Comments on the Department of Energy Quadrennial Technology Review Framing Document
Submitted by the
Fuel Cell and Hydrogen Energy Association
April 15, 2011

The Fuel Cell and Hydrogen Energy Association (FCHEA) appreciates the opportunity to comment on the Quadrennial Technology Review (QTR) Framing Document. We note the drafters of the QTR have omitted fuel cells and hydrogen energy in their framing document; whether an intentional oversight or otherwise, this is in error.

We believe any rational analysis of the facts, the data, the market experience, and their actual and potential benefits leads to the conclusion that fuel cells and hydrogen energy have a crucial role to play in America's energy security. As the Framing Document welcomes " . . . comment on the selection of . . . technologies and sources, as well as suggestions of alternate technologies and sources, and updated technology, cost, and forecast data, particularly in rapidly-moving fields," (p.23) we welcome the authors' openness and the chance to respond.

The Department of Energy's excellent work and the strong public-private partnership in fuel cells and hydrogen ought to be a model for the Department's activities. Certainly the progress on fuel cells and hydrogen energy amply justifies raising the profile of fuel cells and hydrogen in the QTR and at DOE generally.

Fuel cells and hydrogen technologies are transforming the energy network through distributed generation of clean, efficient and reliable power using a broad range of domestic fuels. They are proven to play a unique and vital role in enhancing the performance of renewable and nuclear power, boosting the efficiency and lowering the emissions of fossil fuels, and generating power closer to the point of consumption, relieving grid congestion and reducing the need for high voltage transmission lines.

Leading corporations like Coca-Cola, Google, FedEx and Walmart are using fuel cells and hydrogen to meet mission critical power needs for 7/24 materials handling, grocery store refrigeration and data center operations. The U.S. military is relying on fuel cells and hydrogen energy for light, long duration soldier power and to power unmanned vehicles, increasing their efficiency and effectiveness on the battlefield, as well as for materials handling and stationary applications in non-tactical base operations.

The men and women of the fuel cell and hydrogen energy industries strive daily to produce energy from domestic fuels—renewable and fossil—as cleanly, as efficiently, as reliably, and as cost-effectively as possible. Our companies and research partners are at the cutting edge of high-tech manufacturing, engineering, and materials science. We are the last clean energy technology in which the United States is the recognized manufacturing and technical leader, an advantage other countries are positioning themselves to take away.

The FCHEA is the advocacy organization dedicated to the commercialization of fuel cells and hydrogen energy technologies. FCHEA and its membership are at the forefront of efforts to transform the energy network, fundamentally altering the way energy is generated and used. Fuel cells and hydrogen technologies are being commercially deployed today to solve critical problems in our energy infrastructure and deliver clean, reliable power to leading edge corporate, academic and public sector users. FCHEA's membership represents the full spectrum of the supply chain from universities, government laboratories and agencies, trade associations, fuel cell materials, components and systems manufacturers, hydrogen producers and fuel distributors, utilities and other end users.

Summary

The family of technologies comprising the fuel cell and hydrogen energy industry play a central role in the new energy network outlined in the QTR.

- With an estimated $1 billion in sales, more than 10,000 employees in the US, and more than 30,000 worldwide, our industry is emerging as a significant contributor to the new energy architecture.
- With 15,000 fuel cell systems (representing over 90 mW) shipped in 2010, our industry is proving it can meet market needs *and* deliver benefits to society **today** with high efficiency and low emissions, and up to 100% renewable generation.
- Electrical conversion efficiencies up to 60% and combined heat and power efficiencies higher than 80% bring economic benefits to customers and energy security benefits to the nation.
- The ability to use low- and zero-carbon fuels efficiently brings up to 100% reductions in greenhouse gas (GHG) emissions and in conventional pollution, and substantial environmental benefits even when using conventional hydrocarbons.
- Nearly 1,000 patents, including 200 developed with DOE funding, and the potential for up to 675,000 jobs by 2035, according to a DOE estimate, strengthen the nation's knowledge base and bring economic growth in critical industries.

FCHEA looks forward to continuing our dialogue with you as you develop the QTR.

Background on the Industry

Fuel cells are electrochemical systems that convert the energy of a fuel directly into heat and electricity. Since there is no combustion, the process is inherently efficient and low polluting. In structure fuel cells are similar to batteries but with a fundamental difference. Batteries store electricity and must be recharged. Fuel cells generate electricity and will do so as long as fuel is supplied.

Hydrogen is abundant and in hydrocarbon compounds is essential to life on earth. It is an excellent energy carrier and when used in a fuel cell yields its energy with no emissions other than water and heat.

The fuel cell and hydrogen energy industry is international in scope, with $1 billion[1] in sales in at least 40 countries. Public and private estimates project exponential growth as products gain market share in a wide range of markets, including power generation, combined heart and power, industrial equipment, backup power, portable generation, military, consumer electronics and, by 2015, passenger vehicles.

Investment in the industry by venture capital firms and private equity sales exceeded $570 million between 2008 and 2010. Over the past two decades, an estimated $10 billion has been spent on research, development and commercialization of fuel cells and hydrogen energy, 80% from the private sector: federal research dollars have been matched more than four-to-one.

Employment in the industry is expected to grow exponentially. DOE estimates that 677,000 jobs could be created by 2035 in 41 fuel cell and related [fuel cell and related? I don't understand the 41 industries reference] industries.[2] The Korean government estimates 2.8 million jobs will be created worldwide with global sales of $126 billion.[3]

Knowledge is growing rapidly in the industry. According to the Clean Energy Patent Growth Index[4] fuel cell patents lead in the clean energy field (and has since 2002), with 996 fuel cell patents registered worldwide in 2010. This number is three times greater than the second place holder, solar, with just 363 patents. The number of fuel cell patents grew more than 57 percent in 2010. The top holder is General Motors; IdaTech, United Technologies, Delphi, Plug Power and Bloom Energy are among the U.S. companies with significant patent positions.

