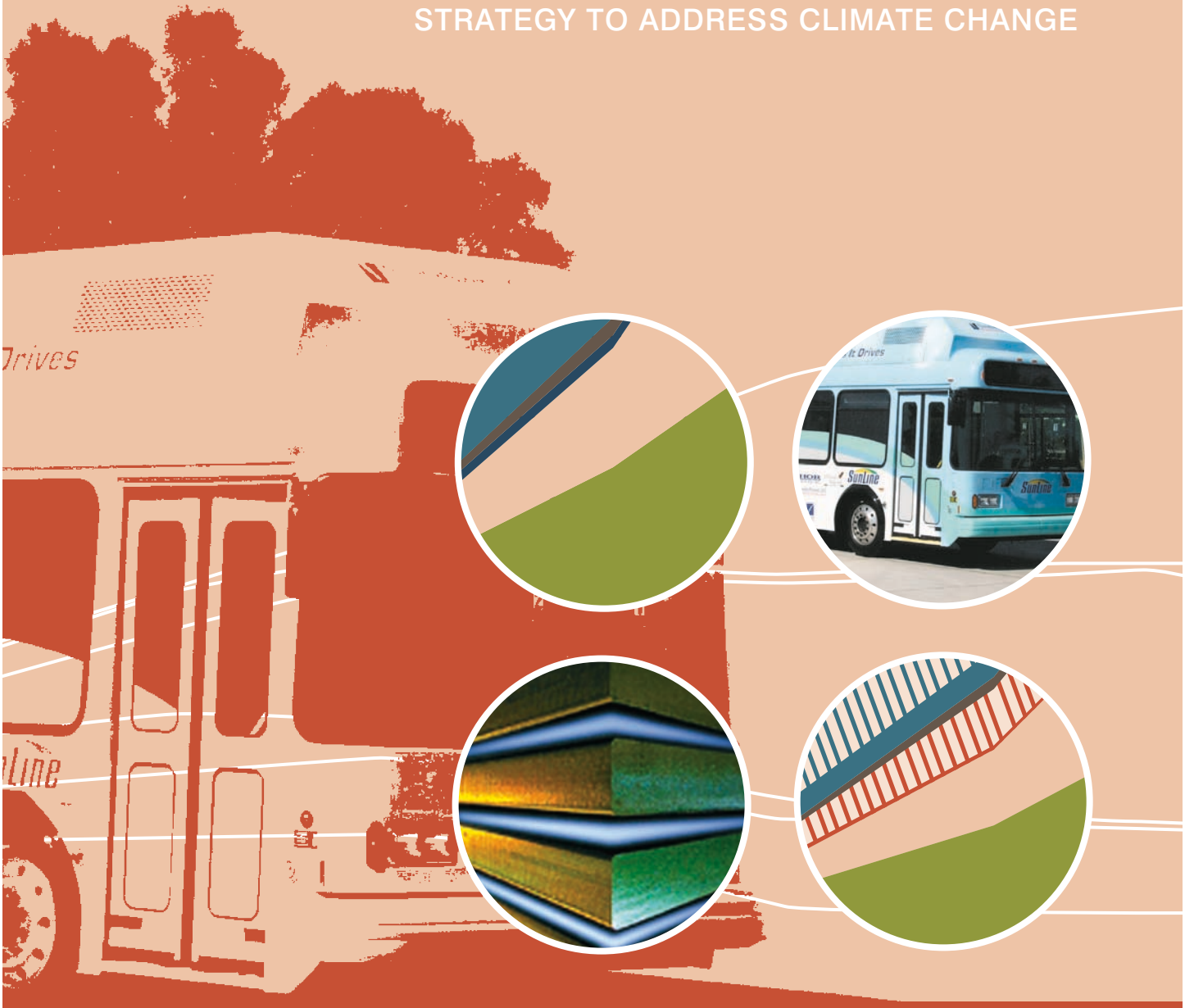
Hydrogen Systems

A CORE ELEMENT OF A GLOBAL ENERGY TECHNOLOGY STRATEGY TO ADDRESS CLIMATE CHANGE



A TECHNOLOGY REPORT FROM THE SECOND PHASE OF THE GLOBAL ENERGY TECHNOLOGY STRATEGY PROGRAM

GTSP

Global Energy Technology Strategy Program

Hydrogen Systems

A CORE ELEMENT OF A GLOBAL ENERGY TECHNOLOGY STRATEGY TO ADDRESS CLIMATE CHANGE

PHASE 2 FINDINGS FROM AN INTERNATIONAL PUBLIC-PRIVATE SPONSORED RESEARCH PROGRAM

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TO THE READER

This report reflects research conducted as part of the Global Energy Technology Strategy Program (GTSP) at the Joint Global Change Research Institute and in collaboration with partner research institutions around the world. The first phase of the GTSP began at a time when the importance of a technology strategy in addressing climate change was unappreciated. GTSP Phase 1 made the case that a technology strategy was an important part of a larger strategy to address climate change and needed to be included along with the other major components: climate science research, adaptation to climate change, and emissions mitigation.

