way forward?

The way forward: sustainable hydrogen

Civil society supports clean energy. Corporations have the skills, resources, and incentive to deliver profitable solutions. The President, DOE, and Congress have sound and profitable reasons discussed in this report to recalibrate policies toward sustainable hydrogen options and climate action. Sustainable hydrogen must be based on fundamental policy shifts and priorities:

- Hydrogen production must reduce net emissions of greenhouse gases and most other pollutants.
- Hydrogen production should boost domestic employment.
- U.S. hydrogen production should improve global equity and enhance global security.
- Hydrogen production must not rely on market-busting Federal or state subsidies. Indeed, existing subsidies should be phased out to create fair competition between competing hydrogen pathways. It is suboptimal to level the playing field by adding new layers of incentives and tax expenditures.
- Markets work best when prices tell the truth: sustainable hydrogen production can be fostered by reforms that gradually and predictably internalize social and environmental costs into prices.
- Federal and state reforms must systematically remove regulatory biases against market-oriented opportunities to reduce energy, carbon, and material intensities.
- Even sustainable hydrogen production is likely to degrade sustainability unless serious efforts are made to improve end-use efficiency prior to or in parallel with hydrogen development.
- Hydrogen production pathways should account for and minimize vulnerability to disruption, embargoes by international cartels, terrorist attacks, accidents, and price fluctuations.
- Communities and consumers must feel—and be—safe in proximity to hydrogen production and fueling infrastructure.
- U.S. DOE and other Federal agencies must adopt sustainability guidelines that reflect societal, environmental, security, and economic concerns in RD&D planning and budgeting priorities; it follows that energy policy should not be developed in secret meetings nor by incumbent industry participation alone and that great care should be mustered to avoid "group think" by experts, political donors, and companies seeking to profit from particular policies at great societal costs.
- Hydrogen production and delivery pathways are most reliable and secure when diverse.

[4] White House Daily Briefing, 7May01. After 9/11, President Bush told us to go shopping.

In pursuit of a sustainable and profitable hydrogen transition, the U.S. DOE should recalibrate its own budgetary and RD&D priorities to (a) de-emphasize its nuclear hydrogen development and demonstration programs, (b) develop a roadmap to a sustainable hydrogen economy, and (c) substantially re-allocate its RD&D resources in support of its new sustainable hydrogen mission. As shown on pages 36-41, renewable energy resources can provide many times the projected hydrogen demand (though often remote from hydrogen markets and existing transmission grids). Renewable energy systems are more resilient, less vulnerable, creates domestic jobs, and already economically competitive with coal-fired and nuclear generation. The intermittency of solar and wind-generated hydrogen or electricity is resolvable with storage, geographic and technologic diversity, substitution, back-up systems, and demand management. Supplying hydrogen from renewable electricity, direct solar catalysis, and domestic biomass can amply supplant hydrogen from centralized, vulnerable, costly, and environmentally destructive options now the principal focus of DOE's hydrogen production efforts. We commend the DOE for its work on distributed and renewable hydrogen production, but urge that these efforts be rationalized and strengthened.

While the Bush Administration has tied a knot between clean hydrogen use and unsustainable hydrogen production and delivery, there is a way to untie this unworkable conundrum. Energy efficiency is the critical (and still largely ignored) component to first reduce demand, since neither a black nor a green energy future can sustain the consequences of rapid energy growth throughout the 21st Century. Energy efficiency is eminently practical and profitable in every sector, in nearly every application, and in every nation. U.S. efficiency gains since 1973 now trim annual energy costs by nearly $200 billion per year, and we can profitably dig far deeper. Electric efficiency and renewable electricity can eliminate the need for any new coal-fired electric generation before renewable surplus can be applied to hydrogen production. Saving natural gas in buildings and industry frees up gas for distributed hydrogen production and for backing up renewable electricity and hydrogen). Domestic bio-fuel resources from organic wastes and biomass crops can contribute a third or more of projected hydrogen demand. Renewable energy can substantially decarbonize the U.S. electricity sector *and* supply all projected hydrogen demand, *if* we so choose.

The U.S. DOE has not endeavored to develop a roadmap of how to realize these opportunities, and must do so with the speed and thoroughness the diverging path before us deserves. We urge DOE to collaborate with a broad spectrum of stakeholders in this roadmap effort. A sustainable hydrogen roadmap would endeavor to overcome technical barriers and propose policies in order to, as Ray Anderson says, turn "stumbling-blocks into stepping-stones."

"We are confronted by insurmountable opportunities," Pogo said years ago. A practical and brighter vision takes economics seriously, honors fair competition, encourages innovation, and leverages the enormous value of working toward a well-articulated common goal. A vision that values human ingenuity and gradually creates a level playing field where the best ideas can succeed. It shifts taxation from goods to bads so prices tell the truth and markets become, in David Korten's phrase, "mindful," gradually de-subsidizes the energy sector, sets achievable targets for reducing emissions, and spurs market-oriented approaches to decarbonize and dematerialize the economy. These challenges will create jobs and new economic opportunities. This is a vision called into action on behalf of all humanity, as if, truly, all people matter.

Better-functioning markets are not enough. To foster this vision, active leadership is essential. Real security is not ensured by the most powerful military the world has ever seen. It springs from the most empowering, honorable, and decent principles the human mind has ever known.

Recommendations

"If you want to build a ship, don't drum up the men to gather wood, divide the work and give orders. Instead, teach them to yearn for the vast and endless sea."… "As for the future, your task is not to foresee it, but to enable it." —Saint-Exupéry[5]

"Unless we change direction, we are likely to end up where we are headed" —Chinese proverb

We believe the United States can envision a better world than where we are headed. To achieve it, the President and Congress must assume leadership. Progress toward sustainable business practices is expanding at a gratifying pace; still, American business leaders are at a disadvantage. Our energy markets fail to signal the value of efficiency and the cost of atmospheric carbon dumping. To address market failures and to foster a shift to sustainability requires fundamental domestic policy changes as well as international cooperation on energy and climate issues. The hydrogen economy offers enormous opportunities—and the potential of staggering losses. The Administration must provide guidance to prudently steer our economy's vast momentum. The coming transformation necessitates enormous infrastructure changes. It's essential to squander neither capital nor hope on the black hydrogen path. It's beyond this report's scope to develop a coherent set of sustainable hydrogen policies, but a few recommendations are offered:

Recommendations to DOE and the Administration:

- Climate change is a national security issue and the White House and DOE must communicate it as such. Mitigating the danger can be profitable, if done right. The White House should pursue a profitable, equitable, and security-enhancing climate mission focused on energy efficiency, GHG emissions reduction, international engagement, and adaptation.
- A carbon tax can be revenue neutral and should be applied *first* to energy efficiency opportunities and climate mitigation options across all economic sectors (including agriculture). Once GHG emissions show promise of decline, facilitating the hydrogen transition then becomes imperative.
- Revenue neutral feebates on new vehicles are more effective, faster, and more flexible than strengthened automobile fuel economy (CAFE) standards.[6]
- Rationalize and prioritize DOE's RD&D on the basis of best buys first, then prioritize as if sustainability matters.
- In most cases, this means efficiency first, then boost least-cost renewable electricity, then least-cost renewable hydrogen production. The market—once unfettered and steered on a rational, profitable, and sustainable path—will yield results far superior and durable than the black path.
- Remove barriers to sustainable and profitable technologies and implementation strategies.
- Transfer RD&D funds from high-cost hydrogen production to less costly (and likely more successful) *delivered* hydrogen pathways. Sustainability, jobs, and security must be part of the decision matrix. This suggests de-centralized hydrogen production, initially by small reformers and later by renewable hydrogen production and delivery pathways.
- To this end, DOE should undertake a comprehensive assessment of America's regional renewable hydrogen production and delivery pathways.
- Identify and pursue rational policies to vastly improve the efficiency of America's consumption of oil, energy, and materials.[7] U.S. oil imports can be *eliminated* by 2030 and oil consumption eliminated by 2050. Electric and natural gas efficiency can reduce consumption by half or more.
- Identify and gradually phase out the most onerous and market-distorting subsidies & regulations. Eliminate perverse incentives, such as tax breaks for purchasing massive fuel-guzzling vehicles.

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[5] Antoine de Saint-Exupéry (1948) *Citadelle*, quoted in Lovins et al, 2004, p. 30.

[6] Lovins et al (2004), pp. 186-190.

[7] An excellent place to start is with the comprehensive set of oil-saving policies in Lovins et al (2004) *Winning the Oil Endgame*. See also Romm (1999), the extensive electric efficiency information in the E SOURCE Technology Atlases (www.esource.com), Hawken et al (1999), Interlaboratory Working Group (1997), and the many efficiency and policy reports by ACEEE, IEER, NRDC, RMI, SEI, WRI, Worldwatch, and other energy NGOs.

- Gradually internalize external costs of energy use. As the DOE acknowledges: "Existing energy policies do not promote consideration of the external environmental and security costs of energy that would encourage wider use of hydrogen".[8]
- Assist states to set improved energy building codes. Strengthen DOE's appliance standards. Reward builders and manufacturers who exceed energy codes. Use golden carrot programs. Publicize voluntary efforts by American companies that exceed aggressive commitments.
- Active and visible government *and* corporate leadership is even more important than rationalizing the market, since profitable and efficient climate-mitigation opportunities exist in every sector.
- Encourage effective community energy-efficiency retrofits and upgrades. Reward success.
- Set binding national GHG emissions targets; adopt market-oriented trading mechanisms.
- Phase out nuclear power; abandon the costly Yucca Mountain waste repository in favor of temporary storage until a permanent solution can developed later in this century; provide funds for training of operators of U.S. foreign nuclear facilities (to lessen physicist Hannes Alfvén's concern that the nuclear enterprise will "pass into ever less competent hands").

It is extremely important to get the hydrogen transition right, or we waste enormous capital, energy, materials, hope, and time.

Comments to environmental NGOs:

- Genetic engineering will enter the hydrogen-from-biomass debate. ENGOs must think through the implications and prepare position statements.
- Renewable hydrogen production pathways are plentiful, even without better price signals of the full costs of using non-renewable and nuclear energy. U.S. wind power resources alone can electrolyze all of the hydrogen an efficient transportation system is projected to need.
- If DOE is unwilling to do so, ENGOs should research a path to sustainable hydrogen for the U.S. and present a coherent vision to policymakers and the public. A focus on the pathways, resources, costs, and geography of the first decade of this sustainable hydrogen path would be very valuable.
- Carbon capture and storage (CCS) technologies are likely to become important for both climate and hydrogen reasons, and should not be dismissed by the ENGOs without careful deliberation of how to proceed. Environment NGOs must apply continuous pressure to ensure that CCS is adopted by utilities and large emitters, verifiably safe, and adequately monitored. The costs of CCS should be predominantly borne by ratepayers and hydrogen consumers, not taxpayers.
- A broader objective is the reduction of U.S. carbon emissions, and this can be accomplished cheaper (chiefly through end-use efficiency) than by putting diapers on hydrogen or electric plants and dumping the waste in geologic pits or, worse, in the atmosphere. A likely hydrogen delivery winner—on-site methane reforming—currently vents the methane's carbon. Technical progress may yield methods to pelletize the carbon for collection and storage.
- ENGOs should help set long-term goals for total U.S. carbon and GHG emissions. In order to establish early-, mid-, and long-term goals for U.S. emissions and offsets this effort must embrace the best science on radiative forcing, cooling *vs* warming compounds, biologic sequestration, JI and CDM, atmospheric concentrations, and the "sustainable" absorptive capacity of each gas.
- Cap and trade, carbon pricing, and similar mechanisms will help usher in sustainable hydrogen by putting a cost on emissions, a value on mitigation, and a clear signal that corporations, citizens, and communities can take additional action to be part of the solution.
- Keep up the pressure on the security vulnerabilities of nuclear power, radioactive waste transport, nuclear materials containment, and continued destruction of weapons & weapons-grade materials.
- ENGOs have done an excellent job of speaking for the public and influencing government policy, albeit less effectively in the U.S. than in Europe. Continued collaboration, consensus-building, and communication with progressive corporations and business groups is essential.

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[8] U.S. DOE (2002b) *National Hydrogen Energy Roadmap*, p. 1; cited in U.S. DOE (2004j) *Nuclear Hydrogen R&D Plan*, p. 1-1.

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Black Hydrogen

"If God did create the world with a word, that word would have been hydrogen."[9]

"Trying to solve climate change with nuclear power is like trying to cure the plague with a dose of cholera."[10]

Introduction

The Bush Administration has launched an effort to burden—at considerable public expense—the emerging hydrogen economy with capital-intensive and dangerous ways to produce otherwise clean hydrogen fuel. The oft-misguided U.S. Department of Energy is poised to invest hundreds of millions, if not billions, of dollars into revitalizing nuclear power. Thought that dog was dead? Think again. Why is the DOE trying to reconstitute what Amory Lovins calls "the greatest failure of any enterprise in the industrial history of the world"?[11] Yet, the DOE and the nuclear power industry are gaining support for a nuclear revival from unexpected quarters. Says Gaia proponent James Lovelock:

> *"Opposition to nuclear energy is based on irrational fear fed by Hollywood-style fiction, the Green lobbies, and the media. … Even if they were right about its dangers—and they are not—its worldwide use as our main source of energy would pose an insignificant threat compared with the dangers of intolerable and lethal heat waves and sea levels rising to drown every coastal city of the world. We have no time to experiment with visionary energy sources; civilization is in imminent danger and has to use nuclear, the one safe, available energy source, now, or suffer the pain soon to be inflicted by our outraged planet."*[12]

This report evaluates the rationale for and against a nuclear revival for the transition to a "clean and green" hydrogen economy within the context of climate mitigation. What are the issues that will blunt the arguments by "green" and "black" nuclear advocates alike? What are the other options for producing hydrogen, and what domestic energy sources will be used? Will hydrogen be as sustainable as it must be to succeed in the 21st Century? Can the hydrogen transition really avoid dangerous anthropogenic climate change and solve the vaunted search for "energy independence"? Indeed, the Bush Administration is hanging its climate action plan on the hope that hydrogen fuel will decarbonize the U.S. economy fast enough to prevent dangerous climate change, and thus obviate the need to do anything about reducing emissions now. This report ignores hydrogen end-use technologies as well as safety and testing issues, codes and standards, and current technology shortcomings such as on-board hydrogen storage, driving range, re-fueling time, high cost of fuel cells, public education, liability, and other barriers.[13] Here we focus on DOE's policies for ushering in hydrogen supply pathways, with particular attention to the pros and cons of its support for expanding nuclear power for manufacturing hydrogen.

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[9] Harlow Shapley, quoted in Romm (2004), p. 68.

[10] Claire Greensfelder (Plutonium Free Future), CNN interview, Kyoto, Dec97; quoted in Hoffman (2001), p. 11.

[11] Lovins et al (2004), p. 259.

[12] Lovelock (2004) editorial, *The Independent*, London, ~28May.

[13] We direct the reader to the many publications that discuss general aspects of the hydrogen economy and end-use technology, particularly: Romm (2004a), Hoffmann (2001), American Physical Society (2004), National Research Council (2004), Dunn (2001), Kruse et al (2002), and (on the under-appreciated liability issues) Moy (2003).

The nuclear hydrogen vision thing

A linchpin of the Administration's longer-term plans is a strong commitment to help usher in the coming hydrogen economy, and President Bush pledged $1.7 billion toward the Hydrogen Fuel Initiative and the FreedomCAR Partnership over five years in his 2003 State of the Union address. "With a new national commitment," said President Bush, "... the first car driven by a child born today could be powered by hydrogen, and pollution-free." In Spencer Abraham's words: "the transition to hydrogen as a major energy carrier over the next several decades could transform the nation's energy system and create opportunities to increase energy security by making better use of diverse domestic energy sources for hydrogen production and to reduce emissions of air pollutants and CO_2."[14] Here is the home run appeal of hydrogen: it's (potentially) sustainable, reduces U.S. security risks and trade deficit, makes use of domestic resources, has a green image, is inevitable anyway, *and* reduces carbon emissions. Hydrogen can, says DOE's David Garman, reduce the $188 billion U.S. oil import bill projected for 2025.[15]

The nuclear advocates' vision can be summarized as follows: 'in support of the hydrogen economy, nuclear power plants will provide the electricity and heat to centrally produce inexpensive hydrogen for distribution by pipeline to tens of thousands of service stations to energize fuel cell vehicles and thus displace oil, reduce the use and burgeoning cost of imported oil, improve air quality in our cities, leverage economic growth using our ingenuity and domestic resources, and dramatically lower future emissions of climate-altering carbon dioxide.' Nuclear power plants do not emit carbon dioxide (although their fuel cycle does). The DOE hopes that a new generation of nuclear power plants can be built for a fraction of the cost of existing reactors and thus become competitive for both electric power and hydrogen production. Giddy congressional boosters, never flinching from a boondoggle, added funding in the stalled Senate Energy Bill (S.2095) for research and the Advanced Reactor Hydrogen Cogeneration Project at the Idaho National Laboratory totaling $1.14 billion for FY2004-08 plus "such sums as are necessary" beyond 2008; we discuss nuclear and related RD&D budgets starting on page 21. DOE also contends that the new plants will be inherently safe and proliferation-resistant. This sounds good, so what's the problem?

Well, the fundamental problem is that it's not going to work, it therefore wastes money and effort, and, worse, the opportunity costs of pursuing this chimera are grave. The U.S. is rich enough to throw a few bones to the nuclear industry, even a billion bones, but we can ill afford the delays in reducing carbon emissions and the profits available from doing so, nor the delayed implementation of the hydrogen economy from the misguided nuclearization efforts. Yet the risks of success, though unlikely (at least in the United States), are far graver: nuclear proliferation potential will remain serious, the transport and storage of thousands of tonnes of spent uranium and weapons-grade plutonium will be required, the cost of nuclear waste disposal and uranium enrichment facilities will mushroom, and the number of radiological terrorist targets conveniently pre-positioned around the American landscape will double or quadruple. Thus, on the bases of capital cost, operating cost, lack of clear environmental benefit, increasing domestic and international security risks, waste disposal, human health impacts, retarding the hydrogen economy, wasting billions, and delaying effective action on climate change, the hopes of the atomic hydrogen proponents are frayed beyond repair.

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[14] Abraham (2004).
[15] Garman (2003), p. 3, Congressional testimony, hearing on "The Path to a Hydrogen Economy."

This report argues that deploying new nuclear reactors as a hydrogen production pathway is uncompetitive and burdened with incurable vulnerabilities. The technology is doomed for a variety of sound reasons. Most of us remember the oft-recalled promise that nuclear power would provide electricity "too cheap to meter," a phrase uttered by hyperventilating officials in the early dawn of the nearly defunct nuclear age more so than by technical folk who knew better.[16] The technology suffers from fundamental economic, security, safety, and environmental failures; curiously, the very same "advantages" claimed by its supporters:

- New nuclear power plants are variously estimated to cost $2,000 to $2,500+ per kW (whereas the track record of current reactors is up to $3,000+ per kW), based on which an MIT team accurately calculates levelized electricity costs of 6.7 cents/kWh.[17] Since (a) there are many ways to produce and deliver hydrogen cheaper than the nuclear pathway, and (b) the competition to new nuclear is not old nuclear but inexpensive combined-cycle gas turbine power plants (3.8 cents/kWh)[18] and electricity savings (conservatively ≤2 cents/kWh).[19] Even new wind farms continue to deliver electricity at ≤4.4 cents/kWh and declining, which is why worldwide windpower capacity is expanding at 30 percent per year vs nuclear ~0.6 percent per annum over the last ten years.[20]
- While DOE has a nominal responsibility to fund a broad range of high-risk energy technologies, it also has to funnel its support to the most promising *emerging* technologies that private industry cannot adequately support. Advanced nuclear generation RD&D meets neither of these criteria. Just because the DOE aims to subsidize the next generation of nuclear technology to emerge from under a rock doesn't mean it's an emerging energy technology justifying heavy taxpayer support.
- Conservative estimates are that the nuclear industry received $66 billion in research support and direct subsidies from 1948 to 1998.[21] Moreover, the nation's energy RD&D has fallen by nearly 80 percent since 1980 (see Figure 9). DOE investment in renewables and energy efficiency has fallen faster than support for fossil fuel (e.g., clean coal) and nuclear options.[22]
- The opportunity costs of DOE's investment strategies delays the development and deployment of more cost-effective technologies, but a more serious opportunity cost occurs by private investment leveraged by DOE's subsidies to capital-intensive energy technologies such as nuclear power. American utilities learned this exceedingly expensive lesson over the last four decades. Furthermore, a dollar invested in new electricity supply (or invested in capital-intensive hydrogen production) is therefore not available to save electricity at a fraction of the cost of new supply. That was estimated as high as seven to one (using 1980s data): that is, a dollar invested in nuclear power to avoid carbon emissions can, if instead invested in saving electricity, keeps seven times as much carbon in the ground.[23] Today, with improved nuclear plant performance, the efficiency advantage is smaller, but still ~3 to 1 (or 2 cents or less per kWh saved vs ~6.7 cents for nuclear).
- Even if we assume rather optimistically that new reactors and their hydrogen production infrastructure can be built and operated without radioactive releases or accidents (and the history strongly argues against this assumption), we cannot realistically assume the same for radiological exposures to uranium mining and milling (and their enormous waste piles), enrichment, transportation of spent fuel, and eventual storage.
- Re-nuclearization will provide civilian cover for proliferation of nuclear weapons, technology, and expertise in the world's least reliable and often non-democratic states, as we are now witness to in North Korea and Iran. Bomb-making materials, and even assembled and easily deliverable micro-nukes, are or unnervingly close to being in the wrong hands in the new jihadist world.

[16] Makhajani & Saleska (1996). The phrase is by AEC Chairman Lewis Strauss in a 1954 speech: "It is not too much to expect that our children will enjoy in their homes electrical energy too cheap to meter …"

[17] MIT (2003), p. 7. This implies a delivered cost of 9.3 cents/kWh (according to Lovins et al 2004, p. 258, note 951).

[18] Ibid, p. 7: low natural gas prices ($3.77/million cubic feet) or up to 5.6 cents/kWh at high ($6.72/MCF) gas prices.

[19] Lovins et al (2004), p. 258.

[20] Worldwatch Institute (2003) *Vital Signs 2003*, pp. 37, 39; Sawin (2004), p. 7.

[21] Taxpayers for Common Sense (2004b). The Senate Energy Bill (S.2095) is rife with handouts for Generation-IV reactor design RD&D, loan guarantees, Nuclear Hydrogen Initiative, support for core nuclear programs, construction of a demonstration reactor, education and training, nuclear infrastructure, waste RD&D, etc. Furthermore, the industry is shielded from a great deal of liability in the event of an accident; even though the liability protection has never been used, it lowers the perceived capital risk.

[22] Kammen et al (2004), in press. See also Koplow (1993).

[23] Keepin & Kats (1988).

- The nuclear waste transportation and storage issue is far from solved, even after an investment in Yucca Mountain climbing through $7 billion. The State of Nevada doesn't want it (and has filed numerous law suits against it), the repository is unlikely to meet its planned 2010 deadline, and the U.S. Court of Appeals ruled in July 2004 that EPA's 10,000-year safety standard for the facility does not meet the requirements of the 1992 Energy Policy Act.[24] While the safe storage of high-level nuclear waste will remain a concern for hundreds of generations hence (imagine the chutzpah of this proposition!), a more immediate concern is the safe transportation of 70,000 tonnes of existing waste across the nation's urban and rural highways, railroads, and waterways. Harvey Brooks of Harvard University said in 1979 that "should nuclear energy ultimately prove to be socially unacceptable, it will be primarily because of the public's perception of the waste disposal problem."[25] While the caskets are deemed "safe" by DOT and DOE they are unlikely to prove safe against readily conceivable terrorist acts.
- Reactors and spent fuel storage pools at the nation's 103 operating nuclear power plants remain tempting terrorist targets, slightly beefed-up post-911 security at such facilities notwithstanding. As an anonymous observer saliently quipped: "No terrorist would bomb a wind turbine."
- The Nuclear Hydrogen Initiative will likely fail because it will be too late: new high-temperature Generation-IV reactor designs suitable for hydrogen production are not expected to be deployable until 2020-2025 or later, by which time other hydrogen production and related infrastructure will likely be in full swing—and probably dominated by on-site decentralized hydrogen production. In other words, the nascent competition will not sit still; Romm makes a parallel point regarding hydrogen fuel cell vehicles and its competition: namely advanced internal combustion and efficient hybrid-electric vehicles.[26]
- Centralized hydrogen production faces critical competition from cheaper centralized options, especially gas- and coal-based production with carbon capture and storage and zero-carbon wind and solar production. Centralization, of course, maintains the energy industry's stranglehold on the energy market with their pipes and wires delivery compatriots. Contrarily, the evolution of the energy services market is toward distributed generation, energy efficiency, combined heat and power, and load management.

The dangers of climate change

Human-induced global warming is a "weapon of mass destruction," a threat akin to terrorism, and U.S. inaction on climate change is an "abdication of leadership of epic proportions" says Sir John Houghton, co-chair of the Intergovernmental Panel on Climate Change's scientific assessment working group.[27] Sir David King, Chief Scientific Advisor to the U.K. government, warns that "millions will increasingly be exposed to hunger, drought, flooding and debilitating diseases such as malaria. Inaction due to questions over the science is no longer defensible."[28] Even if these warnings come across as a bit over the top, there is no doubt that climate change will be very costly—the United Nations and the insurance industry warn that the damages from climate change will likely reach into the hundreds of billions *annually* by 2030—and there will be a number of surprises for which we cannot prepare.[29] The U.S. will increasingly be seen as the unrepentant culprit, with all of the security, diplomatic, and economic costs thereof.

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[24] Dawson (2004), p. 29; see also Environmental News Service (2004b); Taubes (2003); Craig (2004).

[25] Quoted in Rifkin (1980), p. 109.

[26] Romm (2004a).

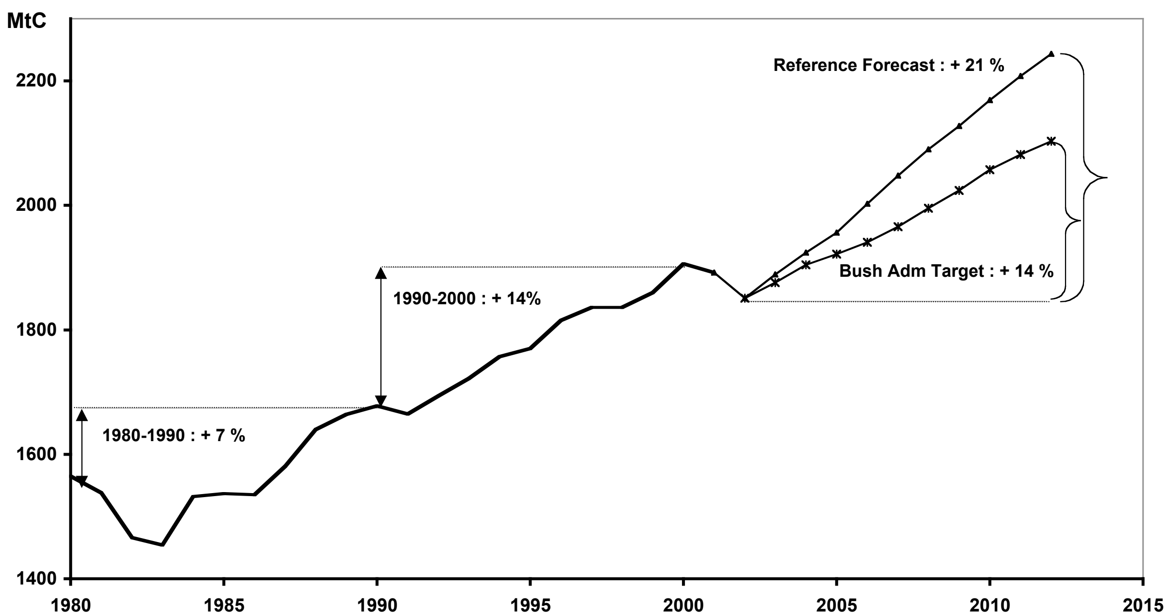
[27] Houghton (2004) "Global warming is now a weapon of mass destruction," *The Guardian*, London, 28Jul03.

[28] In Geoffrey Lean (2004) "Britain Talks Tough to Bush on Kyoto," *The Independent*, 15Feb04. King wrote in *Science* magazine's Policy Forum: "In my view, climate change is the most severe problem that we are facing today—more serious even than the threat of terrorism." *Science*, vol. 303:176-177. Goklany (2004), in a refutation of King, obfuscates that malaria can be controlled by means far less expensive than reducing emissions.

[29] SwissRe (2003) estimates that "the economic costs of global warming [could] double to $150 billion a year in 10 years, hitting insurers with $30-40 billion in claims, or the equivalent of one World Trade Centre attack annually … The human race can lead itself into this climatic catastrophe—or it can avert it." The United Nations' estimate is even higher: "over $300 Billion a year" by 2030, UNEP, Nairobi, 3Feb01. On climate surprises, see Alley (2004), Schneider (2001a), and Schwartz & Randall (2003a).

This impending humanitarian crisis deserves an emergency preparedness plan, or, better yet, an emergency *avoidance* plan. The Bush Administration's response appears clear: "The United States shares with many countries [the] ultimate objective: stabilization of greenhouse gas concentrations in the atmosphere at a level that prevents dangerous interference with the climate system," Abraham Spencer, DOE Secretary, wrote recently in *Science*.[30] The Administration invests nearly $2 billion annually on science and research, plus nearly $3 billion on the Climate Change Technology Program.[31] Appearances aside, the Administration's objective with respect to emissions reductions is stunningly non-existent, inasmuch as the aim is merely to reduce the greenhouse gas *intensity* of the U.S. economy (carbon-equivalent per dollar of GDP) by 18 percent below business-as-usual by 2012 (with the proviso that "as the science justifies and the technology allows [we will] stop and reverse that growth" in emissions).[32] Actual emissions are projected to *increase* by 14 percent 2002-2012, and 25 percent above 1990.[33] "My approach recognizes that economic growth is the solution, not the problem," contends President Bush. Yet a number of authoritative studies have shown that the U.S. can reverse the growth and reduce emissions at a *profit* to corporations, customers, shareholders, citizens, and governments.[34]

Figure 1. Projected result of the Bush Administration's climate policies



U.S emissions of Greenhouse Gases (MtC-equiv), as projected by Blanchard & Perkaus (2004, in press).[35]

[30] Abraham (2004) "The Bush Administration's Approach to Climate Change," *Science*, 30Jul04, vol. 305:616-617. The IPCC references three "metrics" that should not be exceeded: ecosystem adaptation, food production, and sustainable development, but little progress has been made on how to define, measure, or avoid such impacts, least of all by the U.S. administration. See Schneider (2003), and Mastrandrea & Schneider (2004).

