From: Exparte Communications

Subject: FW: 2nd set of presentations and material for meeting with M Holland on Mon May 9
Date: Monday, May 02, 2011 11:40:23 AM
Attachments: CaFCPProgressand2011Actions.pdf
Power_trains_for_Europe.pdf
Letter_of_Understanding_final_all_signatures.pdf
http___www.meti.go.jp_english_press_2011_0113_01.pdf
13_Japanese_Companies_Eye_SmoothDomestic_Launch_of_FCVs___TOYOTA_MOTOR__CORPORATION_GLOBAL_WEBSITE.pdf
RFI
DOE Fuel Cell and Hydrogen Program Plan Infrastructure Initiative.pdf

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Second e-mail

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From: sigmundgronich@aol.com [mailto:sigmundgronich@aol.com]
Sent: Monday, May 02, 2011 11:38 AM
To: Exparte Communications
Subject: 2nd set of presentations and material for meeting with M Holland on Mon May 9

Attached are additional material and presentations to be discussed with Dr. Holland and staff on Monday, May 9 at 2 pm.

Presenters will be:
Dr Sigmund Gronich, President, Charisma Consulting
E F Kiczek, Global Manager, HES
Catherine Dunwoody, Executive Director, California Fuel Cell Partnership
Dr Robert Rose, FCHEA

Sig Gronich

Progress and 2011 Actions for Bringing Fuel Cell Vehicles to the Early Commercial Market in California

February, 2011

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West Sacramento, CA 95691
916-371-2870
www.cafcp.org

This document refers to CaFCP's current consensus plan for deploying fuel cell vehicles and hydrogen stations in California. This consensus vision does not necessarily represent the views or commitments of individual CaFCP members.

Building the Early Commercial Market

In the 2009 document *Hydrogen Fuel Cell Vehicle and Station Deployment Plan: A Strategy for Meeting the Challenge Ahead,*[1] CaFCP members identified the specific actions needed to enter a commercial market for fuel cell vehicles and hydrogen fuel through 2017. Based on data and real-world experience, the roadmap called for about 40 new hydrogen stations to prepare for commercial launch. In April 2010, CaFCP released an update that reported progress and next steps toward the action plan goals.[2]

This report is the second update and a precursor to a roadmap coming later this year. This document identifies immediate actions required in 2011 to prepare for coming fuel cell passenger vehicles and transit buses. These actions are the next important steps toward commercialization and user acceptance, and point to future needs and challenges to establish the early commercial market.

Vehicle technology has moved from R&D toward commercialization and, therefore, actions have evolved to focus on consumer confidence, acceptance and usability. This requires:

- Successfully opening and operating the stations announced, funded and under construction. To customers, a station in planning or under construction does not exist. It's vital that awarded stations move quickly from announcement to retail operation so automakers can deploy vehicles in planned timeframes.
- Establishing early clusters of stations to enable vehicle deployments. To be successful, clusters need multiple fueling stations to meet customer needs and provide station redundancy. Hydrogen supply must also exceed customer demand by considering peak usage in addition to average daily usage. Early clusters will ultimately expand geographically and quantitatively to accommodate greater FCV deployments within the decade.
- Meeting current technical requirements and preparing for codes and standards now under development. All stations, regardless of funding parties or equipment providers, must meet applicable J2601 requirements, provide fuel at H35 and H70, deliver sufficient daily and peak supply, and adhere to developing hydrogen fuel quality standards.
- Meeting customer expectations for retail fueling. Stations and refueling protocols must be safe and open to all automaker vehicles, be retail oriented and provide a customer experience similar to today's conventional fuel stations (e.g. 24/7 operating hours, no use agreements or classroom training requirements, and conventional payment methods).
- Meeting retailers' business expectations for dispensing fuel. Owners and operators of retail hydrogen stations must be able to sell hydrogen as a retail fuel, understand applicable regulations and requirements for dispensing hydrogen and be able to integrate hydrogen with normal business operations, including a path to profitability. Owners must be able to see when they can recover operating and maintenance costs, and make a return on capital investment competitive with other investment opportunities.

[1] CaFCP 2009 Action Plan www.cafcp.org/sites/files/Action%20Plan%20FINAL.pdf
[2] CaFCP 2010 Progress and Next Steps report www.cafcp.org/sites/files/FINALProgressReport.pdf

2011 Coordinated Stakeholder Actions

The following are priority actions for 2011:

- Fill the gaps in areas where hydrogen supply will fall short of demand based on automakers' projected vehicle deployments to early customers.
  - ✓ Direct available 2011 hydrogen station funding to support new stations in shortfall areas listed in Table B.
  - ✓ Identify additional funding, to be available in 2012 and beyond, to support a growing network of fueling stations necessary to fuel vehicles in 2015 and beyond, as shown in Figure A.
  - ✓ Find ways to fund ongoing operation and maintain early retail-like demonstration stations, as these will continue to be vital in the early years of commercialization
- Synchronize and augment regulations, including the Clean Fuels Outlet, Zero Emission Vehicle Regulation, Zero Emission Bus Regulation and renewable hydrogen, to better support successful deployment of FCVs.
- Complete many of the codes and standards that enable retail sales of hydrogen as fuel.
- Use information from industry and academia to identify new funding models to transition away from year-to-year government co-funding.
- Target education and training in the early market communities that are receiving their first hydrogen stations this year.

2010 Snapshot

At the end of 2010, California had four publically accessible hydrogen stations that customers from each automaker can use, two of which already have more demand for fuel than they can supply. A new station in Torrance was being commissioned as this document was written. Four more stations are expected to open in Southern California in early-2011 and one in San Francisco near the end of 2011. (See Appendix 1 for a list of current and planned stations.)

Several of these demonstration stations are first of their kind, building upon the experience from earlier stations and becoming a proving ground for new technology and ideas. The Torrance station is the first to take fuel from an active underground hydrogen pipeline. The Harbor City station is the first to have high-pressure delivered gas, minimizing on-site compression. Fountain Valley will be the first to make 100% renewable hydrogen from wastewater digester gas. Jointly, the new stations will provide more fueling options for existing fuel cell vehicle customers and transit buses, and enable automakers to place more new vehicles with retail customers and into fleet operation.

In 2010, a collaboration of five San Francisco Bay Area transit agencies began operating a fleet of 12 new fuel cell buses. The buses have the latest improvements and upgrades learned from prior demonstrations including a fully integrated hybrid fuel cell/battery electrical system with an advanced lithium-ion energy storage system. The buses have more passenger capacity and carry 40kg of hydrogen, yet weigh 5,000 pounds less than the previous generation of fuel cell bus and cost about 35% less.

The buses will use two stations, both using new ideas and technology. The station in Emeryville is a solar electrolysis station with two dispensers: one inside the fence for buses and one outside the fence for passenger vehicles. The transit-only station in Oakland will be the first to use a

biogas-fed stationary fuel cell system to fully power an electrolyzer and all other electrically driven equipment at the station with renewable energy.

Two additional California fuel cell bus demonstrations are underway: one with SunLine Transit in Thousand Palms and the other with the City of Burbank. San Francisco MTA is also demonstrating the use of a hydrogen fuel cell auxiliary power unit in a hybrid diesel/electric transit bus. At a one-day workshop[3] in Washington DC hosted by the U.S. Department of Energy, technical experts from industry, end users, academia, DOE national laboratories, and other government agencies concluded that the fuel cell vehicle technology is close to commercial readiness.

Fuel Cell Vehicles on the Road

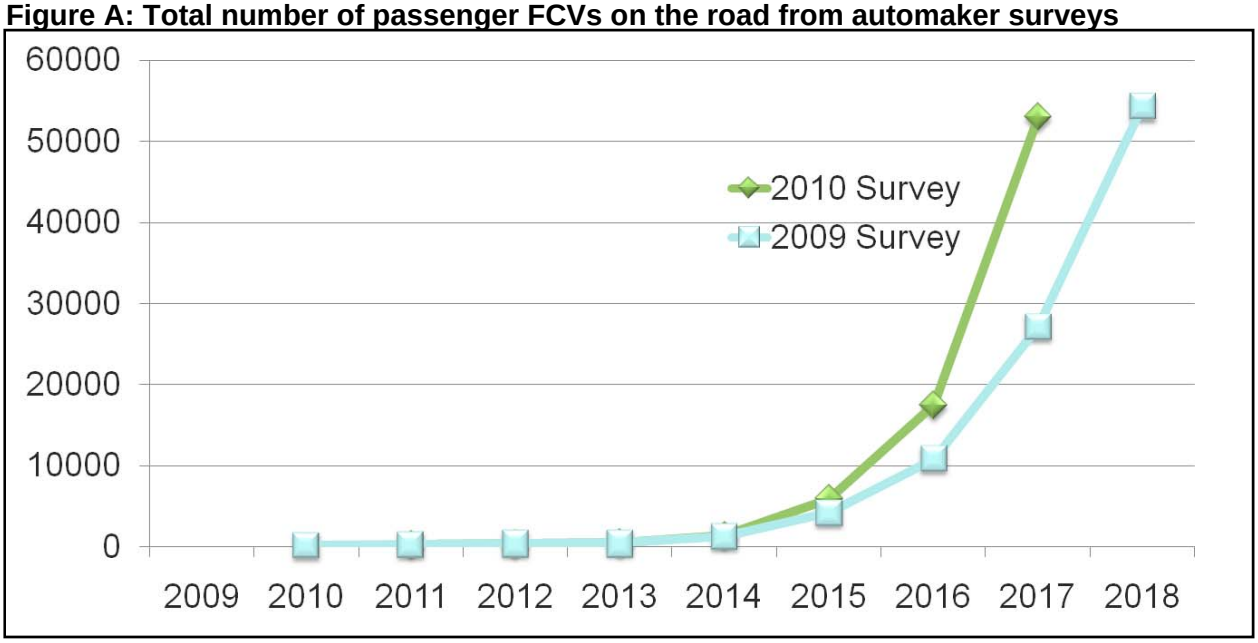
Fuel cell passenger vehicles

CaFCP conducts annual surveys of its automaker members to gain an accurate projection of planned vehicle deployments in the coming years. The December 2010 results show trends similar to previous surveys, confirming automaker plans for hundreds, thousands and then tens of thousands of fuel cell vehicles. Table A presents the 2010 CaFCP automaker survey results while Figure A presents a summary of CaFCP's 2010 automaker survey results for passenger FCVs compared to the 2009 survey. Result show that automakers now expect FCVs to reach tens of thousands slightly earlier than they did in 2009.

Table A: 2010 CaFCP survey of automaker passenger fuel cell vehicles

	Hundreds	Thousands	Tens of thousands
	Through 2013	2014	2015-2017
Total Passenger Vehicles*	430	1,400	53,000

Figure A: Total number of passenger FCVs on the road from automaker surveys



[3] Joint Fuel Cell Bus Workshop Summary Report, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/buswksp10_summary.pdf

Fuel cell buses

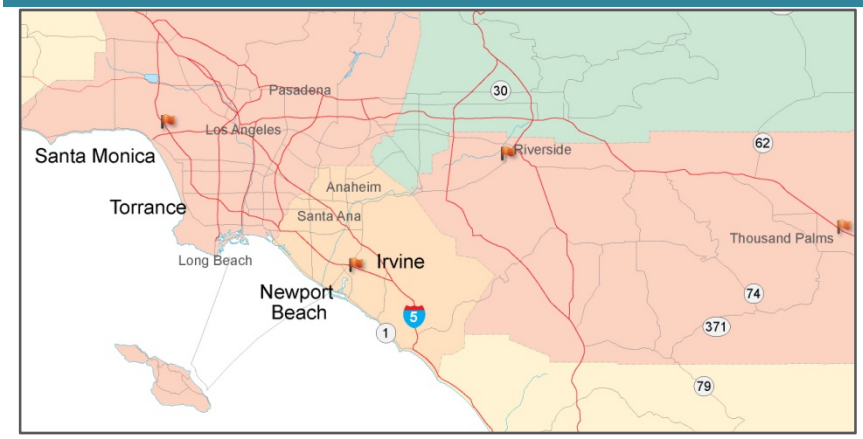
The California Air Resources Board is currently monitoring all California fuel cell bus demonstrations by measuring bus performance characteristics such as reliability, availability, durability and cost as they compare to conventional buses in transit service today. As fuel cell buses reach commercial readiness, CARB is prepared to propose regulatory actions to require large transit agencies to purchase a small percentage of all new bus acquisitions as zero emission buses. When this purchase requirement is implemented, the 10 largest California transit agencies will begin deployment, further expanding the need for hydrogen infrastructure, including high-volume stations, in the most densely populated regions of the state.

Hydrogen stations

Four publicly accessible hydrogen stations were open in California at the end of 2010. Eight more stations were in development in 2010 and in November 2010 the California Energy Commission proposed funding for eight new and three upgraded/expanded stations. Proposed funding is expected to be awarded in early 2011, with stations to begin operation in 2012.

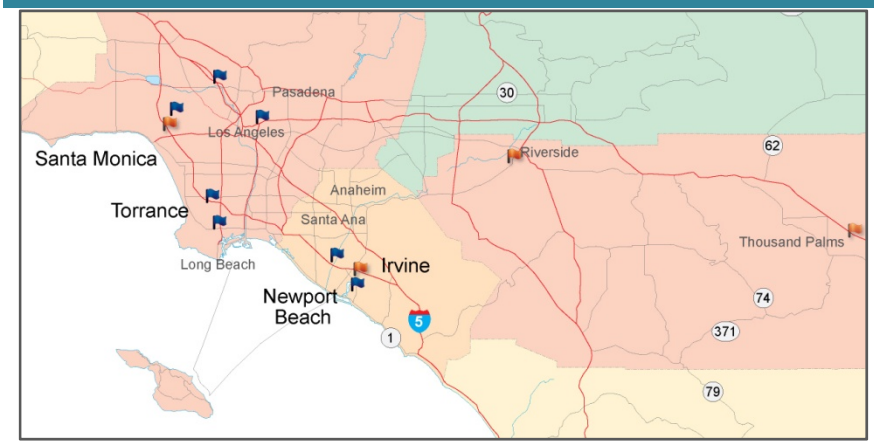
The maps on the following page (Figure B) show a progression of public hydrogen stations in Southern California from those open at the end of 2010 to those projected to be open by the end of 2012. Figure C shows the stations expected in Northern California by the end of 2012.

Figure B: Progression of hydrogen stations in Southern California



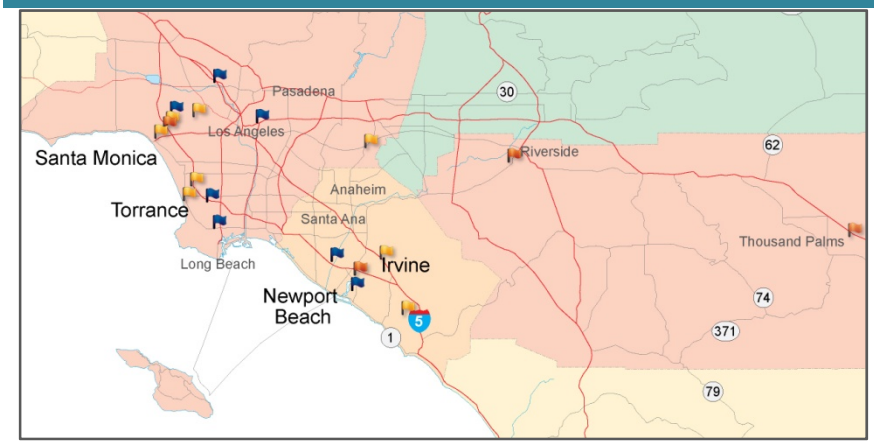
Stations open to the public in 2010

West Los Angeles
Riverside
Irvine
Thousand Palms



Stations to be added in 2011

Newport Beach
Harbor City
Los Angeles
Burbank
Fountain Valley
Torrance
Westwood



Stations to be added in 2012

West Los Angeles
Irvine (2)
Beverly Hills
Diamond Bar
Santa Monica
Hawthorne
Hermosa Beach
Laguna Niguel

Proposed for funding in 2010

Figure C: Northern California hydrogen stations

2010 Progress and 2011 Recommended Actions

In 2010, CaFCP members made progress with each of the five points in the Progress and Next Steps report. Most of the actions are specific steps to bringing clusters of demonstration retail-ready hydrogen stations into operation in the early market areas.

Fund showcase stations

Progress: In the 2010 progress report, automakers and transit agencies identified seven specific communities that needed new stations before 2012, and four existing stations that needed upgraded, expanded or extended operation. Automakers identified these locations as best suited to provide "primary" stations to their first customers. The goal is to maximize station utilization, make the best use of limited funding, and provide adequate fuel and convenience for customers.

In November, the California Energy Commission released its Notice of Proposed Awards that identifies the Transportation Committee's support for co-funding 11 new, expanded or upgraded stations.[4] The solicitation included specific points to ensure public access, longevity and faster station planning and construction.

In addition, South Coast Air Quality Management District and the California Air Resources Board funded continued operation of the Burbank station.

[4] Alternative and Renewable Fuel and Vehicle Technology Program Grant Solicitation PON-09-608 Hydrogen Fuel Infrastructure http://www.energy.ca.gov/contracts/PON-09-608_Revised_NOPA.pdf

2011 Action: Fill the gaps in areas where hydrogen supply will fall short of demand based on automakers' projected vehicle deployments to early customers.

- Direct available 2011 hydrogen station funding to support new stations in the shortfall areas listed in Table B.
- Identify additional funding, to be available in 2012 and beyond, to support a growing network of fueling stations necessary to fuel vehicles in 2015 and beyond, as shown in Figure A.
- Find ways to fund ongoing operation and maintenance of early retail-like demonstration stations, as these will continue to be vital in the early years of commercialization

Customers need confidence they will be able to fuel their new vehicles where they want to go, and at times that are convenient for their schedules. It is important that hydrogen stations have adequate supply on a daily and peak basis to supply the growing vehicle fleet. Fulfilling customer needs with sufficient locations will initially result in more hydrogen than needed, but location is a key to customer adoption that will start the early commercial market.

Through the survey and ongoing planning meetings, the automakers jointly identified areas where they project a shortfall in fuel supply by 2014, based on vehicle placement plans. Stations in these areas (listed in Table B) will fill these gaps. Areas within the South Coast air basin refer to South Coast AQMD's forecast map.

Table B: Areas where additional hydrogen stations are needed before 2014*

Air Basin	County	Area
South Coast‡ (Los Angeles region)	Los Angeles	South LA County Coastal (region 4)
		West San Fernando Valley (region 6)
	Orange	North Orange County (region 16)
		Central Orange County (region 17)
		Saddleback Valley (region 19)
		Capistrano Valley (region 21)
South Central Coast	Santa Barbara	Santa Barbara
San Diego	San Diego	San Diego
San Francisco Bay Area	San Francisco	San Francisco
	Santa Clara	Santa Clara
Sacramento Valley	Sacramento & Yolo	Sacramento

** Areas having hydrogen supply shortfall by 2014 or sooner, based on projected publicly accessible hydrogen supply (kg/day) compared to automakers' projected vehicle deployments.*

‡Regions within the South Coast air basin refer to the South Coast Air Quality Management District forecast area maps, the location basis used for the 2010 automaker survey.

In addition to location, new stations must also consider retail customer fueling habits. Most people fuel their vehicles in the few hours before and after work.[5] Therefore, stations must be designed to provide 75-80% of their capacity in a three-hour window. For example, a station that has 50 customers a day will typically see 20 of the customers between 6:00am and 9:00am, 25 customers between 5:00pm and 8:00pm, and the other five throughout the day. Therefore, that station's design must consider both daily and peak fueling capacity.

As FCVs approach the early commercial market, clusters of stations need to grow into an urban network and ultimately a system. Meeting this challenge requires continued operation of existing public stations as well as adding new stations. Stations must prove reliability in retail-like use so automakers can be confident their new customers will have access to sufficient fuel supply and locations.

Additional hydrogen stations will need to be funded and built before 2015 to prepare for commercial launch of vehicles, and stations will need to be added and expanded each year to fuel the rapidly growing vehicle fleet. In the next few years, as more customers drive fuel cell vehicles, automakers will better understand how fueling location impacts early adoption. Automakers will prioritize new station locations as they understand customer market needs.

Synchronize and augment regulations and policies

Progress: Federal, state and regional government regulatory agencies took early action to synchronize vehicle regulations that emphasize zero emissions with fuel regulations that aim to lower carbon content through biofuels. Agencies will continue to look at ways to synchronize the regulations and policies.

2011 Actions: The California Air Resources Board will consider revisions to several regulations, including the Clean Fuels Outlet, Zero Emission Vehicle Regulation and Zero Emission Bus Regulation in 2011. CaFCP and its members will continue to work with U.S. Environmental Protection Agency to include fuel cell vehicles in the new EPA vehicle labels. In addition, California and the Department of Energy will continue research and evaluation of ways to make hydrogen from renewable resources, including biogas and biomass, in a more cost effective manner.

Complete codes and standards for retail sales of hydrogen

Progress: Several of the first standards for hydrogen quality have been adopted by standards setting organizations. The National Institute of Standards and Technology accepted the standards for hydrogen signage and dispenser marking. California Division of Measurement Standards, with support from NIST and the U.S. National Working Group and funding from CEC, expects to finalize hydrogen metrology standards by early 2012. In addition, the California Energy Commission executed a contract with the California Department of Food and Agriculture to establish a hydrogen dispenser type approval and hydrogen fuel quality standards.

2011 Actions: CDFA to develop a one-year timeline for completing the rest of the codes and standards that includes:

- Perform tolerance testing at existing stations

[5] *Driving demand: What can gasoline refueling patterns tell us about planning an alternative fuel network?*, M. Nicholas, UC Davis Institute of Transportation Studies, September 2010

- Determine best practices for testing and evaluating hydrogen gas-measuring devices
- Create a standard for type and field evaluation based on the most efficient, cost-effective, and precise method
- Develop an examination procedure outline for compliance testing and examination for weights and measures officials

Support business model development by the private sector

Progress: CaFCP initiated a series of meetings with people in the traditional and alternative fuel businesses to learn how hydrogen can become a future profit center. CaFCP has also been evaluating existing business reports to understand how best to analyze and present the business case for selling hydrogen as a retail fuel. The International Partnership for Hydrogen and Fuel Cells in the Economy, in conjunction with the National Renewable Energy Laboratory and the California Fuel Cell Partnership, held workshops to identify early market fuel infrastructure options.

2011 Actions: In early 2011, CaFCP and SIGMA, a membership organization of independent retail fuel marketers, began a joint workgroup to better understand the potential business case of hydrogen dispensers in retail fuel stations. CaFCP will also complete a report that uses UC Davis and UC Irvine costs analyses. NREL will hold an additional workshop with station equipment providers to better identify component cost targets and needs for R&D. With this information, CaFCP aims to identify new funding models to transition away from year-to-year government co-funding.

Support early market communities

Progress: Through outreach, education and training, CaFCP helps speed the permitting and construction process of hydrogen stations in the first communities. CaFCP members and staff met with many state and local elected officials in the early market areas to help them understand the benefits of bringing fuel cell vehicles into their communities. CaFCP also conducted first responder training, permitting workshops and business breakfasts in the Los Angeles and Orange County areas.

2011 Actions: Target education and training in the early market communities that are receiving their first hydrogen demonstration stations this year. The goal is to provide information and hands-on experience to officials and residents to ensure that the planning and permitting processes move quickly and smoothly.

Progress must continue if California is to retain leadership in fuel cell vehicle commercialization, bringing environmental and economic benefits, including a potential 25,000 new jobs that DOE estimates the industry could create.[6]

[6] *Department of Energy. Effects of a Transition to a Hydrogen Economy on Employment in the United States Report to Congress*. July 2008, www.hydrogen.energy.gov/pdfs/epact1820_employment_study.pdf

Conclusion

Hydrogen fuel cell vehicles offer zero-emission vehicle attributes with range, refueling time and performance comparable to current conventional vehicles while using domestic energy sources. FCVs are one of the few vehicle technologies that can meet the demands of a diverse consumer market while significantly reducing greenhouse gas emissions and local air pollutants and diversifying our energy sources. Hydrogen is a domestically produced low-carbon fuel and has demonstrated the ability to be a zero-carbon fuel when produced from renewable resources.

Commercializing fuel cell vehicles is a dynamic and challenging process. Actions and priorities will change as deployment proceeds, requiring refinements and adjustments as progress is made. This report presents the second such refinement by identifying immediate steps required in 2011 to bring FCVs to the commercial market as part of the portfolio of solutions.

Automakers' plans for commercializing fuel cell vehicles remain strong and consistent with previous years' projections, even as some OEMs begin to roll out other advanced technologies. Many automakers have stated that fuel cell vehicles are the ultimate solution and vital to meeting consumer expectations for zero emission vehicles.[7] By 2017, more than 50,000 fuel cell vehicles are expected to be on California roads. The FTA recently awarded $16.6 million in grants to help speed commercialization of fuel cell buses.[8]

Building clusters of stations in early market communities is the right strategy to provide benefits of customer convenience, reduced operational costs and ease of transferring experience from one location to another. UC Irvine's STREET model shows that eight hydrogen stations clustered in the Irvine area can match the level of service that the existing 34 retail gasoline stations provide.[9] While initially the stations will be able to provide more hydrogen than customers demand, as the number of vehicles increases from hundreds to thousands the stations will be ready to meet the increased demand.

Current station deployment can work for hundreds of FCVs, but there needs to be a fundamental increment in infrastructure development and sustainability in the longer term to allow automakers to go from thousands to tens of thousands of FCVs. Uncertainty about stakeholders' ability to overcome this hurdle remains high and is the main challenge in the years to come. Funding mechanisms, retail sales of hydrogen, cost-effective renewable hydrogen and synchronizing government regulations around low-carbon fuels and zero-emission vehicles are as necessary for commercialization as reducing costs and improving durability.

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[7] *Toyota Advances Hydrogen Fuel Cell Plans Amid Industry's Battery-Car Push*, Bloomberg, January 12, 2011 http://www.bloomberg.com/news/2011-01-13/toyota-advances-hydrogen-plans-amid-industry-s-battery-car-push.html
Mercedes-Benz Brings the Latest Fuel Cell Fleet to the USA, Daimler press release, November 18, 2010 http://www.daimler.com/dccom/0-5-633234-1-1348590-1-0-0-0-0-0-9293-7145-0-0-0-0-0-0-0.html
Big three Japanese carmakers in 'green' push, Financial Times, January 13, 2011 http://www.ft.com/cms/s/0/ac949ba6-1f44-11e0-8c1c-00144feab49a.html?ftcamp=rss#axzz1Bya2M4Vm
Honda president Ito says fuel cell vehicle is ultimate solution, Detroit Auto Show January 11, 2011 http://hondanews.com/channels/corporate/releases/a54bfbfb-5b9b-2574-9eba-b7004c34ba4b?query=ito+fuel+cell
Hyundai Details Global Fuel-Cell Vehicle Plans, Edmunds Inside Line, October 15, 2010 http://www.insideline.com/hyundai/hyundai-details-global-fuel-cell-vehicle-plans.html
GM Fuel-Cell System Edges Closer to Reality, Edmunds Inside Line, March 2010 http://www.insideline.com/chevrolet/equinox/gm-fuel-cell-system-edges-closer-to-reality.html

[8] http://www.fta.dot.gov/news/news_events_12231.html

[9] *Systematic planning to optimize investments in hydrogen, infrastructure deployment,* Shane D. Stephens-Romero, et al., International Journal of Hydrogen Energy 2010

Other technologies benefit from the progress of automotive fuel cells. Fuel Cells 2000's report *The Business Case for Fuel Cells*[10] profiles 38 nationally recognized companies, including Coca-Cola, Staples, Wal-Mart, Whole Foods, Hilton Hotels and Sysco that have ordered, installed or deployed more than 1,000 fuel cell forklifts, 15 MW of power from stationary fuel cells and 600 fuel cell units at telecom sites.

