Fuel Cell & Hydrogen Energy Association
TRANSFORMING THE ENERGY NETWORK

From: James Warner, Director of Policy, Fuel Cell and Hydrogen Energy Association
To: Dr. Steven Koonin, Under Secretary for Science, U.S. Department of Energy
Re: Quadrennial Technology Review Open Government Disclosure
Date: May 2, 2011

On April 25, I had the pleasure of meeting with Holmes Hummel, Senior Advisor to the Office of Policy and International Affairs.

In that meeting, we discussed the Fuel Cell and Hydrogen Energy Association's (FCHEA) concerns over:

- the omission of fuel cell and hydrogen energy from the Quadrennial Technology Review (QTR) Framing Document;
- the lack of invitations to fuel cell and hydrogen energy companies were for to the alternative fuel QTR workshop;
- Secretary Chu and Under Secretary Koonin's opinion of fuel cell and hydrogen energy technologies, which do not reflect, and do not appear to be informed by, the current state of the industry;
- DOE policy towards fuel cells and hydrogen energy does not reflect the findings of DOE studies and reports on the industry and its own programs, nor does it reflect the successes of these programs;
- the disproportionate cuts proposed to fuel cell and hydrogen energy programs in the DOE's FY 2012 budget;
- the omission of fuel cells and hydrogen energy from the President's Blueprint for a Secure Energy Future.

We also discussed policy priorities and opportunities for the fuel cell and hydrogen energy industry, including:

- inclusion in a Clean Energy Standard;
- inclusion in electric vehicle and electric vehicle infrastructure policy;
- Participation in renewable energy and energy efficiency export initiatives;
- Participation in the Clean Cities program;
- the ability of fuel cells and hydrogen technologies to provide a solution for air quality problems at our nation's ports;
- the ability of fuel cells and hydrogen technologies to provide a solution for excess capacity in regions such as the Bonneville Power District

2010 ANNUAL REPORT of The Hydrogen and Fuel Cell Technical Advisory Committee

Hydrogen and Fuel Cell Commercialization and Technical Development Activity

2010 was a year of significant activity for hydrogen and fuel cell technologies in multiple applications. Fuel cell markets for stationary generation, back-up power, and material handling applications continued to expand by providing added value to customers, and automotive applications progressed as fuel cell vehicle deployment moved from demonstration fleet applications to real-world consumers. Many automakers confirmed 2015 as the target for large-scale deployment, and studies affirmed that hydrogen and fuel cell technologies can offer substantial, cost-effective reductions in greenhouse gases and petroleum consumption as part of a portfolio of technologies to meet our national energy and environmental goals.

Fuel cell system cost, durability, and performance continue to improve and have met or exceeded all of the milestones set by the industry and DOE. Low-carbon and renewable hydrogen production technologies are advancing, and analysis shows that some central and distributed production, distribution, and dispensing pathways can be competitive with gasoline on a per-mile bases at a commercial scale while offering substantial reductions in greenhouse gases and petroleum use. Public investment in research, development, and demonstration has contributed substantially toward the commercial readiness of these technologies, but more is needed to address the remaining challenges as the global competition for clean energy technologies intensifies.

Commercial Deployments in 2010

Sales in the material handling, combined heat and power (CHP), back-up power, and auxiliary power sectors led expansion in the global commercial market for fuel cells in 2010. These early commercial applications provide performance advantages for consumers, build valuable experience and customer awareness, and provide revenue to support the supply chain of fuel cell and hydrogen suppliers. Several of these applications are becoming cost competitive with incumbent technologies; however, government funding continues to be an important driver of sales. Funding from the American Recovery and Reinvestment Act (ARRA) enabled the installation of more than 400 fuel cells in 2010, putting DOE on track to meet its goal of up to 1,000 fuel cell installations with ARRA funds.

Material Handling Equipment

- **Rising sales volumes, reductions in first costs, and a strong track record of operating success are moving fuel cell forklifts toward sustainable long-term markets.** For example, Plug Power reported sales of more than 400 lift trucks in the fourth quarter of 2010 alone without federal government subsidy.[1] ARRA funding supported the placement of over 290 forklifts that gained 149,000 hours of use in commercial operations in the first half of 2010. Participating companies include Sysco, GENCO, Kimberly-Clark, Whole Foods, Wegmans, Coca-Cola, and FedEx. In addition, 75 forklifts in two Defense Logistics Agency (DLA) distribution depots gained 150,000 hours of use.

- **The DLA and ARRA projects logged more than 44,000 refueling events** at 12 forklift refueling facilities with no major safety incidents, dispensing almost 24,000 kilograms (kg) of hydrogen.

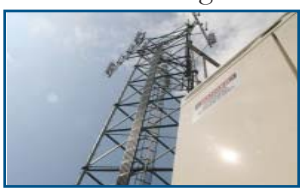
- **User experience with fuel cell forklifts has been positive.** Nissan North America realized productivity savings of 35 hours per day in its Smyrna, Tennesse plant by redirecting staff time previously spent changing and recharging forklift batteries in 60 tugs. Nissan also eliminated more than 70 electric battery chargers that used almost 540,000 kilowatt-hours (kWh) of electricity annually.[2]

Back-up and Remote Power Generation

- **Government grants (ARRA) and federal early adoption increased U.S. fuel cell back-up power installations.** With ARRA funding, U.S. companies like Sprint, AT&T, and PG&E installed more than 50 fuel cell back-up power (BUP) units at U.S. cell tower sites. The U.S. Army base at Fort Jackson, South

[1] Citations and references for the 2010 HTAC Annual Report may be found at http://www.hydrogen.energy.gov/pdfs/2010_htac_report_refs.pdf

Carolina, installed 10 fuel cell BUP systems, reporting zero power interruptions to critical loads during three 2010 grid power outages, and provided hands-on experience to fuel cell technician students from Midlands Technical College.



- **Other major U.S. and international telecommunication providers recognized the benefits of fuel cells for off-grid and remote power support.** In late 2010, T-Mobile placed fuel cell BUP systems at 35 sites in Florida, and Motorola deployed more than 100 in their U.S. network. Many countries are increasingly using fuel cell BUP systems to provide continuous power for off-grid cell towers as well. For example, IdaTech shipped over 350 back-up power systems in 2010, mainly to telecommunications companies in Southeast Asia and Central and South America.

Stationary Power Generation (including CHP)

- **Retail stores, office buildings, and manufacturing facilities are increasingly using fuel cell systems for heat and/or power generation.** Companies such as Whole Foods, Albertson's, Coca-Cola, FedEx, UPS, Adobe, Walmart, Cox Enterprises, Bank of America, Safeway, Cypress Semiconductor, eBay, Google, and Price Chopper use stationary fuel cells to provide reliable prime and back-up power for continuous operation while cutting emissions and lowering operating costs. In 2010, Whole Foods installed a fuel cell for CHP at a third supermarket; the 400 kilowatt (kW) UTC fuel cell has an 80,000 hour guarantee and is expected to deliver power at over 60% efficiency.[3]

- **The demonstration of fuel cells in single- and multi-family buildings is expanding.** In May 2010, Barksdale Air Force Base began using a 300 kW molten carbonate fuel cell system (FuelCell Energy) to provide electricity, heat, and hot water for dormitory residents. In addition, two apartment buildings in the New York region became the first large-scale residential buildings powered by fuel cells in the United States. Each building's fuel cell generates enough power to supply 675 apartments and reduces resident utilities bills by 50% compared to a traditional building. Federal and state grants enabled the developers to pay back the capital costs within five years.

- **Strong government support is increasing the international use of fuel cells for residential power generation.** In Japan, government incentives and the dedication of several manufacturers (Panasonic, Toshiba, and Eneos) to supplying the commercial market have spurred the sale of thousands of residential CHP fuel cell systems. Toyota continues partnering with Aisin Seiki Company to develop solid oxide fuel cells for residential use. In South Korea, a new government program is subsidizing up to 80% of the installed costs of a residential fuel cell, with the goal of installing at least 1,000 systems by 2012. By 2020, the program aims to install more than 100,000 residential fuel cells.[4] In mid-2010, the United Kingdom announced a feed-in tariff for low-carbon residential generation up to 5 kW that will pay British homeowners for every unit of low-carbon power generated or sold to the grid.

- **Many countries are showing interest in hydrogen and fuel cells for baseload power generation and grid support.** POSCO Power of Korea, one of 15 power producers influenced by South Korea's new renewable portfolio standard, has already installed more than one-third of its planned 68 megawatts (MW) of fuel cells at a power plant outside Seoul. In Canada, Enbridge and FuelCell Energy are demonstrating a hybrid fuel cell power plant that will provide energy to about 1,700 Canadian homes. Italy's Enel launched a first-of-its-kind 100% hydrogen-fueled 12 MW combined cycle power plant near Venice that will generate close to 60 million kWh per year from by-product hydrogen provided by nearby petrochemical plants. FirstEnergy and Ballard Power began testing the peak generating capacity and load management of a utility-scale proton exchange membrane (PEM) fuel cell system at FirstEnergy's plant in Eastlake, Ohio that has the potential to provide peak power to more than 600 homes.

Technology and Demonstration Activities in 2010

Automakers, energy companies, and government agencies around the world are converging on 2015 as the target date for full commercial introduction of fuel cell vehicles and hydrogen fueling infrastructure. To prepare for large-scale deployment, automakers are leasing next-generation fuel cell vehicles (FCVs) to regular customers with positive results. Publicly available hydrogen infrastructure is expanding in targeted regions throughout the world in step with vehicle deployment. Studies and demonstration projects are highlighting hydrogen's energy storage potential to support electric grids and integrate variable renewable energy sources.

Hydrogen Infrastructure

- **GM and The Gas Company (TGC) announced plans to build 20-25 retail hydrogen stations on Oahu by 2015.** The plan, known as the Hawaii Hydrogen Initiative (H2I), joins 12 public and private sector stakeholders in an effort to make hydrogen available to Oahu's one million residents and seven million annual visitors before mass production of FCVs. TGC makes enough hydrogen as a by-product in its Oahu-based synthetic natural gas production plant to power 10,000 FCVs and has capacity to produce more, particularly from locally sourced bio-products such as animal fats, vegetable oil, and landfill gas. TGC will distribute hydrogen via its existing 1,200-mile gas pipeline system, tapping into it at key locations and separating the hydrogen for use by local fueling stations. H2I also established other ways to integrate hydrogen infrastructure to enable the state to meet its clean energy objectives.

- **California continues adding fueling infrastructure to keep pace with vehicle rollout.** California has the largest number of FCVs and hydrogen stations nationwide; to date, approximately 300 vehicles have driven over 3.5 million miles in California, filling up at 20 private and 4 public hydrogen stations throughout the state. An additional 16 hydrogen stations were either funded or started construction in 2010 and will be opened to the public in 2011, establishing an early network in targeted clusters across the state. The location and capacity of these new stations will be matched to automakers' vehicle deployment plans, which anticipate thousands of vehicles by 2014 and tens of thousands of vehicles after 2015.[5]

- **SunHydro opened its first hydrogen station in Wallingford, Connecticut, as part of the "East Coast Hydrogen Highway."** Sister companies Proton Energy Systems and SunHydro completed the first of nine planned privately funded renewable hydrogen stations that will be open to the public and will make it possible for a hydrogen fuel cell vehicle to travel from Maine to Miami. The Wallingford station generates hydrogen on-site using a solar-powered electrolyzer.[6]

- **The global hydrogen fueling infrastructure is expanding, with Germany, Japan, and South Korea anticipating over 300 stations combined by 2017.** Germany's public-private Clean Energy Partnership, which includes 13 member companies from Germany, France, the United Kingdom, Norway, Sweden, Japan, and the United States, is adding two new renewable hydrogen stations in Berlin. As of November 2010, the total number of stations in Germany is 27, with as many as 15 more planned in the regions of Berlin, Hamburg, and North Rhine-Westpahlia by 2013. Canada is home to the largest fueling station in the world, a 1,000 kg/day station in Whistler, British Columbia, built for the fleet of 20 fuel cell buses launched during the 2010 Winter Olympics. Japan's Hydrogen and Fuel Cell Project currently operates 14 hydrogen stations and one hydrogen liquefaction facility, with Japanese car and energy companies planning for as many as 100 fueling stations in four Japanese cities by 2015. South Korea continues efforts to develop its own Hydrogen Highway, with six stations in operation and four additional stations planned.

- **Next-generation refueling components and systems are moving to market.** Developers are making progress in reducing the capital, operating, and maintenance costs associated with hydrogen compression. Linde North America introduced a novel "Ionic Compressor" system that uses an ionic liquid in direct contact with hydrogen to replace relatively high-maintenance, inefficient mechanical piston systems. Air Products offers compression-less hydrogen fueling with its new "composite pressure vessel" trailer, which is connected directly to the fuel dispensing unit.

Fuel Cell Cars

- **DOE's Technology Validation program continues to provide valuable data on early-generation fuel cell and hydrogen infrastructure performance and operating experience.** Started in 2004, the cost-shared industry-government program includes 152 fuel cell vehicles that have accumulated 114,000 hours and 2.8 million miles of real-world driving, demonstrating ranges over 400 miles between fill-ups and fuel cell efficiencies of up to 59%. The program's 24 fueling stations have produced and/or dispensed over 134,000 kg of hydrogen.

- **Other U.S. government agencies continue to sponsor hydrogen vehicle demonstrations.** For example, DoD's Army Tank Automotive Research, Development, and Engineering Center operated 11 hydrogen FCVs and 10 hydrogen internal combustion engine (ICE) vehicles at four locations in 2010, reporting a very high rate of customer satisfaction.

- **Next-generation FCVs are hitting the road, building on technology advances and lessons learned from earlier generations.** While early-generation technology showed better-than-expected results, next-generation FCV technology will be substantially improved. For example, Ford's fleet of 30 FCVs, launched in 2005, has reached a combined total 1.3 million miles driven, well beyond the anticipated life span for these early-generation vehicles. Third-party testing of Toyota's latest-generation fuel cell sport utility vehicle, the Highlander FCHV-adv, validated a driving range of 431 miles on a single tank of compressed hydrogen gas, an average fuel economy of 68.3 miles per gallon of gasoline equivalent, and cold-start capability down to -30°C. General Motors' next-generation fuel cell electric vehicle (FCEV) is expected to have a fuel cell system that is 50% smaller, 220 pounds lighter, and uses less than half the precious metal of the current Equinox FCEV.

- **Automakers are converging on 2015 for high-volume production of FCVs.** In a move that builds on previous statements from seven of the world's leading automakers, 13 Japanese companies (3 automakers and 10 energy companies) formed a partnership to expand the introduction of hydrogen FCVs in 2015 and develop a supporting hydrogen station network. The companies plan to build at least 100 filling stations by 2015, centered around four major Japanese cities. The Japanese Ministry of Economy, Trade, and Industry has pledged to support the development of hydrogen infrastructure ahead of the start of FCVdeployment.[7] Additional relevant announcements include the following:
  - Toyota plans to introduce a fuel cell sedan in 2015, priced to sell at $50,000.
  - Hyundai could introduce FCVs as early as 2012 (500 vehicles), increasing production to 10,000 per year in 2015 at a cost below $50,000.
  - General Motors introduced its "production intent" FCEV system and restated its plan to introduce a commercial vehicle by 2015.
  - Daimler began small-series production of its Mercedes-Benz B-Class F-Cell vehicle and plans to increase production to tens of thousands of vehicles by 2015–2017.

Fuel Cell Buses

- **U.S. fuel cell bus (FCB) demonstration projects continue to show strong performance.** In August 2010, AC Transit and UTC Power announced some significant milestones for its three-bus demonstration fleet in California, which has carried more than 695,000 passengers. The latest-generation UTC fuel cell system in one bus passed 7,000 operating hours with its original fuel cell stacks and no cell replacements. Compared to the control fleet of diesel buses, the FCBs also achieved 60% better fuel economy, reduced maintenance by 80%, and reduced greenhouse gas emissions (GHG) by 43% (using hydrogen produced from natural gas).

- **Federal demonstrations are collecting systematic data on FCB performance.** The National Renewable Energy Laboratory (NREL) has collected data for DOE and the U.S. Department of Transportation on nine FCBs in service at sites in California, New York, Massachusetts, Connecticut, South Carolina, and Texas. Since 2006, the buses have been driven more than 395,000 miles, consumed more than 80,000 kg of hydrogen, and demonstrated a fuel economy that is at least 53% higher than diesel or compressed natural gas buses.[8]

- **Hydrogen bus programs around the world are expanding.** The European Commission completed the CUTE project, which included 33 hydrogen fuel cell and 14 hydrogen ICE buses that operated in 10 cities on three continents, transporting more than 8.5 million passengers and traveling more than 2.5 million kilometers. A new project under the European Fuel Cell and Hydrogen Joint Technology Initiative, known as the "Clean Energy for European Cities" project, will deploy up to 28 hydrogen fuel cell buses in 5 major European regions. High-profile events showcasing full-size FCBs included the 2010 World Expo in Shanghai, China and the 2010 Winter Olympics in Vancouver, for which British Columbia, Canada, launched the largest fleet of FCBs to date (20 full-size buses).[9]

Energy Storage

- **A recent NREL study concludes that hydrogen may be suitable for utility-scale energy storage.** The analysis compared hydrogen and competing technologies for utility-scale energy storage systems and explored the cost and GHG emissions impacts of interaction on hydrogen storage and variable renewable resources. The study concluded that hydrogen energy storage is competitive with batteries and could be competitive with compressed air energy storage and pumped hydro in certain locations.

- **Projects are exploring the use of hydrogen for energy storage.**
  - The Naval Air Warfare Center, China Lake, California, is developing a field deployable Regenerative Fuel Cell system that will use a photovoltaic system to create hydrogen via high-pressure electrolysis combined with a PEM fuel cell to power the system load during dark periods.
  - To reduce overall system cost and increase system efficiency, AREVA developed their new "GreenBox" technology, which combines their electrolyzer and PEM technologies into an integrated storage system.
  - In Canada, a partnership between the federal government, BC Hydro, Powertech, and General Electric in Bella Coola, British Columbia, is converting excess off-peak electricity and storing it as hydrogen via an electrolyzer, and reducing diesel consumption by an estimated 200,000 liters per year and GHG emissions by an estimated 600 tons per year.
  - The "Ikebana" pilot project in Russia is using hydrogen for energy storage. It aims to improve power generation efficiency with a variety of power sources, including renewable energy.
  - Germany's Enertrag AG, one of the world's largest wind power companies, is building Germany's first hybrid power plant, which uses excess wind energy to produce hydrogen for energy storage and for transport applications. The 6.7 MW plant will have a hydrogen storage capacity of 1,350 kg. Also in Germany, the RH2-WKA project in Mecklenburg-Western Pomerania is developing a hydrogen storage system in conjunction with its 180 MW wind park to balance fluctuating wind energy.

Research and Analysis in 2010

Basic and applied research is making progress toward resolving remaining cost and performance barriers for fuel cells. Expanded analysis confirms the need for a portfolio of technologies that can meet medium- and long-term energy and environmental goals.

Technical and Economic Analysis

Several new studies published in 2010 assessed the potential costs and benefits of various alternative fuel technologies, including their contributions to reducing oil imports and GHG emissions. The reports include the following:

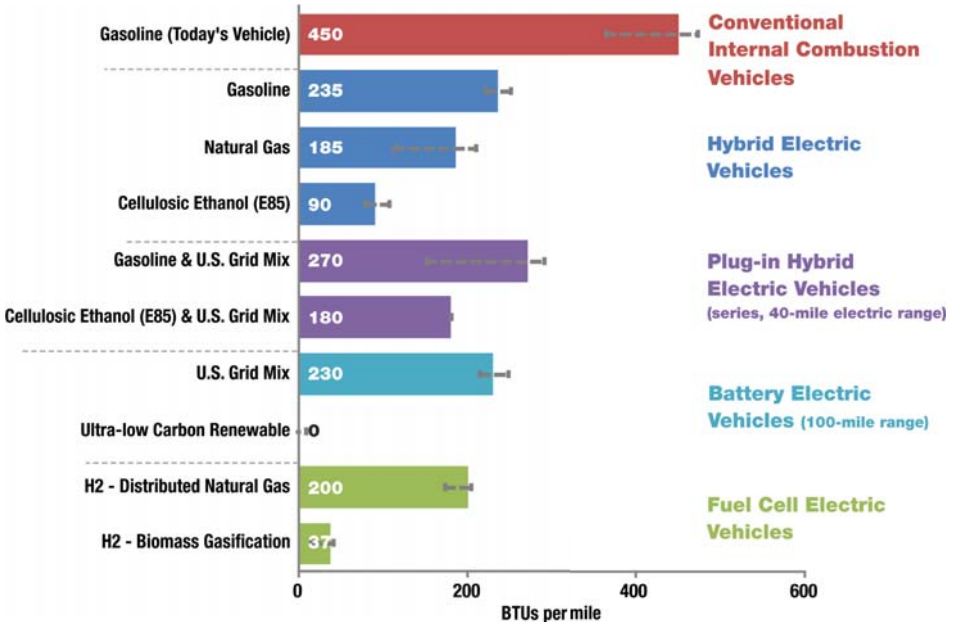
- **A 2010 study published by McKinsey & Company** finds that the costs of ownership of several vehicle power trains are likely to converge in the next 10 to 20 years, and that costs for electrical and hydrogen infrastructures are comparable and affordable. The report, which gathered over 10,000 proprietary data points from more than 30 industry stakeholders, suggested an evolution from today's ICEs toward a portfolio of technologies, in which battery electric vehicles (BEVs) are specifically attractive in the small-car segments and urban mobility patterns, and hydrogen FCVs are "the best low-carbon substitute" in the medium- and large-car segments, which account for 50% of all cars and 75% of carbon dioxide emissions.[10]

- **The third biannual National Research Council review of the FreedomCAR and Fuel Partnership** included two key findings: (1) improved ICEs with biofuels, plug-in hybrid electric vehicles, and BEVs, and hydrogen FCVs are the primary alternative pathways for substantially reducing petroleum consumption and greenhouse gas emissions; and (2) the hydrogen fuel cells research program is an effective public research effort, and government-industry collaboration should continue.[11]

- **A new report by Fuel Cells 2000** profiles fuel cell use by many well-known companies, including warehouses, stores, office and manufacturing facilities, hotels, data centers, and telecommunications sites. Collectively, these companies ordered, installed, or deployed more than 1,000 fuel cell forklifts, 58 stationary fuel cell systems (15 MW total), and more than 600 fuel cell units at telecommunications sites.[12]

- **An updated well-to-wheels analysis** of the GHG performance for various vehicle/fuel combinations shows that fuel cell vehicles operating on hydrogen from natural gas or biomass are among the lowest emitters of GHGs per mile (see chart next page).[13]

Well-to-Wheels Greenhouse Gas Emissions of Alternative Transportation Options (grams of GHG/mile)



Source: Well-to-Wheels Greenhouse Gas Emissions and Petroleum Use for Mid-Size Light-Duty Vehicles, U.S. Department of Energy, Offices of Vehicle Technologies and Fuel Cell Technologies, October 25, 2010, http://hydrogen.energy.gov/pdfs/10001_well_to_wheels_gge_petroleum_use.pdf.

Fuel Cell Technologies

- **Projected high-volume transportation fuel cell system costs, using today's best available technology, declined to $51/kW.** The DOE fiscal year 2010 modeled cost assessment, projected for a manufacturing volume of 500,000 80–kW automotive fuel cell systems per year using today's best technology (including balance of plant), represents a 30% reduction in cost since 2008 and an 80% reduction in cost since 2002.[14] These reductions are largely due to R&D efforts that enabled reduced platinum group metal content (down from 0.35 to 0.18 grams [g]/kW), increased power density (up from 715 to 813 mW/cm^2), and simplified balance of plant. At the current level of platinum (0.18 g/kW), the cost of platinum for a medium-sized fuel cell car would be $510, compared to a cost of $140 to $175 for platinum used in the catalytic converter of an equivalent gasoline-powered car.*

- **The DOE fuel cell R&D portfolio continues to show progress.** Significant R&D progress lowered fuel cell costs and improved durability and performance by, for example, using catalysts with low or no platinum (Pt), increasing power density, improving water management, reducing impacts of contaminants, and simplifying and lowering the cost of the balance of plant. Some research highlights include the following:

  - Brookhaven National Laboratory, Los Alamos National Laboratory, Argonne National Laboratory, and 3M each developed innovative low or no Pt catalysts with ex-situ activity levels that exceed DOE targets, and scale-up efforts are underway.

  - Case Western Reserve University and 3M developed membranes for PEM fuel cells that achieve high conductivity at higher temperatures (above 100°C), which could reduce cost and increase power yield.

  - 3M's new nanostructured thin-film (NSTF) catalyst was incorporated into membrane electrode assemblies (MEAs) in short stacks (>20 cells) that demonstrated total platinum group metal (PGM) content of less than 0.2 g PGM/kW, successful 10°C cold- and -20°C freeze-starts, and lifetimes of 2,000 hours under various automotive drive cycles. New NSTF-based MEAs with catalyst loadings of 0.15 mg total PGM/cm^2 also demonstrated 6,500 hours of operation under automotive load cycling.

  - A new process for making nanofiber composite membranes was developed and demonstrated by Vanderbilt University. The process may significantly increase the durability of polymer-based membranes without compromising performance.

- **The Solid State Energy Conversion Alliance (SECA), supported by DOE's Office of Fossil Energy, realized considerable advances in large-scale solid oxide fuel cell (SOFC) technology.** SOFC stack scale-up efforts resulted in greater than 25 kW stacks based on large active area (greater than

* Calculations assume an 80 kW fuel cell system and a platinum cost of $1,100 per troy ounce, which is the value used in DOE's fuel cell cost analysis. A range of 4–5 grams was assumed for the amount of platinum in the catalytic converter of a comparable ICE vehicle.

Challenges to Commercialization

Although hydrogen and fuel cell technologies are now being offered in early commercial markets, their widespread adoption faces key challenges:

- Some hydrogen and fuel cell technologies must continue to improve performance and reduce cost to be competitive with the capabilities and cost of incumbent technologies.
- Although safe, lightweight, low-volume hydrogen storage systems are available now, their cost remains an issue.
- The public has little awareness of hydrogen and fuel cell systems, and a misconception that hydrogen is unsafe and unreliable still prevails.
- It is critical that R&D reduce the cost of producing and delivering clean hydrogen to end users. Coupled with this is the need to improve emissions-free methods of hydrogen production.
- Current regulations and standards do not reflect real-world use of hydrogen and fuel cell technologies and need to be synchronized among countries.

400 cm^2) planar cells. Laboratory testing validated the achievement of SECA's 2010 cost goal: $700/kW for the system power block and $175/kW for the SOFC stacks based upon mass production (2007 dollars). Laboratory-scale testing also demonstrated degradation rates of less than 1%/1,000 hours in intermediate-duration testing.

Hydrogen Production, Distribution, and Storage

- **Researchers addressed ways to reduce capital costs and improve the overall efficiency and performance of distributed and centralized low-carbon and renewable hydrogen production and delivery.** For some pathways (e.g., distributed natural gas reforming and biomass gasification), estimated high-volume costs for delivered hydrogen are already at or near the newly established DOE target of $2.00–$4.00 per gallon of gasoline equivalent (gge). For other pathways, continued R&D is needed to bring costs down.
- **DOE's Fuel Cell Technology Program reassessed the cost threshold at which hydrogen is projected to become competitive with gasoline in hybrid electric vehicles (HEVs) in 2020 to be between $2.00–$4.00/gge (formerly $2.00–$3.00/gge).** The reassessment accounts for changes in technology options, feedstock costs, and gasoline prices, and this year also includes an incremental cost of ownership for FCVs over gasoline HEVs of zero to four cents per mile over the vehicle's life.[15] The new threshold, developed with input and review from stakeholders including Hydrogen and Fuel Cell Technical Advisory Committee members, industry, international stakeholders, and laboratory experts, will help prioritize hydrogen technology R&D needs.
- **The projected cost of several key hydrogen delivery modes dropped considerably between 2005 and 2010,** including a 30% reduction in tube trailer delivery costs, a 20% reduction in pipeline delivery costs, and a 15% reduction in liquid hydrogen delivery costs. These modeled cost reductions are made possible by various technical advances, such as new materials for tube trailers and pipelines, liquefaction process improvements, and improved compressor technology.[16]
- **Several projects reduced the cost of hydrogen from renewable sources.** For example, research at Proton Energy reduced catalyst loading by 55% and optimized a flow field design to reduce electrolyzer cell costs by over 20%. United Technologies Research Center demonstrated the use of an inexpensive base-metal catalyst in converting woody biomass to hydrogen. Efficiency improvements can also lead to cost savings. For example, Lawrence Berkeley National Laboratory improved photosynthetic solar-to-chemical energy conversion from 3% to 25% for photobiological hydrogen production by maximizing chlorophyll's ability to absorb light. Stanford University demonstrated novel nanoparticle catalysts to optimize photoelectrochemical water splitting for producing hydrogen from sunlight.[17]
- **On July 22, 2010, DOE created a new "Energy Innovation Hub" that will develop revolutionary methods to generate fuels directly from sunlight.** The new Joint Center for Artificial Photosynthesis, led by the California Institute of Technology, will receive up to $122 million over five years to demonstrate a scalable and cost-effective solar fuels generator that mimics the photosynthetic system "to produce fuel from the sun 10 times more efficiently than typical current crops." One of the intermediate products in the process is hydrogen from direct separation of water, which could become a source of renewable hydrogen.

Regulations, Codes, and Standards

A diverse array of codes and standards are required to integrate hydrogen and fuel cells into buildings, vehicles, electronics, and other equipment. Many organizations are engaged in critical efforts worldwide to develop consistent, harmonized codes and standards to facilitate commercialization and international trade. Great progress has been made in the last five years, in part due to DOE's involvement in (1) conducting research needed to inform science-based codes and standards; (2) coordinating and prioritizing the efforts of the various organizations and agencies involved in codes and standards development; and (3) informing code officials, emergency personnel, and others responsible for implementing codes and ensuring public safety. Key accomplishments in 2010 include the following:

- **DOE research informed codes and standards development.** The National Fire Protection Association published the 2010 code for compressed gases and cryogenic fluid based on Sandia National Laboratory's hydrogen release behavior data and updated separation distances for bulk hydrogen storage using a quantitative risk assessment approach. DOE researchers also tested forklift tank materials to enable design qualification.

- **R&D enabled the development of harmonized domestic and international fuel quality specifications,** including standardized sampling and analytical methodologies that were developed with ASTM International.

- **DOE-sponsored training reached hundreds of code officials.** The DOE Hydrogen Program supported permitting workshops that reached more than 300 code officials and published several online courses. DOE supported the development of an advanced, prop-based course for first responders that was delivered to almost 400 trainees from 18 states. The web-based Introduction to Hydrogen Safety for First Responders course averaged 300-500 unique visits per month in 2010, for a total of 17,000 visits since January 2007.

Financial Climate in 2010

Although financial markets strengthened in 2010, the climate for the financing of hydrogen and fuel cell companies, both private and public, remains weak. Analysts and investors continue to view companies in the hydrogen and fuel cells market with considerable caution, given the relatively slow pace of market development and the long path to profitability. However, there have been some encouraging developments—several small private and public companies raised needed capital, while only a few were unsuccessful and had to close facilities or shut down entirely. The continued success of commercial applications such as forklifts, distributed generation, and back-up power, and automotive companies' recently announced plans for large-scale vehicle deployment in 2015, have helped rekindle a degree of interest from the financial community that has not been seen in recent years.

As hydrogen and fuel cell technologies progress, worldwide momentum is building toward their commercialization in stationary, distributed generation, material handling, and automotive markets. Fuel cell forklifts, CHP systems, back-up power units, and fuel cell cars and buses are creating positive value for users today in early commercial and pre-commercial markets. Globally, as consumers and governments increasingly emphasize the need to diversify the transportation and power sectors with clean, low-carbon energy carriers, the value proposition for hydrogen and fuel cells will grow and the pace of commercialization will accelerate. United States researchers, technology developers, and government funding agencies have made important contributions to the current state of hydrogen and fuel cell technology. With continued commitment in the United States, we can overcome the remaining challenges and reap the full economic and environmental benefits of these promising technologies. Without such commitment, we risk being left behind as other nations bring these technologies to market.

The Hydrogen and Fuel Cell Technical Advisory Committee (HTAC) was established under Section 807 of the Energy Policy Act of 2005 to provide technical and programmatic advice to the Energy Secretary on DOE's hydrogen research, development, and demonstration efforts.
http://www.hydrogen.energy.gov/advisory_htac.html

Hydrogen is a Competitive Alternative Fuel, Today!

Docket 10-ALT-1

Air Products is pleased to submit written comments to the 07 March 2011 Advisory Committee Meeting.

Significant technology breakthroughs have advanced the infrastructure deployment forward to make the dispensing of hydrogen cost competitive to existing transportation fuels. Earlier programs sponsored by federal, state and local agencies have provided hydrogen infrastructure developers with the opportunity to gain valuable experience regarding the supply chain associated with the production, distribution, and dispensing of hydrogen for the developing fuel cell electric vehicle (FCEV) market. California has been a key location for this activity, as many auto manufacturers have chosen the state as the site for their U.S. alternative vehicle research/development/demonstration facilities. The auto manufacturers have indicated plans to deploy thousands of FCEVs in 2015, and tens of thousands more through 2017. In addition, system capacity of hydrogen production exists which would serve the fueling needs of over 100,000 vehicles in CA. Given California's efforts to improve local and regional air quality (by reducing emissions of criteria pollutants) and to reduce greenhouse gas emissions in the transportation sector (for example, the Low Carbon Fuel Standard), fuel cell vehicles provide an important pathway to achieve these objectives. Although activities in Europe are focusing on development and deployment of hydrogen infrastructure, the infrastructure requirements to serve the marketplace for refueling and the transportation needs of consumers in California (and the U.S.) will likely need a different approach and result in a different solution.

Since 1995, Air Products has been a key supplier of hydrogen and fueling technology infrastructure to over 130 fueling station projects for light duty vehicles, material handling applications, mass transit and for other markets in 19 countries. The current fueling rate for a variety of vehicles and stationary systems is in excess of 325,000 events per year. Based upon this experience, Air Products has developed advanced fueling station technology for light duty vehicles that meets the following objectives:

- Utilize improved delivery technologies to reduce the cost of transporting low-priced hydrogen from central facilities with high product availability.
- Develop station concepts that are simple, modular, expandable to full-sized station capacities, and reduce capital costs at the point of use.
- Reduced overall site maintenance costs.
- Minimize station footprint to use existing retail gasoline forecourt locations, which significantly lowers the initial cost of infrastructure.
- Utilize renewable resources most efficiently to meet the requirements of CA SB 1505.
- Meet U.S. Department of Energy commercial price targets that are competitive with gasoline <u>today</u>, as well as for hydrogen applications in other emerging fuel cell markets with smaller station capacity than other station configurations.
- More closely match the projected rollout of fuel cell vehicles to serve the market as it grows, as opposed to the installation of large stations that will be underutilized for longer periods of time (which would further suppress a business case for hydrogen fueling).
- Provide a model for national fueling infrastructure, which piggybacks on existing production capabilities. And would provide for energy independence as hydrogen can be produced from domestic sources.

For a delivered hydrogen product and fueling of FCEVs, the current supply chain (shown in Figure 1) includes the steps of (1) production/purification, (2) preparation for transport, (3) distribution, (4) site storage, (5) preparation for fueling, and (6) dispensing.

Figure 1 – Current Supply Chain for Delivered Hydrogen to Refueling Stations

As a more detailed depiction of steps 4 through 6 in Figure 1, Figure 2 below shows a conventional fueling station for light-duty vehicles requiring hydrogen at 35 MPa (H35) and 70 MPa (H70). Compression is required for delivery of hydrogen at either pressure (whether from a single compressor or two separate machines as illustrated here), which means station availability is strongly impacted by downtime associated with onsite processing. These types of stations cost between $2 million (for stations integrated with an existing application) and $5 million (for a Greenfield hydrogen fueling station). Onsite generation of hydrogen at the point of use would also add to station costs when compared with delivered product.

Data from hydrogen refueling station operating history worldwide shows that the most downtime and maintenance at fueling stations is attributed to onsite processing systems and specifically those including compressors. Unlike gasoline stations where low pressure fuel pumps are a low-cost and highly reliable means of providing fuel, addition of redundant systems would only increase capital costs and station footprints from today's levels. Station throughput is set by processing capacity, so expansion would require additional compressors, for example, at the fueling station. In order to improve viability of hydrogen refueling stations, this bottleneck can be overcome with a fueling station that is simpler and more robust.

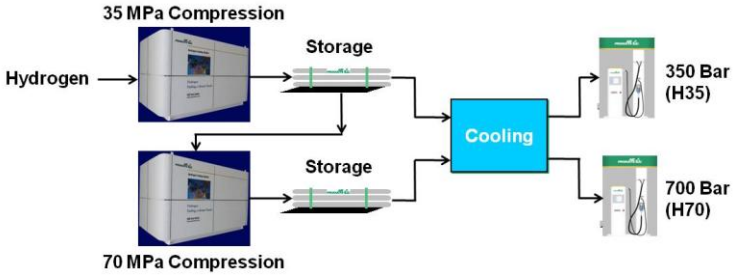


Figure 2 – Conventional Light-Duty Hydrogen Station (delivered product)

The new station concept being deployed by Air Products will merge the several steps from Figure 1 into a single operation with a unique cost effective offering by operating from a central production location. Figure 3 depicts the simplification of the supply chain for the proposed station concept. Instead of each station having its own processing system onsite and (in the case of liquid hydrogen) site storage, a single system can be located at a distribution hub. Therefore, the equipment at the hub, which would include all processing equipment, can be sized for larger throughput and utilized for a greater percentage of the time, and its capital cost and product output can be allocated to a number of sites instead of dedicated to a particular station, each of which results in significantly lower cost to each fueling outlet.

Figure 3 – Proposed Low-Cost Supply Chain for Delivered Hydrogen to Refueling Stations (Patents/Patents Pending)

A key to the enabling technology for this step-change in delivery/station design is the use of proprietary high-pressure gaseous delivery trailers. Air Products has worked under an exclusive contractual funding arrangement with Structural Composites, Inc. (SCI) (Pomona, CA) in the development and testing of composite vessels that achieve higher operating pressures at a significantly lower weight than steel tubes. Three delivery trailers using this vessel technology have already been deployed for use in the marketplace with patents and pending patents filed related to this technology area.
As shown in Figure 4, utilizing this trailer in a light-duty fueling station eliminates the need for onsite processing systems for H35 fueling, providing a significantly higher reliability for fuel supply than hydrogen fueling systems deployed to date. The H70 equipment can be bolted on as needed for the particular application. This innovative fueling station configuration can cost around $1 million as opposed to the $2 million or more for conventional hydrogen refueling stations, requires 30 to 50% less area than stations using liquid hydrogen as feedstock, and significantly reduces the setback distances from property lines compared to most existing stations.

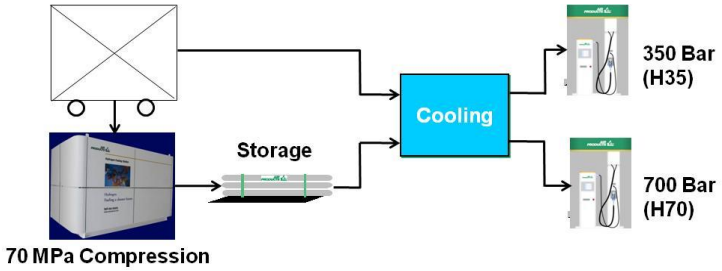


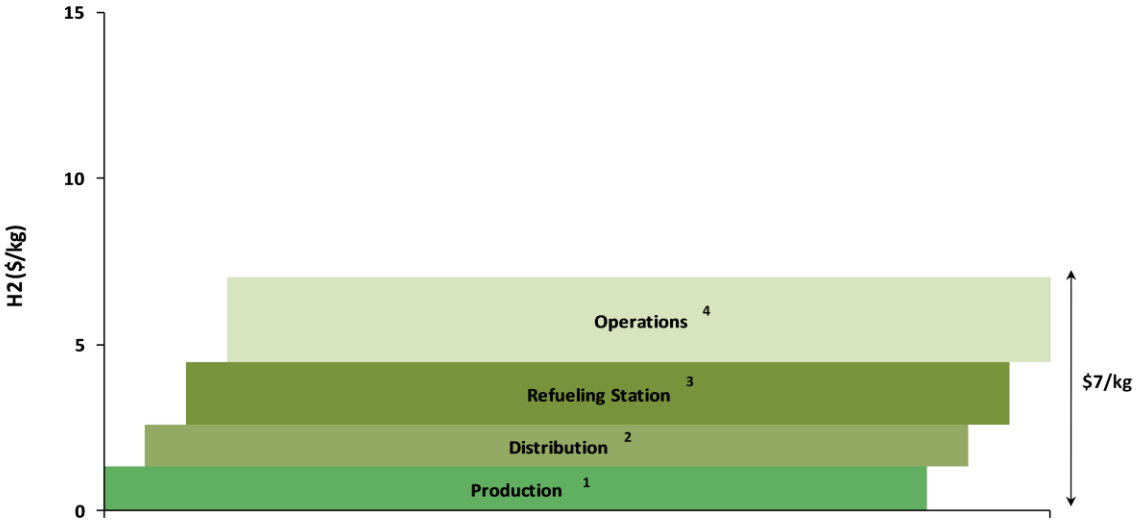
Figure 4 – Proposed H35/H70 Light-Duty Hydrogen Station (delivered product)

Capacity at the station is determined by a combination of station footprint (which might limit the size of the trailer) and number of deliveries per unit time. As volumes build at the station, an additional dispenser and associated equipment can be added by a station owner based on the economics of added vehicle traffic (both for fuel and other products/services) through the station. The high-pressure gaseous delivery trailers can be filled either from a central production plant or from a mobile two-phase liquid hydrogen trailer that can supply compressed gas (currently six of these systems are deployed worldwide) in the same fashion that gasoline is delivered today. Duplicating the gasoline model of deliver, store and dispense is the most reliable and lowest cost pathway for hydrogen as it takes advantage of existing station forecourt and existing hydrogen production capability. This model provides the least capital risk to “seed” an early market. Other models which employ larger stations may provide better capital utilization in a fully developed market but at multiples of capital investment to “seed” the market and are beholden to orders of magnitude higher hydrogen demand to reach breakeven.

Under the funding support provided by the Energy Commission during the 2010 solicitation for hydrogen fueling infrastructure (PON-09-608), Air Products will be deploying eight stations (six new

retail locations/two retrofit stations) which will result in hydrogen pricing for early market users of fuel cell vehicles at less than $10 per kilogram based on anticipated demand.

Our analysis indicates that these types of stations can become self-sufficient financially at throughputs as low as 200 kilograms per day. The consumer price decreases as station capacities increase up to 400 kg/day. Further cost reductions are possible with continued technology advancements in storage, compression and distributed production, and also with expected market economies of scale. There are significant opportunities to lower the dispensed fueling costs for hydrogen because hydrogen as a transportation fuel is less mature than traditional petroleum based fuels. A price today with proper demand loading would be approximately $7.00/kg. A cost breakdown based on the latest technology is provided in Figure 5.



1- NREL, Ruth et al 2009. Central SMR production
2- US DOE 10/2010. Infrastructure (Station with Tube Trailer Delivery)
3- APCI 2011 (Hydrogen refueling station under CEC 2010 program)
4- $250k/yr: Based on UCD 2011 Hydrogen Station Analysis plus CA Excise Tax

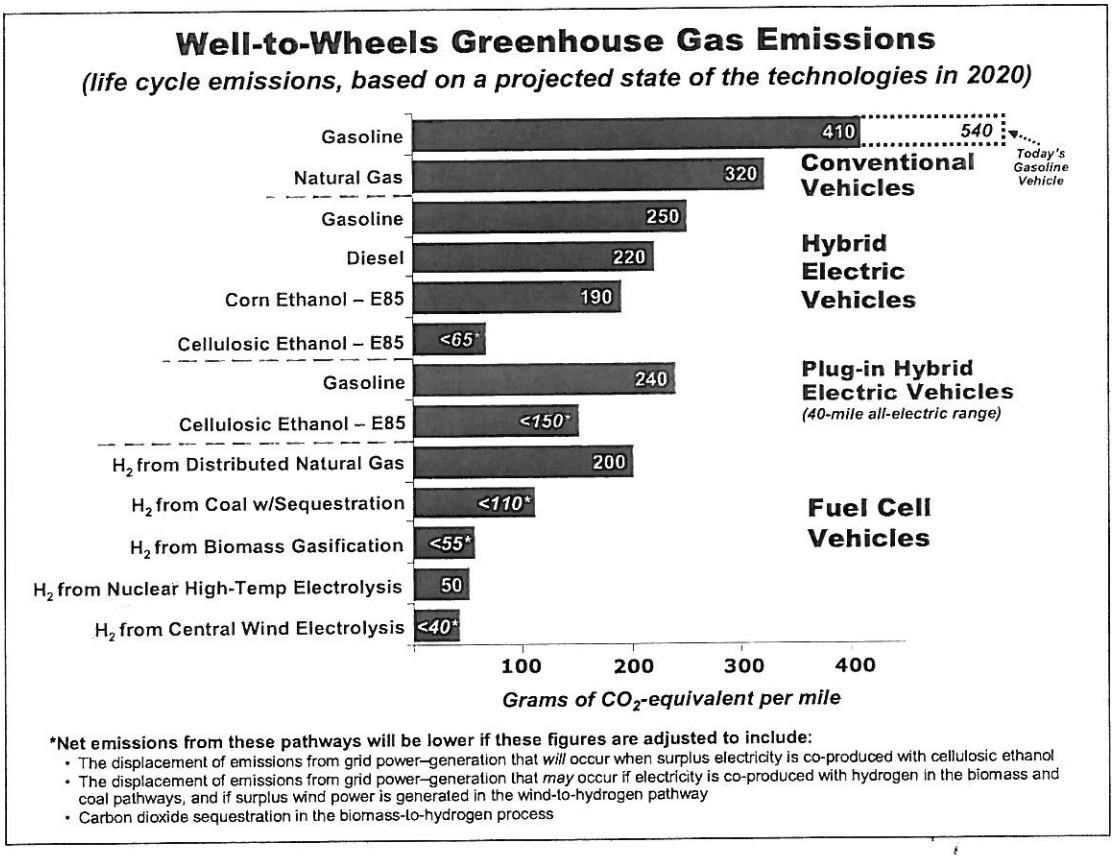
Figure 5 – Cost Breakdown for Light-Duty Hydrogen Station (delivered product)

Air Products believes the $40 million funding level in the first CEC Investment Plan released in April 2009 would be sufficient capital to provide for a self-sustaining infrastructure for these small station configurations in southern California. A total of $13.3 million has already been targeted for southern California, and an additional $10.2 million has been allocated for 2011. If another allocation of $16.5 million were made over the next two years, it would allow for 20 more fueling stations using Air Products' latest technology to be installed. We believe at that point with the developing hydrogen fueling station infrastructure in southern California that private investment would consider taking a more active investment role. Air Products would be willing to work with the Commission and the key stakeholders on an optimum hydrogen infrastructure rollout strategy using an analysis tool such as the STREET software being developed at UC Irvine to assist with station site selection. Air Products believes with continued and targeted funding through the AB118 program that hydrogen fueling can be made readily available at the lowest possible cost to stakeholders, can confirm the value proposition for fuel cell vehicles to meet customer requirements for transportation, and provide a domestically available fuel that can move the transportation sector toward significant reductions in greenhouse gas emissions.

DOE Hydrogen Program Record	
Record #: 9002	**Date:** March 25, 2009
Title: Well-to-Wheels Greenhouse Gas Emissions and Petroleum Use	
Originator: Fred Joseck	
Approved by: Sunita Satyapal	**Date:** March 25, 2009

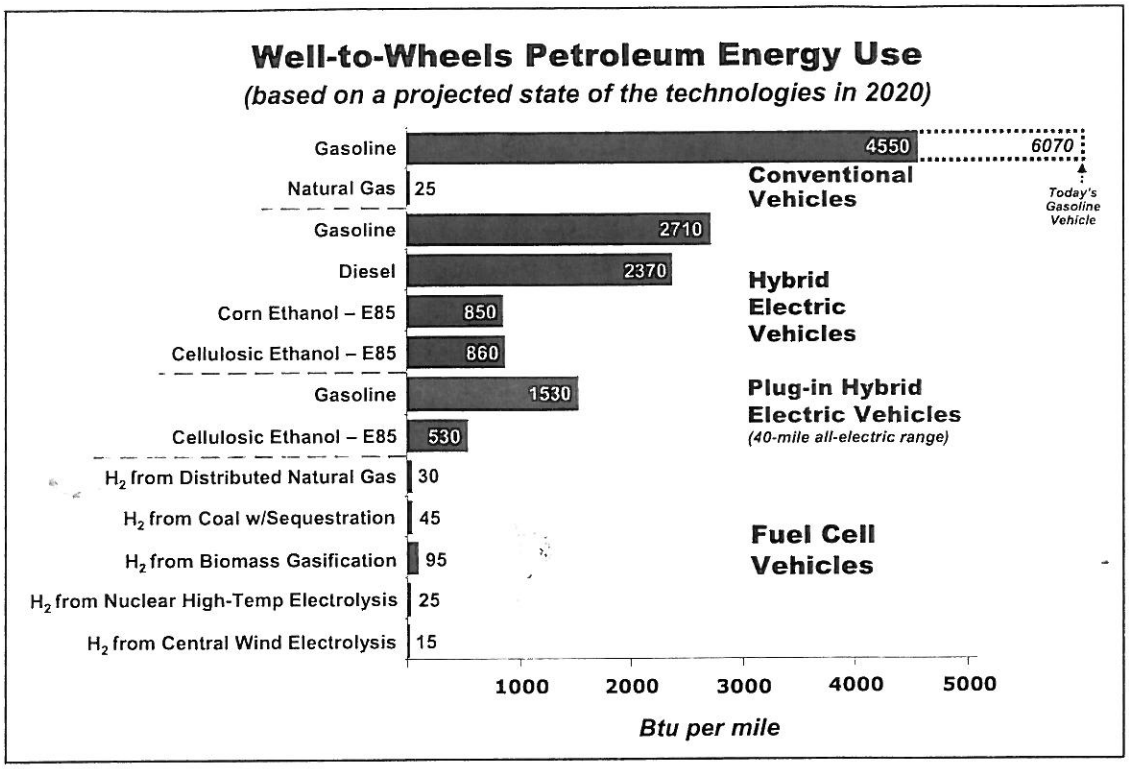
Items:

DOE is pursuing a portfolio of technologies with the potential to significantly reduce greenhouse gas (GHG) emissions and petroleum consumption. This record documents the assumptions and results of analyses conducted to estimate the emissions and petroleum energy use resulting from several fuel/vehicle pathways.



*Net emissions from these pathways will be lower if these figures are adjusted to include:

- The displacement of emissions from grid power–generation that *will* occur when surplus electricity is co-produced with cellulosic ethanol
- The displacement of emissions from grid power–generation that *may* occur if electricity is co-produced with hydrogen in the biomass and coal pathways, and if surplus wind power is generated in the wind-to-hydrogen pathway
- Carbon dioxide sequestration in the biomass-to-hydrogen process



Data, Assumptions, References:

- Results for all pathways are based a projected state of the technologies in 2020, and they incorporate fuel economy improvements based on new corporate average fuel economy (CAFE) standards adopted in the Energy Independence and Security Act of 2007 (EISA 2007).
- Results for all pathways represent a weighted average of petroleum use and emissions by light trucks and cars, based on a projection by the Energy Information Administration (EIA) of new-vehicle sales in 2020, which shows a proportion of 51% light trucks and 49% cars. For the specific projected values, see the following spreadsheet from the EIA's *Annual Energy Outlook 2008*: www.eia.doe.gov/oiaf/archive/aeo08/supplement/sup_tran.xls (lines 1014 and 1040).
- Estimated fuel economies for all fuel/vehicle pathways are based on a combination of urban and highway fuel economies, with 55% urban driving and 45% highway driving.
- Argonne National Laboratory's (ANL's) Greenhouse gases, Regulated Emissions and Energy use in Transportation (GREET) model (version 1.8b, September 2008) was used to determine all the well-to-wheels (WTW) greenhouse gas (GHG) and petroleum energy use estimates shown in the table below. For more information on the GREET model, see: www.transportation.anl.gov/modeling_simulation/GREET/index.html.
- Key input parameters for hydrogen production simulations were developed by the National Renewable Energy Laboratory using the H2A hydrogen production and delivery models (version 2.01). For more information on the H2A models, see: www.hydrogen.energy.gov/h2a_analysis.html.
- The Hydrogen Macro-System Model (MSM) version 1.0 – build 1061 (developed by the National Renewable Energy Laboratory and Sandia National Laboratories) was used to

guarantee consistency of assumptions between the H2A models and GREET. For more information on the MSM, see: www.hydrogen.energy.gov/pdfs/review08/an_4_ruth.pdf

- Fuel economies for all fuel/vehicle pathways were determined using ANL's Powertrain Systems Analysis Toolkit (PSAT Model) V6.2 SP1, summer 2008. For more information on the PSAT Model, see: www.transportation.anl.gov/modeling_simulation/PSAT/index.html.
- Fuel economy estimates for fuel cell vehicles are based on the gallon gasoline equivalent (gge) of hydrogen, which is 1.02 kg of hydrogen (with an energy content of 116,000 Btu on a lower heating value [LHV] basis).
- Hydrogen used in fuel cell vehicles is assumed to be dispensed from filling stations at 6,250 psi for 5,000-psi vehicle tank pressure.
- Upstream energy and emissions associated with electricity use are based on the EIA's reference-case projections for the national average generation mix in 2020: 51.1% coal, 19.2% natural gas, 18.5% nuclear, 1.9% residual fuel oil, 1.0% biomass, and 8.4% other renewables (including hydropower). These figures are derived from the *Annual Energy Outlook 2007*, which is available on the Web at: www.eia.doe.gov/oiaf/archive/aeo07/index.html.
- These results will be periodically updated to reflect changes in the assumptions and refinements to the models used.
- Assumptions used to generate this latest set of results are based on discussions among DOE staff and the following technology analysts: Amgad Elgowainy, Argonne National Laboratory (ANL); Mark Ruth, National Renewable Energy Laboratory; Margaret Singh, ANL; and Michael Wang, ANL.