[31] Emissions reduction from energy consumption, production, and infrastructure; reducing non-CO_2 emissions; carbon capture and storage; measurement and monitoring; and bolstering science research. Abraham (2004), p. 617.

[32] This is a far cry from the commitment the first Bush Administration made in Rio de Janeiro in 1990: to return U.S. emissions to 1990 levels by 2010. Quote from Abraham (2004).

[33] Blanchard & Perkaus (2004) forecast ~25 percent increase 1990-2012, following a recessionary dip in emissions. Pew Center on Global Climate Change (2002) forecast is slightly higher (30% increase 1990-2012) *Analysis of President Bush's Climate Change Plan*, www.pewclimate.org/policy_center/analyses/response_bushpolicy.cfm. See also Gugliotta & Pianin (2004).

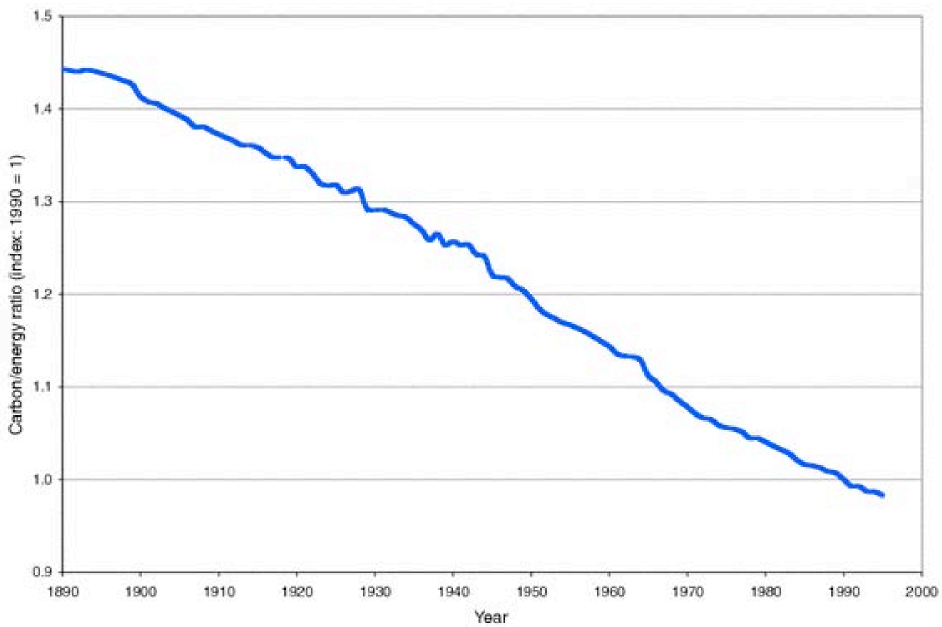
[34] For example, Romm (1999), Swisher (2002a), Hawken *et al* (1999), Lovins & Lovins (2001), Noble (2001), Climate Group (2004), and Interlaboratory Working Group (1997). Pacala & Socolow (2004) reiterated that the lack of political will is the relevant resource constraint, not effective technology.

[35] Reprinted from Blanchard, Odile, & Perkaus, James F. (2004) "Does the Bush Administration's climate policy mean climate protection?" *Energy Policy*, vol. 32:1993-1998, December, ©2004, with permission from Elsevier.

Decarbonization and clean fuel

There is a growing recognition that the U.S. and global economies are inexorably heading toward climate-friendly low- and zero-carbon fuels and continuing a long-term decarbonization trend (Figure 2). Hydrogen, potentially the penultimate carbon-free fuel, must be manufactured, and its clean and green image depends on how hydrogen is produced and delivered as well as the unintended consequences and opportunity costs of these choices. That said, there is little consensus about the timing of the evolution toward hydrogen: the enthusiasts argue that the requisite technologies such as fuel cell vehicles (FCVs) and hydrogen appliances (as well as implementation policies) are ready to burst on the scene, whereas the doubters do not dispel the advantages but caution that the hydrogen economy will take decades to mature and displace the entrenched higher-carbon fuels.

Figure 2. The decline of global carbon intensity 1800-1996.



Carbon intensity of global primary energy consumption, 1890-1995, indexed. Grübler & Nakicenovic via NRC (2004).

What is hydrogen and where will it come from?

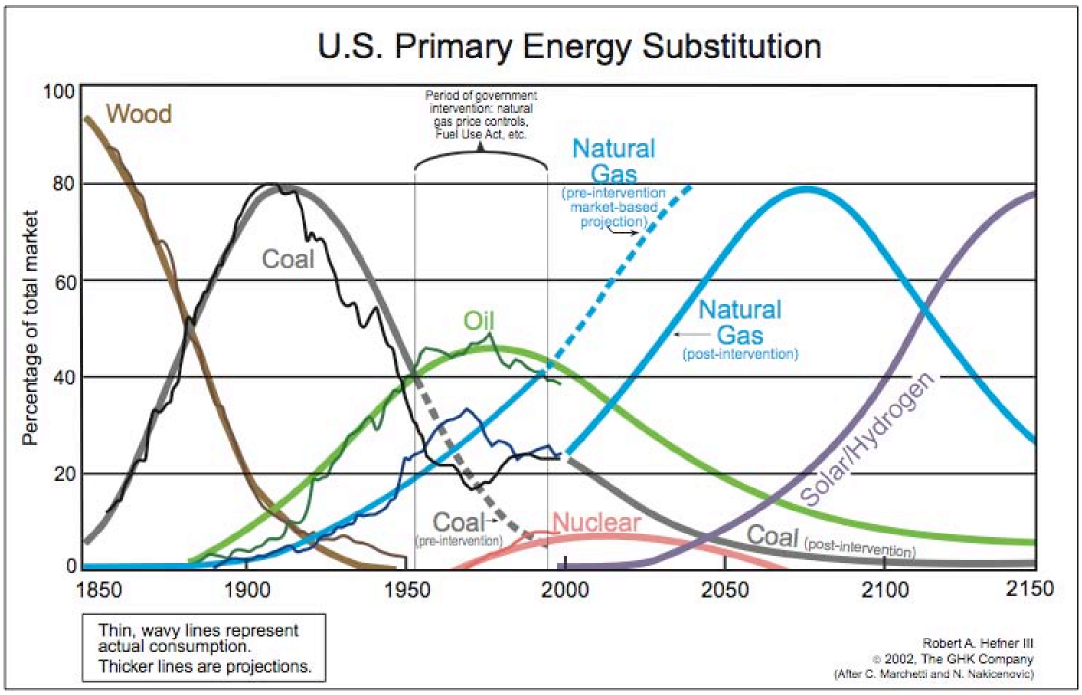
"Yes, my friends, I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable… Water will be the coal of the future." —Jules Verne[36]

Hydrogen is the simplest atom (one proton and one neutron circled by one electron). It's the first element in the periodic table, and makes up 75 percent of the mass and nearly 93 percent of the atoms of the universe. The rest is mostly helium, with about three percent for all of the heavier elements combined. On Earth, however, nearly all hydrogen is bound to other molecules to form carbohydrates, proteins, hydrocarbons (fossil fuels), hydrogen sulfide, and most famously as an oxide of hydrogen to form water. Both hydrogen and carbon are essential elements of life as we know it, both physiologically and technologically. After using renewable carbohydrates—in the

[36] Verne (1874) *The Mysterious Island*; quoted in Romm (2004), pp. 69-70.

form of vegetation and trees—for millennia, and a couple of centuries of using hydrocarbons for heating, cooking, and running machinery, humanity now faces the prospect of abandoning still-plentiful carbon resources in favor of hydrogen. Energy transformations are nothing new, and typically take 50 to 75 years to complete (Figure 3). The global economy's use of hydrocarbon fuels has transitioned from predominantly coal until the rise of petroleum in the early 20th Century to gas likely to surpass oil in the first quarter of this century, which will in turn yield to zero-carbon hydrogen by the end of this century.[37] Such transitions are driven more by preference and technology development and the stench of the incumbent systems than on exhaustion of the previous resource. One such preference is for cleaner fuels, and we will exit the 21st Century with large reserves of coal (or at least its carbon) holding up the ground.

Figure 3. Energy transition waves, U.S.



Substitution waves in the energy sector. Source: Hefner (2002), p. 8, with permission.

Our principal energy source remains the sun, which derives its heat through the fusion of 600 million tonnes of hydrogen into helium every second, thus converting 4,300 tonnes of matter into light every second. It may soon be a cosmic irony indeed to use hydrogen-powered solar energy from 150 million km distant to convert water on Earth into elemental hydrogen and oxygen, then to derive work out of recombining the two in fuel cells of every conceivable size. Hydrogen is chemically very active and combines readily with other elements. Molecular hydrogen (H_2), which is what we need to run fuel cells, is produced naturally but in insignificant quantities, and the molecule's lightness means that it drifts upwards in the atmosphere and escapes.[38] While there may be quantities of trapped hydrogen from biogenic sources in the Earth's crust, it is likely too dispersed and uneconomic to extract.[39] Hydrogen is typically bound up in a great many organic compounds and minerals, and, overall, makes up a very small percentage of the crust.

[37] See Hefner III (2002); Grübler and Nakicenovic (2001).
[38] Hydrogen's atmospheric budget and chemistry are incomplete. Tromp et al (2003) cite estimates of ~0.5 ppmv.
[39] Freund et al (2002).

Hydrogen is present in most organic compounds and in all fossil fuels. The total resource base in conventional and presumed recoverable fossil fuels alone—excluding clathrates and deep natural gas—is ~370 GtH_2, or "equivalent" to 150 years of today's global energy consumption.[40]

Table One: Hydrogen content of fossil fuels and organics[41]

Fuel Type	% Hydrogen (by mole)	% Hydrogen (by weight)	% Carbon (by weight)
Crustal average		0.14%	na
Dry wood	9.5%	na (9.5%?)	90%?
Coal	38%	5-6%	70%(60-80%)
Human body	63%	10%	18%
Sea water	65%	11%	0%
Oil	64%	9-10%	82-84%
Natural gas	80%	~25%	~75%

The largest potential source of hydrogen is water (two atoms of hydrogen plus one atom of oxygen, or dihydrogen oxide ☺). Global precipitation averages 16.4 billion tonnes of water per second, and the world's current energy consumption is equivalent to the hydrogen contained in ~33 minutes worth of rain and snow.[42] The amount of hydrogen in water on the planet is truly enormous: a total of ~1.4 billion cubic kilometers of water, in which there is 156 million billion tonnes of hydrogen, with 0.01 percent in freshwater lakes.[43]

Hydrogen has to be produced in one of three major ways: separate the hydrogen from vegetable matter or hydrocarbon fuels, split hydrogen and oxygen water through electrolysis, or thermo-chemically "crack" water using catalysts and high temperatures. As we'll discuss on pages 13-17, there are many different and hybrid approaches. Since hydrogen has to be produced, it is referred to as an "energy carrier" rather than as an energy resource—much like electricity, which also has to be produced. Both are high-value forms of energy, easily transported and converted from one to the other and back again (with electrolyzers and fuel cells). Hydrogen is far easier to store in large quantities. Indeed, fuel-cell pioneer Geoffrey Ballard thinks of hydrogen and electricity as one fungible commodity he refers to as Hydricity™.

If the emerging hydrogen economy relied solely on the hydrogen produced from estimated recoverable fossil fuels, the resource base would be exhausted considerably quicker than the 150 years suggested in Table Two, unless efficiency improvements out-gain demand growth. In any

[40] Assuming global energy consumption is all provided by hydrogen, but not including production and conversion losses. More significantly, this does *not* credit hydrogen with much higher efficiencies: the efficiency of a hydrogen fuel cell vehicle, for example, is typically modeled as 2.3 to 3.0 times better than existing gasoline ICE vehicles. This estimate is for scale purposes only. Furthermore, as Bartlett and others show, the rate of *current* consumption is a deceptive way of looking at resource durability, given exponential growth and decline curves. Bartlett (2004).

[41] Hoffmann (2001), pp. 12, 169. Hydrogen in the body (madsci.wustl.edu/posts/archives/jun2000/962225341.Bc.r.html) also shows carbon in the human body at 18% (by weight), 9% (by mole), and 39% (by mole, dehydrated); hydrogen (by mole, dehydrated) = 52%. Crustal abundance data: www.scescape.net/~woods/elements/hydrogen.html Hydrogen in biomass is 6-6.5 percent by weight (Kruse et al, 2003).

[42] Total annual precipitation is 0.52×10^{15} tonnes of water (of which 0.11×10^{15} tonnes is on land, Bodyko, 1974), containing 58 trillion tonnes of hydrogen (11.11 percent (H_2:H_2O = 2/18)). World energy consumption totaled 434 exajoules (EJ) in 1999 (UNDP (2000) *World Energy Assessment*), and at hydrogen's lower heating value of 120 million joules per kg, 434 EJ ≈ 3.62 billion tonnes H_2; H_2 in annual precipitation: 58 trillion tonnes H_2 ÷ 3.62 billion tonnes H_2 = 16,000 times world energy consumption; 3.156×10^7 s/yr ÷ 16×10^3 = 1,980 seconds = 33 minutes. (Note: Table Two uses the adjusted hydrogen equivalent of fossil fuel consumption, not total energy, as above.)

[43] Earth's total water = 1,409 million km^3 (97.25 percent in the oceans) and thus contains ~156×10^{15} tonnes of hydrogen. Of course, "burning" the hydrogen oxidizes it back into water. Is the additional water content in the atmosphere a potential problem? No: the water volumes are low relative to natural flows, even in desert areas (the evaporation from irrigated lawns and golf courses swamps H_2O flows from transportation. Global water inventory from Michael Pidwirny, Okanagan University College, www.geog.ouc.bc.ca/physgeog/contents/8b.html

case, producing hydrogen from fossil fuels is not a long-term sustainable solution, even if the carbon is effectively sequestered. Fossil-based hydrogen production will face environmental pressures of its own from coal mining, land degradation, water demand, water pollution, and substantial energy and material investments in infrastructure and processes. Sooner or later, therefore, we will make the shift to alternative ways to produce hydrogen, such as biomass sources, thermo-chemical water cracking, or electrolysis. See Hydrogen production, pp. 17-21.

Table Two: Global hydrogen resource base[44]

Fuel Type	**Carbon** (billion tonnes C)	**Hydrogen** (billion tonnes H_2)	**Yrs of current consumption** (if H_2 replaces global C fuels)[45]
Coal	2,931	216	87
Oil & NGL	325	36	15
Natural gas	175	58	24
Tar sands bitumin	190	19	8
Oil shale kerogen	383	38	16
Total fossil fuels[46]	4,004	368	149
Biomass (global prod./yr)	60[47]	0.2-1.1[48]	0.1-0.4 annual
Top 1 cm of ocean water	na	389	157
Annual precipitation	na	57,900	23,400

Society's willingness to incur large conversion losses and infrastructure investments is based on hydrogen's end-use efficiency and clean-burning characteristics. We invest lower-quality energy into high-value hydrogen (as we do with electric generation when we use ~11,000 Btu of coal to produce one kilowatt-hour with a heat content of 3,412 Btu before accounting for ~6 percent transmission and distribution losses and the enormous quantities of energy and materials invested

[44] Hydrogen content of coals varies: ~4.7 to 6.0 percent. We take 5.3 percent hydrogen by weight in coal and 72% carbon by weight (hydrogen:carbon ratio of 1:13.6) in our recoverable resource estimate. Assuming full hydrogen recovery (though ~0.05 to 0.25 percent remain in fly ash), we have: 2,931 billion tonnes of recoverable carbon (GtC), therefore 2,931 GtC x 5.3/72 = 2,931 GtC x 0.0736 = 215.8 billion tonnes of recoverable hydrogen (GtH_2). Oil's hydrogen:carbon ratio (HCR) is ~1:9, or (325 GtC / 0.84) x 0.093 (%H) = 36.1 GtH_2. Natural gas: HCR = 1:3, or 175 GtC x 0.333 = 58.3 GtH_2. Tar sands: HCR of ~1:10, or 190 GtC x 0.10 = 19.0 GtH_2. Oil shale: HCR of ~1:10, or 383 GtC x 0.10 = 38.3 GtH_2. This "resource" estimate includes neither the energy investment in the resource extraction nor the subsequent separation of hydrogen nor the process gains from water-shift reactions that yield additional quantities of hydrogen. Nor are unconventional gas resources included, estimated at 502 GtC by Rogner (2000) in *World Energy Assessment*, UNDP. Calculations based on estimated remaining *recoverable* fossil fuel resources (Heede, 1983, *A World Geography of Recoverable Carbon Resources in the Context of Possible Climate Change*, National Center for Atmospheric Research, Thesis #72, Boulder). Ocean area equals 360.2 million km^2; hydrogen in seawater by weight is 108 g/liter; annual precipitation ~521 trillion tonnes (see footnote supra).

[45] Global energy consumption (excluding traditional biomass) is 13.5 TW (2001), of which ~83.3 percent is fossil; 11.26 TW of fossil fuels is equivalent to 2.96 GtH_2/yr (direct equivalence, LHV). We make two adjustments: first, we consider hydrogen extraction losses of 40 percent (likely conservative in view of continuous large investment in new hydrogen infrastructure and if we require carbon capture and storage), second, hydrogen end-use efficiency gains, which in transportation applications are typically taken as ~2.3-3.0 factor improvement but we use 2.0 to account for slower uptake of stationary applications' efficiency gains. Thus, we have 2.96 GtH_2/yr ÷ (1.0 – 0.4) ÷ 2.0 = 2.47 GtH_2/yr. Thus our "Years of current consumption" divides estimated hydrogen resource bases by hydrogen demand of 2.47 GtH_2/yr. See note in Future hydrogen requirements, p. 17. No adjustment is made for population or energy services demand growth, or for future efficiency gains; this example is merely illustrative.

[46] Total presumed recoverable hydrogen resources in fossil fuels equals an estimated 368 billion tonnes. Total annual primary carbon-based energy consumption is equivalent to 2.96 billion tonnes H_2 per year, but adjusted to 2.47 GtH_2/yr (see note supra); presumed recoverable hydrogen would thus "last" 149 years. "Actual" duration would be far shorter under geometric growth and decline rates. No one is proposing that we substitute hydrogen for all primary energy. If we instead replace worldwide gasoline consumption (20.1 million bbl/d = ~42 EJ/yr = 350 million tonnes H_2), then the hydrogen "resource base" would last approximately 1,050 years; if we add gasoline, sixty percent of distillate fuel oil (~diesel), and jet fuel for total apparent transportation consumption of 20.07 + 12.8 + 4.5 million bbl/d = 37.37 million/bbl-d = 13.64 billion bbl/yr = 69.5 EJ/yr, or 580 MtH_2/yr, the "resources base" of 367 GtH_2 would potentially last 633 years. These estimates are illustrative, as none factor in demand growth (~2.1%/yr), nor the greater efficiency of hydrogen-powered road, marine, and air transportation, but does factor in the conversion losses of cracking hydrogen from fossil fuels. World oil products consumption from: www.eia.doe.gov/emeu/iea/pet.html

[47] Global total annual carbon fixation through photosynthesis (worth 2,300 EJ). Spitzer (2004), p. 4.

[48] Hoehler et al 2001, via U.S. DOE (2003k), p.17. Hoehler et al estimate global biological hydrogen production at 230-1,090 million tonnes H_2/yr, primarily from cyanobacterial splitting of water. Note: other sources suggest a carbon to hydrogen ratio (by weight) of ~~1:10, but the ratio of Spitzer to Hoehler is 1:60.

in electricity's vast infrastructure). If hydrogen is sustainably produced, the gains easily justify the losses. We'd use hydrogen in superior and clean technology, such as fuel cells, which convert 50 to 70 percent of the energy of the delivered hydrogen into electricity that run 96 percent efficient motors to run a fuel cell vehicle (FCV).

Accounting for the energy required to produce, compress, and deliver the hydrogen we'd "lose" another ~30 percent of the energy in natural gas, for an overall system efficiency of ~35 to 48 percent to move the FCV. A conventional car with an internal combustion engine converts gasoline to shaft power at 15-17 percent efficiency, running an obese steel car; refining and delivering gasoline to the car's tank consumes about 25-30 percent of the energy in the gasoline. The comparative result: the hydrogen to fuel cell vehicle system can move a driver far more efficiently than conventional ICE-powered vehicles burning gasoline.

Figure 4.

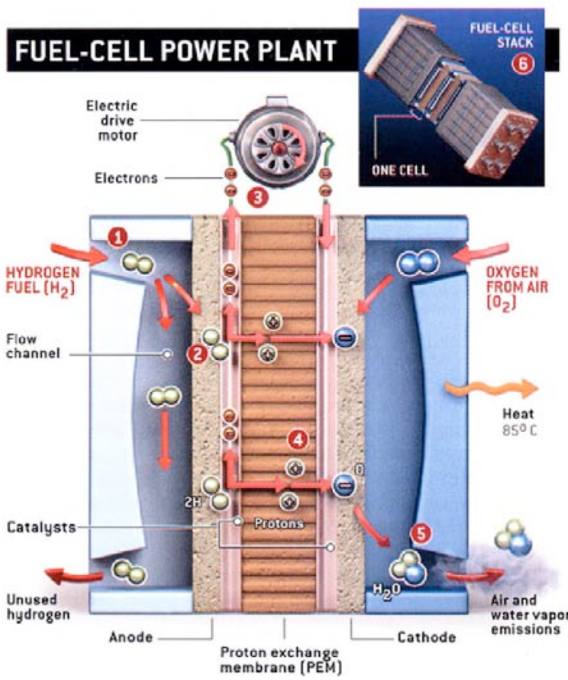


Diagram of a PEM fuel cell. Source: Sylvester-Bradley (2003).

Fuel cell development

Fuel cells are not a modern invention: William Grove built the first small fuel cell (a reverse electrolyzer) in the late 1830s.[49] Such early experimental fuel cells produced almost no electricity until research focused on the issue in the 1950s. In 1923, the eclectic J.B.S. Haldane delivered a prophetic lecture before the University of Cambridge *Heretics Society*: "Liquid hydrogen is weight for weight the most efficient known method of storing energy, as it gives about three times as much heat per pound as petrol." He envisioned "great rows of metallic windmills … where during windy weather the surplus power will be used for the electric decomposition of

[49] Hoffmann (2001) provides an excellent history of hydrogen, its future uses, and the many hydrogen pioneers. Cavendish had first described hydrogen in the 1760s, which he called "phlogiston" (an early notion of a substance that imparted combustibility to matter). Charles used hydrogen in 1783 to provide lift to his balloon, instead of the conventional (and dangerous) on-board fire. Lavoisier combined oxygen and hydrogen to form water in the 1780s; he was later guillotined on "trumped-up" tax fraud charges. Haldane quote in Hoffmann, p. 31, from Haldane's *Daedalus or Science and the Future*, 1925. Fuel cell discussion from Hoffmann, pp. 146-148.

water into oxygen and hydrogen … These huge reservoirs of liquefied gases will enable wind energy to be stored so that it can be expended for industry, transportation, heating, and lighting, as desired."[50]

Significant progress in fuel cell development languished until Francis T. Bacon of Cambridge University whose advances in the 1930s-1950s with cells using higher temperatures and pressures as well as better materials selection improved efficiency and lowered costs. This work lead to demonstration fuel cells powering fork lifts, tractors, and electric boats. NASA funded research in the 1960s and procured fuel cells from General Electric (Gemini), Pratt & Whitney (Apollo), and United Technologies (Space Shuttle). In addition, NASA has used cryogenic hydrogen in its boosters for decades.

The principal future use of hydrogen will, eventually, be in fuel cells, but hydrogen can also be burned as a fuel in conventional combustion devices. The beauty of fuel cells is that it re-combines the hydrogen with oxygen in the air to produce only electricity and hot water. No carbon. And little waste— assuming use is made of the moderate- to high-temperature water that's a co-product of the reaction. The clincher, as we will see below, is the mechanism of producing hydrogen and how much energy and waste goes into those processes.

Carbon capture and storage

It is hoped that humanity can continue to make use of enormous quantities of fossil hydrocarbon fuels without incurring unacceptable climate risks. This involves separating the hydrogen and capturing the carbon in a gas separation chamber. There are numerous well-understood processes described elsewhere, most involving an energy and cost penalty ranging from 15 to 35 percent, once the costs of compressing and piping the CO_2 to a suitable injection site is included.[51]

There is a growing consensus that very large quantities of carbon can be safely stored away from the atmosphere for suitably long periods and with low leakage rates. Early proposals for deep-sea injection are being rejected due to unacceptable risks to oceanic ecosystems from increased acidity and eventual cycling of the injected carbon back into the atmosphere. Geologic reservoirs are large enough (1,000 to 10,000 $GtCO_2$) to store decades' or even centuries' worth of global carbon emissions (now ~23 $GtCO_2$/yr) and are well-distributed throughout the world's sedimentary basins, saline aquifers, unminable coal beds, and depleted oil and gas reservoirs. Magnesium silicates can be mined, milled, and reacted with CO_2, costing ≤$10 per tonne and adding ~0.5-1.0 ¢/kWh.[52] The U.S., though lacking any price signal for the atmospheric dumping of carbon dioxide, has several operational CCS projects, most of which inject CO_2 separated from oil and gas production to enhance recovery from oil and gas fields; some use virgin CO_2, and none use CO_2 captured from power plants. This is cheaper, as long as the external costs of climate impacts are ignored. Energy companies in Canada and Norway have operated large CCS projects for years.[53]

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[50] Readers interested in fuel cells should see: Burns et al (2002), Keith & Farrell (2003), Kruse et al (2002), Lovins & Williams (1999), Lovins (2003a), Patch (2001), Romm (2004a), Swisher (2002a), Thomas (2002), Weiss et al (2003).

[51] Williams (2002), and Kreutz et al (2002). See also Gray & Tomlinson (2002).

[52] Lackner (2003), p. 1678.

[53] The Sleipner project in the North Sea injects ~1 million tonnes of CO_2 annually at a cost of ~$14 per tonne but thus avoids Norway's $44 per tonne carbon tax, and is closely monitored for CO_2 seepage. The offshore platform's natural gas contains 9 percent CO_2, typically vented at most gas facilities. Herzog (2000); Lackner (2003).

Ronald Oxburgh, Shell's new chief in London, considers sequestration the last best hope for climate stability. "If we don't have sequestration, then I see very little hope for the world," he told the British newspaper *The Guardian*. Carbon capture is evidently the Bush Administration's hope for future climate action: "We all believe technology offers great promise to significantly reduce emissions—especially carbon capture, storage, and sequestration technologies."[54]

Carbon capture and storage (a detailed analysis of which is beyond the scope of this paper) is viewed as critical for a successful transition to a sustainable hydrogen economy. CCS is currently under intense study by U.S. DOE, other federal agencies, foreign governments—and with strong participation from oil companies and electric utilities with a deep interest in a possible solution that might allow continued use of carbon resources.[55] DOE's CCS research budget is $62 million (FY04), not counting the Clean Coal and FutureGen initiatives.[56] The FutureGen initiative funds a $920-million 16-year RD&D proof-of-concept of coal-gasification for combined hydrogen and power production coupled to CCS.[57] A new initiative at the Rocky Mountain Oilfield Testing Center aims to inject CO_2 and monitor its migration at Teapot Dome in Wyoming.

Coal gasification combined cycle (CGCC) including the cost of carbon sequestration is a likely cost-competitive option according to researchers at Princeton University, a conclusion supported by the recent assessment by the National Research Council.[58] Technical uncertainties remain, and gas separation, carbon capture and (reliable) storage, monitoring, and related technologies must be proven feasible and cost competitive. CCS is a monumental enterprise that requires thousands of km of new pipelines to transport ~0.7-1.5 billion tonnes of supercritical CO_2 annually.[59] Market success is uncertain, and its implementation will have to be mandated, regulated, and monitored for compliance, as emitters won't willingly adopt its substantial infrastructure costs.

Current Hydrogen Production and Uses

World production of hydrogen totaled 48.6 million tonnes in 2001 (equivalent to ~1.5 percent of global primary energy consumption).[60] U.S. produces 8 to 15 million tonnes of hydrogen (MtH_2), 96 percent of which is produced from fossil fuels.[61] Hydrogen is used to produce ammonia (NH_3) fertilizer (51%), in hydrodesulfurization and hydrocracking crude oil into gasoline and diesel fuel (45%), in welding, metallurgy, and chemicals (~3%), and in miscellaneous uses such as methanol production, as rocket fuel, and in hydrogenated processed foods and edible fats. While

[54] President Bush, 11June2001.

[55] Ogden (2002) models two systems: a large SMR facility (178 million kgH_2/yr, enough to supply ~1.4 million FCVs) with compression to 68 bar ($1.09/$kgH_2$) plus distribution cost to a set of 250 H_2 service stations ($0.41/$kgH_2$) plus the levelized cost of the refueling infrastructure ($0.86/$kgH_2$) plus cost of pipeline transmission and carbon injection into a 2 km-deep geologic reservoir ($0.06/$kgH_2$); total cost of H_2 delivery with carbon sequestration = $2.42/$kgH_2$. Comparable cost for a coal-source system with carbon capture and storage: $2.41/$kgH_2$. The coal plant produces nearly twice as much carbon dioxide per hour at full capacity than the natural gas plant (406 vs 204 tonnes/hr), given the higher carbon to hydrogen ratio for coal vs natural gas.

[56] National Research Council (2004) DOE Hydrogen Budget, FE: "sequestration," p. 138. FY03 budget: $40 million.

[57] For details, see Gray & Tomlinson (2002), IPIECA (2003), Kallbekken & Torvanger (2004), Kreutz et al (2002), Lackner (2003), Pacala & Socolow (2004), Parson & Keith (1998), Service (2004), U.S. DOE (2002e), U.S. DOE (2003c), and Williams (2002). See also: http://carbonsequestration.us/, www.co2captureproject.org FutureGen's coal to H_2 + power with CCS, see U.S. DOE (2003e).