California is a world leader in fuel cell vehicle demonstration and hydrogen infrastructure development, which has created jobs and new businesses in the ever-growing green technology sector. The state is positioned to continue its leadership by successfully initiating the commercial launch of hydrogen fuel cell vehicles as a part of the transition to electrification of the fleet.

[10] *The Business Cars for Fuel Cells* www.fuelcells.org/BusinessCaseforFuelCells.pdf

Appendix A

Open and Planned Hydrogen Stations in California

Status		Station	LDV Capacity kg/day	Pressure (H35/H70)
Open		Irvine #1	25	35/70
		Thousand Palms	60	35
		Riverside	12	35
		West Los Angeles #1	30	35
Planned		Burbank	60	35/70
		Los Angeles	60	35/70
		Emeryville	60	35/70
		Fountain Valley	100	35/70
		Harbor City	100	35/70
		Newport Beach	100	35/70
		Torrance	50	35/70
		Westwood	140	35/70
		Oakland (transit only)	0	35
		Santa Monica	100	35/70
		Beverly Hills	100	35/70
		West Los Angeles #2	100	35/70
		Hermosa Beach	100	35/70
		Irvine #2	100	35/70
		Hawthorne	100	35/70
		San Francisco	120	35/70
		Laguna Niguel	100	35/70
		West Sacramento	100	35/70
		Diamond Bar	100	35/70

* Irvine #1 is currently open (25kg/day) with planned upgrade in 2012 (100kg/day)

** Thousand Palms is shared bus and light-duty vehicle station, total capacity 160 kg/day (100kg for buses, 60kg for light duty)

*** Emeryville is a transit and light-duty vehicle co-located station, 60 kg/day capacity represents light duty

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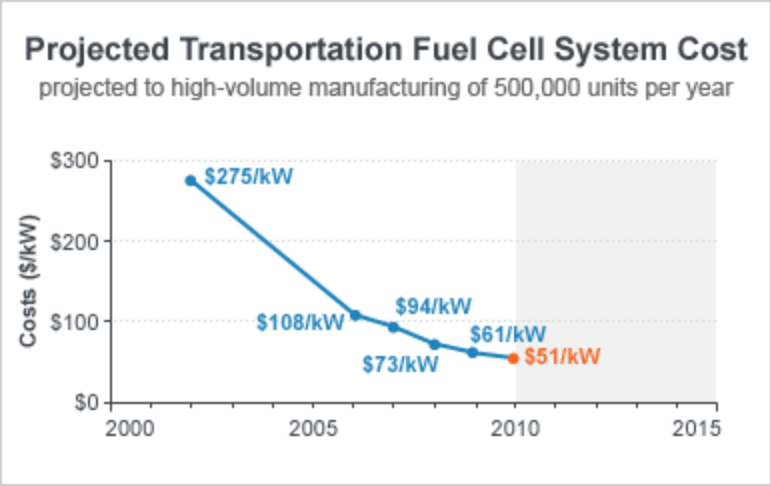
- Hydrogen Production
- Hydrogen Delivery
- Hydrogen Storage
- Fuel Cells
- Technology Validation
- Codes & Standards
- Education
- Systems Analysis

Accomplishments and Progress

The U.S. Department of Energy's (DOE) efforts have greatly advanced the state of the art of hydrogen and fuel cell technologies—making significant progress toward overcoming many of the key challenges to widespread commercialization. These include reducing the cost and improving the durability of fuel cells and improving technologies for producing, delivering and storing hydrogen. DOE has also made major advances by demonstrating and validating the technologies under real-world conditions, supporting early markets through Recovery Act deployments, and leveraging domestic and international partnerships to advance the pace of commercialization. See the program's accomplishments fact sheet.

Reducing the Cost and Improving the Durability and Performance of Fuel Cells



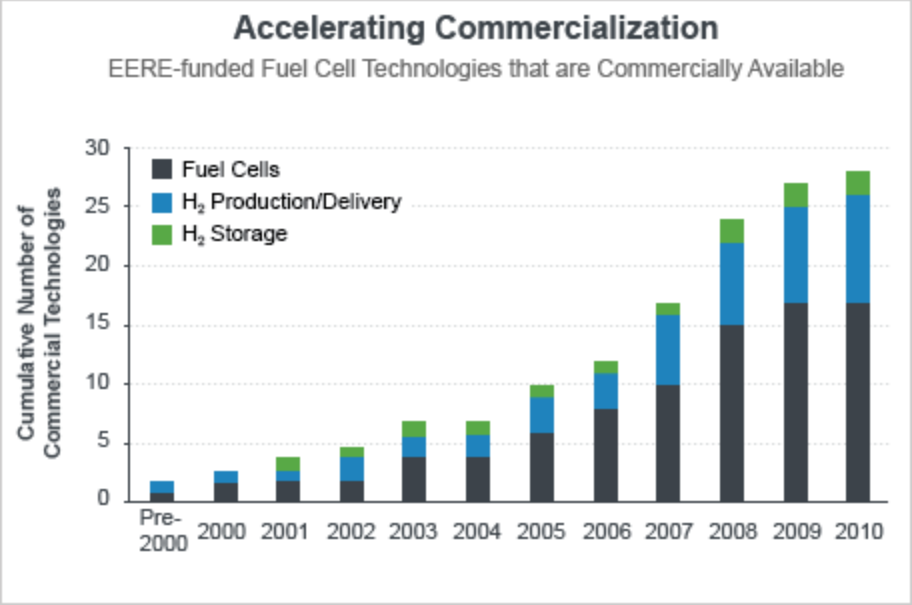
DOE has reduced the cost of automotive fuel cells from $275/kW in 2002 to $51/kW in 2010 and is targeting a cost of $30/kW by 2015.

- **Reduced the cost of automotive fuel cells by 30% since 2008 and 80% since 2002** (from $275/kW in 2002 to $51/kW in 2010, based on projections of high-volume manufacturing costs).

These cost-reductions reflect numerous individual advances in key areas, including the development of a durable membrane electrode assembly (MEA) with low platinum group metal (PGM) content (this MEA simultaneously met the 5,000 hour durability target, with a PGM loading of <0.2 grams of PGM per kW).

- **Demonstrated more than 2500-hour (75,000 miles) durability of fuel cell systems in vehicles operating under real-world conditions, with less than 10% degradation.** This is more than doubled the maximum durability of 950 hours demonstrated in 2006.
- **Improved the performance of stationary fuel cells**, including development of a solid-oxide fuel cell for micro-combined heat and power applications with a 24% increase in system power density, which has enabled a 33% reduction in stack volume and a 15% reduction in stack weight.
- **Developed advanced manufacturing methods and materials** that enabled a 61% decrease in the projected cost of gas diffusion layers since 2008.

Improving Technologies for Producing, Delivering, and Storing Hydrogen



DOE-funded R&D has resulted in nearly 200 patents. And almost 30 hydrogen and fuel cell technologies developed with program funding have entered the market.

Examples include 3M, DuPont, Fuel Cell Energy, Nuvera, Proton Energy Systems, Plug Power, Quantum, UTC, and many others.

Source: Pathways to Commercial Success: Technologies and Products Supported by the Fuel Cell Technologies Program. Pacific Northwest National Laboratory, August 2010.

- **Reduced the projected cost of hydrogen**
    - **Producing hydrogen from natural gas:** Projected costs of hydrogen (assuming high-volume production and widespread deployment) have been reduced to $3.00 per gallon gasoline equivalent (gge)—a cost that is competitive with gasoline.
    - **Producing hydrogen from renewable resources:** Costs have been reduced for several pathways, including wind electrolysis, ethanol reforming, and biomass gasification. Key examples of advances include: reducing capital costs for distributed hydrogen production by water electrolysis by over 35% since 2008 and improving the photosynthetic conversion of sunlight in hydrogen-producing microalgal cultures by up to 300% by minimizing chlorophyll antennae to maximize efficiency.
    - **Delivering hydrogen to the end-user:** costs have been reduced by 30% for tube-trailer delivery of high-pressure gas, 20% for pipeline delivery of high-pressure gas, and 15% for tanker truck delivery of liquid hydrogen.
- **Improved the capacity of hydrogen storage systems**
    - DOE developed a novel "cryo-compressed" tank concept for hydrogen storage and made improvements that increased the gravimetric and volumetric capacity of these systems by 51% and 48% respectively.

      DOE's four centers of excellence have developed materials-based technologies for hydrogen storage—leveraging the efforts of multiple university, industry, and national lab partners.

      > *Among the key accomplishments in materials-based hydrogen storage are the discovery of new materials with more than 50% improvement in capacity since 2004 and the improvement of kinetics for metal hydride storage by a factor of more than 60.*

Conducting Real-World Demonstrations and Technology Validations

- **Deployed 152 fuel cell vehicles and 24 hydrogen fueling stations in learning demonstrations.** The vehicles have traveled more than 2.8 million miles, and the fueling stations have produced or dispensed more than 150,000 kg of hydrogen. These demonstrations have validated the status of several key technologies in integrated systems, operating under real-world operating conditions. Key results include demonstrating fuel cell system efficiency of up to 59% (more than double the efficiency of gasoline internal combustion engines), fuel cell system durability of 2,500 hours (about 75,000 miles) with less than 10% degradation, and a driving range of more than 250 miles between refueling. The program also validated one vehicle that can achieve 430 miles on a single fill of hydrogen.

  > *DOE has also collaborated with the Department of Transportation,*

to collect and analyze data from their fuel cell buses, and the Department of Defense, to validate the performance of their fuel cell forklifts and backup power units.

Funding Early Market Deployments through the American Recovery and Reinvestment Act

Government and Global Partnerships

DOE established the **Hydrogen and Fuel Cell Interagency Task Force** to coordinate federal adoption of hydrogen and fuel cell technology to support commercialization and industry growth.

DOE also works with the **International Partnership for the Hydrogen and Fuel Cells Economy** (IPHE)—a partnership involving 17 countries and the European Commission—to foster international cooperation on R&D, common codes and standards, and information sharing on infrastructure development. In addition, the Department coordinates with more than 25 countries through the International Energy Agency's (IEA) two implementing agreements on hydrogen and fuel cells.

- **DOE awarded $42 million under the American Recovery and Reinvestment Act to accelerate the commercialization and deployment of fuel cells**—These efforts will deploy up to 1,000 fuel cells, primarily in backup power and forklift applications. Success in these early markets will help pave the way for longer term success of fuel cells in larger markets, such as transportation.
    - Industry participants provided approximately $54 million in cost-share funding—for a total of nearly $96 million. These funds are helping to deploy fuel cells across several industries, including bringing several high-profile companies into the fuel cell arena, such Sprint, AT&T, FedEx, Whole Foods, Sysco, Wegmans, and Coca-Cola.
    - These projects are also supporting fuel cell manufacturers like ReliOn, Plug Power, and Nuvera—helping to create fuel cell jobs and keep these jobs in the U.S.
    - As of December 2010, 60% of these funds have been spent and put into the market, and we exceeded our 2010 goal for deployments by 90%, with 300 fuel cells already delivered.

DOE Fuel Cell and Hydrogen Program Plan Infrastructure Initiative

The Program Plan needs to be updated to more accurately reflect the status of hydrogen fuel cell vehicle technology, and the industry and their needs. In particular, it is imperative to establish a Vehicle Market Transformation program to support the industry to deploy 4,000 HFCVs by 2014 and 50,000 HFCVs by 2017 in the United States in concert with other foreign infrastructure programs. This imperative is in recognition that electric platform vehicles, both HFCVs and PHEVs, among DOE programs address not only climate change, but also our dependence on foreign oil most directly and can provide results by 2018 or sooner. Hydrogen as a fuel produced from natural gas, coal and/or biomass from abundant national resources can in particular establish the United States as a major exporter of fuel with significant balance of payment benefits.

The following initiative is proposed to accomplish this goal:

A Vehicle Market Transformation program is established as an activity in the Technology Validation program within the Fuel Cell and Hydrogen Program. The Department of Energy should issue a solicitation in FY 2012 to support a vehicle market transformation infrastructure activity within the hydrogen and fuel cell program. The solicitation shall provide for government cost share of 50% for the requisite hydrogen infrastructure for 3,000 hydrogen fuel cell vehicles by 2014, and 30% cost share for infrastructure for an additional 50,000 hydrogen fuel cell vehicles by 2017. The Department upon the award of the contracts shall inform the Congress of the expected costs for the program during budget years 2013 thru 2014 for the expected 3000 hydrogen fuel cell vehicles and budget years 2014 thru 2018 for the expected 50,000 hydrogen fuel cell vehicles. $5 million of the $10 million Technology Validation Administration's request within the Fuel Cell program is hereby appropriated in FY 2012 to initiate the vehicle market transformation activity for hydrogen infrastructure deployment.

Figure 1
Current Supply Chain for Delivered Hydrogen to Refueling Stations

AIR PRODUCTS

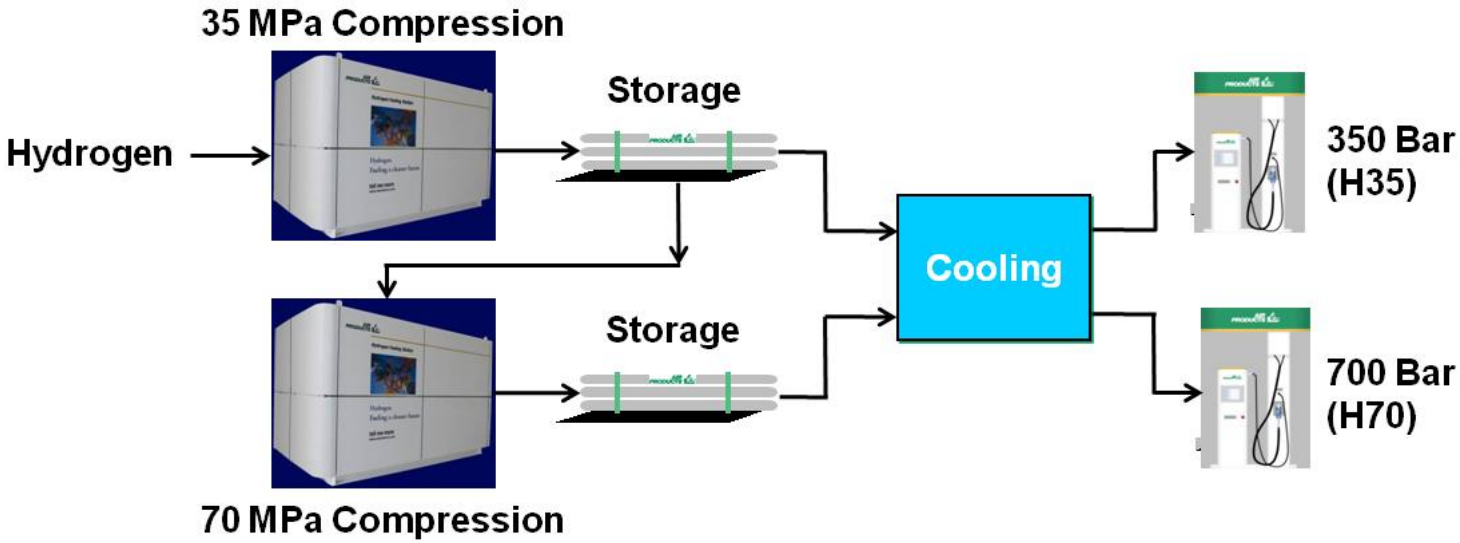


Figure 2
Conventional Light-Duty Hydrogen Station (delivered product)

AIR PRODUCTS

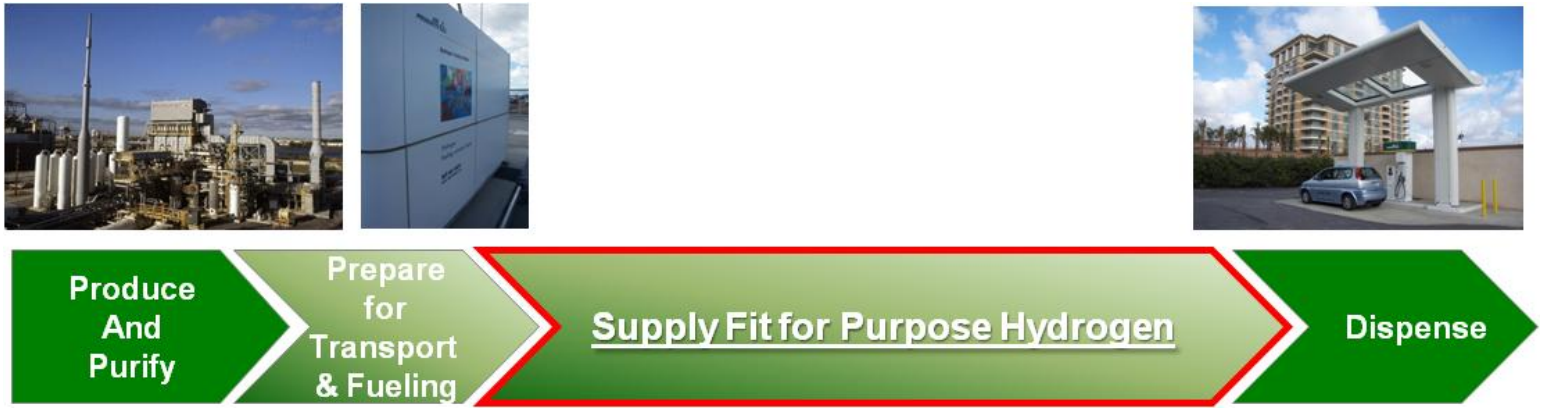
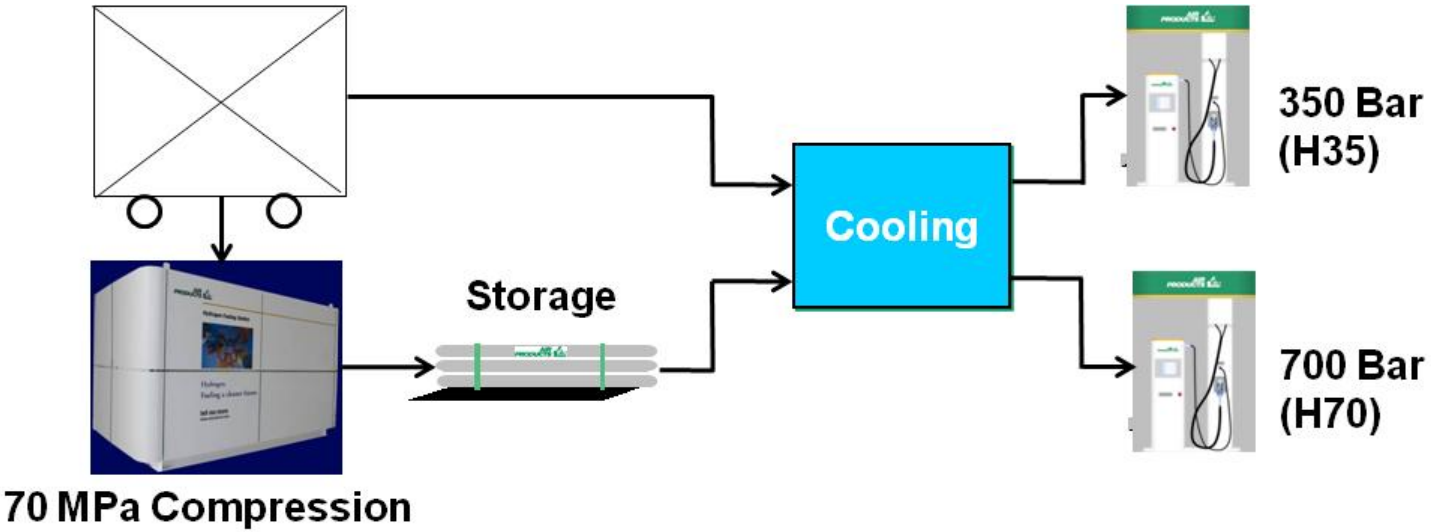


Figure 3
Proposed Low-Cost Supply Chain for Delivered Hydrogen to Refueling Stations (Patents/Patents Pending)

AIR PRODUCTS



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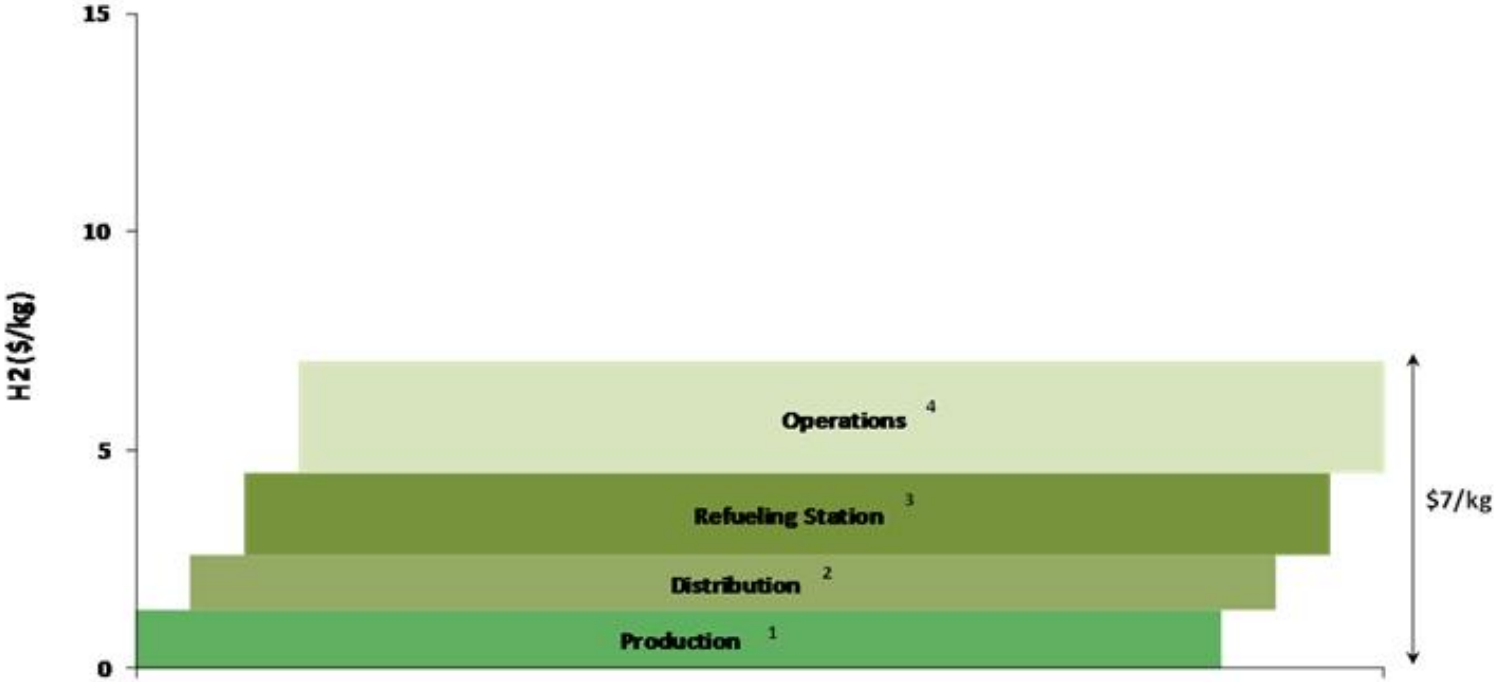


1- NREL, Ruth et al 2009. Central SMR production
2- US DOE 10/2010. Infrastructure (Station with Tube Trailer Delivery)
3- APCI 2011 (Hydrogen refueling station under CEC 2010 program)
4- $250k/yr: Based on UCD 2011 Hydrogen Station Analysis plus CA Excise Tax

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

AIR PRODUCTS

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.

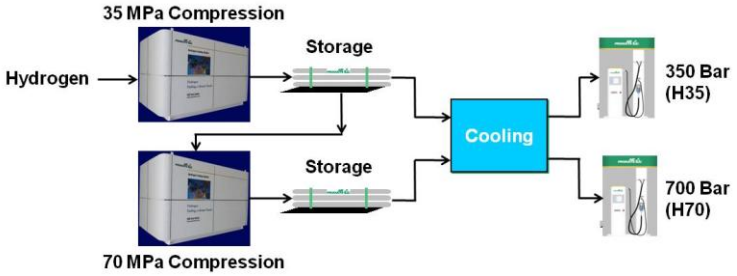


Figure 2 – Conventional Light-Duty Hydrogen Station (delivered product)

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.

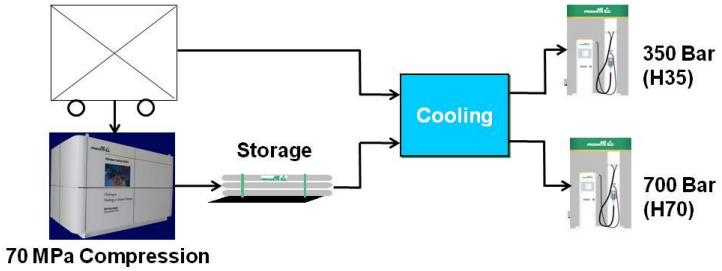


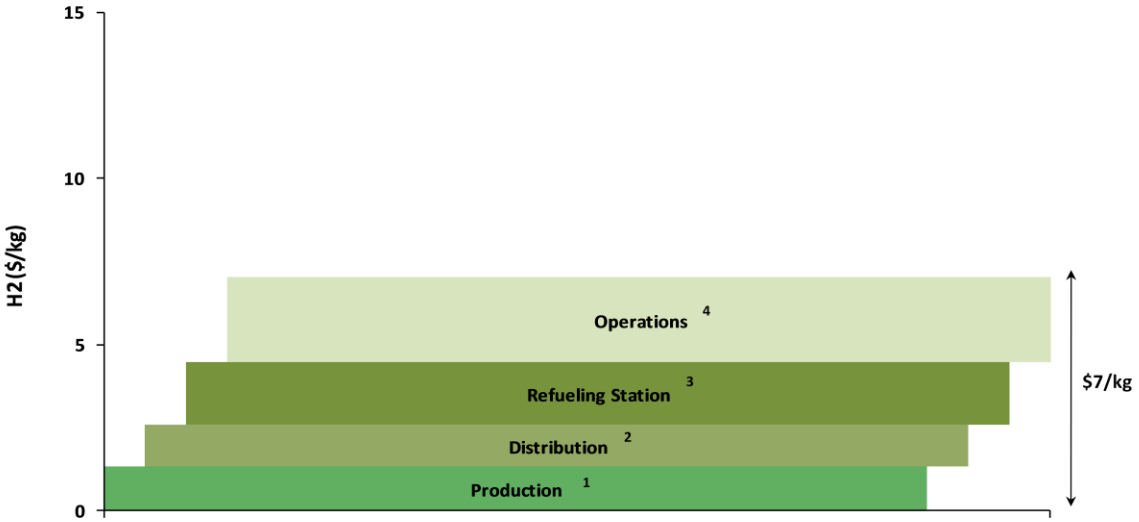
Figure 4 – Proposed H35/H70 Light-Duty Hydrogen Station (delivered product)

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
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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.

Are plug-in/battery electric vehicles more market ready than hydrogen fuel cell vehicles?