The second phase of the GTSP recognized that to craft a global energy technology strategy it was important to develop a deeper understanding of potentially important technologies and technology systems, and to embed that knowledge in the context of the larger global energy and economic systems. In Phase 2 we identified six energy technologies and technology systems with the potential to play a major role in a climate-constrained world: CO_2 capture and storage, biotechnology, hydrogen systems, nuclear energy, other renewable energy, and end-use technologies that might be deployed in buildings, industry and transportation. Knowledge gained in each area has been integrated into a larger global energy-economy-climate frame. That combination of depth of study and integrated assessment produced a unique strategic perspective and a bounty of fresh insights. In this document, we have distilled and summarized some of the most salient.

The past nine years have flown by and, looking back from the present, it is amazing to see how far we have come. The GTSP has accomplished much, but much work remains. As we enter Phase 3, we will build on the knowledge gained thus far. We will continue to deepen our understanding of technology and we will continue to integrate that understanding into a larger energy and economic context. And, we will add a new dimension to our work to provide a deeper understanding of the *regional* and *institutional* contexts in which technology is developed and deployed.

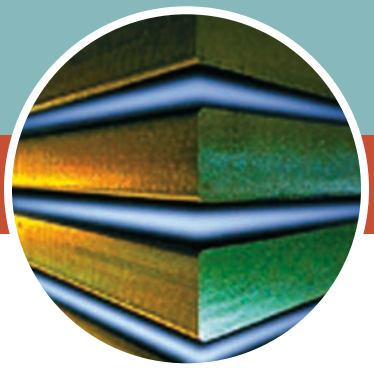
Our research has been supported by numerous firms, nongovernmental organizations, and government agencies. Their support has enabled us to continue to explore the implications of designing and implementing a technology strategy. Moreover, we have received the help of many peer reviewers, who throughout the process of developing this document provided their expertise and advice. And for that support we are grateful. Of course, the views and opinions of the authors expressed herein do not necessarily state or reflect those of the sponsoring, participating institutions, or reviewers and any errors that remain are our own.

Jae Edmonds
May 2007

Hydrogen Systems

Hydrogen is appealing in the context of climate change because it is a portable energy carrier that does not emit any CO_2 as it is consumed. Hydrogen is also appealing in terms of conventional pollutants since water vapor is the only byproduct of its use. Hydrogen can be used to serve transportation energy demands—to operate automobiles, trucks, and other commercial carriers—that are now almost completely met by fossil fuel-based liquids that emit CO_2. Hydrogen can also displace fossil fuel-based end-use applications in buildings and industry. Among the key insights from the GTSP regarding hydrogen are the following:

- The major challenge for hydrogen and climate change policy is to develop and use production methods that do not release CO_2 emissions. Depending on the fuels and methods used, substantial CO_2 emissions may be involved in producing hydrogen.
- Without a carbon price, a hydrogen system would not necessarily reduce CO_2 emissions. Emissions would be reduced only to the extent that low-carbon or carbon-free hydrogen production technologies are economically competitive with hydrogen production from fossil fuels.
- Moreover, hydrogen energy systems may not deploy to as great an extent in a climate-constrained world because hydrogen production from fossil fuels (with CO_2 capture and storage to limit emissions) is more costly.
- The wide-scale deployment of hydrogen depends much more on significant improvements in the performance of future hydrogen technologies (e.g., for storage, distribution, and use) than on the price of CO_2.



- Biomass and nuclear thermal sources of hydrogen will be more important sources of hydrogen in a greenhouse-gas-constrained world than in a world without climate policies.
- Hydrogen has a very low energy density compared to liquid transportation fuels. Since the transportation sector has been the principal focus of discussion for hydrogen, storage of hydrogen in vehicles is a critical technical and economic challenge.
- In addition to the transportation sector, hydrogen use in stationary applications such as buildings and industrial facilities may be just as be important and should also be a focus of research and development.

Technologies to produce hydrogen are already commercially viable, but its use is in small niche markets and not directly as an energy carrier.

HYDROGEN SYSTEMS TECHNOLOGY

Hydrogen energy systems have three principal components: (1) production; (2) transport, storage, and dispensing; and (3) end-use.