[58] See also Williams & Larson (2003), Williams (2003), Ogden (2002), National Research Council (2004), Lipman et al (2004), Padró & Putsche (1999), and Simbeck & Chang (2002).

[59] National Research Council (2004), p. 85: 200-400 MtC by 2050.

[60] 48.6 million tonnes H_2 = 6.9 EJ (at HHV). Global primary energy =~440 EJ (2000).

[61] Lovins (2003a), note 29, citing Air Liquide presentation at Hannover Messe in 2003. US DOE data shows 48% from natural gas, 30% from oil, 18% from coal, and 4% electrolysis. DOE estimates U.S. consumption at 9 million (short) tons, but RMI cites 15 MtH_2/yr as more accurate. Lovins et al (2004), p. 242, cites 11%/yr demand growth.

reliable hydrogen production and consumption data are scarce, it appears that production is doubling every decade (~7%/yr) and primarily driven by refinery and desulfurization demand. It is worth noting that the transition to hydrogen transportation fuel will make unnecessary nearly half of the current demand for hydrogen, namely that fraction now used to produce gasoline and diesel fuels. Lovins estimates that if the ~7 MtH_2 currently used in U.S. refineries instead powered efficient fuel cell cars and trucks it would displace 15 percent of current gasoline and diesel used by all highway vehicles—equivalent to all U.S imports from Saudi Arabia in 2002.[62]

Hydrogen Production Pathways

Molecular hydrogen (H_2) can be produced in three principal ways that underscore the fuel's supply diversity and its potential for a wide set of geographic circumstances. Hydrogen can be stripped from hydrocarbon or carbohydrate fuels using heat and pressure, it can be electrolyzed from water using electricity, or "cracked" through thermochemical reactions of water using catalysts and temperatures exceeding 850ºC. A number of novel and hybrid approaches are also being studied.

Hydrogen production from hydrocarbon sources

Fossil hydrocarbon source fuels include natural gas (steam reformation of methane (SMR)), gasification and liquefaction of coal, and reformation of heavy oils under partial oxidation. Steam reformation of methane combines high-temperature steam at 700 to 1000 ºC and methane (or other light hydrocarbons) in a pressure chamber at 3 to 25 bar; a secondary water-gas shift reaction with carbon monoxide and steam produces additional hydrogen. Hydrogen production efficiency is typically 75-80 percent in large centralized facilities and ~70 percent in smaller-scale systems.[63] Novel technologies such as sorbent enhancement reformers, ion transport membrane reformers, and plasma reformers also show promise.[64]

SMR is a fully commercialized technology, the least expensive hydrogen production process, and is currently used to produce 48 percent of U.S. hydrogen. Today's production cost of SMR hydrogen is ~$0.78 per kg at the plant gate, which is equivalent to $0.78 per gallon of gasoline, exclusive of taxes, profits, and delivery. Delivered cost, assuming a large production facility and pipeline delivery, is estimated at ~$1.98/$kgH_2$ without carbon sequestration, $2.26/$kgH_2$ with sequestration using current technology, and $1.80/$kgH_2$ assuming future technology.[65] This means that hydrogen can be delivered at costs equivalent to current gasoline prices with the carbon sequestered—*before* considering the large efficiency advantages of future hydrogen fuel cell vehicles typically modeled as twice to three times (but up to five times) as efficient.[66] The

[62] Lovins (2003a), p. 22 and fn 103: all U.S. highway vehicles now consume 21.9 EJ of gasoline and diesel fuel; Lovins' analysis estimates that quintupled-efficiency H_2FCVs and doubled-efficiency trucks will demand ~5.5 EJ of H_2; current H_2 to refineries of 0.84 EJ/yr is 15.3 percent of estimated H_2 demand (5.5 EJ/yr); finally, 15.3 percent of current oil consumption for highway vehicles (21.9 EJ x 0.153 = 3.34 EJ/yr) equals U.S. oil imports from Saudi Arabia (1.563 million barrels per day = 570 million bbl/yr = 3.31 EJ/yr). U.S. oil imports from Saudi Arabia from EIA (2003) *Annual Energy Review 2002*, p. 132, www.eia.doe.gov

[63] Ogden (2001), and Simbeck & Chang (2002).

[64] Kruse et al (2002) describe the Kværner plasma carbon black process that uses hydrocarbon feedstocks and produces carbon black used in tire manufacturing and metallurgy. MIT researchers are developing a plasmatron (electric arc) reformer that uses hydrocarbon feedstocks and operates at temperatures >2,000 ºC; Ogden (2001).

[65] From National Research Council (2004), in Lipman et al (2004), p. A-10.

[66] Weiss et al (2000), p. 5-7: 2020 H_2 FCV 94 mpg vs current ICE 28 mpg or vs 2020 baseline ICE 43 mpg (3.36:1 or 2.18:1); Lovins (2003a), p. 17: 99 mpg Hypercar[tm] *Revolution* vs 19 mpg Lexus *RX300* (4.95:1); U.S. DOE (2003b), p. 17 cites GREET model of H_2FCVs vs future ICEs: 3.0:1.

use of fuel cells in buildings also captures significant efficiency gains compared to typical grid and heating fuel efficiencies. One-quarter of the total natural gas input is used to heat the steam, and the final efficiency is typically around 75-78 percent, with future improvements indicating 85 percent utilization efficiency. Steam reforming produces ~7 $kgCO_2$ per kgH_2 produced.

A fully deployed hydrogen economy will most likely seek to capture the economies of scale inherent in large centralized hydrogen production facilities and delivery by pipelines. Yet, how can society overcome the "chicken and egg" problem: who would build expensive hydrogen production and delivery infrastructure (estimates range up to $500 billion) required for effective marketing of H_2 fuel cell vehicles? Early plans to reform gasoline into hydrogen on-board—and thus make use of the existing infrastructure—were abandoned in favor of direct to hydrogen vehicles. Stumped by the expense of fuel cells (~30-100 times more expensive than competing ICE engines, kW for kW) and on-board hydrogen storage tanks that are bulky and/or heavy or provide poor driving range, at least for personal vehicles, the H_2FCV developers may be out-competed by advances in the internal combustion technology or hybrid electric vehicles.[67]

One possible solution is to generate hydrogen on-site at service stations using small methane reformers or electrolyzers. Thomas concludes that this provides an effective way to get the hydrogen economy off the ground and can be done at a reasonable cost, especially when the ~$37 billion cost (U.S. only) of maintaining the current oil and gasoline infrastructure is taken into account.[68] Other deployment pathways have been suggested.[69] Several electrolytic hydrogen appliances for the home fueling market are under development.

The nation's vast coal resources are also being viewed as hydrogen feedstocks. This involves, however, the mining and, with partial oxidation processes, the release of large quantities of carbon dioxide—unless the CO_2 by-product stream is captured, pressurized, pipelined, and injected into suitable geologic reservoirs. This is the goal of the DOE's FutureGen powerplant RD&D project that aims to demonstrate the viability of using coal for both power generation and hydrogen production.[70] Princeton's Robert Williams estimates hydrogen production costs from coal with CCS as competitive with natural gas reforming with CCS assuming gas costs at ~$3.90/GJ.[71] Moreover, he finds that carbon capture and storage adds 15 to 35 percent to the electricity generation and hydrogen production costs, depending on the technology selected. Currently, natural gas hydrogen production facilities have a lower capital cost and higher fuel costs than coal facilities, making gas facilities more vulnerable to price fluctuations. Coal has a much higher carbon to hydrogen ratio than liquid or gaseous fuels (see Table 1) and thus carbon capture and storage becomes both a larger and more critical issue for coal-derived hydrogen.

Hydrogen can also be produced using the heat output of nuclear reactors with natural gas, as in the steam reformation discussed above, but reducing the gas input (since the steam is raised using nuclear heat rather than additional gas). A Japanese research program begun in 2001 has

[67] Romm (2004) points out that the competition to new technology never stands still and hampered deployment of alternative fuels such as compressed natural gas. Certainly, "conventional" technology will not be static.

[68] Thomas (2004), p. 12 estimates that the global oil and gas industry invests as much as $130 billion *annually* to fuel the world's car fleets. Argonne National Lab. estimates average U.S. investment in gasoline infrastructure at $37 billion per year; Thomas (2004), p. 12, citing Wang et al (1998), ANL/ESD-37. See also Ogden (2001), and Simbeck & Chang (2002). Keith & Farrell (2003) are dubious that Thomas' distributed reformer technology can be deployed at such low cited per H_2FCV cost (see their response in *Science* letters, vol. 302:1330).

[69] See Lovins & Williams (1999), Lovins (2003a), U.S. DOE (2002a) and (2004a), and Lipman et al (2004).

[70] It's anticipated that such plants will capture 85-90 percent of the CO_2.

[71] Williams (2002), pp. 5-6 and 17. CCS cost is based on the Ogden (2002) model, piping CO_2 100 km, and saline aquifer injection to a depth of 2 km. The cost of CCS from coal can be reduced by co-storing CO_2 and H_2S.

experimented with a 30-MW helium-cooled reactor operating at ~950ºC and coupled to a gas reformation unit.[72] Solar thermal concentrators can also assist in steam methane reforming.[73]

Hydrogen production from biomass sources

Hydrogen can readily be pyrolyzed or thermochemically processed into a hydrogen-rich bio-oil or gasified from biomass sources such as agricultural residues, biomass crops (e.g., soy, corn, sugarcane, or switchgrass), and post-consumer wastes such as plastics and greases.[74] Biomass gas can also be used directly (as can many other hydrogen-rich fuels) in a high-temperature molten-carbonate fuel cell.[75] Biomass, like most forms of renewable energy, is dispersed and with low energy density (~0.6 Wm^{-2})[76] and best suited for small- and mid-sized hydrogen production facilities. About 15 percent of the U.S. land area is cultivated, and an additional 3 percent (about the size of Nevada) are needed under energy-crop cultivation to provide sufficient biomass to replace all current oil used for transportation.[77] The solar-to-chemical conversion efficiency of two biomass crops (switchgrass and poplar) is ~0.4 percent of solar irradiance.[78] Based on the availability of agricultural wastes, forestry operations, and other available biomass sources, the U.S. potential for 2020 is estimated at 19 to 29 billion kg/yr.[79]

Hydrogen production from electrolysis of water

Electrolysis is a mature technology, though (for cost reasons) only used to make about 4 percent of the 48 million tonnes of H_2 produced today. Electrolytic dissociation of hydrogen and oxygen of ubiquitous H_2O requires the input of ~39 kWh of electricity per kg of hydrogen produced.[80] Adding heat reduces the electric input requirement, but the total amount of energy remains fairly constant. "Hot electrolysis" has been proposed for using the heat and electricity from nuclear power plants. Conversion efficiencies are typically 60-73 percent using current electrolyzers; PEM electrolyzer costs are expected to decline by 90 percent.[81] The cost of electrolysis of water from grid power is ~\$6-7/kgH_2, with future potential of ~\$4/kgH_2.[82]

While any source of electricity can be used for electrolysis, it is counter-productive to use fossil-fueled electricity to do so. Many observers agree with John Heywood, Director of the Sloan Automotive Laboratory at MIT: "If the hydrogen does not come from renewable sources, then it is simply not worth doing, environmentally or economically."[83] If we were to produce 46 to 84 million tonnes of hydrogen (see "Future Hydrogen Requirements" below) by electrolysis using today's electric system's carbon intensity, the U.S. would emit 1.1 to 2.0 billion tonnes CO_2 just

[72] Forsberg (2003); National Research Council (2004), p. 210.
[73] Spath et al (2002).
[74] See Spath et al (2000), and Meyers et al (2003).
[75] Lipman (2004), p. 24.
[76] Hofffert et al (2002), p. 984. For comparison, solar PV and windpower are ~15 W_em^{-2}.
[77] Grant (2004), p. 130. Grant does not, however, include H_2FCV and other end-use efficiency gains. Grant cites an estimate of current U.S. crop yield at ~23,000 TWh (or ~2,600 GW continuous). U.S. net generation was 3,840 TWh in 2002, and a net summer capability of 902 GW; EIA (2004) *Annual Review of Energy 2002*, pp. 224 & 243.
[78] U.S. DOE (2003k), p. 14. This report suggests that genetic engineering could improve yields "two- to three-fold."
[79] Ogden & Nitsch, (1993), and Mann & Overend (2003), respectively, in Lipman (2004), p. 24. Ogden & Nitsch also estimate land requirements of renewable hydrogen production options, in m^2/GJ-yr: Solar PV: 1.89 m^2/GJ-yr; solar thermal electric: 5.71 m^2/GJ-yr; Windpower: 6.3-33 m^2/GJ-yr; Hydroelectric: 11-500 m^2/GJ-yr; Biomass: 50 m^2/GJ-yr. Note: 1 GJ of H_2 = 8.33 kgH_2 (at LHV: 121.1 MJ/kgH_2), or 7.04 kgH_2 (at HHV: 142 MJ/kgH_2).
[80] Turner (2004), p. 973. Hydrogen at HHV. This does not include hydrogen compression or delivery.
[81] National Research Council (2004), p. 54.
[82] Lipman (2004), p. 42.
[83] Quoted in Lynn (2003).

to make hydrogen for transportation.[84] This quickly fails to be sustainable. This is also why the nuclear power industry argues for fission reactors as the ultimate hydrogen production pathway.

The amount of water required for electrolysis to produce 230 million tonnes of hydrogen is ~2.07 trillion liters (~546 billion gallons) per year. An estimated 1.14 trillion liters (300 billion gallons) are annually used to refine gasoline, 265 trillion liters (70 trillion gal) are used for power plant cooling.[85] About 9,800 trillion liters of rain and snow fall on the U.S. landmass per year.[86]

Hydrogen production from thermo-chemical water cracking

Another proposed pathway of future hydrogen production involves direct dissociation of water using new high-temperature (850 to 1,100ºC) nuclear reactors designed for hydrogen production. Higher temperatures improve hydrogen production efficiency as well as reactor operating efficiencies. New designs are being developed by reactors vendors, with participation from U.S. DOE (Next Generation Nuclear Plant NGNP, aka Generation IV) and foreign governments. Investigators have identified the Sulfur-Iodine (S-I) process and the High-Temperature Gas-Cooled Reactor (HTGR) as the most promising system for thermo-chemical hydrogen production.

Since none of the Gen-IV nuclear reactor designs have reached the demonstration phase (and are not scheduled to do so until 2015-2025), nuclear hydrogen production costs are difficult to estimate, but range from 0.95 to 1.63 per kg H_2, and $2.33 per delivered kg.[87] While there is strong hope among the partners in the Nuclear Hydrogen Initiative that thermo-chemical technologies will work and be competitive, nuclear thermo-chemical processes are "far from being commercially available." Williams estimates process efficiency of 50 percent in converting nuclear heat into hydrogen and a cost of $5.33/kg$H_2$: or 140 percent higher cost than coal-derived hydrogen *with* carbon capture and storage (see page 29 for details).[88]

Solar thermal energy systems can also provide the high temperatures required to superheat steam to >1,700ºC by using solar concentrators (with greater amounts of hydrogen produced as temperatures increase to >2,700ºC). This technology is in early stage of development.[89]

Other hydrogen production pathways

Additional pathways that liberate hydrogen from water using direct sunlight[90] or harvest biogenic hydrogen from algae and micro-organisms may prove useful in the future, but such techniques are currently in the early R&D stages. These include photoelectrochemical and biomimetic processes (using photons and catalysts for direct dissociation of water into hydrogen and

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[84] 46 to 84 x 10^9 kgH_2 x 39 kWh/kgH_2 x 0.613 kg CO_2/kWh = 1,100 to 2,008 million tonnes CO_2. U.S. transportation sector CO_2 in 2001 (EIA, 2003, *AER 2002*, Table 12.2): 1,876 million tonnes CO_2. U.S. electricity-sector carbon intensity: 2.243 x 10^{12} kg CO_2 ÷ 3.660 x 10^{12} kWh consumed = 0.613 kgCO_2 per kWh consumed. DOE's 2040 forecast of 150 MtH_2/yr ⇨ 3,590 MtCO_2/yr.

[85] Turner (2004), p. 973 says "100 billion gallons per year": based on 2.6 trillion km traveled in U.S. (light-duty vehicles only), 60 miles per kg H_2, and 0.42 kg per gallon of water. Our calculation (used above) is 5.5 higher: 230 million tonnes H_2 / 0.1111 = 2.07 trillion kg (liters) water / 3.79 l/gallon = 546 billion gallons. Refinery water use: Mann & Whitaker, unpublished data. U.S.: ~80 gallons per day per capita = 8.5 trillion gallons per year.

[86] Total hydrologic cycle over the U.S. landmass: 9.363 million km^2 (9.363 x 10^{12} m^2) times average precipitation of 1,050 mm/yr (1.05 tonne per m^2/yr; global average) = 9.83 trillion tonnes (9,830 trillion liters) of precipitation.

[87] Low estimate: Brown et al (2002); high estimate and delivered cost (pipeline): National Research Council (2004).

[88] Williams (2001), p. 19

[89] Lipman (2004), p. 26. Ogden & Nitsch (1993) estimate future production costs at $2.56 to $5.11 per kg H_2, but this should be taken with caution considering the nascent stage of this technology.

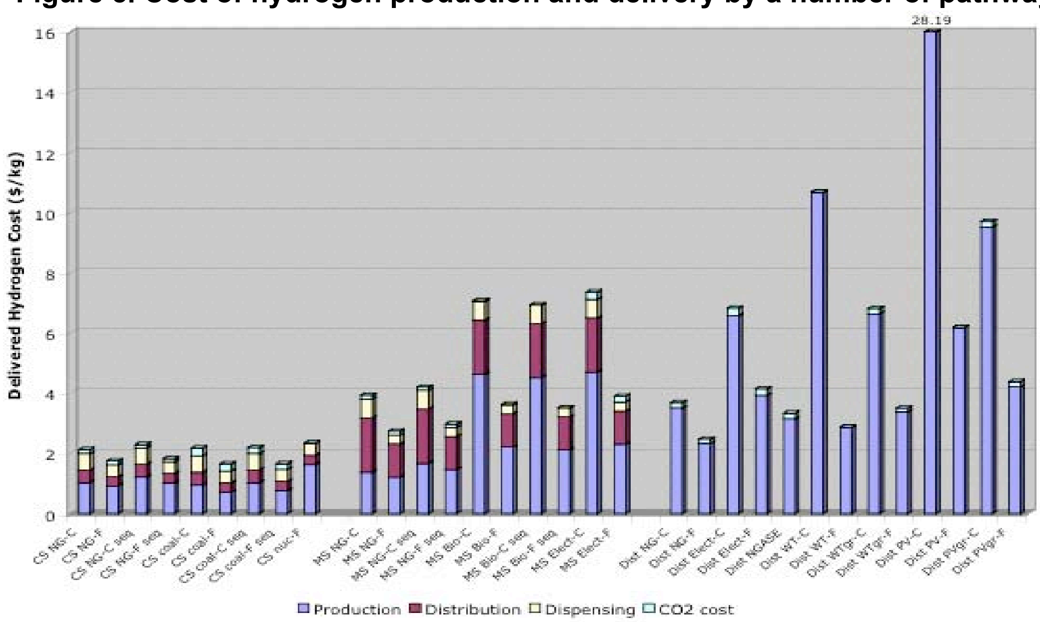
[90] The thermodynamic potential for splitting water into H_2 and O_2 is 1.23 V. Electrolyzers typically run at 1.7-1.9 V, and 1.9 eV corresponds to red light of 650 nm. In fact, "the entire visible spectrum of light has sufficient energy to split water … The key … is to find a light-harvesting system and a catalyst that can efficiently collect the energy and immediately direct it toward the water-splitting reaction." Turner (1999), at note 12.

oxygen), phytobiological processes (some microorganisms and algae can photosynthetically generate hydrogen), fusion energy, municipal solid waste, landfill gas, and effluent gases from wastewater treatment plants.[91]

Hydrogen production and delivery costs

Hydrogen is produced today at costs comparable to the retail price of gasoline ($0.78-$2.00 per kgH_2, which is equivalent to $0.78-$2 per gallon). Delivering hydrogen, however, is costly, and the alternatives are delivery by truck, tube trailers, adding hydrogen to natural gas in existing pipelines, re-lining pipelines with polymer and metal composites, and building new transmission pipelines.[92] The literature contains a great range of production and delivery cost for a variety of production pathways, technologies, delivery distances, discount rates, source types, and current or near-term or future technologies. Lipman has provided a useful survey of cost estimates.[93]

Figure 5. Cost of hydrogen production and delivery by a number of pathways



Source: NRC, 2004. Notes: Bio = biomass gasification; C = current technology; CS = large central station; Dist = distributed production at small scale; Elect = grid-power electrolysis; F = future technology; gr = grid assisted electrolysis; MS = medium-scale; NG = natural gas SMR; PV = solar photovoltaic powered electrolysis; seq = with carbon sequestration; WT = wind turbine powered electrolysis. CO_2 cost = carbon disposal cost and/or carbon tax of $50 per ton.

Lipman (2004)

Future hydrogen requirements

Over the past century we replaced the hay grown on one-quarter of all U.S farmland to feed 20 million horses used for transportation and agriculture with 137 billion gallons of gasoline and diesel fueling 222 million light-duty vehicles (U.S. only: 531 million worldwide)[94] with an

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[91] See National Research Council (2004), Romm (2004a), Cannon (1995), Lipman (2004), Williams (2002), and Hoffman (2001). Meyers et al (2003) estimate that hydrogen can be produced and delivered from MSW and landfill gas at ~$2.50 per kg across much of the U.S. A lot of new work shows promise, e.g.: a Virginia Polytechnic Institute team has created molecular machines containing ruthenium, rhodium, and organic compounds that generate, when exposed to sunlight, the two electrons needed to efficiently produce H_2 from water. *Science News*, 11Sep04, p. 174.

[92] Lovins (2003), p. 14; Romm (2004a), pp. 99-103; Simbeck & Chang (2002), and Huizing (2004).

[93] Lipman (2004), p. 31.

[94] Worldwatch Institute (2004) *Vital Signs 2003*, p. 56.

installed capacity of about 34 billion horsepower, or 46 TW.[95] U.S. highway vehicles use ~11.1 million bbl/day, which equates to a flow of nearly 1,300 cubic feet per second—enough to fill the volume of both now-gone World Trade Center Towers *every thirty-six hours*.[96] The U.S. is poised to replace this vehicle stock with hydrogen-powered fuel cell vehicles with average power of ~35 kW and using approximately ~120 to 363 kg of hydrogen per year.[97]

Estimates of the amount of hydrogen needed to replace all *current* U.S. use of oil products for surface transportation range from 125 to 230 million kgH_2/day or 46 to 84 MtH_2/yr (~5.5 to 10.1 EJ/yr at LHV, 46 to 84 MtH_2/yr), compared to the 12 million bbl per day (14.96 EJ) currently used.[98] Grant's higher estimated hydrogen requirement is enough, in gaseous form, to lift 13,000 Hindenburg airships daily.[99] The U.S. DOE forecasts hydrogen requirements for light-duty vehicles in 2040 at 411 million kg per day (18 EJ/yr ~150 MtH_2/yr).[100]

Estimates of future total U.S. hydrogen requirements range upwards from 50+ MtH_2/yr to 136+ MtH_2/yr. Neither are estimates of economy-wide hydrogen demand. The lower estimate is for all highway transportation (using 2000 vehicle stock and consumption data upgraded overnight to doubled and quintupled-efficiency hydrogen vehicles).[101] The latter estimate is for year 2040 H_2 demand by cars and light trucks only.[102] Hydrogen aircraft are contemplated (hydrogen jets are ~2x as efficient as kerosene-fueled jets),[103] millions of buildings may eventually use fuel cells for distributed generation of reliable electricity and heat,[104] and hydrogen will prove its mettle in a plethora of micro-applications such as cell phones and billions of other portable devices.[105]

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[95] Cannon (1995), p. 4: cites 19 billion horsepower. A recalculation: 137.6 million cars @~145 HP plus 84.2 million light-duty trucks @~170 HP = 34.3 billion HP. ORNL (2003) *Transportation Energy Data Book*, 23rd, www-cta.ornl.gov/data/Index.html. HP by vehicle class: www.eia.doe.gov/emeu/25opec/sld012.htm. 1 HP = 1.341 kW. Fuel cell vehicles will typically have engines of ~20-40 kW (27 to 54 HP). 34.3 billion HP = 46 TW. Installed U.S. electric generating capacity totals 0.9 TW (2002); the major difference is that power plants have an average utilization factor of 49 percent vs typical cars that are driven (at far less than full HP) only ~4 percent of the hours in a year.

[96] 11.1 million bbl/day = 62.2 million cubic feet/day = 720 cfs; WTC1&2 = 34,545 sq.ft./floor x 110 floors x 2 buildings = 94 million cubic feet filled in 36.3 hrs. Total U.S oil consumption = 19.7 million bbl/day = 110.4 million cubic feet/day = 1,277 cfs; compare the Mississippi River, which averages 536 km^3 per year (600,200 cfs), or 470 times the U.S. oil flow. Dai & Trenberth (2002) "Estimates of Freshwater Discharge from Continents," *J. of Hydrometeorology*, vol. 3:660-687.

[97] 120 kgH_2/yr derived from Lovins (2003b), p. 18, using Hypercar *Revolution* H_2FCV concept vehicle: U.S. stock of passenger cars drive, averaging all registered cars, 18,700 km/yr (*TEBD*, Ch. 4), Revolution has a range of 530 km per fill (3.4 kgH_2), thus annual consumption ≈120 kgH_2/yr. High estimate: U.S. DOE (2002b). Replacing 222 million ICEs with 35 kW FCVs ⇨ 7.8 TW.

[98] ORNL (2003) *TEBD* 23, Table 2.6; 15.8 Q for gasoline and diesel consumed by light-duty vehicles = ~137 billion gallons/yr.

[99] Lovins (2003a), fn 103, p. 44 (lower estimate). Grant (2004), p. 129 (higher estimate). Grant uses 12 million bbl per day for surface transportation, but EIA statistics for 2002 show 13.1 million bbl/d all transport, less 1.6 jet fuel less 0.3 residual (bunker fuel) less 0.1 misc = 11.1 million bbl/d. Lovins cites 21.9 EJ of gasoline and diesel used for 2000 surface transport and estimates ~5.5 EJ of hydrogen per year (=~46 million tonnes H_2/yr = 125 million kgH_2/day) assuming quintupled-efficiency light vehicles and doubled-efficiency medium and heavy vehicles. Lovins also estimates that 50 MtH_2/yr "would displace two-thirds of today's entire worldwide consumption of gasoline." (p. 22, fn 101: quintupled-efficiency H_2FCV vehicles would displace 30 EJ of gasoline equivalent, 71 percent of global apparent gasoline consumption of ~42 EJ (2000)). A higher estimate is DOE (2002b) *Hydrogen Roadmap*, p. 11, estimates 40 million tons (36.3 Mt) of hydrogen required annually to fuel 100 million fuel-cell powered cars (= 363 kgH_2/FCV-yr). This equates to ~80.6 MtH_2/yr (9.7 EJ) for the 222 million light-duty vehicles in use today (making no adjustments for the type of vehicles replaced and excluding medium and heavy trucks, off-road vehicles, etc).

[100] US DOE (2003k), p. 11: replacing projected U.S. transportation demand of light vehicles *in 2040* of 18.3 million bbl/day will require, assuming H_2FCVs with 2.5 greater efficiency than today's vehicles, 150 million tonnes H_2 per year (18 EJ/yr, and 411 million kg/day). Current U.S. hydrogen production is ~8.2 million tonnes per year.

[101] Lovins (2003a), fn 103, p. 44; see our fn supra.

[102] U.S. DOE (2003k) *Basic Research Needs*, p. 11 estimates 136 MtH_2/yr (373 million kgH_2/d) required by 2040 (in cars and light trucks only, displacing 18 million bbl of oil/day; assumes FCVs 2.5xMPG of advanced ICEs).

[103] Hoffmann (2001), p. 168. One engineering study compared 400-passenger long-range jets designed for hydrogen (161 tonnes fueled with LH_2) vs jet fuel (215 tonnes of kerosene). The lighter weight reduced thrust requirements by 11 percent, which compounds to engine and structural weight savings. However, the LH_2 jet emits twice as much water vapor (82.4 lb/nmi = 20.2 kg/km), which leads to jet contrails and high-altitude cloud formation and are of significant climate concern.

[104] We have not come across plausible estimates of future hydrogen demand in stationary applications in buildings and industry. By way of developing a *preliminary* baseline, suppose we replace one-half of electricity used in U.S. buildings (4.33 Q = 4.57 EJ residential, 4.12 Q = 4.35 EJ commercial, 3.39 Q = 3.58 EJ industrial (excluding 1.31 EJ in T&D losses + 27.2 EJ in conversion losses)), which means, at 60 percent electric output per fuel cell and H_2 at LHV, 0.5 x (4.57 + 4.35 + 3.58 EJ) ÷ 0.6 = 6.25 ÷ 0.6 = 10.42 EJ of H_2/yr, or 86.8 MtH_2/yr. The recovered heat will also reduce demand for direct heating and water heating fuels (principally natural gas, secondarily electricity).

[105] See Patch (2001).