By Sigmund Gronich, PhD, President, Charisma Consulting

The U.S. Department of Energy (DOE) Fuel Cell Technologies Program states: "The mission of the program is to enable the widespread commercialization of fuel cells in diverse sectors of the economy—with emphasis on applications that will most effectively strengthen our nation's energy security and improve our stewardship of the environment. "

In addition, it is reported in the 2011 Vehicle Technologies budget submission that President Obama has stated, "Increasing fuel efficiency in our cars and trucks is one of the most important steps that we can take to break our cycle of dependence on foreign oil. It will also help spark the innovation needed to ensure that our auto industry keeps pace with competitors around the world." The following goals are listed:

- **Within 10 years (by 2020) save more oil than currently imported from the Middle East and Venezuela combined (about 3.5 mbpd);**
- **Invest in developing advanced vehicles, including the development and deployment of enough advanced battery manufacturing capacity to support 500,000 plug-in hybrid electric vehicles a year by 2015;**
- **Reduce the production cost of a high energy battery from $1,000/kWh in 2008 to $300/kWh by 2014, enabling cost competitive market entry of PHEVs (Battery/Energy Storage).**

The latter statement is supported by the Multi-Path Transportation Futures Study (Plotkin et al) conducted by Argonne National Laboratory for DOE. It is made on the basis of a literature review case for gasoline at $3.15/gallon but where the price of future fuel costs are discounted at 4%/year over the life of the vehicle. This is called a societal model which is defined as the buying public making their vehicle purchase decisions based on societal needs. Two other discount rates are explored at 10% and 20% which more typically represent actual public and business decision making. The automobile industry feels the public makes their vehicle purchasing decisions based on receiving a fuel payback in three years. In the literature review cases for 40 mile electric range plug-in hybrid vehicles, the battery is estimated at $300/kWh (the above 2014 target) and for fuel cell vehicles the fuel cell system is $50/kW and the storage system is $15/kWh (2010 and 2009 targets). Both vehicle systems are commercially viable with gasoline at $3.15/gallon and the "societal" assumption of a 4% discount rate. In fact the hydrogen fuel cell vehicle is slightly better than the 40 mile plug-in hybrid vehicle and is a break even proposition at the 10% discount rate.

Yet in DOE's budget submission for the Hydrogen Program there is no vehicle market transformation activity and the battery program receives significant development funds and $2.5 billion of American Recovery and Reinvestment Act funding for battery manufacturing capability in the U. S. The only market transformation activity funded in the hydrogen program

budget is for stationary power systems even though only programs dedicated to transportation are able to directly address global climate change issues, and the dependence of this nation on foreign oil imports for the foreseeable future.

The Obama administration has implemented a vigorous CAFÉ standard schedule to 35.5 miles per gallon by 2016 and has maintained the ethanol tax credits as the initial step to decrease our dependence on foreign oil. However, these actions are recognized as only initial steps directed to the 10 year goal, and that electric platform vehicles will ultimately be necessary to make significant reductions in greenhouse gas emissions and eliminate the country's dependence on foreign oil. Both plug-in and hydrogen fuel cell vehicle market transformation strategies need to be deployed aggressively. In that regard, the statements issued by the DOE concerning a long-term prognosis for hydrogen fuel cells is not in concert with what industry leaders are saying. As part of a letter of understanding signed by seven major automobile manufacturers: **"Based on current knowledge and subject to a variety of pre-conditions, OEMs strongly anticipate that from 2015 onwards, a quite significant number of hydrogen fuel cell vehicles could be commercialized at a few hundred thousand (100,000) units ---- on a worldwide basis."** In the United States, California has implemented a Zero Emission Vehicle (ZEV) regulation for 7500 ZEVs by 2014 and 25,000 to 50,000 ZEVs by 2017 which is in concert with the OEM's position.

Whether plug-in hybrid or battery electric vehicles will precede or follow HFCVs is immaterial at this point in time. Both are going to be more expensive than gasoline cars for now and the near future. The truth of the matter is that the more expensive platforms will not be competitive in the marketplace with gasoline at $3.15/gallon. The question is when will the price of oil rise to allow them to be cost competitive in the marketplace? Electric platform vehicles are going to be required not only to forestall global warming but for the future national and economic security of the U.S. The ZEV mandate is an important regulation and appears to match what several of the automobile manufacturers anticipate and is in concert with the German initiative. National policy needs to be instituted to support that effort. It is not a state policy but the beginning of a national deployment strategy to keep the U.S. in step with Europe, Japan and Korea as an international partner.

National Research Council Report

The National Research Council's National Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies Research recently extended their scope of activities and published their assessment for the Transitions to Alternative Transportation Technologies--Plug-in Hybrid Electric Vehicles. Their assessment concluded the following:

1. Lithium-ion battery technology has been developing rapidly, especially at the cell level, but costs are still high, and the potential for dramatic reductions appears limited.

2. Costs to a vehicle manufacturer for a PHEV-40 built in 2010 are likely to be about $18,000 more than an equivalent conventional vehicle, including a $14,000 battery pack. The incremental cost of a PHEV-10 would be about $6,300, including a $3,300 battery pack.

3. PHEV-40s are unlikely to achieve cost-effectiveness before 2040 at gasoline prices below $4.00 per gallon, but PHEV-10s may get there before 2030.

5. --- PHEV-10s will reduce oil consumption only slightly more than can be achieved by HEVs

6. PHEV-10s will emit less carbon dioxide than non-hybrid vehicles, but more than HEVs after accounting for emissions at the generating stations that supply the electric power.

The above conclusions are not in concert with President Obama's initial policy proposal to build a million electric vehicles by 2015 or establish the manufacturing capacity for 500,000 units by then. Such a program would be costly and ineffective as neither the PHEV-10 nor the PHEV -40 would be cost effective vs the hybrid vehicle by that time. A comparison was made in that report to the potential marketability of the Hydrogen Fuel Cell Vehicle (HFCV).

The conclusion reached by the panel was that the HFCV could be market ready by 2023 if gasoline prices were at $3.65/gallon. In addition the market investment and time is less for the fuel cell vehicle than the electric vehicles. Most importantly, their assessment indicated that there was a hydrogen success case in 2023 for the HFCV. DOE needs to implement a vehicle market transformation program to meet that target date.

Breakeven year	2028 PHEV-10 (maximum practical)	2040 PHEV-40 (maximum practical)	2023 HFCV (hydrogen success)
Vehicle subsidy to breakeven year	$33 billion	$408 billion	$40 billion
Infrastructure subsidy	$20 billion (for home fueling)	$20 billion (for home fueling)	$8 billion
GHG reductions by 2050	- 29%	-36%	-59%
Oil Reductions by 2050	-67%	-83%	-100%

It is interesting to note that the infrastructure costs are less for the HFCV vs either plug-in hybrid option. And that the infrastructure costs represented for the electric vehicle option is for home refueling only. According to D W Crane, President and CEO of NRG Energy, Inc. in his testimony before the U.S. Senate Committee on Environment and Public Works, Oct. 28, 2009

(Electrification Roadmap), an additional $90 to $200 billion would be necessary to electrify roadside stations. Now much of that cost can be supported as well as the cost for hydrogen stations as commercial enterprises once we proceed beyond an introductory period. In a comparison of infrastructure costs reported by Thomas, he indicated that once any given region has thousands of HFCVs deployed, the average cost of the hydrogen infrastructure per vehicle would be approximately $955: 2,300 HFCVs supported by each fueling pump costing $2.2 million. This compares with $500 to $2,150 per BEV just for home charging outlets, and another $250 to $1,000 per BEV for the public stations recommended by the Electrification Coalition. Thus the total electricity infrastructure cost would be in the range between $750 to $3,150 per BEV (excluding transformer upgrades and any added electrical generation for daytime charging), while the total hydrogen infrastructure cost is estimated at approximately $1,000 per HFCV.

Lastly, it is also interesting to note that the HFCV and the PHEV -10 share equivalent development costs, but the NRC assessment that it would provide little benefit over hybrid vehicles would challenge the judgment to proceed with the more costly vehicle. There have been several challenges to the NRC estimates as being too conservative on battery costs and improvements in time. The NRC study used a 50% usable/nameplate battery energy which is today's technology and included the impact of battery fade, and the DOE uses a 70% usable/nameplate battery energy. So I will use the more optimistic DOE assessments for the status of the technology for the comparisons to the HFCV in this paper.

HFCV targets for marketability

There are several misconceptions concerning the HFCV that are based on achieving targets that would make it competitive to today's gasoline vehicles. There is little possibility of doing that. Instead, a more realistic assessment is needed that is consistent with the NRC's conclusion of achieving commercial viability by 2023 to 2025 which was based on the low EIA 2009 gasoline projected prices. The EIA 2010 forecast for motor gasoline prices (from table A 12) is:

Year	2015	2020	2025	2030	2035
Motor Gasoline Price/gallon (low)	$3.07	$3.34	$3.49	$3.68	$3.91
Motor Gasoline Price /gallon (high)	$3.42	$4.08	$4.74	$5.55	$6.57

The low forecast is based on a 1.0% annual increase in the cost of imported crude oil that leads to a resultant $104/barrel of oil by 2025 and a consequent .7% annual growth rate in the price of gasoline with a price for gasoline at $3.49. The high estimate is based on a 3% annual growth

rate in the price of imported crude oil and a 2.6% annual increase in motor gasoline price with a resultant price for gasoline of $4.74. The imported crude oil price is expected to be $141/barrel for this scenario. There are several sources that document the depletion of the existing major oil fields with the need for significant water injections (30%) to maintain oil production in early developed and huge fields (i.e., Ghawar in Saudi Arabia) and in spite of more sophisticated exploration and drilling techniques, smaller fields are being found today (Roberts). Also, most experts predict, as does Jim Lentz , Toyota Motor U.S.A. Sales President, who said: "Within the next 10 – 20 years, we will not only reach peak oil we will enter a period where demand for all liquid fuels will exceed supply." Thus, considering the expected rising demand for oil from Asian nations and the expected peak production of oil by 2015-2020, one might believe that the high EIA estimate is the more valid one, but for the purposes of this analysis, I assume an average motor gasoline price estimate which in 2025 would be $4.11/gallon of gasoline. It seems eminently reasonable to proceed with an advanced vehicle development program considering the major uncertainties associated with shrinking provable reserves and increasing demands for oil.

Where do we stand in the development of Hydrogen Fuel Cell and Plug-in Hybrid Vehicles?

I attended the DOE Hydrogen and Vehicle Technologies Annual Merit Review May 19 to 21, 2009. I attended the plenary and technical sessions on analysis, fuel cell systems, battery systems, hydrogen storage, and technology validation.

Sinha, et al (TIAXLLC) and James, et al (DTI) presented their 2008 cost projections for fuel cell systems at $57/kw and $73/kw respectively. The DTI model was used with accepted catalyst loadings and membrane specific power estimates for the 2008 technology assessment to arrive at a composite cost estimate of $73/kw (Papageorgopoulus). Debe (3M) presented results for 2009 membranes which showed an ability to achieve a lower catalyst loading below .2 mg/cm2 and thin nanotechnology membranes that should permit a higher power density. He also reported demonstrating 7300 hours lifetime in the laboratory for these membranes. Recently, James and Kalinoski (DTI) updated their cost projections in 2009 for the mass production of fuel cells and reported a peer–reviewed $61/kw production cost for the fuel cell systems (500,000 units annual production) with improvement potential to achieve $45/kW to $50/kW.

Dillich (DOE) and Lasher, et al (TIAXLLC) presented their cost projections for hydrogen storage tanks at $15/kWh for 5000 psi tanks and $23/kWh for 10,000 psi tanks. Liu (Quantum) presented their study of optimal flexible fiber placement and commercial filament winding, and improved manufacturing machinery for low cost hydrogen storage vessels but did not present any cost results. The project is due to be completed in 2011. Subsequently Lasher, et al (TIAXLLC) published expected storage system costs of $13.4/kWh and $17.4/kWh for the two pressures respectively.

Howell (DOE Vehicle Technologies program) reported on the status of Lithium Ion batteries. He presented a summary chart for a 10 mile range battery that is currently at 3+ year lifetime but is projected to have a 10+ year lifetime by 2012 and a cost projection of $500/kWh by 2012. This will be able to be achieved by American companies as the result of the American Reinvestment and Recovery Act expenditure of $2.5 billion. Barnett (TIAXLLC) presented a cost study of a 5.5 kWh usable energy battery at the end of life. He investigated 0% and 30% fade. With 30% fade the battery size is 9.8 kwh nominal to deliver 5.5 kwh at end of life. At a State of Charge range of 10-90% the battery size is 6.9 kWh nominal to deliver 5.5 kWh usable. PHEV battery configurations modeled in this study resulted in battery costs of about $360/kWh manufactured in the U.S. and ranged from $264/kWh to $710/kWh depending on assumptions of where manufactured, speed of manufacture and fade. Howell projected a 40 mile range battery by 2014 with a cost projection of $300/kWh. Subsequently, Nelson, et al (ANL) examined four battery formulations and arrived at a manufacturer's cost of production at $3400 or about $300/kWh of usable power based on a 70% state of charge.

Keith Wipke (NREL) presented the latest data from the Hydrogen Technology Validation program. Some second generation vehicle data showed a significant improvement in the range of the vehicles due to the use of 700 bar storage and the window sticker value was 200 to 250 miles. The 250 miles was the 2009 DOE target. 80% of the fuelings were at less than 50% of the dynamometer range due to lack of hydrogen infrastructure or fear of running out of hydrogen. Some generation 1 fuel cell stacks reached 2000 hours but the average was about 800 hours. Stacks that had 4 trips (start ups) per hour demonstrated lifetimes of 0 to 1000 hours. Stacks that had 2 trips per hour demonstrated 1750 to 2000 hours durability. Generation 1 and 2 vehicles were significantly below 2010 DOE targets in specific power and power density (50 to 60% for either). Most of the infrastructure safety reports were non-events and were alarms only.

Based on the above information presented at the Annual Review Meeting and the 2011 DOE budget submission, the following assessment was made concerning the hydrogen fuel cell and plug-in hybrid vehicle programs over the next seven years. In reality electric platform vehicles are going to be more expensive than gasoline vehicles and neither extended range batteries nor fuel cell vehicles are going to be commercially viable for at least ten years. And it would be expensive and premature to proceed with 1 million plug-in hybrids by 2015 considering the projected cost of battery technology and the resulting high cost of the vehicles. Furthermore, both vehicles need to meet 2015 targets that make them market ready if mass produced, but those targets need to be re-assessed to be compatible with more expensive vehicle platforms that can be expense neutral on a cents/mile basis consistent with the expectation of more expensive fuels by 2023-2025.

Four Misconceptions about Hydrogen Fuel Cell Vehicles

1. Hydrogen fuel cell vehicles are too expensive

DOE/industry targets for 2015 are set at $30/kw for fuel cell systems and $2/kWh for hydrogen storage systems to make them competitive to gasoline vehicles today. The fuel cell target is unlikely to be achieved and the storage target is beyond any reasonable expectation. However, as reported in the most recent assessment of the mass manufacturing estimate for fuel cell systems of $61/kW (James & Kalinoski, DTI) and the expectation with some further system improvements of achieving $45/kW to $50/kW, the expected incremental cost (not price) above an advanced gasoline vehicle according to Kromer & Heywood (2007) would come to $1800 based on $50/kW. Durability is still an issue that can affect cost. Two stacks have demonstrated 1750 to 2000 hours duration as part of the technology validation program, but 5000 hours are required for 150,000 mile vehicle lifetimes. Given the Debe (3M) laboratory results for their new membranes one should expect longer lifetimes in the next generation fuel cells. When gasoline is more than $4/gallon that incremental cost can be recovered and the cents/mile would be equivalent to less expensive gasoline vehicles by 2025. This suggests that the DOE target be specified for 2025 commercialization and be established at $45 to$50/kW.

2. Breakthroughs are needed in hydrogen storage

The most recent report by Lasher, et al (TIAXLLC) reported 5000 psi composite tanks at $13.4/kWh and $17.4/kWh for 10,000 psi composite tanks. These are slightly better than reported at the 2009 Annual Merit review. The DOE target for the hydrogen storage system is $2/kWh to make them compatible to gasoline tanks. That will never happen. We need new targets based on the expected marketplace by 2025.

The Department of Energy has monitored and evaluated real-world performance of 140 fuel cell vehicles which have safely accumulated over 85,000 hours of operation and 1.9 million

miles. Second generation FCV's exceeded the 250-mile DOE range target for 2008. Hydrogen storage tanks projected to have 10+ year lives.

The figure above shows two vehicles that have achieved greater than 250 mile range. The Honda Clarity achieved 280 mile EPA rated range with 5000 psi tanks for a vehicle that attained 70+ mile/gallon. The Toyota Highlander achieved 480 mile range based on Japanese mileage tests with 10,000 psi tanks. With the tanks at 5000 psi, a range greater than 300 miles would still be probable for the Toyota vehicle. The real issue for hydrogen storage is for the Civic and smaller class vehicles. Larger vehicles (Accord and greater) can achieve 280 mile range with 5000 psi tanks especially for HFCVs that can attain 60 to 75 miles/gallon. The cost of 10,000 psi tanks may make the HFCV non-competitive for a longer time frame. Industry may need to consider 5000 psi, intermediate pressure tanks or cryo-compressed tanks. And, I suggest a target of $12/kWh be established for future 5000+ psi tanks with a more optimum filament winding program.

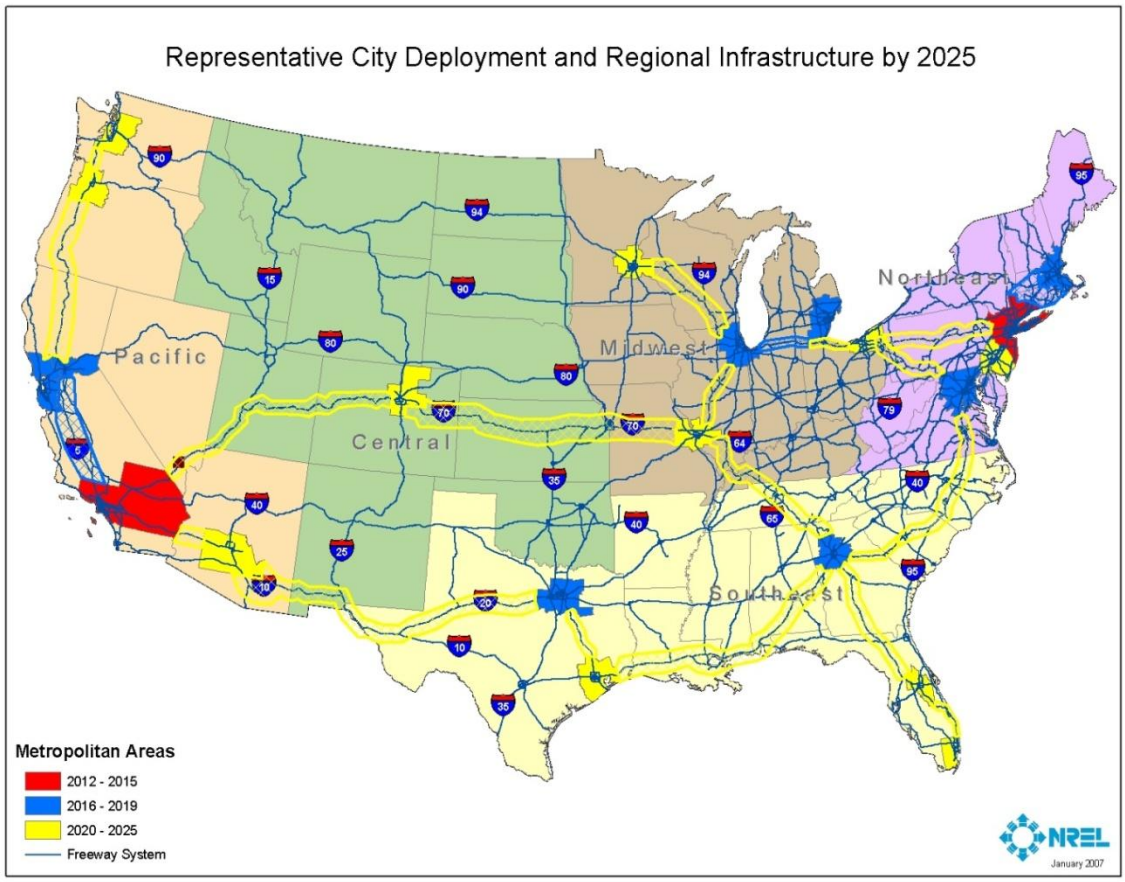
3. It is inefficient to make hydrogen.

As a transition strategy, DOE compared "well -to-wheel" emissions of GHGs from various pathways, and the results show that FCVs using hydrogen from natural gas emit 60% fewer GHGs than today's gasoline vehicle, and 35% fewer GHGs than natural gas vehicles. FCVs using hydrogen from biomass emit 60% fewer GHGs than a PHEV running on cellulosic ethanol.

Hydrogen produced from coal, natural gas or biomass with CO2 capture and sequestration can be dispensed for about $4 to $5/kg, (James, et al (DTI)) comparable to $2 to $2.50 per gallon gasoline (untaxed). Per vehicle, hydrogen stations cost about the same as home charging. These fossil resources are estimated to be 12 times the expected provable oil reserves. And considering major coal resources are located in the United States, Australia, Russia (Europe), China and India, the very nations expected to be the primary fuel consumers, such a prospect can have major energy security and balance of payment implications.

4. Building a hydrogen infrastructure is too difficult and costly

A study by Melendez, et al (NREL) has shown that it is possible to roll-out infrastructure regionally concurrently with vehicle deployment to maximize utility and minimize costs for early markets. In assessing a transition to hydrogen fuel cell vehicles, the National Research Council modeled a fuel production pathway to supply fuel for millions of vehicles through 2025 by starting in LA and NYC. The selections of LA and NYC were done on the basis of city population demographics best able to support early deployments with a reasonable infrastructure network. From those cities, HFCVs would be introduced in Chicago/Detroit, San Francisco, Philadelphia, Boston and Dallas or Houston by 2016 to 2019. Fourteen additional cities would be subsequently added by 2025 as well as 280 stations along major interstate highways.



Hydrogen is a technology that is going to need both regulation and support to be introduced into the United States marketplace. Regulation is going to be required in order to give the fuel suppliers a better understanding as to when the demand is going to be there. It would be significantly riskier without some sort of a representative guide as to when the vehicles would show up to warrant the capital investments necessary to deploy the infrastructure. It currently is the greatest deterrent to the deployment of the infrastructure.

The Zero Emission Vehicle Mandate

- 7500 Zero Emission Vehicles by 2014 (can be Battery Electric (BEV) or Hydrogen Fuel Cell (HFCV) Vehicles
- 25,000 to 50,000 ZEVs by 2017
- Industry survey by California Fuel Cell Partnership indicates up to 4200 are likely to be HFCVs to be provided by several OEMs and the remainder would be BEVs
- Need both stick (ZEV mandate) to line up industry efforts and send signal for infrastructure requirements
- And carrot of 50/50 cost sharing between industry and government for vehicles and infrastructure, $8000 vehicle tax credit and existing investment tax credits thru 2016.

Fortunately, the California Zero Emission Vehicle mandate which includes New York State as a participating member does provide the regulation at a level that is consistent with a logical path to several million HFCVs worldwide by 2025 with federal support to introduce these vehicles. The table above describes the current ZEV mandate which is going to be modified this coming December. The mandate for 2012 to 2014 is fixed, but it is likely to be modified and extended from 2015 onwards.

In a similar attempt to encourage the development of a network of stations in Germany, seven automobile manufacturers (Daimler, Ford, GM/Opel, Honda, Toyota, Hyundai/Kai and Renault/Nissan) signed a letter of understanding that subject to market uncertainties, the "OEMs strongly anticipate that from 2015 onwards a quite significant number of hydrogen fuel cell vehicles could be commercialized. This number is aimed at a few hundred thousand (100,000) units ---- on a worldwide basis." "Therefore, a hydrogen infrastructure with sufficient density is required by 2015 ----- to be built-up from metropolitan areas ---- into an area-wide coverage." This approach is less direct than the ZEV mandate but two oil companies have expressed an interest in deploying the necessary infrastructure (Total and Standard Oil of Norway).

Germany, Japan and Korea have already instituted such efforts. The price of gasoline is already $6 to $8/gallon in those countries so one can expect the HFCV to be economically viable sooner in those countries. Irv Miller, Toyota Motor Systems group vice president of environmental and public affairs, stated that: "We plan to come to market in 2015, or earlier, with a reliable and durable, with exceptional fuel economy and zero emissions, at an affordable price." Honda plans to offer hydrogen powered cars at costs comparable to mid-size gasoline autos by 2020. Based on the California Fuel Partnership Action Plan their members indicated that they would provide about 4000 of the 7500 ZEVs as HFCVs. From public statements by the automobile manufacturers, a reasonable assumption is that Toyota, Honda, Daimler, Hyundai and GM would respond with HFCVs and Ford, Chrysler and Nissan/Renault would provide battery electric cars. According to the ORNL model (Greene, et al), if Toyota and three other automakers were to produce 10,000 HFCVs each over the next three years (2015-2017) which is consistent with a ZEV mandate for that period, the HFCV production costs would be about $60,000 if there is a worldwide program. That doesn't seem to meet the definition of an affordable vehicle or Toyota may have made more significant progress than previously thought or plan to internally support the price. However, with a 50/50 cost share of the HFCV and an $8000 tax credit, an affordable option can be introduced to spur consumer demand. Also importantly would be the necessity for the infrastructure deployments for that introductory period.

Greene (ORNL) delineates the required investments that the government needs to make in order to achieve three scenarios of 2, 5 and 10 million HFCVs by 2025. The larger scenarios are similar to the NRC report of about $40 billion being required. However, I propose an option to deploy 1 million HFCVs in the U.S. with the expectation that four million more vehicles will be

deployed worldwide. Such an approach would lead to an $8 billion government cost over 10 years. Thus as part of an international effort the cost to the U. S. taxpayer would be less.

Vehicle Ownership Costs

I want to now present the prospects of the hydrogen fuel cell vehicle being cost competitive to advanced gasoline vehicles by 2025. DOE and the industry have always developed hydrogen fuel cell vehicle targets on being competitive in the marketplace today. On that basis they developed 2015 fuel cell and storage systems cost targets of $30/kW and $2/kWh respectively. These targets are not realistic and especially true for the storage system. I propose that targets of $45 to $50/kW and $12/kWh respectively are much more realistic and adequate to meet the forthcoming market conditions. The hydrogen program at DOE (Report to Congress) proposed a 1.74 mark-up for fuel cell and hydrogen storage systems to go from manufactured cost to retail price as against the NRC report that used a 1.4 and the Multi-Path Analysis (Plotkin et al) that used a 1.5 factor. I will use the 1.74 mark-up factor. If the lesser numbers can be used then that will be an advantage for the electric platform vehicles.

The vehicle ownership costs are based on payments by the owner for five years that leaves a 45% residual value of the vehicle by the fifth year (Lasher, et al (TIAXLLC)). The annual vehicle miles driven are 15,000 miles. For the comparison, I assumed during the introductory market period that the OEMs would provide 0% APRs on the battery, fuel cell and storage systems. At a rate of 5% APR, an additional penalty would need to be accounted for. The price of gasoline is the average EIA forecast price of $4.11/gallon by 2025. I used the estimates of vehicle incremental costs, vehicle fuel consumption per mile, and electricity costs from two reports (Kromer & Heywood, and the Argonne National Laboratory Multipath Analysis) for two separate analyses of the vehicle ownership cost differentials for advanced gasoline, plug-in hybrid, and two hydrogen fuel cell vehicles (5,000 and 10,000 psi storage systems). The results generally show that electric platform vehicles if program goals are met (i.e., $300/kWh batteries, $50/kW fuel cell systems and $15/kWh hydrogen storage systems), can be competitive with advanced gasoline vehicles if the price of gasoline is $4.11 and greater. The buying public would need both the perception of high gasoline prices and price escalation. Table 1 shows the expected fuel and power system costs based on input from the Kromer and Heywood report, and table 2 is derived from input from the Multi-Path Vehicle Analysis:

Table 1 – Fuel and Power System Ownership Costs (input from Kromer & Heywood)

Vehicles	Advanced Gasoline Vehicles	Plug-In Hybrid – 40 mile electric range	Hydrogen Fuel Cell - 5,000 psi storage sys.	Hydrogen Fuel Cell 10,000 psi storage sys.
Incremental vehicle costs (cents/mile)	0	6.2	4.6	5.3
Fuel costs (cents/mile)	9.0	2.9	3.5	3.7

Total (cents/mile)	9.0	9.1	8.1	9.0

Table 2 – Fuel and Power System Ownership Costs (input from Multi-Path Vehicle Analysis)(for mid-size vehicles)

Vehicles	Advanced Gasoline Vehicles	Plug-in Hybrid - 40 mile electric range	Hydrogen Fuel Cell – 5,000 psi storage sys.	Hydrogen Fuel Cell 10,000 psi storage sys.
Incremental vehicle costs (cents/mile)	0	5.3	5.3	5.8
Fuel costs (cents/mile)	10.9	4.6	4.9	5.0
Total (cents/mile)	10.9	9.9	10.2	10.8

What Government Programs Are Necessary?