Hydrogen Production. Technologies to produce hydrogen are already commercially viable, but its use is in small niche markets and not directly as an energy carrier. About 15.9 trillion cubic feet of hydrogen are presently produced globally per year, mostly to manufacture ammonia, but also for chemical processes, e.g., in gasoline refining. However, these processes produce hydrogen today at a price that cannot compete with traditional transportation fuels such as gasoline.

Although most hydrogen today is produced by chemically reforming natural gas, there are many other options. Hydrogen can be produced from fossil fuels or biomass feedstocks using conventional chemical processes. It can also be produced by dissociating water using electricity or heat, or by using specialized micro-organisms and an external energy source, such as sunlight.

The use of fossil fuels as feedstocks for hydrogen production creates a waste stream of CO_2 emissions. Since energy is required to transform fossil fuels into hydrogen, the resulting energy content of hydrogen is less than the total energy content of the fossil fuel input. Consequently, more CO_2 is emitted in transforming fossil fuel into hydrogen than from the direct combustion of fossil fuel for an equivalent energy content of hydrogen. However, these transformation losses to produce hydrogen may be acceptable in that, much like with conversion from fossil fuels to electricity, energy is required in converting a source to a more useful energy carrier.

Hydrogen from fossil fuel feedstocks could provide a major avenue of CO_2 emissions reduction if the CO_2 is captured and stored rather than vented to the atmosphere. The CO_2 emissions from hydrogen production are in a concentrated stream amenable to capture.

Without CO_2 capture and storage, fossil fuel-based hydrogen use could still lower overall CO_2 emissions for society, but only if the efficiency of its use were sufficiently greater than the efficiency of its production from fossil fuels. This is especially relevant in stationary applications such as buildings, where the excess heat generated by converting hydrogen in a fuel cell can be used in addition to the electricity produced. However, the amount of emissions reductions would be limited relative to using a non-carbon source.

Several alternative processes that do not use fossil fuels are available, including producing hydrogen from water, or using nuclear energy or biomass fuels.

Hydrogen can be produced by splitting water into its constituent parts, hydrogen and oxygen. This can be accomplished through electrolysis or thermal decomposition. If the electricity is taken from the grid, CO_2 emissions will be produced from that portion of power generation that employs fossil fuels in the production of hydrogen. However, dedicated electrical sources using wind or solar power could potentially provide carbon-free hydrogen.

Nuclear energy can be used to produce hydrogen without any direct emissions of greenhouse gases, either via electrolysis or thermal decomposition. Current light-water nuclear reactors that are in operation do not reach temperatures high enough for thermal decomposition of water. Nuclear reactor concepts capable of producing high temperatures suitable for hydrogen production are under investigation.

Biomass feedstocks can be used to produce hydrogen by gasifying the biomass and separating the hydrogen from the resulting syngas. If biomass comes from crops grown for this dedicated purpose, the net CO_2 emissions balance in producing hydrogen from biomass is small.

Transport and Storage. Once produced, the hydrogen must be moved from the point of production to the point of use. Compared to other energy sources such as fossil fuels and electricity, transport and storage may be problematic because the hydrogen must be converted to a highly concentrated form. Hydrogen is the smallest and lightest of all the elements; it tends to disperse rapidly at room temperature and therefore has a very low energy density unless it is concentrated.

That concentration can be accomplished either by increasing the pressure or lowering its temperature. However, raising the energy density of hydrogen to levels that make it useful as an energy carrier can be expensive. In fact, 30 to 40 percent of the energy content of hydrogen may be required to liquefy and store it. Again, just as with the energy losses in producing hydrogen, this additional energy requirement is acceptable if the economics signal a high value of having hydrogen available at the end-use.

The proximity of the production site to the point of use strongly affects hydrogen transport and storage costs. Current transport methods include truck, rail, barge, and pipeline. Over relatively short distances hydrogen can be transported as compressed gas, over longer distances as a liquid. It is presently stored in high-pressure cylinder tanks or cryogenic liquid containers.

Although storage of hydrogen for end-use demand is not an issue for all hydrogen applications, it is a major concern for hydrogen use in vehicles for transportation services. Safe storage capacity must be provided for sufficient vehicle range.

When the hydrogen is stored on board the vehicle, several problems emerge. Tanks that contain sufficient energy to move a vehicle 300 miles are presently large and heavy. Furthermore, because hydrogen easily penetrates many common materials and its boiling point is extremely low (21°K), hydrogen fuel loss from the tank can be significant if the vehicle is left unused for a significant period. Advanced methods are under study including reversible solid systems. But these are not yet practical.