A plausible hydrogen development scenario

Distributed hydrogen production is the likely market winner until "large geographically concentrated hydrogen demand has built up" justifying enormous investments in thousands of miles of hydrogen pipelines and central production facilities. The DOE has the first part right, but not the second, which drives DOE's support for large centralized hydrogen production. While nuclear hydrogen production is a colossal red herring, it is possible that large coal and natural gas facilities will eventually produce and deliver cheap and relatively environmentally benign hydrogen (though significant impacts from coal mining will remain until in-situ hydrogen extraction is realized). The early years of the hydrogen transition will likely be based on on-site natural gas reformers scaled in size to meet growing demand.[106] There are compelling reasons to believe that hydrogen ICE vehicles will be the hydrogen sunrise technology—later, perhaps, to be supplanted by hydrogen fuel cell vehicles (H_2FCVs). Electrolysis—whether using grid power or renewable electricity—is neither cost-effective against small on-site reformers nor rational from a climate perspective: it is far better to use wind power to displace coal-fired electricity than to displace gasoline with hydrogen until electricity has been largely decarbonized.[107]

Far from the hoopla—and current hype—of the hydrogen economy is the consensus (including within the DOE) that the shift to hydrogen as a significant energy carrier is really decades hence, not years. Manufacturers' promises of residential fuel cells have stumbled; the commercial fuel cells market is expanding slowly and primarily in premium applications where their superior reliability is worth the extra cost. Fuel cells remain too expensive for vehicle applications, and, as Joseph Romm points out, the competition will not sit still while H_2FCVs are being developed. American Physical Society and the National Research Council concur that hydrogen storage technology, especially for passenger cars where space is a greater constraint, provides inadequate driving range. Other difficult issues include but are not limited to fueling time (several minutes), slow vehicle start-up time, and public perceptions about hydrogen safety. Hydrogen is rapidly entering the market in California, Iceland, Norway, and other pioneering regions, although the displacement of a significant share of U.S. oil consumption or emissions reduction (if any) may be far slower than the most ardent boosters suggest. U.S. energy and climate policy may delay the hydrogen transition, but over the long term the hydrogen age is probably inevitable, and there is little doubt that automakers and innovators will continue to make rapid progress.[108]

The DOE's Hydrogen Posture Plan

The hydrogen-related RD&D budgets of the U.S. Department of Energy have grown substantially and have reached several hundred million dollars per year. The comprehensive research agenda covers all aspects of the hydrogen transition from production technology to fuel cells, hydrogen storage and materials, safety and codes, and education to facilitate its acceptance. DOE, says Secretary Abraham will work "to develop both the vehicle and the infrastructure in parallel—and

[106] Ogden (2001); Thomas (2002 and 2004); Simbeck & Chang (2002); Keith & Farrell (2003).

[107] Romm (2004a); Romm (2004c); Anderson (2004) also points out that some regions (notably Denmark, Iberia, and Scotland) can justify some hydrogen production during periods of excess generation.

[108] Readers interested in the details of hydrogen development scenarios and important bits thereof should consult: Cho (2004), Demirdöven & Deutch (2004), Dunn (2001), Eames & McDowell (2004), Fairley (2004), Freedman (2002), Hoffmann (2001), Jensen & Ross (2000), Keith & Farrell (2003), Leighty (2003), Lipman et al (2004), Lovins & Williams (1999), Lovins (2003a), Ogden et al (2001), Rifkin (2002), Romm (2004a), Schwartz & Randall (2003b), Sperling & Cannon (2004), Swisher (2000a), Thomas (2002, 2004), U.S. DOE (2003j, 2003k), Vogel (2004), Bossel et al (2003) and its rebuttal by Weindorf et al (2003).

by so doing advance a commercialization decision by 15 years, from 2030 to 2015."[109] "Hydrogen will become America's 'clean energy choice,' joining electricity as a primary energy carrier and providing the foundation for a globally sustainable energy system."[110] Sensibly, the plan recognizes that "the research is not guaranteed to be successful and better options could arise for addressing foreign oil dependency and carbon emissions in the transportation sector, [and] a commercialization decision precedes the infrastructure investment phase."[111]

Steve Chalk (Manager for DOE's Hydrogen, Fuel Cells, & Infrastructure Technologies Program) has it right when he points out that rushing fuel cell technologies to market is premature, that codes and standards are not yet in place, that hybrid vehicles are a good transition technology, and that "wide adoption of fuel cell vehicles will most likely not take place until 2020, and a minimum of 20 years will be required for the majority of petroleum-based ICEs to be effectively replaced."[112] Joe Romm, in his book *The Hype About Hydrogen*, cautions further that hopes of a fast transition to hydrogen that, not forthcoming, has dire opportunity costs in our neglect of real, better, available, and effective ways to reduce our emissions and risks of severe climate change.

DOE's key hydrogen production program objectives include:[113]

1. Hydrogen production from natural gas or liquid fuels and delivered at 5,000 psi at a price equivalent to gasoline at $1.50 per gallon (without carbon sequestration and before taxes).
2. Combined hydrogen and electric plants using coal at a delivered cost equivalent to gasoline of $1.80 ($0.80 at the plant gate), including the cost of carbon capture and storage.
3. Hydrogen production from wind-powered electrolysis "approaching" $2.00 per gallon of gasoline equivalent, delivered at 5,000 PSI, using wind power at 4¢/kWh.
4. DOE, as well as the Administration (as expressed in its National Energy Plan), considers nuclear hydrogen production to be desirable, clean, and sustainable.
5. As DOE's Hydrogen Posture Plan and numerous other documents make clear, DOE supports a number of renewable energy pathways to hydrogen production: biomass, photoelectrochemical, phytobiological, wind-power and PV electrolysis; "a mix of diverse energy feedstocks to produce hydrogen is needed to gradually make the transition to a sustainable, secure, affordable, and environmentally safe hydrogen energy system."
6. DOE aims to facilitate a commercialization decision by 2015 to allow "rapid market penetration and significant oil displacement and environmental benefits for the year 2030 and beyond."
7. In its latest assessment, DOE is on track to meet the 2015 milestones.

The National Research Council released its *Hydrogen Economy* report in February 2004 that identified several technical hurdles to the emerging hydrogen economy, including the cost of fuel cells, storage technology, and the cost of hydrogen production. With respect to hydrogen production, the NRC made several recommendations:

- DOE's natural gas program should focus on distributed production technology and the development of a small and reliable natural gas reformer appliance for use at service stations.
- Focus on technology required for an integrated hydrogen fueling facility, including ancillary systems such as compressors, on-site storage, dispensing systems, etc.
- Commends the DOE for its proposed FutureGen coal-to-hydrogen + electricity coupled to sequestration (and storage) of the combusted carbon on a large scale, and cautions that this complex and high-cost demonstration project must be closely monitored by DOE.

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[109] U.S. DOE (2003) *2004 Budget Submission*, quoting Spencer Abraham.
[110] U.S. DOE (2004a) *Hydrogen Posture Plan*, p. iii..
[111] Ibid, p. iii.
[112] Chalk & Inouye (U.S. DOE 2003i) *The President's Hydrogen Initiative: U.S. DOE's Approach*, p. 5.
[113] Ibid, p. iv, 14, 15, (first four bullets); U.S. DOE (2002a and 2002b).

- Nuclear hydrogen production systems are in the laboratory stage of development; focus on promising high-temperature electrolysis and thermo-chemical cycles; focus on materials durability, effects of operating pressure, safe separation of hydrogen and oxygen; if research is successful, then select most promising cycles for demonstration (NRC recommends increasing and front-loading the nuclear RD&D budget in order to expedite technology selection).
- Research the safety aspects of the nuclear-chemical integrated system and "establish guidelines to arrest accident propagation from one part of the system to another."[114]
- Continue efforts to reduce cost and improve efficiency and durability of distributed hydrogen production from electricity and water; reduce electrolyzer cost to $125/kW and improve efficiency to 70 percent or better; develop electrolyzers able to use electricity from (intermittent and variable quality) wind and solar PV systems.
- "Wind energy for hydrogen production does not appear at present in [DOE's] multi-year research, development, and demonstration plan. Wind-energy-to-hydrogen systems need to be an important element in the DOE's hydrogen program and need to be integrated into the hydrogen production strategy. The plan should address the technical issues related to costs and capacity factor, particularly wind sites in class 3 and below."[115] DOE should partner with industry to create robust, efficient, cost-effective, and optimized wind-electrolysis-hydrogen systems that will be "ready for deployment as the distributed hydrogen infrastructure begins to develop." Characterize and integrate co-production of wind-derived hydrogen and electricity.
- De-emphasize DOE's current biomass gasification program and refocus its bio-hydrogen work on photosynthetic microbial systems; make use of advances in genomics and bio-engineering; continue research on co-firing biomass with coal coupled with carbon capture and storage; "resist pressure for premature demonstration projects of developing technologies."
- The number of approaches to and large potential of solar hydrogen means that multiple production pathways should be pursued until a "clear winning technology" emerges; alternative new technologies for harnessing solar energy must be developed as well as novel ways to reduce manufacturing costs of promising technologies; continue work on both direct solar-to-hydrogen and solar-powered electrolysis options; set a more aggressive target of ~2 cents/kWh for PV electricity; research new and novel technologies.

DOE's RD&D programs supporting the hydrogen mission

There are several DOE programs that support the hydrogen mission. Current expenditures for the core hydrogen programs total $227 million (FY05 request[116]), but this excludes RD&D on "peripheral" hydrogen technology such as FutureGen, Gen-IV nuclear reactors, clean coal, and capital cost for the Nuclear Hydrogen Initiative. The core hydrogen research programs are coordinated by DOE's Office of Energy Efficiency and Renewable Energy, the Office of Fossil Energy, and the Office of Nuclear Energy, Science, and Technology. The two principal research pathways are the FreedomCAR Initiative with RD&D on fuels cells, vehicle development, and related technologies, and the Hydrogen Fuel Initiative focused on hydrogen sources and production pathways; the combined funding totals $1.7 billion for FY2004-2008.[117] Cross-cutting research on materials issues (nanotechnology, carbon-tubes, fullerenes, and other innovative hydrogen storage materials) are under DOE's Office of Science. Consistent with our focus, we look at a few DOE programs that support the overall hydrogen production mission.

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[114] National Research Council (2004), p. 97.

[115] Ibid, p. 100.

[116] U.S. Dept. of Energy (2004b), Garman, p. 2.

[117] U.S. Dept. of Energy (2004g), Section 2. budget request for FY2005, EERE: hydrogen technology: $95.3 million, plus Energy Conservation: fuel cell technologies: $77.5 million. A large number of associated programs directly or indirectly support hydrogen technology (e.g., vehicle technologies [$156.7 million], wind energy [$41.6 million], solar energy [$80.3 million], biomass energy [$72.6 million], distributed energy resources [$53.1 million], hydropower [$6.0 million], biomass and bio-refinery systems R&D [$72.6 million],

FutureGen and Clean Coal Power Initiative

FutureGen, DOE's *Integrated Hydrogen, Electric Power Production and Carbon Sequestration Research Initiative*, "will showcase cutting-edge technologies that can virtually eliminate environmental concerns associated with coal utilization."[118] DOE's budget for FY2004-18 totals $920 million, with expected consortium and international contributions of ~$330 million.[119]

The Clean Coal Power Initiative, in its second round of solicitations, received replies to RFPs for projects valued at $6 billion, of which President's Bush's Clean Skies Initiative has pledged $2 billion in support of the next ten years.[120]

Table Three: DOE's hydrogen and related RD&D budgets, in $millions

	FY2004[121]		FY2005 Request	
	Direct	Associated	Direct	Associated
EERE	$164	$105	$95[122]	na
Fossil Energy (see below)	$12	$160	na	na
Nuclear Hydrogen Initiative[123]	$4	$20	$9	$10
Science	$0	$25	na	na
Total Hydrogen	$182	$301	na	na
Additional programs				
Clean Coal/FutureGen [124]	$179	$200	$287	$160
GenIV/Advanced Fuel Cycle[125]	$28	$67	$31	$46
Science/Environmental Mngt[126]	na	na	$29	na

Next Generation Nuclear Plant

The Next Generation Nuclear Plant (NGNP, AKA Generation-IV[127]) program aims to develop advanced, efficient (up to 48 percent efficiency [the lower-temperature Gen-II plants typically

[118] U.S. DOE (2004a) *Hydrogen Posture Plan*, p. 15.

[119] U.S. DOE (2004e), p. 9. The DOE aims to raise 35 percent of the projected $950 million cost from existing and future industry and international partners, leaving DOE to budget $620 million over FY2004-18. The 275 MW coal gasification with combined cycle electric generation plant is expected to capture and store 1 million tonnes of CO_2 per year. The plant's performance criteria include 99 percent sulfur removal, 85-90+ percent capture and storage of carbon dioxide, ≥90 percent mercury removal, and with low NO_x and particulate emissions.

[120] U.S. DOE (2004h). These projects include coal gasification, pre-combustion processing, and efficiency and reliability improvements. Project selections will be announced by the end of 2004.

[121] National Research Council (2004), table C-1, p. 138. "Direct" funding equals dedicated to hydrogen; "indirect" funding equals "efforts that are necessary for a hydrogen pathway."

[122] DOE Energy Efficiency and Renewable Energy FY2005 Congressional Budget: FY05 request: $95.3 million.

[123] U.S. Dept. of Energy (2004g), Section 2: Nuclear Energy, Science, & Technology: Nuclear Hydrogen Initiative (direct FY04 and 05), nuclear energy technologies (associated FY04 and FY05).

[124] U.S. Dept. of Energy (2004g), Section 2: Fossil Energy: FutureGen (direct), Coal Research & Techn (associated); these programs include carbon sequestration, hydrogen syngas turbines, integrated gasification combined cycle (gas stream purification), and Clear Skies Initiative, but do not include "other [coal] power systems" [$23 million], clean coal program direction [$14 million]; also natural gas [$26 million] and petroleum technologies [$15 million].

[125] U.S. Dept. of Energy (2004g), Section 2: Nuclear Energy, Science, & Technology: GenIV (direct), advanced fuel cycle initiative (associated). This breakdown excludes other "associated" expenditures that support general nuclear development (FY05): radiological facility management [$69 million], Idaho facilities management [$108 million], safeguards and security [$58 million], program direction [$60 million], and university reactor support [$21 million].

[126] U.S. Dept. of Energy (2004g), Section 2: Science budget request: these activities support basic scientific research into energy, hydrogen, technology, materials (including nanotechnology), physics, energy-related environmental issues, and energy security. The FY2005 budget request totals $3,432 million, including: nuclear physics [$401 million], basic energy sciences [$1,067 million], biological & environmental research (including climate change) [$502 million], and fusion energy [$264 million]. The Environmental Management budgets include programs to remediate DOE's military and civilian sites, including $443 million for non-defense sites and services (plus $6,973 million for defense sites), and $500 million for uranium enrichment decontamination and decommissioning. Also not included are DOE expenditures for the nuclear waste disposal repository (Yucca Mountain and transportation casks) of $749 million. The $29 million (direct) budget is from the Congressional testimony of David Garman (U.S. Dept. of Energy, 2004b, p. 4): $29 million for DOE's Office of Science for basic research on hydrogen production.

operate at 33-36 percent efficiency]), cost competitive, reliable, and safe and secure power plants and fuel cycles. The initial research plan has identified six promising reactors, two of which are compatible with hydrogen-production cycles. The Gen-IV International Forum (GIF) includes Canada, France, Japan, Germany, South Africa, UK, Switzerland, Korea, Argentina, and Brazil. The DOE timetable suggests deployment by 2020 to 2025; estimated development costs for all six reactor types are $5.6 billion, but no more than three of the six designs are likely to graduate from the feasibility phase into research prototypes each costing ~$940 million to build and test.[128]

DOE's aims for the Gen-IV reactors include "sustainable energy generation," "minimize and manage nuclear waste and notably reduce the long-term stewardship burden," have a "clear life-cycle cost advantage over other energy sources," a "level of financial risk comparable to other energy projects," and to "excel in safety and reliability." These objectives are poorly defined and thus unmeasurable except possibly against worse predecessors. In a June 2004 solicitation to the nuclear industry, DOE got more specific than perhaps it intended:

- Development of a system that can generate electric power at a cost of less than 1.5 cents/kWh;
- Development of a system that can produce hydrogen at a cost of less than $1.50/gallon-gasoline equivalent;
- Development of a system that will cost less than $1000/kilowatt with a goal of $500/kilowatt.[129]

The Nuclear Hydrogen Initiative

DOE's Nuclear Hydrogen Initiative aims to construct a demonstration plant to showcase the commercial-scale production of hydrogen using nuclear heat or electricity starting in 2016. Nuclear energy can already use the electricity or heat output to electrolyze water or contribute heat to steam reformation of natural gas. Consequently, NHI is focused on utilizing the high temperatures and more efficient power generation from the Gen-IV series being developed under DOE/GIF to demonstrate hydrogen production from water. That is, by thermo-chemical dissociation (using either the S-I or UTB cycles) or high-temperature nuclear electrolysis. Since the most suitable Gen-IV reactor designs (the very high-temperature reactor (VHTR)) are not expected to enter the demonstration phase until ~2015 and "deployable by 2020",[130] the core purposes of NHI are to demonstrate the technical and economic viability of the balance-of-system, such as the thermo-chemical cycles, high-temperature membranes and materials, heat exchangers, transfer loops, and so forth.

NHI milestones include laboratory-scale thermo-chemical hydrogen production system by FY2005, a complete commercial-scale design (FY2010) and a completed hydrogen production plant (also by FY2010), with operations and further development for several subsequent years. A

[127] Gen-I plants are the early Light Water Reactors; Gen-II are scaled-up LWRs, BWRs, CANDU reactors; Gen-III are the current designs of Advanced BWRs, System 80+, etc (Gen-III+ are evolutionary designs for near-term deployment). The future Gen-IV designs include such reactor designs with water, helium gas, and molten salts and metals as the working fluids. The six identified designs—the Gas-Cooled Fast Reactor (GFR), Lead-Cooled Fast Reactor (LFR), Molten Salt Reactor (MSR), Sodium-Cooled Fast Reactor (SFR), Supercritical Water-Cooled Reactor (SCWR), and Very-High-Temperature Reactor (VHTR)—include the helium-cooled pebble-bed reactor that looks most compatible with the requirements of hydrogen production and related criteria, such as modularity, passive safety, promising economics, low operating costs, high-temperatures, and, the developers hope, will not require expensive concrete containment domes. None of the PBMR designs have been certified by the NRC.

[128] U.S. DOE (2002d) *Technology Roadmap for Gen-IV*, p. 103. Magwood cited in Butler (2004), p. 238.

[129] U.S. DOE (2004f) *Request for Information and Expressions of Interest: Next Generation Nuclear Plant*, June, p. 2.

[130] U.S. Dept. of Energy (2002d) *Gen-IV Roadmap*, pp. 17 and 98. Just a year later the Director of DOE's Office of Nuclear Energy (William Magwood, IV) suggested a delayed timeline for the Gen-IV VHTR: final design FY2011-2014, and construction FY2012-2017. Far be it for us to criticize DOE's plans, but it *seems* premature to plan a construction start three years before the design-work is complete. Of course, it's impossible to forecast the tempo of progress on systems with high barriers and wide technology gaps.

nuclear hydrogen complex is likely to physically separate the reactor and the hydrogen production facility by 1,000 ft or more to reduce the possibility of accident propagation.

The Energy Policy Act of 2003 (S. 2095: introduced 12Feb04 by Sen. Domenici but not enacted) authorizes research, development, and design of the Advanced Reactor Hydrogen Cogeneration Project $35 million for FY2004 and $150 million each year FY2005-2008 (and "such sums as are necessary" beyond FY2008), plus $500 million for construction (Title VI).[131]

Hydrogen: the nuclear industry's second coming

"Technology exists now to produce in virtually inexhaustible quantities just about all the products made by nature … We have in our hands now … the technology to feed, clothe, and supply energy to an ever-growing population for the next seven billion years." —Julian Simon[132]

"A hydrogen economy will mean a world where our pollution problems are solved and where our need for abundant and affordable energy is secure … and where concerns about dwindling resources are a thing of the past." —DOE Secretary Spencer Abraham[133]

The nuclear proponents have a dream. A dream barely tempered by failure to deliver power "too cheap to meter." Well, many utility executives are laughing all the way to the bank, now that they have bought nuclear plants for cheap, upgraded their output and economic performance, creating the equivalent of 23,000 MW of new power over the last decade,[134] and raking in the money on most of the nation's 103 operating nuclear power plants. While no reactors have been ordered in the U.S. since 1978, the reactor designers are biding their time and positioning for the growing chorus calling for "climate-friendly, sustainable, hydrogen-producing" reactors.

Costs are likely to decline with the Next Generation (Gen-IV) of plants, the boosters say, reliability and availability will increase, the Three Mile Island and Chernobyl accidents are fading into the background, and Asian nations (especially China and India) are completing several plants and planning dozens more. China may be first out of the box with a modular Pebble Bed reactor: passively safe, constant re-fueling, easier waste handling, and simpler designs. The arguments are compelling in a carbon-constrained world in which 74 percent of energy consumption is fossil-fuel based.[135] Nuclear reactors "do not produce carbon dioxide"[136] sulfur, or nitrogen oxides, or particulates, leading the industry to market nuclear power on

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[131] United States Senate (2004), p. 392. The same bill also authorizes the construction of the Alaska Natural Gas Pipeline (Title III), $2 billion for the deployment of clean coal technology (Title IV), federal grants and low-interest loans to aid Native American "tribes" to develop energy infrastructure, reauthorizes Price-Anderson liability limitation on nuclear power plants through 2023 and funds Gen-IV nuclear plant RD&D (Title VI), authorizes $2.1 billion for hydrogen technology (not including the Hydrogen Reactor). Hydrogen (Title VIII, which supports RD&D on hydrogen production from fossil fuels, renewables, carrier fuels such ethanol and methanol, and nuclear energy; hydrogen for power generation; pipeline delivery and decentralized hydrogen production; fuel cell vehicle research; hydrogen storage technologies and materials; fuel cells, membranes, and materials; codes and standards, and public education "to develop improved knowledge and acceptability of hydrogen-based systems") authorizes $274 million for FY04, $375 million for FY05, $450 million for FY06, $500 million for FY07, $550 million for FY08. USS (2004), pp. 747-776.

[132] Simon (1995).

[133] Spencer Abraham, in U.S. DOE (2002b) *National Hydrogen Energy Roadmap*, inside cover.

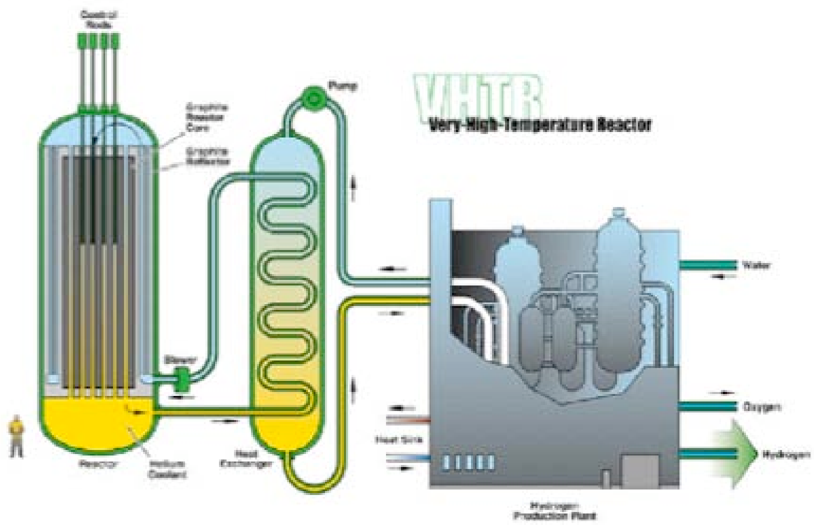
[134] Lake et al (2002), p. 76.

[135] UNDP (2000) *World Energy Assessment*. Fossil = 320 EJ of 434 EJ total (including 50 EJ of traditional biomass). In the U.S. fossil fuels provide 86 percent of the total (88.1 EJ of 102.7 EJ total, 2002). EIA (2003) *AER*, p. 3.

[136] The nuclear *fuel cycle* is not carbon-free: estimates range from 2.5 to 5.7 grams carbon-equivalent per kWh (gC-eq/kWh). Nuclear Energy Agency (2002a), p. 46. The source cited therein (Spadaro et al, 2000, IAEA Bulletin 42/2/2000, Vienna) includes the significant emissions from power plant construction and decommissioning, but this author has not verified the methodology and the boundary used (i.e., are CO_2 emissions from cement manufacturing included?). In any case, nuclear electricity emits far less carbon and other GHG than thermal plants; the same source estimates 105 to 366 gC-eq/kWh for fossil fuel chains and 2.5 to 76 gC-eq/kWh for renewables. Of the renewables, wind is the lowest at 2.5 gC-eq/kWh (UK coastal sites with 30% capacity); the high range is for high-methane tropical hydropower reservoirs (e.g., Brazil = ~65 gC-eq/kWh, but Canada = 4.4 gC-eq/kWh).

environmental grounds. It has been argued that nuclear power generation reduces U.S. oil consumption and imports, but very little (~2.4 percent) of electricity is now generated using petroleum. Nuclear economics are improving, but the proponents acknowledge that new nuclear costs must approach $1,000/kW to be competitive "with the most economical alternative, the combined-cycle natural gas plant."[137]

Figure Six: A Gen-IV reactor + hydrogen plant



VHTR coupled to a hydrogen facility. U.S. Dept. of Energy (2004d) *Nuclear Hydrogen Initiative Overview.*

Edward Teller (the "father of the hydrogen bomb" and other brilliantly nutty things) realized in the 1950s that civilian nuclear power had to be passively safe to succeed in the market, a lesson underscored by the Three Mile Island accident in 1979. Most new designs are therefore passively or inherently or "walk away safe"—meaning that temperature excursions are not controlled by safety systems such as pumps and rods but by the physics of the materials themselves. If new nuclear plants are (a) safe, (b) economically competitive with other ways to generate power and/or hydrogen, and (c) climate-friendly—will they succeed in the market of public acceptance and investor confidence?

The Pebble reactor

One reactor design that has become the darling of the nuclear proponents and nuclear hydrogen enthusiasts alike is the Pebble-Bed Modular Reactor; the PBMR was suggested in 1943 by Farrington Daniels at Enrico Fermi's Manhattan Project lab but ignored the war due to Admiral Rickover's singular interest in water-cooled reactors for naval propulsion.) The German government advanced the designs and built two prototypes in the 1960s & 1980s, but abandoned the program in the mid-1990s. As currently envisioned by the South African company that bought the patents and continued their development, the reactors will be modular 110 MW units. A prototype is planned for 2006-2010, the anticipated construction and operating costs are low (~2.3 cents/kWh busbar, 6 percent discount rate), and the modularity allows utilities to expand capacity in 110-MW bits as demand grows. The reactor itself is a steel vessel with 60 cm of interior graphite cladding into which 310,000 "pebbles" the size of billiard balls are stacked, plus

[137] The cost target and the perceived competition being CCNG are widely held views. Lake et al (2002), p. 76.

130,000 graphite pebbles to act as additional moderators. Each pebble contains 9 g of uranium in ~15,000 uranium oxide TRISO particles (Figures 7 & 8). This gumball-machine configuration permits continuous re-fueling at a rate of ~one pebble per minute from the top of the reactor as the spent pebbles exit at the bottom of the vessel. The working fluid is helium gas entering at 540ºC and exiting at 900ºC to run turbines and/or a hydrogen production facility.

Figure 7. Pebble Bed Modular Reactor gumballs

Photo of the pebbles in a German prototype PBMR reactor. Lake et al (2002) *Scientific American*.

Proponents and opponents alike tremble at the number of nuclear power plants needed to produce hydrogen sufficient to satisfy U.S. transportation requirements alone. Estimates vary from 241 to 444 1,000 MW_e reactors.[138] Suppose these are modular reactors of 110 MW-size: we are then talking about 2,190 to 4,036 reactors, or one reactor per 19 to 34 km (12 to 21 miles) of the U.S. Interstate Highway System or one reactor every 2.4 to 4.4 km (1.5 to 2.8 miles) of lower-48 coastline.[139] This is illustrative only; if any PBMR's or other reactors are built they will likely be clustered in existing or new nuclear parks.

The cost

Assuming each modular reactor can be built at DOE's *hoped-for* capital cost of $1,000 per kWe (overnight cost, not including financing), construction cost for the nuclear plants alone is $241 to $444 billion. According to the MIT report on *The Future on Nuclear Power*, a reasonable cost of future nuclear power plants is ~$2,560 per kWe (based on $2,000 kWe overnight construction cost and five-year construction),[140] which means a total nuclear plant development cost of $617 billion to $1.1 trillion. That is, *before* we add the hydrogen production plant and taxpayer-supported ancillary costs for research and development, decommissioning, waste handling, and

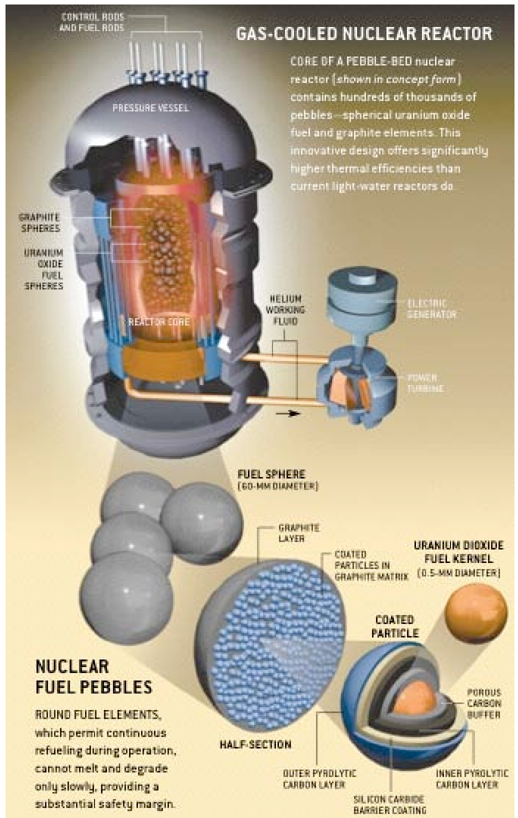
[138] 241 GW: Walters & Wade (2002), slide 9; 444 GW derived from Grant (2003), p. 130: "about 400 gigawatts of continuously available electric power generation"; assuming 90% capacity factor: 400/0.9 = 444 GW.

[139] The highway system totals 75,198 km (46,726 mi). The lower 48 states have 9,741 km (6,053 mi) of coastline, Canadian + Mexican borders add 9,745 km; Alaska and Hawaii add 8,980 and 1,207 km of coastline, respectively.