I believe that the expected scarcity of petroleum fuel and attendant high oil price is a significant factor in driving several automobile manufacturers to pursue electric platform vehicles. However, the vehicle ownership costs are going to be significantly higher than today's vehicles and so it is premature to consider true commercialization of electric platform vehicles prior to 2020.

The authors (Plotkin, et al, page 50) of the Multi-Path Future Vehicles Study also expressed concern that the higher cost platforms would not be competitive initially: "Even for the Program Goals cost case- which we consider optimistic, particularly in the early years – cost for the most advanced drive trains will be high enough at their introductions that commercialization can proceed only if the manufacturers or the U. S. government subsidize their purchase." It is going to require higher gasoline prices with the expectation that they are going to be continuing their cost escalation to make these options viable. But to leave the status quo, the U.S., Japan, Korea and Europe are in a very weak energy security and a large balance of payment deficit situation, and automobiles will be making a significant contribution to greenhouse gases. And there are significant pre-commercial activities that need to be done today.

Because the HFCV appears closer to achieving competitive cost targets (i.e., at $61/kW for the fuel cell system and $15/kWh for the hydrogen storage system in 2010) than the 40 mile electric range plug-in hybrid vehicle (i.e., $1000/kWh today and $300/kWh batteries in 2014), the HFCV could in theory be pre-commercial by 2015. However, there would need to be a period of time to implement the infrastructure nationally and time is necessary to increase the number of vehicles thru a volume of production manufacturing phase to achieve economy of scale and manufacturing learning before producing millions of vehicles. In the case of plug-in

hybrids with 40 mile electric range, such high energy batteries do not yet exist and are not considered to be economically available until 2014. There would be a five to six year period to bring a vehicle to the marketplace with that technology which then would be post 2020. Also, the introduction of a 10,000 psi storage tank may delay the introduction of HFCVs by several years due to the increased capital and fuel costs. The industry should examine such alternatives as pressures between 5000 psi and 10,000 psi or perhaps cryo-compressed tanks for larger luxury vehicles for early introduction of HFCVs.

In summary, considering the probability of reaching peak oil production in the next 10 to 15 years, and the rising demand for oil from Asia, both programs need to be placed on a top priority to incrementally introduce these electric platform vehicles. It is too early to consider mass market introduction but selective vehicle market transformation activities are essential.

Where do we go from here?

The President and the Congress need to recognize the hydrogen fuel cell program as part of a significant international effort to commercialize the hydrogen fuel cell vehicle and the role that the Zero Emission Mandate plays in that scenario. As such, the Congress needs to restore a vehicle market transformation line item in the 2011 hydrogen program budget to support the ZEV mandate through 2017 that would provide for 50/50 cost share of the infrastructure from 2012 through 2017. It should also provide for 50/50 cost share for up to 3000 hydrogen fuel cell vehicles by 2014, up to 30,000 of each by 2017 for up to three to four manufacturers at a cost of $75 million/year for four years (FY 2011-14) and $330 million/year for three years (2015-17) and the supporting infrastructure. The hydrogen budget for the initial four years would need to be restored to $210 million to accommodate the increased budget for vehicle market transformation activity of $75 million FY 2011 – 14). After such a volume of production phase is achieved by 2017 in concert with international programs, a better assessment can be made about the commercial viability of the technology. If Toyota and Honda are right in predicting early commercial viability without further support or the industry can meet targets of $30/kW on the fuel cell system and $12/kWh on the storage system, then no additional government funding may be required by 2020. If not then an additional $8 billion in U. S. funding over the subsequent 8 years (2018-2025) may be required to bring a commercially viable vehicle to the marketplace in the U.S. by 2025 in concert with international efforts.

DOE needs to better understand that the imperatives of our nation's security and improvement of our stewardship of the environment, and additionally rectification of our balance of payment accounts are addressed most directly by electric platform vehicles in the transportation sector. The Hydrogen program needs to once again stress the importance of a vehicle market transformation strategy for hydrogen fuel cell vehicles in concert with the Zero Emission Vehicle mandate. And that their program needs to be coordinated internationally with the market development efforts in Germany, Japan and Korea as well as China and India.

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Are Plug-in/Battery Electric Vehicles More Market Ready than Hydrogen Fuel Cell Vehicles?

Presented by
Sigmund Gronich, PhD
Charisma Consulting
National Hydrogen Association Conference
Long Beach, CA
May 5, 2010

Conclusions from the National Research Council Report on Transitions to Plug-in Hybrid Vehicles

1. Lithium-ion battery technology has been developing rapidly, especially at the cell level, but costs are still high, and the potential for dramatic reductions appears limited.

2. Costs to a vehicle manufacturer for a PHEV-40 built in 2010 are likely to be about $18,000 more than an equivalent conventional vehicle, including a $14,000 battery pack. The incremental cost of a PHEV-10 would be about $6,300, including a $3,300 battery pack.

3. PHEV-40s are unlikely to achieve cost-effectiveness before 2040 at gasoline prices below $4.00 per gallon, but PHEV-10s may get there before 2030.

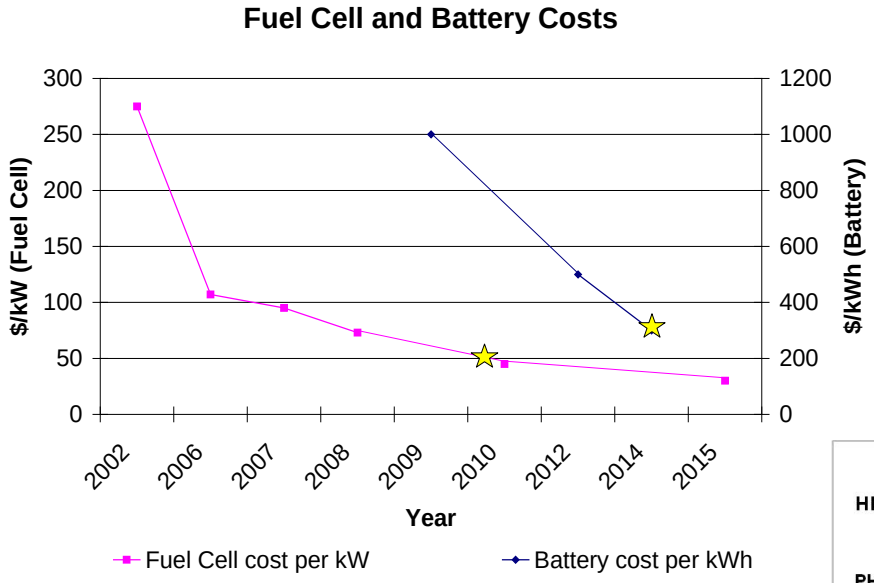
5. PHEV-10s will reduce oil consumption only slightly more than can be achieved by HEVs and

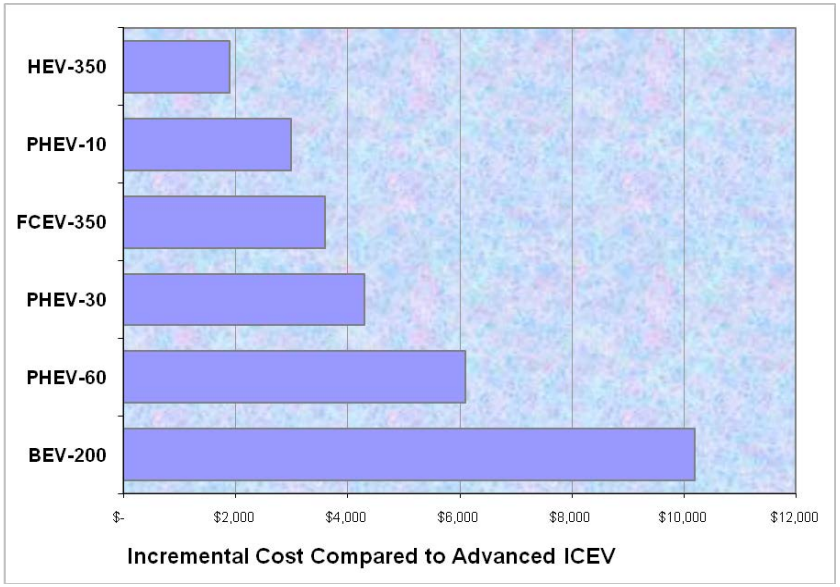
6. PHEV-10s will emit less carbon dioxide than non-hybrid vehicles, but more than HEVs after accounting for emissions at the generating stations that supply the electric power.

Commercialization costs and timing of electric platform vehicles

	PHEV-10	PHEV-40	HFCV
Breakeven year	2028 (maximum practical)	2040 (maximum practical)	2023 (hydrogen success)
Vehicle subsidy to breakeven year	$33 billion	$408 billion	$40 billion
Infrastructure subsidy	$20 billion	$20 billion	$8 billion
GHG reductions by 2050	- 29%	-36%	-59%
Oil Reductions by 2050	-67%	-83%	-100%

Misconception #1: Fuel cells vehicles (FCV's) are too expensive Analysis shows: Fuel cell system costs have been reduced substantially and FCV's are expected to be cost-competitive with other advanced electric vehicles.





Misconception #2: Breakthroughs are needed in hydrogen storage

Analysis shows: Compressed hydrogen tanks safely provide adequate range in a reasonable volume

- The Department of Energy has monitored and evaluated real-world performance of 140 fuel cell vehicles which have safely accumulated over 85,000 hours of operation and 1.9 million miles. Second generation FCV's exceeded the 250-mile DOE range target for 2008. Hydrogen storage tanks projected to have 10+ year lives.

- Larger vehicles (>Accord) can achieve 280 mile range with 5000 psi tanks.
- Current life of 10 mile range electric batteries are 3+ years and is targeted achieve 10+ years by 2012, and the 40 mile range battery needs to be more energy intensive and is targeted to achieve 10+ years by 2014.

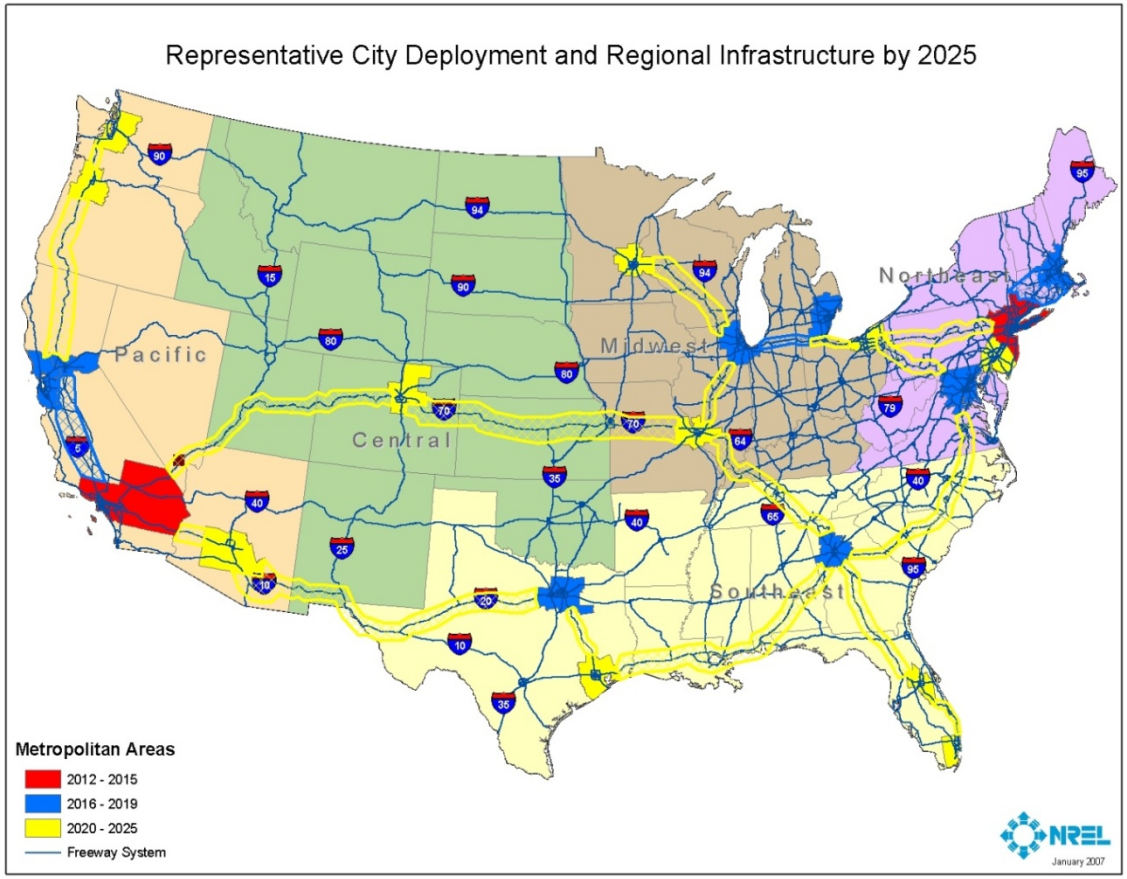
Misconception #3: It is inefficient to make hydrogen Analysis shows: Hydrogen from natural gas, coal and biomass with sequestration is clean, low cost, energy efficient and can be used to transition to renewable

- As a transition strategy, DOE compared "well-to-wheel" emissions of GHGs from various pathways, and the results show that FCVs using hydrogen from natural gas emit 60% fewer GHGs than today's gasoline vehicle, and 35% fewer GHGs than natural gas vehicles. FCVs using hydrogen from biomass emit 60% fewer GHGs than a PHEV running on cellulosic ethanol.

- Hydrogen produced from coal, natural gas or biomass with CO2 sequestration can be dispensed for about $4 to $5/kg, comparable to $2 to $2.50 per gallon gasoline (untaxed). Per vehicle, hydrogen stations cost about the same as home charging.

Misconception #4: Building a hydrogen infrastructure is too difficult and costly

Analysis shows: Hydrogen can be cost-competitive with gasoline and stations can be deployed using a coordinated cost-effective, regional strategy.



Several studies have shown that it is possible to roll-out infrastructure regionally concurrently with vehicle deployment to maximize utility and minimize costs for early markets. In assessing a transition to hydrogen fuel cell vehicles, the National Research Council modeled a fuel production pathway to supply fuel for millions of vehicles through 2025 by starting in LA and NYC.

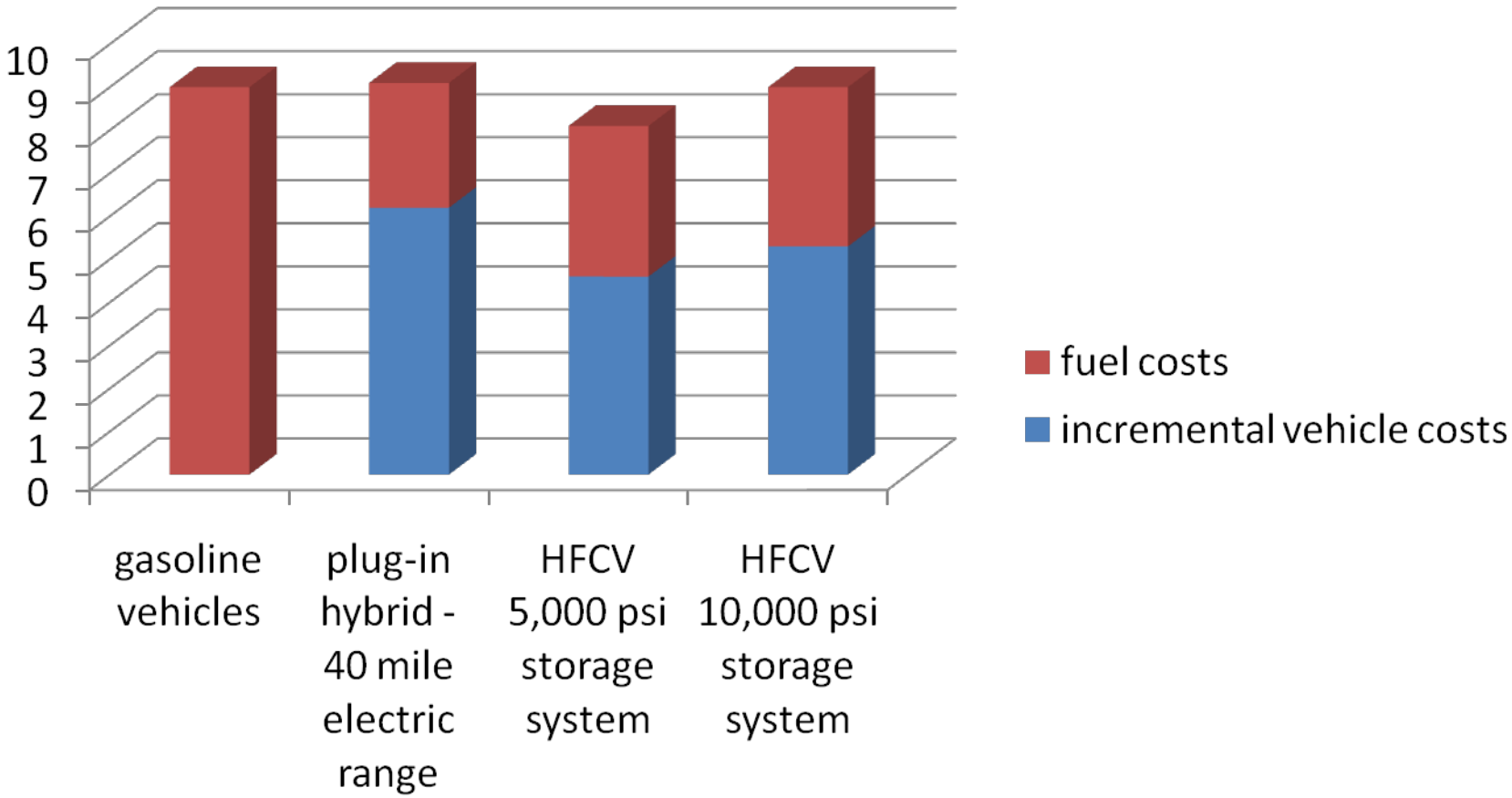
Zero Emission Vehicle Mandate

- 7500 Zero Emission Vehicles by 2014 (can be Battery Electric (BEV) or Hydrogen Fuel Cell (HFCV) Vehicles
- 25,000 to 50,000 ZEVs by 2017
- Industry survey by CaFCP indicates up to 4200 are likely to be HFCVs and remainder would be BEVs by 2014
- Need both stick (ZEV mandate) to line up industry efforts and send signal for infrastructure requirements
- And carrot of 50/50 cost sharing between industry and government for vehicles and infrastructure, $8000 vehicle tax credit and investment tax credits thru 2016.
- The ZEV mandate to 2017 is in concert with proposed international programs

Fuel and Power System Ownership Costs

(cents/mile)

Input from Kromer and Heywood report

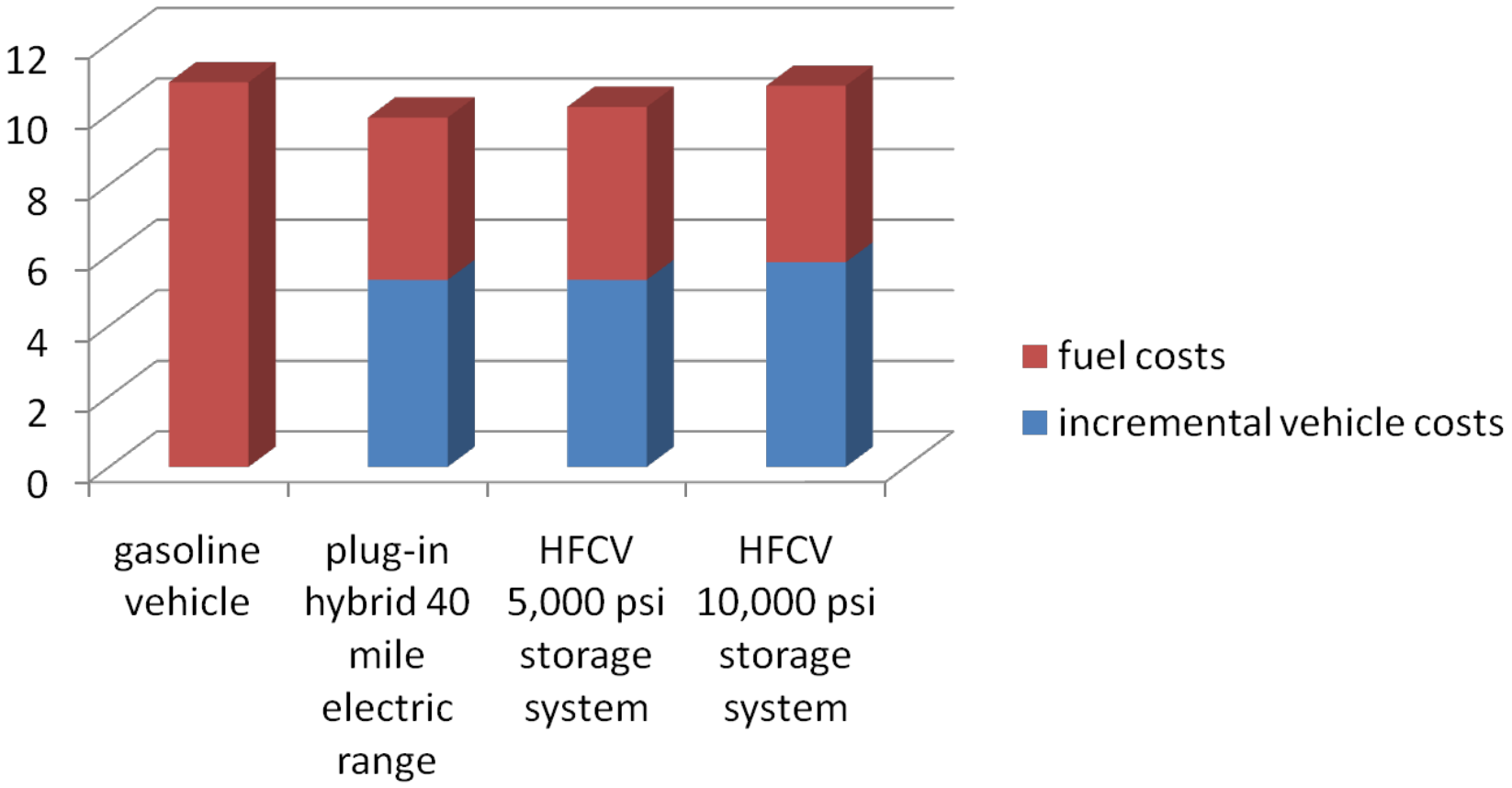


Fuel and Power System Ownership Costs

(cents/mile)

Input from Multi-Path Vehicle Analysis Report

(for mid sized cars)



The Price of Oil is Highly Vulnerable to Externalities and Singularities

- Oil production is approaching peak capacity and will be further concentrated in the OPEC cartel
- New sources are in underdeveloped areas or in deeper offshore sites
- Demand is increasing significantly as developing countries become major societies
- The oil supply chain is highly vulnerable to terrorist and rebel attacks
- The price of oil is a direct function of the strength of the U. S. dollar as the U. S. increases its national debt to unprecedented levels

Conclusions

- President Obama needs to have the U.S. join an international consortium to aid industry to manufacture and sell 5 million HFCVs worldwide by 2025 with 1 million of them being deployed in the U.S.
- DOE and the industry need to adopt viable competitive HFCV targets for a 2025 market for fuel cell (i.e, $45 to 50/kw vs $30/kw) and hydrogen storage systems (i.e., $12/kWh vs $2/kWh).
- DOE/industry needs to reassess the need for 10,000 psi tanks for initial penetration scenarios.
- DOE needs to support a market transformation HFCV program that supports the ZEV mandate from 2012 to 2017 with a 50/50 cost share for vehicles and infrastructure, and tax credits as the first step in a national HFCV rollout.
- Low cost competitive hydrogen will be produced from coal, natural gas and biomass with carbon capture and sequestration and less likely from electrolysis.
- The NHA and USFCC need to develop an educational program with senators and house members from coal and natural gas producing states.

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California Energy Commission Station Build -Out Presentation to DOE

Reference :CEC Docket 10-ALT-1

Edward F. Kiczek
Global Director
Hydrogen Energy Systems
Air Products and Chemicals, Inc.