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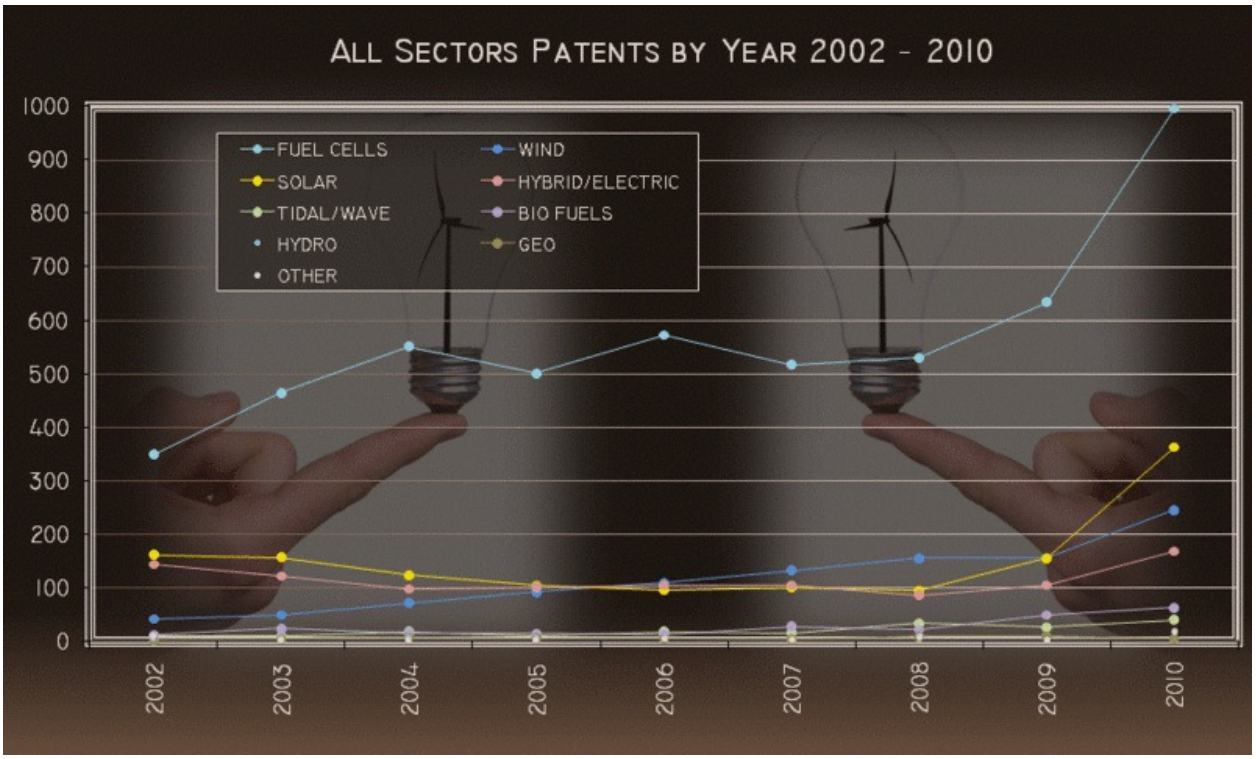
[1] Some estimates are higher; Intertechpira, a private analyst, puts the figure at $2 billion in 2009.

[2] Effects of a Transition to a Hydrogen Economy on Employment in the United States: Report to Congress. 2008.

[3] Park, Dal-Ryung, "Commercialization of Fuel Cell Technologies in Korea," 2010 FC Expo, March 2010. The Korean government has adopted a policy to capture 20% of the world market in fuel cells, and 20% of the jobs.

[4] http://cepgi.typepad.com/heslin_rothenberg_farley_/.



Fuel Cells Address the Challenges Posed in QTR

Fuel cells are an integral part of the solution to the nation's energy challenges.

Energy Security (3.1)

Fuel cells contribute to energy security by

1. Making possible the eventual elimination of hydrocarbon motor fuel in light duty vehicles.[5] Every fuel cell vehicle displaces 12 to 15 times the oil demand of a plug-in hybrid vehicle. Thus on an energy security basis 55,000 fuel cell vehicles are equivalent to more than 600,000 PHEVs. [6]

2. Achieving very high efficiency in the use of natural gas for power generation and heating, even in very small and distributed systems[7]

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[5] "A portfolio of technologies including hydrogen fuel cell vehicles, improved efficiency of conventional vehicles, hybrids, and use of biofuels—in conjunction with required new policy drivers—has the potential to nearly eliminate gasoline use in light-duty vehicles by the middle of this century, while reducing fleet greenhouse gas emissions to less than 20 percent of current levels. This portfolio approach provides a hedge against potential shortfalls in any one technological approach and improves the probability that the United States can meet its energy and environmental goals." NRC, Transitions Report, Summary. National Research Council, Transitions to Alternative Transportation Technologies: A Focus on Hydrogen, 2008.

[6] DOE Office of Vehicle Technologies, *Multi-Year Program Plan,* 2011-2015, page ES-3.

[7] http://www.fuelcellenergy.com/files/FCE%20WhitePaper%20040308_1.pdf, page 5.