[140] MIT (2003), pp. 43, 137. The study compares the cost of nuclear power plants to natural gas and coal-fired power plants (fuel, construction, taxes, interest and principal repayment obligations, and "an acceptable return to equity investors" over the economic life of the project (40 years). They also posit lower capital costs, quicker construction, lower capacity factor (85 percent or better) carbon taxes on the gas and coal plants, and the unmodified comparative costs are 6.7 cents/kWh for nuclear, 4.2 cents/kWh for pulverized coal, and 3.8 cents/kWh for combined cycle gas turbine (at low gas price). MIT, p. 7.

uranium processing facilities. The MIT study did include decommissioning costs and waste fees incurred by the plant operators and operation and maintenance costs of 1.5 ¢/kWh. Not included, however, are security costs such as increased physical protection, perimeter protection, training, and security personnel that now average $7.3 million per reactor-year.[141] These and other security costs for personnel, training, and equipment are sure to increase.

Figure 8. The helium-cooled modular Pebble-Bed reactor



Lake et al (2002) *Scientific American*.

The PBMR consortium (which includes the U.S. utility Exelon, British Nuclear Fuels [owner of the U.S. reactor-builder Westinghouse], and Eskom, the South African utility) claims that the reactor will be affordable and inherently safe. The developers hope that the safety aspects of the design will result in gaining Nuclear Regulatory Commission certification *without* requiring a containment dome (which is key to their affordability) as well as obviating the need for an emergency and evacuation plan. To date, the NRC has expressed a number of pre-certification concerns about the design.[142] Nonetheless, the South African company hopes to compete in the

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[141] At $7.3 million per reactor (Nuclear Energy Institute estimate for 2003), this suggests $750 million for security at the nation's 103 reactors (though some sites host more than one reactor). This equates to ~1 mill per kWh ($752 million ÷ 780 billion kWh nuclear net U.S. generation, 2002). EIA (2003) *Annual Energy Review 2002*, p. 224.

[142] The NRC and nuclear watchdog groups remain concerned about the design's lack of "defense-in-depth" and the possibility of a reactor breach leading to a fire. While the helium-bathed pebbles cannot catch fire and "can't get hot enough to melt," a reactor breach that introduces oxygen and moisture can ignite the carbon-based graphite nodules and lead to catastrophic events. "We need a much more thorough understanding of the fuel behavior and its failure points," explains Ashok Thadani, director of NRC's Office of Regulatory Research (quoted in Talbot, 2002, p. 59). MIT engineering professor Andrew Kadak, a proponent of the pebble reactor who has worked to improve the PBMR, counters that German experience shows that even if the pebbles burn, the graphite-embedded and multi-coated TRISO fuel kernels would protect the uranium from dispersion (Talbot, p. 59). Since about one-fifth of the cost of a typical Gen-II nuclear plants is for the reactor vessel itself, and four-fifths balance-of-plant, containment, siting, planning, etc, the savings on eliminating both the containment and emergency planning are considerable and clearly make the economics more favorable. In order to ease the regulatory burden, the NRC has streamlined the licensing protocol and allows the issuance of a construction *and* operating permit in one step.

~$100 billion annual world-wide power plant market; "if we only get 5 percent of that market, that's very exciting," said PBMR consortium chief David Nicholls. Chinese scientists are advising the government to expand the country's nuclear capacity to 300 GW by 2050 (not much less than the world's installed capacity of 357 GW). The Chinese are pursuing Gen-II reactors from Framatome, Westinghouse, and Mitsubishi as well as developing their own pebble-bed design based on the German engineering in the open literature with, as Spencer Reiss puts it, the "Nike strategy: Just do it" rather than through patent-acquisition.[143] China, India, and other newly industrializing countries are planning to greatly expand nuclear and coal-fired capacities.[144]

We are the cusp of a new world: the engineering is there, alleged affordability, the perceived demand, inherent safety, and, best of all, a super-technology in a green cape: purported savior of the climate and air pollution, fabricator of hydrogen for transportation (thus huge reductions in U.S. oil imports), and purveyor of national security. Can it be done? *Should* it be done?

Shortcomings of the Nuclear Hydrogen Initiative

> *"Ever bigger machines, entailing ever bigger concentrations of economic power and exerting ever greater violence against the environment, do not represent progress: they are a denial of wisdom. Wisdom demands a new orientation of science and technology towards the organic, the gentle, the non-violent, the elegant and beautiful."* —E. F. Schumacher[145]

Alvin Weinberg, for one, "cannot concede that our ingenuity is unequal to living in a 4,000-reactor world," which is his 10-fold nuclear capacity expansion required for a "significant contribution to CO_2 control."[146] Insofar as the objective of the Nuclear Hydrogen Initiative is to reduce carbon emissions and usher in all-American hydrogen production, it will do so (if at all) ineffectively and at high cost. Some analysts think that NHI is not only a colossal waste of taxpayer funds but unlikely to or even incapable of producing hydrogen in a market economy. Lovins argues that nuclear power has "no prospects in market-driven energy systems, for a simple reason: new nuclear plants cost too much to build. In round numbers, electricity from *new* light-water reactors will cost twice as much as from new windfarms, five to ten times as much as distributed gas-fired cogeneration or trigeneration in buildings and factories (net of their credit for recovered heat), and three to thirty times as much as end-use efficiency that can save most of the electricity now used."[147] Monetizing carbon won't help, as most nuclear advocates contend, "because it would equally advantage at least two of the three strongest competitors (efficiency and windpower) and partly advantage the other (gas-fired co-trigeneration)."[148]

Perhaps the greater fallacy, however, is ignoring opportunity costs. As Keepin and Kats pointed out several years ago, investing in nuclear power plants (or any other higher-cost technology) to reduce carbon emissions is inefficient: they found that one dollar invested in the efficient use of electricity saves seven times as much carbon as a dollar invested in new nuclear capacity.[149] (With improved nuclear performance, today's efficiency advantage is probably ~3 to 1 or better.)

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143 Reiss (2004).

144 Hawkins (2004) slide 13: India plans ~150 GW, China ~500 GW, rest-of-world ~780 GW of coal-fired electricity by 2030; data from International Energy Agency, *World Energy Outlook*.

145 Quoted in Lipman et al (2004).

146 Weinberg (2003).

147 Lovins et al (2004), p. 258.

148 Ibid., p. 259.

149 Keepin & Kats (1988). Also see Friends of the Earth-Scotland (1998).

Promoting nuclear power as a solution to climate change (a) by displacing fossil-fueled electric generation or (b) producing hydrogen is counter-productive and diverts needed institutional resources, dollars, and leadership from lower-cost ways to reduce emissions. Holding out false solutions delays action on numerous more effective fronts.

In addition to these economic and environmental blind alleys, let's look at a number of other intractable barriers to using nuclear plants for hydrogen production and climate mitigation, starting with nuclear technology, the waste issue, economics, and security vulnerabilities. We'll follow these points with a discussion of the shortcomings of DOE's nuclear hydrogen policies as a lead-in to sustainable hydrogen development guidelines and renewable hydrogen capabilities.

Nuclear conundra

1. **Cost.** Using nuclear heat for thermochemical dissociation of water into hydrogen and oxygen is expensive, conversion efficiency of heat to hydrogen is relatively low (~45 percent, HHV basis), and the technology is far from commercially available. Robert Williams of Princeton University cites nuclear hydrogen production cost estimates of \$37.50/GJ (\$5.33 per kgH_2, HHV); Williams concludes that even if the nuclear heat were free, "the cost of H_2 would still be \$15.50/GJ, some 2.4 times the cost of H_2 from coal using near-commercial technology *with CO_2 sequestration*." Technical advances may reduce costs, as the PBMR proponents hope. Williams concludes that even if very optimistic PBMR cost projections are realized, even then the low cost of nuclear heat yields uncompetitive thermochemical hydrogen, and that "all other cost components [of hydrogen production] would have to be reduced to *zero* to enable thermochemical hydrogen to compete."[150]
2. The U.S. cannot nuclearize its way to **climate stewardship**. Still, mitigating climate change through low-carbon nuclear power has become a familiar rallying cry. Well, alligator tears and all, it won't fly. Ignoring, for the moment, the replacement of the dozens of reactors scheduled for decommission (or license renewal) and growth in electricity demand, simply displacing currently installed fossil-fired power plants totaling 689 GW (emitting 2.24 billion tonnes of U.S. CO_2 in 2001), this suggests multiplying nuclear power capacity by a factor of roughly seven. At a nuclear construction cost of \$2,560 per kW_e means a national investment of \$1.55 trillion, not including significant investment in uranium enrichment plants and other infrastructure. The DOE hopes to reduce reactor cost to ~\$1,000 per kW_e, which reduces investment to a mere \$610 billion.[151] If U.S. electricity demand growth also has to be "neutralized" (which has averaged ~2.6 percent since the mid-1970s), then the prospect of nuclear climate-mitigation becomes even less tenable: about 788 GW of new nuclear capacity must be added by the early 2030s.[152] A total of 1,477 GW of new nuclear capacity must be built to displace current and future fossil-fueled plants. Using DOE and MIT cost estimates of \$1,000 to \$2,560 per kW_e, an investment of \$1.48 to \$3.87 trillion is required. Ouch. While it's unlikely that this will come to pass (demand growth will likely slow, and efficiency and gas and renewables are all cheaper), let's consider the implied nuclear completion *rate:* 1,477 new GW by 2032 means *one (1.01) new 1,000 MW_e plant every week for 28 years (assuming overnight construction)*. Ouch again.[153] Surely there are better, cheaper, and safer ways to displace the carbon emissions from the electric power sector.
3. **Nuclearization leaves multiple problems.** Even the largely pro-nuclear MIT report acknowledges that "[w]e have not found, and based on current knowledge do not believe it is realistic to expect, that there are new reactor and fuel cycle technologies that simultaneously overcome the problems of cost, safety, waste, and proliferation."[154]

[150] Williams (2001a), p. 19; citing nuclear hydrogen production cost estimates from Tadokoro et al (1997). Williams: low cost PBMR yields low cost nuclear heat (~\$2.60/GJ) and thermo-chemical hydrogen cost of \$6.40/GJ (\$0.91/kgH_2). Emphasis added.

[151] EIA's *Annual Energy Outlook* forecasts, in its Reference Forecast to 2025 Table A9 (and extended to 2031 by this author), 1050 GW of fossil-fueled power capacity (and, interestingly, no new nuclear). If we take EIA's forecast instead. we still get, at \$1,000 to \$2,560 per kWe, \$1.05 to \$2.67 trillion.

[152] U.S electricity's carbon-intensity has declined; gas and, to a lesser extent, coal have comprised most of the capacity additions since 1989. Electricity sector decarbonization has been ignored (it declined modestly from 0.67 kgCO_2/kWh (net generation, not consumption [cf fn #84]) in 1980, 0.59 kgCO_2/kWh in 1990, 0.60 kgCO_2/kWh in 2000. From EIA (2003) *AER*, Tables 8.1, 12.2.

[153] Williams (2001a), p. 3. Globally, Williams calculates a nuclear expansion rate of 85-90 GW_e/yr yielding 4,900 GW_e of new nuclear required by 2100 to replace *all* coal-fired generation. The result: forecasted total year-2100 carbon emission are reduced only to 80 percent of IPCC's IS92a emissions scenario.

[154] MIT (2003), p. 5.

4. **Proliferation.** Deploying nuclear power plants around the world, as the proponents hope to do, increases the risks of providing civilian cover for the fuel cycle, technology, expertise, and diversion of enriched uranium for nation-state military programs, as we are now facing in Iran and North Korea (Brazil is also in non-compliance with IAEA inspection protocols). Diversion can also be accomplished by sub-national groups (e.g., the Khan conspiracy in Pakistan) or even by al-Qa'ida or other jihadist groups with aspirations to acquire enriched uranium to assemble low-yield weapons or dirty bombs, or, preferably, acquire a ready-to-use black market weapons. It is beyond our present scope to evaluate these escalating risks. Let it suffice to mention that civilian nuclear power leaves open the door to proliferation. Clearly, "even a little proliferation, especially to non-state actors, destroys U.S. national security, since anonymous nuclear attacks with no return address, e.g., via shipping container, and with no physical base to retaliate against, can be neither deterred nor punished, and are very difficult to prevent."[155]
5. **Expanded enrichment capacity and vulnerability**. Hal Feiveson of Princeton University estimated enrichment capacity for the 4,900 GW_e nuclear world discussed above (bullet #1). This scenario requires 2,000 enrichment plants of 500 tSWU/yr, each able to provide enough enriched uranium for 150 bombs annually. Feiveson concludes: "Lots of enriched uranium too close to bomb quality, lots of separation plants, lots of incentive for innovation to make separation cheaper and quicker. To me this is an unsettling prospect.'"[156]
6. **Operational safety** of existing or new nuclear power is not a bygone concern as illustrated by troubling recurrences of poor management, inspection, and operation, such as the near-disastrous coolant-system corrosion at the Davis-Besse plant in the U.S. recently, the Mihada complex in Japan, and numerous other less-publicized events. We have not assessed safety concerns with respect to thermochemical hydrogen facilities.
7. **Uranium.** Large-scale nuclearization will eventually face uranium resource shortages, unless breeder reactors are revived, or uranium is recovered (at high cost) from seawater. An assessment of reasonably assured uranium resources totals 2.32 million tonnes of uranium (MtU, <$80/kgU), an additional 0.88 MtU ($80-$130/kgU), and estimated additional resources of 5.1 MtU ($130-$260/kgU). 15–30 tonnes of uranium are typically consumed per TWh of electricity generated.[157] Using a simple model and the high uranium fuel efficiency of 15 tU/TWh, we estimate depletion of reasonably assured uranium resources by 2045 in a very high growth scenario and by 2070 in a low growth scenario.[158] In sum, uranium depletion is the least of the industry's worries, as reactor efficiencies, uranium recycling, and the use of fissionable materials from destroyed weapons are all likely to extend uranium resources. Environmental concerns over uranium mining remain.
8. The **nuclear waste** issue is far from won, although it may, in time, be technically solved. DOE's plans for Yucca Mountain faces stiff opposition from the citizens and government of the "nuclear sacrifice" State of Nevada, even after a DOE investment of ~$7 billion. The site characterization work is incomplete, there are serious concerns over its long-term viability, and in Jul04 the U.S. Court of Appeals ruled that DOE's plan to safeguard wastes for 10,000 years is inadequate. Other proposed storage technologies are ignored by a DOE determined that Yucca must proceed. [159]
9. **Waste transport.** Even if the waste repository is eventually approved and open for business, there remains the insecurity and hazard of transporting the 70,000 tonnes of high-level wastes now sitting in caskets and cooling-pools at America's 103 operating plants. DOE is confident that

[155] Lovins et al (2004), p. 260.

[156] Feiveson (2000). Summarized in Williams (2001a), p. 5.

[157] Uranium resource assessment in Rogner, Hans-Holger (1999) *World Energy Assessment*, draft, UNDP, WEC, Ch. 5.

[158] Using the lower uranium consumption rate (i.e., 30 tU/TWh-yr) lowered the resource depletion date to 2030 (very high expansion rate of 2.8%/yr) and 2041 (low expansion rate of 0.7%/yr). This spreadsheet model starts with year-2000 actuals: 349 GW installed, capacity factor of 79.6%, and 2.43 TWh generated. Low growth = 0.7%/yr, moderate growth = 1.4%/yr, high growth = 2.1%/yr, and very high growth = 2.8%/yr; capacity factor is gradually increased from 79.6% in 2000 to 86.0% in 2030 and to 91.0% in 2060. Only the very high growth scenario approaches Feiveson's and Williams' 4,900 GW_e required for modest carbon mitigation (see bullets 2 and 5). Capacity expansion costs and build rates were not estimated, and decommissioning rates were ignored. Adding the estimated additional uranium resources brings the total remaining resources to 8.3 MtU, which extends the resource life to 2072 under the very high growth scenario (and 2052 with the lower uranium consumption rate). Interestingly, the U.S. Energy Information Administration (2004, *International Energy Outlook*) forecasts 0.6%/yr growth in nuclear electricity generation over 2001-2025 for both the Reference Case (Table A7) and the High Economic Growth Case (Table B7); EIA's World Nuclear Generating Capacity Forecasts are not consistent with Tables A7 and B7, however (High Growth Case: capacity grows by 1.8%/yr [Table E2] but generation only grows by 0.6%/yr).

[159] Wald (2004b). Such as vitrification, ceramic packaging, transmutation, plutonium removal, and "safe" space launches. These are unproven solutions. With Yucca apparently failing its 100,000-year mandate, Wald suggests a temporary (50-100 yr) cooling-off period in large storage casks shipped to a single easily protected above-ground site until better solutions are developed.

transporting wastes across the nation's highways (often through or around cities) can be safely accomplished in crash-worthy caskets. A clever jihadist group could, conceivably, devise a way to attack or otherwise spectacularly crash of one or more convoy trucks in a fashion not simulated by the threat and safety experts at DOT, DOE, and NRC. Will their defense once again be the equivalent of 'no one could have imagined that terrorists would attack us with airplanes'? (Condoleezza Rice, testimony before the 9/11 Commission). The U.S. fuel cycle remains insecure against such low-probability high-risk events.

10. **Terrorism 1.** The difficulty of protecting domestic nuclear power plants from terrorist attacks is daunting and deserves more than denial and obfuscation by the industry and the Nuclear Regulatory Commission. Assurances after 9/11 that containment domes were designed to withstand the crash of a fully loaded jumbo jet proved untrue, as the NRC had to admit: they may be hardened against a RDX-laden Cessna or even a glancing blow by a Boeing 737 but not a fuel-laden heavy. Some observers suspect that UA Flight 93 that crashed in eastern Pennsylvania was en route to one the three reactors (Three Mile Island, Peach Bottom, and Hope Creek) located between the crash-site at Shanksville and the presumed target in Washington. The truth of this is only known by at most a few living souls who may never tell. The FBI, however, did receive "credible evidence" that Three Mile Island had been under surveillance by some of the hijackers in the months before the attacks of 9/11.[160] Even a small aircraft weaponized with conventional explosives deliberately crashed into a reactor's spent fuel pool (typically containing thousands of times the radionuclides released by the Hiroshima bomb) can be devastating. The Indian Point reactor complex's spent fuel pools house 1,300 tonnes of radioactive materials located ~50 km north of New York City. "Imagine a world without New York City," Robert F. Kennedy Jr. said in a film focusing on the vulnerabilities of Indian Point: "the terrorists already have."[161] This scenario requires more than a weaponized Cessna, of course, and Rory Kennedy's film *Indian Point: Imagining the Unimaginable* asks: "what if the terrorists flying AA Flight 11 down the Hudson River toward the World Trade Center had instead turned left?" Some critics worry that inadequate security and structural containment enable "terrorists armed with weapons as simple as buckets and hoses" to start a fire by draining the pools that cool and immerse the fuel rods.[162]

11. **Terrorism 2.** It may be easier for terrorists to launch a ground-attack against a nuclear facility than repeat the airborne attack of 9/11. Regrettably, the industry remains unprepared to guarantee public safety.[163] The NRC has hitherto refused to upgrade its "design basis threat" that requires the industry to protect against "an attack by three outsiders, perhaps aided by one insider, with no team-maneuvering tactics, no attack by boat or air, and minimal hand-held weapons" with a response force only recently upgraded from five to ~ten armed security personnel per shift.[164] The NRC has done force-on-force testing at nuclear facilities that received six month's prior notice of the mock attack. This Operational Safeguards Response Evaluation program succeeded in gaining entry and "simulate the destruction of enough safety equipment to cause a meltdown."[165] What did the NRC attempt to do in response to such dismal results: *kill the testing program*.

12. **Terrorism 3.** The NRC does not require the industry to protect its facilities against a truck bomb larger than the one used at the World Trade Center in 1993, even though more powerful bombs have been used in other attacks. It was recently announced that 342 tonnes of high-intensity HMX, RDX, and PETN explosives were removed from an Iraqi stockpile during the U.S. invasion, possibly for nefarious purposes within or beyond Iraq. Explosives are widely available, and there is no reason to believe that the Iraqi explosives were shipped or delivered by courier to embedded cells in the U.S., even though only ~2-5 percent of containers arriving at U.S. ports are searched.

13. **Security readiness.** Hirsch et al raise other concerns, such as inadequate training of security personnel, boredom, low pay (below that of janitors in many cases), exhaustion from long shifts and overtime, and poor morale. The Nuclear Energy Institute even took out full-page ads in major newspapers in 2002 portraying security guards as highly trained paramilitary units, a portrayal

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[160] Hundreds of stories have been written on this threat; interested readers may start with Rufford et al, (2001) "Nuclear Mystery: Crashed Plane's Target May Have Been Reactor," *Sunday Times of London*, 21Oct.

[161] Quoted in Kiehl, Stephen (2004) "Examining risk of Indian Point," *Baltimore Sun*, 9Sep04.

[162] See Ferrandino, Rita (2002) "Fueling Fears," *Village Voice*, 18Dec02.

[163] The U.S. General Accounting Office (2003b, 2004) is not sanguine about the NRC's poor progress to date on GAO's earlier recommendations to improve security at civilian nuclear installations.

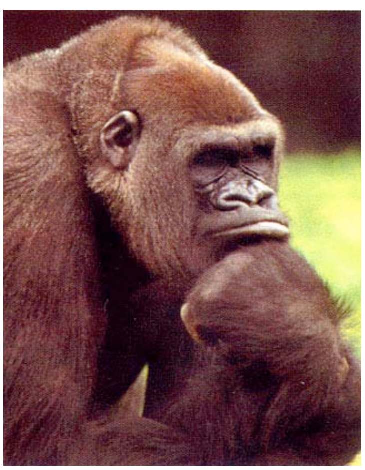
[164] Hirsch (2002) "The NRC: What, me worry?" *Bulletin of the Atomic Scientists*, Jan/Feb, pp. 38-44. Quotes are Hirsch.

[165] Hirsch et al (2003), p. 44.

apparently resented by many guards.[166] The dual problems here are a regulatory agency beholden to the industry it oversees, and an nuclear industry run by for-profit companies more inclined to lower expenses than protect the public's safety against unlikely events.

14. **Technology gaps.** All of the Gen-IV reactor designs include untested engineering, and depend on the development of ultra-hard materials that can resist high temperatures, high neutron flux, and corrosive environments.[167]
15. **Near-misses.** Previous "pre-terrorism" events illustrate on-going threats to nuclear facilities: a light plane lost in fog crashed into the Millstone (CT) reactor complex, disabling the electric supply to the reactor's shutdown systems in 1972; a B-52 exploded and crashed 30 km from Savannah River in 1975; and hijackers who threatened to force a Southern Airways pilot to crash the plane into the Oak Ridge (TN) nuclear complex reportedly collected a $2 million ransom before diverting the plane to Cuba in 1972. Other concerns include nuclear materials theft, staff going "postal," system breakdowns, cascading failures, security breaches, sabotage by insiders, and institutional failures, just to name a few. Amory and Hunter Lovins' 1982 book *Brittle Power* describes in detail the many previous (and mostly persistent) threats to U.S. energy security, including to nuclear power facilities, both accidental and deliberate, and by domestic and international threat-sources; we refer readers to this seminal book for additional information.[168]
16. **Costly large-scale demos.** Steve Chalk's (DOE's Hydrogen, Fuel Cell, and Infrastructure Technologies Program Manager) admonition that "large-scale demonstrations are not necessary, and would be costly," although directed at DOE's fuel cell RD&D, should pertain equally to DOE's expensive nuclear hydrogen demonstration projects.[169]
17. **Public opinion.** The American public remains very concerned about nuclear power and nuclear waste. Also, the public's awareness and concern over the nuclear system's security vulnerabilities (whether from a NIMBY or national perspective) is rising. A series of out-dated Harris public opinion polls found that ~62 percent of American oppose the construction of new nuclear power plants in the United States (~32 percent in favor). Another, slightly more recent poll (1999) found a narrowing ~2 to 1 majority opinion that nuclear power will be important in meeting America's future electricity needs.[170] Public opinion is malleable, and a concerted industry campaign might soften opposition and gather support for "climate-friendly" and "clean hydrogen" nuclear plants.

Our ingenuity is certainly equal to living in a 1,000 or even a 4,000-reactor world. But why on Earth would we? There is a perfectly functional fusion reactor some 150 million km from home



that delivers 2.7 million EJ/yr[171] at the Earth's surface—some 6,340 times humanity's annual energy consumption of 426 EJ. Of course, a small fraction of this energy flow is harvestable, and much less is economic with current technology and market conditions. Yet it is in humanity's certain future (if we avoid societal collapse) that we build the infrastructure to reap a mere one-sixtieth of one percent of the solar wealth to our productive use. This transition will require ingenuity equal to a nuclearized future, but at far lower capital, societal, and environmental costs. Investing in nuclear energy for hydrogen production or carbon reduction is a wrong turn promoted by a shortsighted technological priesthood. This nation can ill afford the multi-trillion-dollar investments in nuclear chimera when that path's opportunity costs are graver still: a hydrogen transition delayed, inattention to immediate and profitable ways to reduce emissions of greenhouse gases, international aid driven more by our own rapacious

166 Ibid.
167 David Lochbaum, nuclear engineer with UCS, quoted in Butler (2003), p. 239.
168 Lovins & Lovins (1982) *Brittle Power: Energy Strategy for National Security.*
169 Chalk & Inouye (2003), p. 10.
170 Rosa & Rice (2004).
171 Smil (2002a), p. 6. 2.7 million EJ ≈87 PW. Global primary energy consumption of 426 EJ ≈13.5 TW.

appetites than by real poverty alleviation, resource conflicts inflamed by competition for dwindling oil and water, and many other problems we would leave to future generations. Nuclear energy can only defer the hope that belongs to the solar hydrogen century.

Is the DOE favoring fossil fuel and nuclear hydrogen production pathways?

The DOE is careful to present a balanced approach to hydrogen production research and development and to avoid the impression that the agency favors incumbent nuclear and fossil fuel industries. To wit, DOE's *National Hydrogen Energy Roadmap:*[172]

> *"Advanced hydrogen production methods need development. While wind, solar, and geothermal resources can produce hydrogen electrolytically, and biomass can produce hydrogen directly, other advanced methods for producing hydrogen from renewable and sustainable energy sources without generating carbon dioxide are still in early research and development phases. Processes such as nuclear thermo-chemical water splitting, photoelectrochemical electrolysis, and biological methods require long-term, focused efforts to move toward commercial readiness. Renewable technologies such as solar, wind, and geothermal need further development for hydrogen production to be more cost-competitive from these sources."*

While this reads as a balanced approach, DOE's budgetary priorities suggest otherwise. Critics point out that DOE has cut funding for renewable and efficiency programs by $86 million, prompting Jason Mark of the Union of Concerned Scientists to remark that "cutting R&D for renewable sources and replacing them with fossil and nuclear doesn't make for a sustainable approach."[173] More insidiously, the incumbent fossil fuel and nuclear industry representatives are awarded choice leadership positions: of the seven segments of the *Hydrogen Energy Roadmap* workshops, five were lead by major hydrogen industry players, while the two non-profit participants were relegated to the System Integration and Public Education & Outreach segments. Said Mike Nicklas, past chair of the American Solar Energy Society and who sat on the Hydrogen Production sessions chaired by Gene Nemanich of ChevronTexaco: "All the emphasis was on how the process would benefit traditional energy industries. The whole meeting had been staged to get a particular result, which was a plan to extract hydrogen from fossil fuels and not from renewables."[174] This should come as no surprise to environmental NGOs: these corporations have the skills to build the hydrogen infrastructure, the balance sheet to pay for it, the resources to control it, and the self-interest to profit from it. This combination does not necessarily lead to good public policy.

The pattern exercised by the DOE at its *Hydrogen Energy Roadmap* meetings in 2002 lead some observers to question the impartiality and objectivity of the agency. Mike Nicklas said that "we're now at the point of making a transition to an entirely new energy paradigm, and we don't need to be continuing the carbon era by other means." Dan Becker of the Sierra Club told Jim Motavalli of *E* magazine that "nuclear-generated hydrogen is like a nicotine patch that causes cancer … This certainly explains one level of the Bush administration's sudden interest. But if we're looking to hydrogen to free us from old forms of energy, why would we suddenly go nuclear, with all the well-known problems?" Motavalli concludes that "DOE's hydrogen production scenario is bizarrely tilted toward nuclear power, echoing the emphasis of Vice President Dick Cheney's closed-door sessions for the 2001 National Energy Policy. The policy directs the Secretary of Energy to vastly expand the nation's nuclear generating capacity and to

[172] United States Dept of Energy (2002b), p. 9.
[173] Quoted in Lynn (2003).
[174] Ibid.

'develop next generation technology including hydrogen and fusion.'" In the same article, Thomas Jackson, president of Avalence, which is developing residential hydrogen electrolyzers, is concerned that federal incentives will go to the nuclear industry and strongly influence what would otherwise be a free market for new technologies. "There needs to be a level playing field that includes all the different approaches," Jackson said.[175]

"Group think" made its notorious entrance into the public lexicon with the release of the 9/11 Commission and Senate Select Committee on Intelligence reports, but it's been a well-oiled slippery slope toward flock behavior since group decision-making began. It concerns not only the CIA or the FAA, or merely the officials of the Bush Administration, although Vice President Cheney's Energy Task Force has been lambasted as particularly favoring this approach.[176] Two converging paths are at work here: one is the buying of influence, and the other is selection of viewpoints representing, oftentimes, the results sought by the dominant players. Both paths tend to lead to the exclusion of dissenting voices. In the planning for a sustainable hydrogen economy it is critical that opposing viewpoints, emerging interests, and other stakeholders are deliberately included. The nation as a whole will benefit by the consideration of future options *not* desired (as well as those that are desired) by today's energy behemoths, though of course the Exxons, Enrons, and Exelons of the world have a right to be heard. We do not intend to belittle the many progressive and intelligent people working for the major carbon and nuclear corporations. These entities control the preponderance of intellectual and financial resources required for a genuinely sustainable hydrogen economy. These same companies may also have interests that conflict with the deeper interests of the nation. Wise leadership must delve deeper than the pockets of the incumbent industries.

Let's be clear: we strongly support American business. Corporations have the resources, skills, and incentives required to build a better world. Our concerns are primarily directed toward misguided government policies operating within an imperfect market that evolves too slowly relative to the challenges at hand. Enlightened business can, and does, anticipate over-the-horizon changes calling for corporate sustainability. Slow implementation is more a reflection of old-think in Congress and the White House than obstinacy in the boardrooms across America.