In a different approach, hydrogen can be produced on board the vehicle from a feedstock, presumably a fossil fuel and potentially a gasified biofuel, eliminating the need for hydrogen storage. However, unless the feedstock fuel comes from carbon-neutral biomass, on-board hydrogen production would release CO_2 to the atmosphere, reducing the climate benefit of hydrogen use. Again, if fossil fuels are used, CO_2 emissions reductions would be realized only if the overall gain in system efficiency of the hydrogen system is greater than the traditional fossil fuel combustion system.

Hydrogen use. Hydrogen is presently used industrially to upgrade vehicle fuels at refineries and to manufacture ammonia, but not generally as an energy carrier. However, the technology to use hydrogen to produce energy via a fuel cell or direct combustion does exist today, although it is far from being economically competitive for most uses (see Figure 1).

Hydrogen could be burned in furnaces or boilers instead of natural gas to provide space heat, with the side benefit that it would produce water vapor that could be used to humidify the air in winter. It could also be combusted directly in internal combustion engines in vehicles. But for producing electricity as well as heat and water without pollutants or CO_2, hydrogen fuel cells are the technologies with the most promise.

Hydrogen fuel cell vehicles offer the potential for high transportation vehicle fuel economy with zero CO_2 and pollutant emissions. Because of their modularity, fuel cells can be sized to the application and therefore are considered for potentially diverse applications, such

Figure 1. Fuel cell-powered bus and solid oxide fuel cell (SOFC).

as sources of combined heat and power for stationary applications in buildings and industry, in addition to their use in vehicles. The opportunity to utilize the heat as well as the electricity can lead to improved economic competitiveness in buildings and industry.

However, safety is a key consideration that must be addressed if hydrogen is to become a viable energy carrier at the end-use. Hydrogen is extremely volatile, leaks easily (although it disperses quickly), and burns with an invisible flame.

COST AND PERFORMANCE

The degree to which hydrogen can be supplied without concurrent greenhouse gas emissions will depend on the options for hydrogen production and the specific technology employed to produce the hydrogen. And that in turn will depend on costs—the cost of feedstocks, the cost of conversion processes, and the price of CO_2.

The relative costs of hydrogen production technologies will evolve over time as feedstock fuel prices change and technology costs and performance characteristics improve. Climate policies that place a cost penalty on emitting CO_2 will also significantly affect the relative costs. Figure 2 illustrates hydrogen production costs at two points in time: the year 2035 and the year 2095, for a GTSP scenario in which a climate policy sets a price path on emitting CO_2 so that atmospheric concentrations of CO_2 are stabilized at 550 ppm.

In the scenario shown in Figure 2, year 2035 carbon prices are low enough that production from natural gas and coal with the CO_2 vented (emitted) to the atmosphere are relatively cheaper than carbon-free options. However, by 2095, the carbon price is sufficiently high that venting CO_2 becomes very costly. The viability of CO_2 capture and storage technologies dramatically affects the competitiveness of coal and natural gas as hydrogen feedstocks under a climate policy. The cost of producing hydrogen from non-carbon sources is also expected to improve over time, and they would become even more competitive under a climate policy.