3. Enabling the continued use of coal by providing a pathway to high efficiency coal power generation (60%) and affordable carbon sequestration (reducing the cost of energy to the consumer by one-third compared to the DOE baseline projection).[8]

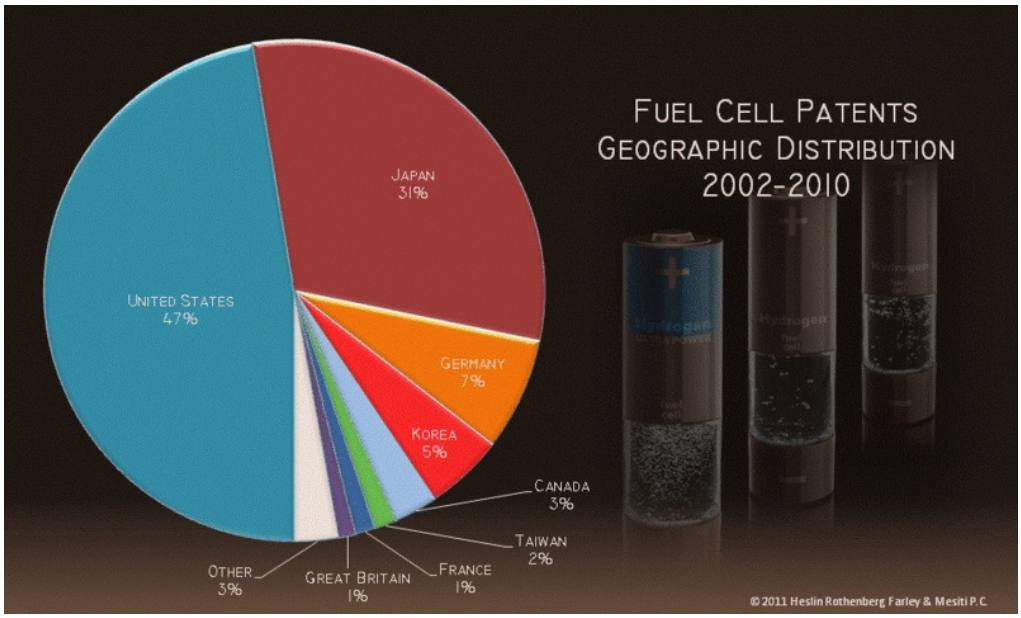
4. Improving the quality and security of the power grid by offering a storage option for intermittent generation and increasing operators' flexibility.[9]

U.S. Competitiveness (3.2)

Fuel cells are a U.S. based technology, with a strong patent position and an estimated 1,000 supply chain companies. We know from painful experience how expensive it is to try to buy back energy technology capability. The U.S. still has a lead that can (and in our view must) be nurtured. Fuel cells contribute to U.S. competitiveness.

Innovation (3.2.1)

The U.S. has a dominant patent position in fuel cells, holding 47% of fuel cell patents registered between 2002-2010 (Japan is second with 31%.). Fuel cell patents originated from 30 U.S. states.[10] Japan, Korea, China, Germany and the European Union, however, all support aggressive fuel cell research programs.



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[8] *Cost and Performance Baseline for Fossil Energy Plants, Volume 1, Revision 2 DRAFT,* 2010 .
Analysis of Integrated Gasification Fuel Cell Plant Configurations, DRAFT, 2010.

[9] NREL, Analysis of Hydrogen and Competing for Utility-Technologies Utility Scale Energy Storage, 2010,

[10] CEPGI, *op. cit.*

Manufacturing (3.2.2)
The early commercial status of the fuel cell and hydrogen energy industry presents an opportunity to foster job growth in the Unites States. There is substantial competition: Korea has announced a long-term program to capture 560,000 fuel cell jobs over the next two decades. But the door is still open for the United States. According to Fuel Cell Today, the global fuel cell industry could create 700,000 manufacturing jobs by 2020. About 25% of the jobs, or 175,000 jobs, were projected for North America.[11]

Deployment (3.3.3)
U.S. fuel cell companies are competing in world markets today although they are under pressure to relocate facilities and jobs where the markets are.[12] Fuel cells are also finding important in the United States, helping commercial and industrial customers convert to highly reliable, high efficiency, low cost distributed systems, and providing effective alternatives to batteries and combustion systems in industrial vehicle, backup power and portable power markets. Fuel cell systems are powering many mission critical energy needs, and saving customers money today in all these applications.[13]

Environment (3.3)

Fuel cells are the cleanest technology that consumes a fuel. A fuel cell generates electricity and useful heat through an electrochemical process rather than combustion. The absence of combustion means fuel cells are inherently clean and highly efficient. Fuel cells produce very low or zero emissions and are up to 80% to 90% efficient when used in a combined heat and power application. This protects the environment in addition to saving customers money.

1. **In Transportation,** fuel cell electric vehicles (FCEVs), as part of a portfolio of vehicle technologies, can achieve the goal of 80% reduction of CO2 emissions from the light duty vehicle fleet by 2050.[14] FCEVs are zero emission vehicles, according to the California Air Resources Board. When emissions from hydrogen production are included, fuel cell EVs can also achieve zero well-to-wheel emissions via renewable pathways. According to a DOE analysis, producing hydrogen from natural gas yields fewer emissions than would be generated by charging a battery EV (based on grid average) even using a "cleaner grid" in 2035.[15]

   If one compares the DOE/industry targets presented in DOE program plans for battery costs and fuel cell and hydrogen storage costs, and employs them in comparative vehicle analyses, neither technology has an obvious economic advantage at this stage of development. It makes sense to embrace the full portfolio rather than picking winners and losers, which the Scoping document specifically says DOE wishes to avoid.[16]

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[11] http://www.fuelcelltoday.com/online/news/articles/2010-01/Fuel-Cell-Industry-Could-Create-
[12] *2009 Fuel Cell market Report,* page 4. http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/49492.pdf.
[13] *The Business Case for Fuel Cells,* 2010. http://www.fuelcells.org/BusinessCaseforFuelCells.pdf.
[14] NRC, *Transitions, op. cit.*
[15] http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/budget_webinar_fy12.pdf.
[16] Gronich, *Are Plug-in/Battery Electric Vehicles More Market Ready than Hydrogen Fuel Cell Vehicles?* NHA 2009.