09 May 2011

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50+ Years of Hydrogen Experience

- World's largest merchant supplier
- H_2 production equivalent to fueling ~8 Million cars/day
- Bulk, liquid and pipeline distribution
- More than 500 H_2 customers
- H_2 Energy projects since 1993
  - >130 hydrogen station projects
  - >350,000 fuellings/yr
- Parlayed MHE, cell tower, DOD experiences
- Stations in 19 countries
- Broad IP estate

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Figure 1
Current Supply Chain for Delivered Hydrogen to Refueling Stations

AIR PRODUCTS

Point of Use – Business Case

- For business case to succeed, investment at station must be $1 million or less
- Station components today:

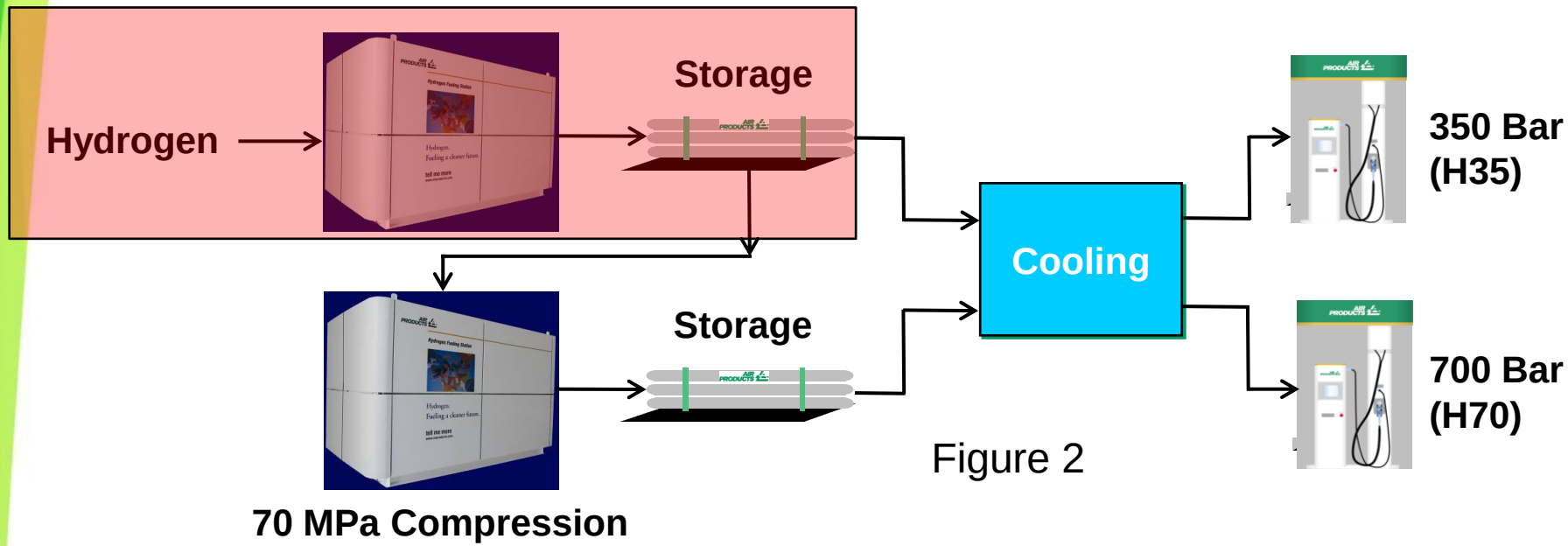

Figure 2

- Limit equipment to dispensers, cooling, 70 MPa system

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

AIR PRODUCTS

Next Generation H35 + H70 Station

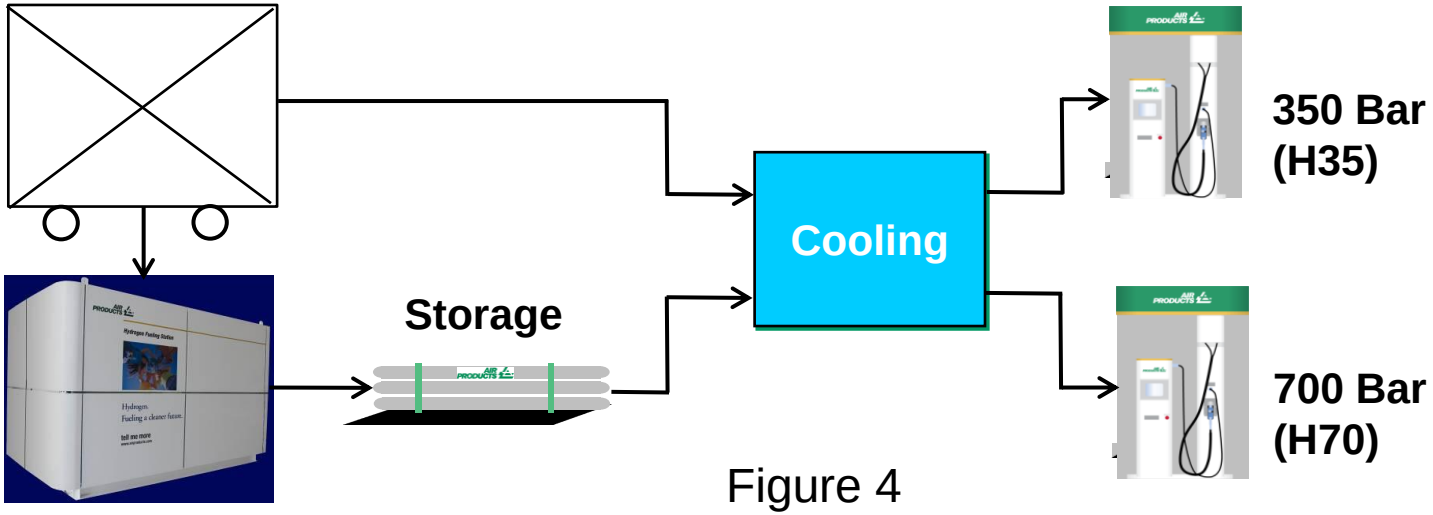

Figure 4

70 MPa Compression

- Replace 350 bar compression and low-pressure ground storage with integrated station/delivery system
- 70 MPa system can be bolted on, with compressor selected to match demand and available site power supply
- Lower onsite maintenance, higher fuel availability (H35 is fit-for-purpose – customers can always get fuel)
- Patents pending

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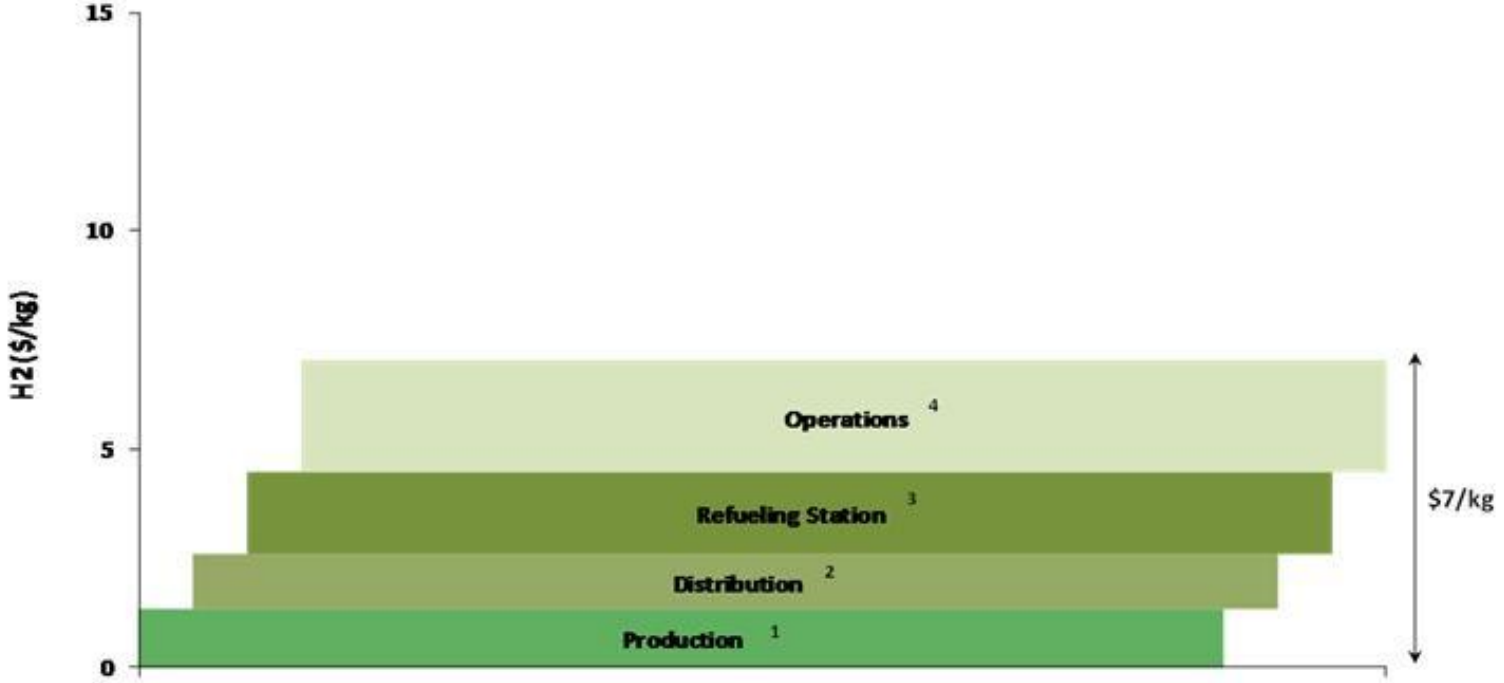

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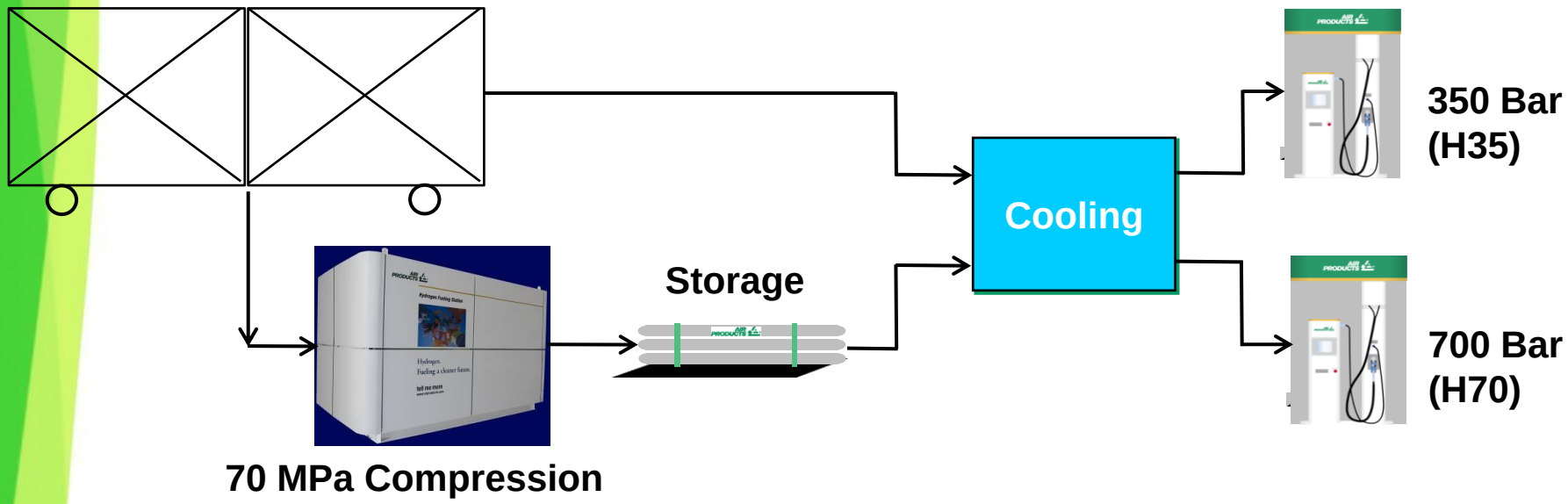
3- APCI 2011 (Hydrogen refueling station under CEC 2010 program)
4- $250k/yr: Based on UCD 2011 Hydrogen Station Analysis plus CA Excise Tax

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

AIR PRODUCTS

Expansion of H35 + H70 Station



- Options for increased throughput:
  - more deliveries or delivery capacity
  - dual phase trailer

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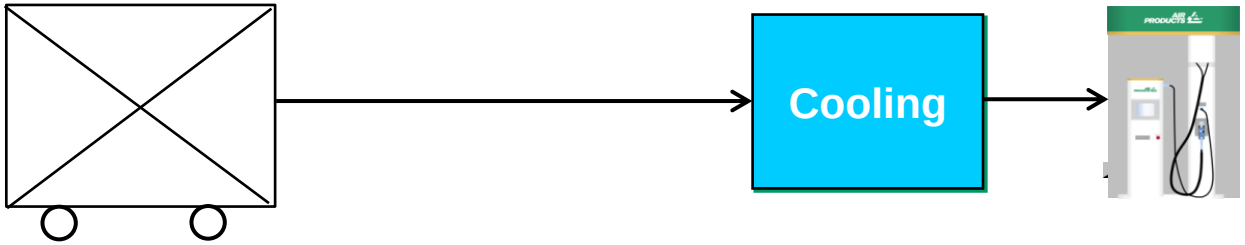
Lowest Cost Fit-For-Purpose Station



- Minimum site investment – dispenser, cooling system (where needed), other low-voltage electricals for controls
- Today's system meets requirements for other fuel cell applications
- Future for light-duty vehicles – can drive station costs down by 50%

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The Delivery and Station Breakthrough
HP Composite Bulk Delivery / Storage

- Enables <u>step-change</u> in bulk hydrogen product payload capacities, up to 3-4X .
- Enables distribution of hydrogen from all forms of distributed and renewable sources with minimum GHG emissions
- Promotes modular and expandable stations on existing gasoline forecourt.
- Potential to eliminate ONSITE COMPRESSION.
- AP Patents pending

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Air Products' Patented Delivery Trailer

- Dual Phase Liquid Hydrogen trailer capable of delivering liquid and high pressure hydrogen up to 10,000 psi to a station
- Enables step-change in liquid delivery to numerous applications, lowering delivery costs

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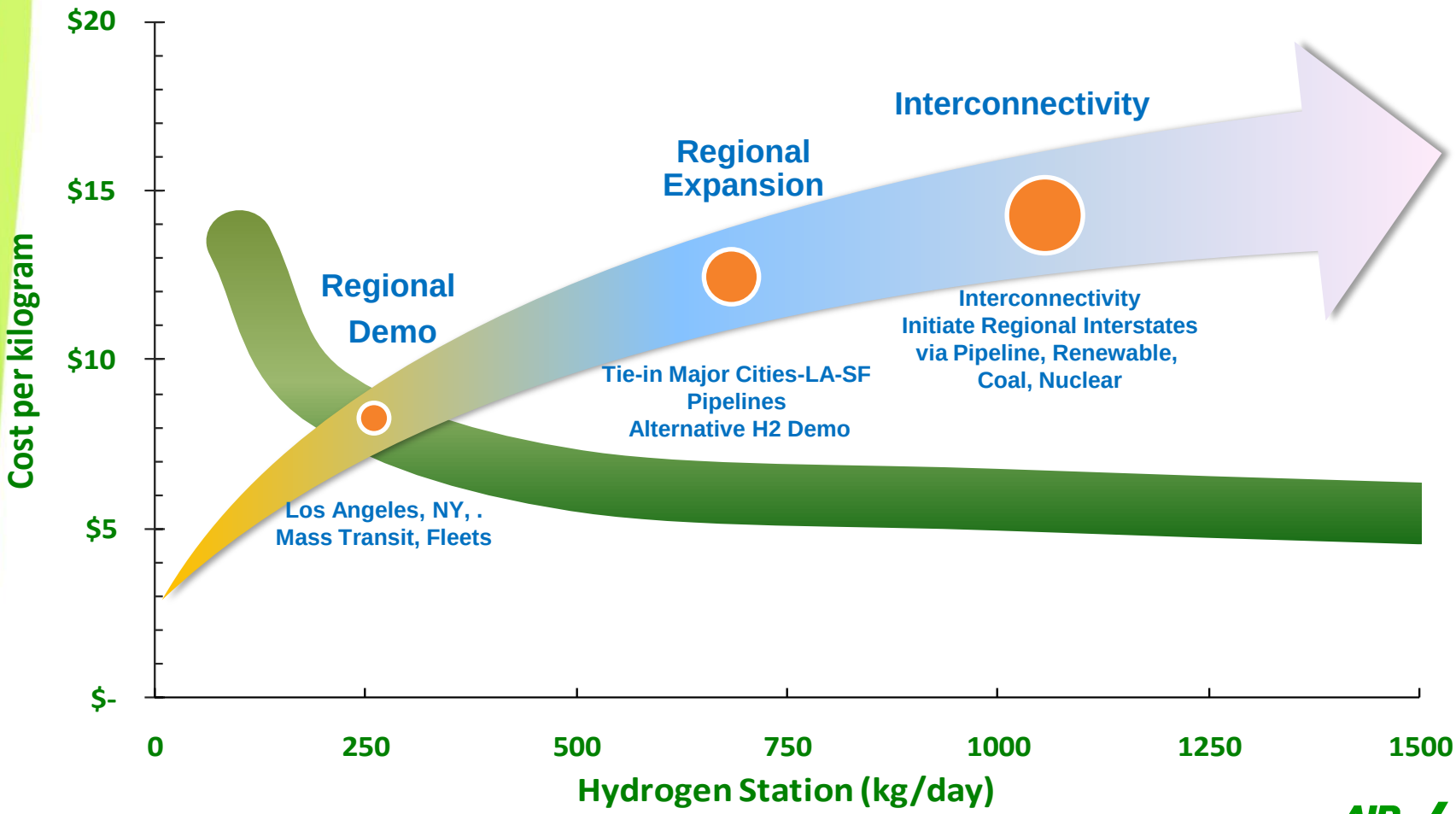
Focused regional markets can demonstrate hydrogen can compete with gasoline



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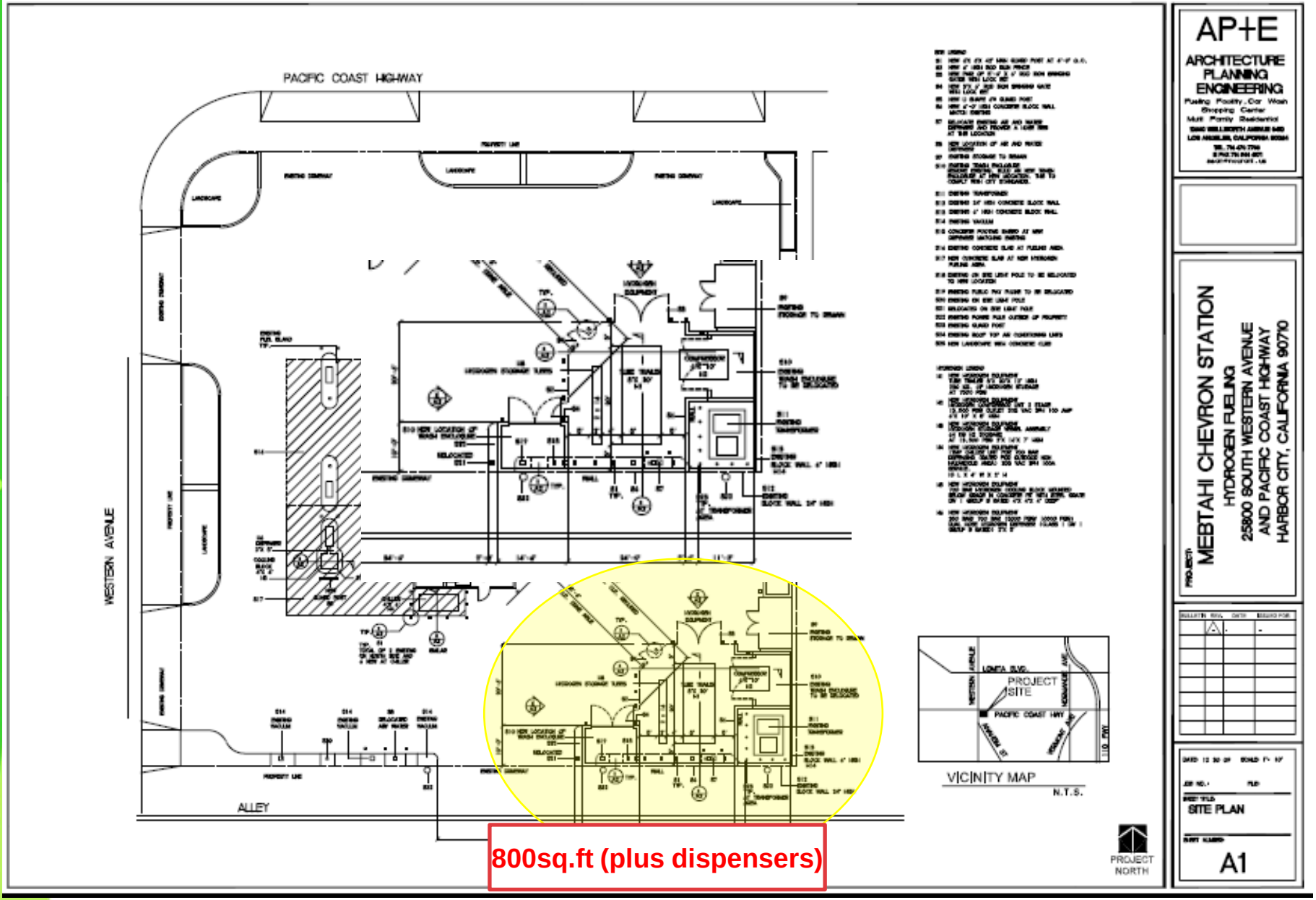
First of nine stations in Southern California



800sq.ft (plus dispensers)

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www.airproducts.com/H2energy

Joint statement by private companies concerning the introduction of fuel cell vehicles onto the domestic market and the development of hydrogen supply infrastructure
- Full launch of FCVs in the market slated for 2015! -

Three auto manufacturers and ten energy suppliers issued a joint statement on their plan for the full launch of fuel cell vehicles (FCVs) onto the commercial market in 2015. FCVs are expected to make a significant contribution to energy conservation and global warming mitigation because they run on hydrogen and emit no CO2 while being driven.

1. Background

In accordance with the Strategic Energy Plan of Japan (approved by the Cabinet on June 18, 2010) the Ministry of Economy, Trade and Industry (METI) is taking measures to increase the use of hydrogen energy with the goal of creating a low-carbon society. FCVs are included in this effort and METI intends to support the development of hydrogen supply infrastructure for them, such as hydrogen stations, ahead of the start of FCV dissemination in 2015.

In METI's Next-Generation Vehicle Strategy 2010 (announced by the Study Group on Next-Generation Vehicle Strategy on April 12, 2010), FCVs are defined as one of the next-generation vehicles that should be promoted for their potential from the viewpoint of global warming countermeasures, energy security and maintenance of Japan's industrial competitiveness.

2. Implications of the joint statement

Thirteen private companies, consisting of auto manufacturers and hydrogen suppliers, have just agreed to take measures jointly with the goal of introducing FCVs onto the domestic market and initiating the development of hydrogen supply infrastructure, and issued a joint statement (PDF:306KB) (in Japanese).

In this joint statement, for the full-scale launch in 2015, mass-produced FCVs* will be on sale by auto manufacturers. Ahead of the debut of these FCVs, a necessary number of hydrogen stations (around 100) are expected to be installed primarily in four metropolitan areas (Tokyo, Aichi, Osaka and Fukuoka) in accordance with the predicted unit sales of the vehicles by energy suppliers.

*Mass-produced vehicles generally refer to vehicles for which systems for quality assurance, after-sales service and other operations for customers are in place and which can be sold in a manner that timely meets consumer demand. Mass-produced FCVs are predicted to sell one thousand to a few thousand units annually immediately after introduction, provided that they follow the same initial sales trend as exhibited by next-generation vehicles previously placed on the market, although this prediction depends on advance in technology development and market trends in the years to come.

3. Next step

Recognizing that this joint statement conforms to goals set forth in the Strategic Energy Plan of Japan, METI will take necessary steps to facilitate the launch in 2015 and subsequent nationwide dissemination.

Release Date

January 13, 2011

Division in Charge

Hydrogen and Fuel Cell Promotion Office, New and Renewable Energy Division, Energy Conservation and Renewable Energy Department, Agency for Natural Resources and Energy

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January 13, 2011

Toyota Motor Corporation
Nissan Motor Co., Ltd.
Honda Motor Co., Ltd.
JX Nippon Oil & Energy Corporation
Idemitsu Kosan Co., Ltd.
Iwatani Corporation
Osaka Gas Co., Ltd.
Cosmo Oil Co., Ltd.
Saibu Gas Co., Ltd.
Showa Shell Sekiyu K.K.
Taiyo Nippon Sanso Corporation
Tokyo Gas Co., Ltd.
Toho Gas Co., Ltd.

13 Japanese Companies Eye Smooth Domestic Launch of FCVs

—Development of Hydrogen Supply Infrastructure Key—

Toyota Motor Corporation (TMC), Nissan Motor Company, Ltd., Honda Motor Company, Ltd., JX Nippon Oil & Energy Corporation, Idemitsu Kosan Company, Ltd., Iwatani Corporation, Osaka Gas Company, Ltd., Cosmo Oil Company, Ltd., Saibu Gas Company, Ltd., Showa Shell Sekiyu K.K., Taiyo Nippon Sanso Corporation, Tokyo Gas Company, Ltd. and Toho Gas, Company, Ltd. jointly announce the following details regarding the launch of mass-produced fuel-cell vehicles (FCVs)—one of a number of potential next-generation vehicles—in the Japanese market in 2015 and the development of the hydrogen supply infrastructure necessary for the successful adoption of the vehicles.

1. As development of fuel-cell systems progresses, Japanese automakers are continuing to drastically reduce the cost of manufacturing such systems and are aiming to launch FCVs in the Japanese market—mainly in the country's four major metropolitan areas—in 2015. The automobile industry hopes to popularize the use of FCVs after their initial introduction as a way of tackling energy and environmental issues.
2. Hydrogen fuel suppliers are aiming to construct approximately 100 hydrogen fueling stations by 2015, based on the number of FCVs expected to initially enter the market, to ensure a smooth launch and to create initial market.
3. With an aim to significantly reduce the amount of CO_2 emitted by the transportation sector, automakers and hydrogen fuel suppliers will work together to expand the introduction of FCVs and develop the hydrogen supply network throughout Japan. The two groups are looking to the government to join them in forming various strategies* to support their joint efforts and to gain greater consumer acceptance.

*As a specific initiative in the immediate future, the companies plan to approach local governments and other concerned parties to discuss strategies for creating initial consumer demand for FCVs and for the optimal placement of hydrogen fueling stations, targeting Japan's four major metropolitan areas (Tokyo, Nagoya, Osaka and Fukuoka).

End

Recommended

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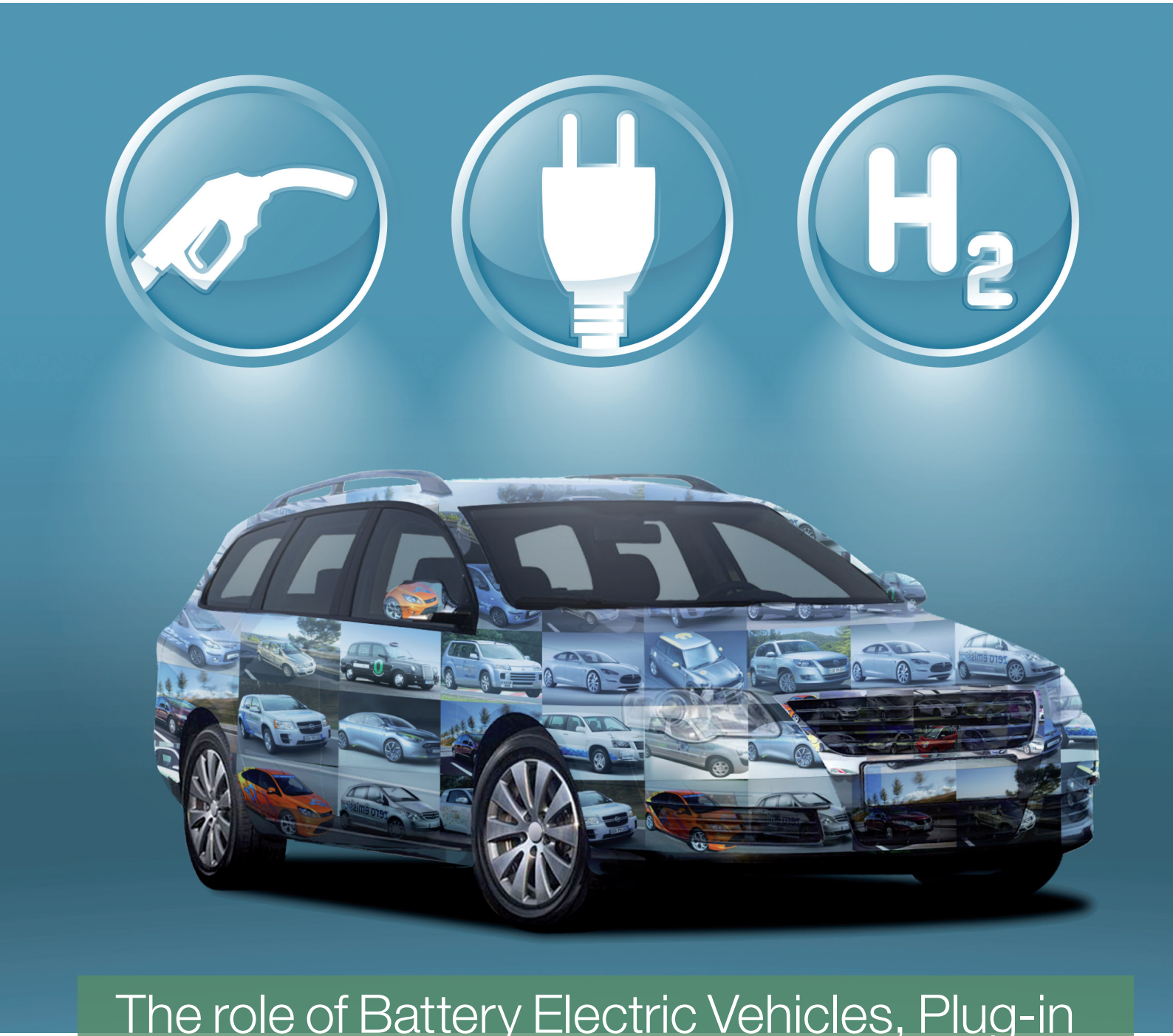
A portfolio of power-trains for Europe: a fact-based analysis



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.