Vehicle/Fuel Pathway	Well-to-Wheels Greenhouse Gas Emissions (*grams of CO_2-equivalent/mile*)	Well-to-Wheels Petroleum Energy Use (*BTUs/mile*)	Pathway-Specific Assumptions
Future Conventional Vehicle: Gasoline ---------- ***Today's** Conventional Vehicle: Gasoline*	410 ---------- *540*	4550 ---------- *6070*	• Fuel economy of 28 mpg was used. This is the projected on-road fuel economy, which was determined by multiplying the projected EPA lab-rated fuel economy by 0.82. ---------- • *Fuel economy of 21 mpg was used. This is the on-road fuel economy, which was determined by multiplying the EPA lab-rated fuel economy by 0.82.*
Conventional Vehicle: Natural Gas	320	25	• Fuel economy of 29 miles per gallon gasoline equivalent (gge) was used. This is the projected on-road fuel economy, which was determined by multiplying the projected EPA lab-rated fuel economy by 0.82.
Hybrid-Electric Vehicle: Gasoline	250	2710	• Fuel economy of 47 miles per gallon gasoline equivalent (gge) was used. This is the projected on-road fuel economy, which was determined by multiplying the projected EPA lab-rated fuel economy by 0.85.
Hybrid-Electric Vehicle: Diesel	220	2370	• Fuel economy of 53 miles per gge (which is roughly equal to 59 miles per gallon of diesel) was used. This is the projected on-road fuel economy, which was determined by multiplying the projected EPA lab-rated fuel economy by 0.85.

Hybrid-Electric Vehicle: Corn Ethanol (E85)	190	850	• Fuel economy of 47 miles per gge (which is roughly equal to 35 miles per gallon of E85) was used. This is the projected on-road fuel economy, which was determined by multiplying the projected EPA lab-rated fuel economy by 0.85.
Hybrid-Electric Vehicle: Cellulosic Ethanol (E85)	65	860	• Feedstock is a hybrid poplar grown as a bio-energy crop. • Fuel economy of 47 miles per gge (which is roughly equal to 35 miles per gallon of E85) was used. This is the projected on-road fuel economy, which was determined by multiplying the projected EPA lab-rated fuel economy by 0.85. • Does not include reductions in *net* GHG emissions and petroleum use that will occur through co-production of cellulosic ethanol and electricity. Surplus electricity produced in this manner (and not used for internal production processes) will replace some grid electricity and effectively displace associated emissions and petroleum use.
Plug-in Hybrid Electric Vehicle (w/ 40-mile all-electric range): Gasoline	240	1530	• The conventional definition of fuel economy does not apply to plug-in hybrid vehicles (PHEVs).[1] Based on PSAT simulations, a mid-sized PHEV with 40-mile all-electric range was assumed to have a fuel consumption of 700 Btu/mile and an electricity consumption of 716 Btu/mi in the blended mode of operation (primarily charge-depletion), and a fuel economy of 47 mpg in the charge-sustaining mode of operation. The share of distance travelled in the blended mode was assumed to be 63%. The 0.85 on-road adjustment factor was used for liquid-fuel operation. The electricity-fueled operation was not adjusted for on-road performance.
Plug-in Hybrid Electric Vehicle (w/ 40-mile all-electric range): Cellulosic Ethanol (E85)	150	530	• Feedstock for ethanol production is a hybrid poplar grown as a bio-energy crop. • The conventional definition of fuel economy does not apply to plug-in hybrid vehicles (PHEVs).[1] Based on PSAT simulations, a mid-sized PHEV with 40-mile all-electric range was assumed to have a fuel consumption of 700 Btu/mile and an electricity consumption of 716 Btu/mi in the blended mode of operation (primarily charge-depletion), and a fuel economy of 47 miles per gge in the charge-sustaining mode of operation. The share of distance travelled in the blended mode was assumed to be 63%. The 0.85 on-road adjustment factor was used for liquid-fuel operation. The electricity-fueled operation was not adjusted for on-road performance. • Does not include reductions in *net* GHG emissions and petroleum use that will occur through co-production of cellulosic ethanol and electricity. Surplus electricity produced in this manner (and not used for internal production processes) will replace some grid electricity and effectively displace associated emissions and petroleum use.
Fuel Cell Vehicle: Hydrogen from Distributed Natural Gas	200	30	• Fuel economy of 65 miles per gallon gasoline equivalent (gge) was used. This is the projected on-road fuel economy, which was determined by multiplying the projected EPA lab-rated fuel economy by 0.85. • 94% energy efficiency for forecourt compression.

[1] Energy use is represented here in Btu/mile, due to the complexities involved in assessing fuel economies in the charge-depleting mode in terms of miles/gallon or miles/gge. For more information on this subject, see: A. Elgowainy, et al., *Well-To-Wheels Energy Use and Greenhouse Gas Emissions of Plug-in Hybrid Electric Vehicles,* Center for Transportation Research, Argonne National Laboratory, 2009, www.transportation.anl.gov/pdfs/TA/559.pdf.

Fuel Cell Vehicle: Hydrogen from Coal Gasification with Carbon Sequestration	110	45	• Fuel economy of 65 miles per gallon gasoline equivalent (gge) was used. This is the projected on-road fuel economy, which was determined by multiplying the projected EPA lab-rated fuel economy by 0.85. • Hydrogen is delivered by pipeline to the forecourt in gaseous form at 300 psi. • 94% energy efficiency for forecourt compression. • Does not include potential reductions in *net* GHG emissions and petroleum use that are possible through co-production of hydrogen and electric power, which could replace some grid electricity and effectively displace associated emissions and petroleum use.
Fuel Cell Vehicle: Hydrogen from Biomass Gasification	55	95	• Fuel economy of 65 miles per gallon gasoline equivalent (gge) was used. This is the projected on-road fuel economy, which was determined by multiplying the projected EPA lab-rated fuel economy by 0.85. • Feedstock is a hybrid poplar grown as a bio-energy crop. • Hydrogen is delivered by pipeline to the forecourt in gaseous form at 300 psi. • 94% energy efficiency for forecourt compression. • Does not include potential reductions in *net* GHG emissions and petroleum use that are possible through co-production of hydrogen and electric power, which could replace some grid electricity and effectively displace associated emissions and petroleum use. • Does not include additional potential reductions in GHG emissions that are possible if CO_2 is sequestered.
Fuel Cell Vehicle: Hydrogen from Nuclear High-temperature Electrolysis	50	25	• Fuel economy of 65 miles per gallon gasoline equivalent (gge) was used. This is the projected on-road fuel economy, which was determined by multiplying the projected EPA lab-rated fuel economy by 0.85. • Hydrogen is produced using only nuclear-generated electricity and thermal energy—nearly all petroleum use and GHG emissions in this pathway are associated with delivery, storage, and dispensing of hydrogen. • 94% energy efficiency for forecourt compression. • Hydrogen is delivered by pipeline to the forecourt in gaseous form at 300 psi. • Electrolyzer efficiency is 74.6% (LHV); it uses 44.7 kWh per kg of hydrogen produced.
Fuel Cell Vehicle: Hydrogen from Central Wind Electrolysis	40	15	• Fuel economy of 65 miles per gallon gasoline equivalent (gge) was used. This is the projected on-road fuel economy, which was determined by multiplying the projected EPA lab-rated fuel economy by 0.85. • Hydrogen production process uses only wind-generated electricity—nearly all petroleum use and GHG emissions in this pathway are associated with delivery, storage, and dispensing of hydrogen. • Electrolyzer efficiency is 74.6% (LHV); it uses 44.7 kWh per kg of hydrogen produced. • Hydrogen is delivered by pipeline to the forecourt in gaseous form at 300 psi. • 94% energy efficiency for forecourt compression. • Does not include potential reductions in *net* GHG emissions and petroleum use possible by using excess wind electricity to displace some grid electricity. It is likely that most wind-to-hydrogen plants would be designed with an excess capacity of installed wind-power to minimize cost by ensuring the most efficient use of the system's electrolyzers. As a result, at times of peak wind-power generation, there would be more power generated than the electolyzers could utilize—this would replace some grid power, and effectively displace associated emissions and petroleum use.

U.S. Department of
ENERGY

Department of Energy Quadrennial Technology Review Framing Document

http://energy.gov/QTR

3/14/2011

The United States Department of Energy (DOE) has initiated a review of its energy technology activities (Quadrennial Technology Review, or QTR). This framing document is a principal means of facilitating stakeholder engagement in that process. It describes the nation's energy landscape and challenges, identifies important research, development, and demonstration (RD&D) policy choices to be made, and summarizes the current status of selected energy technologies and DOE technology program goals. It is intended to serve as the common framework for stakeholder engagement through advisory committees, workshops, and expert discussion groups. Successive drafts of the DOE-QTR will be circulated among U.S. Government stakeholders.

The Department especially seeks input on the questions posed throughout this document, which correspond to those in the Request for Information published in the Federal Register (Ref. 2011-5794). Instructions on submitting comments can be found at http://energy.gov/QTR.

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1 Introduction

The DOE-QTR will provide a context and framework for the Department's energy programs, as well as principles by which to establish program plans with a five-year horizon. It stems most immediately from recommendations in a recent report by the President's Council of Advisors on Science and Technology (PCAST), *Report to the President on Accelerating the Pace of Change in Energy Technologies Through an Integrated Federal Energy Policy*, which echo and amplify numerous prior calls for better prioritization and planning in DOE's energy activities[1]. PCAST recommended a government-wide Quadrennial Energy Review. However, recognizing the scope and challenge of that task, they also recommended beginning with a more limited review centered on DOE activities. Secretary Chu initiated the DOE-QTR in February of 2011, and tasked Under Secretary for Science Steven Koonin with leading the process.

Given DOE's mission and capabilities, the DOE-QTR is concerned primarily with activities to develop and demonstrate new energy technologies in support of national energy goals. These are multi-year efforts in which science, technology, economics, and energy policy intertwine. In view of the multitude of technologies that *could* be developed and demonstrated, analytically-based priorities and coordination of RD&D efforts with policy are essential to facilitate deployment by the for-profit sector.

The scope of the DOE-QTR will include a discussion of the roles of government, industry, national laboratories, and universities in energy system transformation, as a function of technological area. It will describe summary roadmaps for advancing key energy technologies, systems, and sectors, including current status, historical pace of development and market diffusion, technological potential, factors affecting their market prospects, and research and demonstration milestones. The objective will be to include enough detail to enable the other objectives of the DOE-QTR, not to lay out detailed programmatic or technological roadmaps for wider application. The DOE-QTR will also establish principles by which the Department can judge the priority of various technology efforts. Rather than an ordered prioritization of technologies or activities, these principles will be useful to guide the budget process, which is the appropriate mechanism to set priorities. This will include the principles DOE will use to determine which demonstration projects to support. Last, the DOE-QTR will describe the connections between energy technology innovation and energy policy. While the document will be focused on the activities within DOE's purview, it will also identify critical DOE analytical assets that can inform policy making by others.

The DOE draft Strategic Plan, which was recently released for public comment, is a coherent plan for all of the Department's activities, including nuclear security, environmental management, and basic research. It does not have a singlular focus on the energy porfolio. The Plan does include energy goals:

> "Petroleum use will be decreased by raising fuel economy standards, gradual electrification of the vehicle fleet, and increasing production of advanced biofuels. Greenhouse gas emissions will be reduced through improved efficiency, accelerated deployment of low-carbon energy

[1] For example, see the National Academy of Science *America's Energy Future* report, the National Commission on Energy Policy *Ending the Energy Stalemate* report, and the American Energy Innovation Council's *Business Plan for America's Energy Future*.

generation technologies (including conventional renewable, nuclear, and carbon capture and storage), modernization of the electricity grid, and public policy."

This DOE-QTR will discuss more deeply the substance and process of DOE energy technology programs that can accelerate progress toward those goals; the Department's nuclear security, environmental management, and basic science are addressed to the extent that they relate to and inform the energy portfolio.

Coherent multi-year planning through reviews such as the Quadrennial Defense Review (QDR) has been important to success in other government missions. While this DOE-QTR follows the purpose and spirit of other federal "QXRs" (beyond the QDR already mentioned, there is the QDDR for Diplomacy and Development and QHSR for Homeland Security), it is fundamentally different because defense, diplomacy, and homeland security are almost entirely governmental functions that are directly shaped by public spending decisions and policies. In contrast, the deployment, ownership, and operations of energy technologies are almost entirely nongovernmental functions that are determined by government policies and investments. Many government agencies beyond DOE have significant roles to play in establishing those policies. As a result, broad nongovernmental and intra-governmental engagement is central to creating the DOE-QTR. In addition, full transparency of input to the drafting team is an important guiding principle.

This framing document and its accompanying Request For Information (RFI) begin a process that the Department believes will lead to robust, effective technology portfolio to accelerate energy transformation and meet our Nation's energy challenges. We welcome written comments responding to the questions raised in the RFI and in this document throughout the public comment period, lasting from March 14 to April 15, 2011.

Following the close of that comment period, DOE will analyze comments received in preparation for a series of workshops. These will draw on the expertise of the private sector, academia, non-governmental organizations, DOE, and the national laboratories to delve into the questions raised here, as well as additional topics as might arise in response to the RFI. Each workshop will bring together experts and stakeholders to share their individual views on one or more of the six strategies we have described.

In keeping with the Administration's commitment to open government, the names, materials discussed, and subject matter (including transcripts or detailed notes where appropriate), for all of these meetings will be posted on the QTR website. DOE anticipates that vibrant discussion of the technology and policy questions relevant to our technology programs will help us produce a better Quadrennial Technology Review.

This document is organized as follows. Section 2 is a factual description of the national energy landscape and its near-term evolution. Section 3 describes the three challenges that drive the need for a prompt and substantial transformation of the nation's energy system. Section 4 is about the policies and capabilities within the Department's sphere of influence. Section 5 presents crosscutting questions for

comment regarding how to allocate resources for DOE RD&D activities. Section 6 describes six thematic strategies that categorize the approaches to transforming our energy landscape.

2 U.S. Energy Context

Addressing our energy challenges, whether through technology or policy, requires that they be understood. This section provides a brief overview of the U.S. energy context, emphasizing those aspects most relevant to the challenges we face. A more detailed exposition can be found at the Energy Information Administration (EIA) website.

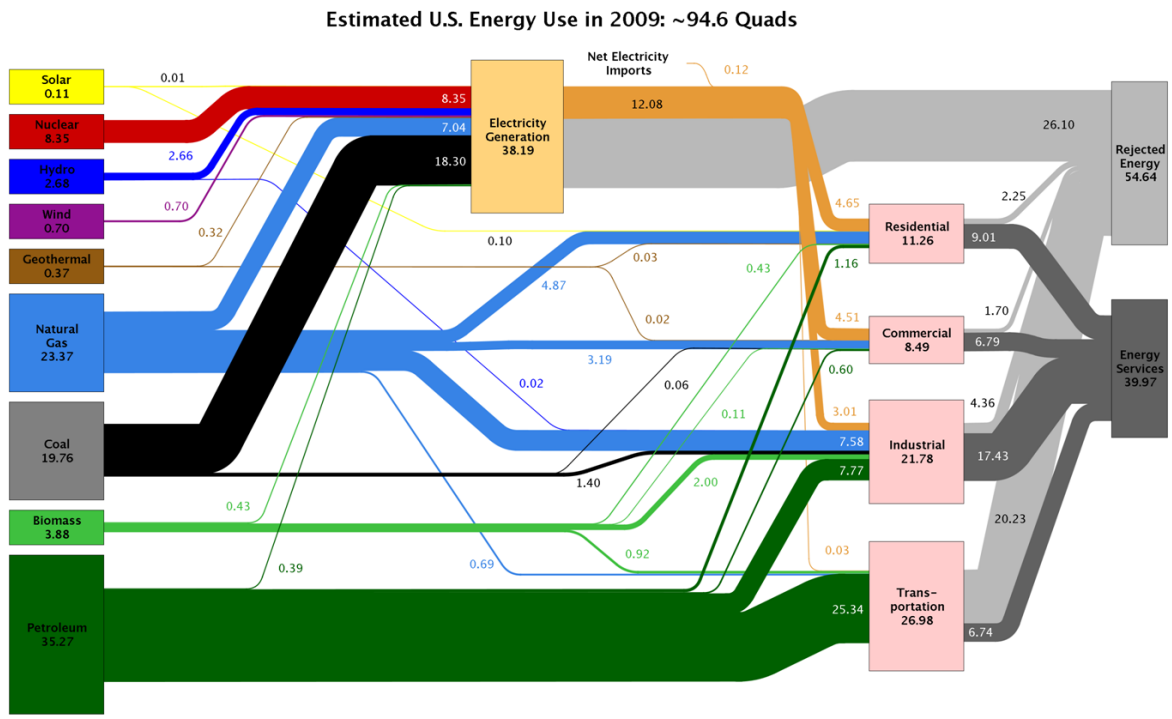

Figure 1. U.S. energy flow (Lawrence Livermore National Laboratory). Data in quadrillion British thermal units (Quads).

The energy sector is a large, complex *system* that touches every aspect of modern life and comprises 9% of gross domestic product (GDP) while enabling the rest of the economy. Figure 1 shows the flow of energy from supply to demand, scaled to show the relative amounts of energy produced from each energy source and consumed by use. Several salient points can be taken from Figure 1 and other data on the energy system.

2.1 Different Fuels for Different Uses

Fossil fuels currently provide 83% of U.S. primary energy, with coal used almost exclusively (93%) for power and oil used largely (72%) for transport. Natural gas (methane) is a flexible fossil fuel source that is used for power and heat across multiple sectors of the economy. Transport is fueled almost exclusively by petroleum-derived liquids (gasoline and diesel), while electricity is fed by many sources

beyond fossil fuels, most significantly nuclear fission and hydropower. Other renewable sources supply less than 4% of U.S. electricity.

The energy system divides between transport and stationary (i.e., electricity and power/heat), with each further partitioned into the supply, intermediate, and demand sectors. These sectors are a useful framework for discussing the energy system and each has its own unique context, challenges, and opportunities.

2.2 Energy Efficiency

Nearly 60% of energy is lost due to waste heat (labeled "Rejected Energy" in Figure 1). Both electrical generation and transport make use of less than one-third of their primary energy inputs. While efficiency is bound by thermodynamic limits, there is significant potential to reduce energy consumption by increasing the efficiency of power plants and vehicles. The movement of goods and people, the least efficient energy use, can be made more efficient by technological changes to engines and vehicles, and by societal changes (e.g., greater use of public transport). Power generation can be improved by progressing to more efficient generating technologies and harnessing the waste heat for useful applications, such as heating water. Importantly, the 80% efficiency depicted in Figure 1 for residential, commercial, and industrial energy use is misleading; there is no rigorous way to measure absolute efficiency in end-use service delivery (relative efficiency can be rigorously measured). Significant opportunities also exist to reduce energy consumption in these sectors via improved building, device, and industrial process efficiencies.

Implementation of efficiency measures generally incurs an up-front capital cost that is offset by reduced ongoing energy costs, although cases do exist in which significant efficiencies can be achieved with little or no capital costs. A number of market failures prevent full utilization of these efficiency measures. For example, consumers and professionals alike often lack the necessary information to choose the best product to meet their needs at the lowest life cycle cost, and there is ample evidence that investment decisions, particularly by individual consumers, are driven by first-cost considerations rather than life-cycle cost analysis. Another notable market failure is the principal-agent problem, which occurs when one person acts on behalf of another, but acts contrary to that person's best interests. For example, this commonly occurs in energy use between landlords and renters.

Energy efficiency reduces energy consumption and expense for the service delivered, allowing that money to be spent elsewhere, including increased use of the more efficient service (direct rebound). In addition, improved energy productivity spurs economic growth, with some associated increase in energy demand in all sectors (indirect rebound). The magnitudes of these rebound effects are topics of active research.

2.3 Stationary vs. Transport Supply

The energy needs of the residential and commercial sectors of the economy, about 40% of our national energy consumption, are met primarily by electricity and natural gas. The industrial sector consumes another 30% of the nation's energy, supplied by diverse feedstocks. New energy technologies that

supply these stationary energy consumers must compete against existing infrastructure that delivers energy reliably and at low cost.

Approximately 94% of transportation services are fueled by petroleum (see Figure 1). The growing price and price volatility of current fuels provide a significant opportunity for making current technologies more efficient, as well as for competing technologies to gain acceptance. However, new fuels must compete against the extraordinary energy density and marginal production costs of petroleum-based fuels and adapt to, or compete with, the established fuel distribution infrastructure.

2.4 Supply Changes Slowly, Demand Rapidly

Throughout U.S. history new energy resources have taken many decades to achieve scale and penetrate markets, often requiring 50 years or more. The timescale of supply change is dominated by long-lived infrastructure and the continual growth in energy consumption that has allowed new technologies to supplement rather than replace existing energy sources. In addition, energy is a commodity, where intermediaries (including refineries, utilities, and other electric power producers) operate on thin margins. Still, significant opportunities for greater efficiency with existing technologies and the introduction of new technologies exist due to the age of current U.S. infrastructure.

In contrast to large, long-lived energy supply assets, energy-consuming devices and vehicles are relatively inexpensive and replaced more frequently. Typical lifetimes for vehicles and home appliances are under 20 years, while consumer electronics and lighting technologies can have significantly shorter lifetimes. New demand-side technologies can therefore enter and dominate the market within a few years.

2.5 Scale

For both the transport and stationary sectors, there is a million-fold difference in the number of energy users and energy producers. This disparity in scale is at the root of the different challenges in transforming the energy system. The current energy supply paradigm is dominated by large, centralized supply facilities that are expensive to replace and affect the overall system when taken offline. Energy demand is the aggregated result of billions of individual end uses, each a miniscule fraction of total demand. Although the cumulative actions of energy consumers are the fundamental drivers of the energy system, the actions of any one end user do not materially affect the overall system.

2.6 Private Sector Dominance

By any measure, the U.S. energy system is in the hands of the private sector, which makes decisions based on cost and profit considerations. It designs, constructs, and operates the overwhelming majority of energy production and transmission facilities. On the supply side, all domestic refineries are owned by the private sector. The power marketing administrations, Tennessee Valley Authority, public utilities, and cooperative utilities combined are less than 25% of national generating capacity and 20% of transmission (and even these generally function like private-sector organizations in striving to serve customer loads reliably at lowest cost). On the demand side, while the federal government is the nation's largest single user of energy, it represents less than 2% of total demand (almost 90% of federal energy use is in the Department of Defense).

2.7 Current Policy Context

The U.S. energy system is regulated and subsidized by many players including the DOE at all levels of government. Incentives, standards, trade policies, and direct government investment shape the markets for fuels, electricity, and demand technologies. More than half of U.S. state governments have instituted renewable portfolio standards (RPS) that require certain fractions of the electricity sold in their states to be generated by renewable technologies. While portfolio standards create a certain level of market access for renewable fuels (federal renewable fuel standards) and renewable power (state RPSs), energy efficiency standards (set by the Department of Energy) and building codes (set by states) establish minimum performance standards that apply to entire markets, with the long-term goal of driving out the most wasteful products in a specific set of end-uses.

In addition, providers of energy are subject to a wide range of consumer-protection and environmental regulation. The electricity industry is owned and regulated by a diverse set of stakeholders. This structure varies across states and regions, and many combinations of roles exist for different entities within the system. The Federal Energy Regulatory Commission (FERC) regulates interstate transmission and sale of electricity, natural gas, and oil. Retail electricity regulation and infrastructure siting is largely controlled by the states, usually by public utility commissions. Natural gas for commercial and residential uses is generally subject to state regulation in a manner similar to electricity.

Environmental regulation affects both the transport and stationary energy sectors. There are federal regulations for criterion air pollutants from both sectors, and since finding that carbon dioxide (CO_2) also endangers public health, the Environmental Protection Agency (EPA) has established standards for CO_2 emissions that apply to light duty vehicles. Some states have taken additional action to curb CO_2 emissions through a wide range of policies and measures. Federal and state vehicle efficiency and emission standards address the emission of CO_2 and other pollutants. Federal regulations exist regarding the custody and disposition of fuel and waste from nuclear generation.

2.8 The U.S. Energy Industry

The U.S. energy industry is large and multifaceted, with activities that can be broadly categorized as deployment, manufacturing, or innovation. In deployment, modest increases in electrical demand and replacement of aging capacity resulted in approximately 16.4 gigawatts (GW) of capacity in new generators added in 2010, corresponding to some tens of billions of dollars in added capital. This deployment is less than 2% of total capacity and will provide an even smaller percentage of total electricity given the associated technology capacity factors. In contrast, more than 100 GW of capacity was added each year in non-Organisation for Economic Co-operation and Development (OECD) countries from 2004-2008, a 6% annual growth rate. While the petroleum refining capacity in the U.S. has plateaued over the last five years, the utilization of that capacity has fallen over the same time period, so major investments in fuel refining necessary to transition to new feedstocks or products will not happen under business-as-usual.

The conservatism of the energy system is reflected in research and development (R&D) investments; U.S. companies invested approximately $3 billion in energy supply R&D in 2010, about 0.3% of total revenue, a small proportion compared to non-commodity sectors, such as pharmaceuticals (18.7%) and

computers and electronics (7.9%). Federal investment in energy RD&D was $4.3 billion in 2010, one-third of benchmark commonly articulated target for developed nations (1% of sector's portion of GDP).

Manufacturing related to energy technologies varies widely. In general, manufacturing facilities for mature technologies are built where the cost of manufacturing is lowest, and those for innovative technologies are built near the site of invention. Decisions regarding manufacturing capacity are also related to the cost of transport of the products. For example, a 2005 study suggested that U.S. suppliers will have inadequate production capacity for the predicted nuclear energy deployment, partially due to the inactivity in the U.S. nuclear market over the last several decades and the emergence of markets abroad. Similarly, while only 6% of solar photovoltaic modules were manufactured in the U.S. in 2008, the U.S. dominated production of innovative thin-film modules, which have been the recent focus of domestic RD&D. Beyond energy supply, end-use technologies responsible for consumer energy demand are manufactured world-wide and subject to vigorous global trade. Manufacturing of energy system components, including end-use technologies, is itself a significant energy consumer.

3 Challenges Posed by Today's Energy Landscape

Access to affordable, secure, and reliable energy has been the cornerstone of America's economic growth. However, the nation's physical and social systems that produce, store, transmit, and use energy remain deficient in several important dimensions.

3.1 Energy Security

The movement of goods and people is essential to our economy, and 94% of the energy used for domestic transportation comes from oil. When other sectors of our economy are considered as well, 37% of all U.S. primary energy is derived from oil, nearly half of which is imported. The crude import fraction has dropped from over 60% in 2005 and is expected to drop further to 42% in 2035; absolute imports are projected to decrease from 9 million barrels per day in 2009 to 8.5 in 2035.

Crude imports at current prices add nearly $1 billion per day to the national trade deficit. In addition, the world relies on OPEC countries for approximately 40% of it oil supply, much of which is produced in regions and countries subject to disruptions. This circumstance shapes U.S. foreign policy and engenders economic vulnerability. Further, there is effectively one global price for oil set by global supply and demand, modulated slightly based on geographic and quality differences in the crude. That price may well continue to be higher than historic norms due to increasing demand in developing economies and concentration of low-cost supply in a few countries. Continued reliance on transportation fuels fungible with oil implies continued U.S. coupling to the global oil price and the drawbacks that entails. However, any reduction in oil use through efficiency would diminish the economic harm of high prices and price volatility.

Security concerns associated with the U.S. energy system extend beyond oil. The security and management of the nuclear fuel cycle will be of critical importance to increased deployment of nuclear energy technologies in the U.S. and abroad. National policy and international agreements are elements of ensuring the availability of the required fuel supply. Effective and credible international nuclear

safeguards, export controls as well as R&D will be required to ensure that future nuclear power systems can be deployed safely and securely with appropriate mitigation of risks from terrorism and proliferation. The nation's electric grid must be more secure and reliable to minimize the impact of potential natural and man-made disruptions.

3.2 U.S. Competitiveness

American leadership in clean energy technologies can be a foundation for future economic growth. The market for clean energy technologies is expected to grow because of global economic development, which is driving dramatic increases in energy demand, and increasing international focus on environmental concerns. The economic opportunities in the clean energy technology market are driving innovation, manufacturing, and deployment worldwide. To participate in that market, the U.S. must have a robust energy technology industry and well-developed supply chains.

3.2.1 Innovation

Innovation has historically been the nation's economic engine, and is an area accessible for continued U.S. leadership. The U.S. has led in innovation because of a culture of creativity and entrepreneurship coupled with investment in basic and applied research by both the government and the private sector. However, the U.S. is out-spent in RD&D as a fraction of GDP by Japan, and China's investments are rising steadily. In energy RD&D, the U.S. is out-spent by its major trading partners (i.e., Japan, Korea, France, and China). Innovation is correlated with RD&D funds, as illustrated by national statistics for patent filings.

3.2.2 Manufacturing

Reversing the decline in domestic manufacturing is often cited as necessary for U.S. economic competitiveness. While the U.S. has steadily shed manufacturing jobs since 2000, manufacturing output and wages have increased over the same period. Although increased manufacturing productivity can be a hazard to individual manufacturing jobs, the associated economic growth benefits the economy as a whole. Investment in manufacturing facilities not only creates immediate capabilities, it facilitates future manufacturing efforts because the existing capital can be updated to accommodate new needs.

Historically, U.S. leadership in innovation enabled its leadership in manufacturing highly differentiated products, since close collaboration between researchers, engineers, and manufacturers is useful for burgeoning technologies. However, once a product becomes a commodity in the broader market, premiums can no longer be garnered by domestically-produced materials and local pools of talent, and manufacturing will shift to where it is economically optimal. Innovation in manufacturing processes, in addition to the invention of new and better products, enables increased productivity and output and creates competitive advantage. Manufacturers in the developing world are becoming ever-more sophisticated; Chinese high-tech manufacturing value-added quadrupled from 1997–2007. Private-sector decisions regarding the location of manufacturing facilities are shaped by a variety of factors, including access to capital, tax incentives, regulatory hurdles, market access, and labor force productivity.

3.2.3 Deployment

Large developing economies are just now building the bulk of their infrastructure and are well suited to adopt new clean energy technologies as they build out a modern energy infrastructure for the first time. This rapid growth abroad is a market opportunity for U.S.-developed clean energy technologies. While the U.S. is unlikely to lead the world in the absolute numbers of clean energy technologies deployed simply because the U.S. energy market is a mature market dominated by replacement and modest demand growth, widely deploying clean energy technologies domestically is attractive for economic competitiveness for several reasons. These include the benefit of the technology itself (e.g., decreased energy costs with efficiency technologies), decreased cost of the technology from lessons learned through deployment, as well as the associated jobs that cannot be outsourced for the sale, installation, operation, and maintenance of the technology.

The president has set a goal of increasing the share of America's electricity supplied by clean energy sources to 80% by 2035.

3.3 Environmental Impacts

Conventional energy production and consumption cumulatively can have significant environmental impacts. Among these are the emission of greenhouse gasses (GHGs) and other airborne pollutants, the production of solid wastes, and ecological impacts due to the use and consumption of significant quantities of water.

The use of fossil fuels is a major source of CO_2 accumulation in the atmosphere, which is perturbing the climate. Global temperatures during the last thirty years have risen about 0.6 °C, consistent with expectations. Substantial climate change over the next 90 years would have a serious impact on society, and could lead to global instabilities if water supplies are threatened or if a substantial rise in sea levels displaces populations. Energy and water are linked; the production of energy requires large volumes of water while the treatment and distribution of water is equally dependent upon readily available, low-cost energy. Climate changes may affect water run-off in the U.S. and elsewhere.

Other pollutants have environmental impacts. For example, highly radioactive and toxic used nuclear fuel is produced and stored at the current fleet of nuclear plants, and presents a future problem for centennial-scale storage. The burning of fuels can lead to other types of solid or airborne waste that may contain mercury, ozone, sulfur oxides, nitrogen oxides, and heavy elements. Extraction of fossil fuels can have significant environmental effects at the location of the extraction.

Significant deployment of any energy technology will have environmental impact simply because of the required scale. Some environmental impacts of large wind or solar farms have been discussed; biomass production can have both direct and indirect environmental impacts

4 DOE Activities

An effective plan for the Department's energy technology programs requires both knowledge of the energy landscape and challenges reviewed in the previous sections together with a realistic

understanding of the government's and DOE's role in shaping the energy system. Since that system is largely in the hands of the private sector, the government can effect change through the pre-competitive RD&D it supports and through its policies that affect the rate of deployment, including market incentives and penalties, regulation, and finance.

As outlined in Section 2.7, nearly every governmental entity defines some policies related to the energy sector. Even within the federal government, many of the regulations and incentives that shape the energy system are not administered by the DOE. The EPA is home to emissions and environmental regulations; all tax incentives are the purview of the Treasury; the Department of Transportation sets the Corporate Average Fuel Economy (CAFE) standards; the Department of the Interior regulates fossil fuel extraction and siting of energy projects on federal lands; the Department of Agriculture regulates and subsidizes the feedstocks for most biofuels; FERC regulates interstate energy transmission; the Nuclear Regulatory Commission (NRC) regulates nuclear power; many federal agencies are involved in the siting of off-shore energy projects; the Department of Defense (DoD) funds energy RD&D for its own substantial, and often unique, energy needs; the Department of Labor regulates worker safety and compensation for energy projects; and the list goes on.

The federal government's direct participation in the energy system as a provider or purchaser of energy is limited. Its major influence is instead exerted by joining with state and local governments to modulate private-sector decisions through policies that set the terms of operation and trade in the energy sector. DOE contributes in part to private sector decisions by developing and maturing technology options that could be rewarded in evolving market conditions.

The Department of Energy's RD&D programs include the Offices of Science, Energy Efficiency and Renewable Energy, Electricity Delivery and Energy Reliability, Nuclear Energy, Fossil Energy, and Nuclear Nonproliferation. The Office of Science is the single largest funder of basic research in the physical sciences in the country. The other Offices primarily support applied research and development in technology-specific areas. In addition, the Advanced Research Projects Agency – Energy (ARPA-E) funds the development of high-risk, high-payoff clean energy technologies. As a whole, the Department's programs are a major U.S. innovation engine, supporting mission-related research in academia, the DOE complex of national laboratories and user facilities, and the for-profit sector. The Department is home to some of the world's most powerful scientific computers and leads the world in simulation capabilities that couple computer modeling with experimental validation. A strategic combination of applied research, test beds and simulation has the potential to decrease risks associated with new technologies, accelerate technological progress, and can catalyze private-sector investment for the wide deployment of clean energy technologies.

The Department's core strength lies in its science and technology efforts, which have led to technology improvements and breakthroughs, and these efforts are the focus of this DOE-QTR process. However, these are not the Department's only responsibilities and policy tools. DOE has some regulatory (e.g., appliance efficiency standards) and financial authorities (e.g., loan guarantees) and its techno-economic analyses play a unique role in informing and shaping energy and related environmental policies and investments.

The *American Recovery and Reinvestment Act* (Recovery Act) channeled an unprecedented amount of funds through the Department in record time. The Recovery Act funding and an increased fiscal year 2009 appropriation provided the opportunity for new, extensive projects. In energy, projects include tax credits, construction of advanced vehicle technology battery manufacturing facilities, and energy efficiency grants available to every state, county, and large city. These projects will help inform future investments in energy technology research, development, demonstration, and deployment (RDD&D).

The Department serves as a repository and disseminator of technical information and best practices for energy consumers, from individuals to industries to the federal government. For example, the Federal Energy Management Program (FEMP) facilitates the federal government's implementation of sound, cost-effective energy management and investment practices to enhance the nation's energy security and environmental stewardship. DOE has the authority to set mandatory minimum energy efficiency standards for a range of residential, commercial, and industrial appliances, including lighting, refrigerators, heating and cooling systems, and motors.

The Department works with dozens of foreign governments and international organizations to promote best practice policies and programs, including appliance standards, to accelerate technology innovation and clean energy deployment. Through leadership in the Clean Energy Ministerial and the Energy & Climate Partnership of the Americas, DOE is catalyzing an array of cooperative activities with countries that account for the vast majority of the world's energy use. With most of the growth in future energy use expected to occur in developing countries, DOE also supports strong strategic bilateral partnerships with both China and India, where the rapid speed and large scale of new energy technology deployment is an important driver for innovation.

In addition, the Department has a core competency in providing unbiased, technically rigorous information for policymakers. The EIA is the nation’s premier source of independent statistical information about energy production and use. The power marketing administrations, DOE independent agencies, offer experience in power generation and transmission activities and can demonstrate and deploy new technologies and capabilities into the electrical grid. The Department collaborates with other federal agencies to leverage expertise, advance research, development, demonstration, and deployment programs, reduce redundancy in energy research programs, and leverage government purchasing power to facilitate commercialization and initial deployment. One example is the Department’s work with the Departments of Agriculture, Commerce, and Transportation on biofuels from farm to certification. The DoD, with whom the DOE has a memorandum of understanding regarding early deployment of new energy technologies, will be an important early adopter of new and improving clean energy technologies, and the information DoD generates from trials at installations can inform DOE’s technology programs.

5 Crosscutting Questions

With the above framework in mind, the Department has a series of questions for which it seeks public input.

5.1 Mission

1) What do you think of the following mission statement for DOE energy research?

To facilitate the invention, refinement, and early deployment of meaningful technologies that enable options for scaling by the private sector toward national energy goals.

The words in this statement are carefully chosen:

- to facilitate – we convene and fund various entities – as well as support the basic research that underpins invention and refinement
- invention, refinement – we work on both revolutionary and evolutionary technologies
- early deployment – we support some activities beyond first commercial demonstration
- meaningful technologies – we pursue technologies that could have a material impact when deployed; accordingly, scale, economics, and timeliness are important criteria
- enable options – we do not pick commercial winners and losers; the markets make those choices
- scaling by the private sector – we support commercialization as an essential part of what we do
- toward national energy goals – we cannot and will not pursue all technologies; only those that enhance energy and national security, reduce environmental impacts, and increase U.S. competitiveness

5.2 Technology Policy

5.2.1 Clean Energy Leadership

U.S. leadership in clean energy technologies can help promote their diffusion around the world and contribute to the nation's economic competitiveness. The Department has long supported RD&D to catalyze energy innovation. Some programs drive entire clean energy fields, while others are focused on specific technical hurdles; we fund individual researchers as well as interdisciplinary teams of investigators addressing a common problem; we fund research at national laboratories, universities, and in the private sector. The Department supports a broad set of basic research in the physical sciences, with world-leading programs in materials science and engineering and in simulation, since these areas are critical to progress not only in energy, but also in our security, environmental, and science missions.

The Department has a number of mechanisms to support the manufacturing of clean energy technologies. The loan guarantee program supports manufacturing of innovative technologies that will avoid, reduce, or sequester GHG emissions. The Industrial Technologies Program funds R&D and provides technical assistance to make manufacturing processes more efficient.

The Department has neither the authority nor resources to significantly deploy technologies itself. However, DOE can facilitate private investment to deploy clean energy technologies. For example, working with the Department of the Interior, DOE is participating in studies to identify resources that will help developers of renewable energy generation projects. In addition, the loan guarantee program

leverages private resources to support renewable energy generation projects that have difficulty finding traditional financing.

As the greatest energy challenges are global in nature, partnering internationally to develop and demonstrate new technologies is both essential and attractive. Other countries can have technical capabilities that complement our own, and greater demand, pace, and/or risk tolerance in energy innovation. International partnerships could offer more diverse projects to increase learning rates, promote the global adoption of clean energy technologies, and perhaps ease foreign market entry for U.S. firms. However, international partnerships require careful management of intellectual property and competitiveness issues.

2) **How can DOE activities best support U.S. leadership in clean energy innovation? In clean energy manufacturing? In clean energy deployment? How do we balance international competitiveness against international cooperation?**

5.2.2 Program Definition and Management

Focusing programs on eliminating the most significant problems and barriers allows the most rapid progress toward our goals. All programs have many more good ideas to fund than resources available to pursue them, and constantly churning priorities, the pursuit of quick wins, or the dilution of resources in the face of too many options sap the effectiveness of our efforts. Programs that ramp up and down before the hard work can be carried out to test an idea, develop an essential tool, or prove a technology cannot effectively deliver results.

The active participation of multiple technologies or resources in a market is frequently beneficial. Competition exerts downward pressure on prices, while diversity reduces the risks associated with technical, economic, or supply chain complications and disruptions. Yet the strategic and economic value of diversity is often difficult to balance against other metrics, and a portfolio guided only by diversity can dilute investments and diminish the likelihood of success.

Clear-cut, baseline standards for entry into the DOE portfolio are useful tools for program definition. The DOE draft Strategic Plan says we will "focus on technologies that can confidently be predicted to enter commercial application at a minimum of 1 Quad annually by 2030 (about 1% of current U.S. primary energy)." Analogous thresholds for technologies that don't supply energy (e.g., carbon capture and storage or efficiency technologies) are more difficult to capture in this way. However, such standards cannot be the sole guide to program definition or budgeting, as mere technical possibility is too low a threshold; they do not capture the readiness of the technology for deployment, the maturity of the industry involved, or the RD&D involvement of outside parties. Furthermore, such standards do not provide guidance for how RD&D efforts should evolve as the technology is deployed and gains market share.

The Department can also use targets to guide its activities in different technologies. For example, the SunShot program aims to achieve a $1/Watt cost for installed utility-scale solar power by 2020. ARPA-E, too, cites specific parameters that technologies must plan to achieve in their funding opportunity announcements. These targets can be useful in that they provide concrete, tangible goals to work

towards without prescribing the specific technological pathway to achieve them. On the other hand, finding the right targets is challenging since the relationship between technical targets within an R&D setting and scaled production can be difficult to determine rigorously, and inappropriate targets can hamper technology development. For example, if DOE targets are underambitious, there is little incentive for the private sector to help the Department increase the aggressiveness of its targets. However, without input from industry, the Department runs the risk of recalibrating targets to unrealistic levels.

These challenges might be addressed by planning that is grounded by rigorous analysis, clear priorities established with broad input from stakeholders, and decisions based upon rigorous peer review. In addition, achieving even the most ambitious targets does not guarantee adoption and deployment by the private sector, as there are many non-technological barriers to technology commercialization.

3) **What principles should the Department follow for allocating resources among technologies of disparate maturity and potential time to impact?**

   a) **What should be the criteria for including a technology in the DOE portfolio? What should be the criteria for removing a technology from the DOE portfolio? How should programs be structured and managed to accommodate entry and exit of technologies within the DOE portfolio?**[2]
   b) **How do we balance the diversity of technology options the Department could provide for the private sector against timeliness, scale, and cost-effectiveness?**
   c) **How can DOE be more effective at each stage of the innovation chain?**
   d) **What are useful metrics to guide DOE technology activities?**

5.2.3 Private Sector Partnership

Since the Government is not the primary driver of either energy supply or use, all DOE energy activities must have the ultimate goal of catalyzing action by the private sector. In general, basic research is conducted solely at universities and national laboratories with funding by the government. As a technology moves through development and demonstration and associated risks lessen, it gains more attention and support from the private sector. Venture capital and small businesses have a higher risk tolerance than large corporations, who deploy technology at scale. To promote commercialization, the Department must partner with the private sector and other federal agencies to move technologies from proof-of-concept to full-scale deployment.

Progress towards an improved energy system in the U.S. will require both basic research and applied technology development. Historically, the feedback loop between science and technology has been a critical part of how progress is made; the more active the feedback loop, the higher the likelihood of rapid progress. To this end, we have developed a portfolio of new research efforts that augment our base programs to provide integration across disciplinary boundaries as well as across multiple phases of

[2] This question appears in the RFI as: "What should the threshold be for entry of a technology into the DOE portfolio? Does every technology deserve a program? Conversely, when should we declare 'mission accomplished' for a government RD&D effort, or cease efforts on a program whose costs may outweigh its benefits?"

RD&D. These include Energy Innovation Hubs, Energy Frontier Research Centers, Bioenergy Research Centers, and ARPA-E.

One of the Department's successful partnering mechanisms is its model of scientific user facilities. These facilities allow researchers to do experiments on large, capital-intensive DOE-owned scientific instruments. To ensure the Department's experimental facilities are used most effectively, proposals to use these facilities undergo rigorous peer review by researchers in academia and the national laboratories. To ensure that the knowledge from experiments is widely disseminated, users must either publish their results or pay for the use of the facility. A similar model could be imagined for clean energy technologies; for example, the Department could create and operate national technology test beds with greater experimental capability than could be developed by the private-sector in order to validate novel energy technologies and explore their system-level performance. While DOE national laboratories have similar capabilities for some technologies (e.g., the National Wind Technology Test Site and the Biomass Process Facility), these facilities are generally not operated under the paradigm described above. In the experience of the DOE, the user-facility model of open-calls for proposals and peer-reviewed selection have resulted in a diverse, high-quality set of research projects. This model may also apply in the arena of technology development. However, the translation of that model to energy technologies may be imperfect, as the majority of the users of these facilities will likely be for-profit and more likely to pay for their time and want to hold the results proprietary.

Energy RD&D management and planning will be most effective when fully informed about the actions of all relevant parties. The private sector is most knowledgeable about the status of commercial technologies and their likely evolution, yet competitiveness concerns may inhibit complete sharing, particularly for commodity products. The Department's current mechanisms to gather information on private sector innovation in clean energy technologies include invention disclosures of innovations that were made with DOE resources (e.g., through partnering with a DOE national laboratory), and efforts by the applied technology programs to hold workshops, read proposals submitted to solicitations, attend technology conferences, tour manufacturing plants, read market reports, and commission technology studies. However, these are imperfect and incomplete.

4) **What are the optimal roles for the private sector, government laboratories, citizens and academia in accelerating technology innovation?**

   a) **How can DOE best coordinate activities between and among these types of organizations (including the wide variety of institutions within each class)? How should we gauge the effectiveness of this coordination? How can the basic-applied coupling be optimized? Are there examples in other sectors or other countries that can serve as models?**
   b) **What are the design principles for an effective 'technology user facility'?**[3]

[3] This question appears in the RFI as: "Are 'technology user facilities' analogous to the Department's scientific user facilities possible, or even desirable? If so, what would be the most effective model for their operation?"

c) **How can the Department best gather technology market information? How can information on private sector innovation be captured without compromising competitive advantage?**

5.2.4 Technology Demonstration

Reducing the risks associated with new technologies is a critical component of government engagement with the private sector. The commercialization, broad diffusion, and regulatory approval of a new energy technology require high confidence in its performance. Uncertainty in operation at scale or in system-integrated operation increases early adopter risk and slows market penetration.

The DOE collaborates with industry on demonstration projects to help catalyze large-scale adoption of promising energy technologies. In order to ensure these efforts have the largest possible impact, DOE is interested in ideas to improve the process for selecting when and under what circumstances to sponsor technology demonstrations with industry, as well as how to best disseminate the results so as to have the largest market impact. To ensure relevance and application beyond the direct participants, learning must be widely disseminated so that test bed and demonstration activities can benefit entire industries. Such practices will require a careful balance of promulgating information for broadest impact against non-disclosure agreements and intellectual property protection necessary for private sector participation. However, specifics of how to chose and operate demonstration projects are unclear.

Failure is a common, and beneficial, fact of experimentation. The Department's R&D programs expect a certain proportion of failed research ideas, although contingency plans are integral to good program management. In contrast, the Department's Loan Guarantee Program is operated such that every funded project has a high likelihood of success (defined as a reasonable prospect of loan repayment). The risk associated with demonstration projects falls somewhere between R&D and commercial viability. Assessing and planning for risk will be essential to demonstration projects the DOE undertakes.

5) **What are principles and best practices in performing large-scale demonstration projects?**

   a) **How close to commercial viability does a demonstration have to be? What are the optimal cost sharing arrangements? How might demonstrations be coordinated with DOE financing activities?**
   b) **How can demonstration projects better benefit all stakeholders beyond the immediate participants? How are lessons-learned best captured and promoted, and how is intellectual property best handled?**
   c) **How should DOE determine whether demonstrations adequately address technical and operation risks?**
   d) **What defines failure or success in the demonstration phase?**

5.2.5 Non-Technical Barriers

DOE is but one of the many entities whose actions impact the energy system; while the energy sector is heavily regulated, few of those regulations are in the control of the Department. Integrated planning at the federal and international levels is essential to accelerating the deployment of new energy technologies. Standards, siting, and permitting are examples of the many issues that require multiple

agency participation. Establishing common understanding and prioritization regarding land or other resource use, and accelerating the process by which applications are considered across multiple agencies, would enable more rapid deployment of clean energy technologies. Other methods for addressing non-technical barriers include voluntary technical standards (like the work of ASTM International and the American National Standards Institute), dissemination of information crucial to market function, and support for workforce skills and availability.A comprehensive discussion of federal policies for addressing non-technical barriers to deployment would be the subject of the government-wide Quadrennial Energy Review suggested in the PCAST report, not this DOE-QTR. However, the Department is interested in comments regarding its role in addressing these barriers.

6) **A number of non-technical barriers—including federal, state, and local regulations, market failures, and non-technical risks—impact the rate of deployment of energy technologies. What, if any, role should the Department have in addressing these barriers?**

6 Six Strategies

The recently released DOE draft Strategic Plan (February, 2011) outlines three important Departmental goals:

- Catalyze the timely, material, and efficient transformation of the nation's energy system and secure U.S. leadership in clean energy technologies.
- Maintain a vibrant U.S. effort in science and engineering as a cornerstone of our economic prosperity, with clear leadership in strategic areas.
- Enhance nuclear security through defense, nonproliferation, and environmental efforts.

President Obama has articulated broad goals for reducing our dependence on oil, reducing pollution, and investing in RD&D of clean energy technologies in the United States to create jobs. These include:

- Reduce energy-related greenhouse gas emissions by 17% by 2020 and 83% by 2050, from a 2005 baseline.
- By 2035, 80% of America's electricity will come from clean energy sources.
- Support deployment of 1 million electric vehicles (EVs) on the road by 2015.

There are six more or less independent strategies that are both necessary and sufficient to address the Administration's goals (see Figure 2) and enhance our energy, economic, and environmental security. These six divide into two trios: one for stationary energy (heat and power), and another for transport. Each trio has supply, efficiency, and "intermediate" strategies.

Implementation of any one of these strategies is a complex undertaking involving policies, economics, and technologies; this DOE-QTR is concerned with DOE's efforts in the latter.

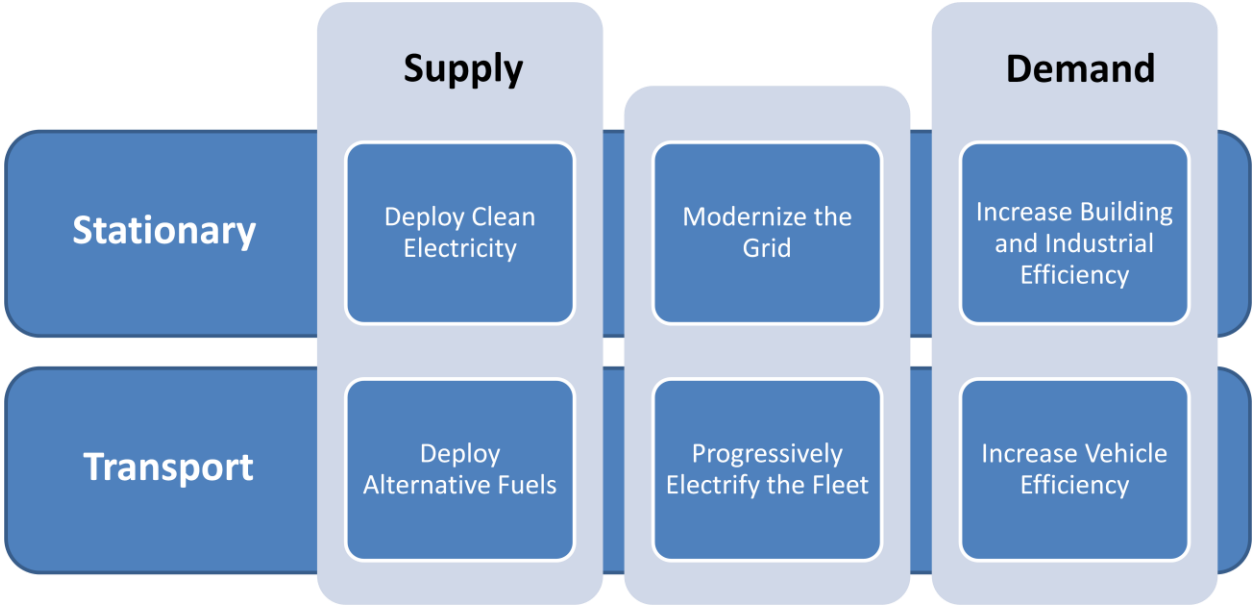

Figure 2. Six Strategies

7) Have we correctly identified and structured these six strategies?

The remainder of this framing document describes each strategy and its context, together with summaries of technologies we believe are important to that strategy. In each of the transportation and stationary sectors we begin with end-use efficiency, since improvements here will have the most immediate impact.

These sections are meant to solicit input on state-of-the-art, learning curves, and potential of each technology. In developing technology and policy priorities, future opportunities must compete on the quality of their ideas, the rigor of their technical approach, and the value of their knowledge return. Because of their importance in prioritization, technology assessments must be made within a systems context under realistic assumptions of scale, technology headroom, and economics. We believe the technologies and strategies discussed below meet the criteria of timeliness, and scale and should be central to DOE efforts going forward. Since we believe DOE's efforts best leverage the private sector in immature industries, our selection deemphasizes established energy sources such as conventional hydroelectric power and fossil fuels without carbon capture and sequestration. We welcome comment on our technology selection.

For each strategy or technology, we list source documents we intend to draw upon in assessing a technology's potential and in developing summary roadmaps towards its realization. In addition to the technology-specific reports listed in each section below, we will draw upon a number of cross-cutting reports and data: the National Academies of Science *America's Energy Future* reports, historical data from the EIA, the European Commission on Energy's *Strategic Energy Technology Plan*, and the *Global Energy Assessment*, when it becomes available.

8) We welcome comment on the selection of these technologies and sources, as well as suggestions of alternate technologies and sources, and updated technology, cost, and forecast data, particularly in rapidly-moving fields.

6.1 Transport

6.1.1 Increase Vehicle Efficiency

Powered almost exclusively by petroleum, U.S. road vehicles travelled three trillion miles in 2009 and consumed more than 150 billion gallons of liquid fuel. Vehicle miles traveled are projected to increase by 50% through 2035, although energy consumption by the fleet is projected to grow by only 20%.

U.S. fuel-economy in cars and light trucks (Light Duty Vehicles, or LDV) has been constant for 25 years, with continuously improving engine efficiency offset by growth in vehicle size, performance, and accessories. During this same period, European and Japanese fuel economics have improved steadily, so that their fleets are now 60% more fuel efficient than the U.S. fleet.

Significant opportunities remain for improving vehicle efficiency and fuel economy without adversely impacting performance, size, and other characteristics. Advanced internal combustion engines (ICEs) could improve efficiency by nearly 50% over today's gasoline engines, and additional opportunities to improve the fuel economy of vehicles with conventional ICEs abound (e.g., improved transmission gearing and reduced vehicle weight).

Beyond the fuel consumption by LDVs, medium- and heavy-duty vehicles (HDVs)—particularly freight trucks—consume an additional 30 billion gallons of diesel fuel per year. There are opportunities to reduce fuel consumption by up to 50% in these vehicles using conventional technologies, at a break-even fuel price of just over $1 per gallon. Given the rapid turnover of HDV stock, the freight sector can effect a significant near-term reduction of petroleum consumption.