2. **In Power Generation,** Fuel cell CHP emissions are so low – pounds compared to tons for the alternatives - that fuel cells are exempt from air quality permitting in Los Angeles and other jurisdictions with serious smog problems.[17] Fuel cells are a low CO2 technology, the result of high efficiency use of hydrocarbon fuels and the ability to operate on biogas and on hydrogen generated renewably via electrolysis of water. Fuel cell systems can be zero net emissions. Natural gas powered fuel cell systems reduce CO2 by 10 to 40 percent compared to alternatives.

   Fuel cells save water. Today's combined heat and power fuel cell systems are water neutral once charged. When solid oxide fuel cell systems are used to separate CO2 emissions from gasified coal, they reduce water use per megawatt hour by 80 percent or more.[18]

Analysis and Assessment

The performance of fuel cells in the marketplace is being documented both via data analysis and individual examples.[19] There is ample real world data to judge the environmental and energy saving performance of fuel cell systems. In Japan, for example, with experience from more than 13,000 installed residential fuel cell systems, the gas companies offering the systems report a 33% reduction in primary energy consumption and a 45% reduction in household CO2, or about 1,500 kilograms per year per household.[20] The National Renewable Energy Laboratory maintains an extensive data collection activity on hundreds of fuel cell forklifts in operation in the U.S., and on an extended trial of more than 150 fuel cell passenger cars and buses,.[21]
Commenters were invited to suggest additional analysis and assessments that might guide the QTR authors, and we do so below.

DOE Fuel Cell Technologies Program, Multi-Year Research, Development and Demonstration Plan: 2005-2015, updated 2009.[22]

The program plan was developed in 2005 and revised in 2009 with extensive input from industry and other stakeholders and represents a consensus view of the cost, performance and durability needed for full commercialization. The program has met every significant milestone, and is on pace to achieve cost reduction and performance benchmarks in 2015 that many once thought were impossible; the program is responsible for more than 200 patents. The public's investment of about $2 billion since 1994 has been matched more than four-to-one by industry. The program is a success and, compared to investment in other advanced and renewable technologies, a bargain.

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[17] www.**aqmd**.gov/rules/reg/reg02/r219.pdf.
[18] NETL analysis presented to Fuel Cell and Hydrogen Energy Association, 2010.
[19] *Business Case, op. cit.*
[20] Hataba, M., Tokyo Gas Company, *Ene-Farm*, presentation to the FC Expo, Tokyo, 2010.
[21] http://www.nrel.gov/hydrogen/proj_tech_validation.html.
[22] http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/index.html.

McKinsey and Co., "A portfolio of power-trains for Europe: a fact based analysis," 2010.[23]

A 31-member public-private coalition sponsored the report, which concludes that "a significant penetration of both fuel cell and battery electric cars" will be needed to build a sustainable transportation system by 2050. McKinsey interviewed every fuel cell vehicle developer and concluded that Fuel cell electric vehicles are ready for commercial scale-up, and are the best EV option for longer trips and medium size and larger cars, The study concluded "The costs for a hydrogen infrastructure are . . . comparable to rolling out a charging infrastructure for BEVs and PHEVs. A dedicated hydrogen infrastructure is therefore justified and doable." McKinsey called the initial infrastructure investment "relatively low."

While the analysis focuses on the European vehicle fleet and CO2 reduction goals, the technology and cost assessment is applicable worldwide –and the policy conclusions are relevant to the United States, since the U.S. has an even greater percentage of medium and heavy duty vehicles than Europe, and we drive our cars longer distances.
Significant conclusions include:

- ICE will continue to improve by up to 30% further to improve, but additional reductions in CO2 will need to come from electrification pathways.
- Battery electric vehicles, given their limited energy storage capacity, shorter driving range and relatively long recharging times are ideal for smaller cars and shorter trips – i.e. urban driving
- Plug-in hybrids are a good transition technology
- Fuel cell electric vehicles have a driving range and performance comparable to internal combustion engines are the lowest-carbon solution for long distance driving and family-size cars which represent 50% of all cars and 75% of all emissions.
- The cost of infrastructure for battery electric vehicle recharging and hydrogen refueling are comparable and the long term cost of ownership for fuel cell electric vehicles is significantly lower than other electric vehicle options.

DOE, Well-to-Wheels Greenhouse Gas Emissions and Petroleum Use for Mid-Size Light-Duty Vehicles, 2010.[24]

This assessment estimates the carbon reduction and petroleum reduction potential of a variety of drive trains and fuels, in an SUV in 2030, including BEV and PHEVs. Fuel cell EVS are consistently among the cleanest vehicles – even when the hydrogen is extracted from natural gas; the cleanest FCEVs are the cleanest of all the vehicles analyzed.

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[23] McKinsey and Co. http://www.now-gmbh.de/en/press/analysis-decarbonisation-of-personal-mobility.html
[24] http://www.hydrogen.energy.gov/pdfs/10001_well_to_wheels_gge_petroleum_use.pdf

National Research Council, Transitions to Alternative Transportation Technologies: A Focus on Hydrogen, 2008.[25]

Following are excerpts from the abstract.

"In response to a congressional request in the Energy Policy Act of 2005, this National Research Council (NRC) study estimated the maximum practicable number of hydrogen fuel cell vehicles (HFCVs) that could be deployed in the United States by 2020 and beyond, together with the investments, time, and government actions needed to carry out this transition.

"The NRC's Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies concluded that the maximum practical number of HFCVs that could be operating in 2020 would be approximately 2 million in a fleet of 280 million light-duty vehicles. The number of HFCVs could grow rapidly thereafter to about 25 million by 2030.

"The use of HFCVs can achieve large and sustained reductions in U.S. oil consumption and CO2 emissions, but several decades will be needed to realize these potential long-term benefits. Considerable progress is still required toward improving fuel cell costs and durability, as well as on-board hydrogen storage. The substantial financial commitments and technical progress made in recent years by the automotive industry, private entrepreneurs, and the U.S. Department of Energy (DOE) suggest that HFCVs and hydrogen production technologies could be ready for commercialization in the 2015-2020 timeframe. Such vehicles are not likely to be cost-competitive until after 2020, but by 2050 HFCVs could account for more than 80 percent of new vehicles entering the fleet.