Contents

EXECUTIVE SUMMARY **2**

INTRODUCTION **11**

EU CO_2 reduction goal for 2050 requires 95% decarbonisation of road transport 11

Electric vehicles (BEVs, FCEVs and PHEVs) are necessary to achieve EU CO_2 reduction goal 12

Technologically ready, FCEVs are now focused on commercial deployment 12

All conclusions are based on proprietary industry data 14

METHODOLOGY **15**

A balanced scenario for the electrification of passenger cars in the EU by 2050 16

A combined forecasting and backcasting approach to maximise accuracy 18

A balanced hydrogen production mix including a variety of technologies 19

Assumptions are robust to significant variations 24

INPUT DATA **26**

The collection, benchmarking and validation of over 10,000 data points 26

RESULTS **28**

1. BEVs and FCEVs have the potential to significantly reduce CO_2 and local emissions 28
2. After 2025, the total cost of ownership of all the power-trains converge 33
3. A portfolio of power-trains can satisfy the needs of consumers and the environment 44
4. Costs for a hydrogen infrastructure are around 5% of the overall cost of FCEVs 46
5. The deployment of FCEVs will incur a cost to society in the early years 48

NEXT STEPS **52**

ANNEX **54**

GLOSSARY **62**

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).

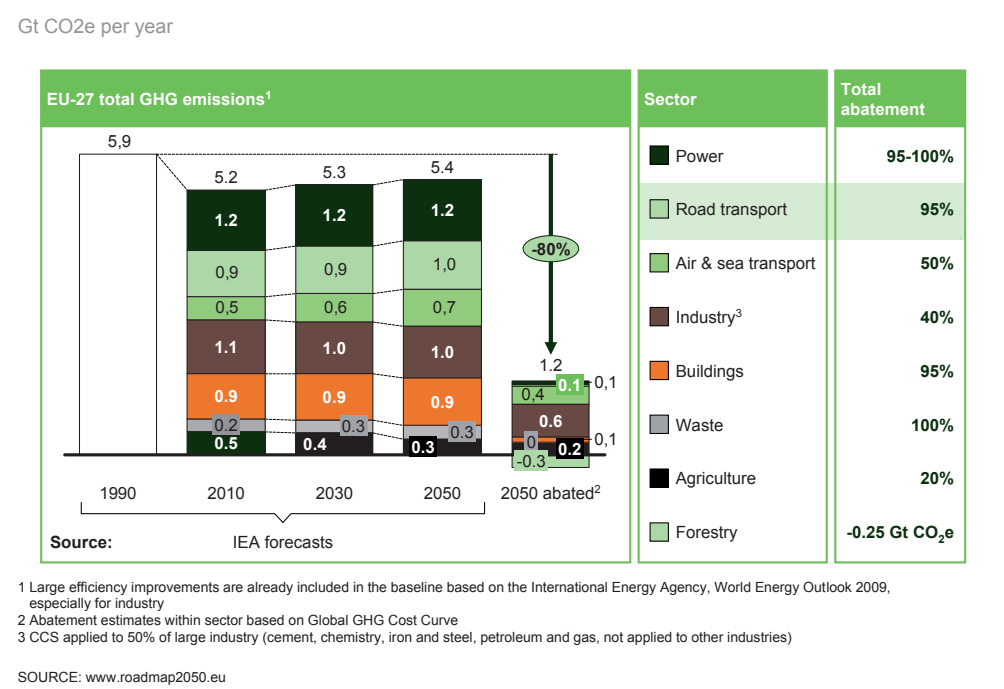


Exhibit 1: In order to achieve EU CO_2 reduction goal of 80% by 2050, road transport must achieve 95% decarbonisation

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.

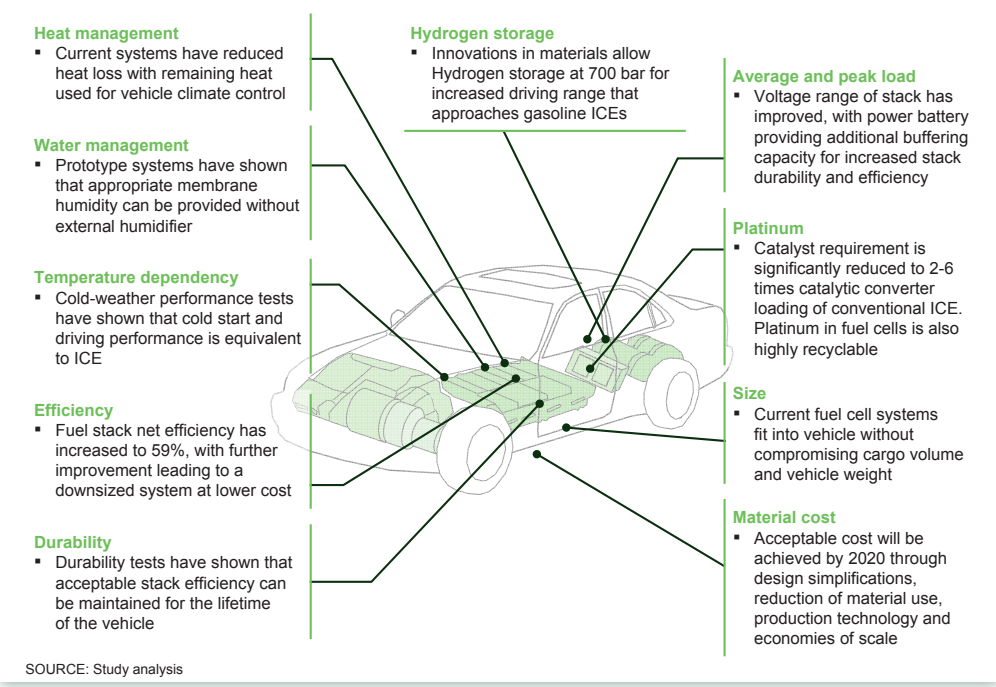


Exhibit 2: With all technological hurdles resolved, the focus for FCEVs has now shifted from demonstration to commercial deployment

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.

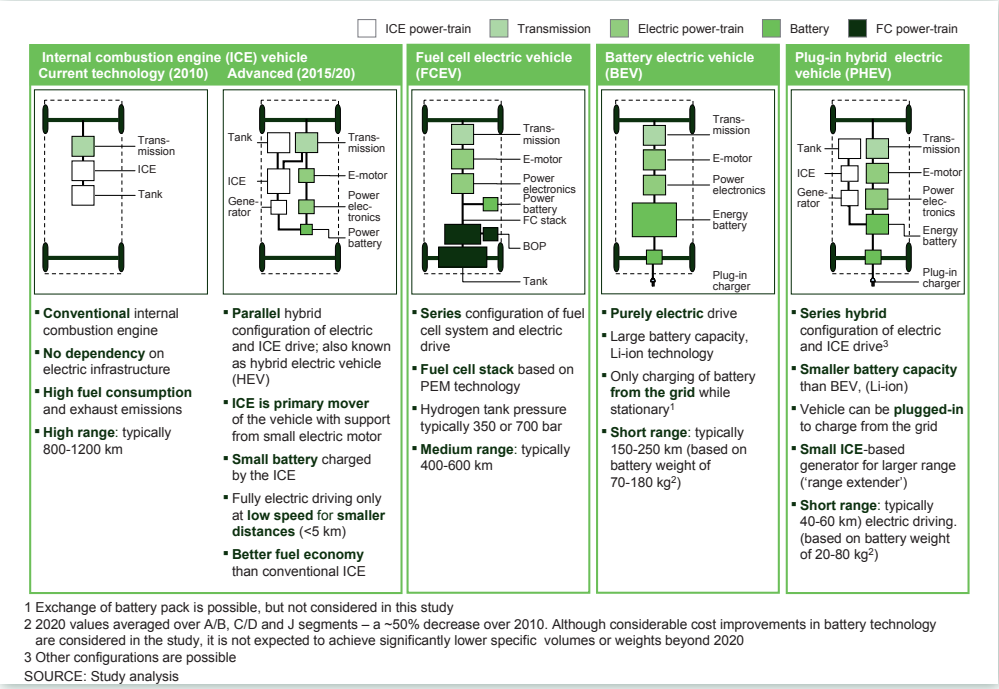


Exhibit 3: The study focused on a portfolio of power-trains: BEVs, FCEVs, PHEVs and ICEs, taking into account significant advances in ICE technology between now and 2020

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).

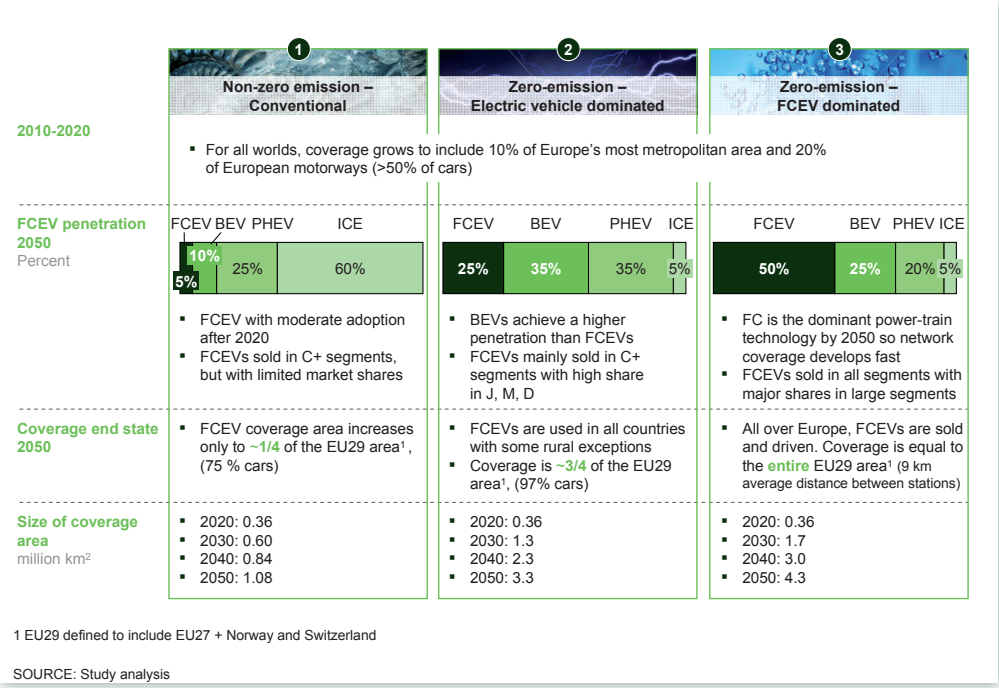


Exhibit 5: Assumptions for the three "worlds", each showing a different penetration scenario for BEVs, FCEVs, PHEVs and ICEs in the EU in 2050

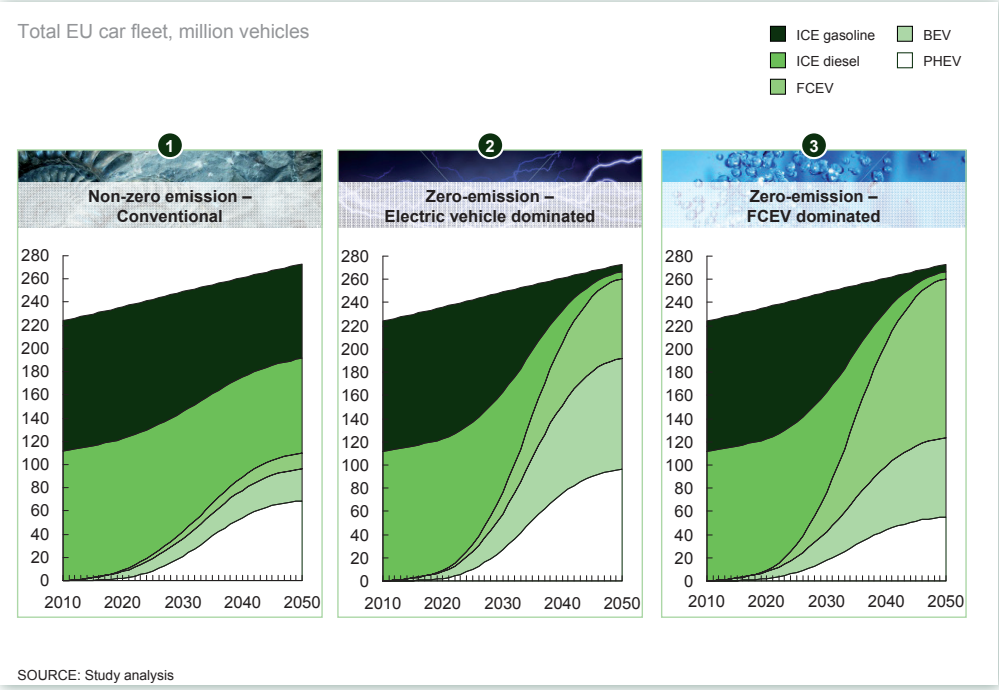


Exhibit 6: For all three "worlds", the car fleet is built up from 2010 to 2050 by introducing BEVs, FCEVs and PHEVs where they are most competitive with ICEs

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.

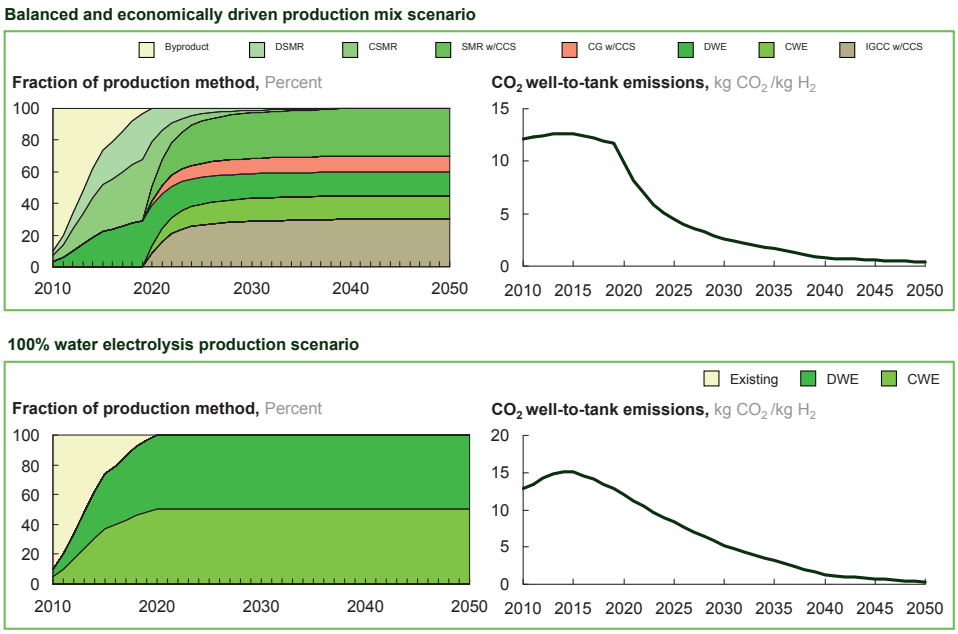
N.B. All the results in this report are based on the first balanced and economically driven production mix described below

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*

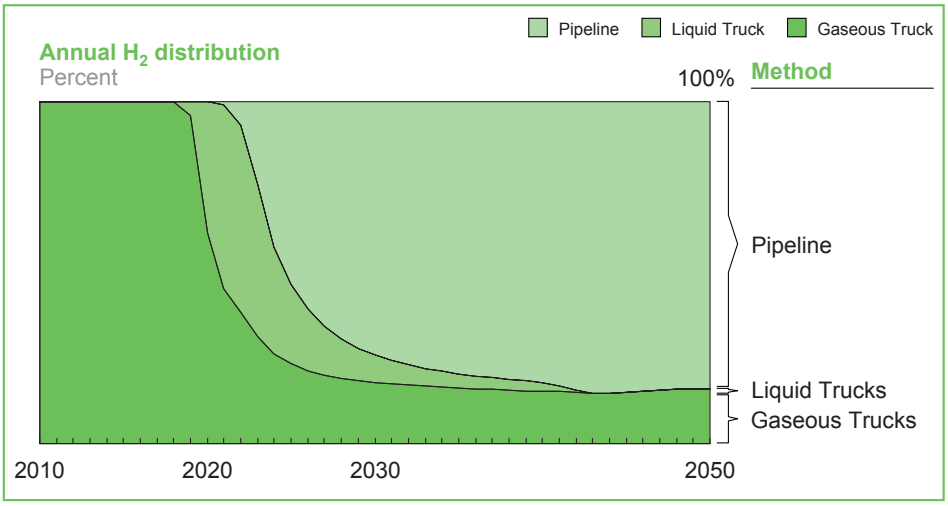
Table 1: An overview of distribution methods included in the study

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*

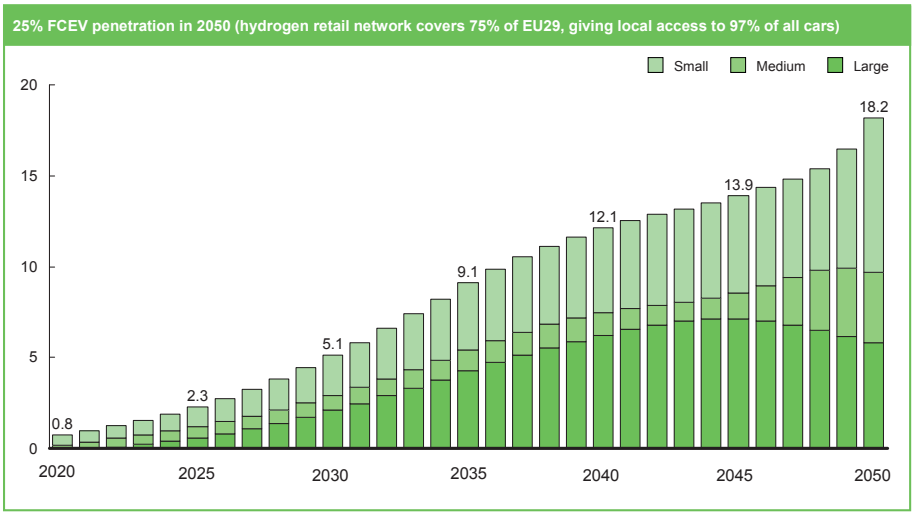
Table 2: An overview of retail stations included in the study

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).

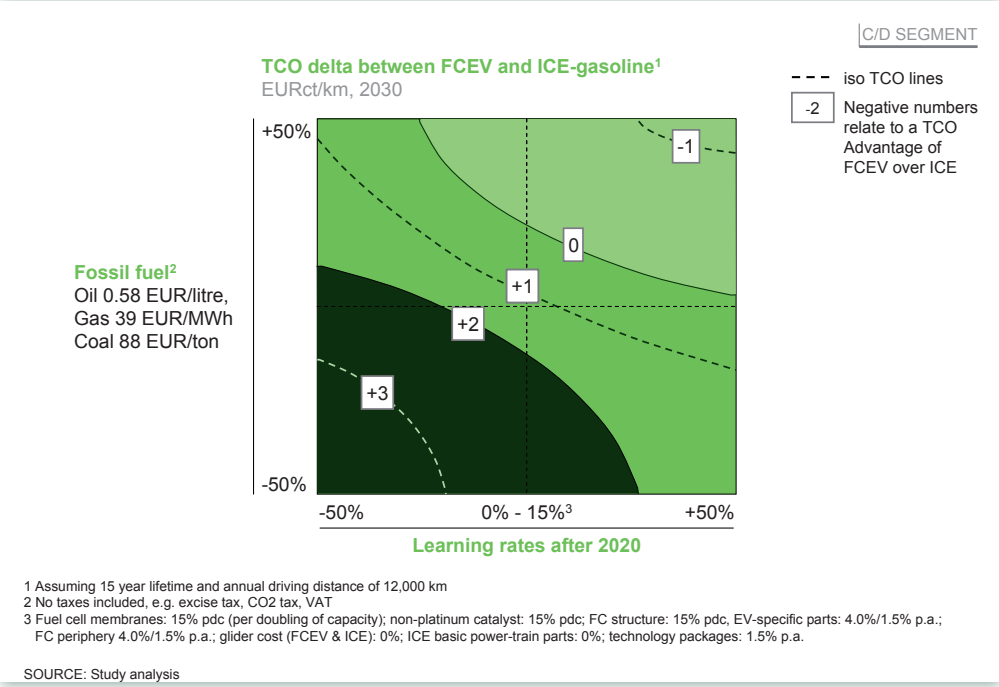


Exhibit 12: All conclusions are robust to significant variations in learning rates and the cost of fossil fuels

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

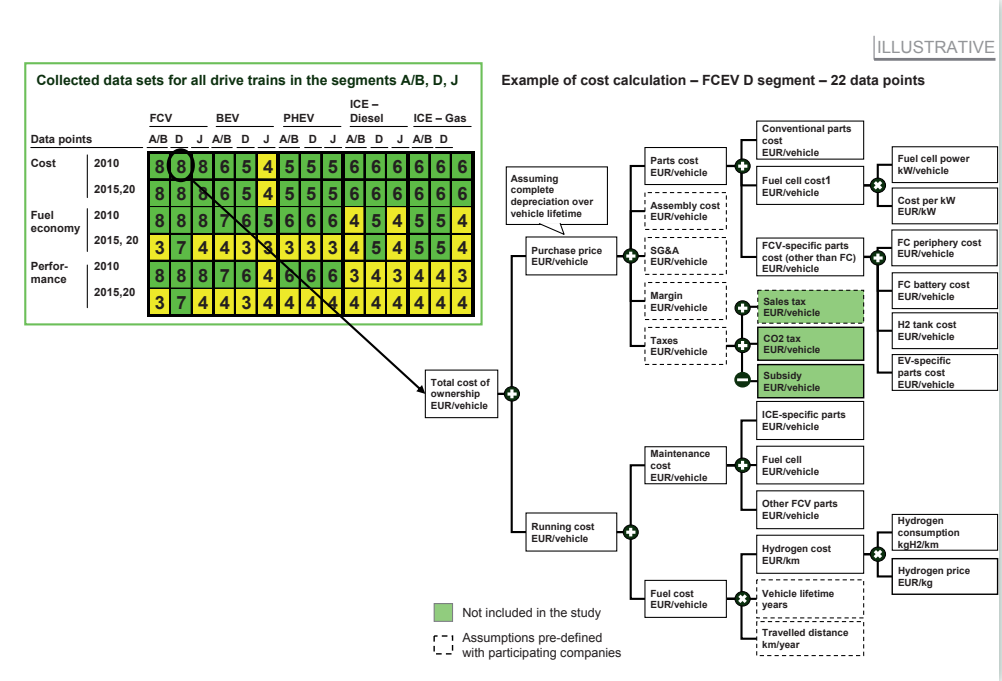


Exhibit 13: An example of cost data collected for a FCEV

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*

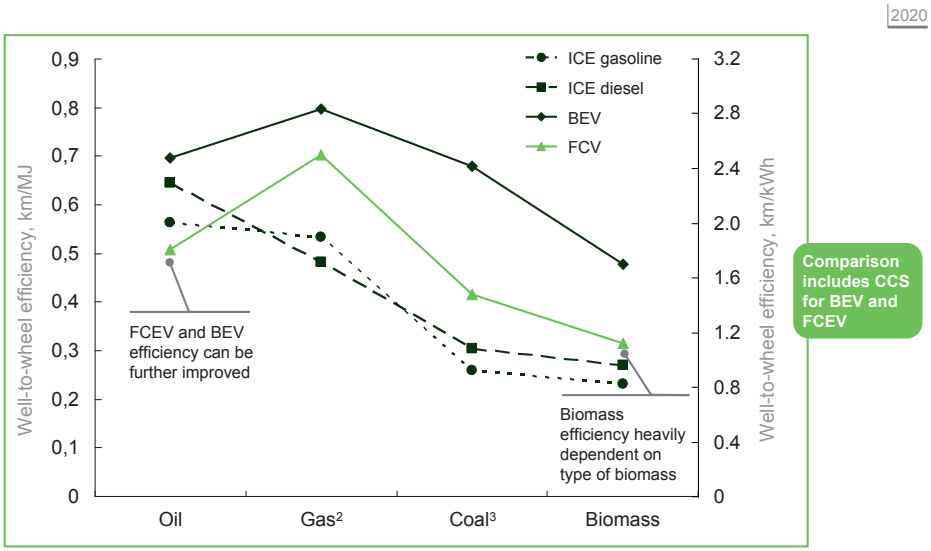
BEVs: given their limited energy storage capacity and driving range (150-250 km[1]) – and a current recharging time of several hours – BEVs are ideally suited to smaller cars and shorter trips, i.e. urban driving.

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).

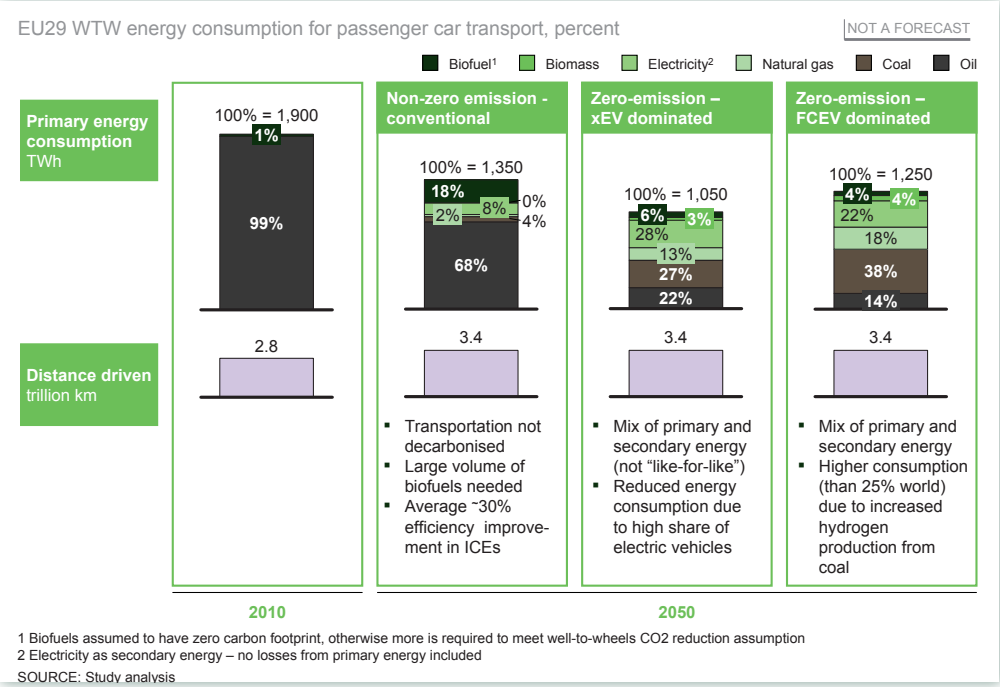
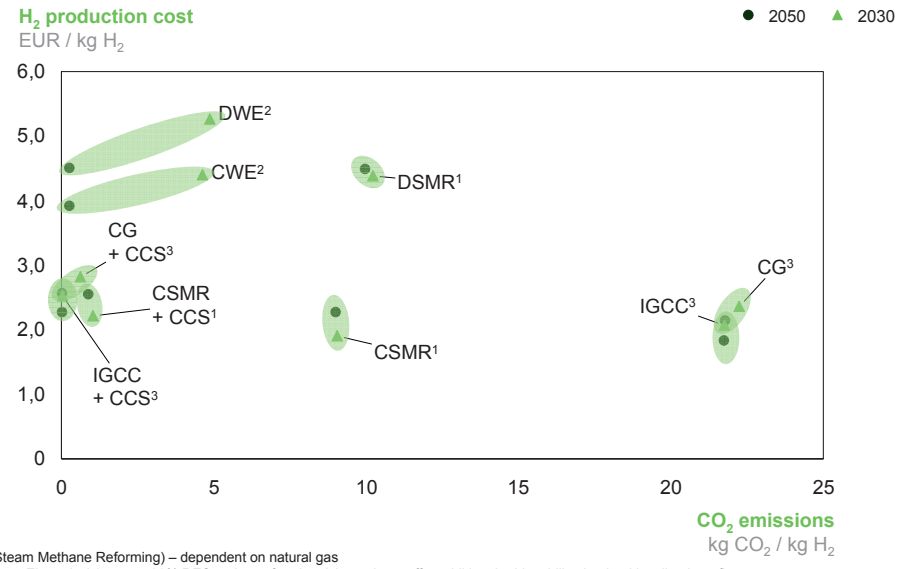


Exhibit 16: On a net-distance-travelled basis, electric vehicles could potentially drive more kilometres than ICEs using less energy

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.