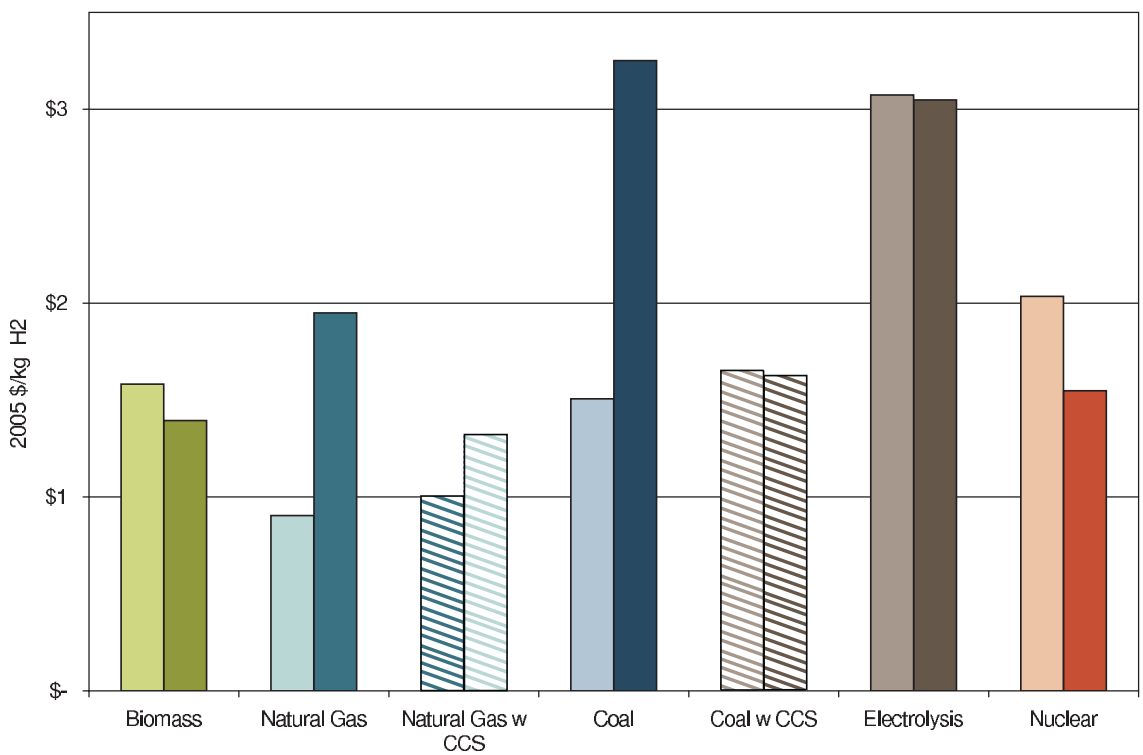


Figure 2. Cost of hydrogen production in 2035 (*left-hand bars*) and 2095 (*right-hand bars*), under a 550 ppm climate policy. The relative cost of hydrogen production technologies will change over time as fuel prices for feedstocks, carbon prices, and technology cost and performance evolve.

THE FUTURE DEPLOYMENT OF HYDROGEN

Most of the technologies discussed in this report benefit greatly from carbon constraints, but the net impact of climate policy on hydrogen will be conditional on how its technology is developed and used. One of the central insights from GTSP analysis is that the hydrogen must compete with other technologies primarily on the basis of its technical performance. Put simply, hydrogen cannot rely on a climate policy to make it economically viable.

In fact, hydrogen may not deploy to as great an extent in a greenhouse-gas-constrained world as it would in a reference world because carbon constraints force hydrogen to compete with energy conservation and energy efficiency technologies, and because hydrogen from fossil fuels (with CO_2 capture and storage to limit emissions) is more costly.

Figure 3 illustrates this point by comparing four scenarios, each pairing an assumption about future climate policy with future improvements in hydrogen technologies. With only incremental improvements in hydrogen technology, there is no large-scale deployment of hydrogen, even under a climate policy that holds CO_2 concentrations to 550 ppm. But with breakthroughs in hydrogen technology, hydrogen would deploy widely both with and without this climate policy. The impact of the climate policy may in fact be to reduce the demand for hydrogen relative to what it would have been without a climate policy.