The cross-cutting questions described in Section 5 should be considered while reviewing these technologies. DOE is particularly interested in feedback on the resources and reports that are listed with each technology, as well as the technology roadmaps described in the *America's Energy Future* reports. Although DOE does continuously track new information emerging from the field, we welcome all data that updates these references on questions of cost, projections, and non-technical barriers to deployment.

In developing roadmaps for all vehicle efficiency technologies, we will draw upon the following sources:

- DOE Vehicle Technologies Program, *Multi-Year Program Plan, 2011-2015*, 2010
- DOE EERE, *2008 Vehicle Technologies Market Report*, 2009
- National Research Council, *Assessment of Fuel Economy Technologies for Light-Duty Vehicles*, 2011
- National Research Council, *Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles*, 2010

6.1.1.1 Light-weight Materials

Light-weight materials like magnesium, aluminum, high-strength steel, and polymer composites can replace the cast-iron and traditional steel in vehicles to significantly increase fuel economy while maintaining safety, performance, and reliability. A 10% reduction in vehicle weight can increase fuel economy by 6–8%. Moreover, replacing traditional components with lightweight materials allows vehicles to carry advanced emissions control equipment, safety devices, power systems, and integrated electronic systems without an overall increase in weight.

For passenger vehicles, DOE is working to validate a cost-effective weight reduction of 50% in body and chassis systems by 2015 compared to a 2002 baseline, while maintaining safety, performance, and reliability. DOE funds research on a variety of lightweight materials, focusing on carbon fiber composites and magnesium. Through these activities, DOE aims to lower the cost of carbon fiber from the current $10–20 per pound to less than $5 per pound.

In developing roadmaps for lightweighting technologies, we will draw upon the following source:

- DOE Vehicle Technologies Program, *2009 Annual Progress Report for Lightweighting Materials*, 2009

6.1.1.2 Internal Combustion Engine Performance

ICEs power 240 million cars and light trucks on our nation's roads, and nearly all of the 10–17 million new vehicles sold each year. Many vehicles of the future, whether traditional combustion, hybrid-electric, or plug-in hybrid, will continue to rely on ICEs because of their relatively low cost, high performance, and ability to use diverse liquid fuels. Increasing the efficiency of ICEs is one of the most promising and cost-effective approaches to improving the fuel economy of our nation's vehicle fleet in the near- to mid-term. ICE thermal efficiency and emission reduction are being driven by innovations in low temperature combustion strategies, emission controls, and fuel injection. Key developments in combustion and emission controls plus low-sulfur fuel have enabled manufacturers to achieve the necessary emissions levels and introduce additional diesel-powered LDV models to the U.S. market.

DOE aims to facilitate improvement of LDV gasoline fuel economy by 25% by 2015 and of LDV diesel by 40% compared to a baseline 2009 gasoline vehicle. The program also aims to improve heavy truck fuel economy by 20% by 2015 and by 30% by 2018.

In developing roadmaps for combustion engine technologies, we will draw upon the following source:

- DOE Vehicle Technologies Program, *2009 Annual Progress Report for Advanced Combustion Engine Research and Development*, 2009

6.1.2 Progressive Electrification of the Vehicle Fleet

Electrification of the transportation sector is a significant opportunity to reduce petroleum consumption, lower GHG emissions, and reduce air pollution. Degrees of electrification range from mild and strong hybrid electric vehicles (HEVs), through plug-in hybrid electric vehicles (PHEVs), to battery electric vehicles (BEVs). More than 1.5 million HEVs have been sold in the U.S. since their introduction in 2005 and new hybrid models are introduced every year.

HEV powertrains are at least 50% more efficient than current gasoline internal combustion engines (ICEs), and do not require infrastructure upgrades. Grid-connected vehicles (PHEVs and BEVs) that further minimize fuel consumption have recently come to market. The first mass produced PHEV (Chevy Volt) and BEV (Nissan Leaf) began delivery in late 2010, and DOE has estimated that auto manufacturers will have the capacity to produce more than one million EVs by 2015. DOE is also supporting large demonstrations of 13,000 PHEVs and BEVs and 23,000 chargers in more than 20 cities around the country.

Partial electrification of the vehicle fleet combined with improvement in conventional vehicles could reduce domestic fuel consumption by more than 80 billion gallons per year in 2035. Estimating GHG reductions becomes more problematic as integration with the electric grid grows and the carbon footprint of future electric power becomes important.

The principal challenge to vehicle electrification continues to be the cost, performance, and physical characteristics of batteries. Other challenges include the supply of rare-earth elements for motors, local barriers to installing charging infrastructure, long charging times, and standardization of chargers and the grid interface. PHEVs and BEVs are both a challenge and opportunity for the grid. Large numbers of EVs could burden residential distribution transformers and reduce grid reliability. High EV penetration combined with smart charging could also provide distributed grid storage that enhances grid operability and reliability and allows for greater integration of renewable power.

As you review these technologies, please keep in mind the cross-cutting questions described in Section 5. DOE is particularly interested in feedback on the resources and reports that are listed with each technology, as well as the technology roadmaps described in the *America's Energy Future* reports. Although DOE does continuously track new information emerging from the field, we welcome all data that updates these references on questions of cost, projections, and non-technical barriers to deployment.

In developing roadmaps for all vehicle electrification technologies, we will draw upon the following sources:

- National Research Council, *Assessment of Fuel Economy Technologies for Light-Duty Vehicles*, 2011
- DOE Vehicle Technologies Program, *Multi-Year Program Plan, 2011-2015*, 2010

6.1.2.1 Batteries

The cost and performance of batteries are key factors determining the growth of electric drive. In 2010, more than 95% of lithium-ion batteries were made in Japan, China, and South Korea. The worldwide market for EV batteries is projected to grow to $8 billion by 2015. The Recovery Act included grants that are enabling companies to build the capacity to produce 50,000 EV batteries annually by the end of 2011 and 500,000 EV batteries annually by December 2014. This represents capacity sufficient to meet the requirements for projected U.S. EV production.

DOE's goal is to drive reduction in the cost of battery storage to $300 per kilowatt hour (kWh) by 2014, roughly half of current costs. This is being done through investments in RD&D of battery chemistries,

including both the mature family of lithium-ion batteries and other less mature chemical systems such as lithium metal polymer batteries and lithium sulfur batteries. ARPA-E supports 14 battery projects. The Recovery Act supported 30 new battery, electric drive, and electric vehicle manufacturing plants, and supported construction of more than 10,000 charging locations.

In developing roadmaps for battery technologies, we will draw upon the following source:

- International Energy Agency, *Technology Roadmap: Electric and plug-in hybrid electric vehicles*, 2009

6.1.2.2 Motors

Electric propulsion components can add significant price to vehicles that require 80–180 kilowatt (kW) motors. An electric motor and inverter, critical components of the electric drive power train, use the energy in the battery to move the EV. Permanent magnet motors are the most popular for EVs because of their high power density, specific power, and efficiency. These permanent magnets require rare earth metals, the supply and cost of which present a potential barrier to wide deployment of EVs.

The DOE aims to facilitate a reduction in the cost of an electric drive system to $12/kW ($7/kW for the motor) in 2015 and $8/kW ($4.70/kW for the motor) in 2020 with specific requirements and targets including power density, efficiency and lifetime. To achieve these metrics, DOE is supporting research, development, and demonstration to decrease cost, weight, volume, and improve thermal management of power electronics (inverters and capacitors) and electric motors.

In developing roadmaps for electric motor technologies, we will draw upon the following source:

- DOE FreedomCAR and Fuel Partnership, *Electrical and Electronics Technical Team Roadmap*, 2010

6.1.3 Alternative Fuels

For reasons of energy density, cost of production, and ease of transport and use, petroleum-derived gasoline and diesel dominate both domestically and globally. Despite improving vehicle efficiencies and progressive electrification, the U.S. is projected to continue to rely on liquid fuels for the foreseeable future, and certain segments of the transportation sector (e.g. HDVs, airplanes, and civilian ships) require the energy density of liquid fuels for effective operation. Use of alternative (non-crude-derived) liquid or gaseous fuels is therefore another strategy to reduce oil consumption.

The existing petroleum fleet is supported by an extensive infrastructure. Substitution of other fuels for petroleum products is therefore a significant challenge, as diverse alternative chemistries face a range of complications. Certain fuels are incompatible with existing infrastructure, and so require new infrastructures to be deployed, an expensive proposition for a sector that includes 250 million vehicles. Other fuels require significant resources and technology advances to achieve production at scale, and still others suffer from low energy density relative to petroleum-derived incumbents. Drop-in compatible alternative fuels (i.e., fuels that can be easily blended with or substituted for their petroleum-derived counterparts) therefore have a structural advantage.

As you review these technologies, please keep in mind the cross-cutting questions described in Section 5. DOE is particularly interested in feedback on the resources and reports that are listed with each

technology, as well as the technology roadmaps described in the *America's Energy Future* report on liquid fuels. Although DOE does continuously track new information emerging from the field, we welcome all data that updates these references on questions of cost, projections, and non-technical barriers to deployment.

6.1.3.1 Advanced Biofuels

Biofuels are substitutes for petroleum-based transportation fuels made by biologically or chemically converting renewable biological feedstock. In 2010, the U.S. produced an estimated 13 billion gallons of ethanol from corn grain, an 800% increase from 2000. The total global ethanol supply was estimated to be 22.5 billion gal in 2010. Biodiesel produced from oilseed crops peaked in 2008 at 691 million gallons and has declined since. These first-generation commercial biofuels total less than 5% of the fuels consumed for U.S. transportation, and interact significantly with food and feed markets.

Lignocellulosic biomass, on the other hand, derives from agricultural and forestry residues or dedicated energy crops. It is estimated that over 400 million tons of U.S. biomass annually is sustainably available today, and that the sustainable resource potential is over 1 billion tons annually. This estimate does not include potentially significant sources of non-terrestrial biomass such as algae. More than 35 biorefineries for lignocellulosic biomass are being designed and/or constructed in the U.S at pilot-, demonstration-, and commercial scales.

Possible biofuels include alcohols, other oxygenates, and drop-in hydrocarbons. There are multiple conversion pathways, including biochemical approaches that use a combination of chemical pretreatment, enzymatic hydrolysis and fermentation; gasification to convert biomass to synthesis gas intermediates; and pyrolysis and other liquefaction that convert biomass to liquid bio-oil intermediates.

DOE's program supports R&D to make cellulosic biofuels cost competitive with petroleum-based fuels. The Energy Independence and Security Act set a goal of 36 billion gallons per year of renewable transportation fuels by 2022, of which at most 12 billion may be corn ethanol. The Recovery Act supported the construction of 19 pilot, demonstration, and commercial-scale bio-refineries.

In developing roadmaps for advanced biofuel technologies, we will draw upon the following sources:

- 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
- DOE, *Biomass Program Multi-Year Program Plan*, 2010

6.1.3.2 Alternative Fossil Fuels

Both coal and natural gas can substitute for petroleum in transportation applications. The abundant domestic supply of both fossil fuels can address challenges associated with oil, although as with all forms of energy, there are environmental aspects to be managed and balanced.

In 2008, 150,000 vehicles (mostly buses and corporate-fleet vehicles) were powered by compressed natural gas (CNG) in the U.S. Natural gas must be compressed to meet the volume requirements of mobile applications, but even CNG takes considerable space in vehicles. Advantages for CNG as a

substitute for petroleum include engine efficiencies greater than those for gasoline and and the existing natural gas infrastructure for domestic and industrial applications.

Coal (with or without added biomass) and natural gas can be converted to syngas, which can be subsequently catalyzed into gasoline components, alternative diesel components, methanol, or dimethyl ether (DME) through a variety of proven chemical processes. Commercial deployment of methanol would require considerable new infrastructure, and methanol's corrosive and toxic properties raise environmental and health concerns. DME is a clean-burning drop-in substitute for diesel, but like other alternative fuels would require upgrades in infrastructure. Coal can also be liquefied directly to synthetic crude oil for subsequent refining.

The primary barriers to all of these conversion processes are scale, capital intensity, and environmental impact. Opportunities for technical improvement include gasification units, separation processes, catalysts, and CCS.

DOE currently has no activities related to alternative liquid transportation fuels from fossil feedstocks.

In developing roadmaps for alternative fossil transportation fuel technologies, we will draw upon the following source:

- California Institute for Energy and the Environment, *Natural Gas Vehicle Research Roadmap*, 2008

6.2 Stationary

6.2.1 Building and Industrial Efficiency

Industry consumes some 30% of U.S. energy, with residential and commercial buildings accounting for a further 40%. Energy efficiency improvements, whereby the same or better services are provided to the end user while consuming less energy, could therefore dramatically reduce energy demand, often with net economic benefit to the end user.

Changes in electrical energy demand directly affect the entire grid system, and can have benefits well beyond the economic value of reduced energy consumption for the consumer. By reducing energy demand, efficiency improvements enable utilities to serve more customers with the same infrastructure, thereby deferring large-capital upgrades to the bulk and distribution power systems. Demand response, where device power consumption is adjusted in response to the state of a larger system, can target efficiency to periods of peak stress where the operational value is often highest and opportunities for revenue generation are greatest.

As you review these technologies, please keep in mind the cross-cutting questions described in Section 5. DOE is particularly interested in feedback on the resources and reports that are listed with each technology, as well as the technology roadmaps described in the *America's Energy Future* report on efficiency. Although DOE does continuously track new information emerging from the field, we welcome all data that updates these references on questions of cost, projections, and non-technical barriers to deployment. The many and varied end uses of energy present a challenge to prioritization, and DOE

particularly welcomes input on Question 3 in Section 5.2.2 with respect to efficiency technologies and priorities.

6.2.1.1 Efficiency in Buildings

Residential and commercial buildings currently use about 40% of U.S. primary energy and 72% of U.S. electricity each year. Building energy use is dominated by heat generation (for air or water), moving heat from one place to another (air conditioning or refrigeration), and lighting. However, end-use devices account for a growing fraction of building electricity use. Direct fossil fuel (primarily natural gas and fuel oil) use in buildings is overwhelmingly for conditioning air and heating water.

Significant energy savings (likely over 20%) would be possible by deploying currently cost-effective technologies. However, the interdependence of building components makes it harder to estimate the potential for energy efficiency. For example, the building envelope, windows, and control systems impact the energy use required for heating, ventilation, and air conditioning (HVAC), and windows have a direct impact on lighting demand.

Building codes and standards govern building construction and have historically been concerned primarily with safety. Recent building codes and voluntary programs have increased attention on energy-efficient design and building operation. Equipment and appliance standards set minimum energy efficiency limits. Technology development and building codes and standards can work together to create beneficial feedback loops.

Building energy use can have two key interactions with the other stationary energy strategies described in this DOE-QTR. Some clean electricity technologies (particularly solar PV) can be installed in or on buildings to provide energy directly. This distributed energy generation changes the nature of the demands on the transmission and distribution grids. In addition, a modern grid system could implement demand response technologies that shed load rather than increase generation at times of high demand or decreases in production (such as from intermittent sources). Many building loads are well suited to participate in demand response.

DOE has identified five key technologies and loads in improving building efficiency.

6.2.1.1.1 Whole Building Design

Integrated approaches to whole building design that incorporate architecture/design, engineering, and construction for new commercial buildings have demonstrated up to 50% energy savings compared with current building codes. In 2006, the U.S. market for the construction and renovation of new and existing residential and commercial buildings was estimated to be approximately $1.22 trillion, which is over 69% of the value of all U.S. construction and over 9% of U.S. GDP.

DOE uses a systems engineering approach to assess and improve the efficiency of residential homes through its Building America program. Additionally, DOE is working with the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) and other stakeholders in commercial buildings to develop advanced energy design guides for commercial buildings that are 50% more efficient than minimum code requirements.

6.2.1.1.2 Energy Management Systems

A system-wide approach to reducing a building's energy consumption combines sensors, controls, feedback loops, and software that integrate information from smart end-use technologies with an intelligent grid. The building control systems market grew from $3.1 billion in the U.S. in 2001 to $4.3 billion in North America in 2008, while remaining approximately one third of the global market for building controls.

Within the U.S., centralized energy management and control systems operate in about 33% of commercial building floor space, all of which is contained within about 10% of commercial buildings.

Automated demand response (ADR) allows smart buildings to adjust energy consumption in response to changing energy prices from a smart grid. ADR has been enhanced by open protocols and wireless technologies, both of which have contributed to the ability of service providers to integrate systems and provide clients with valuable data. ADR has been successfully demonstrated.

DOE is supporting work across several technical pathways including commissioning, standards development, sensors, algorithms for automation systems, integration with existing buildings, and integration with the design and construction of new buildings.

6.2.1.1.3 HVAC and Water Heating

HVAC accounts for 32% of building energy use. U.S. shipments of central air conditioners and air-source heat pumps make up about 10% of the global market. Unitary air conditioners and heat pumps have improved in energy efficiency by more than 13% since 2005. DOE has a goal of driving a reduction of 80% in the energy consumption of commercial HVAC between 2004 and 2020.

Water heating accounts for 9% of building energy use. Efficient water heating includes solar and heat pump devices. These currently comprise about 0.25% of the 8–10 million water heaters installed each year, and about 1% of the 100 million installed in the U.S. Heat pump water heaters have very low global penetration. In solar water heating, however, China leads the world, followed by Australia and New Zealand, Europe, Japan, and the U.S. and Canada. DOE has a goal of driving a reduction of energy use for hot water service by 50% between 2005 and 2015.

6.2.1.1.4 Lighting

Lighting accounts for 14% of building energy use. Compact fluorescent (CFL) shipments increased from about 21 million units in 2000 to 400 million units in 2007, causing CFLs to account for the majority of "light service" sold in 2007. Though light-emitting diodes (LEDs) are still in early deployment stages, DOE projections indicate that a 1000-lumen LED source could cost $2 in 2015. DOE is supporting development of solid state lighting across two main pathways—LEDs and organic LEDs—and across the innovation chain via core technology research, product development, and manufacturing support. DOE's goal is to improve lighting costs from 22 to 118 lumens per dollar and increase lighting output from 78 to 154 lumens per watt by 2015. The Recovery Act supported 17 projects that advanced core technology research, product development, and manufacturing of solid-state lighting.

6.2.1.1.5 Building Envelope and Windows

The windows, roofs, attic, and insulation of a building forms an envelope that determines about 36% of overall building energy use through loss of heating and cooling energy. Efficient windows can reduce a building's heating and cooling demand by up to 35%. From 2005 to 2009, energy efficient windows with low-e (R-3) glass increased from 58% to 74% of all units sold in the residential market and from 37% to 54% of the commercial market. R-5 windows, as well as dynamic windows, are available and could enable system effects such as downsizing HVAC capacity. DOE is supporting activities to lower the cost of R-10 windows to $\$3/ft^2$ price premium by 2020, as well as aiming to improve foam insulation performance by 25-40% by 2015 and enable dynamic thermal response of attics and walls at no extra life cycle cost by 2015.

Cool roofs can reduce a building's heating and cooling demand by up to 15%. Cool roofs for commercial buildings have achieved widespread use in California and will be mandatory in hot climates (zones 1-3) after upcoming changes to the ASHRAE 90.1 standard. Cool roofs for residential buildings currently have a very low market share due to high price premiums.

In developing roadmaps for building efficiency technologies, we will draw upon the following sources:

- Interlaboratory Working Group, *Scenarios for a Clean Energy Future*, ORNL/CON-476 and LBNL-44029, 2000
- Dirks, J.A., et al., *Lost Opportunities in the Buildings Sector: Energy-Efficiency Analysis and Results*, PNNL-17623, 2008

6.2.1.2 Industrial Efficiency

The energy requirements of the industrial sector are significant and diverse, consuming about one-third of all energy produced in the U.S. Approximately two-thirds of the end-use energy is consumed by relatively few energy intensive subsectors including chemicals, refining, pulp and paper, iron and steel, glass, aluminum, metal-casting, and cement. Manufacturing remains a leading contributor to the U.S. economy; in 2009 it accounted for 11% of GDP and directly employed 14 million people, supplied 60% of U.S. exports, and produced nearly 20% of the world's output.

Best practices and deployment of commercially-available state-of-the-art manufacturing technologies to improve efficiency are the fastest routes to improved industrial efficiencies. There is significant headroom both to improve the efficiency of existing processes and technologies (such as through the use of high-efficiency motor systems and combined heat and power) and to develop new processes and technologies that require significantly less energy to perform the same service (such as new fiber or plastic that can replace metals in some applications).

Many cost-effective energy efficient technologies have not been widely adopted due to barriers that include insufficient access to industry-specific energy efficiency expertise and workforce, slow capital stock turnover and uncertainty of energy prices, which deter corporate energy efficiency investments. The National Academies has surveyed a range of studies that estimate industrial energy savings of more than 16% through deploying existing and emerging technologies by 2020. Including the energy-savings potential of combined heat and power increases these estimates to more than 20%.

Next-generation materials and associated production technologies are intended to reduce costs, reduce energy use, reduce pollution, and improve product quality. DOE's industrial technology program includes efforts in coatings, thin films, electrochemicals that require functional surface interactions; ceramics, engineered polymers, and metallics that operate in extreme environments; composites and smart materials integrated in energy systems; and substitutes for magnetic materials containing rare earth elements.

Next-generation manufacturing processes improve efficiency by reducing steps required, developing alternative low-energy pathways, and developing entirely new processes and unit operations. Novel methods are required to produce such energy-intensive materials as steel, chemicals, titanium, and carbon fiber. DOE supports development of new production systems, including innovative bioprocessing techniques, high-performance catalysts and separations, nano-scale manufacturing and processing, next-generation computational tools (including simulation), advanced characterization, integrated sensor and process control systems, and smart process manufacturing.

In developing roadmaps for industrial efficiency technologies, we will draw upon the following sources:

- The Minerals, Metals, and Materials Society, Linking Transformational Materials and Processing for an Energy-Efficient and Low-Carbon Economy: Creating the Vision and Accelerating Realization, *Vision Report of the Energy Materials Blue Ribbon Panel*, 2010, and *Opportunity Analysis for Materials Science and Engineering*, 2011
- Science and Technology Policy Institute, *The White Papers on Advanced Manufacturing Questions*, April 2010 draft

6.2.2 Modernize the Grid

The electrical grid is a large and complex system that moves 4 trillion kWh of electricity in the U.S. annually from more than 40,000 individual generating units through more than 150,000 miles of high voltage transmission lines to distribution systems that service more than 140 million customers. The physical nature of electricity links components together requiring real-time system balancing and every technology and action on the grid affects the rest of the system. Indeed, the utilities, independent power producers, system and transmission operators, and consumers all affect the same system, making forecasting the function, value, operation, and integration of new technologies in the system challenging, and leading to conservatism in the deployment of new technologies.

Much of the grid is based on an historical paradigm of large centralized generators connected to a bulk-energy transmission system, in which the distribution circuits that bring electricity into our homes and businesses are considered simple loads rather than integral components that contribute to overall system health. The system is designed for minimally acceptable operation at the extremes rather than the most efficient use of capital-intensive infrastructure. It is thus under-utilized and requires infrastructure upgrades despite having capacity to spare on most days. Additionally, because the grid evolved to accommodate generation and consumption technologies with physical characteristics different than those of today's technologies, power quality and reliability are compromised. The changing supply mix, increased demand requirements, and emerging vulnerabilities present

unprecedented challenges to grid operation. Any transition toward the energy resources and technologies of the future will be enabled, or limited, by the grid.

The introduction of plug-in EVs will conjoin the transportation and stationary energy systems in an unprecedented manner (see 6.1.2), and distributed generation and actively managed distribution networks will require increased connectivity in both the electrical and telecommunications realms. Smart grid technologies are allowing system operation and engagement all the way to the customer, creating a distribution system with a level of flexibility not previously attainable. The ability to understand and control aspects of both the bulk power and distribution systems in real time will allow full exploitation of new technologies ranging from renewable generation, to efficiency and dynamic response of distribution networks, to EVs, all while supporting the power quality and reliability that is required by modern loads and consumers.

The broader objectives of "grid modernization" are to provide access to new energy resources while simultaneously increasing system utilization and flexibility. While specific needs may vary between the bulk power and distribution systems, the overall needs for improved system control and protection are common.

As you review these technologies, please keep in mind the cross-cutting questions described in Section 5. DOE is particularly interested in feedback on the resources and reports that are listed with each technology, as well as the technology roadmaps described in the *America's Energy Future* reports. Although DOE does continuously track new information emerging from the field, we welcome all data that updates these references on questions of cost, projections, and non-technical barriers to deployment.

In developing roadmaps for all grid technologies, we will draw upon the following sources:

- DOE, *National Transmission Grid Study*, 2002, and associated the Issue Papers, particularly Section F: *Advanced Transmission Technologies*, 2002
- DOE Electricity Advisory Committee, *Keeping the Lights On in a New World – A Report by the Electricity Advisory Committee*, 2009

6.2.2.1 Monitoring, Modeling, and Control

Improving system flexibility across multiple timescales is important to enable system-wide improvements in asset utilization and to accelerate the integration of new technologies. New smart grid technologies that enable monitoring and control of critical electric system parameters are dramatically expanding visibility and flexibility throughout the system.

Phasor measurement units (PMUs) with data sampling rates in excess of 30 Hz, a 100x improvement of over legacy supervisory control and data acquisition systems, will allow users to observe and analyze the bulk power system in real-time. The deployment of advanced metering infrastructure could eventually turn each point of consumption into an active informational stream, thereby enhancing real-time grid monitoring capability. The Recovery Act supported the installation of 18 million smart meters and more than 850 PMUs.

The wealth of operational data provides significant opportunity to improve our models and understanding of the grid. The complexity and interdependencies associated with the electric system result in system-wide dynamic engagements that require improved knowledge and prediction of performance beyond today's capabilities. Modeling, simulation, and forecasting enable improved understanding of issues from operation through planning, and especially the interaction of the interconnected elements.

Leveraging advances in both monitoring and modeling to enable control points across the system will improve reliability and asset utilization. New real-time analysis tools and control protocols will be required, although attention must be paid to concerns over privacy and consumer preference.

In developing roadmaps for grid monitoring, modeling and control technologies, we will draw upon the following source:

- DOE and FERC, *Steps to Establish a Real-time Transmission Monitoring System for Transmission Owners and Operators Within the Eastern and Western Interconnections: A Report to Congress Pursuant to Section 1839 of the Energy Policy Act of 2005*, 2006

6.2.2.2 Power Electronics

New developments in power electronics devices, such as voltage control equipment and volt ampere reactive compensators will provide utilities with the ability to more effectively deliver power to their customers while increasing reliability of the bulk power system. Power electronics enable power flow control and energy conversion, critical to the efficient movement of electricity from generation resource to the consumer. Advances in power electronic devices include both technologies that are new to the grid and evolutionary improvements in existing technologies, both involving the development and deployment of new materials. Overcoming the limitations of silicon-based semiconductors (which include low voltage blocking capability, low switching speeds at high power, and limited junction operating temperature) would enable new technologies. DOE is supporting research in large-bandgap materials.

In developing roadmaps for power electronics technologies, we will draw upon the following source:

- L. M. Tolbert et al., *Power Electronics For Distributed Energy Systems and Transmission and Distribution Applications*, ORNL/TM-2005/230, 2005.

6.2.2.3 Energy Storage

The core function of energy storage is to bridge the gap between the characteristics of the generation, load, and control technologies. The physical characteristics of energy storage technologies govern their most useful applications, and despite the large number of technologies available for storing energy, each technology is best suited to a limited subset of applications and services.

Optimal deployment of storage will require assessment and analysis of technology characteristics, possible system configurations, and service value. Departmental goals in energy storage are to understand how to optimize system integration, to improve performance of storage systems relevant to

their most appropriate application, and to develop the manufacturing innovations necessary for cost-effective storage technologies. The Recovery Act supported the development of two utility-scale energy storage facilities.

In developing roadmaps for energy storage technologies, we will draw upon the following sources:

- DOE Electricity Advisory Committee, *Bottling Electricity: Storage as a Strategic Tool for Managing Variability and Capacity Concerns in the Modern Grid – A Report by the Electricity Advisory Committee*, 2008
- DOE, *Electric Power Industry Needs for Grid-Scale Storage Applications*, 2010
- *Electric Power Research Institute and DOE, EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications*, 2003, and its sup*plement, EPRI-DOE Handbook Supplement of Energy Storage for Grid Connected Wind Generation Applications*, 2004
- DOE, *Advanced Materials and Devices for Stationary Electrical Energy Storage*, 2010

6.2.3 Adoption and Deployment of Clean Electricity Supply

Approximately 50% of our electricity is generated from coal, 20% from nuclear, 20% from natural gas, and a further 10% from renewable resources such as hydropower and wind. The conventional fossil energy technologies that dominate the system (i.e. coal and natural gas) provide a variety of services, including base-load and grid regulation, and are simultaneously consistent and dispatchable to respond to changing loads. However, their environmental impacts can include particulate, mercury, and GHG emissions, and consumption of 27% of non-agricultural fresh water.

There are many alternative generation technologies, each with benefits and challenges relative to the incumbent mix. Renewable technologies such as wind and solar are non-polluting and require little water; successful deployment of carbon capture and storage (CCS) technologies would dramatically reduce the emissions associated with coal and gas. Because the final product of a new generation technology (power into the grid) is indistinguishable from that of legacy technologies, clean energy technologies face considerable hurdles in displacing incumbent technologies, ranging from cost to performance. Recent innovations in extraction, partially driven by DOE research contributions a decade ago, have made natural gas a low-cost power method, and it will likely set cost benchmarks going forward. The low energy density (both per unit area and per project) of renewable resources relative to fossil or nuclear plants requires expansive deployment, often elevating costs and regulatory hurdles beyond conventional technologies. The opportunity to deploy generation in a distributed manner presents opportunities to lower cost burdens to entry of new technologies and provide resilience compared to centralized energy generation, but will require substantially different deployment strategies. New technologies using conventional resources (e.g. CCS and nuclear) are often more expensive to build and operate than their legacy counterparts, with uncertain technical performance.

Beyond cost, the overall conservative and regulated nature of our utility sector places a very high burden on entry of new technologies. The variability of renewable resources, with fluctuations on timescales ranging from seconds to years, is in tension with the desire of system operators to control generator output. A properly designed power system incorporating distributed generation will be

fundamentally more robust than the current system, thereby providing significant benefit and resilience to operators and consumers alike. Given the great projected rise in power demand in non-OECD nations, domestic development and deployment of alternative generation technologies can enhance the global competitiveness of the U.S. economy.

As you review these technologies, please keep in mind the cross-cutting questions described in Section 5. DOE is particularly interested in feedback on the resources and reports that are listed with each technology, as well as the technology roadmaps described in the *America's Energy Future* reports. Although DOE does continuously track new information emerging from the field, we welcome all data that updates these references on questions of cost, projections, integration into the grid, land and water use, and non-technical barriers to deployment.

6.2.3.1 Nuclear Energy

Nuclear power plants use the energy released by fission to produce heat, which then drives a turbine to generate electricity. Twenty percent of electricity produced in the United States comes from nuclear power. There are 104 operating reactors in the U.S. with a combined capacity of 101 GW. The NRC is in the process of reviewing 17 applications to build 26 new reactors with a combined capacity of 34 GW. Globally, 442 reactors are in operation with an additional 65 under construction, the majority of which are in Asia. Known uranium reserves would be more than sufficient to expand nuclear generation by a factor of ten over the course of decades.

Reactors are generally operated at constant output to maximize economic return on the high capital investment, and the capacity factor of nuclear energy (over 0.9) is the highest for any current generation technology. This rigid output prevents nuclear plants from providing dispatchable power.

The oldest nuclear power reactors still operating were built in 1969, and the last reactor built in the U.S. began operation in 1996. Pre-1980 reactors were smaller and had a lower cost per kW installed than those built after 1980. Improvements in operational performance have allowed reactor operators to extend their operational lifetime—sixty-one reactors have received 20-year license renewals from the NRC with an additional 21 currently under review and 17 more that have indicated their intent to apply for renewals.

U. S. utilities are currently proposing to construct Generation 3+ units, with the first expected to be completed by 2016. These are based upon the same light-water reactor technologies in use today, with improved safety and economic characteristics. They require large steel components that can be produced only in a few factories around the world, all of which are located abroad. Small modular reactors (SMRs) have the potential to lower the hurdle for construction financing while leveraging factory construction techniques to lower costs.

International nuclear development has diminished the importance of U.S. nuclear suppliers, and all major U.S. reactor vendors are either owned by or closely aligned with foreign companies. In addition, South Korea may begin exporting SMRs before U.S. suppliers. As more players emerge in the global nuclear power arena, the U.S. must lead engagement with international regulatory bodies to ensure safety and security throughout the nuclear fuel cycle.

DOE supports the continuing operation of existing plants through its Light Water Reactor Sustainability program and the Modeling and Simulation Hub. The DOE program to accelerate SMR development will provide financial support to reactor developers to reach commercialization while the DOE SMR R&D efforts will help to enable the NRC to establish the regulatory basis for SMR licensing. DOE is supporting development of Generation IV and Generation V reactor designs.

In developing roadmaps for nuclear technologies, we will draw upon the following sources:

- Congressional Budget Office, *Nuclear Power's Role in Generating Electricity*, 2008.
- Massachusetts Institute of Technology, *The Future of Nuclear Power: An Interdisciplinary MIT Study*, 2003, and the *2009 Update* to this report.
- Massachusetts Institute of Technology, *The Future of the Nuclear Fuel Cycle: An Interdisciplinary MIT Study*, 2010.
- University of Chicago, *The Economic Future of Nuclear Power*, 2004.

6.2.3.2 Wind

Wind turbines convert airflow directly to electricity. The capacity factor for wind power can be as much as 0.44 for new generation at good sites, but averages ~0.3 across the U.S. Wind power can be used as a distributed generation technology, but because of the size and area requirements it is more typically installed on the utility scale, and can be installed either on- or offshore. The U.S. wind resource is most dense in mountain areas (including the Rockies and Appalachians), in the Great Plains, and in some offshore locations.

Global wind power installations increased by 35.8 GW in 2010, bringing total installed wind capacity up to 194 GW, a 22.5% increase from the end of 2009. China currently has the most installed wind power capacity. In the U.S., just over 5 GW of new wind power capacity was added in 2010, bringing the total installed capacity to 40.2 GW. Wind power now provides over 2% of the nation's annual electricity generation. No offshore projects have yet been built in the U.S.

Over the past 25 years, wind turbine nameplate capacity has increased from about 50 kW to 1.5–3 megawatts (MW) for land-based wind turbines. Offshore wind turbines as large as 5 MW are being deployed, and even larger turbines are under consideration. Continued scaling of rotor size and tower height will increase energy capture, while advanced control and condition monitoring technology will lower installation costs and increase reliability. Installed costs could be further reduced through decreased component weight and simplified transportation logistics. Offshore wind requires further development of turbines, installation, and monitoring mechanisms designed for the marine environment.

The availability of fiberglass, carbon fiber, and permanent magnets (i.e., rare earth minerals) may present long-term barriers to continued scaling and deployment of wind energy. Non-technical barriers to wind deployment include transmission availability at remote locations, noise and viewshed concerns, danger to wildlife, and siting and permitting requirements.

DOE's goals are to facilitate wind deployment and decrease the cost of electricity for onshore and offshore wind systems to $0.036/kWh by 2012 and 0.07/kWh by 2014, respectively. The Recovery Act supported over 8 GW of wind capacity installation, more than 50 wind-related manufacturing projects, and development of innovative wind technologies and test facilities.

In developing roadmaps for wind technologies, we will draw upon the following sources:

- Musial, W. and Ram, B., *Large-Scale Offshore Wind Power in the United States: Assessment of Opportunities and Barriers*, NREL/TP-500-40745, 2010
- DOE EERE, *2009 Wind Technologies Market Report*, DOE/GO-102010-3107, 2010
- DOE EERE, *20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply*, DOE/GO-102008-2567, 2008.

6.2.3.3 Concentrating Solar Power

Concentrating solar power (CSP) systems use mirrors to focus the sun's energy onto receivers in which a heat-transfer fluid is heated; that heat ultimately drives a turbine to generate power. CSP is suited for utility-scale generation, and could be base-load generation if long-term thermal storage is incorporated. The average capacity factor of new CSP generation is 0.3. Short-term storage (30 minutes to 1 hour) reduces the impact of thermal transients (such as clouds), while long-term storage (4–16 hours) can increase the system capacity factor (up to 0.7). The CSP solar resource in the U.S. is geographically concentrated in the desert southwest.

Between 1985 and 1991, 354 MW of solar trough technology were deployed in southern California. These plants are still in commercial operation and have demonstrated the longevity of CSP technology. In the U.S., 431 MW of CSP were in operation in 2009, generating about 0.03% of U.S. electricity, and there are more than 8 GW of CSP projects with signed power purchase agreements. Spain has 435 MW of commercial CSP generation and an additional 2 GW under development, and there are significant markets in the Middle East and North Africa.

CSP technology without thermal storage is relatively mature; integration of thermal storage is an area of active technical development. In addition, new technologies could reduce the use of water in CSP plants (as well as water use in other thermal power generation technologies). The DOE program aims for cost reductions to less than $0.10/kWh, which could make CSP competitive in the intermediate load market without subsidies by 2020.

In developing roadmaps for solar CSP technologies, we will draw upon the following sources:

- GTM Research, *Concentrating Solar Power 2011, Technology, Markets, and Trends*, 2009
- Mehos, M., D. Kabel, and P. Smithers, "Planting the Seed—Greening the Grid with Concentrating Solar Power." IEEE Power & Energy, 7 (3), 55-62, 2009
- SolarPACES/ESTELA/Greenpeace, *Concentrating Solar Power Global Outlook 2009 - Why Renewable Energy is Hot*, 2009.
- Turchi, C., M. Mehos, C.K. Ho, and G.J. Kolb, *Current and Future Costs for Parabolic Trough and Power Tower Systems in the U.S. Market*, NREL/CP-5500-49303, 2010.

6.2.3.4 Solar Photovoltaic

Solar photovoltaics (PV) use semiconductors (such as silicon or thin-film materials) to convert sunlight directly into electrical energy. They can be deployed at both utility (field) and distributed (rooftop) scales. The average capacity factor of new solar PV is ~0.2, with peak generation in daytime. The total solar resource exceeds U.S. energy consumption, although the intermittent nature of that resource requires new paradigms of energy management. The greatest resource density is in the desert southwest, although the resource is significant across the southern tier of the U.S. and the Great Plains.

Global solar PV installations reached nearly 37 GW at the end of 2010, growing at an annual rate of almost 40% over the past decade. U.S. PV capacity grew at similar rates to approximately 2.0 GW in 2010, but nearly 70% of the world's solar capacity is in Europe. Even with this growth, PV currently supplies less than 0.1% of US electricity.

The U.S. solar industry has grown into a $6 billion market, the majority of which is solar PV. However, the U.S. share of global PV manufacturing has fallen from nearly 46% in 1995 to 6% in 2008. China, the world leader, manufactured nearly 9 GW of solar PV in 2010, compared to roughly 900 MW produced in the U.S.

Cost is currently the major barrier to greater solar PV deployment. Improvements in cell efficiency, along with advances in manufacturing and the balance of the PV system, can drive down deployment costs. DOE's PV program aims to facilitate cost reduction to $1/W for utility-scale installations by 2020 through activities on three key components: the module, the power electronics, and the balance of system. At that cost, widespread deployment is expected. The Recovery Act supported the construction of PV manufacturing facilities and the deployment of 322 MW of PV capacity.

In developing roadmaps for solar PV technologies, we will draw upon the following sources:

- International Energy Agency, *Technology Roadmap: Solar photovoltaic energy*, 2010

6.2.3.5 Carbon Capture and Storage

Carbon capture technology removes CO_2 from fossil fuel combustion product stream for potential geologic storage, thereby reducing GHG emissions. Fossil fuels supply 80% of the world's energy, and coal accounts for 25% of world energy supply and 40% of global carbon emissions. The U.S. possesses 1/4 of the known coal resource, and the U.S., Russia, China and India together account for 2/3 of world reserves. The existing and predicted coal-burning energy infrastructure in these countries implies substantial continued coal use in the next few decades.

Currently available CCS technologies are neither cost-effective nor demonstrated with electric generation. The highest-cost CCS step is CO_2 capture, due to the added capital cost and energy required to release the CO_2 from the chemicals that extract it from the combustion flue gas and the subsequent compression. A new generation of capture technologies is under development with DOE support, and DOE expects them to be ready for demonstration by 2015. If these are successful, CCS could be an economically viable GHG reduction option by 2020. Assigning a monetary value to the reduction in CO_2

emissions would provide a market incentive to further improve and deploy CCS technologies. Multiple technology paths are being pursued in an effort to maximize the likelihood of commercial success.

Another challenge to CCS deployment is demonstrating CO_2 storage. This will require comprehensive characterization and monitoring of geologic CO_2 storage sites and the ability to predict underground behavior, migration, and trapping of CO_2 as well as a legal regime that addresses allocation of long term potential liabilities associated with storage. Injection of CO_2 has long been used to enhance oil recovery.

DOE supports the development of 5–10 commercial-scale CCS demonstration projects in the U.S. by 2016 for both retrofit and new-plant applications; these projects have been funded in part by the Recovery Act. DOE's RD&D aims to reduce costs by improving overall power plant efficiency and reducing cost for CCS systems. DOE is also supporting research in CO_2 storage that will lead to the reduction and quantification of risks. DOE participates in several international collaborations to develop and demonstrate CCS technologies.

In developing roadmaps for CCS technologies, we will draw upon the following sources:

- *Report of the Interagency Task Force on Carbon Capture and Storage*, 2010.
- Massachusetts Institute of Technology, *The Future of Coal: Options for a Carbon-Constrained World*, 2007.

6.2.3.6 Other Clean Electricity Supply Technologies

DOE expects that each of clean electricity supply technologies described above could contribute significantly to meeting the Nation's energy goals, and DOE RD&D support has the potential to materially improve these technologies. Other clean electricity supply technologies could also contribute to varying degrees; these include hydroelectric, marine, and geothermal power technologies. Increasing the deployment of hydroelectric power is expected to consist largely of deploying evolutionary technologies, where DOE RD&D would not play a significant role. Geothermal and marine power technologies face uncertainties that exceed those of the previously discussed clean power technologies, including uncertainty in the materiality of their impact.

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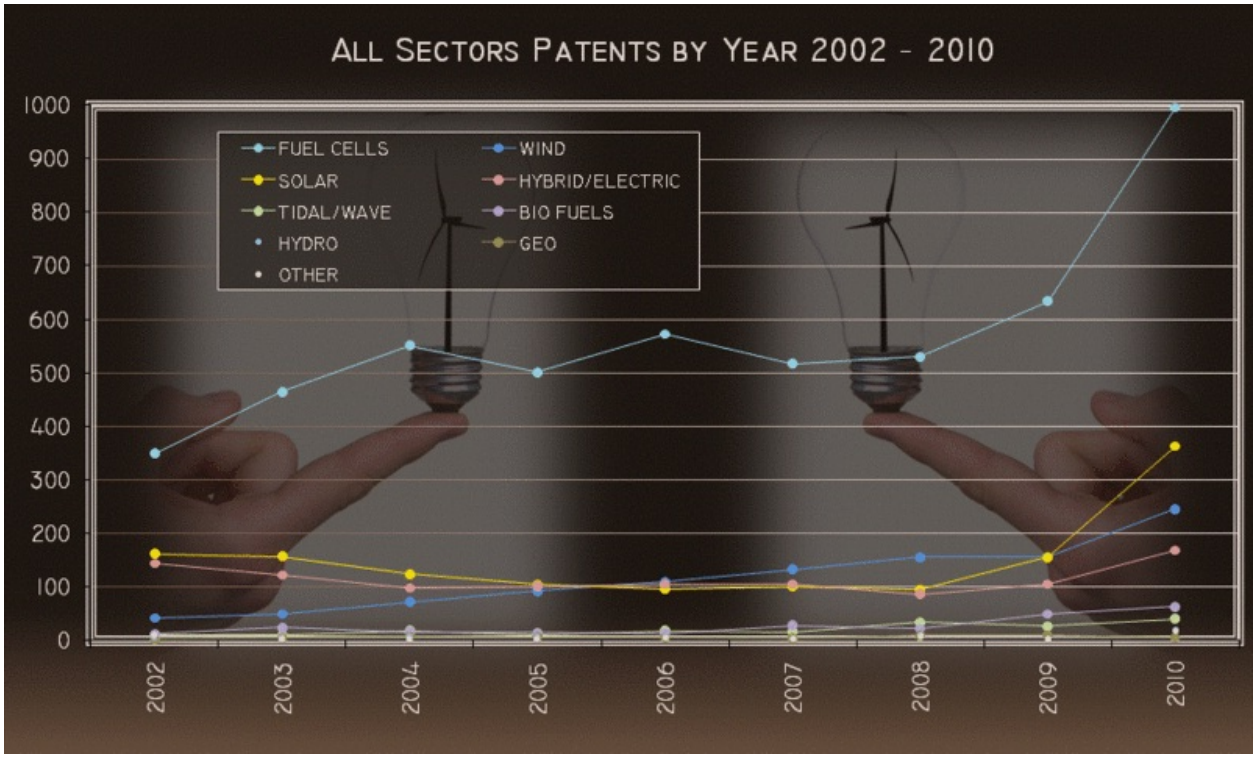
[1] Some estimates are higher; Intertechpira, a private analyst, puts the figure at $2 billion in 2009.

[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]

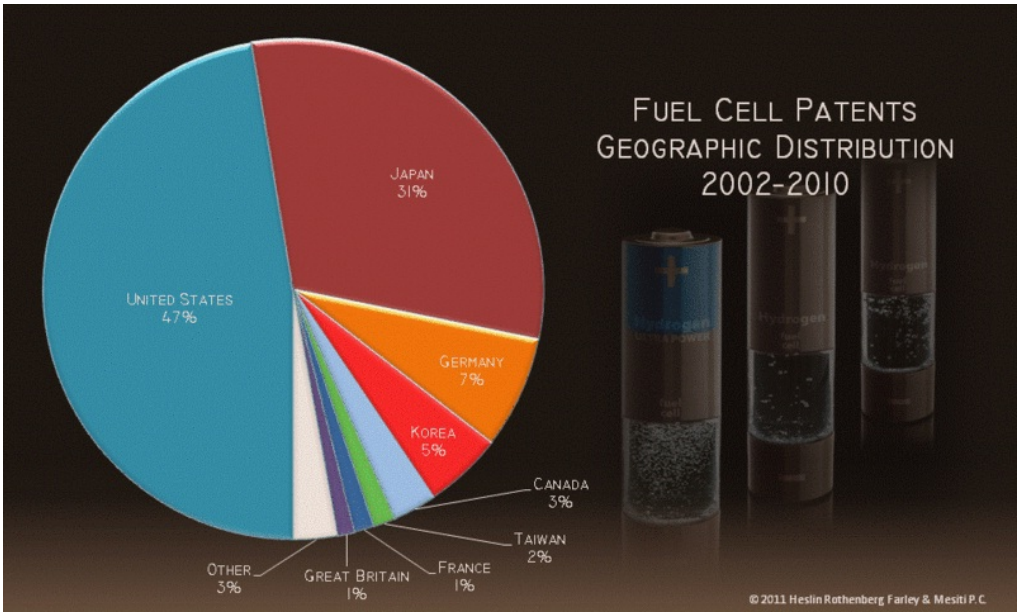
4. Improving the quality and security of the power grid by offering a storage option for intermittent generation and increasing operators' flexibility.[9]

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.

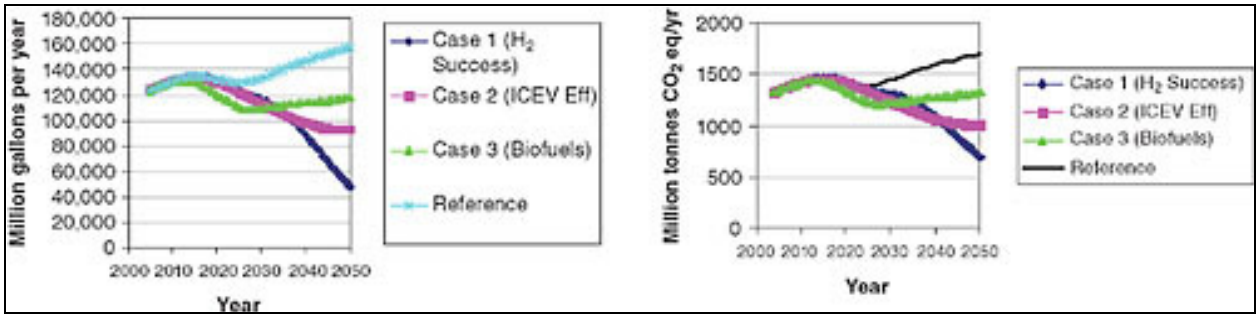


Figure 2. **Comparison of annual greenhouse gas emissions (as equivalent CO_2).** The left figure shows the Reference Case (light blue), ICEV Efficiency Case (pink), Biofuels Case (green), and Fuel Cell Success Case (dark blue). No single approach reaches an 80% reduction by 2050. Right: Comparison of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

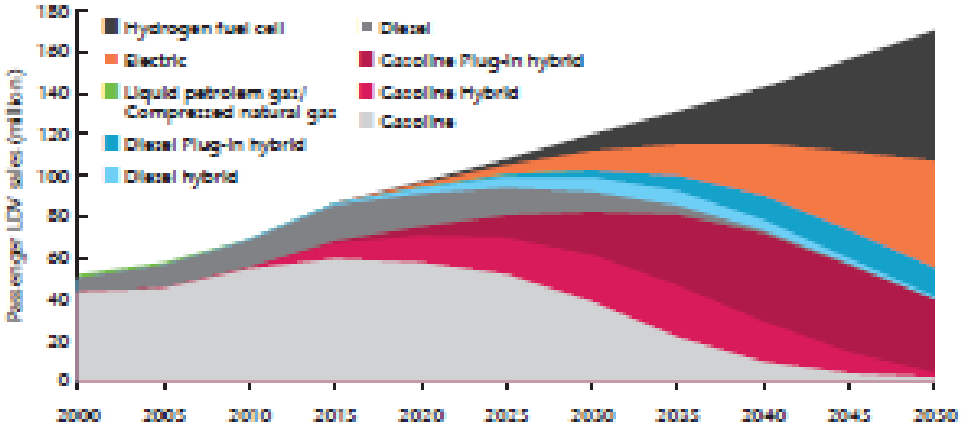
  “As technology moves from HEVs to PHEVs and then to battery electric vehicles (BEVs) and fuel cell electric vehicles (FCVs), the Electrical and Electronics Technical Team (EETT) is charged with advancing the technologies required to make electrically driven transportation preferred to today‘s petroleum-fueled 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)

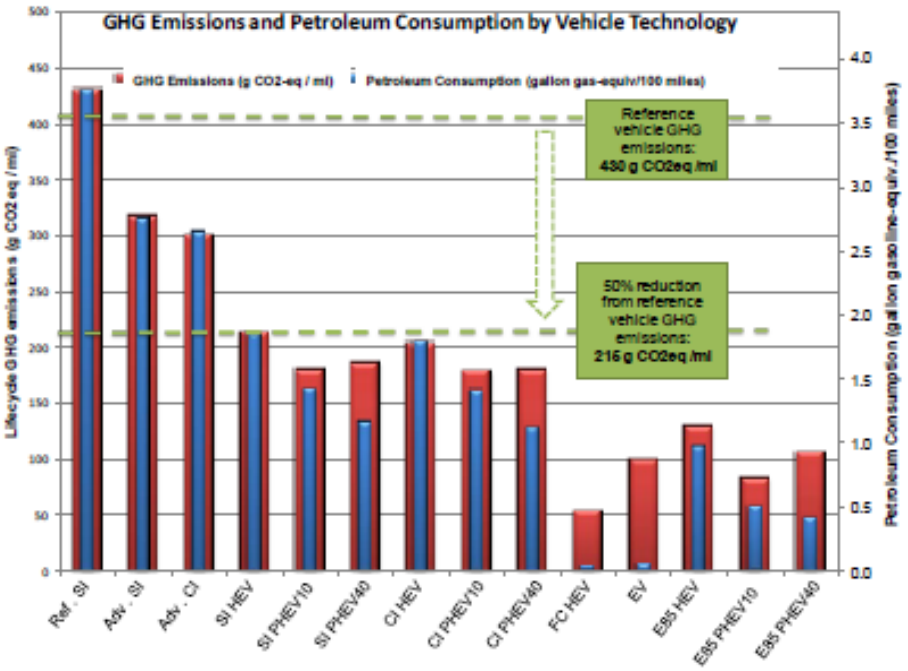


Figure ES-1.GHG Emissions and Petroleum Consumption by Vehicle Technology Projected to 2030

Legend:

Ref. SI – reference spark-ignition gasoline engine vehicle
Adv. SI – advanced spark ignition gasoline engine vehicle
Adv. CI – advanced compression-ignition diesel engine vehicle
SI HEV – spark-ignition gasoline engine/hybrid electric vehicle
SI PHEV10 – spark-ignition gasoline engine/plug-in hybrid electric vehicle (10-mile all electric range)
SI PHEV40 – spark-ignition gasoline engine/ /plug-in hybrid electric vehicle (40-mile all electric range)
CI HEV – compression-ignition diesel engine/hybrid electric vehicle
CI PHEV10 – compression-ignition diesel engine/plug-in hybrid electric vehicle (10 mile all electric range)
CI PHEV40 – compression-ignition diesel engine/plug-in hybrid electric vehicle (40-mile all electric range)
FC HEV – fuel cell/hybrid electric vehicle
EV – electric vehicle
E85 HEV – 85% biomass-gasoline blend/hybrid electric vehicle
E85 PHEV10 – 85% biomass-gasoline blend/plug-in hybrid electric vehicle (10-mile all electric range)
E85 PHEV40 – 85% biomass-gasoline blend/plug-in hybrid electric vehicle (40-mile all electric range)

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)

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)
    - "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)

Congress of the United States
Washington, DC 20515

April 15, 2011

The Honorable Steven Chu
Secretary
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585-0001

Dear Secretary Chu:

As co-chairs of the Hydrogen & Fuel Cell Caucus, we write today in support of the fuel cell and hydrogen energy programs within the Department of Energy (DOE). With the enactment of the Fiscal Year 2011 Continuing Resolution, it is clear the Obama Administration and Congress recognize the need to control excessive government spending. Under the bipartisan agreement, funding for DOE programs have been reduced by 5% for the remainder of the current fiscal year compared to the amount provided by Congress in FY10. While we understand this reduction will result in funding cuts for numerous DOE programs, we encourage you to ensure critical fuel cell and hydrogen energy programs are not disproportionately cut or eliminated.