Sustainable Hydrogen Production

Sustainable hydrogen production would aim to meet the following general objectives:

- Hydrogen production must reduce net emissions of greenhouse gases and most other pollutants.
- Hydrogen production should boost domestic employment.
- U.S. hydrogen production should improve global equity and enhance global security.
- Hydrogen production must not rely on market-busting Federal or state subsidies. Indeed, existing subsidies should be phased out to create fair competition between competing hydrogen pathways. It is suboptimal to level the playing field by adding new layers of incentives and tax expenditures.
- Markets work best when prices tell the truth: sustainable hydrogen production can be fostered by reforms that gradually and predictably internalize social and environmental costs into prices.
- Federal and state reforms must systematically remove regulatory biases against market-oriented opportunities to reduce energy, carbon, and material intensities.

[175] Motavalli (2003c), p. 38-39.

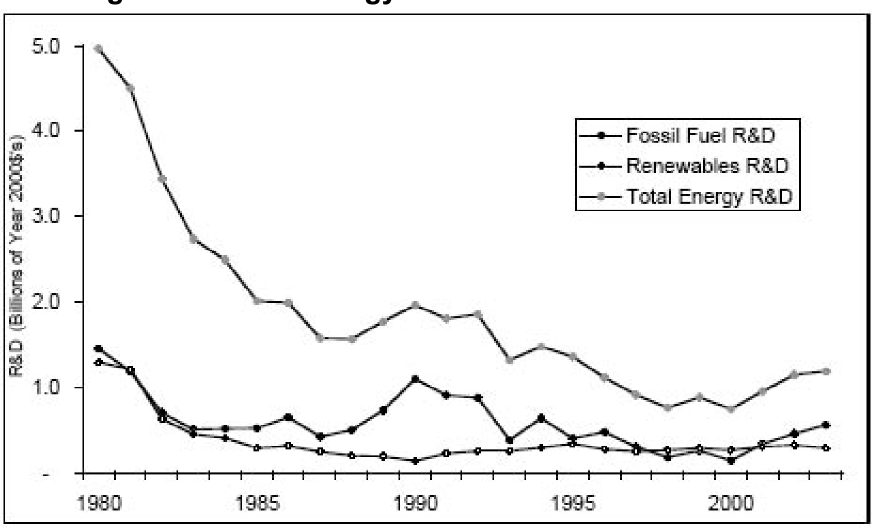
[176] United States General Accounting Office (2003a); Natural Resource Defense Council (2001, 2004). See also Cheney (2001) and White House (2002).

- Even sustainable hydrogen production is likely to degrade sustainability unless serious efforts are made to improve end-use efficiency prior to or in parallel with hydrogen development.
- Hydrogen production pathways should account for and minimize vulnerability to disruption, embargoes by international cartels, terrorist attacks, accidents, and price fluctuations.
- Communities and consumers must feel—and be—safe in proximity to hydrogen production and fueling infrastructure.
- U.S. DOE and other Federal agencies must adopt sustainability guidelines that reflect societal, environmental, security, and economic concerns in RD&D planning and budgeting priorities; it follows that energy policy should not be developed in secret meetings nor by incumbent industry participation alone and that great care should be mustered to avoid "group think" by experts, political donors, and companies seeking to profit from particular policies at great societal costs.
- Hydrogen production and delivery pathways are most reliable and secure when diverse.

Federal incentives and research programs can ameliorate but more often exacerbate market failures. These failures must be addresses head-on. Fundamental changes are required in the U.S. energy economy in order to shift the momentum toward rather than away from sustainability.

A number of studies argue that investment in sustainable energy creates millions of jobs through private-sector and government programs that cost-effectively reduce oil imports, manufacture alternative fuels and renewable equipment, improve efficiency in all sectors of the economy, and cut greenhouse gas emissions.[177] Furthermore, U.S. DOE research dollars have declined sharply over the past two decades and are increasingly tilted toward incumbent industry interests, compromising job growth and the emergence of a sustainable energy system (Figure 9).

Figure 9. DOE's energy RD&D investment 1980-2004



Kammen et al (2004), forthcoming in *Issues in Science and Technology*.

Concerns have been raised over the amount of materials, energy, and emissions that must be invested in renewable energy technologies.[178] Using photovoltaic panels as an example, Turner concluded that manufacturing 10 m^2 of crystalline PV emits ~4,000 kg of carbon dioxide but

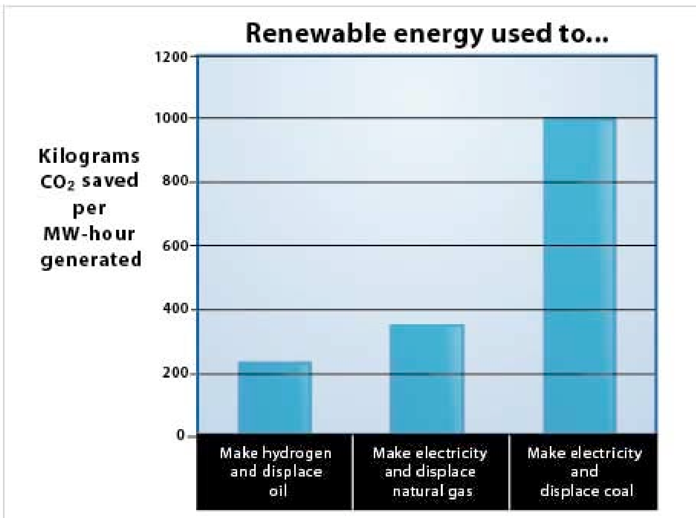
[177] E.g., Lovins et al (2004), pp. xii, 243-244: creates ~2.7 million net job by 2025 at very large net savings ($70 billion *annually* by 2025 while "checkmating" oil imports to zero by 2050), competitive advantages, and enhanced U.S. security; Apollo Project (2004), p. 7: creates 3.3 million new jobs at net savings to the U.S. Treasury, stimulates $1.4 trillion in new GDP, and generates $284 billion in net energy savings over 10 years; Kammen et al (2004), summarizing 13 other studies of renewable energy employment, conclude that wind, biomass, and PV installation generate ~0.7 to 11 times as many jobs per MW installed than coal- and gas-fired power plants over the life of each facility (de-rated for the capacity factor of each technology). Hoerner & Barrett (2004), p. 2 estimate an addition of 1.4 million new (not net) jobs by 2025 and savings of $76 billion per year by 2025.

[178] We ignore here the far larger infrastructure investments by the conventional energy industries.

avoids 1,330 kg CO_2 per year when installed in a region of moderate solar income and average carbon intensity of the electricity supply, which yields an emissions payback period of 3 years. PV's electricity payback periods are about 3-4 years, including the energy invested in modules, infrastructure, and electronics, but are expected to decline to 1-2 years with improved module and manufacturing efficiencies. [179] Wind energy has a much faster payback of ~3 to 8 months.[180]

For climate mitigation reasons, renewable electricity must first displace coal-fired electricity; only thereafter should it be diverted for sustainable hydrogen. Romm forcefully argues in his book *The Hype About Hydrogen* that premature reliance on the not-yet-emerging hydrogen economy threatens to delay effective action on one of the most pressing problems facing the 21st century: climate change. A systematic sustainability roadmap encompassing climate mitigation, hydrogen production, and other environmental values is not available but should be undertaken.

Figure 10. Relative carbon reduction potentials



Romm, 2004a, *The Hype About Hydrogen*, with permission.

Renewable Hydrogen Options

Solar power and solar hydrogen

> *"The potential capacity for solar hydrogen is quite large. The estimated power output from 10% efficient solar cells covering 1.7% of the land area of the U.S. is 3.3 TW, equivalent to the total U.S. fossil fuel use in 2000. To place this capacity in perspective, 3,300 new 1-GW nuclear power plants would need to be built—~1 for every 10 miles of coastline or major waterway—to supply the same 3.3 TW of power."*[181]

The conversion efficiency of photovoltaic systems is steadily improving while costs are falling dramatically. Global installed PV capacity is now ~3.3 GW and growing at 22 percent per year; global generating capacity totals 3,400 GW and is growing by ~75 GW/yr (~2.2 percent/yr).[182]

[179] Turner (1999), pp. 687-688. Turner envisions "a renewable energy breeder plant" relying on renewable energy to manufacture additional renewable energy conversion equipment.
[180] Ibid, p. 687. Turner cites Paul Gipe (1992) *Wind Energy Weekly* #521: www.awea.org/faq/bal.html
[181] U.S. DOE (2003k). pp 12-13.
[182] Sawin (2004), pp. 18 and 23. Global capacity from EIA (2003) *Annual Energy Review 2002*, Table 11:16.

PV system costs are high ($4 to $20 per watt, including balance of system and installation), and generating costs range from $0.11 to $1.00 per kWh. Solar electric systems are being installed by early adopters in developed countries, in remote villages in Africa and Asia using external and indigenous financing, and in other applications with expensive access to grid power such as weather reporting stations and telecommunications sites. Manufacturers are hoping to reduce module costs from $3-$4 per peak watt today to around $1.00 per peak watt.

How large is the U.S. potential for PV-generation and hydrogen production? One analysis found that inexpensive fixed flat-plate collectors with a modest 10 percent conversion efficiency covering half the area of a 25,900 km^2 (161 x 161 km) site in southern Nevada would generate electricity equal to total U.S. consumption.[183] If Lovin's estimate that ~2.25 PWh/yr is sufficient to produce nearly all of the 50 million tonnes of hydrogen required for upgraded highway H_2FCVs (based on the wind potential of the Dakotas alone),[184] Taylor's PV generation in a bit of Nevada can be correspondingly reduced from 25,900 km^2 to 18,600 km^2; if PV efficiency is doubled, then the area can be halved to 9,300 km^2. This is an enormous collector area equal to 15 percent of the macadam of U.S. roadways.[185] Photovoltaic systems can be distributed around the U.S. in various sizes to reduce hydrogen and/or electricity delivery losses and infrastructure costs. Solar concentrator technology, module cost reduction, and integration into building envelope materials can improve performance and lower costs sufficiently to attract major capacity expansion in the U.S. Last year, the Western Governors Association adopted a goal of deploying 20 GW of renewable energy in western states by 2015 (plus 10 GW from efficiency improvements), and the DOE has awarded $90,000 plus technical support toward WGA's plan to build 1 GW of concentrating solar power capacity in southwestern states. Seventeen U.S. states have adopted renewable portfolio standards, renewable energy development funds, or similar mandates—many bolstered by carbon emissions reduction targets—that will expedite renewable electricity generation and thus build the capacity for renewable hydrogen production.[186]

Williams believes that "it is not unrealistic to expect that PV could ultimately be deployed at an average global per capita rate of the order of 1 kW$_{ac}$, which would require a collector area of about 7 m^2 per capita near users in areas characterized by average insolation" and generating 16 PWh/yr worldwide in 2100.[187]

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[183] This equivalence ignores electricity storage and intermittency issues, but the purpose is to suggest the sufficiency for solar hydrogen production. Taylor (1999), p. 687. Solar insolation in SE Nevada is ~2,300 kWh/m^2-yr (~3.8 W$_e$/m^2 average); PV generation at 10 percent conversion efficiency is 230 kWh/m^2-yr, which translates to a collector area of 13.9 billion m^2 to generate 1997 U.S. power demand of 3.29 PWhr/yr (twice as much land when one accounts for spacing between modules); hence total land area is 27.8 billion m^2, or 27,800 km^2. Efficiencies as high as 30+ percent have been demonstrated in the laboratory, but with far higher expected production costs per m^2. In order to compare land-use intensity for renewable electricity and hydrogen production options, we estimate the amount of land area covered with PV (including the area between modules) using Taylor's data: 27,800 km^2/3.29 PWh/yr = 8,450 km^2 per 1.0 PWh-yr (halved with doubled-efficiency arrays). Hoffert et al (1999), p. 984 cite H. C. Hayden (2001, *The Solar Fraud*) data that PV shipments totaled ~3 km^2 from 1982-1998, requiring a "massive (but not insurmountable) scale-up is required to get to 10 to 30 TW" that the authors estimate is required for global non-fossil energy production by 2050; if this is supplied by PV, they calculate 260,000 km^2.

[184] Lovins et al (2004), p. 240; assuming on-site electrolysis at 75 percent efficiency, 10 percent H_2 transportation or electricity transmission losses, and ~40 percent capacity factor for the turbines.

[185] U.S. public roads cover 63,450 km^2 (24,500 sq miles) or 0.7 percent of U.S. land area of 9,161,924 km^2. Other paved areas (parking lots, drive ways) add 27,200 km^2 and 0.3 percent. *Environmental Building News*, May 2001. Highway construction spending appears to run $30-$60 billion per year, but it isn't clear whether these expenditures are on Federal highways only, or all federally-supported road and infrastructure construction.

[186] Northrop (2004), Lipman et al (2004). Most affected utilities are likely to invest in the lowest-cost renewable, principally wind power and small hydro. Again, renewable electricity should displace coal- and gas-fired generation before H_2 production.

[187] Williams (2001a), p. 9. Average insolation is ~1,800 kWh/m^2/yr in the U.S. Higher insolation levels occur in tropical or near-tropical desert regions such as the Arabian Peninsula, which is called the Saudi Arabia of solar income for good reason, just as the U.S. upper Midwest has been called the Saudi Arabia of wind. Many observers from Buckminster Fuller forward have speculated on creating a global electricity network to maximize the productivity of diurnal cycles, match generating capacity to demand in a rolling fashion, and connect southern high-irradiance regions with the over-developed North. For insolation levels, see e.g., www.aeiveos.com/~bradbury/Papers/SW.html

Photovoltaic hydrogen production cost estimates range from a low of \$1.42 per kgH_2 (future technology with 18 percent efficiency, module cost of \$30/m^2, and 6 percent discount rate) up to \$28.19 per kgH_2 (current technology, stand-alone production).[188] The photovoltaic hydrogen production potential is very large: up to 335 MtH_2/yr (47.6 EJ/yr), or 2.5 to 6.7 times U.S. hydrogen demand projections (see "hydrogen demand," pp. 17-18).[189]

Wind power and wind hydrogen

Wind power capacity is the fastest growing energy source in the world. Wind capacity expanded at an average rate of 30 percent/yr over the last decade, and added 6.7 GW in 2002, outstripping nuclear additions of 5 GW.[190] While wind power plus all other "new renewables" (which exclude large hydro and traditional biomass) still comprise a small percentage of total primary energy production of 1.7 percent, its resource base is enormous and widely dispersed around the globe. Vaclav Smil estimates an aggregate wind resource below 1 km of ~1.2 PW—nearly 90 times today's world primary energy consumption rate of 13.5 TW.[191] Grubb & Meyer estimated global onshore wind power potential at 500 PWh/yr (including 139 PWh/yr in North America),[192] of which the *practically exploitable* global onshore potential ranges from 20 to 53 PWh/yr, or 1.3 to 3.6 times current world generation of 14.9 PWh/yr.[193] This is comparable to global electricity demand of 68 PWh/yr projected for 2100 (in IPCC's business-as-usual IS92a scenario).[194]

Estimates for net wind power potential of Class 3+ areas of the Dakotas alone are 2,250 billion kWh/yr (2.25 PWh/yr), equivalent to 59 percent of 2002 net U.S. generation of 3.84 PWh/yr, based on 1990s 750 kW turbine technology. Today's 2 MW machines use 100 m towers to capture the far greater wind energies higher off the ground and employ more efficient turbines, blades, and electronics. A 1991 assessment of recoverable U.S. wind energy potential: even with "moderate" land class exclusions for environmental, urban, agricultural, forest, and range set-asides, the aggregate capacity is ~500 GW and the net power generation is more than 10 PWh/yr, or 2.7 times current U.S. net generation of 3.84 PWh/yr.[195] Jacobsen & Masters propose to displace two-thirds

[188] Cited estimates from Ogden & Nitsch (1993) and National Research Council (2004, respectively. Also see Lipman (2004).

[189] Ogden & Nitsch (1993), cited in Lipman (2004), p. 19.

[190] Renewable capacity additions: Sawin (2004); Net nuclear capacity slowed to ~0.7 percent/yr in the 1990s and added 21 GW between 1993 and 2002 while wind added 29 GW; meanwhile, the nuclear industry also had to retire and commission ~12 GW of capacity. Calculated from Worldwatch (2003) *Vital Signs*, pp. 37, 39. Nuclear *generation* has increased ~2.5 percent/yr since the late 1980s—largely due to improved performance and availability factor: International Atomic Energy Agency (2004).

[191] Smil (1999) *Energies*, MIT Press, p. 14.

[192] Grubb, M.J., & N.I. Meyer (1993), wind classes 3-7; cited in Rogner (1999) *World Energy Assessment*, UNDP, section 5.9.

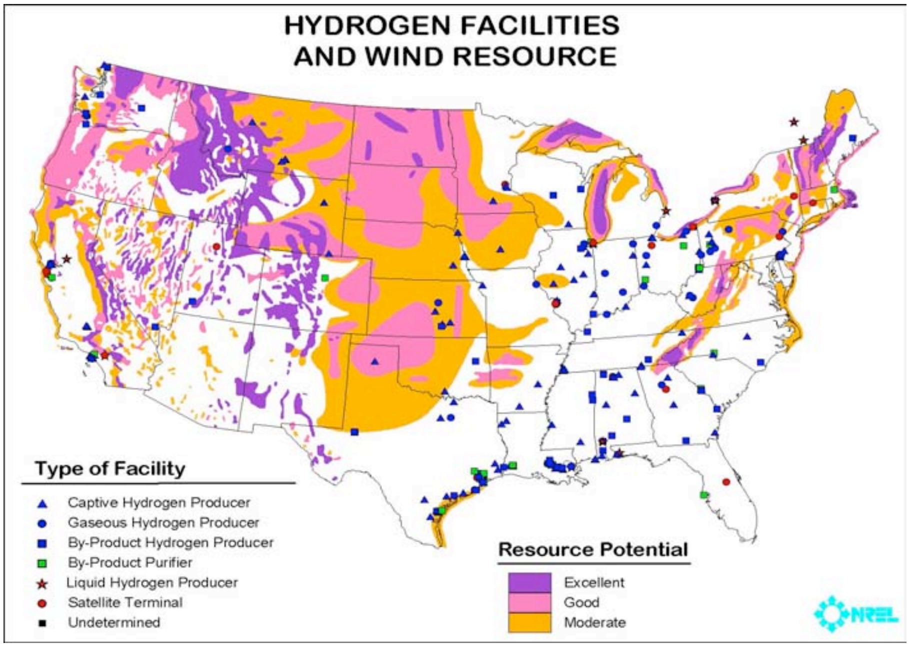
[193] World Energy Council (1994): 20 PWh-yr; Grubb & Meyer (1993): 53 PWh-yr; both cited in Williams (2001a), whose own estimate is 43 PWh-yr. World net generation from U.S. EIA (2003) *Annual Energy Review*, Table 11.16: 14,868 TWh-yr, of which 9,528 TWh-yr [64.1 percent] was fossil, 2,521 TWh-yr [17.0 percent] was nuclear, 2,571 TWh-yr [17.3 percent] was hydropower, and 248 PWh-yr [1.7 percent] was renewables plus miscellaneous).

[194] Williams (2001a), p. 2, points out that the IPCC scenario projects carbon emissions to grow from 6.2 GtC to 19.8 GtC/yr by 2100. Such B-A-U scenarios, including IPCC's IS92a, are treated with skepticism by some; e.g., Ausubel (2002), who refers to such technologically stagnant and ingenuity-vacuous models as "Brezhnev Scenarios."

[195] Elliott et al (1991) updated by Elliott & Schwartz (1993): U.S windy areas of Class 4–7 total 460 billion m^2, ~6 percent of lower-48 states, on which the average *intercepted* power density is ~7 to 14 W_e per m^2/yr (of 400 to 900 Wm^{-2}/yr wind *resource*); annual generation estimated at 11.7 to 23.2 kWh/m^2. See also Williams (2001a), p. 9. P = Peta = 10^{15}; PWh/yr = petawatthours per yr. U.S. net generation in 2002: 3,839 TWh/yr = 3.84 PWh/yr.

of U.S. coal-fired generation (1.1 PWh/yr) through the deployment of ~225,000 1.5 MW turbines on ~37,600 km^2 of land distributed through the Great Plains states. They estimate a generation cost of 3-4 ¢/kWh, and a total investment of $363 to $470 billion.[196]

Figure 10: U.S. wind resources



Source: National Renewable Energy Laboratory, Golden, CO.

The cost of wind power electricity is widely expected to decline even lower than today's 4.3-6.8 ¢/kWh to 3.0-4.0 ¢/kWh by 2020, or even less in the best wind sites, enabling large wind farms in remote locations to compete with advanced natural gas combined cycle power plants in major markets.[197] The intermittency of wind can be handled by a number of storage technologies such as flywheels, batteries, conventional pumped hydro storage, ultra-capacitors, compressed air energy storage, superconducting magnetic storage, and, of course, *hydrogen*. A high fraction (50 percent or more) of wind power in the U.S. electricity mix appears feasible and economic, and can be smoothly integrated with other grid resources. Since wind is dispersed over time and space, its intermittency imposes potential costs to generators by dispatchers who value reliability. This cost can be effectively minimized by the use of improved wind prediction, dispersal of wind farms across regions with differing wind regimes, back-up gas or hydrogen generation combined with compressed air or shorter-term storage, and integration with load management to optimize demand.[198] Wind power can be used to run hydrogen-producing electrolyzers on-site, thereby eliminating expensive gear boxes, electronics, and O&M.[199] Hydrogen can be stored in modified wind towers,[200] or pipelined to market via new or refurbished gas grids.[201]

[196] Jacobsen & Masters (2001) Each of the 214,000-236,000 turbines plus ancillaries costs ~$1.9 million, or $149,000–$183,000 per turbine-year (construction, land, grid-connection, O&M, financing, and interest) when amortized over its 20-year life. The total investment is non-trivial, but far less than the nuclear option discussed above, and without the environmental and security risks. Elliott et al (1991) estimate Great Plains wind potential at ~9.2 PWh/yr, of which Jacobsen & Masters aim to capture only ~1.1 PWh/yr. Note: existing power plants are *not* likely to be retired early; indeed, life-extension is common.

[197] Williams (2002), p. 4; National Research Council (2004), p. 226; Turkenburg (2000) *World Energy Assessment*.

[198] A rich literature exists on wind system integration, reliability, back-ups, and dispatch, e.g., see DeCarolis & Keith (in press).

[199] Lovins et al (2004), p. 240.

[200] Kottenstette & Cotrell (2003).

[201] Leighty et al (2003).

In order to compare various renewable electricity and hydrogen production options, we estimate the land required to generate 1.0 PWh/yr for each renewable source. The land area required for wind energy is based on Elliott & Schwartz's estimate that "about 0.6 percent of the land of the lower 48 states would have to be developed with wind turbines" to provide 20 percent of the nation's electricity—thus ~85,000 km^2 of land is needed to generate 1 PWh/yr of wind power.[202] Wind farms only use 3 to 5 percent of the land for towers, equipment, and access roads, leaving 95+ percent of the land available to agriculture, forests, ranching, or open range. Williams points out that royalties to land owners are frequently worth more than net farm income, acre by acre.[203]

Ogden & Nitsch estimated a U.S. wind power hydrogen production potential up to 220 MtH_2/yr (31.3 EJ/yr),[204] identifying North Dakota (25 MtH_2/yr) and Texas (24 MtH_2/yr) with the largest potential. Lovins, using PNL data, calculates that North and South Dakota wind resources can alone produce the ~50 MtH_2/yr deemed sufficient to fuel the replacement of all of today's cars, light trucks, and heavy trucks with ultra-efficient hydrogen fuel cell vehicles.[205] (This estimate excludes electricity or hydrogen transmission losses or compressor energy.) The numerous studies summarized in Lipman estimate wind power hydrogen production costs for various configurations, sizes, and discount rates. Cost estimates range from a low of \$1.14/kgH_2 (future technology, small stand-alone) to \$10.69/kgH_2 (current technology, stand-alone production).[206]

Biomass and biomimetic hydrogen

Biomass is plentiful and, like most renewables, dispersed. Global primary photosynthetic production is ~220 billion dry tonnes (4,500 EJ). Photosynthesis typically converts ~4 percent of incoming solar radiation into biomass resources. Critics point out that biomass is diffuse and land-intensive, the net energy productivity is low, and biomass is often ecologically or aesthetically inappropriate.[207] Its advantage is that biomass can largely rely on resources now wasted (such as agricultural and municipal wastes and forestry residues). Furthermore, biomass can *reduce* carbon emissions by virtue of displacing fossil sources plus (and here's the kicker) *remove* carbon from the atmosphere during the growth of the biomass vegetation. Additional net carbon removal can be realized by sequestering the carbon from power generation or hydrogen production in geologic storage.

Globally, biomass already provides 10-14 percent of total energy supply (40-55 EJ), principally in developing countries as domestic fuel where it often leads to deforestation and desertification. In developed countries the use of biomass is relatively low (~3 percent) as a percent of primary energy. Estimates of the future biomass potential range as high as 2,900 EJ, of which 270 EJ is considered currently available on a sustainable basis,[208] or ~60 percent of current global primary

[202] Elliott & Schwartz (1993), p. 5. They based this estimate on 1988 electricity generation of 2.71 PWh, of which 20 percent equals 0.54 PWh. Thus (roughly), 1 PWh of annual wind generation requires a land area of: (1/0.54) x 0.006 x 7,670,144 km^2 (lower 48 land area) = 85,223 km^2. Note: this scaling does not reflect a progressively lower wind power generation from lower-quality wind resources, but this is probably a wash with Elliott & Schwartz's use of older turbine technology, 25 percent efficiency, 25 percent losses, and 50-m hub height (versus newer high-efficiency turbines reaching higher wind intensities with 100-m hub height). U.S. total land area: 9,161,924 km^2 less Alaska (1,481,347 km^2) and Hawaii (10,433 km^2) = 7,670,144 km^2;

[203] Williams (2001a), fn 13: royalties of \$88 per acre per year vs net farm income of \$51/acre-yr (1999 data).

[204] Ogden & Nitsch (1993), in Lipman (2004), p. 16.

[205] Lovins (2003a), fn 104 (p. 44): "At a nominal 75% electrolyzer efficiency, the total wind electricity from these two states could produce 50 MT/y of hydrogen, excluding electric and gas transmission losses and compressor energy." PNL data from Elliott et al (1991) "not adjusted for the potential effects of the recently discovered larger-than-expected high-level wind."

[206] Padro (2002) & National Research Council (2004), respectively. NRC also cites future stand-alone technology (480 kgH_2/day: \$2.86/kgH_2), current technology, grid-tied (\$6.81/kgH_2), and future technology, grid-connected systems (1,200-1,600 kgH_2/day: \$3.50/kgH_2). See also Ogden & Nitsch (1993); Lipman (2004) neatly summarizes several production technologies and costs.

[207] Ausubel (2002) and Hoffert et al (2002).

[208] Hall & Rosillo-Calle (1998), cited in Rogner (1998) *World Energy Assessment* (draft), UNDP, Ch. 5, p. 41.

energy consumption of 426 EJ. Williams concurs with the IPCC that global biomass electricity production of 1.4 PWh/yr by 2100 is plausible, but a number of observers think both resources and cost-effectiveness will drive deployment faster.[209]

Biomass energy crops require land. Turkenburg reports that to fuel a base load biomass power plant of 1,000 MW_e operating at 40 percent conversion efficiency requires 2,570 to 4,220 km^2 hectares of land (0.64 to 1.04 million acres) including roughly 5 percent energy inputs for cultivation, fertilizer, harvesting, etc.[210] Scaling up to a capacity of 1 PWh/yr suggests a land requirement ~114 times the area required for a 1,000 MWe plant, or 293,000 to 481,000 km^2. Regional differences, seasonal biomass flows, vegetation types, transportation, and process efficiencies—as well as crop selection, technology, and genetic engineering—makes this example barely useful in estimating the land required in the U.S. for biomass electric plants. Nonetheless, the land requirement of biomass is roughly 3.4 to 5.6 times that of wind power, PWh/yr for PWh/yr. To summarize the land required per PWh/yr of electricity generated from each of the renewable systems discussed, we get, very roughly, 8,450 km^2 for photovoltaics, 85,000 km^2 for wind, and 293,000 to 481,000 km^2 for biomass crops. These estimates are illustrative, as technical improvements are rapidly reducing the renewable energy footprints.

In the U.S., the biomass potential is surprisingly large for both use of biomass wastes and dedicated biomass crops. Hydrogen production potential has been estimated at 19.4 million tonnes per year (2.8 EJ/yr) by 2010 and at 28.8 MtH_2/yr (4.1 EJ/yr) available by 2020.[211] The latter estimate is based on 7 EJ of biomass energy available at $3 per GJ, and from source materials including municipal wastes, forestry and agricultural residues, and energy crops. Biomass source material is widely distributed around the U.S.

Summary of renewable hydrogen production

"Trying to perpetuate our existing high-energy lifestyle with hydrogen is a pipe dream."[212]

Renewable sources for hydrogen production are very large relative to anticipated demand. We have not analyzed geographic distribution, deployment schedules, or investment rates. Nor have we evaluated regional delivered hydrogen costs. The potential for renewable hydrogen production is unambiguously very large—and many times the anticipated demand for hydrogen. *Unless*, that is, the U.S. pursues policies that constrain renewable energy development in parallel with bringing hydrogen vehicles and other fuel cell applications to market without first capturing the large available efficiency opportunities. The future demands not only clean hydrogen from the bottom up but a far more efficient palette of end-uses to satisfy. If history is any guide, DOE support for end-use efficiency is haphazard, although occasionally very effective and beneficial. The long-term U.S. trend for efficiency improvement is ~1.2 percent per year (as measured by energy consumption per dollar of GDP). We can do far better with stronger DOE and Administration leadership. We urge the Bush Administration to remove barriers, re-shuffle policy priorities, and show the determination that sustainable energy, climate, and hydrogen solutions deserve. This will simultaneously benefit the economy, U.S. competitiveness, and the environment.

[209] Williams (2001a), pp. 2, 10. Note: 1.4 PWh = 5 EJ, not including harvesting, processing, and conversion losses.
[210] Turkenburg (1999) *World Energy Assessment* (draft), UNDP. Ch. 7, p. 7.
[211] Ogden & Nitsch (1993), and Mann & Overend (2003); cited in Lipman (2004), p. 23. See also Meyers et al (2003).
[212] Michael Winkler, Arcata, California energy activist, www.culturechange.org/hydrogen.htm

Conclusion

"Prediction is very difficult, especially of the future." —Niels Bohr.