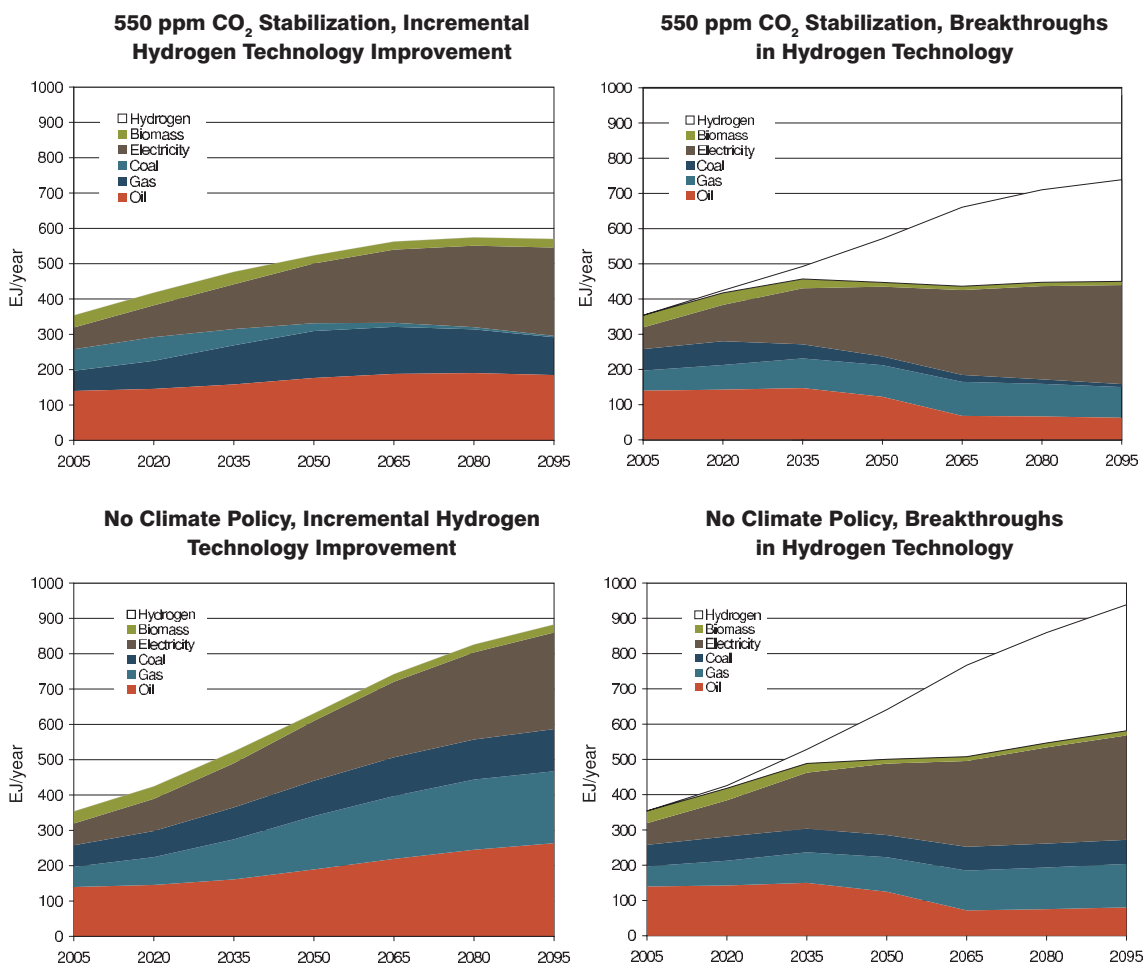


Figure 3. GTSP scenarios of global final energy consumption. Under four sets of assumptions about climate policy and hydrogen technology development, the figures show that the deployment of hydrogen depends not on the presence of a climate policy but on the development of improved hydrogen technology.

Without a constraint on emitting CO_2 in general, hydrogen's climate benefits would be limited to the extent of overall system efficiency improvement and competitiveness of non-carbon hydrogen production sources. Because the cheapest source of hydrogen is fossil fuels, reductions in CO_2 emissions beyond what is achieved through improved systems efficiency will depend on the carbon price.

Figure 4 illustrates two alternative pathways of future hydrogen production under a climate policy. Each panel of the figure shows a scenario in which hydrogen systems are economically attractive and in which a climate policy limits the concentration of CO_2 to 550 ppm. On the left panel, CO_2 capture and storage technologies are assumed to be available and cost competitive, and hydrogen is produced from multiple sources: coal, natural gas, nuclear thermal, and biomass. Most production from fossil fuels employs CCS.

The availability of CO_2 capture and storage is an important determinant of the role of natural gas and coal in a greenhouse-gas-constrained world where hydrogen is a competitive fuel. If CO_2 capture and storage are available, natural gas and coal continue to be used as hydrogen feedstocks. If CCS technologies are not available, then fossil fuels are largely driven out of hydrogen production.

The right panel of Figure 4 shows the same climate policy scenario except that CCS is assumed not to be available and non-fossil means of producing hydrogen are assumed to improve. In this scenario, nuclear thermal dissociation of water and biomass sources of hydrogen dominate the second half of the century as the price of carbon makes them increasingly cost effective relative to fossil fuel feedstocks.

Biomass and nuclear thermal sources of hydrogen will be more important sources of hydrogen in a climate-constrained world than in a reference world. Whereas natural gas and coal are the cheapest sources of hydrogen in the absence of climate policy, a carbon price imposes significant costs on these methods and shifts hydrogen production toward other feedstocks and fuels such as biomass and nuclear.

Hydrogen use in stationary applications may be as important as in transport, as shown in Figure 5. The infrastructure that would be built to support hydrogen production and distribution to large stationary applications could provide the foundation for later expansion to a more dispersed set of hydrogen distribution points for transportation.

From Figure 5, assuming successful development of hydrogen systems and a 550 ppm CO_2 climate policy, hydrogen begins to deploy in all sectors, but the largest deployments in the period through 2035 are in buildings and industry (i.e., stationary applications). Deployment in transportation (i.e., mobile applications) might not exceed stationary applications until the second half of the century.

Finally, the challenges of developing large-scale hydrogen use are enormous. Not only must hydrogen be capable of providing all of the desirable characteristics of existing technology, expand services and amenities where possible, deliver fewer problems in the realms of environment, health, and safety, all at a competitive price, but society must simultaneously develop both a sophisticated infrastructure and a sophisticated set of end-use technologies.