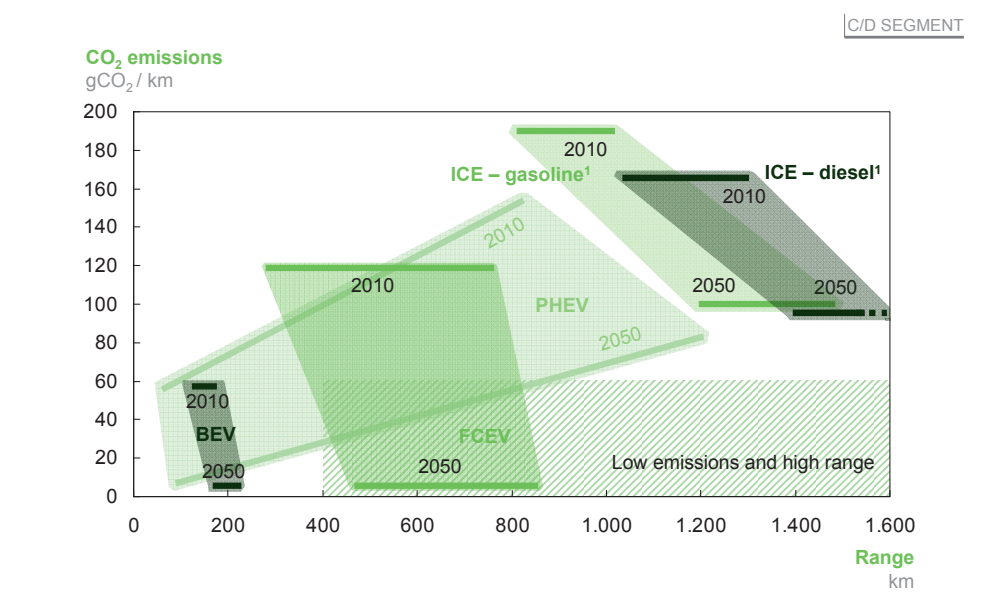
CO_2 capture has already been practised on a small scale, while the technology for CO_2 storage is similar to that used by the oil and gas industry for decades – to store natural gas or for enhanced oil recovery (EOR). CO_2 storage technology combined with EOR is therefore very advanced, providing ample 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

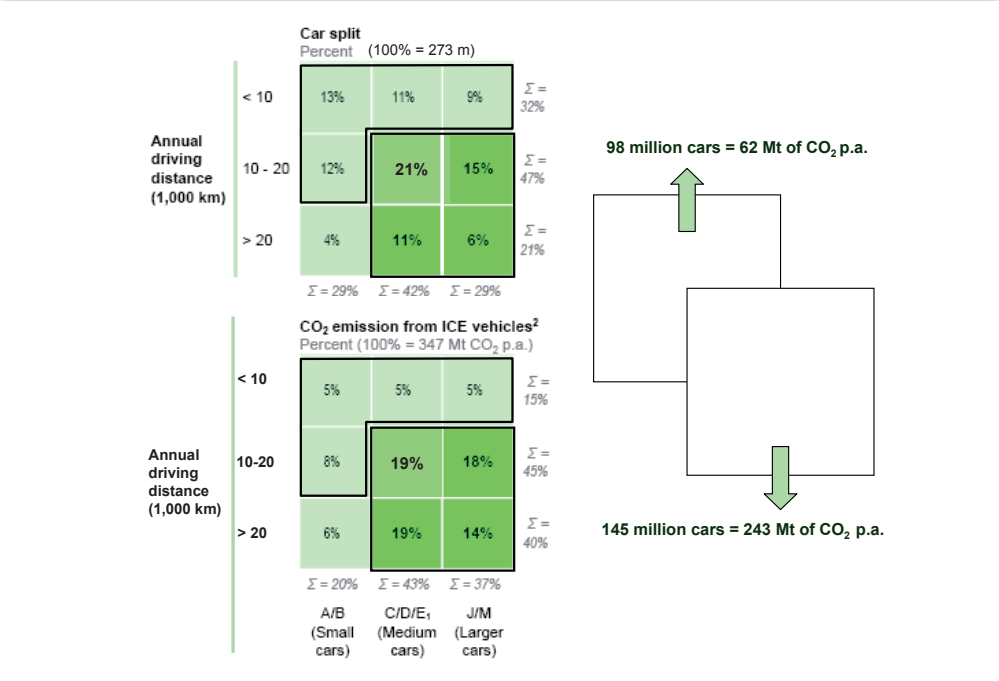


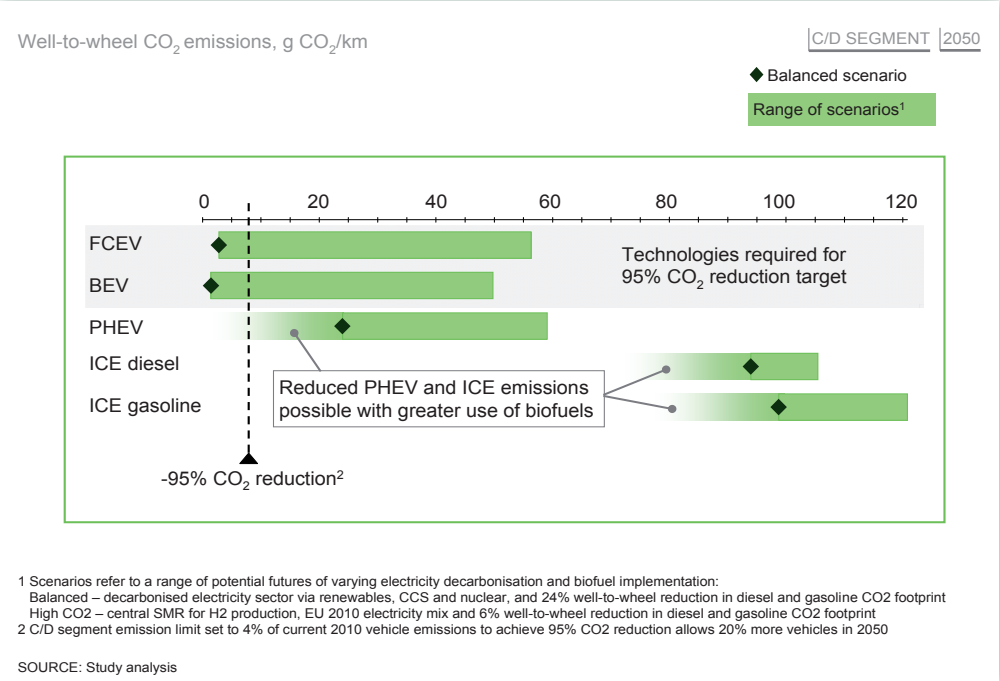
Exhibit 19: Medium/larger vehicles with above average driving distance account for 50% of all cars and 75% of CO_2 emissions

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%

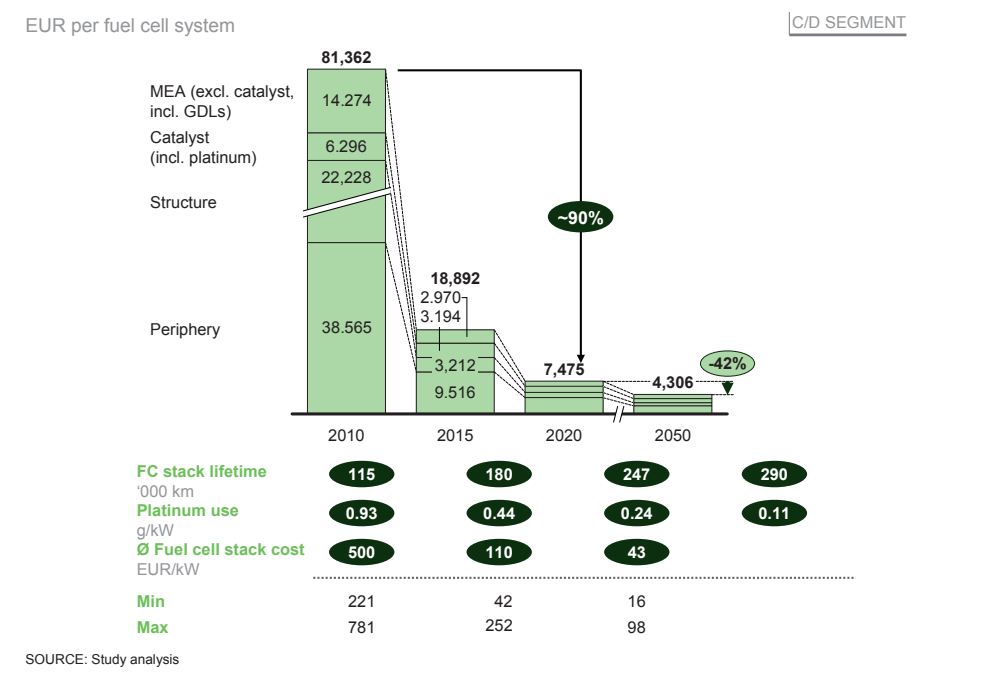


Exhibit 21: The cost of a fuel cell system falls by 90% by 2020

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:

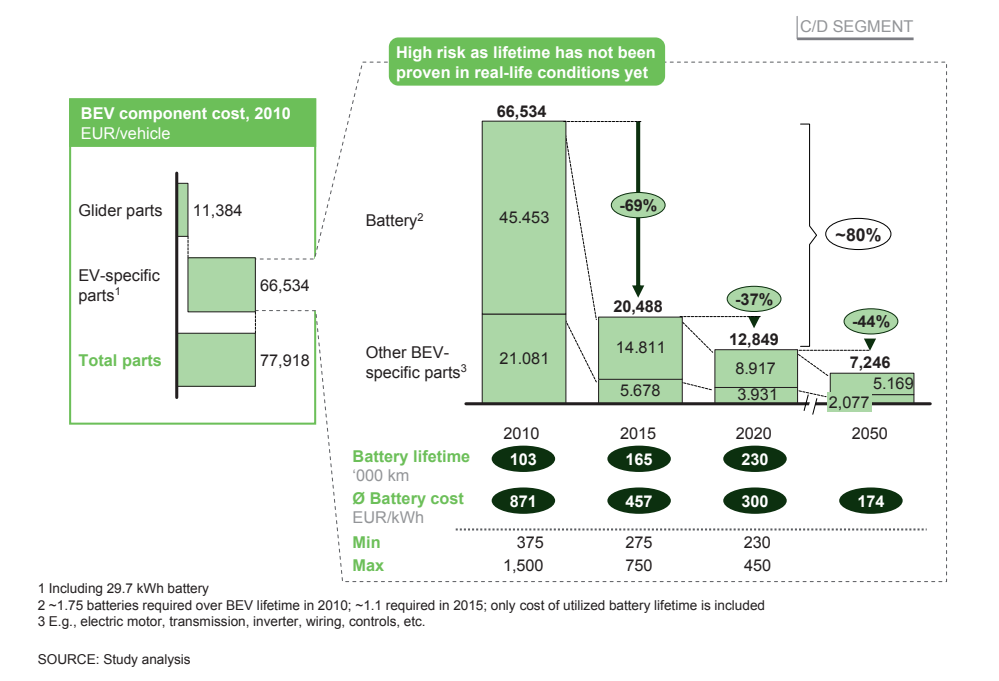
- Improvements in design, e.g. removing components; operating at a higher temperature in order to simplify the units

- 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).

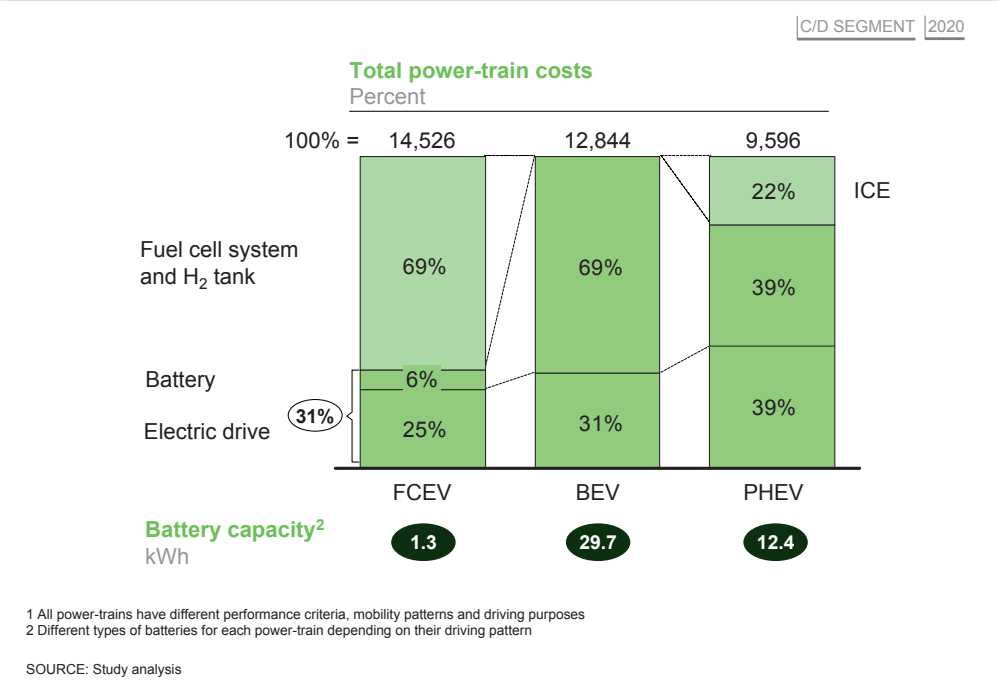


Exhibit 23: In 2020, 31% of technology improvements in BEVs and PHEVs also apply to FCEVs

- 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.

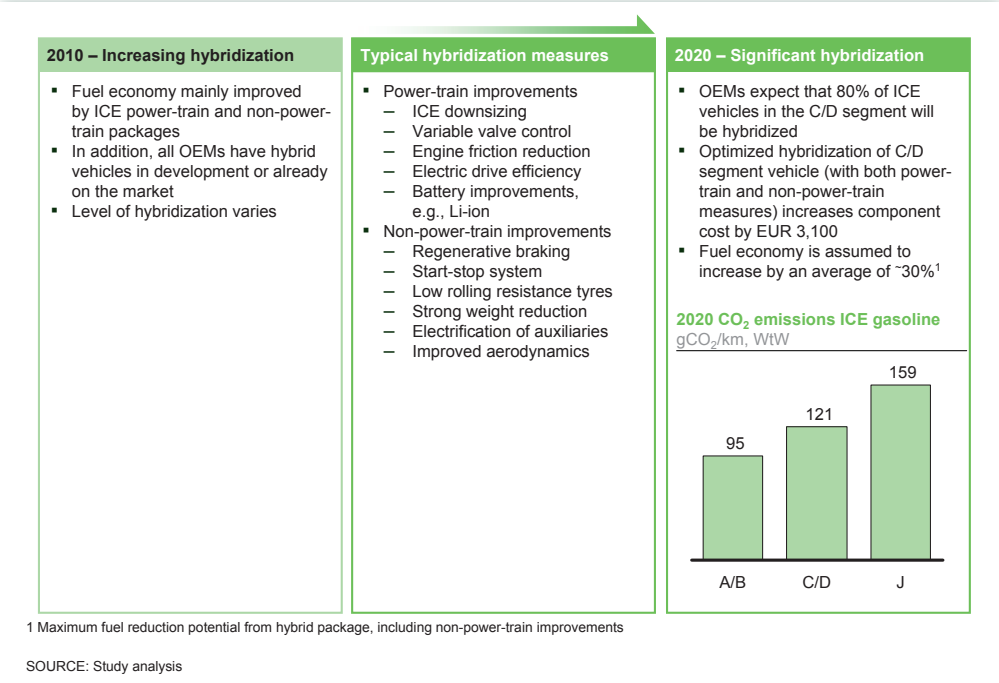
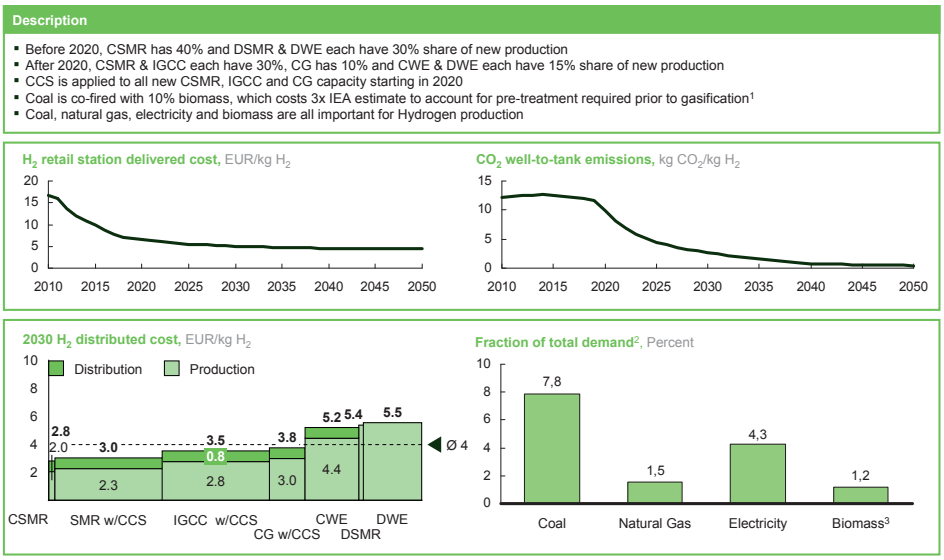


Exhibit 24: ICE fuel economy is assumed to increase by an average of 30% by 2020

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.

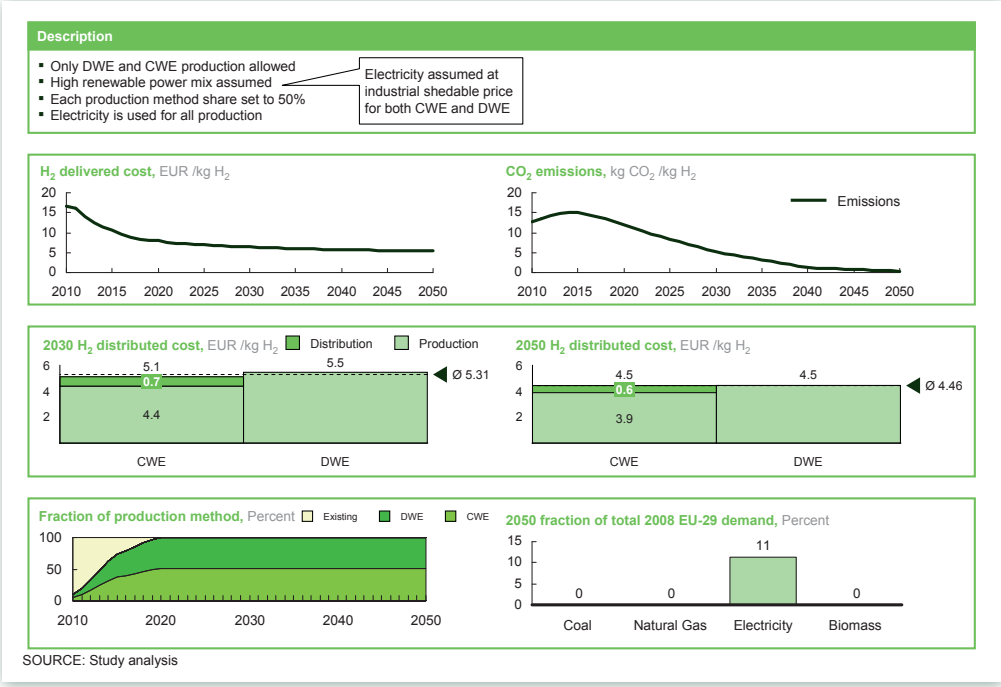


Exhibit 26: An alternative production mix representing 100% electrolysis, with 80% renewable production by 2050

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.

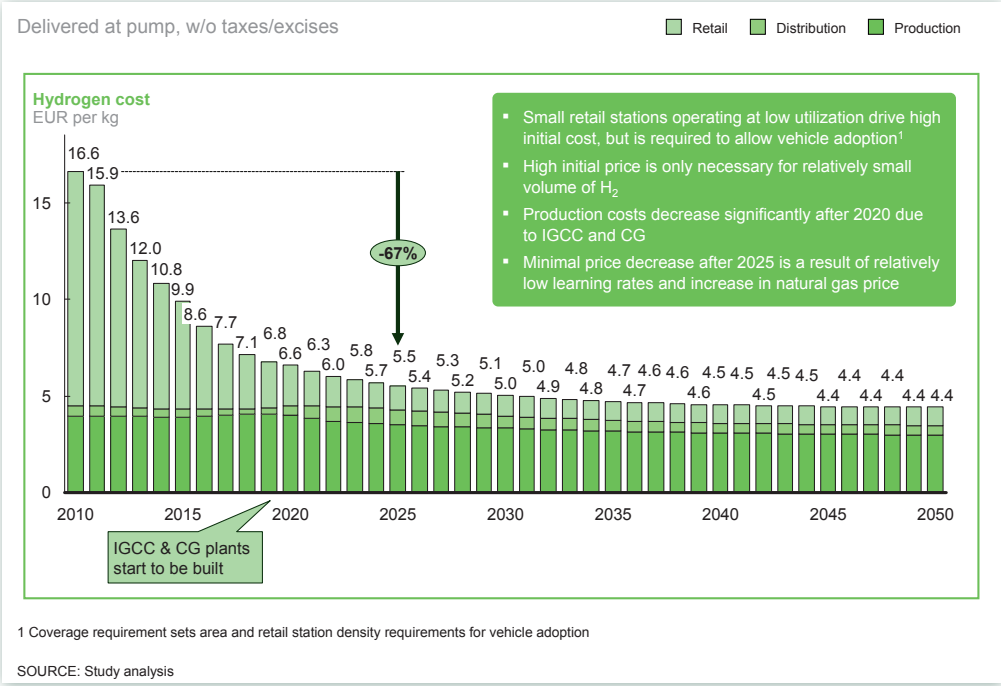


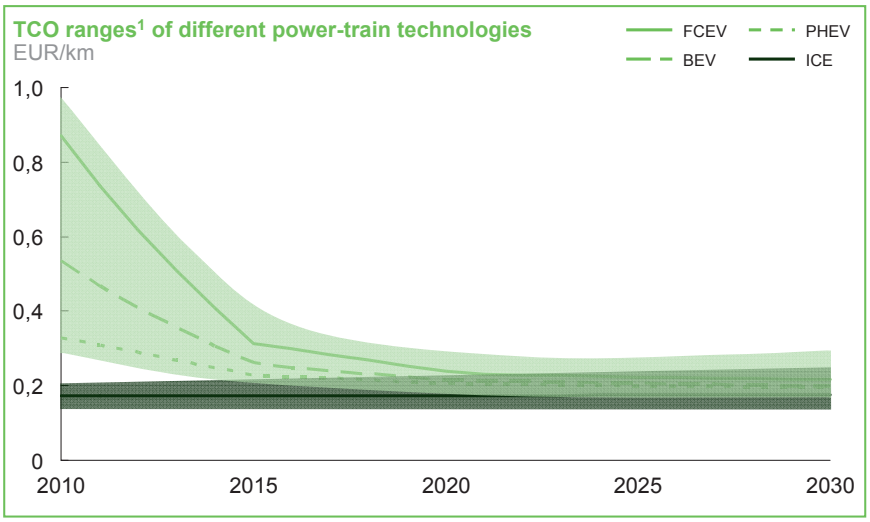
Exhibit 27: The cost of hydrogen reduces by 70% by 2025, then stays relatively flat (excluding taxes and incentives)

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).

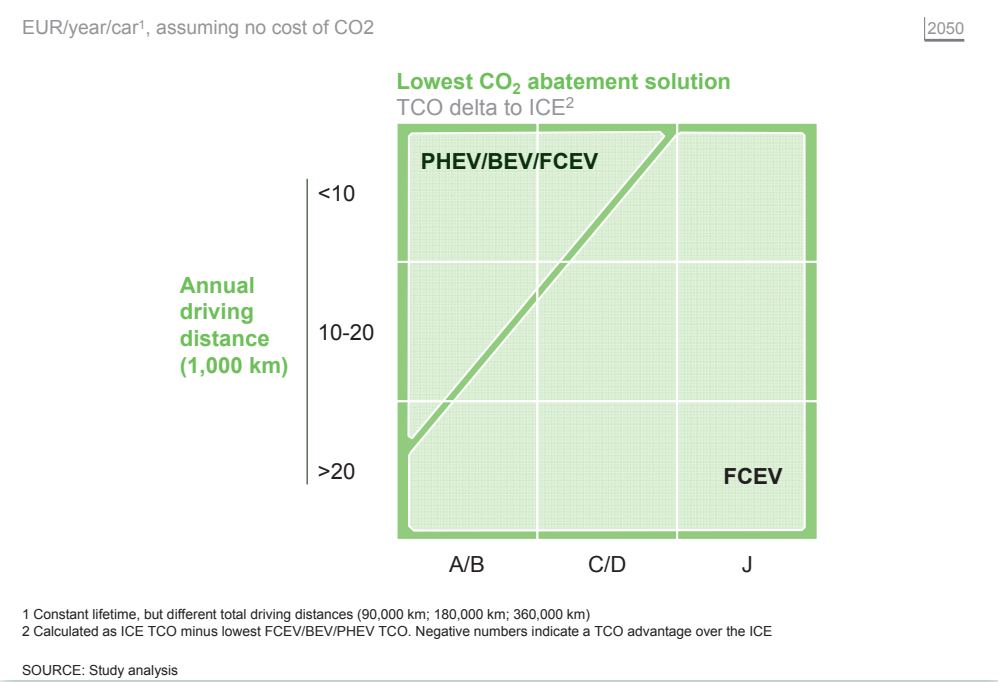


Exhibit 32: The FCEV has a TCO advantage over BEVs and PHEVs in the heavy/long-distance car segments

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

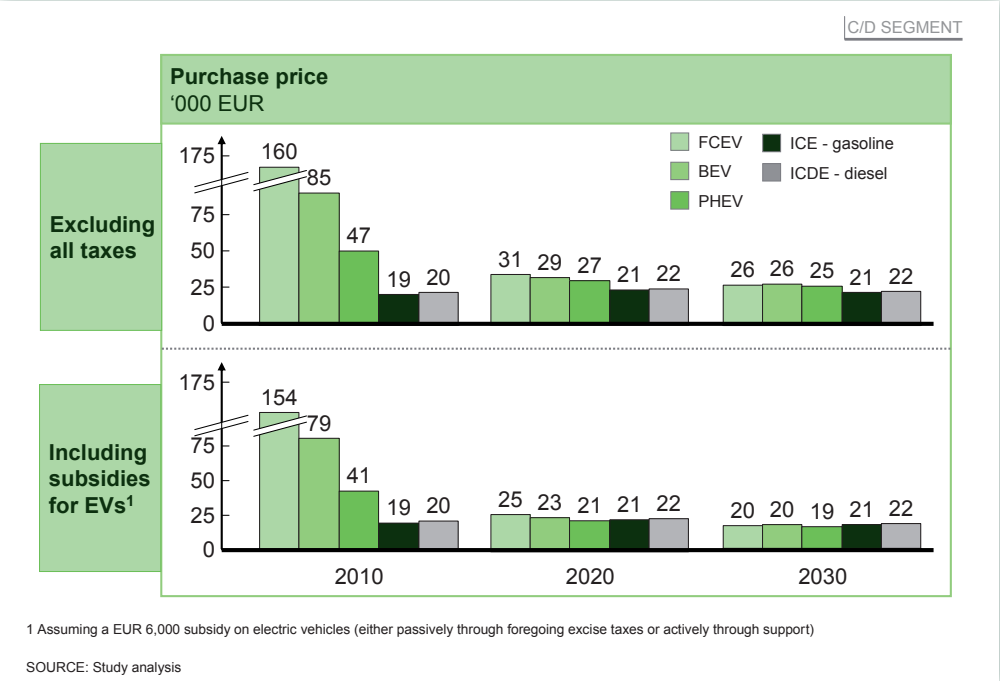


Exhibit 33: The higher purchase price of BEVs, FCEVs and PHEVs could be partially offset by tax exemptions

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.