While funding reductions for these programs are certainly expected, we are concerned disproportionate cuts would inhibit the long-term diversification of our nation's energy portfolio and stunt the development of domestically-produced energy systems powered by hydrogen and fuel cells. We share your belief that reasonable investments in clean energy technology can spur job creation through the growth of new and emerging American industries. However, disproportionate cuts to fuel cell and hydrogen programs would discourage manufacturers, private sector investors, suppliers, and potential customers from fully embracing this promising new technology.

As you know, the fuel cell and hydrogen energy programs within DOE are among its most successful. Within the Office of Fossil Energy (OFE), the Solid-State Energy Conversion Alliance (SECA) has met or exceeded every benchmark established by Congress and DOE since its creation. This public-private partnership, in which industry has contributed three dollars for every dollar of government funding, has helped decrease the cost of solid oxide fuel cells (SOFCs) tenfold, while dramatically increasing their efficiency and durability.

Additionally, we are on the verge of the full scale commercialization of fuel cell systems and hydrogen energy technologies in stationary, backup power and material handling equipment applications, thanks in part to the success of the Fuel Cell Technologies Program within the Office of Energy Efficient and Renewable Energy (EERE). In the case of mobile fuel cells, several auto manufacturers are planning for commercial fuel cell electric vehicle (FCEV) launches beginning in 2014-2015. This program is helping drive down the cost of fuel cell

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systems and hydrogen infrastructure, while familiarizing Americans with these new clean energy technologies.

Fuel cells and hydrogen energy systems must continue to play an important role in our nation's energy diversification. From new clean vehicle technology to stand-alone power generation for military installations, universities, and hospitals, fuel cell and hydrogen technologies are on the cusp of revolutionizing the way we use energy in the United States. We urge you to resist implementing disproportionate cuts to these programs and support true domestic energy diversification.

We look forward to working with you on this critical issue.

Sincerely,

Rep. Charles W. Dent	Rep. Michael F. Doyle	Rep. John B Larson
Co-Chair, H2FC Caucus	Co-Chair, H2FC Caucus	Co-Chair, H2FC Caucus

The Hydrogen and Fuel Cell Technical Advisory Committee

Washington, D.C.

March, 2011

The Hon. Dr. Stephen Chu
Secretary of Energy
U.S. Department of Energy
1000 Independence Ave. SW
Washington, DC 20585

Dear Mr. Secretary:

It is with great pleasure, but with some dismay, that we enclose with this letter the 2010 Annual Report of the Hydrogen and Fuel Cell Technical Advisory Committee (HTAC). Our pleasure comes from being able to report to you on the robust accomplishments of the past year in the hydrogen and fuel cell (HFC) industry, and our dismay is that the Department's Hydrogen and Fuel Cell Program has been singled out for major cuts in funding in the proposed 2012 budget, when all other significant energy options have received increases. We hope that as you read our report you will come to share our view that the HFC option offers one of the most attractive ways to achieve critical objectives of your Department and the Obama Administration:

- Reduce our dependence on foreign oil,
- Enhance energy security,
- Reduce greenhouse gas emissions, and
- Create high quality green jobs here at home.

Our Committee's considered view on these points has been reinforced by a number of important reports prepared by prominent independent experts, both here in the US and in other countries – reports that we have studied carefully and which are summarized in this and our two previous Annual Reports. We believe the Hydrogen and Fuel Cell Program should be supported vigorously.

As is abundantly clear from our Annual Report, R&D on hydrogen and fuel cell technologies over the past few years has led to the development of products that are being adopted in commercial material handling, telecom, and building system applications today. These commercial deployments make it obvious that HFC products are a currently available option – not some distant dream.

In addition, other nations, notably Japan, Korea, China, and the European Union (EU), have made very public policy and financial commitments, memorialized in government-industry compacts and MOUs, to bring hydrogen and fuel cell vehicles (HFCVs), and the infrastructure to fuel them, to market in 2015 or earlier. Already these nations are aggressively preparing for the 2015 roll-out, with a rapidly growing hydrogen infrastructure and numerous hydrogen-powered pre-commercial vehicles already on the road, while the US has far fewer HFCVs and a very modest network of refueling stations to date. Companies that operate in these hydrogen-friendly nations will become the technology leaders of the future. These companies will spend the next 5 to 10 years perfecting designs and driving cost out of the fuel cell and hydrogen infrastructure. This is a substantial threat to U.S.-based companies that will be forced to go off-shore for critical HFC technologies or face substantial competitive headwinds.

We urge you to reconsider the decision to cut back on funding for our nation's HFC program, which has been so successful in meeting its objectives, at this critical moment when the technology is rapidly emerging into commercial markets and HFC products are successfully crossing the "valley of death," where the first generation technologies are inherently more expensive. The World's automotive companies are already ramping up their supply chain for HFCV production launches in just a few short years. We on your Advisory Committee feel that the decision to slash one of the most successful programs in EERE defies logic and is seriously ill-advised. We are deeply concerned that it:

- Will ultimately cause the country to lose its competitive position in what is clearly seen as a massive market opportunity by other nations. We have already allowed that to happen in other energy technologies and we should not let it happen again. We must choose to lead, or resign ourselves to the reality that these technologies will be controlled by foreign governments and companies. If US consumers ultimately end up buying HFCVs only from foreign automakers, that will be a sad outcome indeed.
- Sends a negative signal to the financial community about investing in continued HFC innovation, and will likely drive the emerging supply chain off-shore as well, both of which will negatively impact current HFC jobs (around 30,000) and constrain future growth (projected by DOE's own analysis to be up to 675,000 HFC industry jobs by as early as 2035).
- Will limit our ability to take full advantage of intermittent renewable resources. When the penetration of wind and solar grows beyond the 20 to 30 percent levels, the electricity grid encounters stability challenges that require effective energy buffers. Many state RPS programs already on the books mandate these penetration levels, making storage options essential. Hydrogen production offers an attractive way to capture the value of these renewables when the grid cannot accept their output. The EU and Japan are already aggressively working on projects to use hydrogen as a way to capture stranded wind capacity and shift solar output to the utility system peak.

Our hope is that you will make it a personal goal to look carefully at the reality of what is going on in the HFC industry. We suggest that you consider:

- Driving as many as possible of the superb HFC vehicles that are currently being leased to regular customers in several regions throughout the country. We can help arrange a "ride and drive" for you and your immediate team, and would be pleased to do so.
- Talking to the customers who use fuel cells today (Sprint, Whole Foods, FedEx, etc., as described in our Report) to hear their story.
- Reviewing real data with a truly open mind, to test whether the "miracles" you have said are needed have, in fact, already happened:
    - Fuel cells are being manufactured at acceptable cost for some markets, and have operating lifetimes well in excess of the times needed for many stationary, and most automotive, applications. Continued R&D will further reduce cost and improve performance, just as ongoing R&D will do for batteries and advanced biofuels, but the fuel cells we know how to make today are already commercially ready.
    - Natural gas can be reformed to produce H2 at a cost of $3-4/kg (1kg is 1gge). On a cost/mile basis in an HFCV this translates to $1.50-2.00/gge, while reducing carbon emissions for the same physical outcome (i.e. miles driven) by 50% or more. When

renewables can produce electricity at 5-6¢/kWh, H2 production using renewable electricity and employing electrolyzers that are already available commercially (but will be produced in the near future in much larger numbers at lower cost) will also be cost effective. New technology resulting from continuing R&D will certainly reduce the cost of hydrogen production over time, but the cost is already very competitive with gasoline.

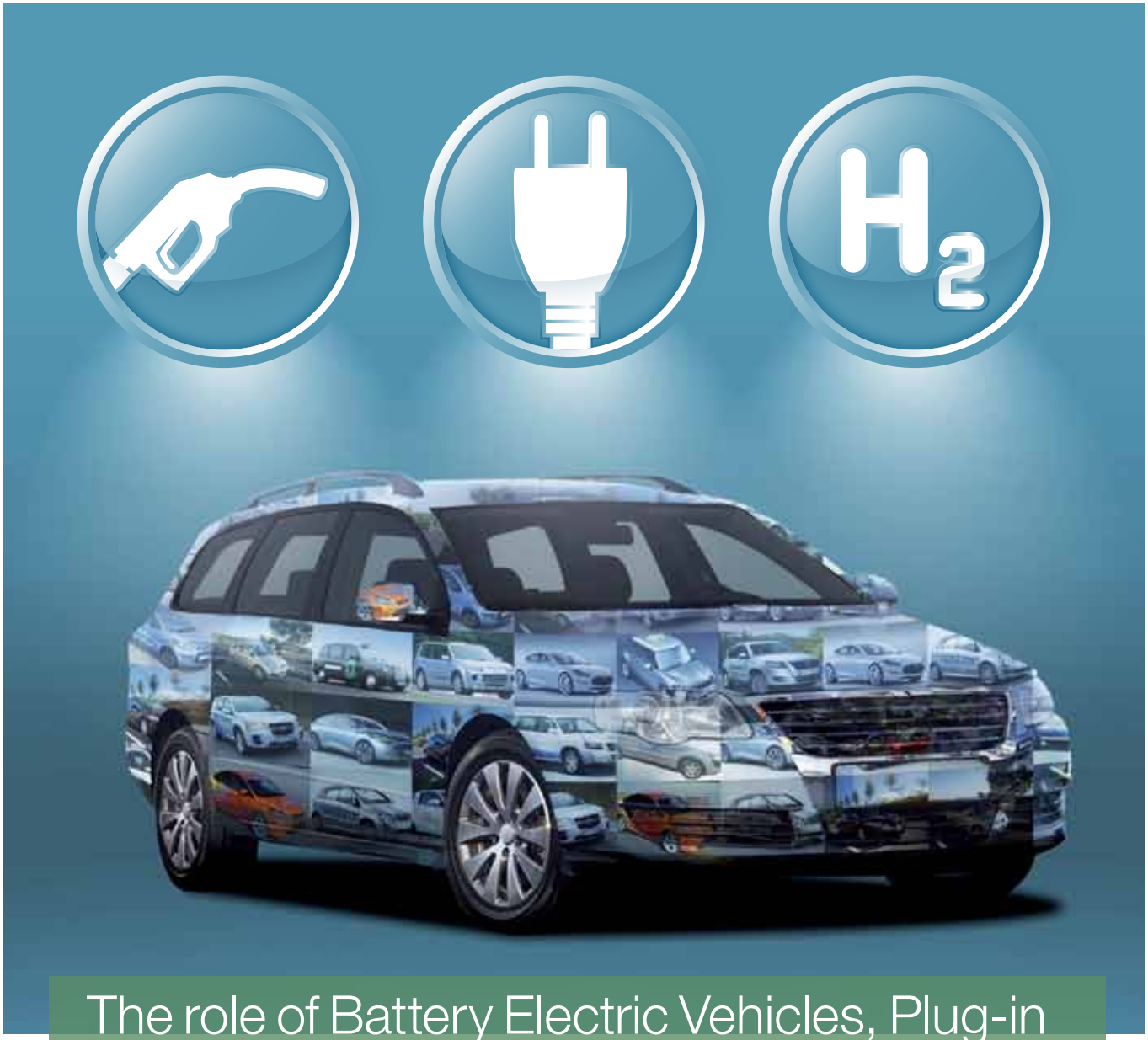
- High pressure (700 bar) storage systems are able to achieve vehicle ranges in excess of 400 miles. For larger scale energy storage, when H2 is stored at the same pressure as air in underground caverns, it enables more than 150X the energy storage in the same volume. Continued research will doubtless lead to ever better storage solutions at ever lower cost, but current approaches are more than adequate for first generation commercial applications.
- All the components required for a robust H2 infrastructure have been developed and are being used today in commercial hydrogen stations around the world. The National Academy, the EU, and industry analysts all point out that the cost of early development of the infrastructure is quite reasonable compared to the incentives being provided to stimulate other alternative technologies. Infrastructure cost is clearly important, but it is not a substantial barrier to early vehicle deployments. Vehicles will be introduced initially in selected geographies, like Los Angeles and Oahu in the U.S., and in Germany, Korea, and Japan. We urge you to talk with the California Fuel Cell Partnership, the leading automakers, the industrial gas companies, and your counterparts in Germany, Korea, and Japan, to learn their views. It is important to note that the recently published EU study, based on proprietary cross-industry data, confirmed the National Academy's earlier conclusion that H2 infrastructure costs are comparable to those needed to support electric vehicles.

Finally, we urge you to engage with your HTAC, whose members devote substantial time and their broad-based expertise to serving you and the Hydrogen and Fuel Cell Program. We commit to sharing real data, careful analysis, and actual commercial experience with you, and to engaging in dispassionate dialog on the facts. We are certain that if you are willing to look seriously at the reality of what has been accomplished and is currently being supported by the HFC Program, and the extent to which the global HFC industry has progressed, you will become convinced that the HFC option deserves a much more prominent place in the nation's advanced energy portfolio than the recent budget proposals signal.

With sincere regards,

Dr. Robert W. Shaw, Jr.
HTAC Chair
On behalf of all of the HTAC Members

A portfolio of power-trains for Europe: a fact-based analysis



The role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles

Introduction

In September 2009, both the European Union and G8 leaders agreed that CO_2 emissions must be cut by 80% by 2050 for global warming to stay below the level of 2°C. But 80% de-carbonisation overall by 2050 requires 95% de-carbonisation of the road transport sector.

With the number of passenger cars set to rise to 273 million in Europe by 2050, de-carbonising road transport may not be achievable through improvements to the traditional internal combustion engine or alternative fuels alone. It is therefore vital to bring to the market a range of technologies that will ensure the long-term sustainability of mobility in Europe.

About the study

A group of 27 private companies, 1 NGO and 2 Government Organisations undertook a study on passenger cars in order to assess the alternative power-trains most likely to de-carbonise the road transport sector. These alternative power-trains have been compared to conventional vehicles with internal combustion engines (**ICEs**) and include three types of electric vehicles:

- **BEVs**: Battery electric vehicles - electric vehicles that use chemical energy stored in rechargeable battery packs
- **FCEVs**: Fuel cell electric vehicles - electric vehicles which use a hydrogen fuel cell as their source of electric power
- **PHEVs**: Plug-in hybrid electric vehicles - hybrid vehicles with rechargeable batteries that can be restored to full charge by connecting a plug to an external electric power source

The conclusions present a balanced scenario for the electrification of passenger cars in the EU by 2050 and a significant role in achieving the de-carbonisation of the sector, provided electricity generation is de-carbonised.

The study "*A portfolio of power-trains: a fact based analysis*" is based on more than 10,000 confidential and proprietary data points provided by participating companies to McKinsey & Company on an unprecedented scale. This data included information on costs (vehicle costs, operating costs, fuels and infrastructure costs), performance, efficiency and emissions across the entire value chain. The results of the analysis have proven to be robust to significant variations in learning rates and cost of fuels.

A comparative analysis

2030
C/D segment
(medium cars)

	FCEV	BEV	PHEV	ICE
Performance	• Driving performance in similar range to ICE • ~600km average driving range • Refuelling only takes a couple of minutes • Fewer services needed	• Limited energy storage capacity and driving range (150-250km) • Refuelling time in the order of hours[2] • Ideally suited to smaller cars and urban driving	• Driving range equal to ICE in ICE drive (>800km) ; 40-60km in electric drive • Similar top speed, gasoline refuelling time & service intervals • Battery recharging takes some hours	• Highest driving range • Best top speed and refuelling time • Only service intervals shorter
Environment	• High CO_2 reduction (~80%) compared to today with CCS & water electrolysis • No local vehicle emissions • Lowest carbon solution for medium/larger cars & longer trips	• High CO_2 reduction (~80%) if CCS or renewable energy is used • Depends on electricity footprint • No local vehicle emissions	• Considerable CO_2 reduction (~70%) • Some local emissions in ICE drive • Low CO_2 if 100% biofuels	• Highest CO_2 and local vehicle emissions • Unlikely to meet EU CO_2 reduction goal for 2050 • Low CO_2 if 100% biofuels
Economics[1]	• Purchase price is ~€4,000 higher than ICE • Total cost of ownership[3] comparable to ICE for larger, but not smaller cars • Infrastructure comparable cost to BEVs	• Economic for smaller cars • Purchase price higher than ICE • Total cost of ownership ~€3,000 higher than ICE • Fuel costs comparable to ICE due to high infrastructure cost	• Higher purchase price and total cost of ownership than ICE • Better fuel economy than ICE for larger cars • Low infrastructure cost	• Most economic vehicle • Lowest purchase price • Higher fuel or maintenance costs • Existing infrastructure

excellent | good | moderate | challenged

[1] Consumer economics can be different, dependent on tax region
[2] Fast charging for BEVs implies reduced battery lifetime, lower battery load and higher infrastructure costs than included in this study
[3] The total cost of ownership (TCO) describes the costs associated over the entire lifetime of the vehicles, i.e. purchase price and running cost. The economic comparison between power-trains is based on the TCO.

SOURCE: Study analysis

Main conclusions

"Europe must achieve a significant penetration of fuel cell, battery and plug-in hybrid electric cars if it is to achieve its CO_2 reduction goal, alongside large efficiency improvement of the internal combustion engines and an increase in the use of sustainably produced biofuels"

SOURCE: Study analysis

ENVIRONMENT - Significant emission benefits

All electric power-trains have the potential to significantly reduce CO_2 and local emissions. BEVs, FCEVs and PHEVs in electric drive have zero tail-pipe emissions while driving and can be made close to CO_2-free, depending on the primary energy source used. They are also more energy efficient than traditional internal combustion engines.

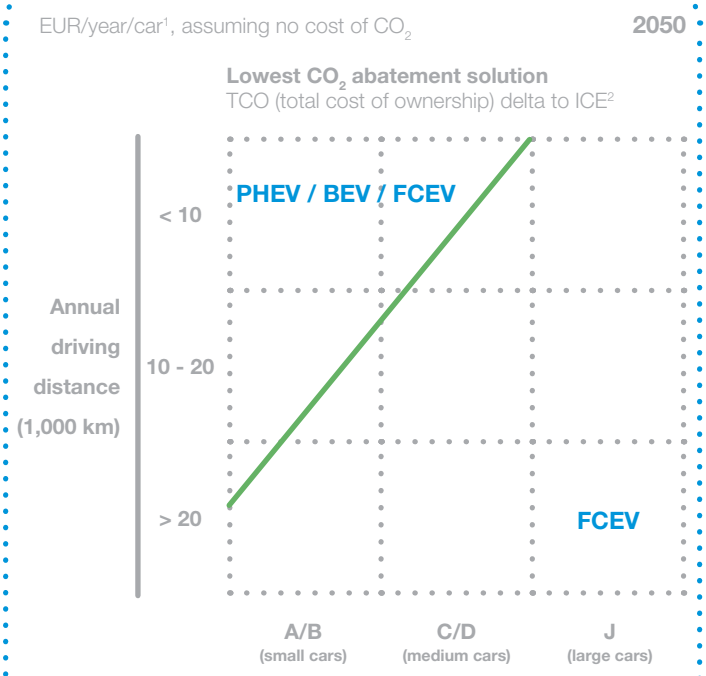
PERFORMANCE - Meeting consumers needs

The range of electric power-trains play a complementary role and can meet the needs of consumers and the environment. BEVs are ideally suited to smaller cars and shorter trips; FCEVs to medium/larger cars and longer trips; PHEVs are an attractive transition solution for short trips or where sustainably produced biofuels are available.

ECONOMICS - Cost-competitive alternatives

After 2025, total costs associated over the lifetime of the electric vehicles (incl. the purchase price, fuel cost and maintenance cost) converge. They all become viable alternatives to traditional internal combustion engines. Together with tax incentives, BEVs and FCEVs could be cost-competitive with traditional internal combustion engines as early as 2020.

By 2050, all electric vehicles are cost-competitive with ICEs



[1] Constant lifetime, but different total driving distances (90,000 km; 180,000 km; 360,000 km)
[2] Calculated as ICE TCO minus lowest FCEV/BEV/PHEV TCO.

SOURCE: Study analysis

FCEVs CAN PLAY A SIGNIFICANT ROLE

Family sized cars (medium/large) account for 50% of all cars and 75% of CO_2 emissions. FCEVs are technologically ready and, in the medium to long term, are the best low-carbon substitute for this segment. Incentives could make FCEVs cost-competitive as early as 2020. The costs for a hydrogen infrastructure are approximately 5% of the overall costs of FCEVs over the coming decades. This is comparable to rolling out a charging infrastructure for BEVs and PHEVs.

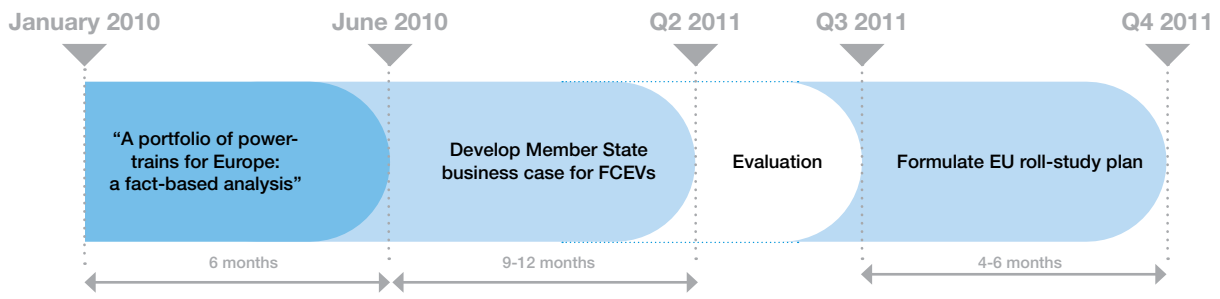
A dedicated hydrogen infrastructure is therefore justified and doable, but, the first companies to build a publicly-accessible hydrogen retail infrastructure are at a disadvantage. This is because the cost for first movers is very high as many infrastructures need to be built simultaneously and sales volumes are low in the first years. The risk is greatly reduced if many companies invest, coordinated by governments and supported by dedicated legislation and funding over the next two decades.

Next steps

Investment cycles in energy infrastructure are lenghty. BEV, FCEV infrastructure and scale up should be initiated now in order to achieve a broad market uptake beyond 2020.

In the short term, CO_2 emissions will be reduced by more efficient internal combustion engines and plug-in hybrids while taking two concrete actions to meet the investment challenge and avoid market failure:

- Study EU market launch plan for FCEVs and hydrogen infrastructure starting with the development of a Member State business case (e.g. in Germany) followed by the formulation of an EU roll-out study based on the learnings from initial experiences
- Co-ordinate a similar roll-out plan for BEVs, PHEVs and battery charging infrastructure in order to avoid the market failure of these technologies



The role of policy–makers

In order to achieve the de-carbonisation of Europe's vehicles, policy makers and industry need to coordinate their efforts. EU and national policy-makers play a critical role in de-risking these technologies and ensuring market uptake, specifically through:

- **Clear political endorsement**
- **Regulation and standards development**
- **Funding and fiscal measures**

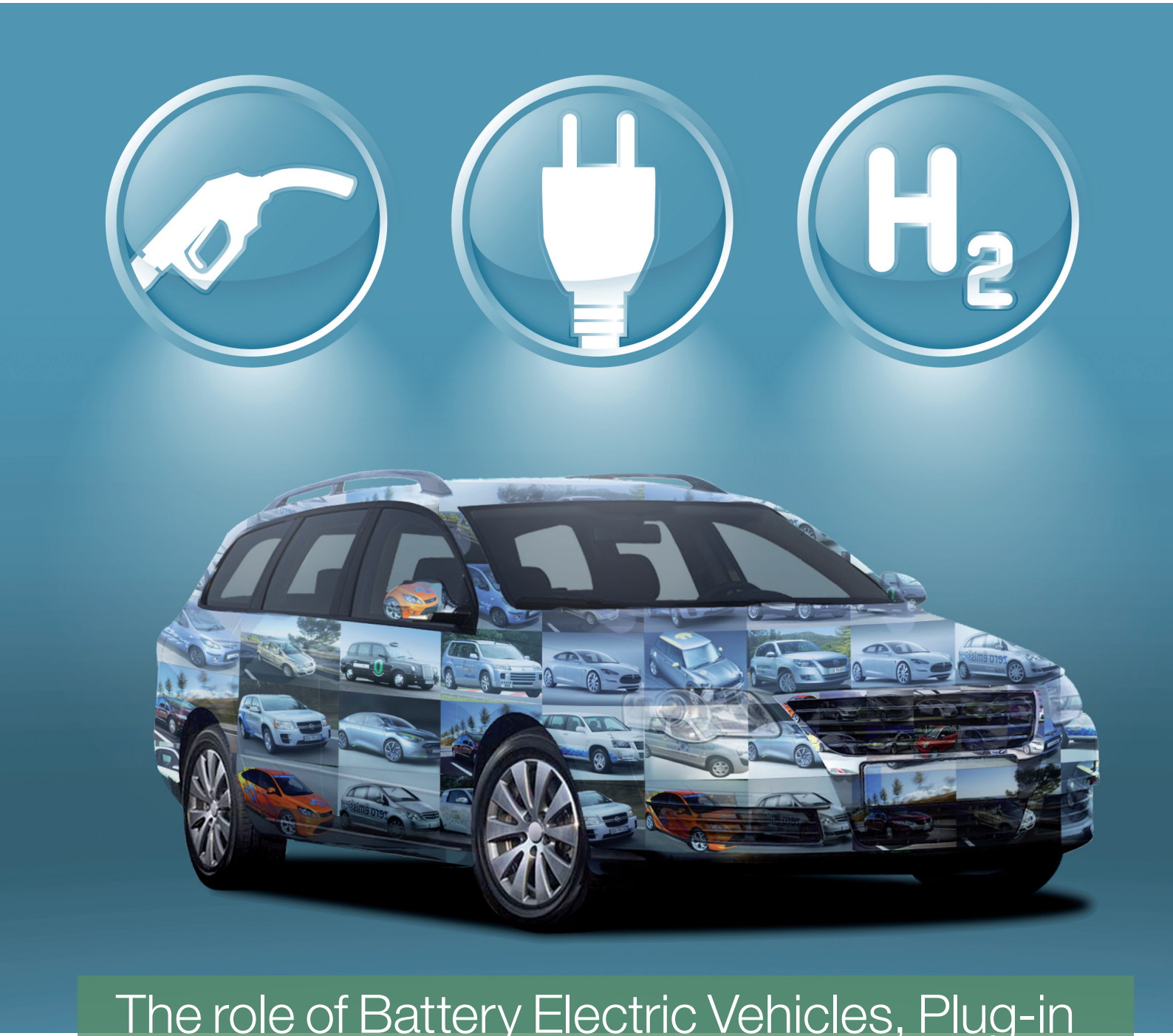
For more information on the 30 organisations that participated in the study (including 11 car manufacturers, 5 oil and gas companies, 3 industrial gas companies, 2 governmental organisations, 1 NGO, etc.) please visit:

www.zeroemissionvehicles.eu

The current brochure does not reflect the study in its entirety.
For the complete version of "A portfolio of power-trains for Europe: a fact-based analysis", please refer to the aforementioned website

E-mail : info@zeroemissionvehicles.eu
Phone: +32 2 54 087 75

A portfolio of power-trains for Europe: a fact-based analysis



The role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles

The following companies and organisations participated in this study:

Car manufacturers
BMW AG, Daimler AG, Ford, General Motors LLC, Honda R&D, Hyundai Motor Company, Kia Motors Corporation, Nissan, Renault, Toyota Motor Corporation, Volkswagen

Oil and gas
ENI Refining and Marketing, Galp Energia, OMV Refining and Marketing GmbH, Shell Downstream Services International B.V., Total Raffinage Marketing

Utilities
EnBW Baden-Wuerttemberg AG, Vattenfall

Industrial gas companies
Air Liquide, Air Products, The Linde Group

Equipment car manufacturers
Intelligent Energy Holdings plc, Powertech

Wind
Nordex

Electrolyser companies
ELT Elektrolyse Technik, Hydrogenics, Hydrogen Technologies, Proton Energy Systems

Non-governmental organisations
European Climate Foundation

Governmental organisations
European Fuel Cells and Hydrogen Joint Undertaking, NOW GmbH

This document reflects the results of a fact-based study that has been prepared on behalf of the companies and organisations listed above. The information and conclusions contained in this document represent the collective view of the working groups of this study and not that of individual companies or organisations. Any information and conclusions provided in this document are for reference purposes only and are not intended, nor should they be used as a substitute for professional advice or judgement with respect to certain circumstances. None of the companies and organisations listed above guarantee the adequacy, accuracy, timeliness or completeness of the document's contents. Said companies and organisations therefore disclaim any and all warranties and representations as to said contents, express or implied, including any warranties of fitness for a particular purpose or use.

McKinsey & Company, the management consultancy, provided analytical support to the study. Any recommendations or positions taken in this report are the responsibility of the authors, not of McKinsey & Company.

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EXECUTIVE SUMMARY

Conventional vehicles alone may not achieve EU CO_2 reduction goal for 2050

In September 2009, both the European Union (EU) and G8[1] leaders agreed that CO_2 emissions must be cut by 80% by 2050 if atmospheric CO_2 is to stabilise at 450 parts per million[2] – and global warming stay below the safe level of 2ºC. But 80% decarbonisation overall by 2050 may require 95%[3] decarbonisation of the road transport sector.

With the number of passenger cars set to rise to 273 million[4] in Europe – and to 2.5 billion[5] worldwide – by 2050, this may not be achievable through improvements to the traditional internal combustion engine or alternative fuels: the traditional combustion engine is expected to improve by 30%, so achieving full decarbonisation is not possible through efficiency alone. There is also uncertainty as to whether large amounts of (sustainably produced) biofuels - i.e. more than 50% of demand - will be available for passenger cars, given the potential demand for biofuels[6] from other sectors, such as goods vehicles, aviation, marine, power and heavy industry.

Combined with the increasing scarcity and cost of energy resources, it is therefore vital to develop a range of technologies that will ensure the long-term sustainability of mobility in Europe.

A factual evaluation of BEVs, FCEVs, PHEVs and ICEs based on proprietary industry data

To this end, a group of companies, government organisations and an NGO – the majority with a specific interest in the potential (or the commercialisation) of fuel cell electric vehicles (FCEVs) and hydrogen, but with a product range also spanning battery electric vehicles (BEVs), plug-in hybrids (PHEVs) and conventional vehicles with internal combustion engines (ICEs) including hybridisation – undertook a study on passenger cars in order to assess alternative power-trains most likely to fulfil that need. Medium- or heavy-duty vehicles were not included.

Electric vehicles (BEVs, FCEVs and PHEVs in electric drive) not only have zero tail-pipe emissions[7] while driving – significantly improving local air quality – they can be made close to CO_2-free over time and on a well-to-wheel basis, depending on the primary energy source used. Zero-emission power-trains therefore go hand-in-hand with the decarbonisation of energy supply, with the potential to significantly reduce emissions from central power and hydrogen production by 2050. Electric vehicles have substantially lower pollution from noise, NO_2 and particles.

It was considered particularly important to re-assess the role of FCEVs in the light of recent technological breakthroughs in fuel cell and electric systems that have now increased their efficiency and cost-competitiveness significantly. Given satisfactory testing in a customer environment - with more than 500 cars covering over 15 million kilometres and 90,000 refuellings - the focus has now shifted from demonstration to planning commercial deployment so that FCEVs, like all technologies, may benefit from mass production and the economies of scale.

1 The Group of Eight industrial powers – Canada, France, Germany, Italy, Japan, Russia, the UK and the United States
2 CO_2-equivalent
3 McKinsey Global GHG Abatement Cost Curve; International Energy Agency World Energy Outlook 2009; US Environmental Protection Agency; European Environment Agency (EEA)
4 Parc Auto Survey 2009, Global Insight 2010; study analysis
5 European Commission, April 2010
6 The study makes the following assumptions: by 2020 biofuels are blended, delivering a 6% well-to-wheel reduction in CO_2 emissions for gasoline- and diesel-engined vehicles, in line with the EU Fuel Quality Directive. By 2050, biofuel blending increases but is limited to 24%, reflecting supply constraints
7 FCEVs emit water vapour only

Over 30 stakeholders therefore came together in order to develop a factual evaluation of the economics, sustainability and performance of BEVs, FCEVs, PHEVs and ICEs across the entire value chain – many with an equal interest in all four power-trains.

It meant providing confidential and proprietary data on an unprecedented scale[8] – including vehicle costs (in this report, purchase price is used to refer to cost plus a standard hypothetical margin, equal for all cars within one segment), operating costs, fuel and infrastructure cost.

In order to ensure a realistic outcome, it was agreed that:

- The study should include a balanced mix of vehicle sizes (or segments) and ensure no bias towards any particular power-train, representing the majority of vehicles on the market[9]
- While it is possible that breakthrough technologies could provide step changes in current pathways to sustainable mobility, the study should only consider vehicle technologies that are proven in R&D today and capable of a) scale-up and commercial deployment and b) meeting the EU's CO_2 reduction goal for 2050
- Average values should be taken, with no "cherry-picking" of the most favourable data
- Input data provided by participating companies would be frozen before results were shared.

A balanced scenario for the electrification of passenger cars in the EU by 2050

A combined forecasting and backcasting approach was then used to calculate the results: from 2010 to 2020, global cost and performance data were forecasted, based on proprietary industry data; after 2020, on projected learning rates (see Annex, Exhibit 42, page 54).

In order to test the sensitivity of these data to a broad range of market outcomes, three European "worlds" for 2050 were defined, assuming various power-train penetrations in 2050:

1. A world skewed towards ICE (5% FCEVs, 10% BEVs, 25% PHEVs, 60% ICEs)
2. A world skewed towards electric power-trains (25% FCEVs, 35% BEVs, 35% PHEVs, 5% ICEs)
3. A world skewed towards FCEVs (50% FCEVs, 25% BEVs, 20% PHEVs, 5% ICEs).

These three "worlds" were then backcasted to 2010, resulting in a development pathway for each power-train. As the impact of the different "worlds" on FCEV costs was found not to be significant (see page 18), this report focuses on results for the second "world" as having a balanced split between the four power-trains (25% FCEVs, 35% BEVs, 35% PHEVs and 5% ICEs).

8 Over 10,000 data points were collected for the study
9 No assumptions have been made on a potential shift in the composition of the car fleet from larger to smaller cars. An average ~30% fuel efficiency gain was included for the entire ICE fleet

Assumptions are robust to significant variations

To test the robustness of results, all assumptions in the study's vehicle and supply models were varied to identify possible "tipping points". However, this showed that the conclusions were robust to significant variations in learning rates for the power-trains and the cost of fossil fuels (see page 24).

The power supply pathway underlying this report is based on the European Climate Foundation's "Roadmap 2050", which was developed in corporation with the industry and describes a pathway to decarbonise the EU power mix by 2050. In 2020, the expected share of renewable (RES) production capacity is approximately 34%. This is the minimum needed to meet the 20% EU renewable energy target, as there is limited RES opportunity outside of the power sector.

For the following results, a conventional hydrogen production mix is assumed to 2020, utilising existing assets – industrially produced hydrogen and centralised steam methane reforming (SMR) – with a growing proportion of distributed units (water electrolysis and SMR). After 2020, a balanced and economically driven scenario is assumed, including CO_2 Capture and Storage (CCS), water electrolysis (increasingly using renewable energy) and avoiding over-dependence on any single primary energy source.

An alternative production mix was also examined (see Exhibit 26, page 38), representing 100% electrolysis, with 80% renewable energy by 2050, which increases the total cost of ownership (TCO) of FCEVs by 5% by 2030 and 3.5% by 2050. However, both production scenarios achieve CO_2-free hydrogen by 2050.

The value of electric vehicles on balancing an (increasingly intermittent) power grid can be significant and could amount to several billions of euros (ref. "Roadmap 2050"). This applies to BEVs (charging when power supply is available) as well as hydrogen cars (using stored hydrogen to produce power when supply is short).

SUMMARY OF RESULTS

1. BEVs, PHEVs and FCEVs have the potential to significantly reduce CO_2 and local emissions

Electric vehicles (BEVs, FCEVs and PHEVs in electric drive) can be fuelled by a wide variety of primary energy sources – reducing oil dependency and enhancing security of energy supply. Well-to-wheel efficiency analysis also shows that electric vehicles are more energy-efficient than ICEs over a broader range of primary energy sources.

Owing to limits in battery capacity and driving range[10] (currently 100-200 km for a medium-sized car[11]) and a current recharging time of several hours, ***BEVs*** are ideally suited to smaller cars and shorter trips, i.e. urban driving (including new transportation models such as car sharing).

With a driving range and performance comparable to ICEs, ***FCEVs*** are the lowest carbon solution for medium/larger cars and longer trips. These car segments account for 50% of all cars and 75% of CO_2 emissions, hence replacing one ICE with one FCEV achieves a relatively high CO_2 reduction.

10 The range chosen in the study for BEVs and PHEVs reflects the car manufacturers' current view on the best compromise between range, cost, and load bearing capacity for the vehicle
11 For C/D segment cars this will increase to 150-250 km in the medium term

With a smaller battery capacity than BEVs, ***PHEVs*** have an electric driving range of 40-60 km. Combined with the additional blending of biofuels, they could show emission reductions for longer trips.

ICEs have the potential to reduce their CO_2 footprint significantly through an average 30% improvement in energy efficiency by 2020 and the additional blending of biofuels. After 2020, however, further engine efficiency improvements are limited and relatively costly, while the amount of biofuels that will be available may be limited.

BEVs, PHEVs and FCEVs have significant potential to reduce CO_2 and local emissions, assuming CO_2 reduction is performed at the production site. They play a complementary role, with BEVs ideally suited to smaller cars and shorter trips and FCEVs to medium/larger cars and longer trips. PHEVs can reduce CO_2 considerably compared to ICEs on short trips or using biofuels, depending on availability. The energy and CO_2 efficiency of ICEs is expected to improve by 30%.

Medium/larger cars with above-average driving distance account for 50% of all cars, and 75% of CO_2 emissions. FCEVs are therefore an effective low-carbon solution for a large proportion of the car fleet. Beyond 2030, they have a TCO advantage over BEVs and PHEVs in the largest car segments (see below).

2. *After 2025, the total cost of ownership (TCO) of all the power-trains converges*

In the study, the economic comparison between power-trains is based on the total cost of ownership (TCO), as it describes the costs associated over their entire lifetime (see page 18). In order to ensure a like-for-like comparison, taxes are not included unless specifically stated.

BEVs and FCEVs are expected to have a higher purchase price than ICEs (battery and fuel cell related) and a lower fuel cost (due to greater efficiency and no use of oil) and a lower maintenance cost (fewer rotating parts).

The cost of fuel cell systems is expected to decrease by 90% and component costs for BEVs by 80% by 2020, due to economies of scale and incremental improvements in technology. Around 30% of technology improvements in BEVs and PHEVs also apply to FCEVs and vice versa. This assumes that FCEVs and BEVs will be mass produced, with infrastructure a key prerequisite to be in place. The cost of hydrogen also reduces by 70% by 2025 due to higher utilisation of the refuelling infrastructure and economies of scale.

PHEVs are more economic than BEVs and FCEVs in the short term. The gap gradually closes and by 2030 PHEVs are cost-competitive with BEVs for smaller cars, with both BEVs and FCEVs for medium cars and less competitive than FCEVs for larger cars.

While the fuel economy of ICEs is expected to improve by an average of 30% by 2020, costs also increase due to full hybridisation and further measures such as the use of lighter weight materials.

The TCOs of all four power-trains is expected to converge after 2025 – or earlier, with tax exemptions and/or incentives during the ramp-up phase.

For larger cars, the TCO of FCEVs is expected to be lower than PHEVs and BEVs as of 2030. By 2050, it is also (significantly) lower than the ICE. For medium-sized cars, the TCOs for all technologies converge by 2050. BEVs have a (small) TCO advantage over FCEVs in the smaller car segments.

PHEVs are more economic than BEVs and FCEVs in the short term. All electric vehicles are viable alternatives to ICEs by 2025, with BEVs suited to smaller cars and shorter trips, FCEVs for medium/larger cars and longer trips. With tax incentives, BEVs and FCEVs could be cost-competitive with ICEs as early as 2020.

3. *A portfolio of power-trains can meet the needs of consumers and the environment*

BEVs have a shorter range than FCEVs, PHEVs and ICEs: an average, medium-sized BEV with maximum battery loading cannot drive far beyond 150 km at 120 km/hour on the highway, if real driving conditions are assumed (and taking expected improvements until 2020 into account) Charging times are also significantly longer: 6-8 hours using normal charging equipment. Fast charging may become widespread, but the impact on battery performance degradation over time and power grid stability is unclear. Moreover, it takes 15-30 minutes to (partially) recharge the battery. Battery swapping reduces refuelling time; it is expected to be feasible if used once every two months or less and battery standards are adopted by a majority of car manufacturers. BEVs are therefore ideally suited to smaller cars and urban driving, potentially achieving ~80% CO_2 reduction by 2030 compared to today.

FCEVs have a driving performance (similar acceleration), range (around 600 km) and refuelling time (< 5 minutes) comparable to ICEs. They are therefore a feasible low-carbon substitute for ICEs for medium/larger cars and longer trips, potentially achieving 80% CO_2 reduction by 2030 compared to today.

PHEVs have a similar range and performance to ICEs, but electric driving only applies to shorter distances, while the amount of biofuels available for longer trips is uncertain. They represent an attractive solution, reducing CO_2 considerably compared to ICEs.

Over the next 40 years, no single power-train satisfies all key criteria for economics, performance and the environment. The world is therefore likely to move from a single power-train (ICE) to a portfolio of power-trains in which BEVs and FCEVs play a complementary role: BEVs are ideally suited to smaller cars and shorter trips; FCEVs to medium/larger cars and longer trips; with PHEVs an attractive solution for short trips or where sustainably produced biofuels are available.

4. *Costs for a hydrogen infrastructure are approximately 5% of the overall cost of FCEVs (€1,000-2,000 per car)*

For consumers who prefer larger cars and drive longer distances, FCEVs therefore have clear benefits in a CO_2-constrained world. This segment represents around 50% of cars driven and can therefore justify a dedicated hydrogen infrastructure. The value of the FCEV over alternative power-trains in terms of TCO and emissions (including the cost of the hydrogen infrastructure) is positive beyond 2030. The economic gap prior to 2030 is almost completely determined by the higher purchase price, not by the cost of the hydrogen infrastructure. It can therefore be assumed that if this consumer segment prefers the FCEV, the cost of the infrastructure (5% of the TCO) will not be prohibitive to its roll-out. Having said that, an orchestrated investment plan is required to build up the first critical mass of hydrogen supply.

In order to develop a portfolio of power-trains, several supply infrastructure systems are required – not only for gasoline and diesel, but potentially new infrastructures for CNG, LPG, 100% biofuels, electricity and hydrogen. Early commercial deployment of BEVs and PHEVs is already happening in several European countries: many car manufacturers have announced the introduction of new commercial models between 2010 and 2014. This report therefore focuses on the commercial deployment of FCEVs, which still needs to be addressed.

One could argue that it is inefficient to build an additional vehicle refuelling infrastructure on top of existing infrastructures. However, the additional costs of a hydrogen infrastructure are relatively low compared to the total costs of FCEVs and comparable to other fuels and technologies, such as a charging infrastructure for BEVs and PHEVs. Costs for a hydrogen distribution and retail infrastructure are around 5% of the overall cost of FCEVs – the vast majority lies in the purchase price. The attractiveness of the business case for FCEVs is therefore hardly affected by the additional costs required for distribution and retail. In other words, if FCEVs make commercial sense – as demonstrated by this study – building a dedicated hydrogen infrastructure can be justified.

In the first decade of a typical roll-out scenario, supply infrastructure costs per car – especially those for a retail infrastructure – are initially higher, due to lower utilisation. Nevertheless, sufficient network coverage must be available for consumers and initial investments required could amount to around €3 billion (covering hydrogen production, distribution and retail) for a region such as Germany. Although a single company would struggle to absorb the risk of such an investment, this is not the case at a societal level. This is confirmed by countries which have built up alternative infrastructures, such as LPG and CNG.

The cost per vehicle for rolling out a hydrogen infrastructure compares to rolling out a charging infrastructure for BEVs or PHEVs. The costs for hydrogen retail and distribution are estimated at €1,000-2,000 per vehicle (over its lifetime), including distribution from the production site to the retail station, as well as operational and capital costs for the retail station itself. Building an infrastructure for 25% market share of FCEVs requires infrastructure investments of around €3 billion in the first decade and €2-3 billion per year thereafter. Annual infrastructure investments in oil and gas, telecommunications and road infrastructure each amount to €50-€60 billon.[12] Additional investments required to decarbonise the power sector amount to €20-30 billion per year.[13]

Current costs for an electric charging infrastructure range from €1,500 - €2,500 per vehicle. The higher end of the range assumes 50% home charging (investment of €200 - €400 per charging station) and 50% public charging at €5,000 for a charging station that serves two cars (€10,000 in the first years). Potential additional investment in the power distribution networks are not included, but could be material, depending on the local situation. In contrast, once the territory is covered, no further investment is needed in hydrogen infrastructure – regardless of the number of cars – due to the fast refuelling time. As the number of FCEVs increase, it also benefits from the economies of scale.

12 Global Insight
13 http://www.roadmap2050.eu/attachments/files/Volume1_fullreport_PressPack.pdf

Under the key assumptions of the study (i.e. zero CO_2 from power by 2050[14]), Europe must achieve a significant penetration of electric cars by 2050, if it is to achieve its CO_2 reduction goal. Early commercial deployment of BEVs has already started in several European countries, but infrastructure for FCEVs remains to be addressed.

Over the course of the next decades, costs for a hydrogen distribution and retail infrastructure are 5% of the overall cost of FCEVs (€1,000-2,000 per car) and comparable to rolling out a charging infrastructure for BEVs and PHEVs (excluding potential upgrades in power distribution networks). The attractiveness of the business case for FCEVs is therefore hardly affected by the additional costs required for distribution and retail: if FCEVs make commercial sense – as demonstrated by this study – building a dedicated hydrogen infrastructure can be justified.

5. The deployment of FCEVs will incur a cost to society in the early years

The benefits of lower CO_2 emissions, lower local emissions (NO_2, particles), diversification of primary energy sources and the transition to renewable energy all come at an initial cost. These will ultimately marginalise with the reduction in battery and fuel cell costs, economies of scale and potentially increasing costs for fossil fuels and ICE specifications.

A roll-out scenario that assumes 100,000 FCEVs in 2015, 1 million in 2020 and a 25% share of the total EU passenger car market in 2050 results in a cumulative economic gap of approximately €25 billion by 2020 – mainly due to the cost of the fuel cell system in the next decade, but also including around €3 billion for a hydrogen supply infrastructure. The CO_2 abatement cost is expected to range between €150 and € 200 per tonne in 2030 and becomes negative for larger cars after 2030.

A hydrogen supply infrastructure for around 1 million FCEVs by 2020 requires an investment of €3 billion (production, distribution, retail), of which €1 billion relates to retail infrastructure – concentrated in high-density areas (large cities, highways) and building on existing infrastructure. If only one energy company were to invest in hydrogen retail infrastructure, it faces a first-mover disadvantage due to the initially low utilisation by a small number of FCEVs and the risk of technology delivery failure or delay. In the latter case it would result in a potential write-off in the order of hundreds of millions per annum. The initial investment risk would be somewhat reduced if further companies also invest and even further if the roll-out is supported by adequate policy measures and risk underwriting all one word by governments.

Hydrogen manufacturers have an incentive – as soon as the economics work – to race to beat their rivals. While financial incentives are required to persuade consumers to appreciate FCEVs, there is nothing to hold the hydrogen manufacturers back – as long as the retail infrastructure is in place. Infrastructure providers, on the other hand, bear a first-mover risk, making a heavy upfront outlay to build a retail station network that will not be fully utilised for some years; the unit cost reduces over time simply because the fixed capital expenditure is used by an increasing number of FCEVs.

The cumulative economic gap of around €25 billion for FCEVs up to 2020 is calculated on a global cumulative FCEV production and is mainly due to a higher purchase price. If this is also only met by a few car manufacturers, they will each need to finance around €1 billion per annum. Bridging this gap could be facilitated by adequate government actions and global co-operation. After 2030, it can be reasonably assumed that the majority of the consumers will be financially driven, making their choice of car in response to an established tax and legislative regime.

14 The power supply pathway underlying this report is based on the European Climate Foundation "Roadmap 2050", which was developed in cooperation with the industry and describes a pathway to decarbonise the EU's power mix by 2050 - See page 24

Provided these are stable and clear, car manufacturers, hydrogen manufacturers and infrastructure providers should all be able to make investments on the basis of well-understood risks and projected returns. A global roll-out would further reduce the economic gap for Europe.

A strong case will be required to persuade governments as to the level of explicit subsidy needed. In subsequent steps, it will therefore be important to make proposals that show how industry is taking responsibility for all the risks that they can reasonably analyse, control and mitigate. Discussions with Member State and EU governments are likely to focus on sharing the costs and risks between public and private sectors.

The emerging FCEV market (2010-20) requires close value chain synchronisation and external stimulus in order to overcome the first-mover risk of building hydrogen retail infrastructure. While the initial investment is relatively low, the risk is high and therefore greatly reduced if many companies invest, co-ordinated by governments and supported by dedicated legislation and funding. With the market established, subsequent investment (2020-30) will present a significantly reduced risk and by 2030 any potentially remaining economic gap is expected to be directly passed on to the consumer.

SUMMARY OF NEXT STEPS

Investment cycles in energy infrastructure are long and BEV and FCEV infrastructure and scale-up should be initiated as soon as possible in order to develop these technologies as material transportation options beyond 2020. In the short term, CO_2 emissions will therefore have to be reduced by more efficient ICEs and PHEVs – combined with biofuels – while taking two concrete actions:

1. Study EU market launch plan for FCEVs and hydrogen infrastructure

Car manufacturers have signalled that they are ready to mass-produce FCEVs, as demonstrated by the Letter of Understanding in 2009 (see page 13). This study shows that FCEVs are technologically ready and can be produced at much lower cost for an early commercial market over the next five years. The next logical step is therefore to develop a comprehensive and co-ordinated EU market launch plan study for the deployment of FCEVs and hydrogen infrastructure in Europe (see pages 52-53). This consists of two phases:

- An in-depth business case and implementation plan for a single Member State (i.e. Germany) in order to de-risk the commercialisation of technology and test the supply chain for the rest of Europe, starting in 2015. At the same time, a series of subsidised FCEV demonstration projects in other Member States should start to gain experience with the technology.

- A potential staged roll-out plan – first, a market introduction in Member States that have developed experience through the demonstration projects, followed by other Member States.

The implementation plan should be fit for investment by companies and the public sector. This includes addressing the risks associated with the plan, how hydrogen will be decarbonised and its impact on future CO_2 emissions from the transport sector.

The dynamics of setting up a hydrogen retail infrastructure are such that there is a limited opportunity to gain "early mover" advantage, so the first player will not be able to compensate for any losses. Indeed, they will develop the market for all other infrastructure providers who will then reap the benefits at a later stage. However, if several hydrogen retail infrastructure providers invest – or a market-based mechanism is developed to spread the risk between different infrastructure providers – none will gain a 'free ride'. The market launch plan must therefore go hand-in-hand with appropriate government policies.

After the technology has been de-risked and achieved cost reductions in one Member State – and at the same time gained more experience with a series of demonstration projects in other Member States – a staged roll-out plan for subsequent introductions in other Member States has then to be studied. This will address the supply constraints of car manufacturers and hydrogen infrastructure providers; the primary energy resources of different Member States; and CO_2 reduction goals for the transport sector as a whole.

2. Co-ordinate roll-out of BEVs/PHEVs and battery-charging infrastructure

A similar action would be helpful to support the roll-out of BEVs and PHEVs in the EU. Here, too, the risk of market failure exists. Although the investments per electric recharging point are low, the financial risk for infrastructure providers remains. As with hydrogen infrastructure, upfront investment for public charging will be necessary in order to give customers appropriate access to infrastructure from the start.

In order to achieve a sound market introduction, the technology also needs to be commercially de-risked and programmes for BEVs currently exist in several European countries and at EU level, addressing issues such as technology, market introduction, funding schemes and standardisation etc. A coherent approach to these activities would help to optimise development and support early market readiness.

INTRODUCTION

EU CO_2 reduction goal for 2050 requires 95% decarbonisation of road transport

In 2009, both the European Union (EU) and G8 leaders agreed that CO_2 emissions must be cut by 80% by 2050 if atmospheric CO_2 is to stabilise at 450 parts per million[15] – and global warming stay below the safe level of 2°C. But 80% decarbonisation *overall* by 2050 requires 95%[16] decarbonisation of the road transport sector (Exhibit 1).

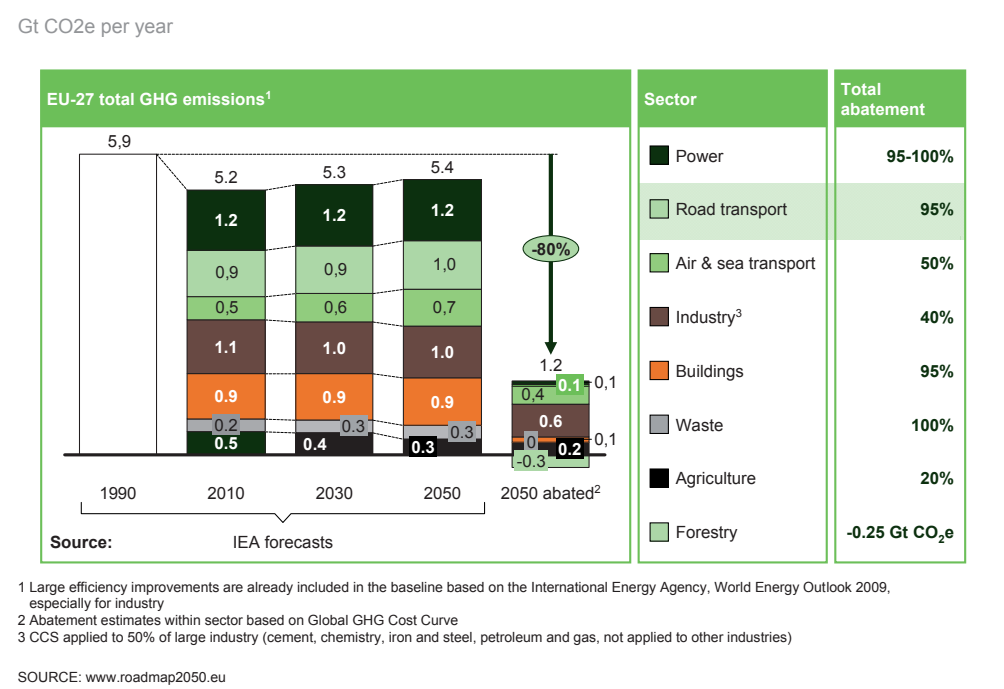


Exhibit 1: In order to achieve EU CO_2 reduction goal of 80% by 2050, road transport must achieve 95% decarbonisation

Decarbonisation may be achieved through efficiency, biofuels and electric power-trains (including hydrogen). With the number of passenger cars set to rise to 273 million[17] in Europe – and to 2.5 billion[18] worldwide – by 2050, full decarbonisation may not be achievable through improvements in the traditional internal combustion engine or alternative fuels alone. A comprehensive analysis would be helpful to determine the true global potential of biofuels and for which sectors and regions they may be most effectively used.