"The main advantage of a transition to HFCVs is the potential for reducing the use of oil and emissions of CO2. Although hydrogen could not replace much gasoline before 2025, the 25 years after that would see a dramatic decline in the use of gasoline in the light-duty vehicle fleet to about one-third of current projections, if the assumptions of the maximum practical case are met. CO2 emissions will decline almost as much if hydrogen is produced with carbon capture and sequestration or from nonfossil sources.

"The committee also found that alternatives such as improved fuel economy for conventional vehicles, increased penetration of hybrid vehicles, and biomass-derived fuels could deliver significantly greater reductions in U.S. oil use and CO2 emissions than could use of HFCVs over the next two decades, but that the longer-term benefits of such approaches were likely to grow at a smaller rate thereafter, even with continued technological improvements, whereas hydrogen offers greater longer-term potential. Thus, as estimated by the committee, the greatest benefits will come from a portfolio of R&D technologies that would allow the United States to achieve deep reductions in oil use, nearly 100 percent by 2050 for the light-duty vehicle fleet.

[25] http://www.nap.edu/catalog.php?record_id=12222

"Achieving this goal, however, will require significant new energy security and environmental policy actions in addition to technological developments. Although broad policies aimed at reducing oil use and CO2 emissions will be useful, they are unlikely to be adequate to facilitate the rapid introduction of HFCVs. A competitive and self-sustaining HFCV fleet is possible in the long term but will require hydrogen-specific policies in the nearer term. These policies must be substantial and durable in order to assure industry that the necessary long-term investments can be made safely."

- All the advanced vehicle pathways have substantial GHG emission reduction potential. But abandoning the hydrogen pathway could make the job impossible. All have similar commercialization costs. All require substantial investment in new infrastructure. Benefits will take time to accrue. Especially over the next decade and until we know which technologies will succeed, the best path is to sustain our options.

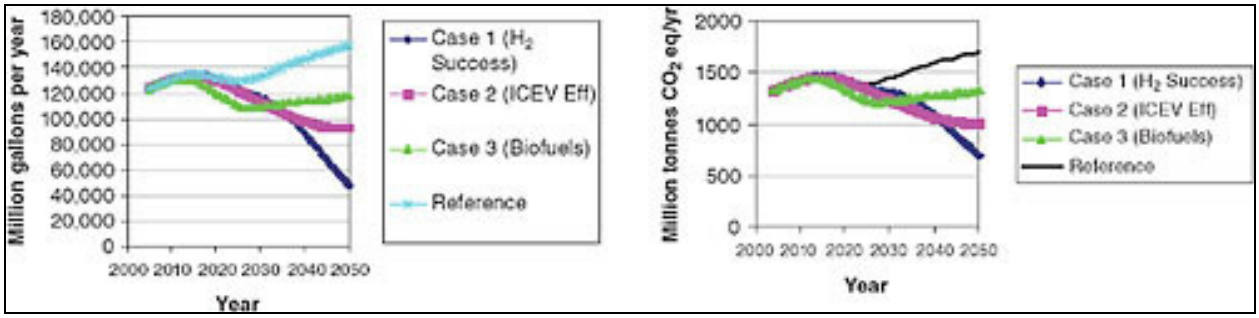


Figure 2. **Comparison of annual greenhouse gas emissions (as equivalent CO_2).** The left figure shows the Reference Case (light blue), ICEV Efficiency Case (pink), Biofuels Case (green), and Fuel Cell Success Case (dark blue). No single approach reaches an 80% reduction by 2050. Right: Comparison of annual greenhouse gas emissions.

QTR's Cited Analyses

One need only look at the analyses cited in the Framing Document to find abundant evidence of the dynamism of fuel cell research, the potential payoff for society, and the priority that a wide range of reviewers give to developing and commercializing fuel cells and hydrogen energy.

President's Council of Advisors on Science and Technology (PCAST), Report

- The PCAST report that provided the impetus for the QTR is direct and positive about the near-term strategic value of fuel cells and hydrogen.

    - "For security: The oil shocks of the 1970s provided a short-lived impetus to reducing oil dependence. Thirty years later, we experienced $140/barrel oil. Today, we are "exporting" about a billion dollars per day for imported oil and face serious national security and foreign policy constraints because of the industrialized world and emerging economy dependence on oil for mobility. The complexities of the Middle East do not require elaboration. However, scientific advances over the last decades in biology, nanotechnology, and other scientific areas have opened promising technology pathways – biofuels, NG and synthetic fuels, advanced batteries, **and hydrogen** – that can provide elasticity in the transportation fuels market. We have the scientific tools and now need to apply them with an urgency appropriate to the national security benefits of reduced oil dependence. These considerations set the stage for extraordinary action by the Federal government to supp ort not only R&D on new energy technologies but also demonstration, adoption, and diffusion of these technologies in concert with the private sector." (p. 2) (emphasis added)

DOE's Strategic Plan, 2011

- The plan notes the importance of its current bioenergy research to the generation of hydrogen, and in embracing fusion energy research for its long-term potential certainly recognizes that some high value advanced energy pathways will require patience and money for success.

    - "Genomics-based systems biology research, agronomic strategies, and fundamental understanding of biological and chemical deconstruction of biomass are particularly important elements of these activities. Research supported in this area will have impacts beyond bioenergy, underpinning technologies such as batteries and fuel cells, catalysis, hydrogen generation and storage, and membranes for advanced separation." (p. 30)

National Academy of Science, America's Energy Future, 2010

- America's Energy Future identifies fuel cell and battery electric vehicles as having substantial energy saving and CO2 reduction potential, though the authors speculate that sales will not be "significant" before 2030, a conclusion they recognize is at odds with the NAS's 2008 assessment discussed above. The potential value of such a transition, however, is also recognized.