In the long term, a clean hydrogen age is certain to emerge. In the next fifty years, however, wide adoption of hydrogen is neither inevitable nor necessarily sustainable, clean, or responsive to this century's carbon-constrained world. The Bush Administration's policies are likely to increase the cost of hydrogen due to its pursuit of capital-intensive production and delivery pathways—many of which are unlikely to succeed in the market. The opportunity costs of these policies include a delayed hydrogen transition and deferred reduction of U.S. greenhouse gas emissions. DOE's Nuclear Hydrogen Initiative is a colossal waste of the public's money and weakens both U.S. and global security. NHI's financial and managerial resources are better applied to safer bets, such as wind power, biomass, solar, and many other renewable hydrogen production and delivery options. The DOE is better advised to fundamentally shift support to and remove numerous barriers from the serious deployment of decentralized, secure, least-cost, and pro-job-growth *clean* hydrogen production and delivery options. Distributed hydrogen production is a likely early winner, presumably via steam methane reforming, and the DOE must support work to minimize this hydrogen production pathway's carbon emissions.

The agency must also draw on a broad constituency of experts to help create a roadmap of a *sustainable* hydrogen transition. A focus on energy efficiency, first and foremost, will help ensure action on climate mitigation, support sustainable wealth-creation and jobs, and usher in a sensible hydrogen age earlier and cheaper. Progressive leaders in government, business sector, and civil society have a momentous opportunity before us. America's embrace of a sustainable transformation will define our nation as stewards of humanity and the world we live in. Or not.

America has a choice.

Appendix A

Hydrogen facts, abbreviations, and conversions

One kg of H_2 contains approx the same amount of energy as one gallon of gasoline.

1 kg H_2: 120.1 MJ (million joules) (lower heating value, LHV); 1 EJ/yr = 8.326 MtH_2/yr (at LHV)

1 kg H_2: 142 MJ (higher heating value, HHV); 1 EJ/yr = 7.042 MtH_2/yr (at HHV)

1 gallon of gasoline: 121.3 MJ (LHV), or 115,400 Btu (LHV; 125,000 Btu at HHV)

1 Btu = 1055 J (joules)

1 Nm^3 of H_2: 12.7 MJ (higher heating value, HHV); N means Normal (0ºC, 1 atmosphere)

1 Quad (Q) = 10^{15} Btu = 1.055 EJ (exajoule = 10^{18} J)

U.S. primary energy consumption, 2002: 97.35 Q = 102.7 EJ (96.32 Q in 2001 = 23.85% of world)

Global primary energy consumption, 2001: 403.9 Q = 426.1 EJ[213] ≈ 13.5 TW (ave).

1 kilogram (kg) = 2.205 pounds (lbs), 1 megagram (Mg) = 1 metric tonne (t) = 10^6 g = 1.1023 short ton

1 kilometer (km) = 1,000 meters (m) = 0.62 mile = 3,281 feet

1 cubic meter (m^3) = 264.17 gallons = 35.31 ft^3.

1 megapascal (MPa) = 145 pounds per square inch (psi)

1 horsepower (HP) = 0.986 metric HP = 0.7068 Btu/s = 0.7457 kW

1 kilowatt-hour (kWh) = 3,412 Btu; 1 Btu = 29.31 x 10^{-5} kWh

1 gigawatt-hour (GWh) = 3.41 x 10^9 Btu

1 megawatt (MW) = 1 x 10^6 J/s

ºC = (ºF – 32)/1.8

1 year = 8,766 hours (365.25 days) = 31,557,600 seconds = ~π x 10^7 s

M = mega = million = 10^6
G = giga = billion = 10^9
T = tera = trillion = 10^{12}
P = peta = quadrillion = 10^{15}
E = exa = quintillion = 10^{18}
D = duh = duhzillion = 10^{∞}

213 U.S. consumption from Energy Information Administration (2003) *Annual Energy Review 2002*, DOE, p. 5, www.eia.doe.gov; world consumption from EIA (2004) *International Energy Outlook 2004*, p. 1

Appendix B

Black Hydrogen
References & Resources

14Nov04

Abraham (2004) "The Bush Administration's Approach to Climate Change," *Science*, vol. 305:616-617.

Allen, Myles (2003) "Liability for climate change," *Nature*, vol. 421:891-892.

Alley, Richard B. (2004) "Abrupt Climate Change," *Scientific American*, November, pp. 62-69.

American Physical Society (2004) *The Hydrogen Initiative*, APS Panel on Public Affairs, Mar04, 17 pp. www.aps.org

Amos, Wade A. (1998) *Costs of Storing and Transporting Hydrogen*, National Renewable Energy Laboratory, 216 pp., www.eere.energy.gov/hydrogenandfuelcells/documents.html#hydro

Anderson, Jason (2004) *Will hydrogen be part of a green energy system?* Confer. Hydrogen in Europe: Towards a Consistent Policy Framework for Sustainable Energy and Mobility, College of Europe, Bruges, Belgium, Jun04, www.coleurop.be

Apollo Project (2004) *New Energy for America: The Apollo Jobs Report*, Institute for America's Future & Center On Wisconsin Strategy, 47 pp. + appendices, www.apolloalliance.org

Arctic Climate Impact Assessment (2004) *Impacts of a Warming Arctic*, Cambrige Univ Press, 241 pp.

Ausubel, Jesse (2002) "Does Energy Policy Matter?" lecture Q&A at Marshall Institute, Washington DC, 28Apr02, www.marshallinstitute.org

Baldwin, Samuel (2002) "Renewable Energy: Progress & Prospects," *Physics Today*, vl. 55(4).

Bartlett, Alan (2004) "Thoughts on Long-Term Energy Supplies: Scientists and the Silent Lie," *Physics Today*, Jul04:53-55.

Bernow, S. et al. (1997) *Energy Innovations: A Prosperous Path to a Clean Environment*, Alliance to Save Energy, American Council for an Energy Efficient Economy, Natural Resources Defense Council, Tellus Institute, Union of Concerned Scientists, Washington, DC (1997).

Blanchard, Odile, Perkaus, James F. (2004) "Does the Bush Administration's climate policy mean climate protection? *Energy Policy*, vol. 32:1993-1998, forthcoming Dec2004. www.upmf-grenoble.fr/iepe/Equipe/blanchard/blanchardPubliGB.htm

Bossel, Ulf, Baldur Eliasson, & Gordon Taylor (2003) *The Future of the Hydrogen Economy: Bright or Bleak?* Final Report, 36 pp., www.efcf.com/reports/hydrogen_economy.pdf

Brown, L. C., G. E. Besenbruch, J. E. Funk, A. C. Marshall, P. S. Pickard, & S. K. Showalter (2002) "High Efficiency Generation of Hydrogen Fuels Using Nuclear Energy," Presentation at U.S. DOE Hydrogen Fuel Cells and Hydrogen Review, Nuclear Energy Research Initiative (NERI).

Burns, Lawrence, Byron McCormick, & Christopher Borroni-Bird (2002) "Vehicle of Change," *Scientific American*, Oct02, pp. 64-73.

Butler, Declan (2004) "Nuclear power's new dawn," *Nature*, vol. 429:238-240.

Cheney, Dick, & National Energy Policy Development Group (2001) *National Energy Policy: Reliable, Affordable, and Environmentally Sound Energy of America's Future*, Report to President George W. Bush, Washington, DC, May01, 170 pp., www.whitehouse.gov/energy/

Cho, Adrian (2004) "Fire and ICE: Revving Up for H_2," *Science*, vol. 305:964-965, 13Aug04.

Climate Group, The (2004) *Carbon Down, Profits Up*, Weybridge, 16 pp., www.theclimategroup.org

Cogan, Douglas G. (2003) *Corporate Governance and Climate Change: Making the Connection*, CERES Sustainable Governance Project, Boston, 129 pp. www.ceres.org

Craig, Paul P. (2004) "Rush to Judgment at Yucca Mountain," *Science for Democratic Action*, vol. 12(3), Jun, Institute for Energy and Environmental Research, Takoma Park, www.ieer.org

Dawson, Jim (2004) "Court rules against 10,000-year radiation safety standard at Yucca Mountain," *Physics Today*, September, pp. 29-30.

DeCarolis, Joseph F., & David W. Keith (in press) "The economics of large-scale wind power in a carbon-constrained world," *Energy Policy*.

Decker, James F. (2004) Testimony before the Sub-committee on Energy, Committee on Science, U.S. House of Representatives, 24Mar04, 12 pp.

Deluga, G., J. Salge, L. Schmidt, & X. Verykios (2004) "Renewable hydrogen from ethanol by autothermal reforming," *Science*, vol 303:993-6.

Demirdöven, Nurettin, & John Deutch (2004) "Hybrid Cars Now, Fuel Cell Cars Later," *Science*, vol. 305: 974-976, 13Aug04.

Dizikes, Peter (2003) "Making Cheaper Hydrogen," *Technology Review*, December, p. 25.

Domenici, Pete, Blythe Lyons, & Julian Steyn (2004) *A Brighter Tomorrow: Fulfilling the Promise of Nuclear Energy*, Rowman & Littlefield, 240 pp., (release date: 25Oct04).

Doniger, David, David Friedman, Roland Hwang, Daniel Lashof, & Jason Mark (2002) *Dangerous Addiction: Ending America's Oil Dependence*, Natural Resources Defense Council & Union of Concerned Scientists, 57 pp., www.nrdc.org/air/transportation/oilsecurity/securityinx.asp

Dunn, Seth (2001) *Hydrogen Futures: Toward a Sustainable Energy System*, Worldwatch Paper 157, Washington, www.worldwatch.org/pubs/paper/157/

Dutzik, Tony (2004) *Making Sense of Hydrogen: The Potential Role of Hydrogen in Achieving a Clean, Sustainable Transportation System*, National Association of State PIRGs, Washington, August, 61 pp., newenergyfuture.com/reports/Hydrogen10_04.pdf

Eames, Malcolm, & William McDowell (2004) *Emerging Niches and Hydrogen Futures: perspectives for the work of the UK Sustainable Hydrogen Energy Consortium*, Hydrogen in Europe: Towards a Consistent Policy Framework for Sustainable Energy and Mobility, College of Europe, Bruges, Belgium, June, www.coleurop.be

Elliott, D.L., L.L Wendell, & G.L. Gower (1991) *An Assessment of the Available Windy Land Areas and Wind Energy Potential in the Contiguous United States*, PNL-7789.

Elliott, D. L. & M. N. Schwartz (1993) *Wind Energy Potential in the United States*, PNL-SA-23109. www.nrel.gov/wind/wind_potential.html

Environmental News Service (2004a) "Poll: Voters Want Fuel Economy, Ethanol, Hydrogen," 7Jun.

Environmental News Service (2004b) "Nevada Sues Again to Block Yucca Mountain Nuclear Repository," *ENS*, 14Sep04.

Fairley, Peter (2002) "Solar on the cheap," *Scientific American*, Jan/Feb., pp. 48-52.

Fairley, Peter (2004) "Hybrids' rising sun," *Scientific American*, April, pp. 34-42.

Feiveson, H. A. (2000) "Diversion-resistance criteria for future nuclear power," *Nuclear Energy and Climate Workshop*, Center for International Security and Cooperation, Stanford University.

Folkers, Cindy (2003) *Hydrogen from Nuclear Power*, Nuclear Information and Resource Service, Washington, 2 p., www.nirs.org

Forsberg, C. (2003a) "Production of Hydrogen Using Nuclear Energy," presentation to National Research Council Committee on Alternatives and Strategies for Future Hydrogen Production and Use, Washington, DC, 22Jan03).

Forsberg, C. W. (2003b) "Hydrogen, nuclear energy, and the advanced high-temperature reactor," *International Journal of Hydrogen Energy*, Oct03, vol. 28:1073-1081.

Forsberg, Charles (2003c) "Production of Hydrogen Using Nuclear Energy," Safety and Economy of Hydrogen Transport, (2nd Internat'l Symposium), Sarov, Novgorod, Russia, 18-21Aug03, 11 pp.

Forsberg, Charles (2003d) "Hydrogen Futures and Technologies," Rohsenow Symposium of Future trends in Heat Transfer, MIT, May, 15 slides.

Freedman, David H. (2002) "Fuel Cells *vs* The Grid," *Technology Review*, Jan/Feb, pp. 4047.

Friends of the Earth–Scotland (1998) *Nuclear power is no solution to climate change: exposing the myths*, Edinburgh, www.foe.scotland.org.uk & www.nirs.org/factsheets/kyotonuc.html

Freund, F., J. Dickinson, & M. Cash (2002) "Hydrogen in Rocks: An Energy Source for Deep Microbial Communities," *Astrobiology*, vol. 2(1):83-92.

Goklany, Indur M. (2004) "Climate Change and Malaria," letter to *Science*, vol. 305:55.

Grant, Paul M. (2003) "Hydrogen lifts off–with a heavy load," *Nature*, vol. 424:129-130.

Gray, D. & G. Tomlinson (2002) *Hydrogen from Coal*, Mitretek Technical Paper MTR 2002-31, for US. DOE/NETL, Nov., 32 pp.

Grossman, David A. (2003) "Warming up to a not-so-radical idea: tort-based climate change litigation," *Columbia J. of Envir. Law*, vol. 28(1):1-61.

Gugliotta, Guy, & Eric Pianin (2004) "Bush plans on global warming alter little; voluntary programs attract few firms," *Washington Post*, 1Jan04, pA1.

Hall, Charles, Pradeep Tharakan, John Hallock, Cutler Cleveland, & Michael Jefferson (2003) "Hydrocarbons and the evolution of human culture," *Nature*, vol. 426:318-322.

Hansen, James (2004) "Defusing the global warming time bomb," *Scientific American*, March, pp. 68-77.

Hasselmann, K., M. Latif, G. Hooss, C. Azar, O. Edenhofer, C. C. Jaeger, O. M. Johannessen, C. Kemfert, M. Welp, & A. Wokaun (2003) "The Challenge of Long-Term Climate Change," *Science*, vol. 302:1923-1925.

Hawken, Paul, Amory B. Lovins, & L. Hunter Lovins (1999) *Natural Capitalism: The Next Industrial Revolution*, Little, Brown, NY, 396 pp.

Hawkins, David (2004) *The Light at the End of the Tunnel*, Natural Resources Defense Council, San Francisco, 16 slides, www.nrdc.org

Hefner III, Robert A. (2002) *The Age of Energy Gases in the New Millennium*, GHK Company, Oklahoma City, 26 pp.

Henderson, A. D. (2002) "Hydrogen from nuclear," presented at National Academy of Sciences Meeting, U.S. DOE Office of Advanced Nuclear Research, Washington, DC, 2Dec.

Herzog, Howard, Baldur Eliasson, & Olav Kaarstad (2000) "Capturing Greenhouse Gases," *Scientific American*, Feb00, pp. 72-79.

Hirsch, Daniel (2002) "The NRC: What, me worry?" *Bulletin of the Atomic Scientists*, Jan/Feb02, vol. 5838-44. www.nci.org/

Hirsch, Daniel, & George M. Woodwell (2003) "Powering the Automobile," *San Francisco Chronicle,* 10Dec03 www.nuclearpolicy.org/NewsArticle.cfm?NewsID=1122

Hirsch, Daniel, David Lochbaum, & Edwin Lyman (2003) "The NRC's Dirty Little Secret," *Bulletin of the Atomic Scientists*, May/Jun, vol. 59:44-51, www.nci.org/

Hoagland, William (1995) "Solar energy," *Scientific American, September*, pp. 170-173.

Hoerner, J. Andrew, & James Barrett (2004) *Smarter, Cleaner, Stronger: Secure Jobs, A Clean Environment, and Less Foreign Oil*, Redefining Progress, San Francisco, October, 6 pp. www.redefiningprogress.org/bluegreen

Hoffert, Martin, Ken Caldeira, Greg Benford, David Criswell, Christopher Green, Howard Herzog, Atul Jain, Haroon Kheshgi, Klaus Lackner, John Lewis, Douglas Lightfoot, Wallace Manheimer, John Mankins, Michael Mauel, John Perkins, Michael Schlesinger, Tyler Volk, & Tom Wigley (2002) "Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet," *Science*, vol. 298: 981-987.

Hoffmann, Peter (2001) *Tomorrow's Energy: Hydrogen, Fuel Cells, & the prospects for a Cleaner Planet*, MIT Press, Cambridge, 289 pp.

Houghton, Sir John (2004) "Global warming is now a weapon of mass destruction," *The Guardian*, editorial, 28Jul03.

Huizing, Rolinda, Nederlandse Gasunie (2004) *NaturalHy Project: Preparing for the hydrogen economy by using the existing natural gas system and a catalyst*, Conference on Hydrogen in Europe, College of Europe, Bruges, Belgium, June, www.coleurop.be

Interlaboratory Working Group on Energy-Efficient and Low-Carbon Technologies (1997) *Scenarios Of U.S. Carbon Reduction: Potential Impacts Of Energy Technologies by 2010 and Beyond*, prepared for the Office of Energy Efficiency and Renewable Energy, U.S. Dept of Energy, LBNL-40533 & ORNL-CON444.

Inter-Laboratory Working Group (2000) *Scenarios for a Clean Energy Future*, Oak Ridge National Laboratory & Lawrence Berkeley National Lab.

International Atomic Energy Agency (2004) *The Year in Review,* Vienna, Aug04, www.iaea.org

International Petroleum Industry Environmental Conservation Association (2003) *Carbon Dioxide Capture and Geological Storage*, IPIECA, London, 14 pp., www.ipieca.org

Ivy, Johanna (2004) *Summary of Electrolytic Hydrogen Production: Milestone Completion Report*, NREL, 28 pp. www.eere.energy.gov/hydrogenandfuelcells/documents.html#hydro

Jacobsen, Mark Z., & Gilbert M. Masters (2001) "Exploiting Wind Versus Coal," *Science*, vol. 294:1438.

Jensen, Marc W, & Marc Ross (2000) "The Ultimate Challenge: Developing an Infrastructure for Fuel-Cell Vehicles," *Environment*, 42(7): 10-22.

Johansen, Bruce E. (2004) "Global Warming as a Weapon of Mass Destruction," *Z Magazine Online*, vol. 17(3), Mar04.

Kallbekken, Steffen, & Asbjørn Torvanger (2004) *Can geological carbon storage be competitive?* Working Paper 05, May. CICERO, Oslo, 13 pp.

Kammen, D. M., A. V. Herzog, & T. E. Lipman (2001) "A National Clean Energy Strategy," Letter to Vice President Richard Cheney, 16Feb2001, Renewable and Appropriate Energy Laboratory, Energy and Resources Group, University of California – Berkeley, 4 pp + attachments.

Kammen, Daniel M. (2004) "Renewable Energy Options for the Emerging Economy: Advances, Opportunities and Obstacles," Background paper for *The 10-50 Solution: Technologies and Policies for a Low-Carbon Future*, Pew Center & NCEP Conference, Washington, DC, 25-26Mar04, 11 pp.

Kammen, Daniel M., Kamal Kapadia, & Matthias Fripp (2004) *Putting Renewables to Work: How Many Jobs Can the Clean Energy Industry Generate?* A Report of the Renewable and Appropriate Energy Laboratory, University of California, Berkeley, 28 pp.

Kammen, D. M. & S. Pacca (2004) "The costs of electricity,"*Annual Review of Environment and Resources*, vol. 30, in press.

Keepin & Kats (1988) "Greenhouse Warming: Comparative Analysis of Nuclear and Efficiency Abatement Strategies," *Energy Policy*, vol. 16:538-561.

Keith, David W., & Alexander E. Farrell (2003) "Rethinking Hydrogen Cars," *Science*, vol. 301:315-316.

Keith, David, Joseph DeCarolis, David Denkerberger, Donald Lenschow, Sergey Malyshev, Stephen Pacala, & Phillip Racsch (2004) "The influence of large-scale wind power on global climate," *Proceedings of the National Academy of Sciences*, vol. 101:16155-16120.

Kemm, Kelvin (1999) *Development of the South African Pebble Bed Modular Reactor System*, The Uranium Institute (24th Intern'l Symposium), www.world-nuclear.org/sym/1999/kemm.htm

Kerry, John, & John Edwards (2004) *A Plan for American Leadership in Energy Technology*, viewed 12Aug04, www.johnkerry.com

Kim, Won Bae, T. Voitl, G. J. Rodriguez-Rivera, & J. A. Dumesic (2004) "Powering fuel cells with CO via aqueous polyoxometalates and gold catalysts," *Science*, vol. 305:1280-1283.

King, Sir David (2004) "Climate Change Science: Adapt, Mitigate, or Ignore?" *Science*, vol 303:176.

Kloosterman, Jan Leen, & Adrian Verkooijen (undated) *CO_2-Free Hydrogen Production: the Nuclear route*, Technical Univ. of Delft, 6 pp., + 39 slides, www.iri.tudelft.nl/~klooster/htr/H2.html, Koplow, Doug (1993) *Federal Energy Subsidies: Energy, Environmental, and Fiscal Impacts*, Alliance to Save Energy, Washington, 91 pp.

Kottenstette, R., & J. Cotrell (2003) *Hydrogen Storage in Wind Turbine Towers*, NREL TP500-34656, 31 pp. www.nrel.gov

Kreutz, T.G., R.H. Williams, R.H. Socolow, P. Chiesa, & G. Lozza (2002) "Production of Hydrogen and Electricity from Coal with CO_2 Capture," Prepared for 6th Greenhouse Gas Control Technologies Conference, Kyoto, Japan, 30 Sept-4 Oct, 2002, Princeton University. 6 pp.

Kruse, Bjørnar, Sondre Grinna, & Cato Buch (2002) *Hydrogen: Status og Muligheter,* Bellona Foundation, Oslo, 53 pp., www.bellona.no/en/energy/hydrogen/report_6-2002/index.html

Lackner, Klaus S. (2003) "A Guide to CO_2 Sequestration," *Science* vol 300:1677-1678.

Lake, James, Ralph Bennett, & John Kotek (2002) "Next-Generation Nuclear Power," *Scientific American*, January, pp. 72-81.

Large, John (2004) *Potential Radiological Impact And Consequences Arising From Incidents Involving A Consignment Of Plutonium Dioxide Under Transit From Cogema La Hague To Marcoule/Cadarache: Road Accidents and Terrorist Attack Considered for the Localities of Paris and Lyon*, Large & Associates, London, for Greenpeace, March04. 38 pp.

Lave, Lester, Michael Griffin, & Heather MacLean (2001) "The Ethanol Answer to Carbon Emissions," *Issues in Science and Technology*, Winter 2001.

Leighty, William, Masaru Hirata, Kazuhiko O'Hashi, Jacques Benoit, & Jeffrey Keith (2003) *Large Renewables – Hydrogen Energy Systems: Gathering and Transmission Pipelines for Wind-power and Other Diffuse, Dispersed Sources*, World Gas Conference, Tokyo, June, 18 pp.

Leslie, Jacques (1997) "The Dawn of the Hydrogen Age," *Wired*, Oct97.

Lipman, Timothy, Daniel M. Kammen, Joan Ogden, & Daniel Sperling, et al. (2004) *An Integrated Hydrogen Vision for California*, A guidance document prepared with support from the Steven and Michele Kirsch Foundation; authors: Energy Resources Group & Institute for Transportation Studies, Univ. of Cal-B & UC-D, 9Jul04, 74 pp., http://socrates.berkeley.edu/~rael/papers.html#new

Lipman, Timothy (2004) *What Will Power the Hydrogen Economy? Present and Future Sources of Hydrogen Energy*, Analysis and report prepared for Natural Resources Defense Council; author: Energy Resources Group, University of California-Berkeley, 74 pp., http://socrates.berkeley.edu/~rael/papers.html#new

Lovins, Amory B., & Hunter L. Lovins (1982) *Brittle Power: Energy Strategy for National Security*, Brick House Publishing, 486 pp.

Lovins, Amory B., & Brett Williams (1999) *A Strategy for the Hydrogen Transition*, 10th U.S. Hydrogen Meeting, National Hydrogen Association, Vienna, VA, Apr99, 17 pp.

Lovins, Amory B. (2000) "A Nuclear Solution to Climate Change?" submitted to *Science*, 2 pp.

Lovins, Amory B, & L. Hunter Lovins (2001) *Climate: Making Sense* and *Making Money*, Rocky Mountain Institute, Snowmass, CO, 38 pp., www.rmi.org/sitepages/pid173.php

Lovins, Amory B. (2003a) *Twenty Hydrogen Myths*, Rocky Mountain Institute, Snowmass, 49 pp.

Lovins, Amory B. (2003b) "Hydrogen Economy: Not So Difficult—Without Nuclear Power," letter submitted to *Nature*, Aug03, 3 pp.

Lovins, Amory B. (2003c) "Assessing the Hydrogen Economy:" Letter re: Tromp et al (2003), *Science*, vol. 302:226-227.

Lovins, Amory B. (2004) "~10x error in energy-hydrogen conversion," Letter in response to Tromp et al response to Lovins (2003c), submitted to *Science*, Feb04; unpublished.

Lovins, Amory B., E. Kyle Datta, Odd-Even Bustnes, Jonathan G. Koomey, & Nathan Glasgow (2004) *Winning the Oil Endgame: Innovation for Profits, Jobs, and Security*, Rocky Mountain Institute, September, 340 pp., www.rmi.org

Lyman, Edwin (2002) Statement on the *Science* article "Nuclear Power Plants and Their Fuel as Terrorist Targets," Nuclear Control Institute, Washington, 20Sep02 www.nci.org/nuketerror.htm

Lynn, Barry C. (2003) "Hydrogen's dirty secret," *Mother Jones*, May, 3 pp., www.motherjones.com

Makhijani, Arjun, & Scott Saleska (1996) *The Nuclear Power Deception: U.S. Nuclear Mythology from Electricity "Too Cheap to Meter" to "Inherently Safe" Reactors*, Institute for Energy and Environ-mental Research, Takoma Park, www.ieer.org

Makhijani, Arjun (1998) "Reducing Greenhouse Gases and Creating a Sustainable Energy Supply," *Energy and Security*, vol. 5, March, 1998, Institute for Energy and Environmental Research, Takoma Park, MD, www.ieer.org

Makhijani, Arjun (2001) *Securing the Energy Future of the United States: Oil, Nuclear, & Electricity Vulnerabilities and a post-September 11, 2001 Roadmap for Action*, Institute for Energy and Environmental Research, Takoma Park, 61 pp., www.ieer.org

Mann, Charles C. (2002) "Getting over oil," *Technology Review*, Jan/Feb., pp. 33-38.

Marcus, Gail H., & Alan E. Levin (2002) "New Designs for the Nuclear Renaissance" *Physics Today*, vol. 55(4), 6 pp. www.physicstoday.org

Margolis, Robert M., & Daniel M. Kammen (1999) "Underinvestment: The Energy Technology and R&D Policy Challenge," *Science*, 285:690-692.

Margolis, R., & D. M. Kammen (2001) "Energy R&D and Innovation: Challenges and Opportunities for Technology and Climate Policy," *A Reader in Climate Change Policy*, S. Schneider, A. Rosencranz, & J. Niles eds, Island Press: Washington, 28 pp.

Massachusetts Institute of Technology (2003) *The Future of Nuclear Power*, Ernest Moniz & John Deutch, co-chairs, MIT, Cambridge, 171 pp.

Mastrandrea., Michael, & Stephen H. Schneider (2004) "Probabilistic Integrated Assessment of Dangerous Climate Change," *Science*, vol. 304:571-575.

McLellan, B., J. C. Diniz da Costa, A. L. Dicks, V. Rudolph, R. J. Pagan, C. Sheng, & T. F. Wall (2003) *Hydrogen Energy Options for Australia*, University of Queensland, Brisbane, 6 pp.

Meyers, D. B., G. D. Ariff, B. D. James, & R. C. Kuhn (2003) *Hydrogen from Renewable Energy Sources: Pathway to 10 Quads For Transportation Uses in 2030 to 2050*, Draft Rpt for U.S. DOE, Directed Technologies, Inc., Alexandria.

Mintz, Marianne, Stephen Folga, John Molburg, & Jerry Gillette (2002) *Cost of Some Hydrogen Fuel Infrastructure Options,* Transportation Research Board, Argonne National Laboratory. www.transportation.anl.gov:80/pdfs/AF/224.pdf

Moniz, Ernest J., & Melanie Kenderdine (2001) "Meeting Energy Challenges: Technology and Policy," *Physics Today*, 55(4). physicstoday.org

Morris, David (2003) "Second Thoughts on a Hydrogen Economy," *Alternet*, 24Feb03, Institute for Local Self Reliance, www.ilsr.org/columns/2003/ 022403.html

Motavalli, Jim (2003a) "Amory B. Lovins: Building the Hydrogen Economy," an interview in *E magazine*, Jan/Feb03, www.emagazine.com

Motavalli, Jim (2003b) "Power Plays: Fuel Cells are Reaching the Market, in What Could be a $100 Billion Industry," *E magazine*, Jan/Feb03, www.emagazine.com

Motavalli, Jim (2003c) "Hijacking Hydrogen: Will Big Oil, Coal Interests and the Nuclear Industry Control the Next Energy Revolution?" *E magazine*, Jan/Feb03, vol. 14:38-39.

Moy, Russell (2003) "Liability and the Hydrogen Economy," *Science*, vol. 301: 47.

Muller, Richard (2003) "A Pollution-Free Hydrogen Economy? Not So Soon," *Techn. Rev*., 11Jul03.

Munson, Richard (2004) "Improving Prediction of Energy Futures," *Issues in Science and Technology*, Spring 2004.

Nakicenovic, N., Arnulf Grübler, & Alan McDonald (editors) (1998) *Global Energy Perspectives*, Cambridge University Press, 317 pp.

National Energy Technology Laboratory (2002) *Fuel Cell Handbook*, Sixth Edition, EG&G Technical Services Inc., U.S. DOE/NETL-2002/1179.

National Research Council (2003) *Progress in Improving Project Management at the Dept of Energy*, Board on Infrastructure and the Constructed Environment, Washington, 125 pp.