Combined with the increasing scarcity and cost of energy resources, it is therefore vital to develop a *range* of technologies to ensure the long-term sustainability of mobility in Europe, with "ultra low-carbon electric power-trains and hydrogen fuel cells the most promising options",[19] according to the European Commission. This study was therefore undertaken in order to compare the performance and costs of alternative power-trains for passenger cars – fuel cell electric vehicles (FCEVs), battery electric vehicles (BEVs) and plug-in hybrids (PHEVs) – with those of conventional vehicles with internal combustion engines (known as ICEs). This included every step of the value chain, or "well-to-wheel".

15 CO_2-equivalent
16 McKinsey Global GHG Abatement Cost Curve; International Energy Agency World Energy Outlook 2009; US Environmental Protection Agency; European Environment Agency (EEA)
17 Parc Auto Survey 2009, Global Insight 2010; study analysis
18 European Commission, April 2010
19 COM(2010)186: A European strategy on clean and energy efficient vehicles, published April 2010

Electric vehicles (BEVs, FCEVs and PHEVs) are necessary to achieve EU CO_2 reduction goal

The benefits of electric vehicles (BEVs, FCEVs and PHEVs in electric drive) over ICEs are:

- Electric vehicles have zero emissions while driving – significantly improving local air quality – and they can be made close to CO_2-free, depending on the primary energy source used[20]. Zero-emission power-trains therefore go hand-in-hand with the decarbonisation of energy supply, with the potential to eradicate emissions from central hydrogen production completely by 2050.

- Electric vehicles can be fuelled by a wide variety of primary energy sources – including gas, coal, oil, biomass, wind, solar and nuclear – reducing oil dependency and enhancing energy security (e.g. through stabilising an increasingly volatile power grid).

- While ICEs have the potential to reduce their CO_2 footprint considerably through improved energy efficiency, this is insufficient to meet the EU's CO_2 reduction goal for 2050. Full decarbonisation through biofuels depends on their availability.

Technologically ready, FCEVs are now focused on commercial deployment

30 stakeholders came together in order to develop a factual evaluation of the four power-trains and their role in decarbonising road transport. It was also considered particularly important to re-assess the role of FCEVs in the light of technological breakthroughs in fuel cell and electric systems that have now increased their efficiency and cost-competitiveness significantly (Exhibit 2). Previous studies[21] predicted that all technological challenges would be addressed simultaneously within a few years. In reality this has happened sequentially, with a steady but significant improvement in all key areas:

- With the implementation of 700 bar storage technology, hydrogen storage capacity has increased – without sacrificing volume – resulting in driving ranges that approach gasoline ICEs. In general, safety concerns have been adequately addressed.

- Cold start is down to -25°C, or even lower, due to the application of purging strategies at shut-down and new materials (e.g. metallic bipolar plates) which have optimised heat management in the stacks.

- With better understanding of the mechanisms affecting durability and the implementation of counter measures, such as enhanced materials (e.g. functionalised or nanostructured catalyst supports) and cell voltage management, durability (hence cost) has significantly improved.

- With the development of CCS, an additional low-cost, low CO_2 hydrogen production route would be made available.

Common standards for hydrogen and FCEV equipment have also been agreed, further reducing their complexity and costs: standard connections, safety limits and performance requirements for hydrogen refuelling have been established by several SAE[22] and ISO[22] standards, while the electric system is fully compliant with SAE and ISO safety standards.

20 This is commonly illustrated by well-to-wheel emissions, integrating the CO_2 footprint of fuel production with its transformation by the power-train (see Annex, Exhibit 43, page 54)
21 See Annex, Exhibit 44, page 55
22 SAE International (formerly Society of Automotive Engineers), the recognised authority on standards for commercial vehicles, together with ISO (International Organization for Standardization)

With more than 500 passenger cars – both large and small – covering over 15 million kilometres and undergoing 90,000 refuellings,[23] FCEVs are therefore now considered to have been comprehensively tested in a customer environment. The result: the focus has now shifted from demonstration to commercial deployment so that FCEVs, like all technologies, may benefit from mass production and the economies of scale.

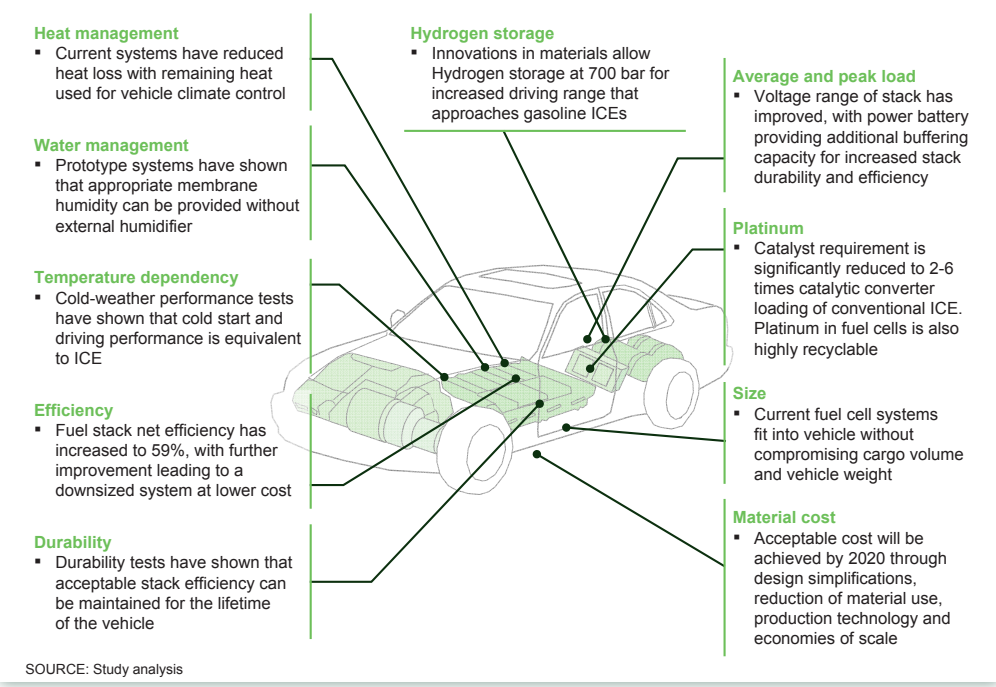


Exhibit 2: With all technological hurdles resolved, the focus for FCEVs has now shifted from demonstration to commercial deployment

This was clearly signalled in a Letter of Understanding issued by leading car manufacturers[24] in September 2009, in which they stated their goal to commercialise FCEVs by 2015, with hundreds of thousands of vehicles being rolled out worldwide shortly thereafter – assuming sufficient hydrogen refuelling infrastructure is in place. This was a catalyst for the in-depth evaluation of the four power-train technologies undertaken in this study.

A public-private partnership called H2 Mobility was also established, which is now developing a business plan for building a hydrogen refuelling infrastructure in a single Member State (i.e. Germany) – complemented by a series of demonstration projects in other Member States – as essential first steps towards a full EU roll-out (see pages 52-53).

The window of opportunity is short. If FCEVs are to achieve economies of scale within the time-frame necessary to meet EU CO_2 reduction goals, action must be taken as a matter of urgency. There is also a danger that Europe will lose its technological leadership as other international markets gain ground. The European Commission has confirmed that "the global trend towards sustainable transport shows that the European automotive industry can only remain competitive by leading in green technologies".[25]

23 Study data
24 Daimler AG, Ford Motor Company, General Motors Corporation/Opel, Honda Motor Co., Ltd., Hyundai Motor Company, Kia Motors Corporation, the alliance Renault SA and Nissan Motor Co., Ltd. and Toyota Motor Corporation
25 European Commission, April 2010

The reality is that no transportation model can be changed overnight – it requires preparation and ramp-up of production. A "knee-jerk" response to external factors, such as a rise in oil prices, supply constraints and the disastrous consequences of global warming will be too little, too late.

All conclusions are based on proprietary industry data

This study represents the most accurate to date,[26] as conclusions are based not on informed speculation, but on confidential, granular and proprietary data, provided by key industry players. This has allowed a true comparison of the power-trains, with all underlying assumptions clearly stated (see Methodology section, pages 15-25).

In order to present an integrated perspective across the entire value chain, the study addresses five key questions:

1. On a well-to-wheel basis, how do BEVs, FCEVs and PHEVs compare to ICEs over the medium-to-long term on emissions, performance and costs?

2. What are the key drivers by car size, miles driven, supply technology and over time?

3. What are the potential market segments?

4. How do fuels, electricity and hydrogen production, distribution and retail pathways compare?

5. What is required at a high level to deploy electric vehicles (BEVs, FCEVs, PHEVs) at scale so that they can benefit society by significantly reducing CO_2 emissions, enhancing energy security and improving air quality – without compromising its current expectations for mobility?

The positive effect of electric vehicles on public health

The benefits of electric vehicles (BEVs, FCEVs and PHEVs in electric mode) go beyond the decarbonisation of road transport and energy security to address the key issue of air pollution in large, congested cities: the exhaust from ICEs not only emits CO_2, but also local pollutants[27] such as carbon monoxide, hydrocarbons and nitrous oxides. Diesel vehicles also emit particles referred to as particulate emissions or "soots". Although these emissions are mitigated by catalytic converters, all pollutants that cannot be processed are released into the atmosphere, degrading air quality and reducing the ability of large cities to meet air quality targets.

Electric vehicles, on the other hand, release zero emissions in their "tank-to-wheel" process, with emissions limited to the "well-to-tank" process – far removed from the vehicle itself. Emissions also depend on the primary energy source used and can be potentially reduced to zero. Finally, unlike ICEs, electric vehicles are virtually silent, also reducing noise pollution significantly.

26 Other studies taken into consideration include "Hydrogen Highway": www.hydrogenhighway.com; Roads2HyCom project www.roads2hy.com; "On the road in 2035", published 2008; "The Hydrogen Economy", published 2009; "Hydrogen Production Roadmap: Technology Pathways to the Future", published 2010

27 This would also apply even if using 100% biofuels

METHODOLOGY

This study provides a factual comparison of four different power-trains (Exhibit 3) – BEVs, FCEVs, PHEVs and ICEs – on economics, sustainability and performance across the entire value chain[1] between now and 2050, based on confidential and proprietary industry data. This was possible due to the central role of an independent consultancy and a strict division between the consultancy's "Clean Team" responsible for input gathering and the "Analysis Team" responsible for output generation.

Data was submitted, challenged and, where necessary, benchmarked and validated for every step of the value chain – including purchase price, operating costs, fuel, as well as infrastructure. While it is possible that breakthrough technologies could provide step changes in current pathways to sustainable mobility, the study only considered vehicle technologies that are *proven* in R&D today – and in many cases demonstrated – and therefore capable of a) scale-up and commercial deployment and b) meeting the EU's CO_2 reduction goal for 2050.

To ensure a realistic outcome, it was agreed that all conclusions should be based on average values derived from the range provided, with no "cherry-picking" of the most favourable data.

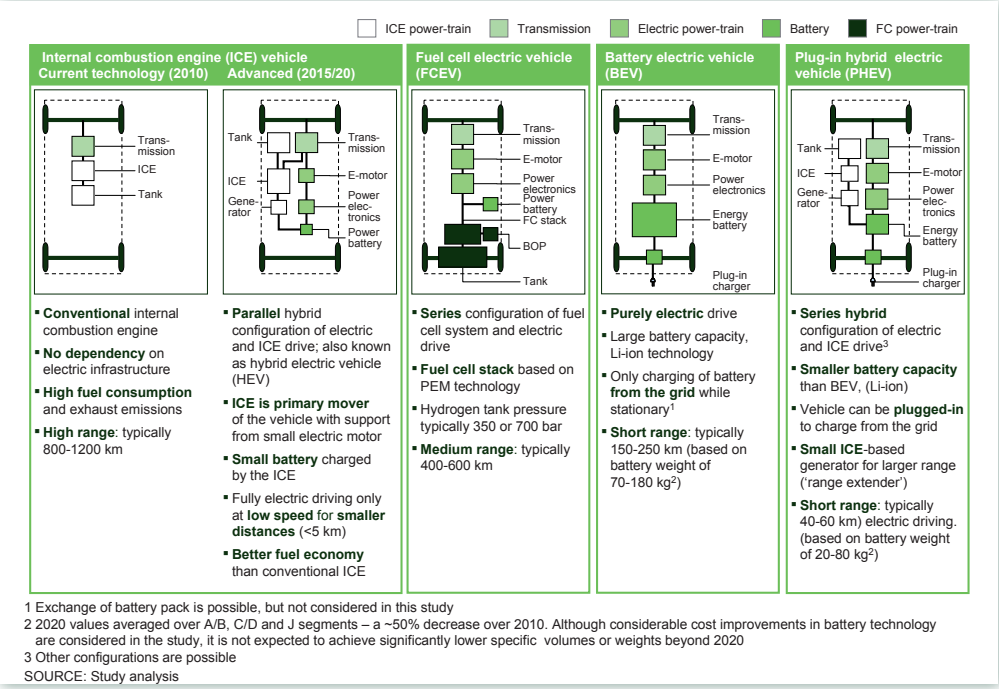


Exhibit 3: The study focused on a portfolio of power-trains: BEVs, FCEVs, PHEVs and ICEs, taking into account significant advances in ICE technology between now and 2020

In order to ensure no bias towards any particular power-train, the study included a balanced mix of car sizes (known as "segments"), representing the majority of vehicles currently on the market and with high data availability among study participants (Exhibit 4). Average values for fleets, as opposed to specific cars, were taken.

1 Commonly referred to as "well-to-wheel"

Defined reference segments

Vehicle segment	Typical characteristics	Example	EU vehicle production 2008, %
A – City	▪ <3,800 mm ▪ 3 door hatchback ▪ €8k-15k	▪ Hyundai i10 ▪ Smart	6
B – Super-mini	▪ 3,700-4,200 mm ▪ 5 door hatchback ▪ €10k-20k	▪ Toyota Yaris ▪ Mercedes A	23
C – Medium	▪ 4,000-4,500 mm ▪ 5 door hatchback ▪ €15k - 25k	▪ Honda Civic ▪ Ford Focus	23
D – Upper medium	▪ 4,400-5,000 mm ▪ 4 door sedan ▪ €25k-45k	▪ Renault Laguna ▪ Honda FCX ▪ Mercedes C	13
E – Large	▪ 4,700-5,100 mm ▪ 4 door sedan ▪ €40k-120k	▪ Mercedes E/S ▪ Lexus GS	5
F – Luxury	▪ 2/4 door sedan ▪ > €100k	▪ Maybach	<1

Vehicle segment	Typical characteristics	Example	EU vehicle production 2008, %
S – Sport	▪ 2 door coupe ▪ >€30k	▪ Mercedes CLK ▪ Nissan 370Z	<1
M1 – Small MPV	▪ 3,900-4,400 mm ▪ 5 door MPV ▪ €10k - 30k	▪ Mercedes B ▪ Renault Scenic	12
M2 – Large MPV	▪ >4,400 mm ▪ 5 door MPV ▪ €25k-50k	▪ Mercedes R	9
J1 – Small SUV	▪ 3,700-4,000 mm ▪ 5 door 4x4 ▪ €10k-30k	▪ Hyundai Tucson ▪ Toyota RAV4	5
J2 – Large SUV	▪ 4,000-5,100 mm ▪ 5 door 4x4 ▪ €25k-75k	▪ Toyota Highlander ▪ Ford Explorer	3

SOURCE: HIS Global Insight 2010; study participants

Exhibit 4: The study focuses on the vehicle segments that represent the majority of the EU car fleet (75%) – selected small (A/B), medium (C/D) and larger (SUV) cars

A balanced scenario for the electrification of passenger cars in the EU by 2050

In order to test the sensitivity of the economics to a broad range of market outcomes, the study envisioned three "worlds" with varying degrees of BEV, FCEV and PHEV penetration (Exhibit 5). These cover:

a. The full spectrum of expected futures for hydrogen, electricity and primary energy sources

b. Market shares and segment penetration rates for the different power-trains

c. Coverage area and availability of hydrogen.

All "worlds" assume 273 million passenger cars in the EU in 2050, with a hydrogen retail network infrastructure starting in the most densely populated areas (i.e. large cities) and growing to meet the needs of expanding vehicle clusters, leading to mass market roll-out. The car fleet is built up by introducing BEVs, FCEVs and PHEVs where they are most competitive with ICEs (Exhibit 6).

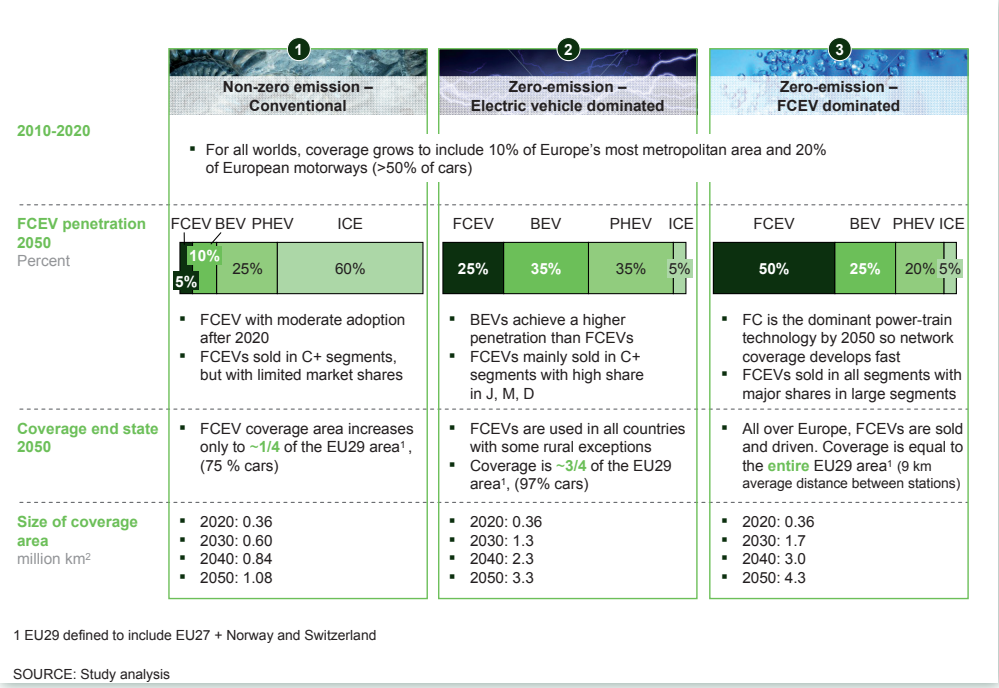


Exhibit 5: Assumptions for the three "worlds", each showing a different penetration scenario for BEVs, FCEVs, PHEVs and ICEs in the EU in 2050

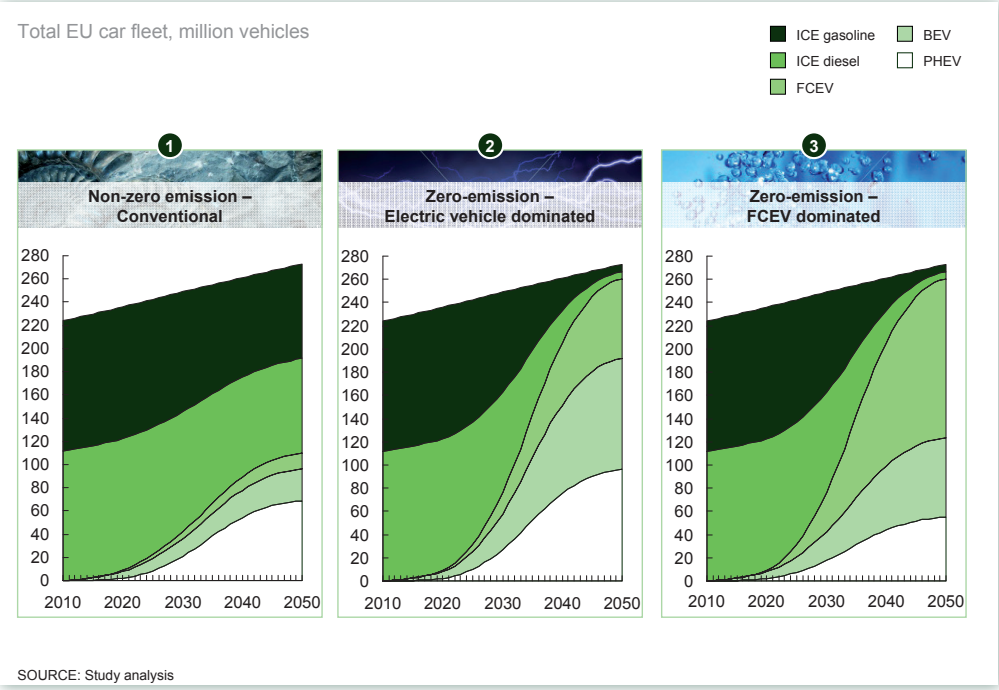


Exhibit 6: For all three "worlds", the car fleet is built up from 2010 to 2050 by introducing BEVs, FCEVs and PHEVs where they are most competitive with ICEs

A combined forecasting and backcasting approach to maximise accuracy

In order to ensure conclusions were as accurate as possible, both a forecasting and backcasting approach was then used: from 2010 to 2020, all cost and performance projections are based on proprietary industry data; after 2020, on projected learning and annual improvement rates. These forecasted data were then backcasted from the envisioned penetration of power-trains in the EU in 2050, as described above. The results showed that the impact on costs for varying FCEV penetrations is not significant[2] (see Annex, Exhibit 45, page 55):

- 5% penetration of FCEVs might be expected to be uncompetitive, but this is not the case:
  - While a Europe-wide highway infrastructure is deployed, clustering of vehicles in higher population density regions could keep fuel costs from escalating significantly
  - Focusing FCEV deployment on the medium/larger car segments where FCEVs are more competitive helps offset the lower economies of scale and increased vehicle costs
  - Comparing 5% to 25% FCEV penetration in 2050 on a "like-for-like" basis, a C/D segment FCEV has a 6.1% higher purchase price and 17.4% higher fuel costs, resulting in a 7.3% increase in TCO
- No significant improvements in economies of scale exist that improve the economics of FCEVs or hydrogen infrastructure between 25% and 50% penetration.

The study therefore focused on the "world" with a penetration of 25% FCEVs, 35% BEVs, 35% PHEVs and 5% ICEs as a balanced scenario for the penetration of electric vehicles in the EU.

Total cost of ownership (TCO)

In the study, the economic comparison between power-trains is based on the total cost of ownership (TCO), as well as purchase price (see Annex, Exhibit 46, page 56 for a sample TCO calculation for an FCEV).

Consumers buy cars for a wide variety of reasons, including purchase price, new vs. second-hand, depreciation rate, styling, performance and handling, brand preference and social image. The cost of driving the same vehicle when new is also greater than that for the next owner. Calculating the TCO of the power-trains is therefore important because it describes the costs associated over their entire lifetime – on top of which individual customer criteria are applied. TCO includes:

- Purchase price: the sum of all costs to deliver the assembled vehicle to the customer for a specific power-train and segment
- Running costs:
  - Maintenance costs in parts and servicing specific to each vehicle type and power-train combination
  - Fuel costs based on the vehicle fuel economy and mileage, including all costs to deliver the fuel at the pump/charge point and capital repayment charges on investments made for fuel production, distribution and retail; or for BEVs/PHEVs, for charging infrastructure

N.B. There is no discounting of cash flows over the years and no residual value after 15 years. Time value of money has not been taken into account. All taxes on vehicles and fuel (including VAT) are set to zero to ensure that comparisons reflect the true costs of driving and are revenue-neutral to governments.

TCO equation

TCO =	Purchase price	+	Running cost
	=		=
	Parts cost		Maintenance cost
	+		+
	Assembly cost		Fuel cost (incl. infrastructure & fuel costs)
	+		
	SG&A		
	+		
	Margin		

2 The TCO of BEVs and PHEVs is constant over the three worlds due to the fact that their learning rates are defined on a yearly basis, not on an increase in capacity.

A balanced hydrogen production mix including a variety of technologies

N.B. Assumptions on power generation are in line with the European Climate Foundation's "Roadmap 2050", which describes a realistic scenario for all power-trains (see page 24 and Annex, Exhibit 47, page 56).

In this report, well-to-wheel emissions do not incorporate indirect emissions resulting from feedstock exploration and the associated infrastructure build-up (e.g. Exploration platforms, mining activities, power plant build-up), nor so-called CO_2 equivalent green-house gases. If these indirect emissions are taken into account, the well-to-wheel emissions of the different power-trains will change over time, depending on the production and supply pathway. In future analysis, it would be useful to take these into account as well.

The study consists of two business models – the vehicle model (generic for all power-trains) and the supply model (more detailed for hydrogen as the electricity supply chain already largely exists). In each "world" scenario, the demand for each fuel in each year is set by the annual driving and fuel economy of the power-trains on the road.

1. The vehicle model (see Annex, Exhibit 48, page 57) calculates the purchase price, operating cost, TCO and CO_2 emissions based on the cost of electricity and hydrogen and the CO_2 footprint calculated from the supply model. It also includes key assumptions agreed among participating car manufacturers (Exhibit 7).

Parameter	Proposed value
▪ Average vehicle lifetime	▪ 15 years
▪ Average annual distance driven	▪ 12,000 km
▪ Combined fuel economy	▪ Distance weighted average of ECE-15 and EUDC cycles
▪ Sales tax	▪ *Tax-free base model run*
▪ Vehicle assembly cost as % of ICE purchase price[1,2]	▪ 13.5%
▪ SG&A (including distribution) cost as % of ICE purchase price[1,2]	▪ 13.5%
▪ Return on investment as % of ICE purchase price[1,2]	▪ 2% - A/B segment ▪ 7% - C/D segment ▪ 8.5% - J segment

1 Assumed to be similar across reference segments, with the exception of profit assumption, since margins vary significantly between vehicle segments
2 Percentage will be applied to ICE purchase price per reference segment; same absolute cost will then be applied to all power-trains in the segment

SOURCE: Euromonitor, Polk, EU MVEG, Credit Suisse, Goldman Sachs Global Investment Research report, study analysis

Exhibit 7: Key assumptions for the vehicle model were agreed among participating car manufacturers

2. ***The supply model*** (for FCEVs) then calculates the CO_2 footprint, the cost of delivered hydrogen and investment required, based on cost and performance data received for the three components of hydrogen infrastructure – production, distribution and retail.

Key assumptions included:

- Each year, based on hydrogen demand for vehicles, components are added to meet new demand and replace components that are at the end of their life
- With the exception of retail infrastructure and delivery trucks, utilisation is set to 95% (80% for distributed production) due to rapid increase in hydrogen demand, allowing installed equipment to achieve full utilisation within a few years (see Annex, Exhibit 49, page 57).
- Shifting from small to medium to large installation size depends on the annual hydrogen capacity added each year, i.e. small components are built when hydrogen demand is low, large components when demand is high.

a. Production

Nine major production pathways were considered for hydrogen, representing all the main technologies with the potential for rapid, large-scale deployment in Europe (Exhibit 8). Based on these production pathways, many different production mixes are possible.

Among other options, the study examined two hydrogen production mixes: a balanced and economically driven production mix with CCS; the other without CCS, representing 100% electrolysis with 80% renewable energy by 2050. Both, however, lead to CO_2-free hydrogen production by 2050 (Exhibit 9). While the production of hydrogen from SMR with CCS remains the lowest-cost scenario, the 100% electrolysis production mix only increases the TCO of FCEVs (C/D segment) by 5% by 2030 and 3.5% by 2050.

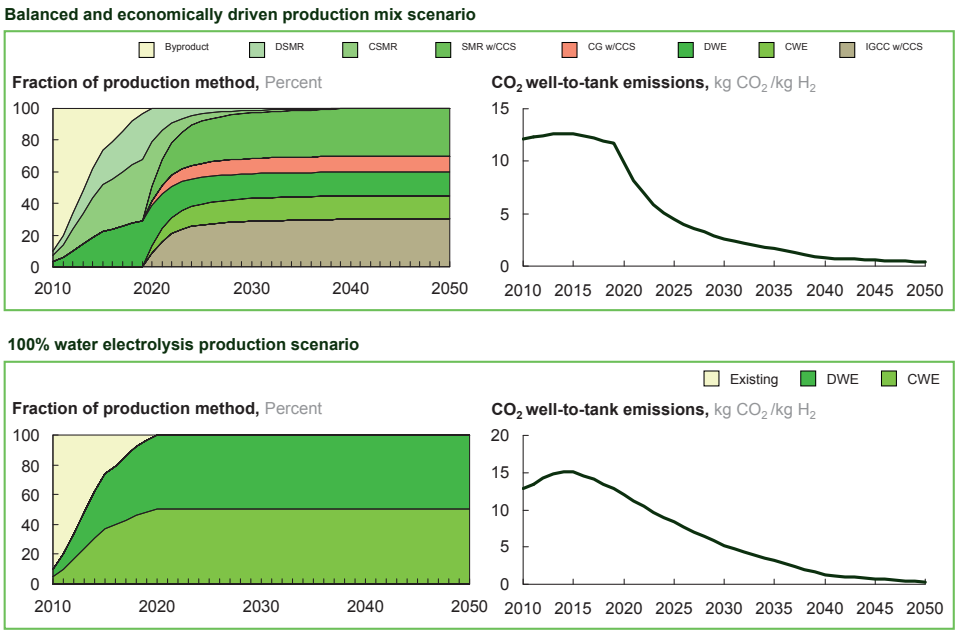
N.B. All the results in this report are based on the first balanced and economically driven production mix described below

Technology	Process	Governing reaction[1]	Variations
SMR Steam Methane Reforming	Methane, Steam → H_2, CO_2	$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$	▪ On-site SMR ▪ Central SMR ▪ Central SMR + CCS
WE Water Electrolysis	Water, Electricity[3] → H_2, O_2	$2H_2O \rightarrow 2H_2 + O_2$	▪ On-site WE ▪ Central WE
CG/(IGCC) Coal Gasification /Integrated Gasification Combined Cycle	Coal[2], Steam → H_2, CO_2	$C + 2H_2O \rightarrow CO_2 + 2H_2$	▪ CG ▪ CG + CCS ▪ IGCC ▪ IGCC + CCS

1 Simplified reaction
2 Includes co-firing with biomass
3 100% CO2 reduction from power by 2050: www.roadmap2050.eu

SOURCE: Study analysis

Exhibit 8: Nine major production pathways were assessed



SOURCE: Study analysis

Exhibit 9: The study examined two hydrogen production mixes, both of which lead to CO_2-free hydrogen by 2050

As total hydrogen demand for FCEVs is comparatively low up to 2020, a conventional production mix is assumed, utilising excess hydrogen from existing assets (industrial sites and centralised SMR), with a growing proportion of distributed units (water electrolysis and SMR).

Beyond 2020, when hydrogen demand for FCEVs increases rapidly, a balanced and economically driven scenario is assumed, reflecting the diversity of resources available in different parts of Europe and including new sources of clean and green hydrogen.[3] This scenario avoids over-dependence on any single primary energy source and provides the most cost-effective means of decarbonising hydrogen supply.

In summary:

- Before 2020, utilising existing production assets, Central Steam Methane Reforming (CSMR) has 40% and Distributed Steam Methane Reforming (DSMR) and Distributed Water Electrolysis (DWE) each have 30% share of new production.

- After 2020, CSMR and Integrated Gasification Combined Cycle (IGCC) each have 30%, coal gasification has 10% and Central Water Electrolysis (CWE) and DWE each have 15% share of new production.

- In line with the "Roadmap 2050" study, it is assumed that the share of renewable energy in the power mix increases steadily (important for electrolysis) – see Annex, Exhibit 47, page 56.

- CO_2 Capture and Storage (CCS) is applied to all new CSMR, IGCC and coal gasification capacity starting in 2020 and coal is co-fired with 10% biomass, which costs three times the IEA[4] estimate to account for pre-treatment required prior to gasification.

3 "Clean hydrogen" refers to the use of CCS; "green hydrogen" to renewable energy
4 International Energy Agency

- Coal, natural gas, clean electricity and biomass are all important for hydrogen production.

Both water electrolysis and IGCC could play a key role in supporting the electricity grid: electrolysis for demand management; IGCC for dispatchable power, i.e. for storage or export. Both technologies are also compatible with providing load balancing services, which will be in high demand in an electricity grid which includes a high percentage of renewable energies.

The role of biofuels

There is still uncertainty as to the amount of (sustainably produced) biofuels that will be available for passenger cars in the medium and long term in Europe. The study takes the following assumptions: by 2020 biofuels are blended, delivering a 6% well-to-wheel reduction in CO_2 emissions for gasoline and diesel engined vehicles, in line with the EU Fuel Quality Directive; by 2050 this increases to 24% to reflect growing supplies.

It also reflects the fact that this market will face increasing competition from other sectors – especially goods vehicles, aviation, marine, electric power and heavy industry to meet the needs of these sectors and a global passenger car fleet of 2.5 billion cars in 2050. A comprehensive analysis on the true global potential of biofuels is needed to determine both their availability and for which sectors and regions they may be most effectively used.

b. Distribution

A range of distribution methods was included in the study (Table 1).

Distribution method	*Tonnes of hydrogen/day*
Liquid trucks	*3.5*
Gaseous trucks	*0.4 (250 bar), 0.8 (500 bar)*
Pipelines	*1, 2.5, 10, 100*

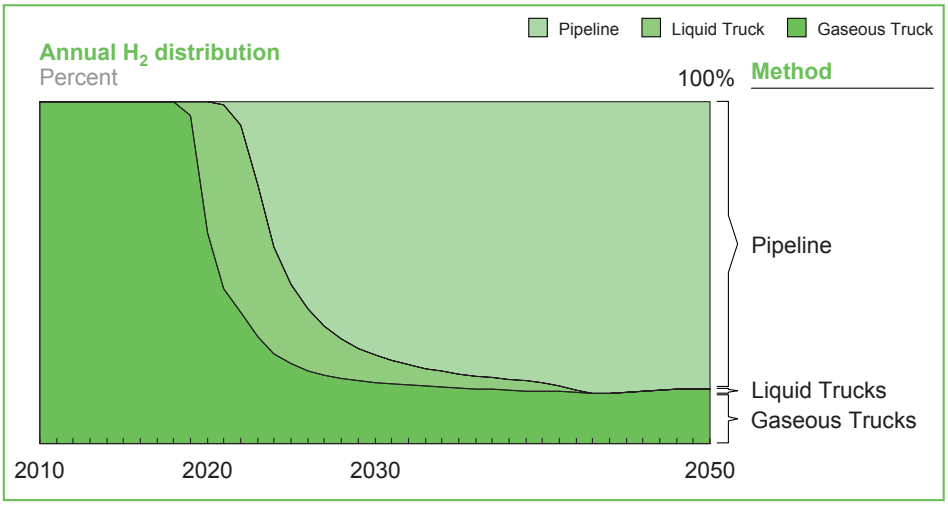
Table 1: An overview of distribution methods included in the study

Industry data were then used to calculate the distribution costs[5] for different volumes and distances, with the least expensive distribution method chosen for the required delivery distance.

A wide variety of distribution infrastructures may be considered, according to hydrogen volumes, distances and local specificities. This study assumes a distribution roadmap where gaseous trucks are initially the most important method, with liquid trucks bridging the gap to pipelines,[6] which will result in a significant reduction in delivery cost and CO_2 emissions (Exhibit 10).

5 Delivered cost = production cost + distribution cost + retail cost (each cost comes from the weighted average cost of all operating components using current feedstock and electricity prices). Components already built are assumed to continue operating for their lifetime until retired

6 Private companies in Europe already own and operate the world's largest hydrogen pipeline network covering ~1600 kilometres in France, Germany and the Benelux countries. Smaller pipelines are also operating in Italy and Sweden.



SOURCE: Study analysis

Exhibit 10: The hydrogen distribution mix assumed for the study

c. Retail stations

Small station (70-100 cars per day)	*2 dispensers, 0.4 tonnes of hydrogen/day*
Medium station (150-250 cars per day)	*4 dispensers, 1 tonne of hydrogen/day*
Large station (450-600 cars per day)	*10 dispensers, 2.5 tonnes of hydrogen/day*

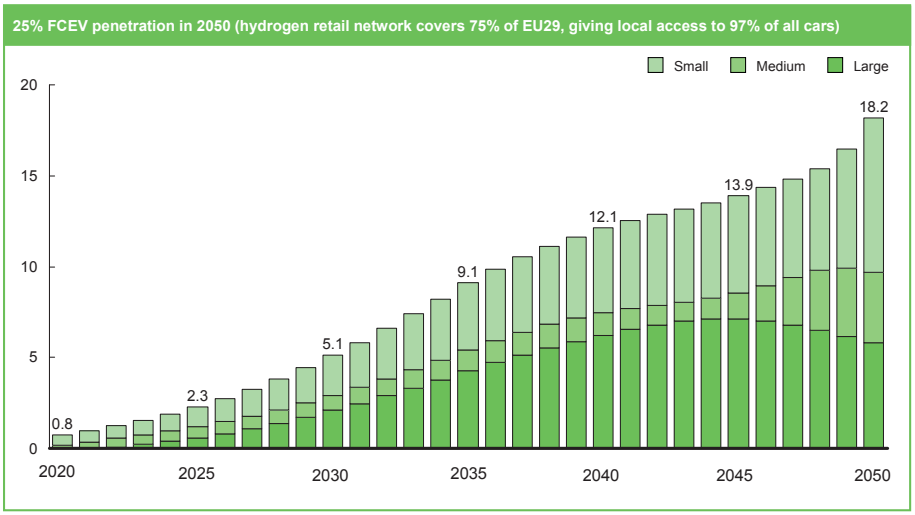
Table 2: An overview of retail stations included in the study

The size of retail stations added was determined by hydrogen demand and coverage area: when coverage expands faster than demand, new retail stations are small; when demand grows faster than the coverage area, larger retail stations are added etc.

In the first decade, utilisation of retail stations is low, resulting in higher costs, but by 2020 it achieves 80% of the designed capacity, based on industry experience in fuels retail (see Annex, Exhibit 49, page 57). As expected, large retail stations have better economics than small and medium stations.

For the simulation in all "worlds" (see pages 16-18), the number of retail stations grows from an initial cluster of four in 2010 to 198 in 2015 and 755 in 2020; for the electric vehicle-dominated "world", Exhibit 11 shows a breakdown of retail stations from 2020 to 2050.

Thousand retail stations in EU29



Note Small stations have maximum capacity of 400 kg H2/day, medium have 1 tonne H2 /day and large have 2.5 tonnes H2 /day

SOURCE: Study analysis

Exhibit 11: The number of hydrogen retail stations from 2020 to 2050 in the electric vehicle-dominated "world"

Key assumptions

- WACC (Weighted average cost of capital) of 7% in nominal terms (post corporate tax), with no additional margin
- An asset lifetime of 20 years (30 years for pipelines)
- Oil, gas and coal prices are assumed from the IEA (see Annex, Exhibits 50-52, pages 58-59)
- Key raw material prices (e.g. metals) are taken from industry consensus analysis

The power supply pathway underlying this report is based on the European Climate Foundation "Roadmap 2050", which was developed in cooperation with the industry and describes a pathway to decarbonise the EU's power mix by 2050. In 2020, the expected share of renewable production capacity is approximately 34%. This is the minimum needed to meet the 20% EU renewable energy target, as there is limited RES opportunity outside of the power sector (see Annex, Exhibit 47, page 56). This ensures that the treatment of the power sector is consistent with the EU CO_2 reduction goal of 80% by 2050 (i.e. zero CO_2 from power by 2050) and draws a self-consistent set of electricity tariffs for wholesale, industrial and retail use, together with CO_2 emissions from power generation.

Assumptions are robust to significant variations

Projected cost reductions are based on years of experience of conventional vehicles – ICEs – including learning rates, the simplification of systems and economies of scale achieved by scaling up to larger production lines. The introduction of hybrid electric vehicles (HEVs), on the other hand – with millions now on the road – has given a deep insight into the pace of cost reduction for innovative power-trains and components over the last 10 years.

Nevertheless, all conclusions are robust to significant variations in learning rates and the cost of fossil fuels; and by 2030, there is only a small difference of –1 to +3 cents per kilometre (based on a pre-tax cost of 18 cents per kilometre), even with variations of +/– 50% (Exhibit 12).

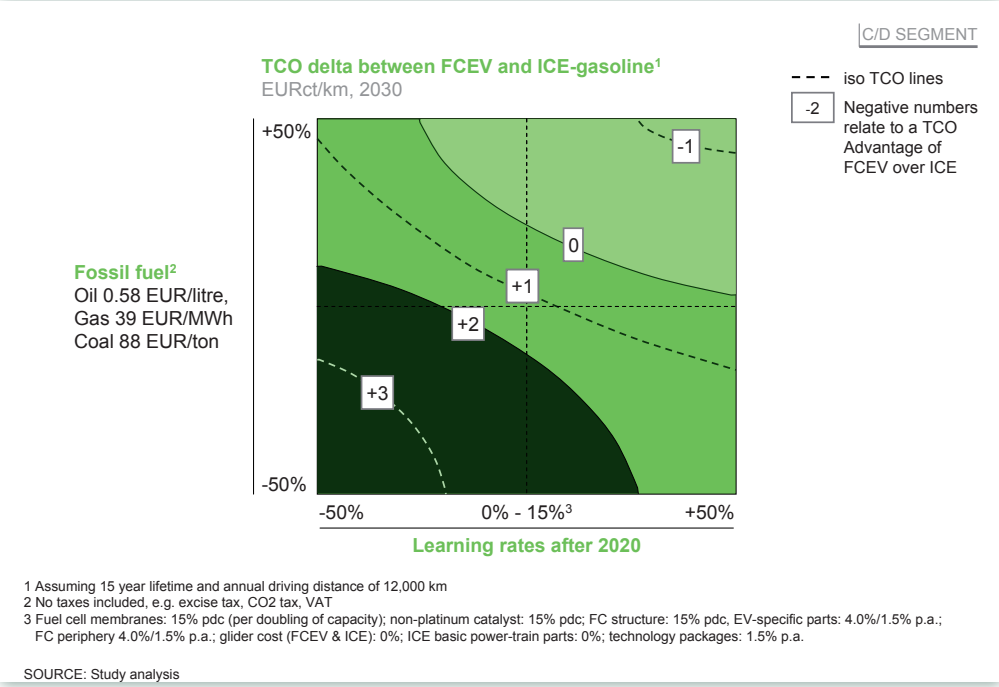


Exhibit 12: All conclusions are robust to significant variations in learning rates and the cost of fossil fuels

INPUT DATA

The collection, benchmarking and validation of over 10,000 data points

The process of collecting and sanitising data from participating companies was both methodical and rigorous:

1. The independent consultancy and participating companies together defined precisely the data to be collected in order to evaluate the four power-trains on a well-to-wheel basis.

2. The consultancy's "Clean Team" then sent out detailed data requests on economics (Exhibit 13), sustainability and performance for all four power-trains (BEV, FCEVs, PHEVs and ICEs), including the following supply chains: Gasoline and diesel, Electricity, and Hydrogen

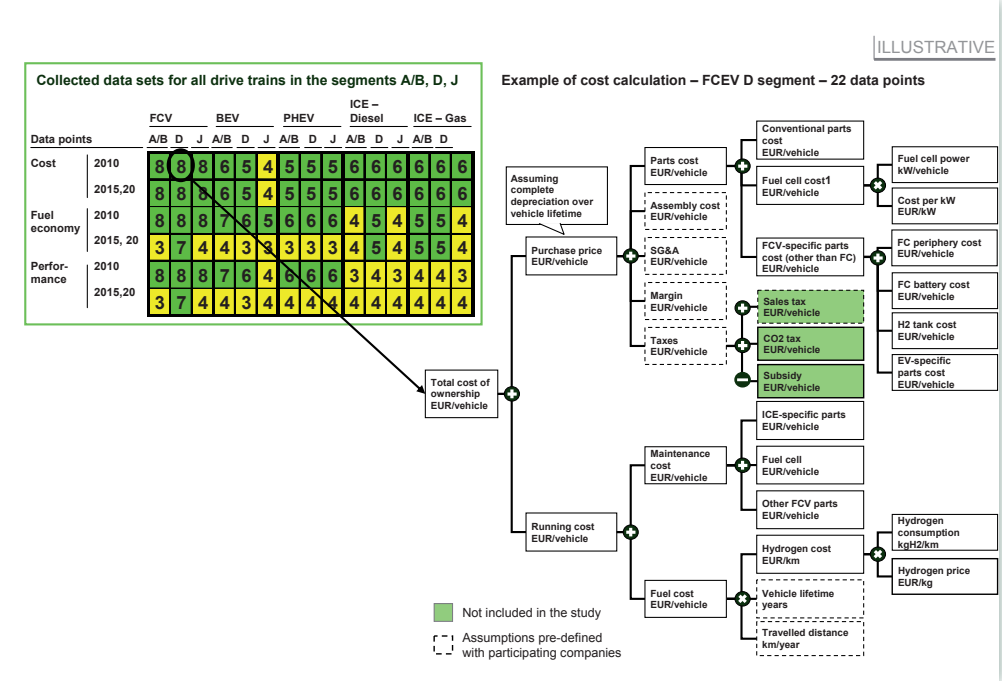


Exhibit 13: An example of cost data collected for a FCEV

3. The Clean Team collected the data and assessed whether they were of the appropriate quality.

4. The Clean Team reviewed the submitted data in order to understand the differences between the data sets of the various companies, asking them to preside correct data, where necessary.

5. Individual output data were submitted to relevant companies for sign-off (Exhibit 14)

Exhibit 14: An example of cost output data for water electrolysis

After all the output data had been signed off, it was then considered frozen and the analysis of the power-trains began.

RESULTS

The following conclusions are not forecasts, but one possible outcome – the result of a backcasting exercise based on a penetration of 25% FCEVs, 35% BEVs, 35% PHEVs and 5% ICEs in the EU by 2050 *(see pages 16-18)*.

1. *BEVs and FCEVs have the potential to significantly reduce CO_2 and local emissions*

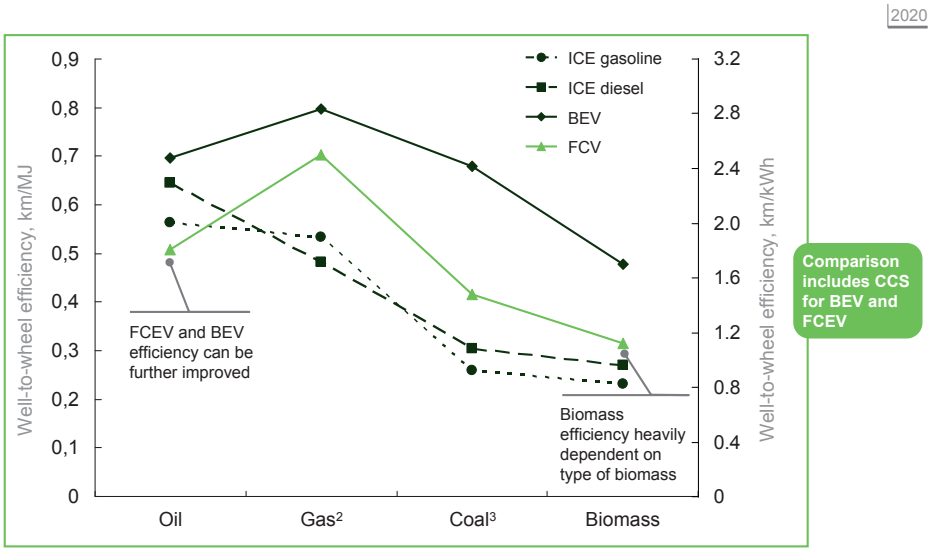
BEVs: given their limited energy storage capacity and driving range (150-250 km[1]) – and a current recharging time of several hours – BEVs are ideally suited to smaller cars and shorter trips, i.e. urban driving.

FCEVs: with a driving range and performance comparable to ICEs, FCEVs are the lowest-carbon solution for medium/larger cars and longer trips.

PHEVs: with a smaller battery capacity than BEVs, electric driving for PHEVs is restricted to short trips (40-60 km). Combined with the additional blending of biofuels (see page 2), they also show emission reductions for longer trips, but uncertainty remains as to the amount of sustainably produced biofuels that will be available for this market. Nevertheless, they are an attractive solution, reducing emissions considerably compared to ICEs.

ICEs: ICEs also have the potential to reduce their CO_2 footprint significantly through improved energy efficiency and biofuels. After 2020, however, further engine efficiency improvements are limited and relatively costly, while the availability of biofuels may also be limited.

a. Electric vehicles are more energy efficient than ICEs over a broader range of feedstocks



1 All power-trains have different performance criteria and therefore different driving missions
2 CNG used in gasoline ICE; diesel production from natural gas through Fischer-Tropsch process
3 Gasoline and diesel production from coal-to-liquids transformation through Fischer-Tropsch process

SOURCE: CONCAWE-EUCAR JEC-WTW study; study analysis

Exhibit 15: The well-to-wheel efficiency of FCEVs is comparable to ICEs, while BEV remains the most efficient power-train

1 For C/D segment cars in the medium term

In the energy- and carbon-constrained world in which we now live, the efficient use of primary energy resources is essential.

Exhibit 15 shows the well-to-wheel efficiency of the different power-trains using different types of primary energy sources. BEVs are the most efficient solution. FCEVs are more efficient than ICE on gas and coal. On oil and biofuels, the difference between ICE and FCEVs is small (see Annex, Exhibit 43, page 54, for a more detailed analysis).

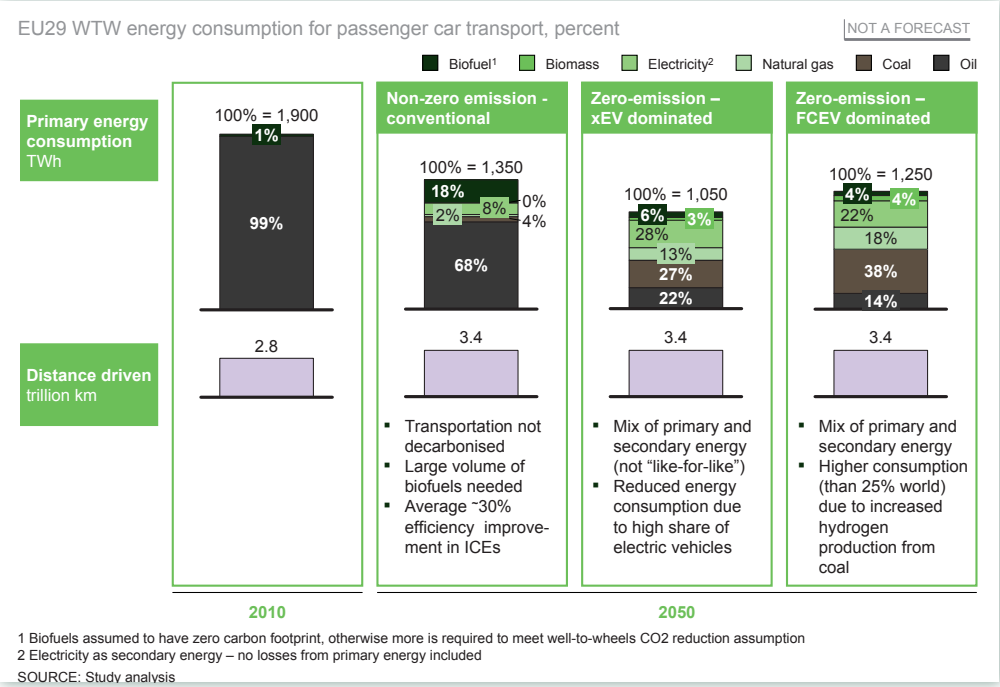
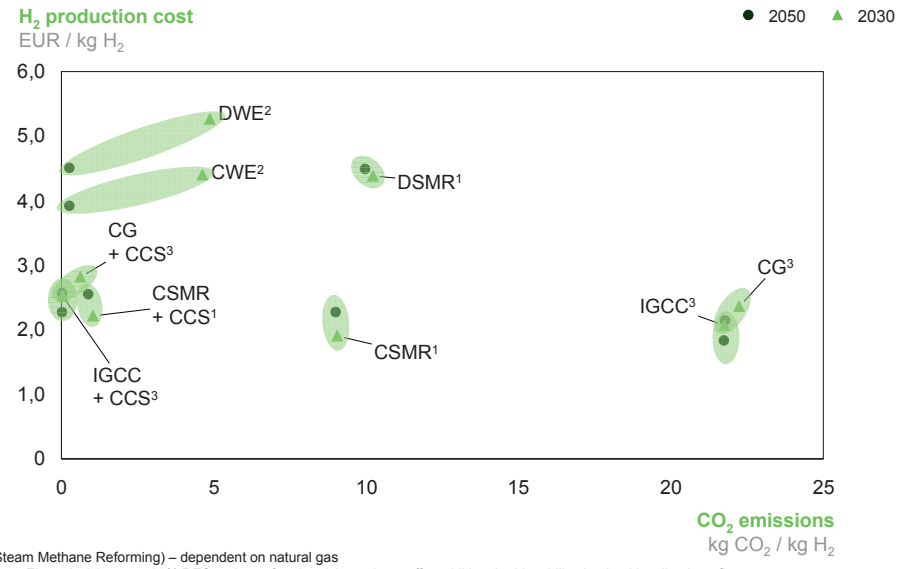


Exhibit 16: On a net-distance-travelled basis, electric vehicles could potentially drive more kilometres than ICEs using less energy

The data in this exhibit are the result of a backcasting exercise based on FCEVs achieving a range of penetrations in the EU by 2050 (see pages 16-18) and the scenario for power generation outlined in the European Climate Foundation's report, "Roadmap 2050" (see page 24).

While oil will remain the main source of energy for passenger cars in the short-to-medium term, switching to a high percentage of electric vehicles will increase flexibility and security of energy supply as they can be fuelled by a variety of primary energy sources.

For all future scenarios – and on a total global vehicle travel basis – BEVs, FCEVs, PHEVs and future ICEs can drive more total kilometres than today's ICEs using less primary energy due to increased efficiency.



1 SMR (Steam Methane Reforming) – dependent on natural gas
2 WE (Water Electrolysis) – uses 80% RES pathway for electricity and can offer additional grid stabilisation load leveling benefits
3 CG (Coal Gasification) – relies on domestic coal and when combined with CCS is assumed to be co-fired with 10% biomass

SOURCE: Study analysis

Exhibit 17: A variety of technologies are available to produce CO_2-free hydrogen (future cost levels)

A variety of technologies and feedstocks will be able to produce CO_2-free hydrogen, including fossil fuels, renewable electricity, nuclear and biomass.

The most cost-effective future production methods use existing technologies – steam reforming and coal gasification.