    - "Hydrogen has considerable potential, as discussed in previous National Research Council reports.[17] Hydrogen fuel-cell vehicles could yield large and sustained reductions in U.S. oil consumption and greenhouse gas emissions, but it will take several decades to realize these potential long-term benefits. (Summary, p. 46)

    - After 2030, hydrogen fuel-cell vehicles and battery-electric vehicles may also make up a significant portion of vehicle sales. Because fuel-cell and battery-electric vehicles could ultimately eliminate the need for petroleum in transportation, they could also reduce and possibly even eliminate light-duty-vehicle tailpipe emissions of greenhouse gases. However, the full-fuel-cycle emissions of greenhouse gases—cumulative emissions associated with all steps in the use of a fuel, from production and refining to distribution and final use—will depend on how hydrogen is produced for use in fuel cell vehicles and how electricity is produced for PHEVs. The success of PHEVs will depend on the development of batteries that have much higher performance capabilities and lower costs than those currently available. The success of fuel cell vehicles will depend on improved and lower-cost fuel cells and probably on a better means of storing hydrogen on board the vehicles. (Summary p. 14)

DOE and U.S. Department of Agriculture, Biomass as Feedstock for a Bioenergy and BioProducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply. ORNL/TM-2005/06, 2005

- This report contemplates a role for fuel cells in electricity generation via biofuels by defining biopower as the use of biomass to produce electricity via"…engines, turbines, fuel cells, or other equipment."

FreedomCAR & Fuel Partnership, Electrical and Electronics Technical Team Roadmap, 2010

- The tech team roadmap endorses a portfolio approach to accomplishing its energy security mission, specifically including fuel cells as part of the portfolio, and anticipates a gradual progression to fuel cell vehicles as the motor vehicle fleet electrifies. As the Tech Team expresses it, the portfolio approach offers the greatest chance for success.

- **"Mission/Vision:** Achieving energy independence demands hybrid electric and fuel cell vehicles that are economically justifiable for the average consumer. Essential to this effort is the development of advanced power electronics and electrical machines, as key enabling technologies for propulsion systems. . . .

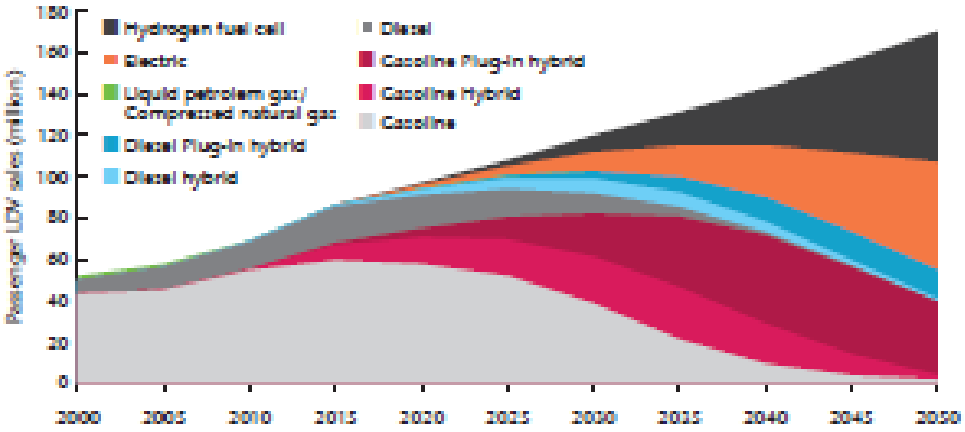
  "As technology moves from HEVs to PHEVs and then to battery electric vehicles (BEVs) and fuel cell electric vehicles (FCVs), the Electrical and Electronics Technical Team (EETT) is charged with advancing the technologies required to make electrically driven transportation preferred to today's petroleum-fueled vehicles. The team will encourage the national research community and industry to focus on developing technologies that will lead to the commercial viability of electric propulsion in the future." (pp. 1-2)

- " **Address multiple technologies**, because no single new technology will achieve of all of the targets. For the motor, it is necessary to consider issues such as new designs, magnet materials, and manufacturing methods. For the power electronics, it is necessary to consider semiconductor switches, capacitors, magnetics, packaging, and new topologies. Added to all of those issues is the challenge of thermally managing the modules. (p. iii)

IEA, Technology Roadmap: Electric and plug-in hybrid electric vehicles, 2009

- The IEA roadmap contemplates annual sales of about 50 million battery and fuel cell electric vehicles by 2050, about evenly divided, with PHEVs seen as a bridge technology.
    - "PHEVs and EVs are expected to begin to penetrate the market soon after 2010, with EVs reaching sales of 2.5 million vehicles per year by 2020 and PHEVs reaching sales of nearly 5 million by 2020 (see Figure 3, Figure 5 and Table 3). By 2030, sales of EVs are projected to reach 9 million and PHEVs are projected to reach almost 25 million. After 2040, sales of PHEVs are expected to begin declining as EVs (and fuel cell vehicles) achieve even greater levels of market." (p. 14)