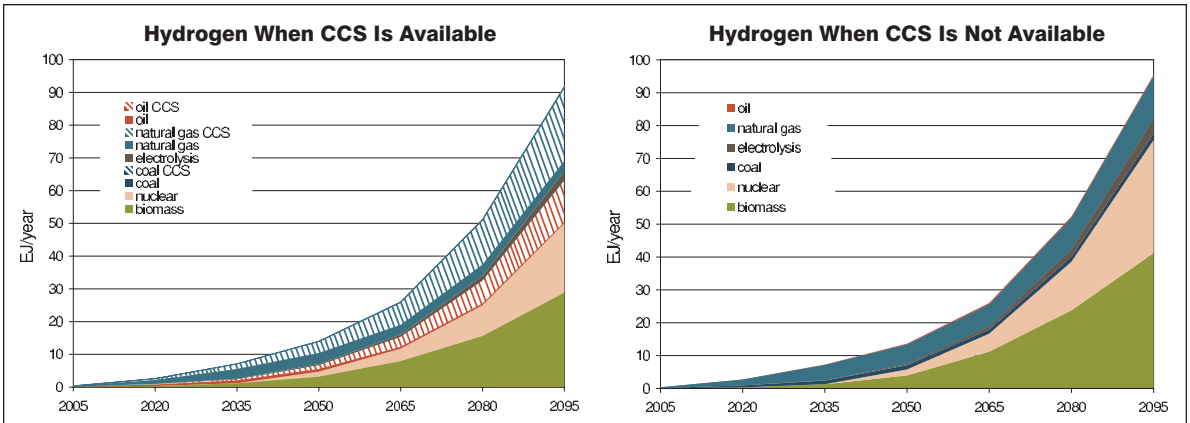


Figure 4. GTSP scenarios of global hydrogen production under a 550 ppm climate policy. CO_2 capture and storage (CCS) enables fossil fuels to be used as feedstocks for hydrogen production under a climate policy. Without CCS, non-fossil sources must be developed and used.

THE VALUE OF CONTINUED RESEARCH AND DEVELOPMENT

The introduction of hydrogen into the global energy system requires several simultaneous changes to occur. System components must develop in parallel. That is, the capability to produce, distribute, store and use hydrogen must be developed and the costs lowered. Although hydrogen production is relatively well established and could go into service relatively quickly, transport, storage, and use remain to be developed.

The economic challenge for a new technology seeking to penetrate the market is to provide all of the desirable characteristics of existing technology, expand services and amenities where possible, and deliver fewer problems in the realms of environment, health, and safety, all at a competitive price.

To accomplish that goal, hydrogen technologies must improve substantially from their present state. Moreover, technology must chase a moving economic and performance target, since other technologies are also capable of improvement. In transportation this means continuous improvements in internal combustion engine, hybrid, biofuel, natural gas, and electric vehicles.

All aspects of hydrogen systems may improve, from production to transport and storage to end use. The greatest uncertainty in future cost and performance is associated with transport, storage, and end-use technologies.

If the potential for hydrogen technologies to contribute to CO_2 emission reductions is to be realized, all aspects of hydrogen production, transport, storage and use must be significantly improved in terms of cost and performance. Selected R&D, demonstration, commercial deployment challenges and opportunities for hydrogen energy systems include:

- Develop methods for producing hydrogen without emitting CO_2, such as CCS, biomass, renewable electricity, or thermonuclear, and demonstrate the ability to commercially deploy these methods on a large scale.
- Significantly improve the cost competitiveness and performance of vehicle fuel cells so that fuel-cell-based vehicles could play a significant role in decarbonizing the transportation sector.
- Reduce the cost of transporting hydrogen in order to build an economic hydrogen distribution system.
- Reduce the cost and improve the performance of storing hydrogen in sufficient energy quantities on board vehicles to allow safe use with driving ranges comparable to conventional vehicles.