Costs of existing technologies such as SMR and coal gasification, will increase due to increasing fuel prices and costs of CCS (partly offset by technology advancements).

Cost of water electrolysers reduces due to efficiency improvements. The assumed power price reflects that these units can be run intermittently, providing a balancing solution for the power grid.

Hydrogen can be produced cost-effectively on both a small and large scale – from 0.4 to 1000 tonnes per day – from centralised or decentralised production.

CO_2 Capture and Storage (CCS)

CO_2 Capture and Storage (CCS) has been identified as an important solution for reducing CO_2 emissions, with the potential to provide 20% of the cuts required in the EU by 2030 and 20% of global cuts required by 2050

While the technology is being developed to reduce the CO_2 footprint of power generation, an additional benefit is that pre-combustion CO_2 capture technology also allows the production of large volumes of CO_2-free hydrogen. This is important to the economic assumptions of the study, as in the balanced and economically driven hydrogen production scenario (see pages 20-22), 70% of hydrogen is assumed to be produced using CCS.

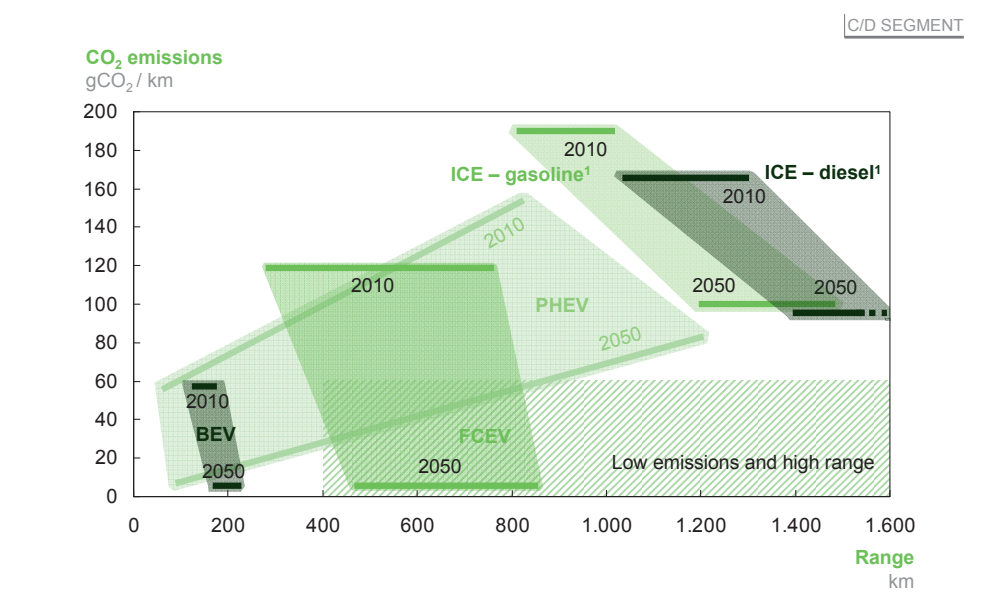
CO_2 capture has already been practised on a small scale, while the technology for CO_2 storage is similar to that used by the oil and gas industry for decades – to store natural gas or for enhanced oil recovery (EOR). CO_2 storage technology combined with EOR is therefore very advanced, providing ample data for storage in depleted oil and gas fields, while pure storage has been demonstrated for over a decade in a limited range of deep saline aquifers. However, the inherent risks associated with scale up and deployment are recognised.

The next step is therefore to scale-up the technology, with demonstration projects of a size large enough to allow subsequent projects to be at commercial scale. This will also build public confidence, as it is seen that CO_2 storage is safe and reliable.

The EU has already made significant progress in advancing CCS, establishing a legal framework for the geological storage of CO_2 and public funding to support an EU programme of up to 12 CCS demonstration projects. The goal: to enable the commercial availability of CCS by 2020. This has been echoed by many similar initiatives worldwide.

For more information, please refer to the European Technology Platform for Zero Emissions Fossil Fuel Power Plants (ZEP), otherwise known as the Zero Emissions Platform: www.zeroemissionsplatform.eu.

b. BEVs are ideally suited to smaller cars and shorter trips



1 ICE range for 2050 based on fuel economy improvement and assuming tank size stays constant. Assuming 6% CO2 reduction due to biofuels by 2020; 24% by 2050

SOURCE: Study analysis

Exhibit 18: BEVs and FCEVs can achieve significantly low CO_2 emissions, with BEVs showing limitations in range

Despite improvements in fuel economy, the capacity of ICEs to reduce CO_2 is significantly less than that of BEVs and FCEVs, which can achieve close to zero CO_2 emissions (well-to-wheel). As the range of BEVs is limited for medium sized cars, they are ideally suited to smaller cars and shorter trips.

See Annex (Exhibit 53, page 59) for a graphical analysis of how BEVs, FCEVs and PHEVs can reduce CO_2 emissions over time.

c. FCEVs are the lowest-carbon solution for medium/larger cars and longer trips

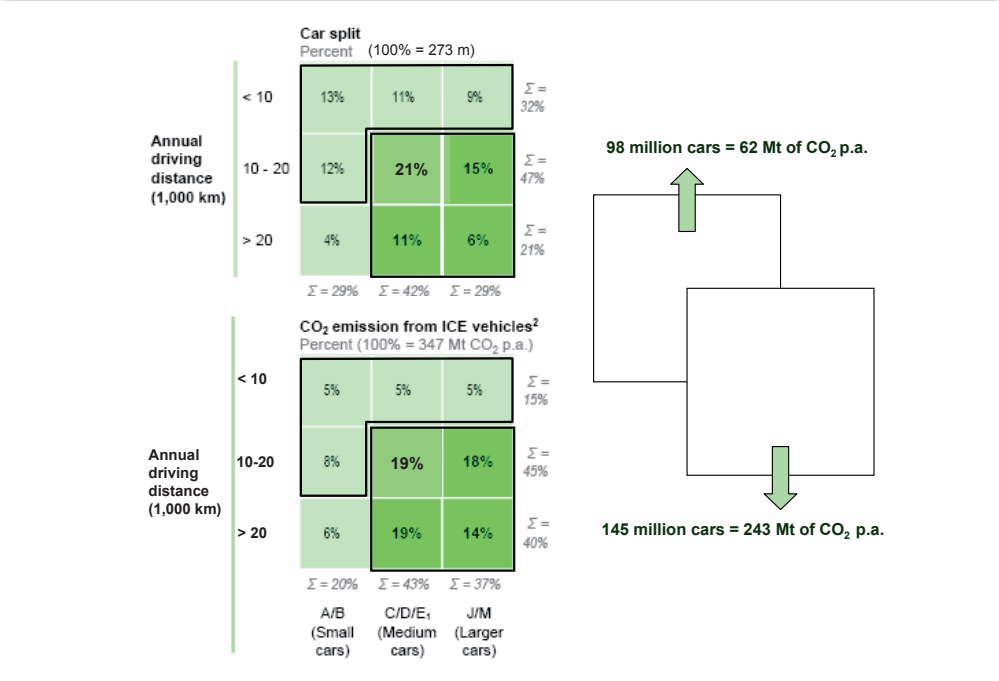


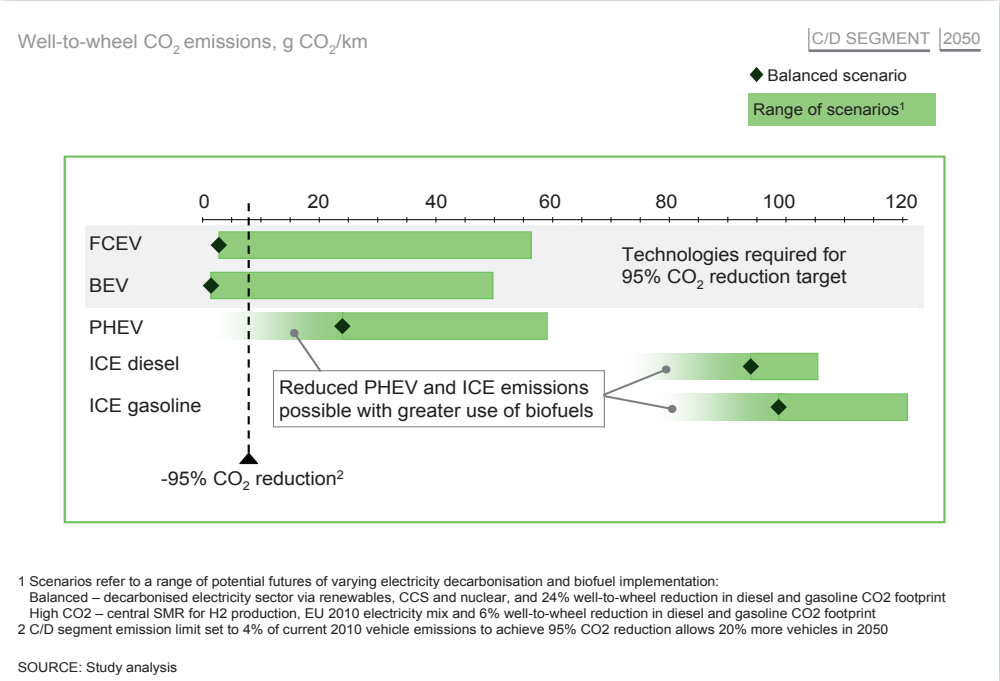
Exhibit 19: Medium/larger vehicles with above average driving distance account for 50% of all cars and 75% of CO_2 emissions

Medium/larger cars are responsible for a disproportionately greater share of CO_2 emissions due to the fact that they generally cover longer distances, as well as emit more CO_2. Replacing one ICE in these segments with one FCEV therefore achieves a relatively higher CO_2 reduction.

As FCEVs also have a clear TCO advantage over BEVs and PHEVs for medium/larger cars and longer trips (see Exhibit 32, page 42), FCEVs represent the lowest-carbon solution for a large proportion of the car fleet, based on current mobility patterns.

BEVs and FCEVs have the potential to significantly reduce CO_2 and local emissions.

d. PHEVs are an attractive solution for short trips or using biofuels



1 Scenarios refer to a range of potential futures of varying electricity decarbonisation and biofuel implementation:
Balanced – decarbonised electricity sector via renewables, CCS and nuclear, and 24% well-to-wheel reduction in diesel and gasoline CO2 footprint
High CO2 – central SMR for H2 production, EU 2010 electricity mix and 6% well-to-wheel reduction in diesel and gasoline CO2 footprint
2 C/D segment emission limit set to 4% of current 2010 vehicle emissions to achieve 95% CO2 reduction allows 20% more vehicles in 2050

SOURCE: Study analysis

Exhibit 20: BEVs and FCEVs can achieve 95% decarbonisation of road transport by 2050

In order to achieve the EU's goal to reduce CO_2 emissions by 80% by 2050, CO_2 emissions in the road transport sector must be reduced by 95%.

PHEVs can reduce CO_2 emissions when using the electric drive, but only for short trips (40-60 km). Combined with the additional blending of biofuels, they also show emission reductions for longer trips, but uncertainty remains as to the amount that will be available for this market (see page 2).

2. *After 2025, the total cost of ownership of all the power-trains converge*

In the study, the economic comparison between power-trains is based on the total cost of ownership (TCO), as well as purchase price, as it describes the costs associated over their entire lifetime (see page 18). All costs are "clean" of tax effects, including carbon prices.

BEVs and FCEVs are expected to have a higher purchase price than ICEs (battery and fuel cell related) lower fuel cost (due to greater efficiency and no use of oil) and a lower maintenance cost (fewer rotating parts).

The cost of fuel cell systems is expected to decrease by 90% and component costs for BEVs by 80% by 2020, due to economies of scale and incremental improvements in technology. Around 30% of technology improvements in BEVs and PHEVs also apply to FCEVs and vice versa. This assumes that FCEVs and BEVs will be mass produced, with infrastructure as a key prerequisite to be in place. The cost of hydrogen also reduces by 70% by 2025 due to higher utilisation of the refuelling infrastructure and economies of scale, e.g. the capital cost of hydrogen refuelling stations is expected to reduce by 50% between 2010 and 2020.

PHEVs are more economic than BEVs and FCEVs in the short term. The gap gradually closes and by 2030 PHEVs are cost-competitive with BEVs for smaller cars, with both BEVs and FCEVs for medium cars and less competitive than FCEVs for larger cars.

While the fuel economy of ICEs is expected to improve by an average of 30% by 2020, costs also increase due to full hybridisation and further measures such as the use of lighter weight materials. The TCOs of all four power-trains are expected to converge after 2025 – or earlier, with tax exemptions and/or incentives during the ramp-up phase.

For larger cars, the TCO of FCEVs is expected to be lower than PHEVs and BEVs as of 2030. By 2050, it is also (significantly) lower than the ICE. For medium-sized cars, the TCOs for all technologies converge by 2050. BEVs have a (small) TCO advantage over FCEVs in the smaller car segments.

By 2020, the cost of a fuel cell system falls by 90%, BEV components by 80%

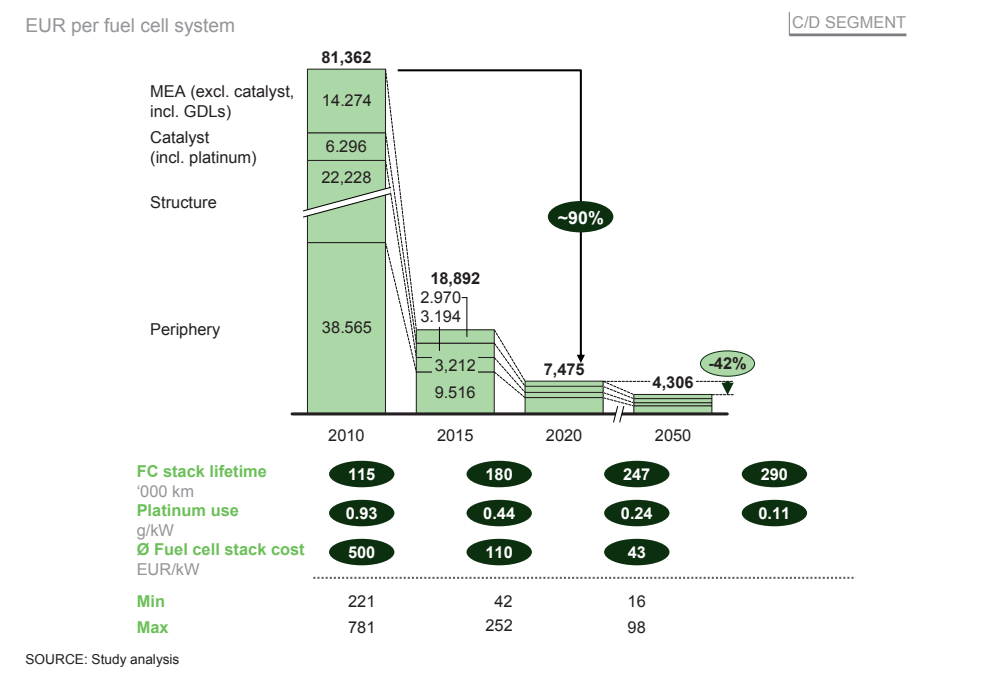


Exhibit 21: The cost of a fuel cell system falls by 90% by 2020

Exhibit 21 is based on a set of data provided by the participating companies. As discussed in the Methodology section, the average value for the fuel cell system cost is used for further calculations. The data set in 2010, 2015 and 2020 forms a broad range (see Annex, Exhibit 54, page 60), which is normal for an industry planning on mass production. The difference between the best and the worst cost data points can vary by a factor of 5, depending on the different technologies and processes used by car manufacturers.

The fuel cell system is the most significant cost component in an FCEV (other cost elements include the electric power-train and hydrogen tank). With all critical technological hurdles resolved, all projected cost reductions for FCEVs are based on engineering improvements and manufacturing efficiencies for commercial production. These include:

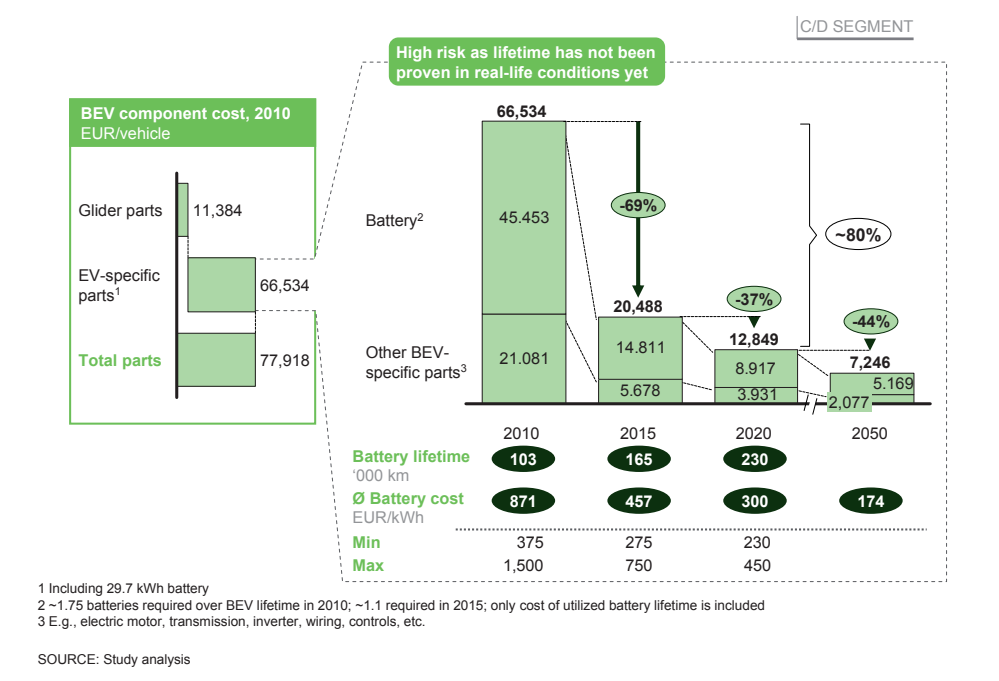
- Improvements in design, e.g. removing components; operating at a higher temperature in order to simplify the units

- Different use of materials, e.g. reduced platinum use; using alloys and smart catalyst structure; mitigation of fuel cell degradation

- Improvements in production technology – moving from batch to continuous production patterns; solvent-free (dry processes) with high throughput

- Economies of scale (1 million FCEVs in the EU by 2020).

All projected cost reductions for FCEVs and hydrogen supply until 2020 are based on proprietary data. In order to ensure a realistic outcome, learning rates after 2020 are conservative and considerably lower than historical improvements of comparable technologies, such as Wind, Solar PV or LNG (see Annex, Exhibit 42, page 54).



1 Including 29.7 kWh battery
2 ~1.75 batteries required over BEV lifetime in 2010; ~1.1 required in 2015; only cost of utilized battery lifetime is included
3 E.g., electric motor, transmission, inverter, wiring, controls, etc.

SOURCE: Study analysis

Exhibit 22: The cost of BEV components falls by 80% by 2020

Exhibit 22 is based on a set of data provided by the participating companies. As discussed in the Methodology section, the average value for the BEV component cost is used for further calculations. The data set in 2010, 2015 and 2020 forms a broad range (see Annex, Exhibit 55, page 60), which is normal for an industry that has just started mass production. The difference between the best and the worst cost data point can vary by a factor of 3.

All projected cost reductions for BEV components are based on proprietary data and include:

- Improvements in production engineering: operations such as electrode cutting, forming, stacking and contacting of the collectors will gradually grow more efficient through the introduction of advanced laser technologies and a shift from "batch to continuous" production modes. The automatisation and rationalisation of quality testing along the production line will also generate efficiency gains.

- Economies of scale from larger production plants (3 million BEVs in the EU by 2020).

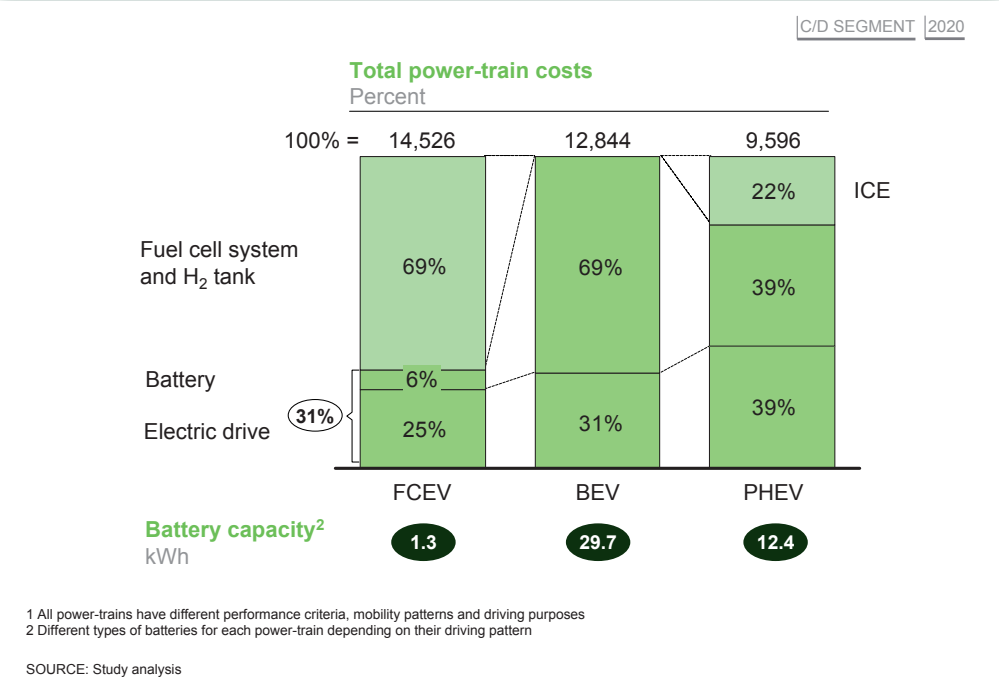


Exhibit 23: In 2020, 31% of technology improvements in BEVs and PHEVs also apply to FCEVs

- BEVs, FCEVs and PHEVs are complementary technologies as they share many similar electrical drive-train components, i.e. battery and electric drive. Investments in BEVs and PHEVs therefore also benefit FCEVs and vice versa.

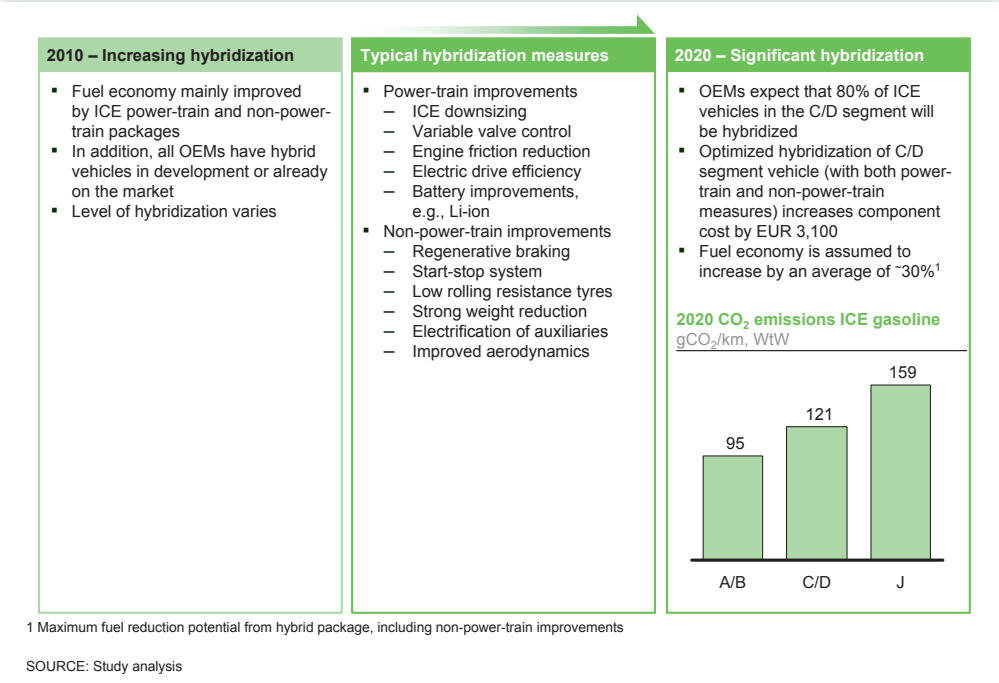
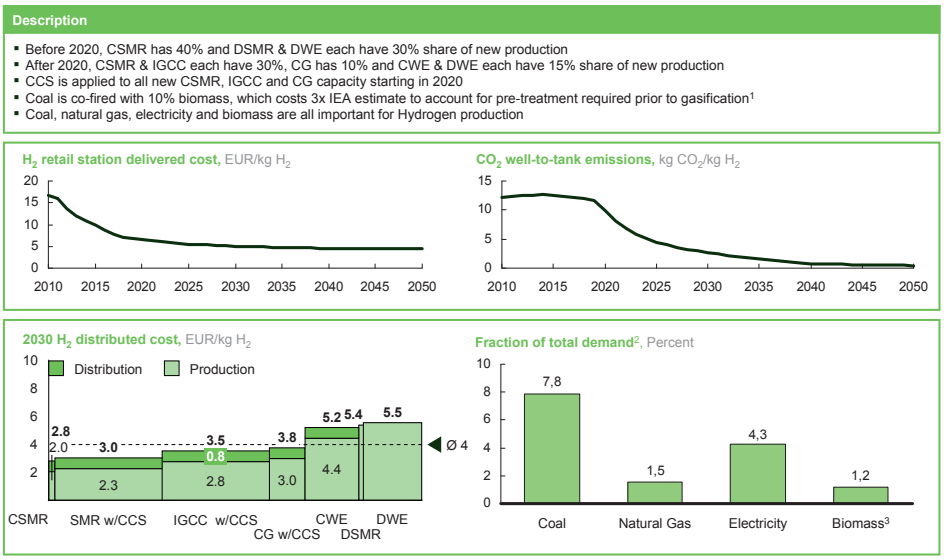


Exhibit 24: ICE fuel economy is assumed to increase by an average of 30% by 2020

The results of the study take into account significant improvements in fuel economy in ICEs by 2020.

a. The cost of hydrogen reduces by 70% by 2025



1 Co-firing more than 10% biomass with coal in IGCC and CG with CCS can allow negative CO2 emissions
2 Fraction is the amount of primary energy source consumed in 2050 divided by total EU-29 wide consumption in 2008
3 Fraction of biomass is that assumed available to the power generation sector (1,600 TWh/year)

SOURCE: Study analysis

Exhibit 25: The production mix assumed in the study is robust to energy shocks

Of the nine hydrogen production mixes studied, two were considered the most relevant for this study: the first (Exhibit 25) is more economically driven and based on a mix of fossil fuels and renewable energy; the second is based entirely on renewable energy (see Exhibit 26). Both production mixes reduce CO_2 emissions (well-to-tank) to near-zero.

Before 2020, the first production mix assumes that the limited volume of hydrogen required will be produced using centralised SMR (40%), distributed SMR (30%) and distributed water electrolysis (30%). After 2020, when the costs of FCEVs have come down and hydrogen demand rapidly increases, it assumes centralised SMR + CCS (30%); IGCC + CCS (30%); coal gasification + CCS (10%); centralised water electrolysis (15%); and decentralised water electrolysis (15%). Between 2010 and 2050, the study assumes an increasing share of renewable energy in the power mix (see Annex, Exhibit 47, page 56).

The exhibit shows results for the first hydrogen production mix on which the study is based: the lower left hand chart indicates the costs of the chosen production mix. In the upper left hand chart, hydrogen retail delivered costs rapidly approach €4.50/kg, while in the upper right hand chart, the CO_2 well-to-tank emissions first increase, then reduce rapidly after 2020.

As can be seen in the lower right hand chart, hydrogen can be produced, distributed and retailed cost-effectively by 2020 from a variety of feedstocks to suit local and market conditions.

N.B. All the results in this report are based on the balanced and economically driven production mix described in Exhibit 25.

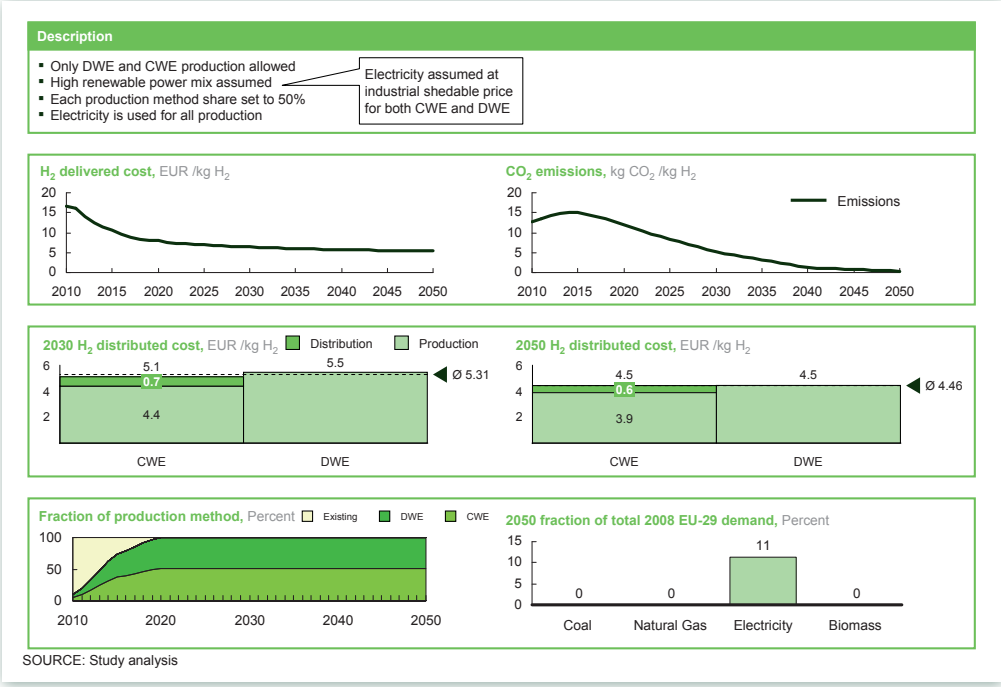


Exhibit 26: An alternative production mix representing 100% electrolysis, with 80% renewable production by 2050

The alternative production mix – representing 100% electrolysis, with 80% renewable production by 2050 – increases the TCO of FCEVs by 5% by 2030 and 3.5% by 2050.

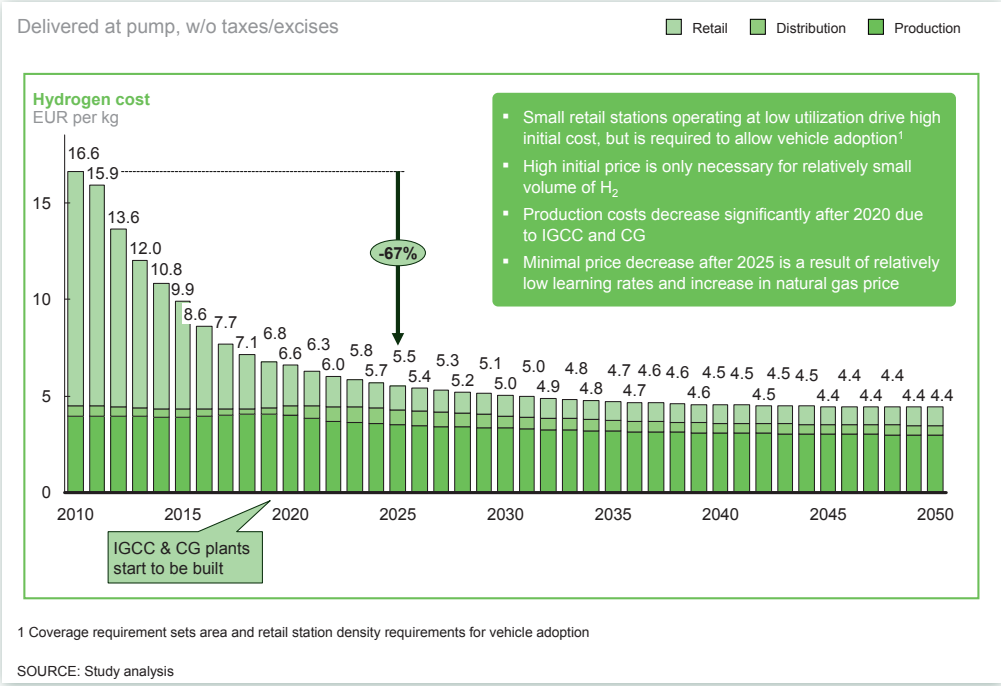


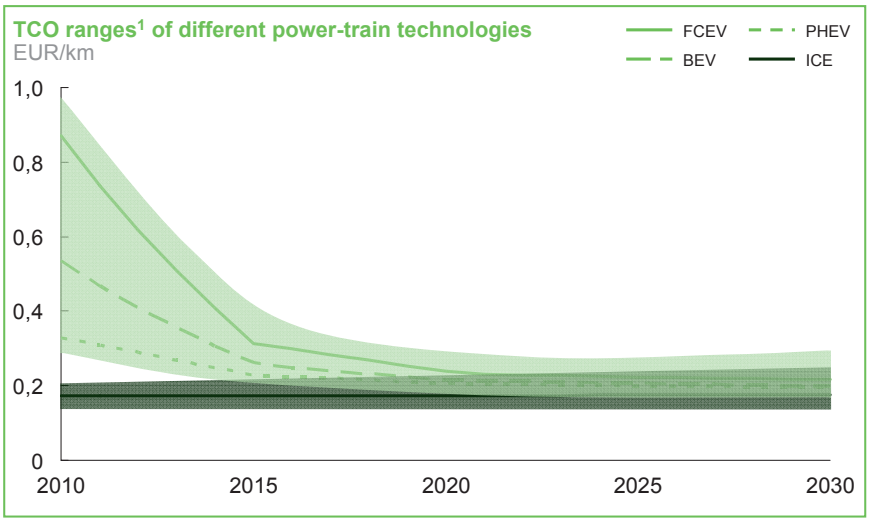
Exhibit 27: The cost of hydrogen reduces by 70% by 2025, then stays relatively flat (excluding taxes and incentives)

The cost of hydrogen will be high in the first five years (2010-2015), as a result of the under-utilisation of retail stations and the fact that very small stations will be built to reduce capital costs. This is still a pre-commercial market, so these stations will have very low economies of scale. For example, in order to persuade current gasoline and diesel station owners (dealers) to start providing hydrogen, hydrogen will need to be untaxed and dealers will require subsidy.

In the next five years – in the early commercial phase, when stations become larger and utilisation grows as more FCEVs come on the road – hydrogen (assuming it is untaxed) could become cost-competitive with gasoline ICEs (assuming gasoline is taxed).

By 2020, retail costs will have significantly reduced, as more FCEVs come on the road and large stations, with multiple pumps and a higher utilisation, are built. New large-scale IGCC and CG plants will also start to be built, further reducing the cost of hydrogen.

b. By 2030, BEVs, FCEVs, PHEVs are all cost-competitive with ICEs in relevant segments



1 Ranges based on data variance and sensitivities (fossil fuel prices varied by +/- 50%; learning rates varied by +/- 50%)

SOURCE: Study analysis

Exhibit 28: After 2025, the TCOs of all the power-trains converge

Due to the initial steep decrease in the cost of fuel cell systems, BEV components and hydrogen as a result of higher utilisation and economies of scale, the TCOs of all the power-trains converge after 2025.

EUR thousands

EXCLUDING ALL TAXES | 2020

A/B Segment

Vehicle	Purchase price ⊕	Maintenance ⊕	Fuel cost[1] ⊕	Infrastructure[2] ⊖	TCO
FCEV	20.0	2.8	4.6	2.2	29.6
BEV	16.9	2.3	2.8	2.5	24.5
PHEV	14.7	2.9	3.3	1.4	22.3
ICE - gasoline	11.3	3.0	3.7	0.5	18.5
ICE - diesel	11.3	3.0	3.7	0.4	18.4

C/D Segment

Vehicle	Purchase price ⊕	Maintenance ⊕	Fuel cost ⊕	Infrastructure ⊖	TCO
FCEV	30.9	4.5	5.6	2.7	43.8
BEV	28.9	3.7	3.4	2.5	38.5
PHEV	26.8	4.9	3.8	1.4	36.9
ICE - gasoline	21.4	5.5	4.7	0.6	32.3
ICE - diesel	21.9	5.7	4.7	0.5	32.8

J Segment

Vehicle	Purchase price ⊕	Maintenance ⊕	Fuel cost ⊕	Infrastructure ⊖	TCO
FCEV	38.9	5.6	6.9	3.3	54.8
BEV	41.0	5.4	4.2	2.5	53.1
PHEV	37.0	6.7	5.1	1.4	50.2
ICE - gasoline	28.5	7.1	6.2	0.8	42.5
ICE - diesel	29.5	7.5	6.5	0.7	44.1

1 Includes production and distribution cost
2 Includes retail cost
NOTE: Assuming 15 year lifetime, annual driving distance of 12,000 km, no tax (e.g., fuel excise, VAT)

SOURCE: Study analysis

Exhibit 29: By 2020, the purchase price of BEVs, FCEVs and PHEVs is several thousand more euros than ICEs, which could be offset by tax exemptions

By 2020, the purchase price of electric vehicles is still several thousand euros more than that of ICEs, but reasonable public incentives on vehicle, fuel and an attractive customer value proposition could be sufficient to bridge this cost gap (see page 43). The purchase price of BEVs is lower than FCEVs.

The purchase prices of electric vehicles may vary widely according to market conditions and car manufacturers who may either be further advanced in achieving cost reductions and/or choose to limit the premium. They also depend on branding strategies, with a whole range of purchase prices within any car segment – from lowest cost to premium vehicles.

EUR thousands — EXCLUDING ALL TAXES — 2030

	Vehicle	Purchase price	Maintenance	Fuel cost[1]	Infrastructure[2]	TCO
A/B Segment	FCEV	16.0	2.5	4.4	1.2	24.0
	BEV	15.2	2.2	2.7	2.5	22.6
	PHEV	13.7	2.8	3.4	1.4	21.3
	ICE - gasoline	11.1	3.0	4.1	0.5	18.7
	ICE - diesel	11.2	3.0	4.1	0.4	18.7
C/D Segment	FCEV	25.7	4.2	5.2	1.4	36.5
	BEV	26.3	3.6	3.2	2.5	35.6
	PHEV	25.0	4.9	3.7	1.4	35.0
	ICE - gasoline	21.1	5.4	5.3	0.6	32.3
	ICE - diesel	21.6	5.6	5.2	0.5	32.9
J Segment	FCEV	32.7	5.3	6.2	1.7	45.9
	BEV	37.3	5.2	3.9	2.5	48.9
	PHEV	34.7	6.7	5.1	1.4	47.9
	ICE - gasoline	28.3	7.0	6.9	0.8	42.9
	ICE - diesel	29.1	7.4	7.2	0.7	44.4

1 Includes production and distribution cost
2 Includes retail cost
NOTE: Assuming 15 year lifetime, annual driving distance of 12,000 km, no tax (e.g., fuel excise, VAT)

SOURCE: Study analysis

Exhibit 30: By 2030, all electric vehicles are viable alternatives to ICEs, with running costs that are comparable and a purchase price that is close to comparable for larger cars

By 2030, the advantages of lower running costs almost outweigh the higher purchase price of electric vehicles, which start to close the gap with ICEs on both purchase price and TCO. Typically, electric vehicles (BEVs, FCEVs, PHEVs) cost 2-6 cents more per kilometre than ICEs.

EUR thousands — EXCLUDING ALL TAXES — 2050

	Vehicle	Purchase price	Maintenance	Fuel cost[1]	Infrastructure[2]	TCO
A/B Segment	FCEV	14.3	2.3	3.7	1.0	21.4
	BEV	13.4	2.2	2.4	2.5	20.5
	PHEV	12.8	2.8	3.5	1.4	20.5
	ICE - gasoline	10.8	2.9	4.6	0.5	18.8
	ICE - diesel	11.0	2.9	4.6	0.4	18.9
C/D Segment	FCEV	23.7	4.0	4.0	1.1	32.8
	BEV	23.5	3.5	2.8	2.5	32.3
	PHEV	23.5	4.8	3.6	1.4	33.3
	ICE - gasoline	20.5	5.1	5.8	0.6	32.0
	ICE - diesel	21.2	5.4	5.8	0.5	32.9
J Segment	FCEV	30.4	5.0	4.6	1.3	41.4
	BEV	33.3	5.1	3.4	2.5	44.3
	PHEV	32.6	6.6	5.1	1.4	45.7
	ICE - gasoline	27.9	6.9	7.7	0.8	43.2
	ICE - diesel	28.7	7.2	8.0	0.7	44.6

1 Includes production and distribution cost
2 Includes retail cost
NOTE: Assuming 15 year lifetime, annual driving distance of 12,000 km, no tax (e.g., fuel excise, VAT)

SOURCE: Study analysis

Exhibit 31: By 2050, FCEVs are more economic than ICEs for larger cars and fully competitive for medium-sized cars

By 2050, all electric vehicles are cost-competitive with ICEs, FCEVs are the lowest-cost solution for larger cars (J segment).

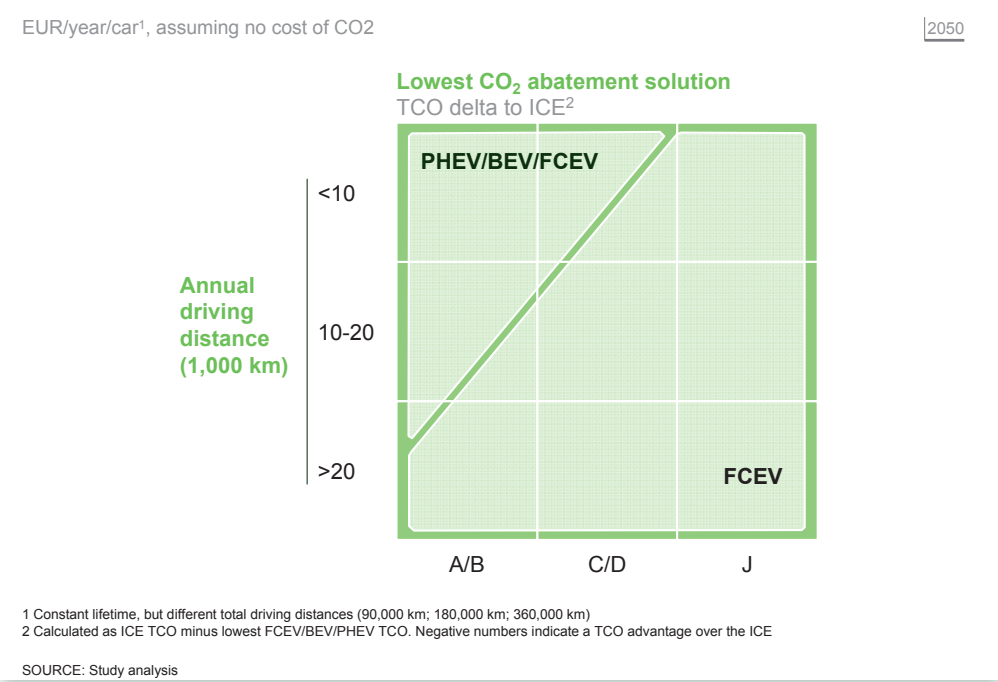


Exhibit 32: The FCEV has a TCO advantage over BEVs and PHEVs in the heavy/long-distance car segments

In terms of car size and annual driving distance, BEVs are economic for smaller cars and shorter trips while FCEVs perform best for C/D and J segments (medium and larger cars) and longer trips.

FCEVs score almost as well as BEVs on annual driving distances of 10,000-20,000+ km in the A/B (small car) segments.

As medium/larger vehicles with above average driving distance account for 50% of all cars, but 75% of CO_2 emissions, FCEVs are therefore an attractive abatement option for a large proportion of the car fleet.

c. Incentives could make BEVs and FCEVs cost-competitive with ICEs by 2020

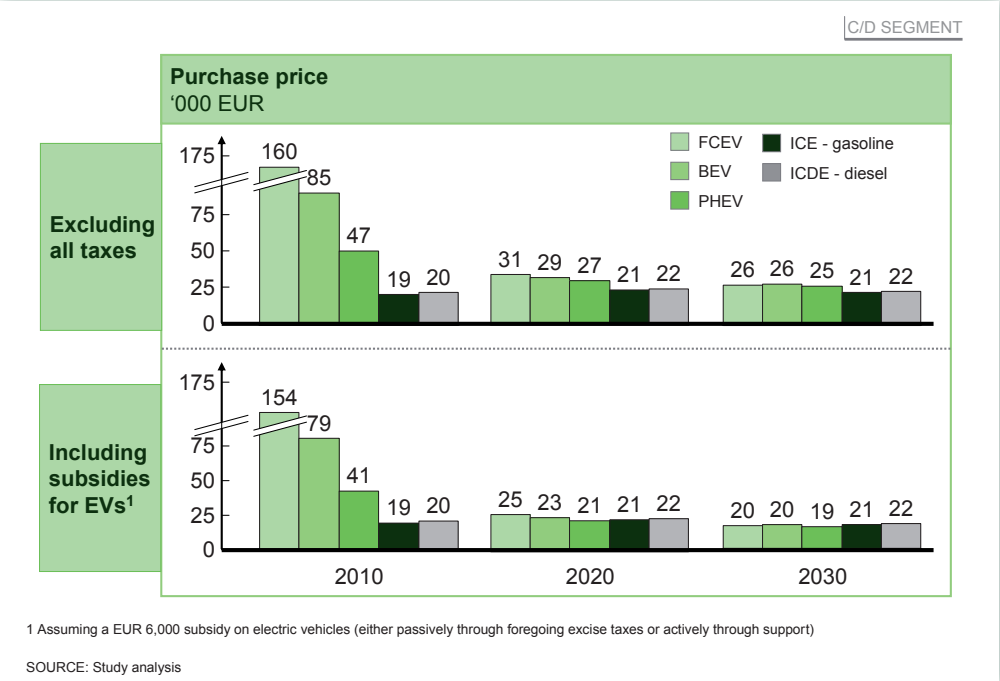


Exhibit 33: The higher purchase price of BEVs, FCEVs and PHEVs could be partially offset by tax exemptions

With an average vehicle subsidy of nearly €6,000 for FECVs as currently provided for BEVs in several Member States , the purchase price of FCEVs could start to close with ICEs by 2020 and be lower in 2030.

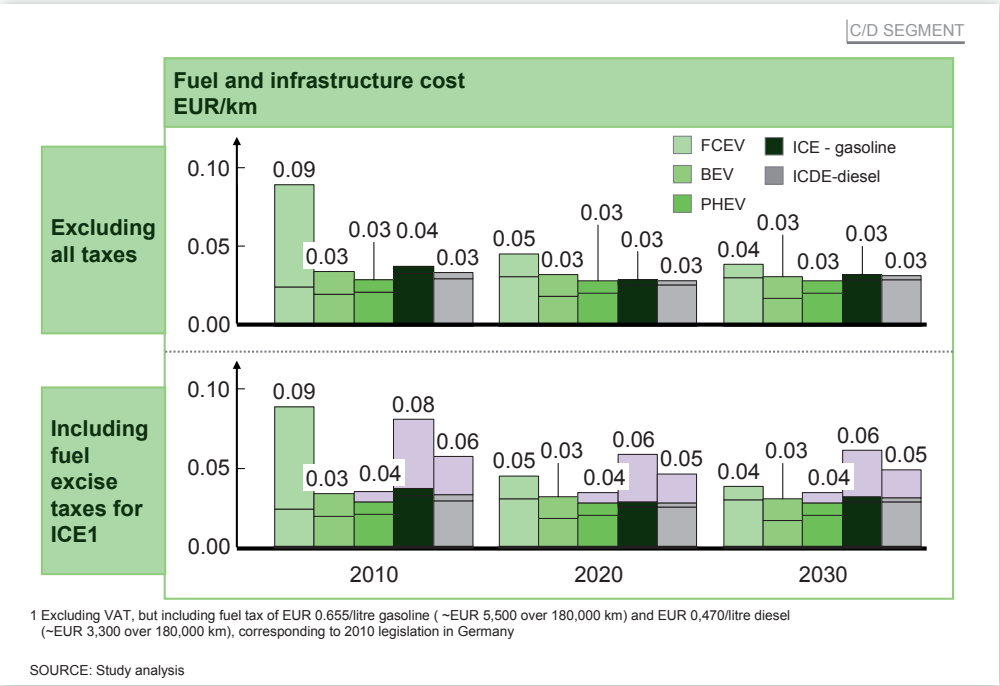


Exhibit 34: Temporarily forgoing fuel taxes on hydrogen or electricity will level fuel costs for all power-trains over the next 10 to 20 years

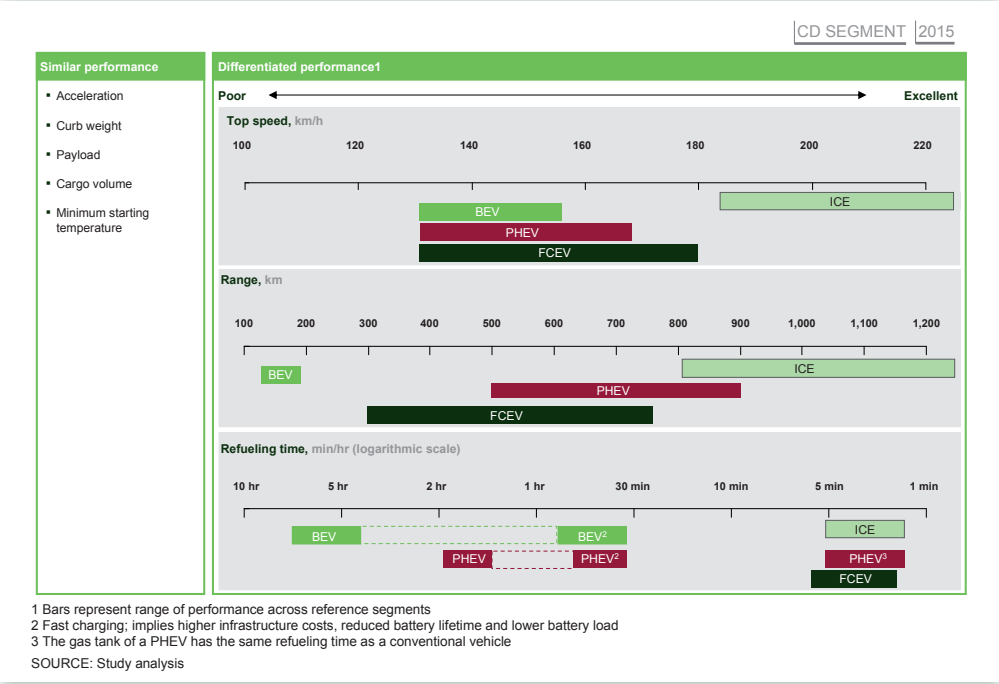
If hydrogen is not taxed like gasoline and diesel in the ramp-up phase, infrastructure and fuel costs for FCEVs could become cost-competitive with ICEs as early as 2020.

3. *A portfolio of power-trains can satisfy the needs of consumers and the environment*

Over the next 40 years, no single power-train satisfies all key criteria for economics, performance and the environment. As different power-trains meet the needs of different consumers, the world is therefore likely to move from a single power-train (ICE) to a portfolio of power-trains in which BEVs and FCEVs play a complementary role.

The results show that BEVs are ideally suited to smaller cars and shorter trips, FCEVs to medium/larger cars and longer trips, with PHEVs providing an intermediate solution to a zero-emission world.

a. FCEVs and PHEVs are comparable to ICEs on driving performance and range



1 Bars represent range of performance across reference segments
2 Fast charging; implies higher infrastructure costs, reduced battery lifetime and lower battery load
3 The gas tank of a PHEV has the same refueling time as a conventional vehicle
SOURCE: Study analysis

Exhibit 35: FCEVs and PHEVs have a driving performance and range comparable to ICEs

With limited energy storage capacity, BEVs are in a different category to FCEVs, PHEVs and ICEs with regard to speed, range or refuelling times:

- For example, an average, medium-sized BEV with maximum battery loading e.g. 30 kWh, around 220 kg in 2020) will not be able to drive far beyond 150 km at 120 km/hour, if real driving conditions are assumed (taking expected improvements until 2020 into account).

- Charging times are longer, even at maximum proven battery technology potential: 6-8 hours using normal charging equipment. Using more sophisticated and expensive technologies can reduce charging time. Fast charging may become widespread, but the impact on battery

performance degradation over time and power grid stability is unclear. Moreover, it takes 15-30 minutes to (partially) recharge the battery. Battery swapping reduces refuelling time; it is expected to be feasible if used once every two months or less and battery standards are adopted by a majority of car manufacturers.

FCEVs have a driving performance and range comparable to ICEs: an average driving range of 500-600 km, similar acceleration and a refuelling time of less than 5 minutes, similar to ICE fuelling which is a proven business model.

The driving range and performance of PHEVs is similar to ICEs when in ICE drive.

See Annex, Exhibit 56, page 61, for a graphical analysis of the impact of cruising speed on range.

b. Snapshot of 2030: different power-trains meet different needs

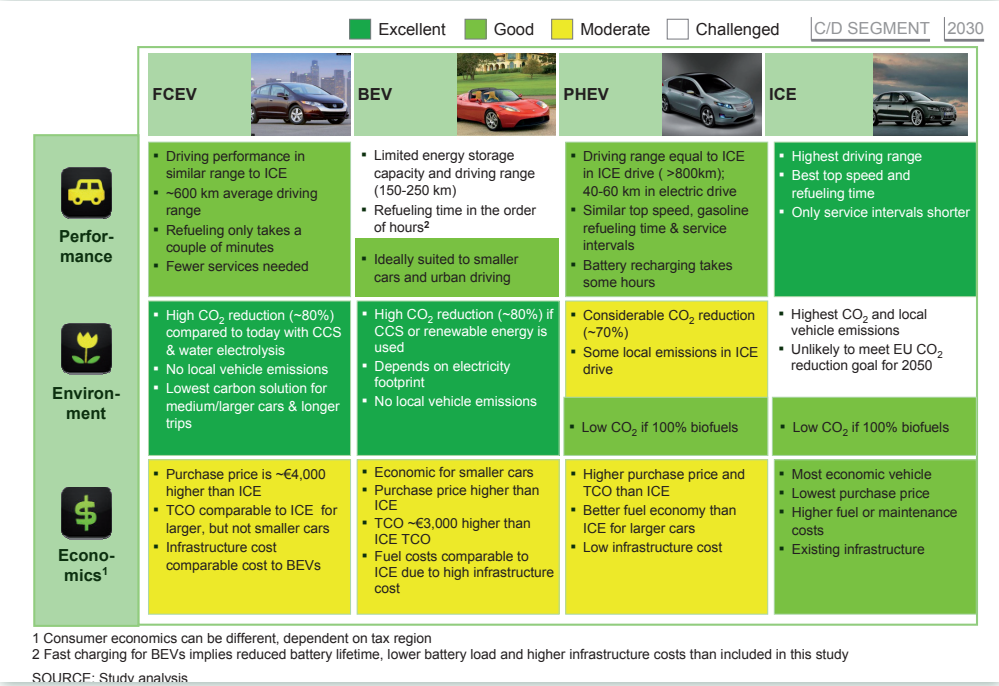


Exhibit 36: Snapshot of 2030 – only a portfolio of power-trains can satisfy key criteria for performance and the environment

With a driving performance comparable to ICEs and a TCO comparable in the J segment, FCEVs are the lowest-carbon solution for medium/larger cars and longer trips.