Figure 2: Annual light-duty vehicle sales by technology type, BLUE Map scenario

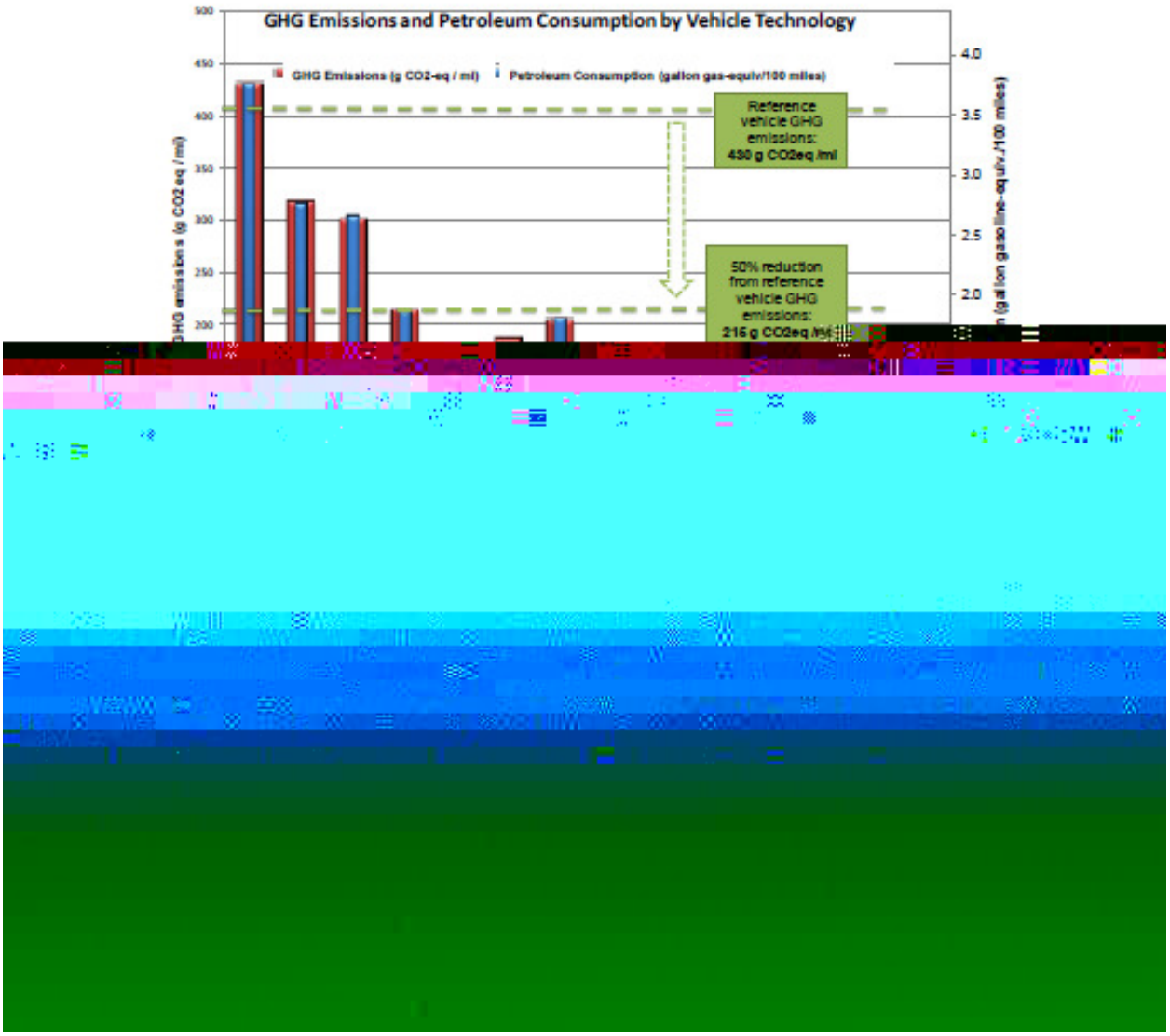


Source: IEA 2009.

KEY POINT: This roadmap sees rapid light-duty vehicle technology evolution over time.

DOE Vehicle Technologies Program, Multi-Year Program Plan, 2011-2015

- The Vehicle Technologies Program coordinates its work with the Fuel Cell Technologies program, and specifically lists thermal system integration, control strategies and combustion R&D as benefitting hydrogen fuel and/or fuel cell vehicles. The program office evaluated a long list of vehicle technology options based on the assumption of success for the VTP's research by and concluded that the per-vehicle potential for CO2 reduction and petroleum savings is greatest for fuel cell electric vehicles. (Fig. 2-0-1)



European Commission on Energy's Strategic Energy Technology Plan

- The Commission's Smart Cities initiative includes a significant demonstration of fuel cell electric vehicles and fuel cell power generation:

    - **"** – 10-20 t**esting programmes** for the large deployment of alternative fuel vehicles, from road public transport and municipal fleets to private passenger vehicles (electric vehicles, hydrogen and fuel cells, low consumption vehicles, natural gas vehicles, biofuels, etc.) including the fuel/energy supply infrastructure". (p. 50)

DOE Biomass Program Multi-Year Program Plan, 2010

The biomass program notes the work under way to extract hydrogen from biomass and discusses the important of hydrogen in upgrading biomass (p. 2-23 and elsewhere.)

- **"Fuel Cell Technologies Program (FCT):** The production of hydrogen from biomass is pursued through two main pathways – distributed reforming of bio-derived liquids and biomass gasification. Research efforts on reformation and gasification, the availability of biomass, and renewable hydrogen as an enabler for biofuel production are coordinated between FCT and the Biomass Program. In addition, the programs collaborate on using algae to produce biofuels and hydrogen." (p. 1-17)

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    - "joint programming for smart grids, fuel cells and marine energy, preparatory steps to develop a Joint Programme have been undertaken." (p. 54)

Massachusetts Institute of Technology, the Future of Coal: Options for a Carbon-Constrained World, 2007.

MIT notes the central importance of hydrogen in advanced coal combustion and gasification and liquefaction and encourages research in a portfolio of innovative options.
"**ADVANCED CONCEPTS**
A healthy R&D program needs a component that invites competitive proposals for basic research and innovative concepts that could lead to breakthroughs for high efficiency clean, CO2 emission 'free' coal use, or for new sequestration approaches. The transport gasifier and chemical looping, mentioned in Chapter 3, are examples. New system ideas, such as integration of fuel cells with IGCC, is another example. The program should be sufficiently large to allow for evolution of promising research results into pilot scale facilities." (p. 85)

DOE EERE, 20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply, DOE/GO-102008-2567, 2008.