National Research Council, Committee on Alternatives and Strategies for Future Hydrogen Production and Use (2004) *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, National Academy of Engineering Board on Energy and Environmental Systems, 394 pp. www4.nationalacademies.org/news.nsf/isbn/ 0309091632?OpenDocument

Natural Resources Defense Council (2001) *The Bush-Cheney Energy Plan Players, Profits and Paybacks*. www.nrdc.org/air/energy/aplayers.asp, 11 pp.

Natural Resources Defense Council (2004) *Is Hydrogen the Solution?* April 2004, 7 pp., www.nrdc.org/air/transportation/phydrofuel.asp

Nature (2004) "Leapfrogging the power grid," *Nature*, vol. 427:661.

Nemet, G. & D. Kammen (2004, forthcoming) "The Effectiveness of Energy Research and Development Programs," *Issues in Science & Technology*.

Noble, Duncan (2001) *Cool Business Guide: Lower Costs, Higher Productivity, and Climate Change Solutions*, Pembina Institute, Drayton Valley and Ottawa, www.pembina.org

Northrop, Michael (2004) "Renewable Energy, at Last," 8Nov04, www.renewableenergyaccess.com

Nuclear Energy Agency (2002) *Nuclear Energy and the Kyoto Protocol*, Organization for Economic Co-operation & Development, Paris, www.nea.fr

Nuclear Energy Agency (2002) *Society and Nuclear Energy: Towards a Better Understanding*, OECD, 127 pp., Paris, www.nea.fr

Nuclear Energy Agency (2003) *Nuclear Electricity Generation: What Are the External Costs?* Organization for Economic Co-operation and Development, NEA-4372, 80 pp., Paris, www.nea.fr

Nuclear Information and Resource Service (2001) "The Senate Energy Bill: The Pursuit of a Brown, Dying Planet," 4 pp., www.nirs.org

Office of Management and Budget (2004) "Nuclear Energy, and Nuclear Hydrogen Initiative," in *President's Budget to Congress FY2005*, OMB, Washington, DC, pp. 329-477.

Ogden, Joan, & Robert Williams (1989) "PV Hydrogen: Moving Beyond Fossil Fuels," World Resources Institute, Washington, DC, 8 slides.

Ogden, Joan, & J. Nitsch (1993) "Solar Hydrogen," in *Renewable Energy: Sources for Fuels and Electricity*, Thomas Johansson et al, editors, Island Press.

Ogden, J. M. (2001) *Review of Small Stationary Reformers for Hydrogen Production*, Report to the International Energy Agency, March.

Ogden, Joan M. (2002) "Hydrogen: The Fuel of the Future?" *Physics Today*, vol. 55(4): 69-74. www.physicstoday.org

Ogden, J. M., R. H. Williams, & E. D. Larson (2001) *Toward a Hydrogen-Based Transportation System*, Princeton University, 57 pp., www.princeton.edu/ ~energy/publications/texts.html

Ogden, Joan M. (2002) "Modeling Infrastructure for a Fossil Hydrogen Energy System with CO_2 Sequestration," Prepared for 6th Greenhouse Gas Control Technologies Conference, Kyoto, Japan, 30Sep-4Oct2002, 6 pp., www.princeton.edu/ ~energy/publications/texts.html

O'Neill, Brian C., & Michael Oppenheimer (2002) "Dangerous Climate Impacts and the Kyoto Protocol," *Science*, vol. 296:1971-1972.

Pacala, S, & R. Socolow (2004) "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies," *Science*, vol. 305:968-972.

Padró, C. E. G. & V. Putsche (1999) *Survey of the Economics of Hydrogen Technologies*, National

Renewable Energy Lab., 57 pp., www.eere.energy.gov/hydrogenandfuelcells/documents.html#hydro

Parson, E. A., & D. W. Keith (1998) "Fossil Fuels Without CO_2 Emissions," *Science*, vol. 282:1053-1054.

Patch, Kimberly (2001) "Hydrogen chip to fuel hand-helds," *Technology Research News*, 12Sep.

Pembina Institute (2000) *Climate-Friendly Hydrogen Fuel: A Comparison of the Life-cycle Greenhouse Gas Emissions for Selected Fuel Cell Vehicle Hydrogen Production Systems*, Pembina Institute for Appropriate Development & Suzuki Foundation, 50 pp., www.pembina.org

Petit, Charles W. (2003) "Yellow light for a green fuel," *U.S. News & World Report*, 22Dec03.

Reeves, A. (2003) *Wind Energy for Electric Power*, Renewable Energy Policy Project, Washington, www.repp.org

Reiss, Spencer (2004) "Let a Thousand Reactors Bloom," *Wired*, September, vol. 12(9).

Revkin, Andrew C. (2004) "U.S. report, in shift, turns focus to greenhouse gases," *New York Times*, 26Aug04.

Rhodes, Richard, & Denis Beller (2000) "The Need for Nuclear Power," *Foreign Affairs*, Jan/Feb.

Rifkin, Jeremy, & Ted Howard (1980) *Entropy: A New World View*, Bantam Books, 302 pp.

Rifkin, Jeremy (2002) *The Hydrogen Economy: The Creation of the Worldwide Energy Web and the Redistribution of Power on Earth*, Tarcher Putnam, 294 pp.

Rifkin, Jeremy (2003) "The Hydrogen Economy After Oil, Clean Energy From a Fuel-Cell-Driven Global Hydrogen Web," *E* mag, Jan03.

Rigden, John (2002) *Hydrogen: The Essential Element*, Harvard University Press, 288 pp.

Ritch III, John B. (1999) "Nuclear Green," *Prospect*, March 1999.

Romm, Joseph J. (1999) *Cool Companies: How the Best Businesses Boost Profits and Productivity by Cutting Greenhouse Gas Emissions*, Island Press, 277 pp.

Romm, Joseph J. (2004a) *The Hype About Hydrogen: Fact and Fiction in the Race to Save the Climate*, Island Press, 238 pp.

Romm, Joseph (2004b) "The Hype About Hydrogen," *Issues in Science and Technology,* Spring 2004.

Romm, Joseph (2004c) "The Hype About Hydrogen," *Technology Review,* 17March2004.

Rosa, Eugene (2001) "Public Acceptance of Nuclear Power: Déjà vu All Over Again?" *Physics and Society* (April), www.aps.org/units/fps/newsletters/2001/april/ap5.cfm.

Rosa, Eugene A., & James Rice (2004) "Public Reaction to Nuclear Power Siting and Disposal," *Encyclopedia of Energy*, vol. 5, pp. 181-194.

Ryskamp, John M. (2003) *Hydrogen Production from Nuclear Energy*, IEEE Power Engineering Society Meeting, INEEL, 28Apr03, 20 pp.

Sandell, L. (2003) *High-Temperature Gas-Cooled Reactors for the Production of Hydrogen: An Assessment in Support of the Hydrogen Economy*, Electric Power Research Institute, Palo Alto.

Sawin, Janet L. (2004) *Mainstreaming Renewable Energy in the 21st Century*, Worldwatch Institute, Paper 169, Washington, 76p. www.worldwatch.org

Schneider, Stephen H. (2001a) "What is 'dangerous' climate change?" *Nature*, vol. 411:17-19.

Schneider, Stephen H. (2001b) "Earth systems engineering and management," *Nature*, vol. 409:417-421.

Schneider, Stephen H. (2003) *The Case for Climate Change Action*, Testimony before the U.S. Senate Committee on Commerce, Science and Transportation Hearing, 01Oct03, 16 pp.

Schultz, Ken (2002) *Efficient Production of Hydrogen from Nuclear Energy*, California Hydrogen Business Council, 27Jun02, 19 pp., General Atomics, San Diego, www.ch2bc.org/General%20Atomics/NuclearH2-27June02.pdf

Schultz, K. R. (2003) "Use of the Modular Helium Reactor for Hydrogen Production," World Nuclear Association, Annual Symposium, www.world-nuclear.org/sym/2003/schultz.htm

Schultz, Martin G., Thomas Diehl, Guy P. Brasseur, & Werner Zittel (2003) "Air Pollution and Climate-Forcing Impacts of a Global Hydrogen Economy," *Science*, vol. 302: 624-627.

Schwartz, Peter, & Doug Randall (2003a) *An Abrupt Climate Change Scenario and Its Implications for United States National Security*, commissioned by the U.S. Dept of Defense (Andrew Marshall), Global Business Network, Oct, 22 pp.

Schwartz, Peter, & Doug Randall (2003b) "How Hydrogen Can Save America," *Wired*, April. www.wired.com/wired/archive/11.04/hydrogen_pr.html

Service, Robert F. (2004) "The Hydrogen Backlash," *Science*, vol. 305:958-961, 13Aug04.

Service, Robert F. (2004) "The Carbon Conundrum," *Science*, vol. 305:962-963, 13Aug04.

Simbeck, D., & E. Chang (2002) *Hydrogen Supply: Cost Estimate for Hydrogen Pathways—Scoping Analysis*, 69 pp., National Renewable Energy Lab, www.nrel.gov, NREL SR-540-32525.

Simms, Andrew, John Magrath, & Hannah Reid (2004) *Up in Smoke*, Working Group on Climate and Development, New Economics Foundation, London, 40 pp., www.neweconomics.org

Simon, Julian (1995) *The State of Humanity: Steadily Improving*, Cato Policy Rpt, vol. 17(5).

Sims, Ralph, Hans-Holger Rogner, & Ken Gregory (2003) "Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation," *Energy Policy*, vol. 31:1315–1326.

Smil, Vaclav (2000) "Energy in the 20th century: resources, conversions, costs, uses, and consequences," *Annual Review of Energy and the Environment*, vol. 25:21-51.

Smil, Vaclav (2002a) "Energy Resources and Uses: A Global Primer for the Twenty-First Century," *Current History*, vol. 101:126-132. http://home.cc.umanitoba.ca/~vsmil/

Smil, Vaclav (2002b) *Energy at the Crossroads: Global Perspectives and Uncertainties*, MIT Press, 443 pp.

Solli, Christian (2004) *Fission or Fossil? A Comparative Hybrid Life Cycle Assessment of Two Different Hydrogen Production Methods*, Norwegian Univ. of Science and Technology, Oslo, Masters Thesis, 72 pp.

Solomon, Barry D., & Abhijit Banerjee (2004) *A Global Survey of Hydrogen Energy Research, Development, and Policy*, Michigan Technical University, draft 21July, 14 pp.

Spath, P. L. & W. A. Amos (2002) *Assessment of Natural Gas Splitting with a Concentrating Solar Reactor for Hydrogen Production*, National Renewable Energy Laboratory, TP-51031949.

Spath, P. L., M. Mann, & W. A. Amos (2003) *Update of Hydrogen from Biomass: Determination of the Delivered Cost of Hydrogen,* NREL MP-510-33112, 104 pp.

Spath, Pamela, & Margaret Mann (2004) *Biomass Power and Conventional Fossil Systems with and without CO_2 Sequestration: Comparing the Energy Balance, Greenhouse Gas Emissions and Economics*, NREL TP-510-32575, 38 pp.

Sperling, Daniel, & James Cannon, eds. (2004) *The Hydrogen Transition*, Academic Press, 266 pp.

Sperling, Daniel, & Joan Ogden (2004) "The Hope for Hydrogen," *Issues in Science & Technology,* Spring 2004, www.issues.org.

Spitzer, Joseph (2004) "Energy from Biomass: A Promising Option for a Future Sustainable Energy System," *Biomass and Agriculture: Sustainability, Markets, and Policies*, OECD, Paris, Sep04, 15 pp

Stevens, William K. (1999) "Global Economy Slowly Cuts Use of Fuels Rich in Carbon," *New York Times*, 30Oct99.

Stokstad, Erik (2004) "States Sue Over Global Warming," *Science*, vol. 305:590.

Savage, Peter, & Shirley Strzelecki Savage (2004) *Back to Coal: Why Utilities Must Reconsider this Cheap, Plentiful Fuel,* Thinking Companies, Falmouth, ME, 240 pp., www.thinkingenergy.com

Stronberg, Joel B. (2004) *Renewable Hydrogen: Policy Statement*, American Solar Energy Society, Boulder, 16 pp., www.ases.org

Swisher, Joel N. (2002a) *Cleaner Energy, Greener Profits: Fuel Cells as Cost-Effective Distributed Energy Resources*, Rocky Mountain Institute, Snowmass, CO, 36 pp., www.rmi.org

Swisher, Joel N. (2002b) *The New Business Climate: A Guide to Lower Carbon Emissions and Better Business Performance*, Rocky Mountain Institute, Snowmass, CO, 98 pp., www.rmi.org

Sylvester-Bradley, Oliver (2003) "Can the Hydrogen economy provide a sustainable future?" 6 pp., Defacto Design, www.defactodesign.com

Talbot, David (2002) "The Next Nuclear Plant," *Technology Review*, Jan/Feb, pp. 54-59.

Taubes, Gary (2002) "Whose nuclear waste?" *Technology Review*, Jan/Feb., pp.60-67.

Taxpayers for Common Sense (2002?) *Federal Loan Guarantees to the Nuclear Industry Are Sure to Burn a $14 to $16 Billion Hole in the Taxpayer's Pocket*, Washington, 2 pp., www.taxpayer.net/energy/nuclear/nukepowergiveaways.htm

Taxpayers for Common Sense (2003a) *An Overview of Senate Energy Bill Subsidies to the Fossil Fuel Industry,* Aileen Roder, www.taxpayer.net

Taxpayers for Common Sense (2003b) *Senate Energy Bill Grants Unparalleled Subsidies for New Reactors,* Washington, 1 p., taxpayer.net/energy/nuclear/nukepowergiveaways.htm

Taxpayers for Common Sense (2004a) *Nuclear Subsidies in the Senate Energy Bill: A Spending Explosion*, Washington, 2 pp., viewed 24Jun04, www.taxpayer.net/greenscissors

Taxpayers for Common Sense (2004b) *Analysis of Nuke Power Giveaways in Senate Energy Bill*, Washington, DC, 3 pp., viewed 09Jul04, www.taxpayer.net/energy/nuclear/nukepowergiveaways.htm

Taylor, John J. (2004) "The Nuclear Power Bargain," *Issues in Science and Technology,* Spring 2004, www.issues.org

Thomas, C. E. (2002) *Hydrogen and Fuel Cells: Pathway to a Sustainable Energy Future*, H2Gen Innovations, Inc., 34 pp., www.h2gen.com

Thomas, C. E. (2004) "An Affordable Hydrogen Entry Pathway," 15th Annual National Hydrogen Association, Los Angeles, 29Apr04, H2Gen Innovations, Inc., 16 pp.

Torvanger, Asbjørn, Steffen Kallbekken, & Kristin Rypdal (2004) *Prerequisites for Geological Carbon Storage as a Climate Policy Option,* Working Paper 2004:04, CICERO, Oslo, 16 pp.

Tromp, Tracey K., Run-Lie Shia, Mark Allen, John M. Eiler, & Y. L. Yung (2003) "Potential Environmental Impact of a Hydrogen Economy on the Stratosphere," *Science*, vol. 300:1740-1742.

Turner, John A. (1999) "A Realizable Renewable Energy Future," *Science*, vol. 285:687-689.

Turner, John A. (2004) "Sustainable Hydrogen Production," *Science*, vol. 305:972-974, 13Aug04.

United States Dept of Energy (2001) *Generation-IV Roadmap*, Rpt of the Fuel Cycle Crosscut Group, Nuclear Energy, Science, & Technology, US DOE, Mar01, 337 pp., http://gen-iv.ne.doe.gov/

United States Dept of Energy (2002a) *A National Vision of America's Transition to a Hydrogen Economy—to 2030 and Beyond*, U.S. DOE, based on the results of the National Hydrogen Vision Meeting, Washington, 15-16Nov01, 35 pp.

United States Dept of Energy (2002b) *National Hydrogen Energy Roadmap*, Workshop, Washington, (Apr02), Nov02, 49 pp.

United States Dept of Energy (2002c) *Nuclear Hydrogen Initiative: Programmatic Overview*, Mr. Remer, Office of Advanced Nuclear Research, FY2003, 21 slides, www.doe.gov

United States Dept of Energy (2002d) *A Technology Roadmap for Generation IV Nuclear Energy Systems: Technical Roadmap Report*, Subcommittee on Generation IV Technology Planning, submitted to the Nuclear Energy Research Advisory Committee, 114 pp.

United States Dept of Energy (2002e) *CO_2 Capture and Storage in Geologic Formations*, white paper for the National Climate Change Technology Initiative, CO_2 Capture and Storage Working Group, Office of Fossil Energy, 13 pp.

United States Dept of Energy (2003a) *The Path to a Hydrogen Economy*, USHR Testimony of David K. Garman, Asst. Sec. Energy Efficiency and Renewable Energy, 5Mar, http://energy.gov/engine/content.do?PUBLIC_ID=13612&BT_CODE=PR_CONGRESSTEST&TT_CODE=PRESSRELEASE

United States Dept of Energy (2003b) *Hydrogen Program Plan: Hydrogen from Natural Gas and Coal: The Road to a Sustainable Energy Future*, Hydrogen Coordinating Group, Office of Fossil Energy, 53 pp.

United States Dept of Energy (2003c) *Carbon Sequestration: Technology Roadmap and Program Plan*, National Energy Technology Laboratory, Office of Fossil Energy, 22 pp. at www.netl.doe.gov and www.fossil.energy.gov/programs/sequestration/

United States Dept of Energy (2003d) "Revitalization of Nuclear Research in the U.S.: FY 2004 Nuclear Energy, Science and Technology Budget Request," presentation by William Magwood IV, Dir. Office of Nuclear Energy, Feb03, 8 slides.

United States Dept of Energy (2003e) *Proceedings of a Workshop on Electrolysis Production of Hydrogen from Wind and Hydropower*, Washington, DC, 9-10Sep03, US DOE Office of Energy Efficiency and Renewable Energy, Hydrogen, Fuel Cells, and Infrastructure Technologies Program, 8 slides.

United States Dept of Energy (2003f) *Fuel Cell Report to Congress*, transmitted to USHR Committee on Appropriations by David K. Garman, Asst Sec, EERE, 28Feb03, 64 pp., www.eere.energy.gov/hydrogenandfuelcells/documents.html#hydro

United States Dept of Energy (2003g) *Annual Progress Report for Hydrogen, Fuel Cells, and Infrastructure Technologies Program*, EERE, Office of Hydrogen, Fuel Cells, and Infrastructure Technologies, Oct, ~700 pp., www.eere.energy.gov/hydrogenandfuelcells/annual_report03.html

United States Dept of Energy (2003h) *Annual Report*, Nuclear Energy Research Initiative, 310 pp., http://neri.ne.doe.gov/

United States Dept of Energy (2003i) "The President's Hydrogen Initiative: U.S. DOE's Approach," by Steve Chalk & Lauren Inouye, Asilomar Conf: Hydrogen Transition, 19 pp., www.eere.energy.gov/hydrogenandfuelcells/documents.html#hydro

United States Dept of Energy (2003j) *Multi-Year Research, Development and Demonstration Plan, Planned program activities for 2003-2010*, Hydrogen, Fuel Cells & Infrastructure Technologies Program, EERE, draft Jun03, 477 pp., www.eere.energy.gov/hydrogenandfuelcells/mypp/

United States Dept of Energy (2003k) *Basic Research Needs of the Hydrogen Economy*, Basic Energy Sciences Workshop on Hydrogen Production, Storage, and Use, 13-15May03, 178 pp., www.sc.doe.gov/bes/reports/files/NHE_rpt.pdf

United States Dept of Energy (2003k) *Nuclear Hydrogen Initiative*, Office of Nuclear Energy, Science, & Technology, Washington, 2 pp., www.nuclear.gov/infosheets/hydrogenfactmarch2003.pdf

United States Dept of Energy (2004a) *Hydrogen Posture Plan: An Integrated Research, Development, And Demonstration Plan*, 54 pp., www.eere.energy.gov/hydrogenandfuelcells/documents.html#hydro

United States Dept of Energy (2004b) *Hydrogen Fuel and FreedomCAR Initiatives*, USHR Testimony of David K. Garman, Asst Sec. Energy Efficiency and Renewable Energy, 3Mar04, www.energy.gov/engine/content.do?PUBLIC_ID=15146&BT_CODE=PR_CONGRESSTEST&TT_CODE=PRESSSPEECH

United States Dept of Energy (2004c) Testimony of James F. Decker before the Subcommittee on Energy, Committee on Science, U.S. House of Representatives, 24Mar04, 12 pp.

United States Dept of Energy (2004d) *Nuclear Hydrogen Initiative Overview*, DOE Hydrogen Program Review, by David Henderson, DOE Office of Nuclear Energy, Science and Technology, Philadelphia, PA, 24May04, 8 pp (overheads), www.eere.energy.gov/hydrogenandfuelcells/pdfs/review04/3_nhi_overview_henderson.pdf

United States Dept of Energy (2004e) *FutureGen: Integrated Hydrogen, Electric Power Production and Carbon Sequestration Research Initiative: Report to Congress,* US DOE, 21 pp., Mar04, www.fe.doe.gov/programs/powersystems/futuregen

United States Dept of Energy (2004f) *Request for Information and Expressions of Interest: Next Generation Nuclear Plant*, DOE solicitation for comments and project integrator applications, DOE, Washington, DC, 5 pp., www.id.doe.gov/doeid/RFP NE&NSD/NuclearP/EOI%20NGNP.pdf

United States Dept of Energy (2004g) *FY 2005 Congressional Budget Request: Highlights*, DOE Office of Management, Budget, and Evaluation, 112 pp., www.mbe.doe.gov/budget/05budget/index.htm

United States Dept of Energy (2004h) "$6 billion in proposals: major focus on coal gasification: President's Clean Coal Power Initiative," 26Jul.

United States Dept of Energy (2004i) "Thermochemical Cycles," Advanced Reactor, Fuel Cycle, and Energy Products Workshop, May04, by Dr. Paul Pickard, Sandia NL, 23 ovrhds.

United States Dept of Energy (2004j) *Nuclear Hydrogen R&D Plan*, Draft B, Office of Nuclear Energy, Science & Technology, May04, 48pp. neri.inel.gov/program_plans/nhi_program_plan.shtml

United States General Accounting Office (2003a) *Energy Task Force: Process Used to Develop the National Energy Policy*, 31 pp. GAO-03-894

United States General Accounting Office (2003b) *Nuclear Regulatory Commission: Oversight of Security at Commercial Nuclear Power Plants Needs to be Strengthened*, 40 pp. GAO-03-752.

United States General Accounting Office (2004) *Nuclear Regulatory Commission: Preliminary Observations on Efforts to Improve Security at Nuclear Power Plants*, testimony of Jim Wells before the USHR Subcommittee on National Security, Emerging Threats, and International Relations, GAO-04-1064T, 20 pp.

United States Senate (2004) *S.2095: to enhance energy conservation and research and development and to provide for security and diversity in the energy supply for the American people*, introduced by Mr. Domenici, 12Feb04, 1216 pp., www.energy.senate.gov

Vaitheeswaran, Vijay V. (2003) *Power to the People: How the Energy Revolution Will Transform an Industry, Change Our Lives, and Maybe Even Save the Planet*, Farrar, Straus & Giroux, 358 pp.

Varner, Ken, Scott Warren, & John A. Turner (2003) *Photoelectrochemical Systems For Hydrogen Production*, National Renewable Energy Laboratory, Proceedings of the 2002 U.S. DOE Hydrogen Program Review, 10 pp. www.nrel.gov/hydrogen/proj_production_delivery.html

Vogel, Gretchen (2004) "Will the Future Dawn in the North?" *Science*, vol. 305:966-967.

Voss, David (2002) "Hitting the natural gas jackpot," *Technology Review*, Jan/Feb., pp. 69-72.

Wakabayashi, Hiroaki (2004) "Significance of Controllable Nuclear Fuel Burning for Humanity," *14th Pacific Basin Nuclear Conference*, American Nuclear Society, Honolulu, 21Mar04, 8 pp.

Wald, Matthew (2003) "Dismantling Nuclear Reactors," *Scientific American*, Mar, pp. 60-69.

Wald, Matthew (2004) "Questions About a Hydrogen Economy," *Scientific American*, May, pp. 66-73.

Wald, Matthew (2004b) "A New Vision for Nuclear Waste," *Technology Review*, Dec, pp. 38-44.

Walters, Lean, & Dave Wade (2002) *Hydrogen Production from Nuclear Energy*, Argonne National Laboratory, 12Nov02, 20 overheads.

Walters, Leon, David Wade, & David Lewis (2002) "Transition to a Nuclear/Hydrogen Energy System," *Nuclear Engineer*, vol. 43:169-175.

Watson, Jim, Alison Tetteh, Geoff Dutton, Abigail Bristow, Charlotte Kelly, & Matthew Page (2004) *UK Hydrogen Futures to 2050*, Tyndall Centre for Climate Change Research, Norwich, www.tyndall.ac.uk

Weinberg, Alvin M. (2003) "New Life for Nuclear Power," *Issues in Science and Technology*, Summer 2003, www.issues.org

Weindorf, Werner, Ulrich Bünger, Jörg Schindler (2003) *Comments on the paper by Baldur Eliasson and Ulf Bossel" The Future of the Hydrogen Economy: Bleak or Bright?"* L-B Systemtechnik, Ottobrunn, 26 pp., www.lbst.de

Weiss, Malcolm A., J. Heywood, A. Schafer, E. Drake, & F. AuYeng (2000) *On the Road in 2020: a Life-cycle Analysis of New Automobile Technologies*, MIT Energy Laboratory, 156 pp., http://lfee.mit.edu/publications/reports

Weiss, M. A., J. B. Heywood, A. Shafer, & V. K. Natarajan (2003) *Comparative Assessment of Fuel Cell Cars*, Massachusetts Institute of Technology, Laboratory for Energy and the Environment, MIT LFEE 2003-001 RP.

Weisz, Paul B. (2004) "Basic Choices and Constraints on Long-Term Energy Supplies," *Physics Today*, July, pp. 47-52.

White House (2002) *President Announces Clear Skies and Global Climate Change Initiative*. 14Feb02. www.whitehouse.gov/news/releases/2002/02/20020214-5.html

White House (2003) *Fact Sheet: Hydrogen Fuel: a Clean and Secure Energy Future*, www.whitehouse.gov/news/releases/2003/02/20030206-2.html

Williams, Robert H. (2001a) "Nuclear and alternative energy supply options for an environmentally constrained world," Nuclear Control Institute's 20th Anniversary Conference: *Nuclear Power and the Spread of Nuclear Weapons: Can We Have One Without the Other?* 35 pp., www.princeton.edu/~energy/publications/texts.html

Williams, Robert H. (2001b) "Addressing challenges to sustainable development with innovative energy technologies in a competitive electric industry," *Energy for Sustainable Development*, vol. V (2), June, 26 pp., www.princeton.edu/~energy/publications/texts.html

Williams, Robert H. (2002) "Decarbonized Fossil Energy Carriers and Their Energy Technological Competitors," *IPCC Workshop on Carbon Capture and Storage*, Regina, Sask., Nov, 21 pp.

Williams, Robert H. (2003) "Alternative Technologies and Strategies for Hydrogen Production," *Workshop on Future Energy Issues—Future Energy Resources*, National Defense University, Washington, 9May03, 24 overheads.

Williams, Robert H., & Eric D. Larsen (2003) "A comparison of direct and indirect liquefaction technologies for making fluid fuels from coal," *Energy for Sustainable Development*, vol. VII (4):103-129, December, 27 pp., www.princeton.edu/~energy/publications/texts.html

Winter, Drew (2002) "Behind the Fuel Cell Hype," *Ward's AutoWorld*, Aug02.

Wintour, Patrick, & Paul Brown (2004) "Blair reignites nuclear debate: American lobbying adds to pressure as PM battles to keep controversial energy option on climate change agenda," *The Guardian*, London, 7Jul04.

Wolfe, B. (2001) "Nuclear Energy: Will it Save the World?" *Physics and Society* (April).

World Energy Council (2004) *Energy Efficiency: A Worldwide Review*, London, www.worldenergy.org

Yohe, Gary, Natasha Andronova, Michael Schlesinger (2004) "To Hedge or Not Against an Uncertain Climate Future?" *Science*, vol. 306:416-417.

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About the author

Richard Heede is the Principal of Climate Mitigation Services, a consultancy focused on climate stewardship from emissions inventories to profitable action: greenhouse gas inventories, protocols, boundary definition, and identification of technologies and strategies to *profitably* reduce emissions. Client sectors include municipalities, colleges and universities, corporations, international NGOs, architects, and homeowners. Sample projects: *ExxonMobil Corporation Emissions Inventory 1882-2002: Methods & Results and spreadsheets,* for Friends of the Earth Trust, London, December 2003; *Energy and Climate Plan for the Town of Telluride, Colorado: Audit and Policy Recommendations*, June 2004. *Estimated Annual and Life-Cycle CO_2 and Fugitive Methane Emissions from the Energy-Sector Investments of the Export-Import Bank of the United States and the Overseas Private Investment Corporation from 1990 through 2003*, Dec04.

Rick worked with Amory Lovins and the Rocky Mountain Institute from 1984 to 2002. His work at RMI covered residential energy efficiency and retrofits (*Homemade Money: Saving Energy and Dollars in Your Home* and *The Energy Directory*), energy policy ("Hiding the True Costs of Energy," *Wall Street Journal,* "Energy Policy," *Changing America: Blueprints for the New Administration*, with Amory and Hunter Lovins), commercial sector energy efficiency (*Electricity-Saving Office Equipment,* with Mr. Lovins), and climate mitigation (*Cool Citizens: Everyday Solutions to Climate Change: Household Solutions Brief*; and *Oberlin College: Climate Neutral by 2020* study, with RMI's Joel Swisher).

He wrote *Measuring Energy Sustainability: Evaluating Your Nation's Energy Development: A Manual for Users of Helio's Indicators* for Helio, Paris.

Rick completed his graduate studies at the Univ. of Colorado (MS, Geog., 1983) with a National Center for Atmospheric Research cooperative thesis: *A World Geography of Recoverable Carbon Resources in the Context of Possible Climate Change*.

He designed and built a passive-solar rammed-earth home at 2,300m in the central Rocky Mountains of Colorado. It saves two-thirds of the energy and four-fifths of the carbon emissions of typical homes in this climate zone.

He is working on a book on the global risks of Antarctica's climate-sensitive ice sheets.

Rick is an accomplished pilot and a life-long skier. He is devoted to his 14-year-old daughter Shana Breeze and to life's sacred mysteries.