With limited driving range, BEVs are ideally suited to smaller cars and urban mobility. Although considerable cost improvements in battery technology are considered in this study, it is not expected to achieve significantly lower specific volumes or weights beyond 2020.

PHEVs demonstrate a considerable CO_2 reduction. This applies either when using biofuels or driving short distances. The smaller installed battery depletes quickly when driving at a higher speed, with a heavier load or over a longer distance. Although fuel economy is better than ICEs for larger cars (especially in stop/start city driving), the purchase price and TCO is higher and from 2030, PHEVs no longer have a cost advantage compared to FCEVs.

4. *Costs for a hydrogen infrastructure are around 5% of the overall cost of FCEVs (€1,000-2,000 per vehicle)*

In order to develop a portfolio of drive-trains, several supply infrastructure systems are required – not only for gasoline and diesel, but potentially new infrastructures for CNG, LPG, 100% biofuels, electricity and hydrogen. Early commercial deployment of BEVs and PHEVs is already happening in several European countries: many car manufacturers have announced production and the first commercial models are expected between 2011 and 2014. This report therefore focuses on the commercial deployment of FCEVs, which still needs to be addressed.

One could argue that it is inefficient to build an additional vehicle refuelling infrastructure on top of existing infrastructures. However, the additional costs of a hydrogen infrastructure are relatively low compared to the total costs of FCEVs and comparable to other fuels and technologies, such as a charging infrastructure for BEVs and PHEVs.

Costs for a hydrogen distribution and retail infrastructure represent 5% of the overall cost of FCEVs – the vast majority lies in the purchase price. The attractiveness of the business case for FCEVs is therefore hardly affected by the additional costs required for distribution and retail. In other words, if FCEVs make commercial sense – as demonstrated by this study – building a dedicated hydrogen infrastructure can be justified.

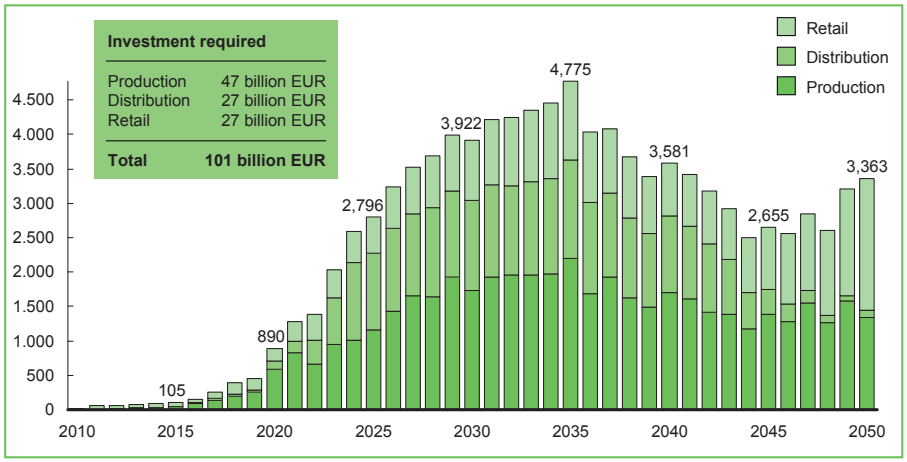
In the first decade of a typical roll-out scenario, supply infrastructure costs – especially those for a retail infrastructure – are initially higher, due to lower utilisation. Nevertheless, sufficient network coverage must be available for consumers and initial investments required could amount to €3 billion (covering hydrogen production, distribution and retail). Although a single company would struggle to absorb the risk of such an investment, this is not the case at a societal level. This is confirmed by countries which have built up alternative infrastructures, such as CNG and LPG.

The cost per vehicle for rolling out a hydrogen infrastructure compares to rolling out a charging infrastructure for BEVs or PHEVs (excluding potential upgrades in power distribution networks) – see Exhibit 38 below. The costs for hydrogen retail and distribution are estimated at €1,000-2,000 per vehicle (over the lifetime), including distribution from the production site to the retail station, as well as operational and capital costs for the retail station itself. The average annual investment of €2.5 billion compares to that for other industries, such as oil and gas, telecommunications and road infrastructure, which each amount to €50-€60 billion[2]. It is also significantly less than additional investments required to decarbonise power (€1.3 trillion[3] over 40 years).

Costs for an electric charging infrastructure range from €1,500 to €2,500 per vehicle. The higher end of the range assumes 50% home charging (investment of €200-€400 per charging station) and 50% public charging (investment of €5,000-€10,000 for a charging station that serves two cars. Potential additional investment in the power distribution networks are not included, but could be material, depending on the local situation. In contrast, once the territory is covered, no further investment is needed in hydrogen infrastructure – regardless of the number of cars – due to the fast refuelling time. As the number of FCEVs increase, it also benefits from economies of scale.

2 Global Insight
3 www.roadmap2050.eu

a. Up to 2020, FCEVs require €3 billion supply infrastructure investment for 1 million cars



1 Current annual capex requirement for the EU

SOURCE: WIS Global Insight; OVUM; OECD / International Transport Forum; study analysis

Exhibit 37: Total capital investment for a large-scale roll-out of hydrogen supply infrastructure in Europe is estimated at €100 billion over 40 years

Initial investment before 2020 is relatively low, as it will be concentrated in areas of high density, such as large cities. Investment in retail stations is required in order to reach sufficient coverage of the territory, while being initially under-utilised. Retail cost then decreases as more vehicles are deployed, with a higher utilisation of the retail station.

The conclusions in this study are based on 25% penetration of FCEVs in Europe by 2050 (see pages 16-18). To achieve a 50% penetration, the cost of infrastructure would rise by another €75 billion, but there would be no significant difference in TCO per vehicle.

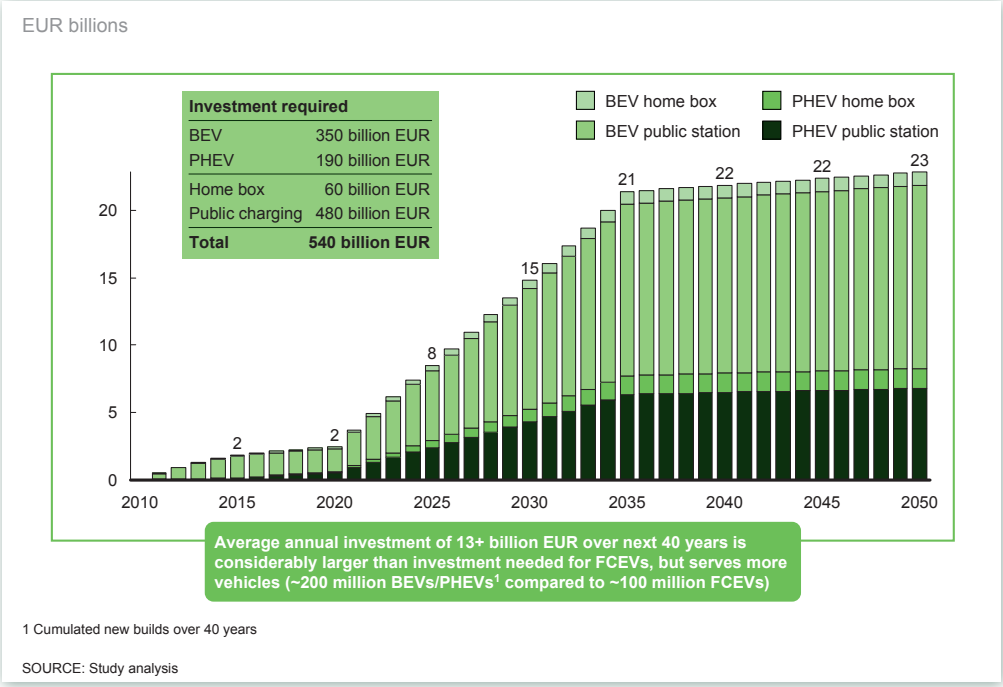


Exhibit 38: A large-scale roll-out of BEVs and PHEVs in Europe could require up to €500+ billion over the next 40 years

Electrical infrastructures could require an average annual investment of €13+ billion until 2050 in order to serve 200 million BEVs/PHEVs. Two thirds of this relates to BEV infrastructure, as they could require a higher share of public charging stations than PHEVs.

5. *The deployment of FCEVs will incur a cost to society in the early years*

The benefits of lower CO_2 emissions, lower local emissions (NO_2, particles), diversification of primary energy sources and the transition to renewable energy all require an initial investment. However, these will ultimately disappear with the reduction in battery and fuel cell costs, higher economies of scale and potentially increasing costs for fossil fuels and ICE specifications.

A roll-out scenario that assumes 100,000 FCEVs in 2015, 1 million in 2020 and a 25% share of the total EU passenger car market in 2050 results in a cumulative economic gap[4] of €25 billion by 2020. Almost 90% of this relates to the relatively higher cost of the FCEV in the next decade. The CO_2 abatement cost is expected to range between €150 and €200 per tonne in 2030 and becomes negative for larger cars after 2030.

A strong case will be required to persuade governments as to the level of explicit subsidy needed. In subsequent steps, it will therefore be important to make proposals that show how industry is taking responsibility for all the risks that they can reasonably analyse, control and mitigate. Discussions with Member State and EU governments are likely to focus on sharing the costs and risks between public and private sectors.

4 Economic gap is the delta between the TCO of the power-train under consideration and the ICE TCO, multiplied by the number of vehicles in the respective year.

Up to 2020: a cumulative economic gap of €25 billion

Around €3 billion investment is required for a hydrogen supply infrastructure (production, distribution, retail) for 1 million FCEVs by 2020. Of this investment, around €1 billion relates to retail infrastructure. This will be concentrated in high-density areas (large cities, highways) and build on existing infrastructure. If only one energy company made the investment in retail, it would face a first-mover disadvantage due to the initially low utilisation by a small number of FCEVs. This could lead to a potential write-off of around €0.5 billion per annum if roll-out is terminated or delayed. The initial investment risk would be somewhat reduced if further companies also invest and even further if the roll-out is co-ordinated by government and supported by dedicated legislation and funding.

The remaining €2 billion required for production and distribution presents a different investment risk: hydrogen producers do not expect a shortfall and can meet hydrogen demand as it arises, being paid-for product at rates that would cover their costs. In the first couple of years, in particular, hydrogen producers can respond with existing production capacity without large speculative upfront expenditures. Incremental capacity could then be added in small units at reasonable cost. The same applies to the distribution of hydrogen envisaged during this period.

While hydrogen producers may enjoy a first-mover advantage, retail investors face a first-mover disadvantage. Hydrogen manufacturers have an incentive – as soon as the economics work – to race to beat their rivals. While financial incentives are required to persuade consumers to appreciate FCEVs, there is nothing to hold the hydrogen manufacturers back – as long as the retail infrastructure is in place. They may also gain a marketing advantage. Infrastructure providers, on the other hand, bear a first-mover risk, making a heavy upfront outlay to build a retail station network that will not be fully utilised for some years; the unit cost reduces over time simply because the fixed capital expenditure is used by an increasing number of FCEVs.

To reap the benefits of lower emissions, energy diversification and technology development, a cumulative economic gap for FCEVs of €25 billion may develop up to 2020, mainly due to a higher purchase price. If this is met by only a few car manufacturers, they will each need to finance €1 billion per year. An incentive to ramp up production therefore only exists if most car manufacturers commit and co-ordinate, and government provides temporary funding support.

This report assumes complete tax neutrality among the four power-trains, which allows clean comparison of technologies, but may not be realistic where practical policy is concerned. Gasoline is heavily taxed throughout the EU and various green incentives are in place (see page 43).

Financial support for car manufacturers could be provided through tuning the tax regime. For the period to 2020, more explicit per-vehicle subsidies could also be applied. In the case of infrastructure support, some form of underwriting or sharing by government of investment risk may be more appropriate – the issue being not so much the cost of building the infrastructure as the risk that the market does not develop, leaving the infrastructure a stranded asset.

It is possible that governments could elect not only to provide the “carrot” of support to both cars manufacturers and infrastructure providers, but also the “stick” of legislation. Legislation would need to be credible and may present the risk of unstable outcomes that could leave the first-mover problem only partly resolved; however, it could have a role.

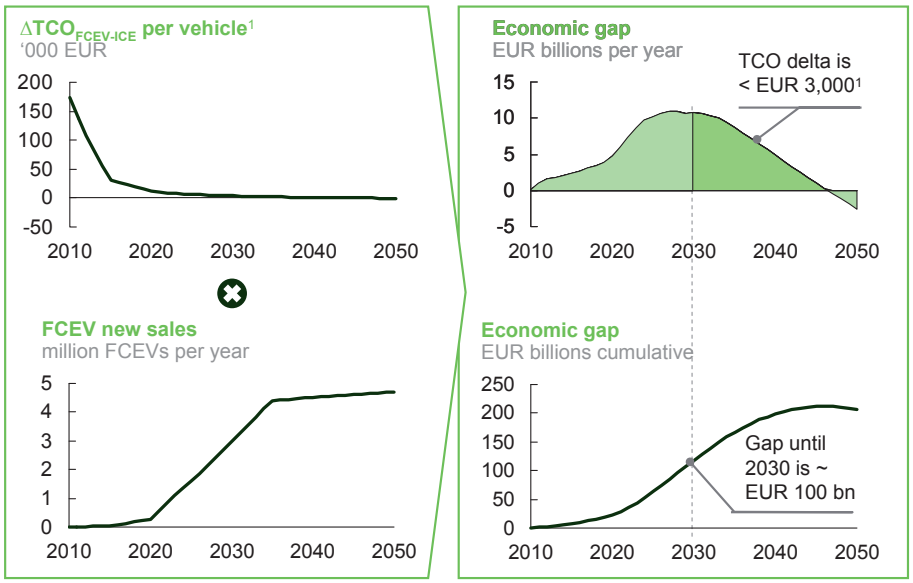
2020-2030: a cumulative economic gap in the order of €75 billion due to increasing car volumes

If a core infrastructure is in place by 2020, even if it were regional, with a critical mass of FCEVs on the road, there could be a much greater willingness to invest and more scope for finely tuned legislative measures and tax incentives. However, as 2020 approaches, it will become clearer whether target numbers and costs are being reached – and whether 1 million vehicles is indeed the critical number to achieve momentum. At this stage, it seems possible that any government support needed during this period could be provided through tax and regulatory systems, without special measures or subsidies.

Beyond 2030: any potential remaining economic gap per vehicle is expected to be small and carried by the consumer

After 2030, it can be assumed that the majority of the consumers will be financially driven, making their choice of car in response to an established tax and legislative regime. Provided these are stable and clear, car manufacturers, hydrogen manufacturers and infrastructure providers should all be able to make investments on the basis of well-understood risks and projected returns.

a. FCEVs face a cumulative economic gap of €25 billion (cars + infrastructure) up to 2020



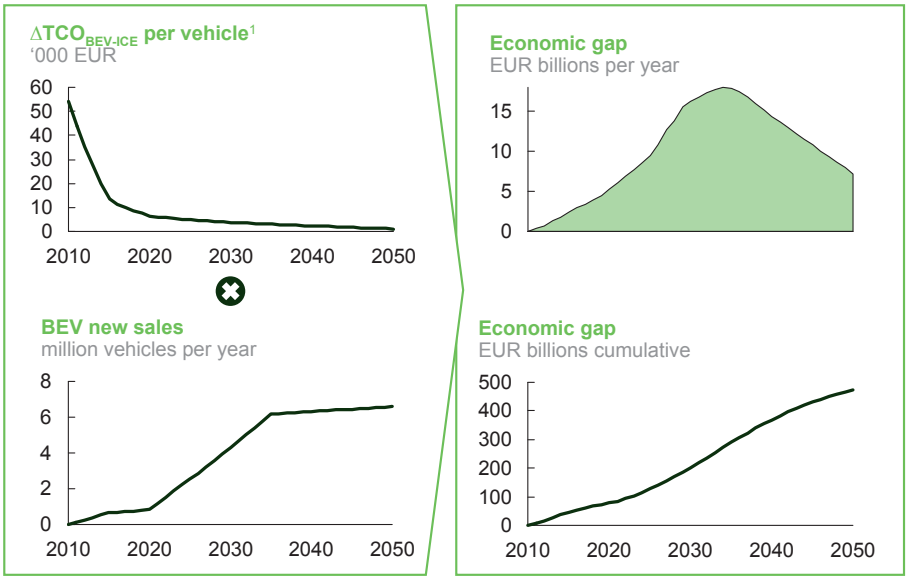
1 Weighted by segments (7% in A/B segments, 39% in C/D/E segments and 54% in J/M segments)

SOURCE: Study analysis

Exhibit 39: The cost of shifting from ICEs to FCEVs may amount to €4-5 billion per year for Europe (€500 per new car), with the economic gap beginning to close after 2030

Up to 2020, FCEVs face a cumulative economic gap (cars + infrastructure) of €25 billion (mainly due to a higher purchase price) and an additional €75 billion up to 2030.

The TCO of FCEVs vs. ICEs falls dramatically by 2020 and is competitive with ICEs by 2030 for medium/larger cars, at which point it is anticipated that the economic gap per vehicle may be passed on to the consumer. However, the economic gap continues to rise due to increased sales.



1 Weighted by segments (53% in A/B segments, 43% in C/D/E segments, and 5% in J/M segments)

SOURCE: Study analysis

Exhibit 40: BEVs could face a cumulative economic gap of €80 billion by 2020, €500 billion by 2050

In total, a cumulative economic gap of €80 billion exists for BEVs by 2020 and €500 billion by 2050. (For an analysis of the economic gap for PHEVs, see Annex, Exhibit 57, page 61.)

Owing to their modular nature,[5] electrical infrastructures are easier to build up, but after 2020, infrastructure costs for FCEVs are less than those for BEVs as the number of public charging stations remains commensurate with the number of cars, due to the lengthy recharging time. In contrast, once the territory is covered, no further investment is needed in hydrogen infrastructure – regardless of the number of cars – due to the fast refuelling time. By 2030, infrastructure for BEVs therefore costs 1.5 - 2.5 cents per kilometre, compared to 1.5 cents per kilometre for FCEVs.

5 The study assumes 50% home charging (75% for PHEVs), 50% public charging, with two sockets serving two cars per public charging station, i.e. four cars

NEXT STEPS

In April 2010, the European Commission confirmed that "Green vehicles, including those capable of using electricity, hydrogen, biogas and liquid biofuels in high blends, are likely to contribute significantly to the Europe 2020 priorities of...promoting a more resource efficient, greener and more competitive economy".[1] This echoed the call of the European Parliament in 2007 to "institute hydrogen fuel cell storage technology, and other storage technologies, for portable, stationary and transport uses and establish a decentralised bottom-up hydrogen infrastructure by 2025 in all EU Member States".

Urgent action is required for passenger cars to achieve EU CO_2 reduction goal

Plans for the market launch of electric vehicles should therefore be initiated jointly by car manufacturers, equipment manufacturers and infrastructure providers. In the short term, CO_2 emissions will have to be reduced by more efficient ICEs and PHEVs, combined with biofuels.

But investment cycles in energy infrastructure are long and for BEVs and FCEVs to achieve the economies of scale necessary to meet the EU's CO_2 reduction goal, action must be taken as a priority. Implementation plans for BEVs and PHEVs are described in other reports, therefore this report focuses on FCEVs.

a. Prepare EU market launch plan study for FCEVs and hydrogen infrastructure

This study presents a first step towards a wider, co-ordinated EU roll-out plan study for FCEVs and hydrogen infrastructure. With all technological hurdles resolved and thousands of hours of testing in a customer environment, industry is clearly ready – as demonstrated by the Letter of understanding issued by car manufacturers in 2009 (see page 13) and the global consortium of stakeholders who have been prepared to share confidential data for the express purposes of this study. The next logical step is to develop a comprehensive and co-ordinated EU market launch plan study (Exhibit 41). This consists of two phases:

1. An in-depth business case and implementation plan for a single Member State (i.e. Germany), starting in 2015. At the same time, a series of FCEV demonstration projects should also start in other Member States in order to gain experience with the technology.

2. A staged roll-out plan study – first, a market introduction in Member States that have developed experience through the demonstration projects above, followed by other Member States.

The above single Member State implementation plan should be fit for investment by companies and the public sector. This includes addressing the risks associated with the plan, how hydrogen will be decarbonised and its impact on future CO_2 emissions from the transport sector.

As this study indicates, there is a first-mover disadvantage for retail investors. ***However, if several hydrogen retail infrastructure providers invest (e.g. via a consortium), or a market-based mechanism is developed to spread the risk between different infrastructure providers, none will gain a "free ride". The market launch plan must therefore go hand-in-hand with clear government incentive mechanisms to offset this risk, or the launch will not happen.***

After the technology has been de-risked and achieved cost reductions in one Member State – with a series of small, subsidised demonstration projects taking place in parallel in other Member States – a staged EU roll-out plan study is required, with market introductions in those Member States that have gained experience through the earlier demonstrations.

1 COM(2010)186: A European strategy on clean and energy efficient vehicles

(Staging the roll-out will address the supply limitations of car manufacturers and hydrogen infrastructure providers who cannot undertake market introductions in all Member States at the same time.) Market introductions and hydrogen supply infrastructure build-up should also take into account the preferred primary energy resources of different Member States and CO_2 reduction goals for the transport sector as a whole.

FCEV demonstration projects in other Member States are likely to start in 2015. These should ideally benefit from the learnings in Germany. Starting too early could result in a 50% higher investment for the same volume of cars, e.g. for a country such as Belgium a FCEV demonstration project comprising 100 vehicles and four stations in 2011 would cost €30 million now, versus €12-13 million if implemented after the German launch (the cost of FCEVs will have reduced by a factor of four to five and retail stations by a factor of two).

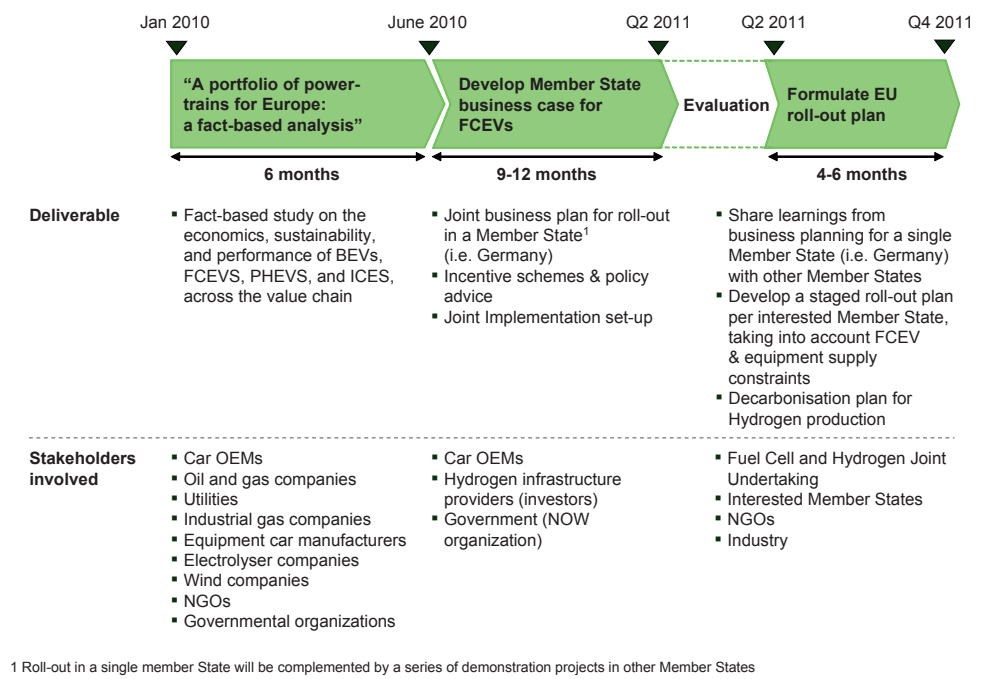


Exhibit 41: Market launch plan for FCEVs in Europe

b. Co-ordinate roll-out of BEVs/PHEVs and battery charging infrastructure

A similar action would be helpful to support the roll-out of BEVs and PHEVs in the EU. Here, too, the risk of market failure exists, but as investment per electric recharging point is low in non-public applications, so is the financial risk for infrastructure providers in such cases. However, as with hydrogen infrastructure, upfront investment for public charging will be necessary in order to give customers appropriate access to infrastructure from the start.

In order to achieve a sound market introduction, the technology also needs to be commercially de-risked and several programmes for BEVs already exist in various European countries and at EU level,[2] addressing issues such as technology, market introduction, funding schemes and standardisation etc. A coherent approach to all these activities would help to optimise development and support early market readiness.

2 European Green Car Initiative

ANNEX

Value set by study participants

Value chain		Learning Rate[1] Percent	Annual Improve[2] Percent
Vehicle	FC stack	15	2.2[3]
	H_2 tank	15	2.2[3]
	FC periphery	15	2.2[7]
	EV-specific parts[4]	10	2.3[7]
	Battery	7	1.5
	ICE related parts[5]	N/A	1.5
	Tech. packages[6]	N/A	1.5
	ICE parts	N/A	0
	"Glider"	N/A	0
Supply[3]	DSMR	6	0.0[8]
	CSMR	5	0.1
	WE	7	0.4
	IGCC/CG	3	0.1
	CCS	7	0.7
	Delivery Trucks	1	0.1
	Pipeline	1	0.2
	Liq./Comp.	1	0.1
	Retail stations	3	0.6

Example Technologies	Learning Rate[1] Percent	Annual Improve[2] Percent
Solar PV	22	10
Wind	15	7
Solar Thermal	9	7
Ethanol	15	6
LNG	13	4

Higher learning rates are observed in other new technologies

1 Percent cost reduction with every doubling of accumulated installed capacity
3 Annual improvement from 2020-2050 from applied learning rate
5 ICE, generator, fuel tank, exhaust
7 Annual improvement rate is 4% and 1.5% from 2020-2030 and after 2030 respectively

2 Annual reduction in cost
4 electric motor, transmission, inverter, wiring, controls
6 Includes power-train and non-power-train efficiency packages
8 No capacity added after 2020, resulting in no annual improvement

SOURCE: Worldwatch Institute; IEA; BTM Consult; ABS; NREL; IIIEE; ABI; Drewry 2007; UC Berkeley ERG

Exhibit 42: Projected cost reductions of FCEVs and hydrogen supply are lower than historical improvements for comparable technologies

Efficiency, Percent

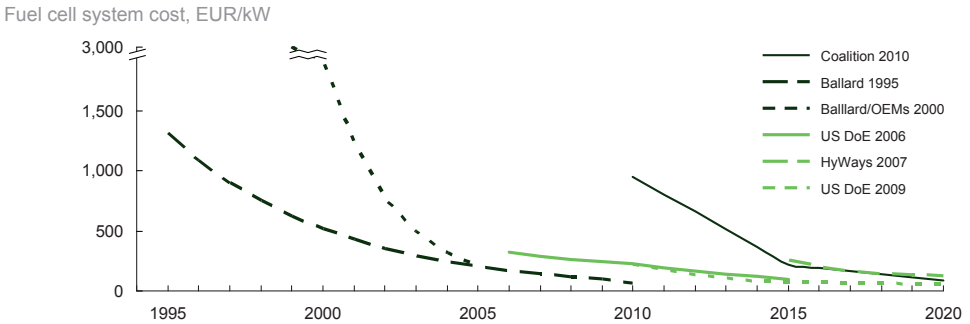
Common production pathways | 2020

Primary energy carrier	Fuel production		Distribution		Retail		Vehicle		Well-to-wheel efficiency
Primary sources: Oil	Gasoline	86%	Distribution	98%	Retail	99%	ICE	30%	25%
	Diesel	84%	Distribution	98%	Retail	99%	ICE	35%	29%
	Power	51%	Distribution	90%			BEV	68%	31%
	Power → H_2	34%	Distribution	89%	Retail	90%	FCEV	56%	15%
	H_2	51%	Distribution	89%	Retail	90%	FCEV	56%	23%
Gas	CNG	94%	Distribution	93%	Retail	90%	ICE	30%	24%
	Diesel[1]	63%	Distribution	98%	Retail	99%	ICE	35%	21%
	Power	58%	Distribution	90%			BEV	68%	35%
	Power → H_2	39%	Distribution	89%	Retail	90%	FCEV	56%	18%
	H_2	70%	Distribution	89%	Retail	90%	FCEV	56%	31%
Coal	Gasoline[1]	40%	Distribution	98%	Retail	99%	ICE	30%	12%
	Diesel[1]	40%	Distribution	98%	Retail	99%	ICE	35%	14%
	Power	50%	Distribution	90%			BEV	68%	30%
	Power → H_2	34%	Distribution	89%	Retail	90%	FCEV	56%	15%
	H_2	41%	Distribution	89%	Retail	90%	FCEV	56%	18%
Biomass	Ethanol	35%	Distribution	98%	Retail	99%	ICE	30%	10%
	Biodiesel	35%	Distribution	98%	Retail	99%	ICE	35%	12%
	Power	35%	Distribution	90%			BEV	68%	21%
	Power → H_2	24%	Distribution	89%	Retail	90%	FCEV	56%	11%
	H_2	31%	Distribution	89%	Retail	90%	FCEV	56%	14%
Power: Renewable power	Power	100%	Distribution	90%			BEV	68%	61%
	Power → H_2	68%	Distribution	89%	Retail	90%	FCEV	56%	30%
Power: Uranium	Power	28%	Distribution	90%			BEV	68%	17%
	Power → H_2	19%	Distribution	89%	Retail	90%	FCEV	56%	8%

1 Gasoline and diesel production through Fischer-Tropsch process

SOURCE: CONCAWE-EUCAR JEC-WTW study; study analysis

Exhibit 43: FCEV well-to-wheel efficiency is competitive with ICE, with a flexible use of feedstocks, while BEV remains the most efficient power-train



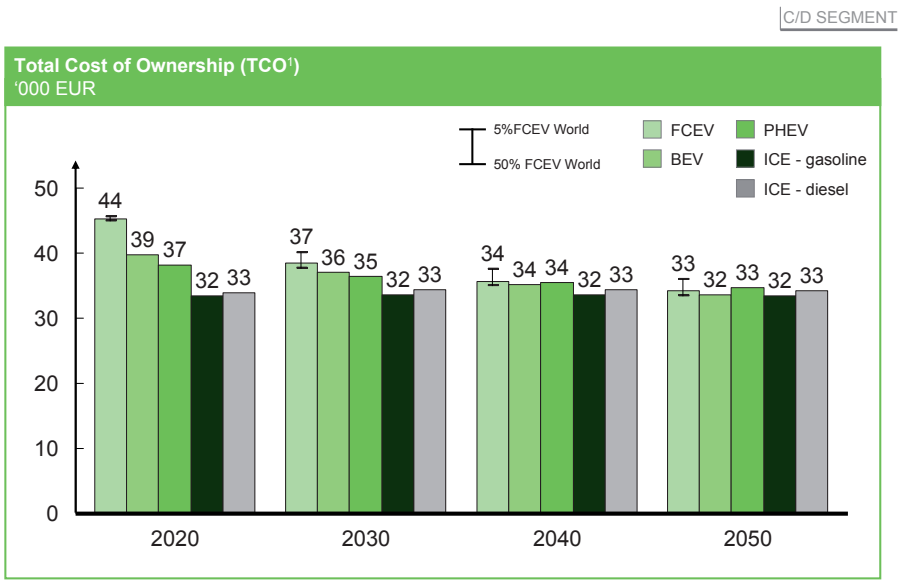
	Ballard, 1995	Ballard/OEMs, 2000	US DoE, 2006
Basis of promise	▪ Technical advance-ments, mass production	▪ Mass production, catalyst reduction	▪ Higher yields, mass production, reduced BOP
Size/timing of FC market	▪ USD 4 billion in 2000, ▪ 10-50 billion in 2010	▪ 100,000 vehicles by 2005	▪ Mass FCEV production by 2020
Data sources	▪ Ballard Power Systems, Daimler	▪ Ballard Power Systems, Daimler, Ford	▪ US Department of Energy
Share of car OEMs committing[1]	▪ ~40%	▪ ~70%	▪ ~75%
"Showstoppers" resolved and major breakthroughs	▪ Sufficient fuel cell power density for automotive use	▪ Advances in materials technology (including platinum reduction), imp-roved manufacturability	▪ Catalyst loading reduction, standardized modular design, improved MEA fabrication

Study fuel cell cost estimates are more conservative than previous estimates and are in line with most recent reports

1 Combined light duty passenger vehicle market share of OEMs committing to fuel cell and/or FCEV research

SOURCE: Press search, OICA, US Department of Energy, study analysis

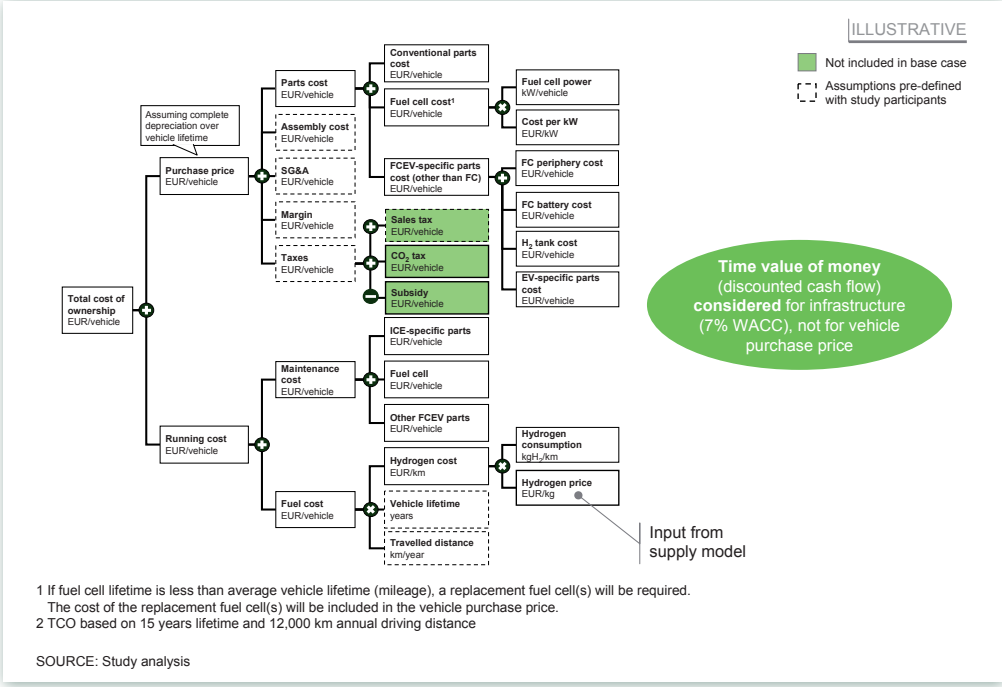
Exhibit 44: Summary of previous studies which were not based on proprietary industry data



1 Based on 15 years vehicle lifetime, 12,000 km annual driving distance, no tax (e.g., fuel excise, VAT)

SOURCE: Study analysis

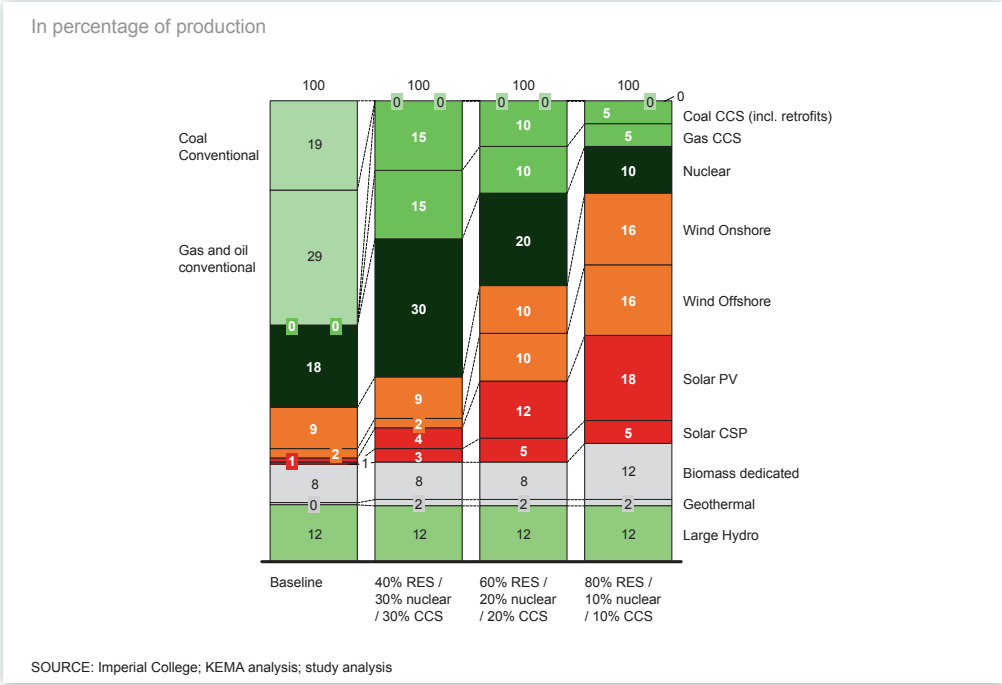
Exhibit 45: The different "world" scenarios for the penetration of FCEVs in the EU – 5%, 25% and 50% – do not alter the business case dramatically



1 If fuel cell lifetime is less than average vehicle lifetime (mileage), a replacement fuel cell(s) will be required. The cost of the replacement fuel cell(s) will be included in the vehicle purchase price.
2 TCO based on 15 years lifetime and 12,000 km annual driving distance

SOURCE: Study analysis

Exhibit 46: An example of a TCO calculation for FCEVs



SOURCE: Imperial College; KEMA analysis; study analysis

Exhibit 47: An EU 2050 production mix of 60% RES was assumed

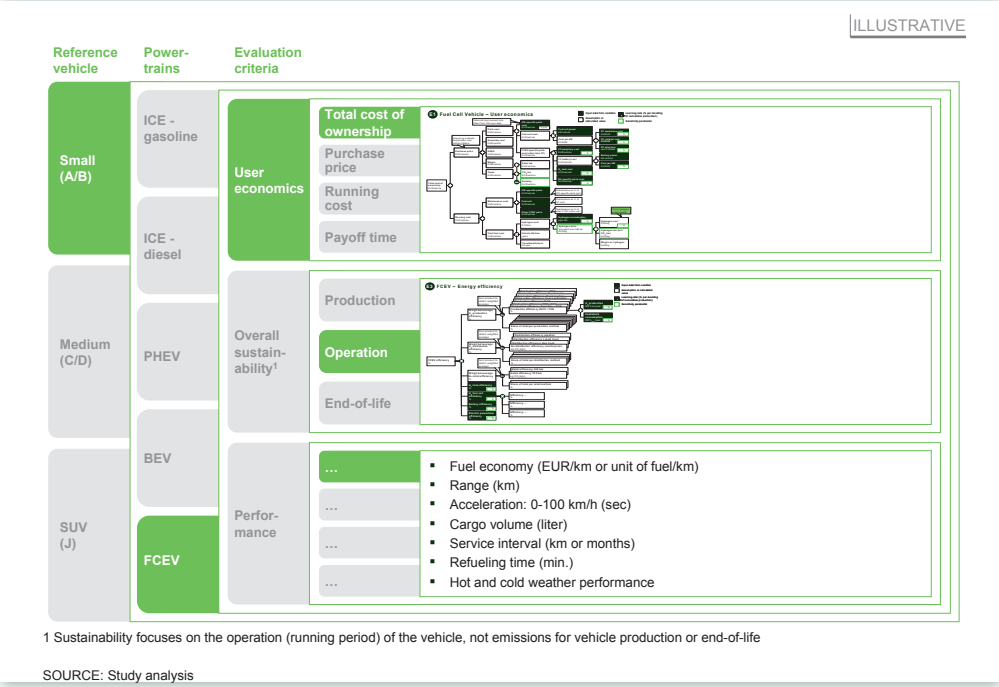


Exhibit 48: The basic structure of the vehicle model used for the study

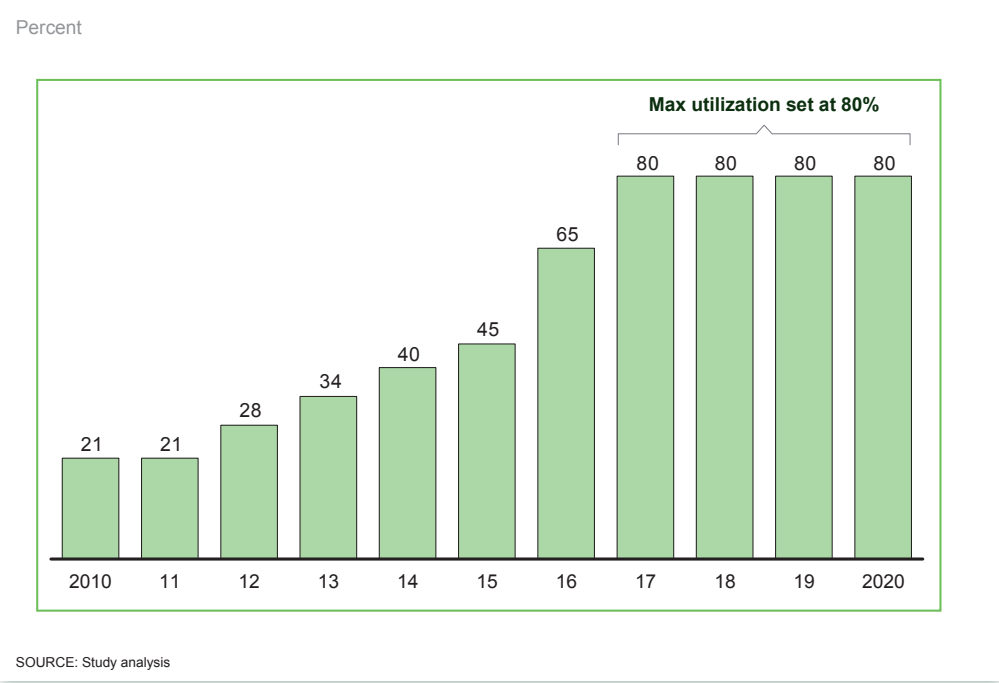


Exhibit 49: Average utilisation rate of hydrogen refuelling stations

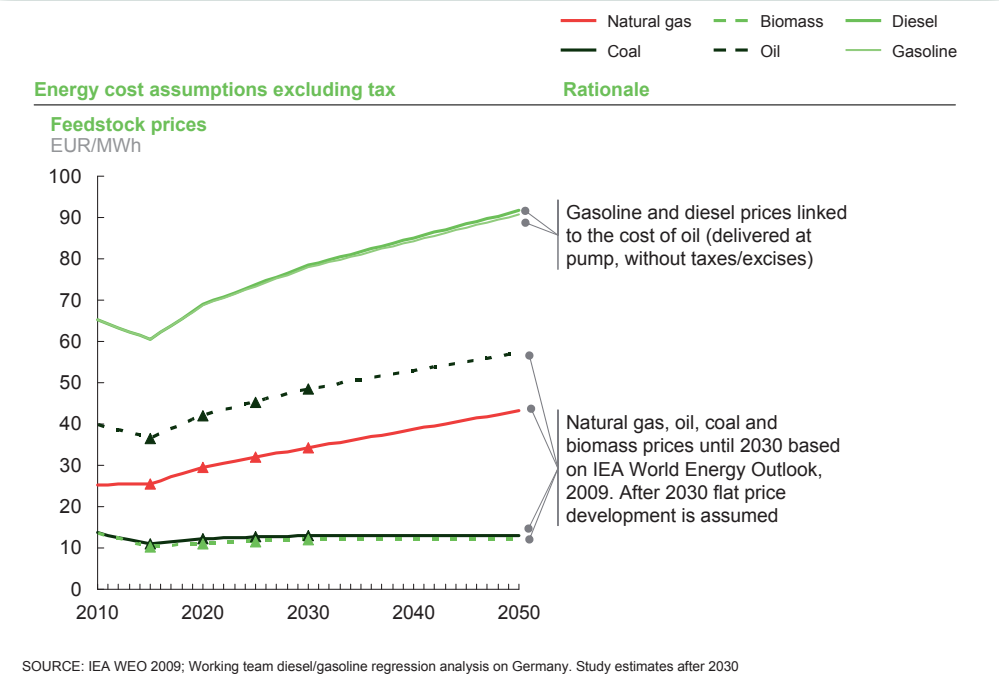


Exhibit 50: Feedstock price assumptions up to 2050 and corresponding gasoline and diesel prices (version 1)

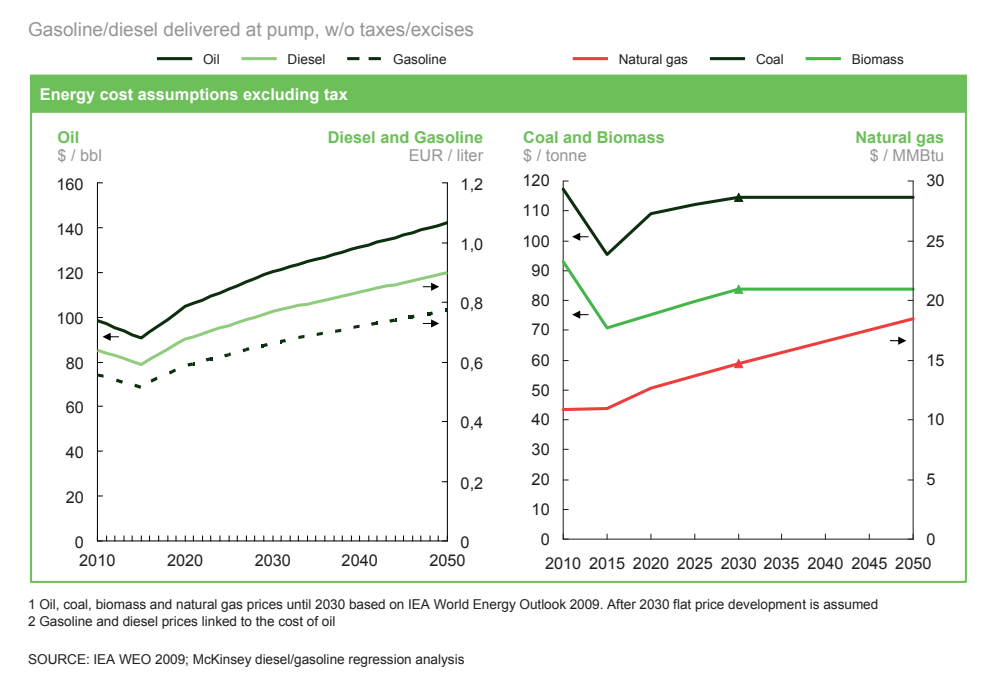
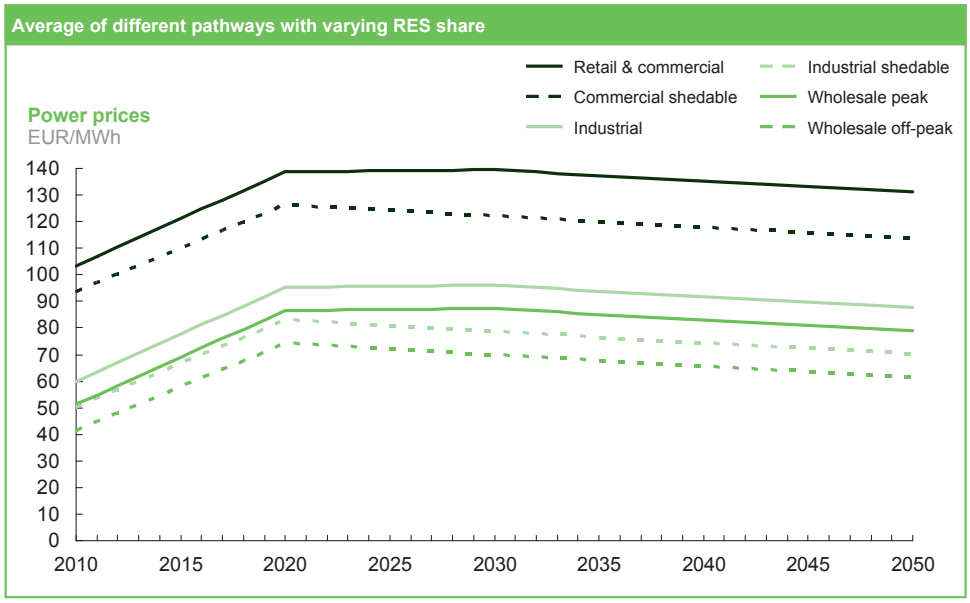
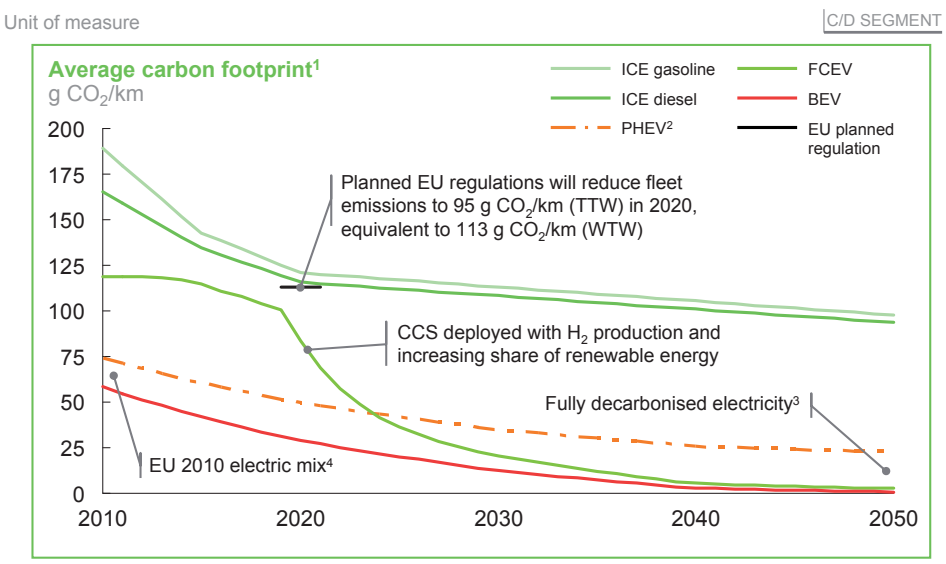


Exhibit 51: Feedstock price assumptions up to 2050 and corresponding gasoline and diesel prices (version 2)



SOURCE: EEX power spot price; "Roadmap 2050" study by the European Climate Foundation; Global Insight; study data

Exhibit 52: Power price assumptions for electrolysis production scenario



1 NEDC efficiency assumed
2 PHEV assumed to drive all electric for 77.5% of its total driving distance
3 EU2050 electricity assumes 80% renewable, 10% nuclear and 10% fossil with CCS generation
4 EU mix in 2010 contains 22% gas, 29% coal, 27% nuclear, 4% biomass, 16% renewable and 2% oil

SOURCE: Study analysis

Exhibit 53: In the long run, BEVs and FCEVs have the greatest potential to reduce CO_2 emissions

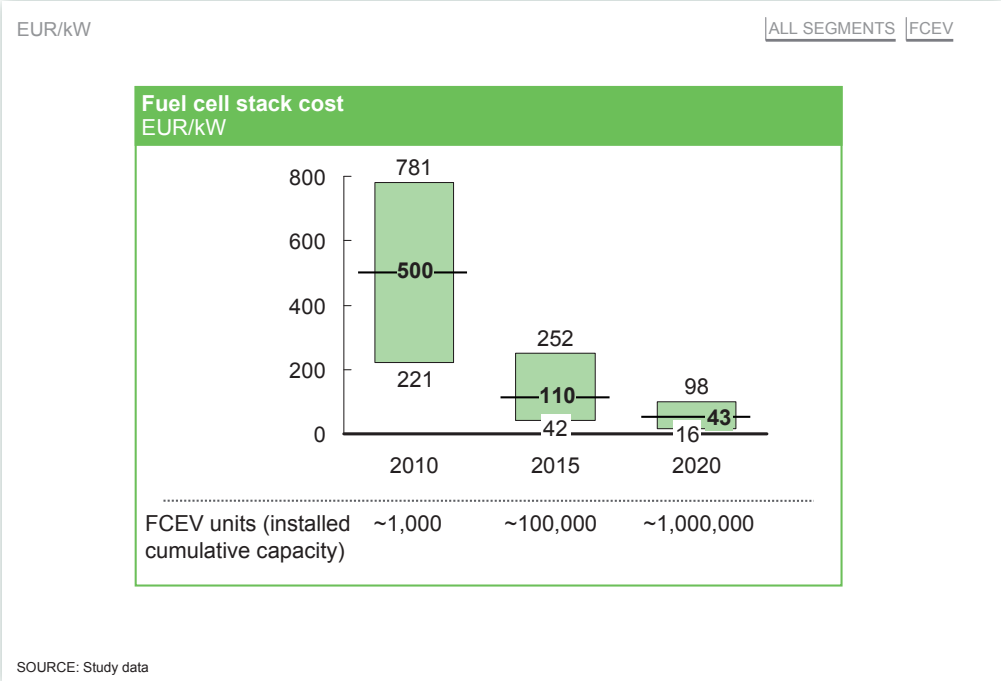


Exhibit 54: The cost of the fuel cell stack, based on data submitted by participating car manufacturers and suppliers

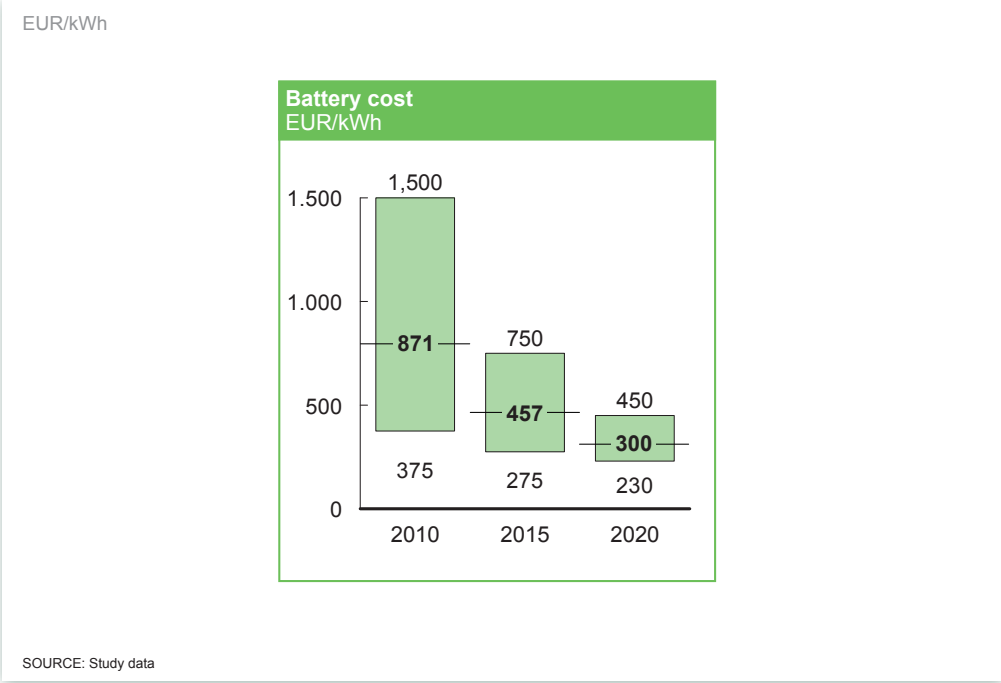


Exhibit 55: The cost of the battery, based on data submitted by participating car manufacturers and suppliers