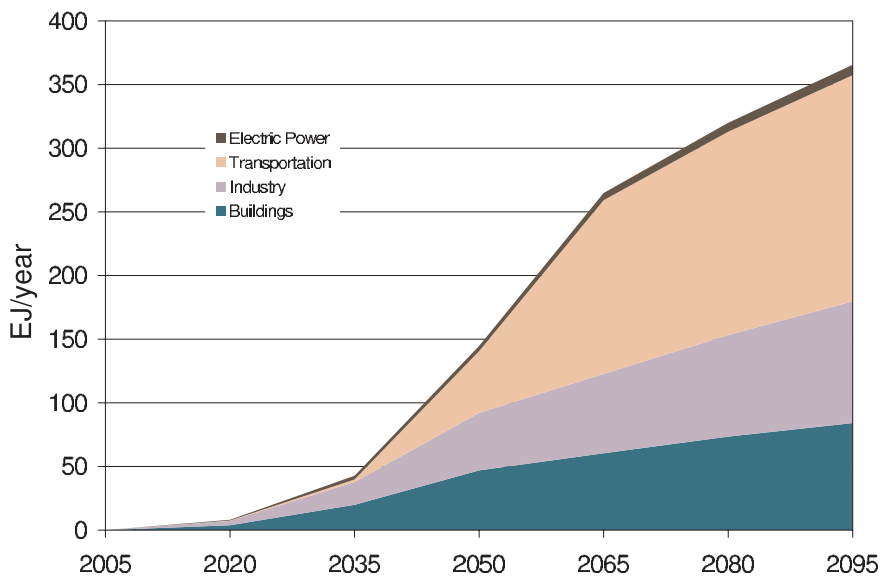


Figure 5. GTSP scenario of future global hydrogen use by sector. Hydrogen deployment may occur first in buildings and industry before expanding in transportation.

APPENDIX Notes and References

Most of the CO_2 emissions in this study are stated in units of million or billions of tons of carbon (MtC or GtC, respectively). This differs from the conventions of the CCS technical community, which expresses values in millions or billions of tons of CO_2 ($MtCO_2$ or $GtCO_2$, respectively). Cost data can be converted to dollars per ton of ($/$tCO_2$) by dividing by 3.667, and mass data can be converted to CO_2-based units of the climate change technical community by multiplying the mass expressed in carbon-based units by 3.667.

This report makes frequent use of a very large measure of mass known as a "gigaton." A gigaton of CO_2 ($GtCO_2$) is a standard measure for scientists and policy makers familiar with carbon management, yet for most other audiences the magnitude of this unit is sometimes hard to comprehend. A gigaton is approximately equal to 77 Empire State Buildings if they were made completely of lead, 10,718 aircraft carriers the size of the USS Enterprise, or all of the iron ore annually mined in the world. For more examples of how massive a gigaton is please consult C.L. Davidson and J.J. Dooley, "A Gigaton Is…" PNWD-3299, Joint Global Change Research Institute, Battelle Pacific Northwest Division (July 2003).

Unless otherwise indicated, all scenarios and analyses result from the GTSP research, using several well-established modeling tools.

Figure 3. This figure depicts results of modeled scenarios exploring broadly the impact of technical improvements in hydrogen systems. "Incremental improvements" in hydrogen technology were modeled as a 50 percent increase in fuel cell performance over the century. "Breakthroughs" in hydrogen technology were modeled as fuel cell performance doubling over the century while the cost decreases by a third. For more detail, see J. Edmonds, J. Clarke, J. Dooley, S.H. Kim and S.J. Smith, "Stabilization of CO_2 in a B2 World: Insights on the Roles of Carbon Capture and Disposal, Hydrogen, and Transportation Technologies," *Energy Economics*, 26 (2004), 517-537.

References of interest for further exploration of this topic include the following:

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THE **GLOBAL ENERGY TECHNOLOGY STRATEGY PROGRAM**

The Global Energy Technology Strategy Program (GTSP) began in 1998 with the goal of better understanding the role that energy technologies might play in addressing the problem of global climate change. The GTSP is unique, a global, public and private sector sponsored research program, whose sponsors and research collaborators are drawn from around the world.

The completion of the first phase of the GTSP in 2001 was marked by the release of a seminal report during a special session of the Sixth Conference of the Parties to the United Nations Framework Convention on Climate Change. This report, *A Global Energy Technology Strategy Project Addressing Climate Change: Initial Findings from an International Public-Private Collaboration,* demonstrated the importance of technology development and deployment as key cornerstones of a broader set of activities designed to address climate change. A central conclusion was that a robust technology strategy required the development of a *technology portfolio*. It found no evidence for a single technology whose development promised to "solve" the climate problem. That is, *a priori*, there is no technological "silver bullet." Rather, the GTSP concluded that various technologies and technology systems show promise for making a substantially expanded contribution to the global energy system in a climate-constrained world. These included biotechnology, hydrogen energy and other advanced transportation technology systems, nuclear power, renewable energy technologies, end-use energy technologies, and carbon dioxide capture and storage. The first phase of the GTSP produced groundbreaking research, including many results that have made their way into the frequently cited literature. This phase of the GTSP successfully added to the dialogue about responses to climate change a new, previously missing, element—technology. But building productive, long-term, real-world technology strategies to address climate change requires a deeper understanding of technologies and their potential. Thus, the GTSP launched its second phase in 2002. GTSP Phase 2 pushed the frontiers of our knowledge to gain a much deeper understanding of how these key carbon management and advanced energy technologies will deploy in practice, and the means for launching and sustaining a meaningful global energy technology strategy.

GTSP Phase 3 will delve into the regional diversity and institutional dimensions of developing and deploying technologies to address climate change.

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