EERE suggests that fuel cell electric vehicles could provide a stimulus for wind power by converting off-peak wind to hydrogen vehicle fuel.

- "Several customer-driven energy trends could have a significant impact on wind development. Much wind generation occurs in hours when energy use is low. Two proposed off-peak electricity uses—the deployment of plug-in hybrid vehicles with off-peak charging and the production of hydrogen to power vehicles—could absorb much of this off-peak, low-cost wind generation. In addition, as more customers gain the ability to practice automated price-responsive demand or to automatically receive and respond to directions to increase or decrease their electricity use, system loads will be able to respond to, or manage, variability from wind and other energy sources." (p. 93)

- "The 20% Wind Scenario would require end users to be able (via price signals and technology) to respond to system needs by shifting or curtailing consumption. Time-shifting of demand would help reduce today's large difference between peak and off-peak loads and encourage more flexible loads (such as plug-in hybrid cars, hydrogen production, and smart appliances) that take energy from the grid during low-load periods. These practices would smooth electricity demand and open a larger market for off-peak wind energy." (p. 101)

DOE, Electric Power Industry Needs for Grid-Scale Storage Applications, 2010

DOE contemplates a role for fuel cells in energy storage as the amount of intermittent energy generation increases.

- "SYSTEM DESIGN, which includes the storage device (e.g., battery, flywheel, regenerative fuel cell, or capacitor), the power conditioning and control systems that allow the system to communicate with the electric grid, and any other ancillary equipment necessary for the device's operation (e.g., auxiliary cooling systems), is also interrelated with the cost and technical performance of an energy storage system. . . . Storage technologies that meet the

economic, technical performance and system design requirements of the intended application are well positioned to achieve widespread adoption in the electric power industry." (p. 15)

The Minerals, Metals, and Materials Society, Vision Report of the Energy Materials Blue Ribbon Panel, 2010

- This Vision Report concludes that materials science and engineering could yield "the greatest potential impact" in battery *and* fuel cell technologies.
    - The Panel's findings are that materials science and engineering (MSE) breakthroughs can be the key enabler for many energy efficiency and carbon reduction solutions. The Panel identified several areas where MSE can have the greatest potential impact:
      • Battery technologies
      • Industrial energy efficiency
      • Vehicle energy efficiency
      • Solar energy
      • Nuclear fission and fusion
      • Fuel cells and hydrogen technologies" (Summary)
    - The Report specifically identifies fuel cells as "a highest priority area." "Hydrogen and fuel cells have been an area of substantial R&D focus to date and are a highest priority area in the long-term. MSE innovations in catalysts and membrane materials, combined with increased infrastructure, could allow hydrogen fuel cells to make a major impact on the long-term state of the U.S. energy sector." (p. 11)

Interlaboratory Working Group, Scenarios for a Clean Energy Future, ORNL/CON-476, 2000

- The Working Group includes as a cross cutting technology in buildings, transportation and combined cycle power generation and suggests it model could be improved by improved modeling of distributed power generation, such as fuel cells in buildings and combined heat and power in industry.

    - "In the longer term, however, the opportunities for a clean energy future depend critically on technologies that do not presently exist in the marketplace or are in early stages of commercial trial. The commercial success of these technologies – which range from technologies that produce energy with low or zero pollutant emissions (renewable, hydrogen, and advanced nuclear power systems) to those that dramatically reduce energy use per activity or output (e.g.100 mile per gallon automobiles and 200 lumen per watt lighting systems) to systems for the

sequestration of carbon – will make the difference between energy futures with high or low economic, social, and environmental impacts" (p.8.1)

- The Working Group also specifically discusses the benefits of fuel cells in transportation, citing fuel cells as "potentially pollution free propulsion."

    - **"Hybrid, Electric, and Fuel Cell Vehicles.** Developing commercially viable, mass-market electric-drive vehicles (EVs) would free the automobile from dependence on carbon-based liquid fuels while simultaneously reducing vehicular emissions. Hybrid electric vehicles (HEVs) combine an electric drive with an auxiliary power unit and energy storage device (e.g., battery). A heat engine could be used as the auxiliary power source, but if fuel cell technology could be sufficiently advanced and the infrastructure for supplying hydrogen fuel developed, a potentially pollution-free propulsion system would be available (depending upon how the hydrogen is produced)." (p. 8.11)

- The Working Group sees fuel cells and hydrogen as a potential pathway for renewable solar power to provide energy for transportation.

    - "In the longer term, PV may also be used to meet the needs of other energy markets. One tantalizing possibility is the light-duty vehicle transportation market (Fig. 8.6). There are several conceivable routes for PV to play a role in this rapidly evolving international market. The most direct possibility is the use of PV either mounted on the surface of a "world car" or stationary applications used to charge the batteries of an electric vehicle. In the long term, PV may also become the major energy source for hydrogen to power fuel cell vehicles. Either electrolysis or some form of direct photoconversion might be used. These concepts are attractive in that they address the long-term issue of petroleum resource availability and because they inherently include storage. They are not hindered by the issue of the intermittent availability of the solar resource." (p.8.15)

DOE, Advanced Materials and Devices for Stationary Electrical Energy Storage, 2010

- DOE indentified fuel cells as a "high priority" technology for energy storage and Identifies regenerative fuel cells as an "emerging technology" and a mid-term priority.

    - "The advancement of large-scale energy storage technologies will require support from the U.S. Department of Energy (DOE), industry, and academia. Figure 1 outlines the high-priority research and development activities that are necessary to overcome the limitations of today's storage technologies and to make

game-changing breakthroughs in these and other technologies that are only now starting to emerge, such as metal-air batteries, liquid-metal systems, regenerative fuel cells, advanced compressed-air energy storage, and superconducting magnetic electrical storage." (p. 1)