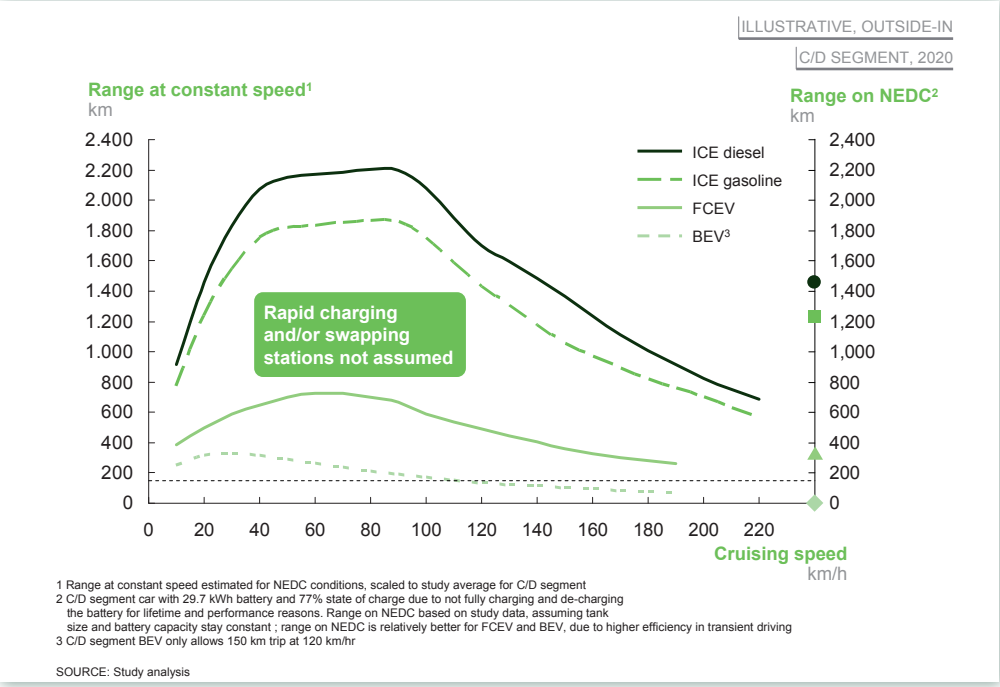


Exhibit 56: FCEVs have sufficient range at higher cruising speed, while BEVs are restricted on range

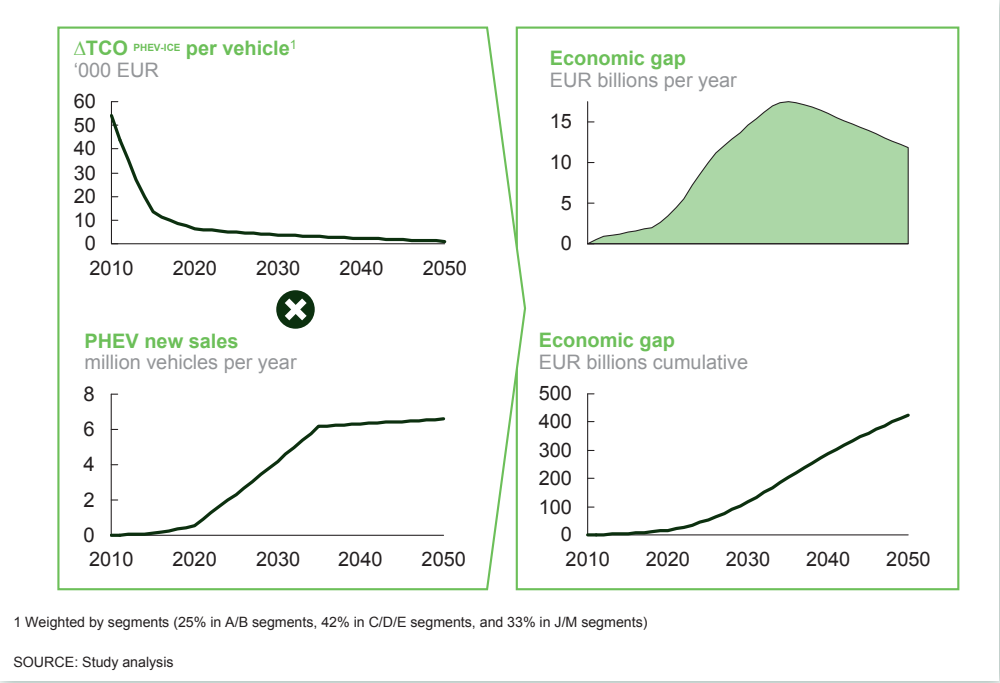


Exhibit 57: PHEVs face an economic gap of €420 billion by 2050

GLOSSARY

350/750 bar	Pressure levels for hydrogen storage tanks
4 x 4	Four-wheel drive
BBL	Barrels of oil
BEV	Battery Electric Vehicle
CCS	CO_2 Capture and Storage
CG	Coal Gasification
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalents
CSMR	Central Steam Methane Reforming
CWE	Central Water Electrolysis
DSMR	Distributed Steam Methane Reforming
DWE	Distributed Water Electrolysis
ECE-15	The United Nations Economic Commission for Europe specification for urban driving cycle simulation
EU	European Union
EU27	European Union Member States
EU29	European Union Member States + Norway and Switzerland
ECE-15	The United Nations Economic Commission for Europe specification for urban driving cycle simulation
EUDC	Extra Urban Driving Cycle – specification for European urban driving cycle simulation
EV	Electric Vehicle
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
GDL	Gas Diffusion Layer
GHG	Greenhouse Gas
Gt	Giga (billion) tonnes
H2	Hydrogen
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
ISO	International Organization for Standardization

kg	Kilogramme
km	Kilometre
m	Million
MEA	Membrane Electrode Assembly
MWh	Megawatt Hour
MPV	Multi-purpose vehicle
MJ	Megajoule
Mt	Mega (million) tonne
NEDC	New European Driving Cycle
NGO	Non-governmental organisation
OEM	Original equipment manufacturer
p.a.	Per annum
PEM	Proton Exchange Membrane
PDC	Per doubling of capacity
PHEV	Plug-in Hybrid Electric Vehicle
PPM	Parts per million
R&D	Research and Development
RES	Renewable energy sources
RTD	Research and Technology Development
SAE	Society of Automotive Engineers (SAE International)
Segment (A/B)	Small-size cars (see page 16)
Segment (C/D)	Medium-size cars (see page 16)
Segment (J)	Larger 4 x 4 SUV-type cars (see page 16)
SG&A	Selling, General and Administrative Expenses
SMR	Steam Methane Reforming
SUV	Sports Utility Vehicle
TCO	Total cost of ownership
TWh	Terawatt Hour
VAT	Value Added Tax
WACC	Weighted Average Cost of Capital
WE	Water Electrolysis
WTW	Well-to-wheel

For questions:
www.zeroemissionvehicles.eu
info@zeroemissionvehicles.eu
Att: Ms Alexandra Reis
+32 2 54 087 75

J. Thijssen, LLC
4910 163rd Ave NE
Redmond, WA 98052
P: 206 229 6882
e: jant@jthijssen.com

Market Impacts of Rare Earth Element Use in Solid Oxide Fuel Cells

J. Thijssen, LLC

Report Number: R102 06 01F2

Date: October 18, 2010

Prepared for: National Energy Technology Laboratory, In Sub-Contract to Leonardo Technologies, Inc.

Contract Number: DE-FE0004002 (Subcontract: S013-JTH-PPM4002 MOD 00)

Summary

Rare earth elements (REEs) are critical to the function and performance of solid oxide fuel cells (SOFCs)[1]. Given the concentration of commercially minable REE deposits and production in China (and especially given recent tightening of its export quota), the US Department of Energy is interested in understanding how REE demand for SOFC applications could impact REE markets and *vice versa.*

Yttria (yttrium oxide), lanthanum oxide, and ceria (cerium oxide) are important materials in the ceramic cells that form the core of any solid oxide fuel cell, imparting on the functional layers of the cells ionic conductivity, electronic conductivity, and/or structural strength. Gadolinium, scandium, and samarium are also used in some SOFC designs.

The amounts of REEs contained in state-of-the-art SOFC are modest, and represent less than 5% of annual production (Table 1). Spent SOFC stacks and production waste will likely be recycled for their metal and REE content, which would reduce REE demand for stack replacements by 80-90%.

Table 1 Overview of SOFC-Driven REE Demand, REE Production and Reserves

	REE Content of SOFC	SOFC-Driven Net REE Demand[2]	REE Production (2009)	Estimated Reserves
	g/kW	t/yr (2030)	t/yr	T
Yttria	21	40	9,000	540,000
Lanthanum Oxide	9.2	95	>12,000	>10 million
Other REE (Ce, Gd, Sm)	<3	<12	20,000	~50 million

Market prices for these REEs have risen considerably over the past year, first doubling and then spiking to 4-5x their 2008 price levels in the past few months. At today's prices then, REEs would contribute about $12/kW to the first cost of SOFC systems (based on pre-2008 prices bulk REE cost would have been about $1/kW). While noticeable, this is a small fraction of overall

[1] In the production of SOFC, REEs may be used as metals, oxides, or salts. However, for consistency and to avoid confusion, they will be expressed as elements throughout this paper.

[2] Assuming annual SOFC production of 4 GW/yr of new capacity plus 4 GW/yr of stack replacements assuming 90% REE recycling.

SOFC manufactured cost, representing less than 10% of the SOFC stack, about 2% of the SOFC module in powerplants, and less than 1% of the SOFC powerplant cost. The combined impact of first cost and stack replacement would contribute about $0.50/MWh to the levelized cost of electricity (LCOE) of SOFC powerplants. This is well within the margin of error of the overall LCOE estimate (around $80/MWh).

In summary, REE demand for SOFC applications is not likely to substantially impact overall supply – demand balances for REEs. And while recent price increases clearly affect the production and O&M cost for SOFC systems, plausible fluctuations in REE prices are not likely to fundamentally alter the economic viability of SOFC in power generation applications.

Introduction & Background

The US Department of Energy (DOE) has recognized that several emerging energy technologies rely to varying degrees on the unique properties of rare earth oxides (REEs)[3]. In fact, the DOE recently requested information from industry regarding the potential impact of emerging energy technologies on REO markets (DOE 2010).

The US DOE (the Office of Fossil Energy through the National Energy Technology Laboratory, primarily) has supported Solid Oxide Fuel Cell (SOFC) development for years, most recently through its Solid State Energy Conversion Alliance progam(Surdoval, Singhal et al. 2000; Vora 2010). Partly due to this support, SOFC technology now appears to be nearly ready for commercialization, with some companies now projecting initial commercial products to be available over the next five years (Delphi 2009; Lim 2010). SOFC rely on unique properties of several REEs, especially in their core components: the ceramic cells. These multi-layer ceramic cells contain several REEs or REE-based components. Almost all SOFC designs contain yttrium (yttrium oxide, yttria, is used as a stabilizer in zirconia in electrolyte, anode, and often cathode) and lanthanum (as the key component of the cathode) and in some cases cerium, scandium, gadolinium or samarium[4]. Therefore the DOE's NETL thought it relevant to investigate the potential impact of SOFC commercialization on REE markets and *vice versa*, and hence the DOE requested the preparation of this paper. This paper is organized in the following categories:

1. ***Uses of REEs in SOFC:*** which REEs are used in SOFC, how, and what is their function? What substitutes are available?
2. ***Impact of SOFC on REE Demand:*** how will commercialization of SOFC increase demand in REEs and how might recycling of REEs used in SOFC impact demand?
3. ***Impact of REE Cost & Availability on SOFC Commercialization:*** how would changes in availability and price of REEs affect the economic viability of SOFC and its commercialization

[3] The rare earth elements are: yttrium, scandium, and the lanthanides (atomic numbers 57 – 71, including lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium). Note that strontium is not considered an REE.

[4] In SOFC REEs are typically found as oxides (rare earth oxides or REOs), but for consistency and transparency, we will refer to the elements throughout this paper.

Uses of REEs in SOFC (DOE RFI[5] Category 2)

REEs in the SOFC Ceramic Cells

REEs fulfill crucial roles in the core electrochemically-active components of SOFC: the ceramic cell.

Basic SOFC Function and Materials

The heart of any SOFC is a multilayer ceramic cell, which allows the generation of power by electrochemically oxidizing the fuel. A simple overview of the ceramic cell's function and architecture are shown in Figure 1.

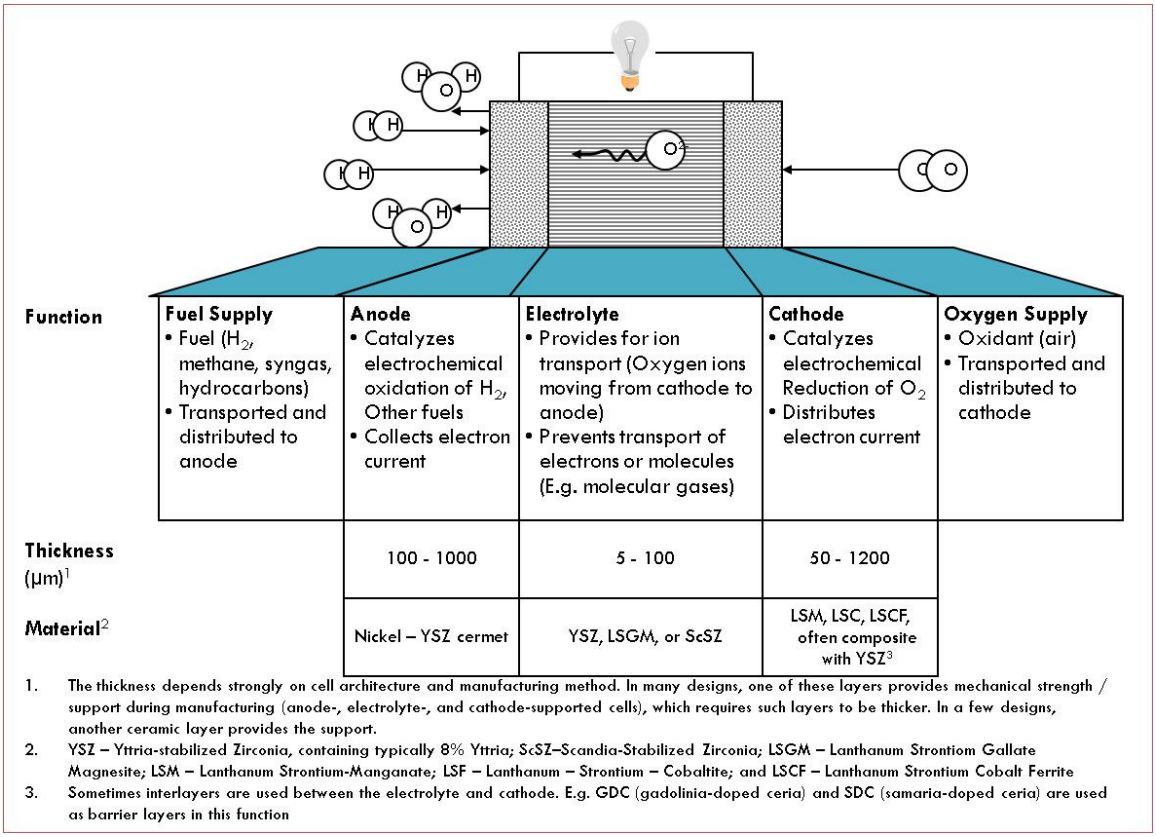


Figure 1 Overview of Architecture, Function, and Materials of SOFC

As can be seen from the diagram, the ceramic cells contain several ceramic oxides with REEs:

- Yttrium is used as a dopant to stabilize the zirconia commonly used for the electrolyte, and sometimes in the electrodes as well. Yttria stabilizes the particular crystal structure that provides the ionic conductivity for the electrolyte (and electrodes)[6]. The yttria

[5] Categories from DOE's RFI (Request for information)

[6] i.e. the yttria stabilizes the crystal structures that provide oxygen mobility (and hence ionic conductivity) combined with low electrical conductivity.

doping level is most typically 8 mole % in those structures (or about 14% yttria or 11% yttrium by weight) but different doping levels are sometimes used, especially for structural components (e.g. the anode support in anode-supported cells). The most commonly considered alternatives to YSZ as an electrolyte are Scandia-Stabilized Zirconia (ScSZ) and Lanthanum Strontium Gallate Magnesite (LSGM), each of which contain significant fractions of scandium or lanthanum, each of which are also REEs. Aside from its role as electrolyte, YSZ is often used in SOFC electrodes (anode, cathode) to provide some ionic conductivity to electrode materials that don't have enough, and, in some SOFC, as a structural cell support. For example, a Ni-YSZ cermet is commonly used as anode material in SOFC. Similarly LSM (see below) cathodes are often mixed with YSZ.

- Lanthanum is another common and key component of most SOFC: several of its oxides provide the electronic conductivity and with high catalytic activity for oxygen reduction needed for efficient cathodes and some, in addition, combine ionic and electronic conductivity[7]. Common compositions are shown in Table 2. The table suggests that while a variety of cathode materials is being considered, many contain ~50% lanthanum. The literature reports experience with several REE-free cathode materials (Singhal and Kendall 2003) though not all alternatives necessarily lead to lower cost cathodes even at today's REE prices (e.g. platinum was used in early SOFC experiments).
- Doped ceria (usually doped with samarium, SDC, or gadolinium, GDC; samarium and gadolinium are also REEs) is commonly used in interlayers used between various SOFC ceramic cell layers (especially in the cathode-electrolyte interface) to prevent or minimize unwanted reactions between electrochemically mismatched layers. Although it may be possible to substitute the REEs in the interlayer structures, the amounts used are so small that this is likely not to be a priority in the near future.

[7] LSM has been commonly used as a SOFC cathode. It is commonly mixed with YSZ to provide the cathode with mixed ionic electronic conductivity (MIEC). More recently, LSC, LSF, and LSCF, which are MIEC cathode materials, have gained in popularity (Borglum (2005), Shaffer (2004)).

Common Name	Chemical Formula	La Content[8]	Other REO Content[3]	Comments
YSZ	Y_2O_3/ZrO_2	-	Y (3-8%)	
LSM	$La_xSr_yMnO_3$ (x= 0.8 – 0.85; y = 0.15 – 0.2)	56%	Sr (9%)	Commonly mixed with YSZ
LSCF	$La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$	44%		
LSC	$La_{0.6}Sr_{0.4}Co_{0.4}O_3$	51%		
LSF	$La_{0.6}Sr_{0.4}FeO_{3-\delta}$	44%		
SDC	$Ce_{0.8}Sm_{0.2}O_{1.9}$		Ce (80%) Sm (20%)	
GDC	$Ce_{0.8}Gd_{0.2}O_{1.9}$		Ce (80%) Gd (20%)	

Table 2 Overview of REO Contents of Various SOFC Materials

SOFC Materials Use in Ceramic Cells

As shown above, all SOFC ceramic cells currently contain some REEs. However, the amounts used (in terms of unit weight per unit power output, e.g. g/kW) are heavily dependent on the cell materials used, cell architecture, and cell power density, as is shown in Figure 2 below.

The overall REE content of planar anode-supported SOFC is modest: around 30 g/kW or less. Tubular cathode-supported SOFC contain ~1500 g/kW[9]. For perspective, the figure for planar anode-supported SOFC is about 100x the platinum loading targets DOE has for polymer electrolyte membrane(aka proton exchange membrane, PEM) fuel cells for vehicle applications (which are 0.2 g/kW for 2015). Platinum (and other Platinum Group Metals or PGMs) are about 10,000 times less abundant than REEs. Even at today's REE prices (September 2010) PGMs are ~500 – 1000 times more expensive than REEs.

[8] For consistency, REEs are expressed in this paper as their elements, rather than as their stable oxides, i.e. Y_2O_3, La_2O_3 etc.

[9] The tubular cells discussed here are flattened, high-surface area tubes, not the older type cylindrical tubes. Other SOFC architectures, including those based on planar electrolyte-supported and tubular anode-supported cells, will contain different amounts of each of the REEs, falling between the two cases discussed here. SOFC that are supported on a REE-free substrate (e.g. strip design cells) may have significantly lower REE content than planar anode-supported cells.

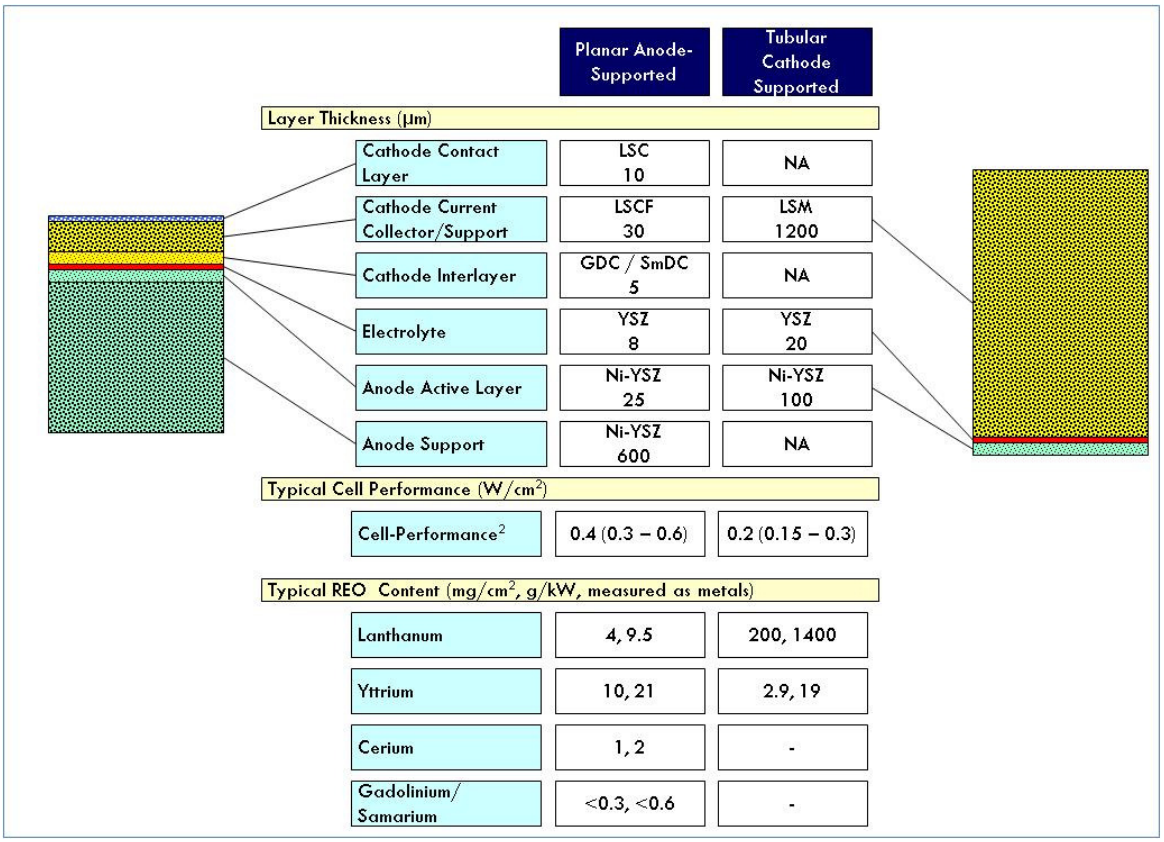


Figure 2 Materials and REO Content of Some Typical SOFC Structures Reflecting the Current State-of-the-Art (for detailed Assumptions, see (Thijssen 2007))

As can be seen in Figure 3, the REE content of SOFC is strongly influenced by the cell structure. Anode-supported SOFC have dramatically (~40x) lower overall REE content than tubular cathode-supported cells, mainly because:

- The supporting anode of planar anode-supported cells has a 10x lower REE content (~5% Yttria, compared with ~50% lanthanum in tubular cells) ,
- The supporting layer (the thickest layer) is less thick (~600 µm for planar anode-supported cells vs 1200 µm for tubular cells),
- Tubular cells tend to have more inactive area than now common large-format planar cells.

In addition, there is a significant difference in the types of REOs used in each type of SOFC (see Figure 3):

- REO content in tubular cathode-supported SOFC is dominated by lanthanum use. This is the consequence of the thick structural cathode made of LSM (Which is ~50% lanthanum)

- Lanthanum and yttrium dominate REO content of planar anode-supported SOFC, together responsible for about 75% of REO content. Cerium and gadolinium or samarium represent the balance.

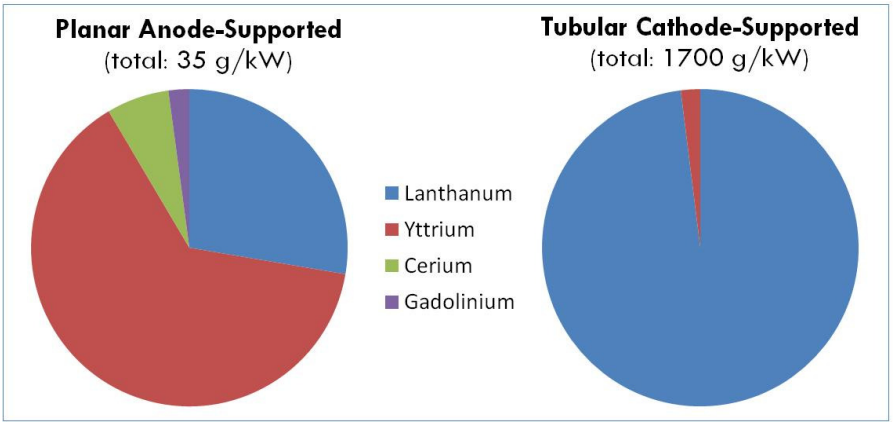


Figure 3 REO Content of Typical State-of-the-Art Planar Anode-Supported and Tubular Cathode-Supported SOFC[10]

The production processes currently envisioned for most planar SOFC mainly involve tape casting, calendaring, and screen printing[11](Thijssen 2007). At maturity, the process yields associated with such processes are typically around 90- 95%. Several studies confirm that such figures are plausible for SOFC and are indeed consistent with pilot production experience.

When considering all of the uncertainties in cell material use, architecture, and production methods the REE use in the production of SOFC ceramic cells based on current state-of-the-art technology already shows a fairly broad range (Figure 4):

- Layer thicknesses between designs vary by a factor two. The supporting layers for planar anode-supported designs vary between about 600 – 800 µm.
- Material choices for at least some of the components could affect uses, especially of the minor constituents (such as cerium, gadolinium, and samarium), which may or may not be used depending on the cell architecture.
- The manufacturing process overall may be expected to reach around 90-95% yield, which has been demonstrated by some developers using pilot production

[10] Cell structures and material uses are consistent with the current state-of-the-art. Details on cell structure are discussed in detail in Thijssen (2007) ,current performance was based on Vora (2010), Ghezel-Ayagh (2010), and Pierre (2010). Figures are on mass basis, accounting for REEs as elements

[11] Other production processes considered, such as extrusion and plasma spray methods may have lower yields, but the losses can be relatively easily recycled either inside the process, or back to the raw material suppliers. As a consequence, the net REO demand from these processes is dominated by the REO content of the product, with process losses a relatively modest factor.

equipment(Borglum 2005). However, yield on individual layers may be lower (e.g. because of overspray in plasma spray processes).

- Variations in power density further broaden the range. In this analysis, power densities for planar anode-supported cells between 0.4 – 0.5 W/cm² have been taken into account, consistent with recent performance

In the future, reductions in REE content of SOFC can be expected, especially if REE prices remain high (see Figure 4 again). This trend is likely because of three principal factors:

- *Increases in power density* will reduce REE content per kW, even if the REE use per unit active area stays the same
- *Reduction of layer thicknesses* especially of the support layers can drastically reduce REEs content
- *Changes in layer composition* can reduce REE content (e.g. via substitution by other materials).

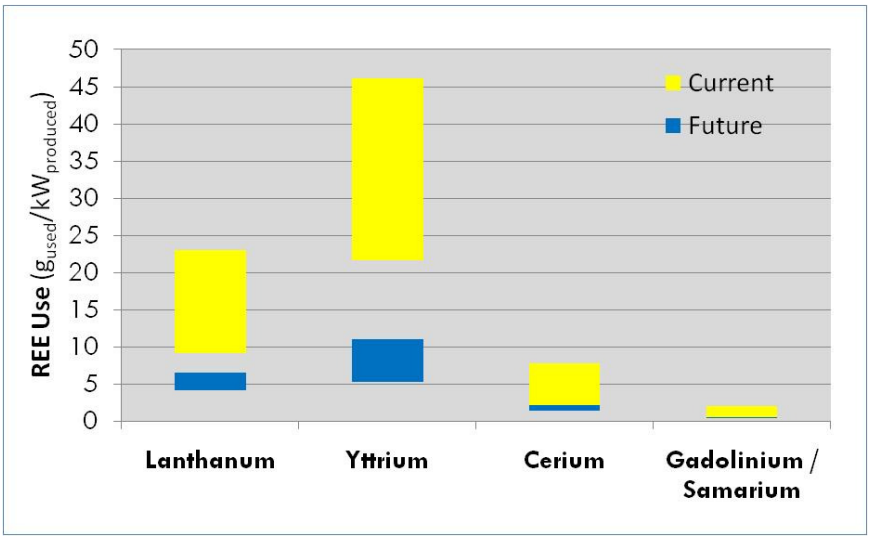


Figure 4 REO Use for the Production of Planar Anode-Supported SOFC Including Production Losses. Ranges Reflect both Typical Current State-of-the-Art and Potential for Future Improvements by 2015[12]

The REEs used in current processes and contemplated for production of SOFCs are high-purity fine powders of the respective REOs (i.e. oxides, they are used in tape casting, screen printing, and plasma spray processes primarily). Currently, purity requirements for these applications are typically in the 99.5% or better range. The purity requirements can, in some cases also be more prescriptive in terms of the specific impurities of interest (e.g. Si). The purity requirements

[12] Range for current state-of-the-art reflects a range of power densities, layer thicknesses, and compositions. Future projections consider improvements in power density, layer thickness, and some material substitution.

vary somewhat according to the precise materials system and cell architecture used. In research projects, higher purities are sometimes used out of an abundance of caution to minimize experimental variations (the added cost of high purity is small compared to the overall cost of the tests).

In addition to the purity requirements, the particle size distribution and surface area of the powders are of importance and differ according to the use of the powder. For example, for the electrolyte typically a fine powder is needed to facilitate rapid densification while for electrodes surface area is typically important.

The price impact of specifications is considerable: ultra-fine pure powders typically sell for 3-10 times the bulk material (still 99.9% pure) market price. The large mark-up results from the additional processing cost, and the supply-demand dynamics in markets for these pure products. Ergo, when basic REE prices increase, the increase in high-quality REO powders may be expected to be less than proportional. In addition, while most REE production is concentrated in China, the purification and processing of REOs is (still) partly the domain of Japanese and Western specialty ceramics companies. Nevertheless, to be conservative, we assumed that the mark-up factor between bulk REE prices (FOB China) and fine powder prices remains constant.

Other REE Uses in SOFC Systems

While use in ceramic cells is clearly the highest-impact use of REEs in SOFC, we want to mention other potential uses for completeness. Other applications of REEs in SOFC systems could include:

- Reformer / fuel processing catalysts may contain certain REEs as catalytic agents or support. Some developers have considered the use of ceria-based catalysts for reforming hydrocarbon fuels.
- Some SOFC systems call for an exhaust gas catalytic oxidation device, which may use a ceria-based catalyst.

Nevertheless, use of REEs in these applications is far from universal, and in most applications competitive alternative materials are available. Even where REEs are used outside the stack, the amount of REEs used in is less than 10% of that used in the ceramic cells. Therefore, we will not delve any more deeply into these other uses of REEs for SOFC systems at this point.

Impact of Stack Replacement

Because current SOFC stacks require periodic replacement (because of gradual irreversible degradation in performance) we must consider the REE demand resulting from the demand for replacement stacks (in addition to stacks for new systems). Currently SOFC stacks degrade at a

rate of around 1% per 1,000 hrs (Borglum 2009; Kerr 2009), which would result in a service life of 2 yrs or less. However, in order to be commercially viable stack life should be extended to about 5 yrs, and the DOE has set R&D targets commensurately. As technology improvements proceed, stack life is expected to continue to improve after the initial commercialization of SOFC. Although technically different, Phosphoric Acid Fuel Cell (PAFC) stack life was around 20,000 hrs for the initial commercial systems, while current stacks last for over 60,000 hrs (UTC-Power 2005). Similar improvements were made with the molten carbonate fuel cells (which are more like SOFC). So for our projection, we consider an initial stack life of around 5 yrs (in 2015) and an improvement to a 10 yr stack life by 2030.

Impact on Demand for REE from SOFC, Impact of Recycling (USDOE RFI Categories 3, 6)

DOE's projects a cumulative installed base of about 15 GW of Integrated Gasification Fuel Cell (IGFC) plant by 2030 (DiPietro and Krulla 2010). Considering typical ramp-up profiles and initial commercial market introduction of IGFC systems in the 2020-2025 timeframe this implies an annual new SOFC capacity addition of 3-5 GW. To assess the implications of this level of market penetration as well as the longer-term impacts of SOFC production on demand for REEs, we consider three scenarios[13]:

1. ***Baseline Projection Gross Demand in 2030*** – the gross demand for new and replacement stacks based on the DOE's SOFC market penetration projections,
2. ***Baseline Projection Net Demand in 2030*** – taking into account a plausible mature recycling rate,
3. ***Long-Term Demand Potential*** – the demand that would result from SOFC stack replacement rate if all coal-fueled capacity were replaced with SOFC.

Scenario 1: Baseline Gross Demand for 2030

The DOE's current projections envision commercial introduction of SOFC around 2015 for initial applications (distributed generation, APUs, industrial, and military applications) and around 2020 for utility –scale applications. Because of their modest cost and high efficiency, as well as the potential to provide CO2 capture at marginal additional cost and loss of efficiency, SOFC sales are thought to increase rapidly, reaching 15 -20 GW of installed capacity by 2030.

Based on this, 2030 demand for new capacity, as stated above, is implied to be around 4 GW/yr. 2030 is an estimated 5-10 yrs into commercialization cycle of coal-based SOFC applications (which represent the majority of projected demand). Hence the projected annual demand is

[13] While other applications may be commercially significant, their impact in terms of production volume, and hence REE use, is small compared with coal-based applications.

sensitive to the assumptions surrounding the commercialization (e.g. initial commercial availability, rate of market penetration).

By 2030 only stacks installed in the initial years of IGFC commercialization will have reached the first stack replacement cycle, so stack replacement would add only about 1 GW/yr or less. Because this figure would rise dramatically in 2031 – 2035, we assume instead that the replacement rate is equal to new capacity additions for this analysis, resulting in a gross demand for SOFC stacks of 8 GW/yr.

Figure 5 shows the projected gross baseline REE demand for SOFC applications obtained by combining the projected REE use (in g/kW from Figure 4) with the projected gross SOFC demand (in GW/yr).

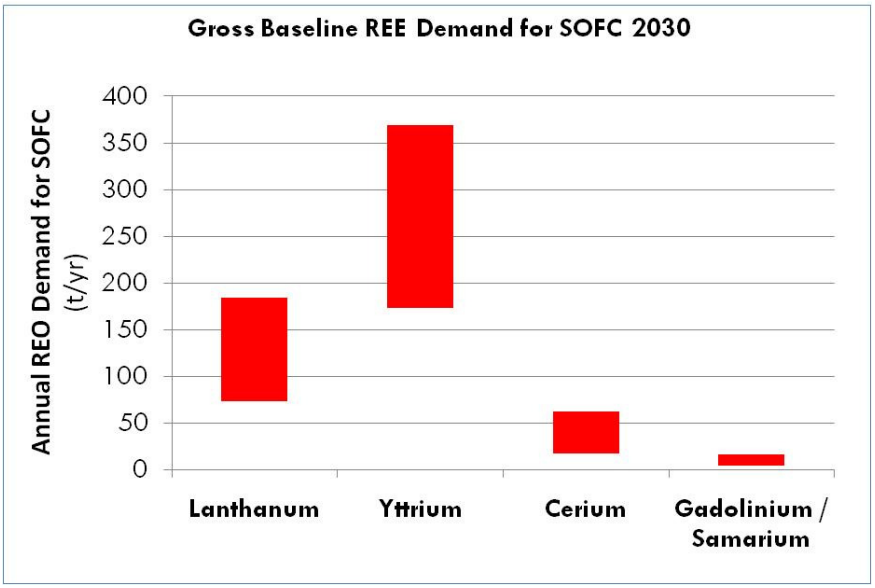


Figure 5 Projected Annual Gross REE Demand for New Systems and Replacement Stacks in 2030 (for Planar Anode-Supported SOFC, Demand in Metric Ton per Year Measured as Metals)

The combined demand for all REEs in this scenario would be 300 – 700 tons / yr. The range shown in the figure reflects only variations in REO use (compare Figure 4). Uncertainties in demand for both new and replacement SOFC capacity would further broaden that range. The reader is encouraged to consider all three scenarios to appreciate the impact of these uncertainties in demand.

The REE demand will of course depend on the choice and performance of SOFC technology. For example, if tubular cathode-supported SOFC technology were used, lanthanum demand would be about 16,000 – 20,000 t/yr, about 40-75x higher than for planar anode-supported technology (yttrium use would be comparable, no other REEs would be used).

Scenario 2: Baseline Net Demand for 2030 – The Impact of Recycling

Recycling of production waste as well as spent stacks will likely significantly reduce REE use for SOFC, especially in the long run. Given the concentration of rare earths and metals in used stacks, it is not unlikely that used stacks will be recycled. The processes used to process REE ores appear suitable for recycling of used stack materials.

Assuming the ceramics from the stacks are separated from the metals first, e.g. using conventional smelting technology, our analysis shows that the REO content of stack ceramics[14] would range from around 20% - 60%, depending on stack architecture, compared with 7-10% for typical ores(Haxel, Hedrick et al. 2002). Concentrations of REOs in production waste (e.g. overspray, rejected parts) can be even higher. These high concentrations will make recycling REEs from spent stacks attractive to REE producers.

Given the use patterns of SOFC, and the anticipated business structures for replacement stacks, a high rate of recycling would appear to be feasible. Especially if stack life remains relatively short (i.e. close to 5 yrs), it is likely that such a market for recycling REOs from the stack will arise even by 2030.

Given the attractiveness of recycling it would not likely impact the cost of SOFC strongly but it would be economically self-sufficient (i.e. REO producers would pay to recover portions of SOFC stacks).

Given the situation, a recycling rate of about 85% - 95% for production waste and spent stacks combined appears reasonable. With a 85% recycling rate the demand for REEs in 2030 would drop by around 50%, as shown in Figure 6. The resulting overall REE demand would be in the 160 – 360 t/yr range[15].

[14] We exclude the nickel from the cermet anodes as we assume that in a recovery process that would be relatively straightforward and profitable to recover as nickel metal.

[15] Even by 2030 85% recycling will not lead to a 85% reduction in demand because a substantial portion of the market will still be a new market. With recycling, demand will stabilize sooner.

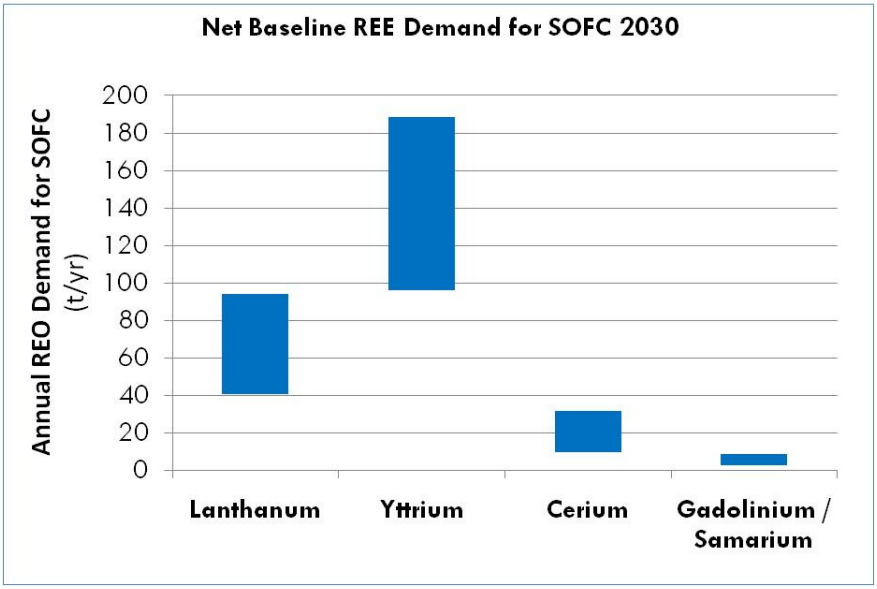


Figure 6 Projected Net REE Demand for SOFC in 2030 (for Planar Anode-Supported SOFC, Demand in Metric Ton per Year Measured as Metals)

Scenario 3: Long-Term REE Demand

Because 2030 is still early in the commercialization of SOFC technology, we thought it useful to assess the potential long-term contribution of SOFC to REE demand. To that end we considered a future scenario in which:

- Installed capacity of SOFC equals 100% of today's coal-fueled electric generating capacity. No growth in capacity is assumed, consistent with negligible net growth in coal-fired capacity over the past 10 yrs.
- SOFC stack life is 10 yrs, requiring stack replacement every 10 yrs.
- Recycling rates vary between 85 – 95%.
- REE use per kW is taken from the future range presented in Figure 4.

As can be seen in Figure 7, REE consumption under such a scenario is reduced by 30 – 80% compared with net baseline consumption. This indicates that REE use for SOFC is likely to be sustainable in the long-term.

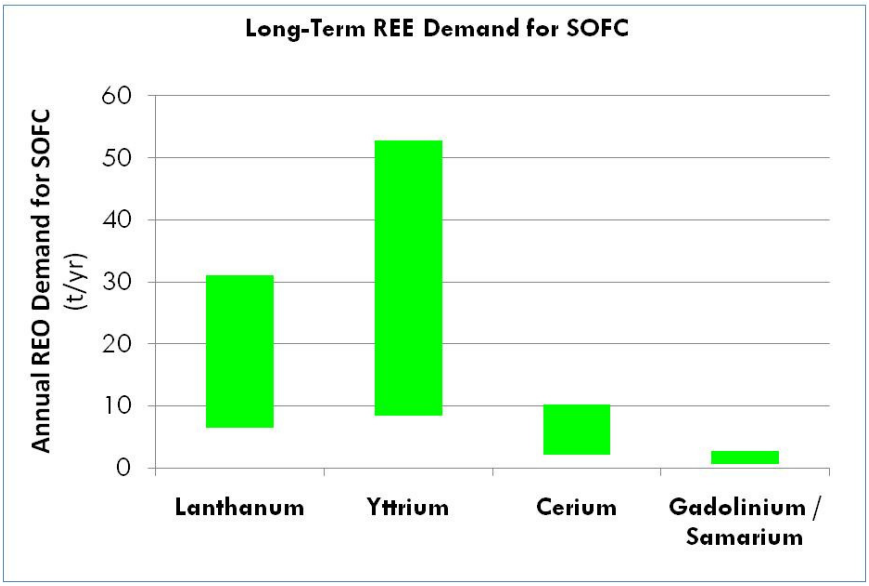


Figure 7 Projected Net Long-Term REE Demand for SOFC (for Planar Anode-Supported SOFC, Demand in Metric Ton per Year Measured as Metals)

Availability and Cost Impact (USDOE RFI Category 4)

Availability in Relation to SOFC Demand

The availability and prices for REOs have been the subject of much media attention recently. One reason for this interest is the recent dramatic rise in REO prices. The Economist reported that an index of REO prices has risen roughly fivefold since 2009 (Economist 2010), which is confirmed by a review of proprietary industry data (Metal-Pages 2010). The recent rise in REE prices is driven primarily by export restrictions being imposed by China. In recent years, China supplied around 90% of all REEs worldwide. Thus it is not surprising that China's announced 40% reduction of REE availability for export has led to dramatic price increases.

In addition to China, other countries, including the US, Australia, and Canada also hold considerable REE deposits. However, production from these countries has dwindled in recent years because Chinese suppliers were low-cost producers. Not surprisingly, in response to China's tightening of supplies, US, Australian, and Canadian companies are considering a resumption or increase in production of REEs in their respective countries.

Compared with the quantities used today, the additional potential REE demand from SOFC applications appears modest. Considering that SOFC demand will grow to projected levels over a period of 5-10 years, SOFC-driven demand for REE products appears unlikely to significantly challenge the supply chain or world reserves. In the following, production and reserve data for REEs are taken from a variety of USGS sources (Haxel, Hedrick et al. 2002; Salazar and McNutt 2010; USGS 2010):

- **Yttrium:**
    - The projected 2030 net baseline SOFC demand for yttrium is 96 ton/yr. A rationalization of yttrium use for the anode could reduce that figure to ~8 ton/yr, as represented in the future scenario.
    - Compared with a 2005 - 2009 US consumption rate fluctuating between 400 – 742 t/yr net baseline use for SOFC is significant. However, the figure for the future scenario is not likely to materially impact overall yttrium markets. USGS estimates world mine production to be at least 8,900 t/yr. In that context, even the impact of baseline demand would be modest. The impact of potential future SOFC demand on overall demand and prices of yttrium is likely to be small.
    - The abundance of yttrium in the earth's crust is 31 ppm similar to that of nickel and chromium. However, as other REEs, it is relatively disperse, with relatively few discovered more concentrated deposits (even in deposits yttrium is not very concentrated: 200 – 500 ppm typically). USGS estimates reserves of yttrium at 540,000 tons, about 220,000 of these in China, and about 100,000 tons in the US (mainly in the Mountain Pass deposit in California).
    - Virtually all Y used in the US is currently imported. More than 90% of world production is currently in China. The Chinese government has recently (in July) announced cuts in REE exports by about 40%.
    - Prices for bulk yttria (Y_2O_3, 99.9% pure or more, FOB China) have risen from around $5/kg in 2002 to around $40/kg in September 2010. High-volume prices for ultra-pure fine powders of yttria however can be 3-6 times higher than bulk prices, depending more on purity level and physical form.
- **Lanthanum:**
    - The projected 2030 net baseline SOFC demand for lanthanum oxide is 40-90t/yr.
    - Compared with annual global production of 33,000 t/yr, the potential demand for SOFC is modest and appears unlikely to materially alter lanthanum markets.
    - Lanthanum's abundance in the earth's crust is about 30 ppm, between that of tin and nickel, although, like other REOs, it is relatively disperse in the earth's crust. But compared with yttrium, REE deposits have high concentrations of lanthanum, with concentrations of ~25% in large deposits such as the Mountain Pass deposit in California and about 15% in many Chinese deposits. Given this, lanthanum reserves in producible deposits are thought to be over ten million tons.
    - Notwithstanding considerable US deposits, nearly 100% of lanthanum is currently imported in the US, mostly from China
    - The prices for bulk lanthanum oxide (La_2O_3, 99.9% pure or more, FOB China) have increased dramatically from around $3/kg in 2002 to nearly $50/kg in

September 2010. This dramatic price increase is driven partly due to short-term supply-demand imbalances caused by drastic increases in lanthanum use in NiMH batteries (primarily for hybrid vehicles) but strongly exacerbated by China's export restrictions.

  - If tubular cathode-supported SOFC are commercialized instead of planar anode-supported ones, lanthanum demand could be about 50x higher (about 60x higher content but likely longer stack life), or up to 7,000 t/yr. That level of demand would likely be sufficient to significantly affect lanthanum oxide markets and prices.

- **Cerium:**
  - Net demand for ceria for SOFC applications appears likely to remain below 10 t/yr.
  - Compared with US consumption of cerium compounds of around 2,000 t/yr this projected demand from SOFC is modest, and appears unlikely to materially affect overall Cerium markets and prices.
  - The abundance of cerium in the earth's crust, at about 60 ppm, is the most abundant of the lanthanides on earth. Its abundance is similar to that of chromium, though it is less concentrated. Found mostly in conjunction with the lanthanides, cerium-rich deposits are found predominantly in China, with smaller deposits in the US and Australia. Ceria are thought to represent almost half of REO reserves; i.e. about 50 million tons. Clearly, demand for SOFC will in not likely strain world reserves.
  - Prices for cerium too have risen sharply from about $2/kg in 2002 to around $37/kg in September 2010.
- **Gadolinium and Samarium:**
  - Projected 2030 baseline SOFC demand for gadolinium or samarium is 2-8 t/yr. Future demands could be reduced to below 1 t/yr.
  - Compared with report current global gadolinium production of around 400 t/yr this demand is modest. Samarium production is estimated at around 700 t/yr.
  - Gadolinium is about 5 times less abundant than yttria, at about 6 ppm, while samarium has a similar abundance as yttrium. Gadolinium and samarium reserves worldwide, found in China, the US, Australia, Brazil and India, are estimated to be around 1 million tons and 2 million tons respectively.
  - Gadolinium and samarium oxide prices were historically several times higher than those of yttria, lanthanum oxide, and ceria (about $10-$12/kg in 2002). Current (September 2010) prices are similar to the other rare earths of interest however at near $40-$50/kg.

The expectation is that if Chinese cuts persist for some time, and prices stabilize at this higher level, additional production capacity in other countries will supplant the reduced Chinese supply. However, because of the market risk the Chinese policy poses (China's marginal cost of production is still lowest, and hence could undercut other suppliers at any time if it wanted), such investments are likely to be made with caution.

Price Impact

The impact of REE prices on SOFC cost and economic viability in the context of IGFC systems(Kearns 2010) is limited, as REOs contribute around $10/kW to the first cost of SOFC:

- The total capital cost[16] + stack replacement cost together represent about 4.5 ¢/kWh
- Of the ~$1750/kW installed CAPEX of IGFC systems about $700/kW is related to the SOFC power unit;
- Of the $700/kW power unit, about $100/kW is the manufactured cost of the stack;
- Of the $175/kW stack, less than $10/kW are represented by the cost of the ceramic powders;.
- Of the ceramic powders, REEs represent about $10/kW based on September 2010 prices (based on pre-2008 prices, REOs would cost about $1/kW). The combined impact of $10/kW stack cost (including both capital cost effects and stack replacement cost) on LCOE would amount to around 0.05 ¢/kWh, which is in the margin of error of such LCOE estimates at this time.

Figure 8 provides a perspective on the historical impact of REE prices on SOFC stack cost.

Although further increases in REO cost are possible, long-term prices substantially above today's levels seem unlikely, because they would stimulate production in other countries (than China). So based on this analysis it appears unlikely that even the dramatic increases in the prices of REOs seen over the past years will not fundamentally alter the economics and viability of SOFC in central power applications.

It is worth noting that the price impact of REEs on SOFC based on some of the other cell architectures can be much more significant. For example, bulk REE cost contributes about $80/kW to the cost of tubular cathode-supported SOFC cells. Where REE use was hardly a factor in determining the relative cost competitiveness of various SOFC technologies based on 2002 prices, it appears that current prices lead to material differences in cost between various technologies.

[16] Total capital cost of the plant, not just the SOFC

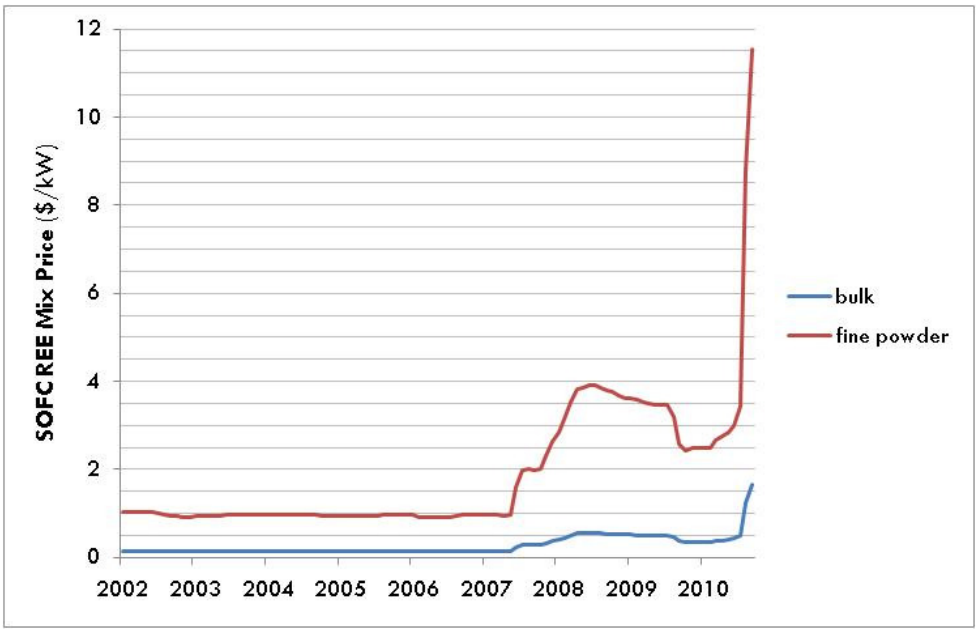


Figure 8 Historical Impact of REE Prices on SOFC Stack Cost (bulk figures represent just REE bulk prices FOB China, fine powder figures assume a 7x mark-up over bulk prices)[17]

Conclusion and Recommendations

A few REEs (notably yttrium, lanthanum, and cerium) are crucial to the functionality of SOFC; viable alternatives have not been identified for all REE applications in SOFC so far. However, it appears that this need not be of significant concern, given that demand for these REEs resulting from even highly successful commercialization of SOFC would not materially impact REE markets and because even dramatic further increases in REE prices would not likely alter the economics and viability of SOFC in central power applications decisively.

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[17] The mix price is determined by the sum of the products of REE use per kW (Figure 2) and REE prices for each of the REEs (all for state-of-the-art planar anode-supported SOFC). The fine powder mark-up presumably presents the supply-demand dynamics as well as processing cost. We show the 7x mark-up as a worst-case scenario.

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