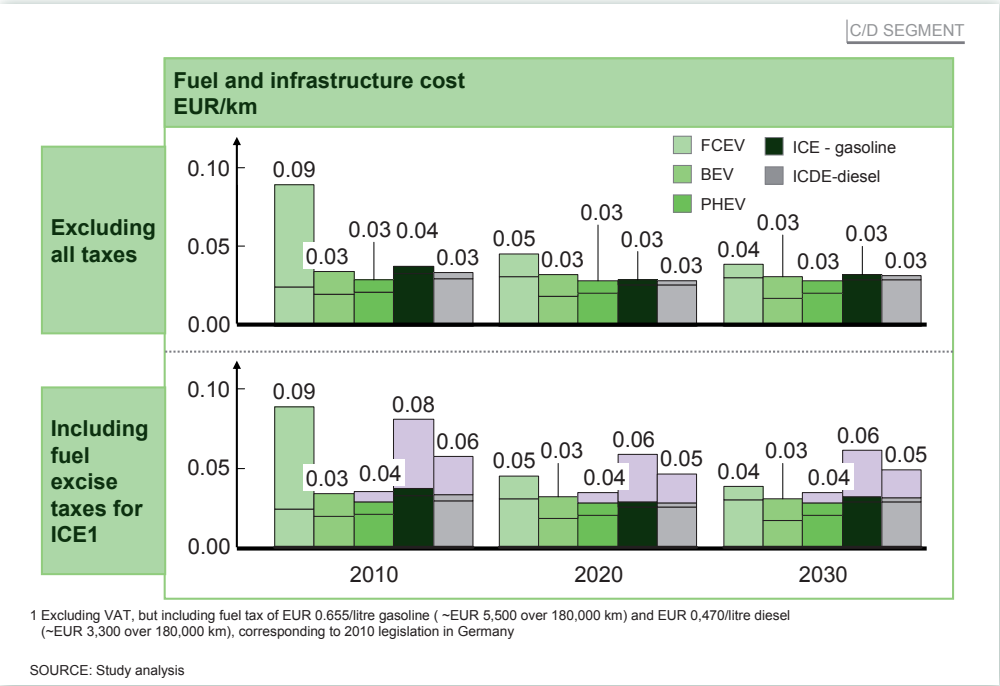


Exhibit 34: Temporarily forgoing fuel taxes on hydrogen or electricity will level fuel costs for all power-trains over the next 10 to 20 years

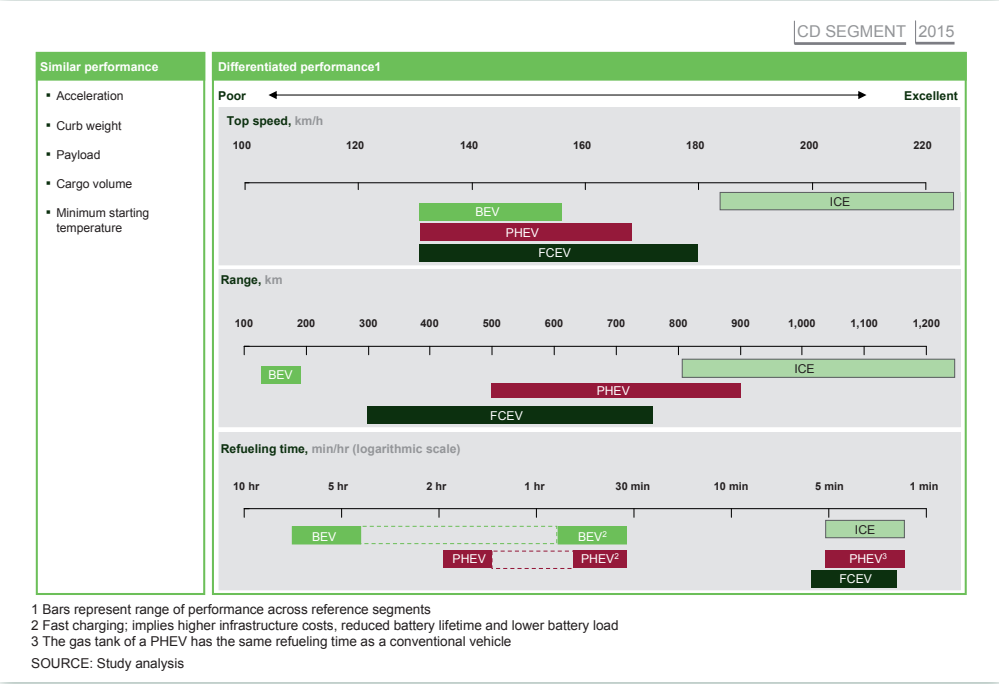
If hydrogen is not taxed like gasoline and diesel in the ramp-up phase, infrastructure and fuel costs for FCEVs could become cost-competitive with ICEs as early as 2020.

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

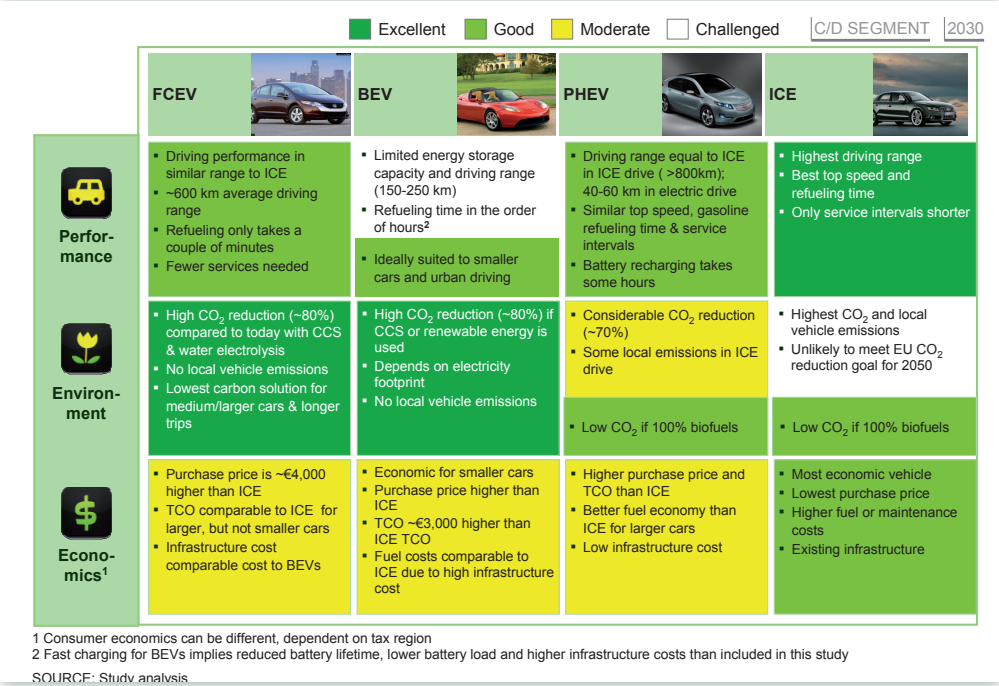


Exhibit 36: Snapshot of 2030 – only a portfolio of power-trains can satisfy key criteria for performance and the environment

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.

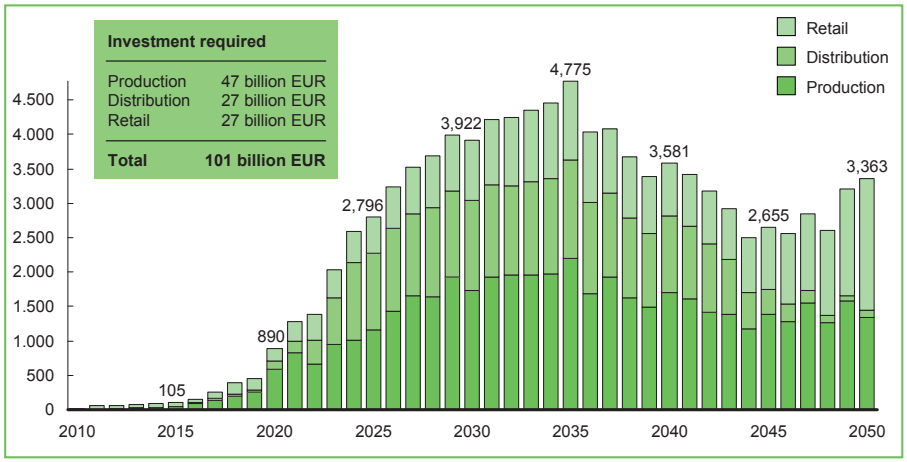
In the first decade of a typical roll-out scenario, supply infrastructure costs – especially those for a retail infrastructure – are initially higher, due to lower utilisation. Nevertheless, sufficient network coverage must be available for consumers and initial investments required could amount to €3 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.

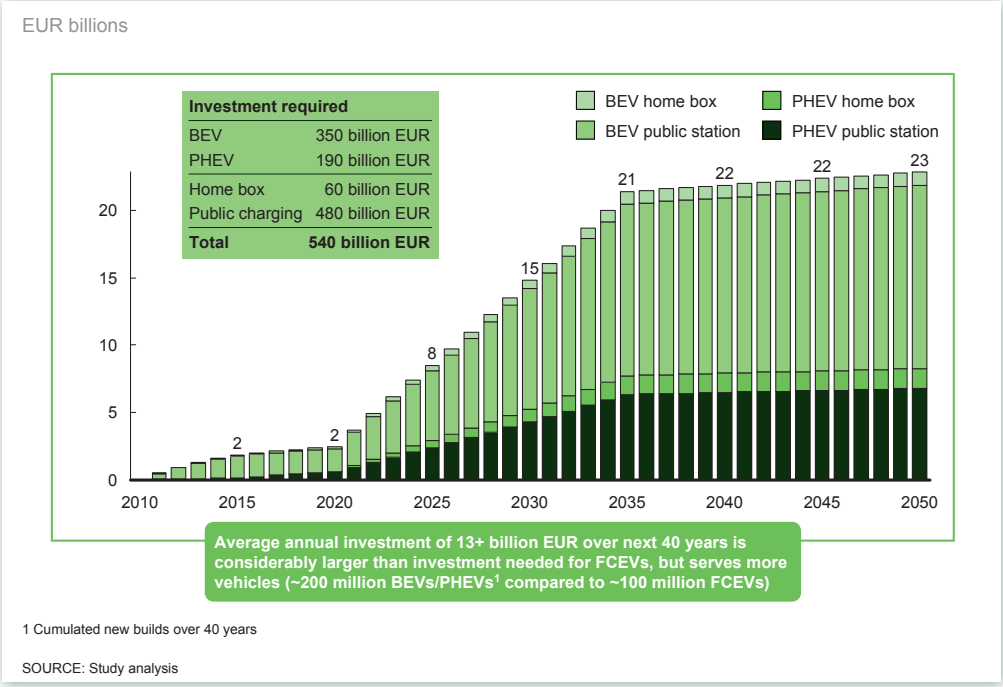


Exhibit 38: A large-scale roll-out of BEVs and PHEVs in Europe could require up to €500+ billion over the next 40 years

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.

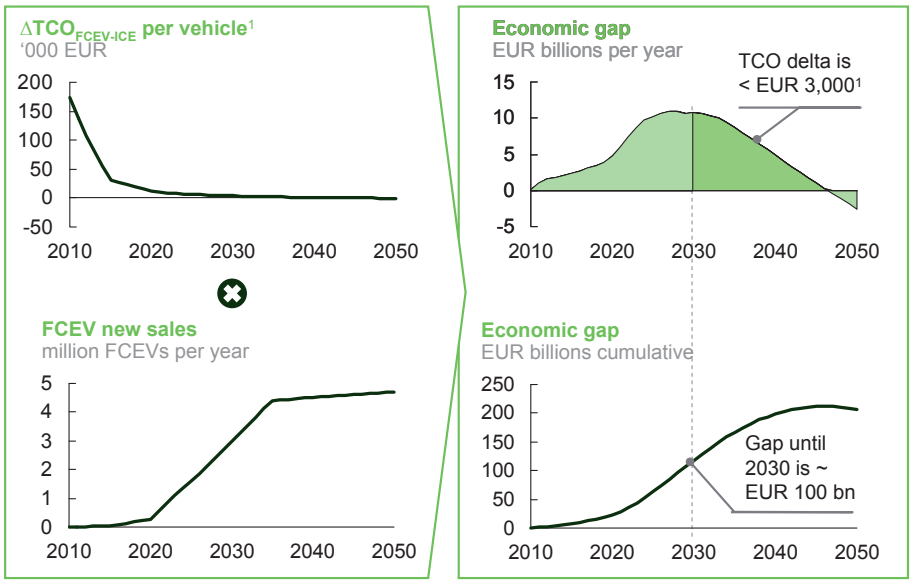
2020-2030: a cumulative economic gap in the order of €75 billion due to increasing car volumes

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



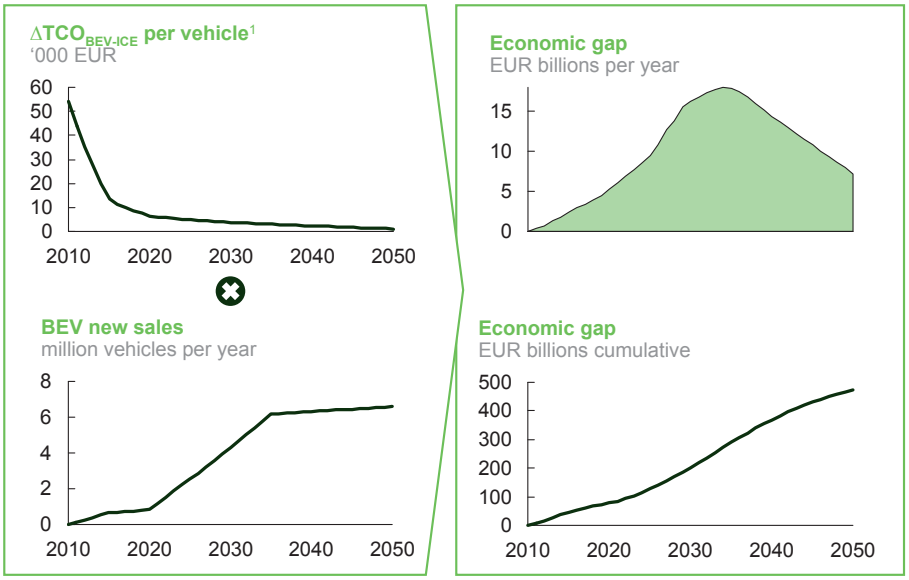
1 Weighted by segments (7% in A/B segments, 39% in C/D/E segments and 54% in J/M segments)

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).

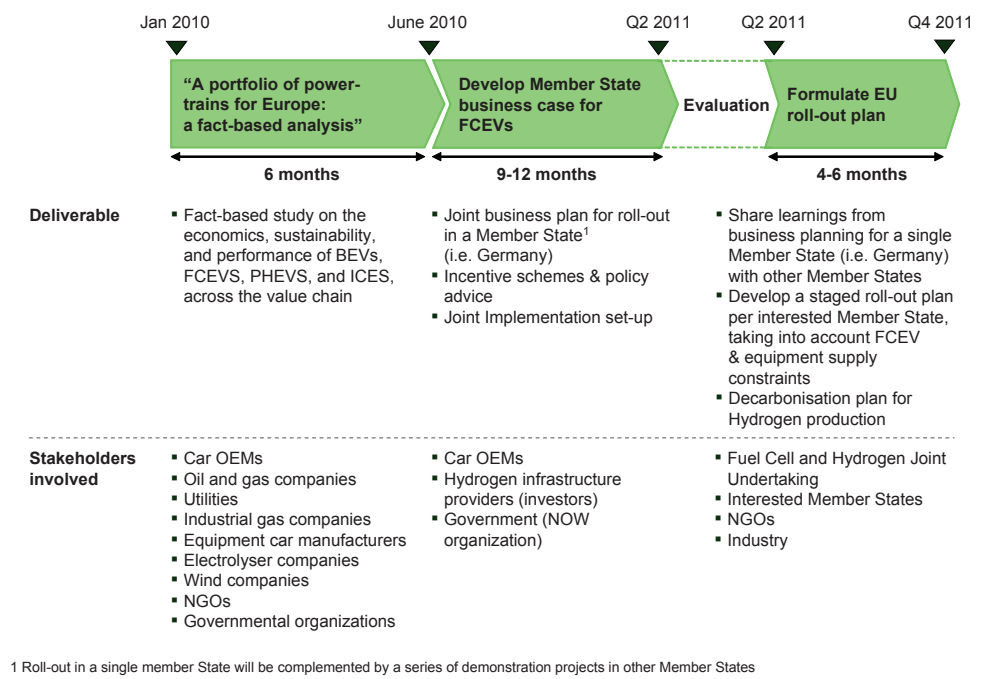


Exhibit 41: Market launch plan for FCEVs in Europe

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

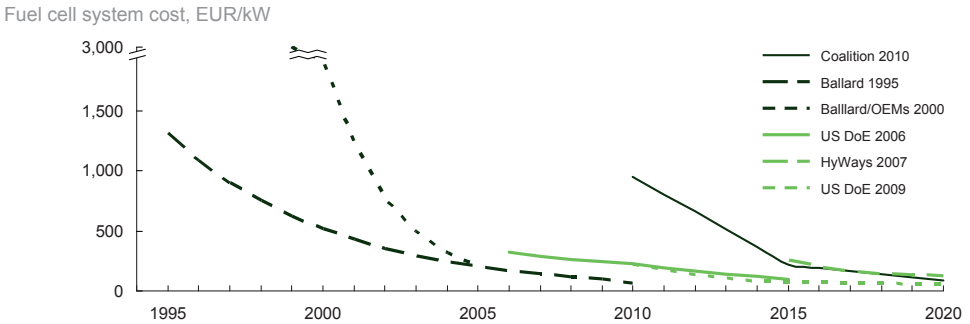
Common production pathways | 2020

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



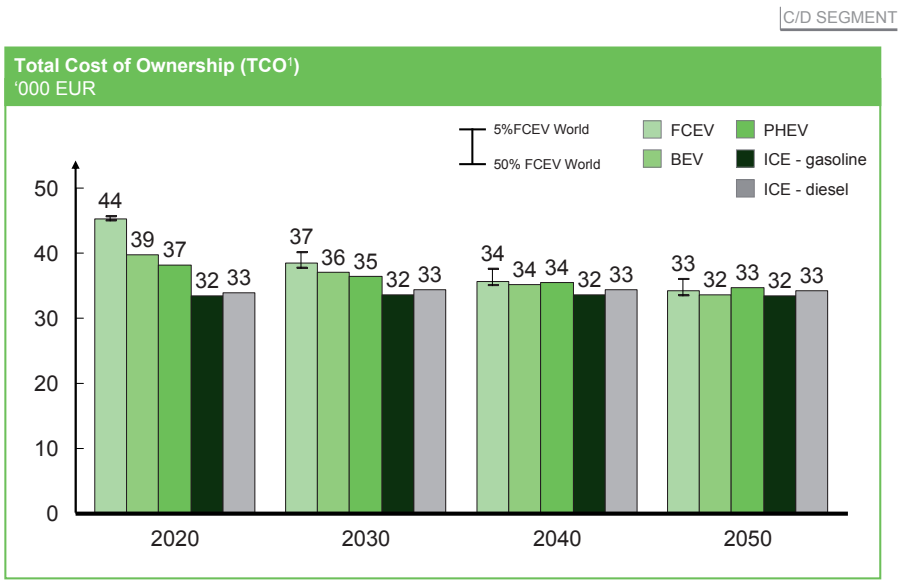
	Ballard, 1995	Ballard/OEMs, 2000	US DoE, 2006
Basis of promise	▪ Technical advance-ments, mass production	▪ Mass production, catalyst reduction	▪ Higher yields, mass production, reduced BOP
Size/timing of FC market	▪ USD 4 billion in 2000, ▪ 10-50 billion in 2010	▪ 100,000 vehicles by 2005	▪ Mass FCEV 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

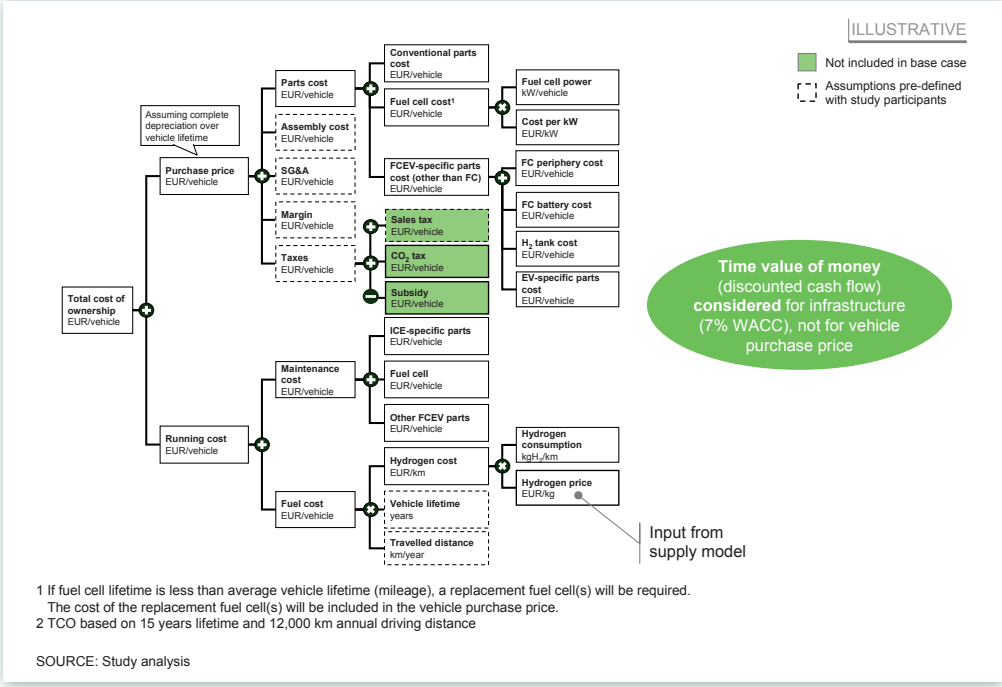
Exhibit 44: Summary of previous studies which were not based on proprietary industry data



1 Based on 15 years vehicle lifetime, 12,000 km annual driving distance, no tax (e.g., fuel excise, VAT)

SOURCE: Study analysis

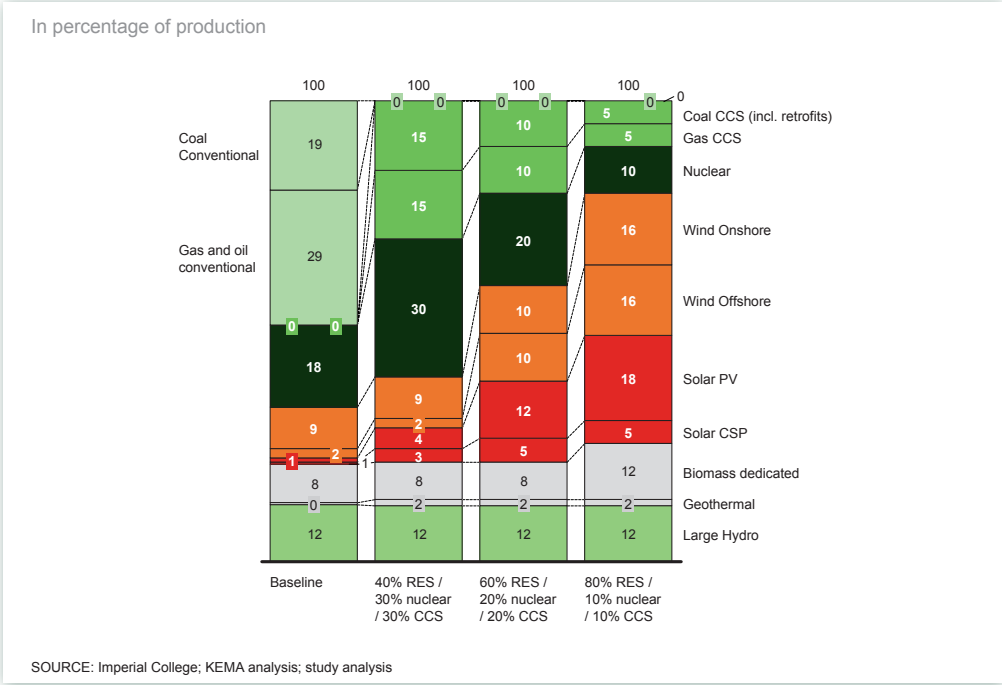
Exhibit 45: The different "world" scenarios for the penetration of FCEVs in the EU – 5%, 25% and 50% – do not alter the business case dramatically



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

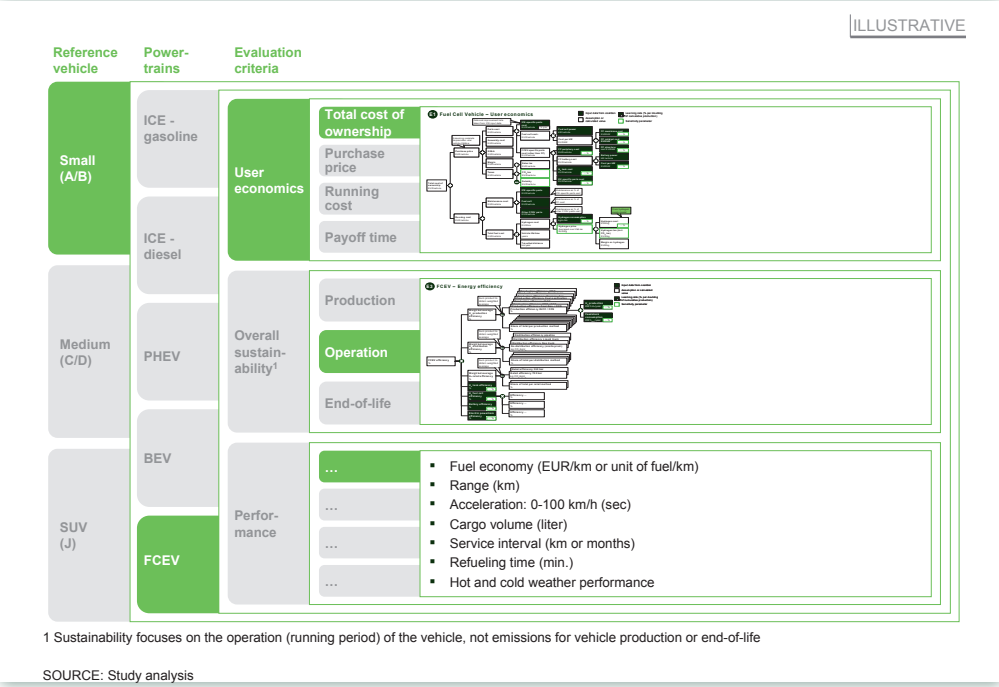


Exhibit 48: The basic structure of the vehicle model used for the study

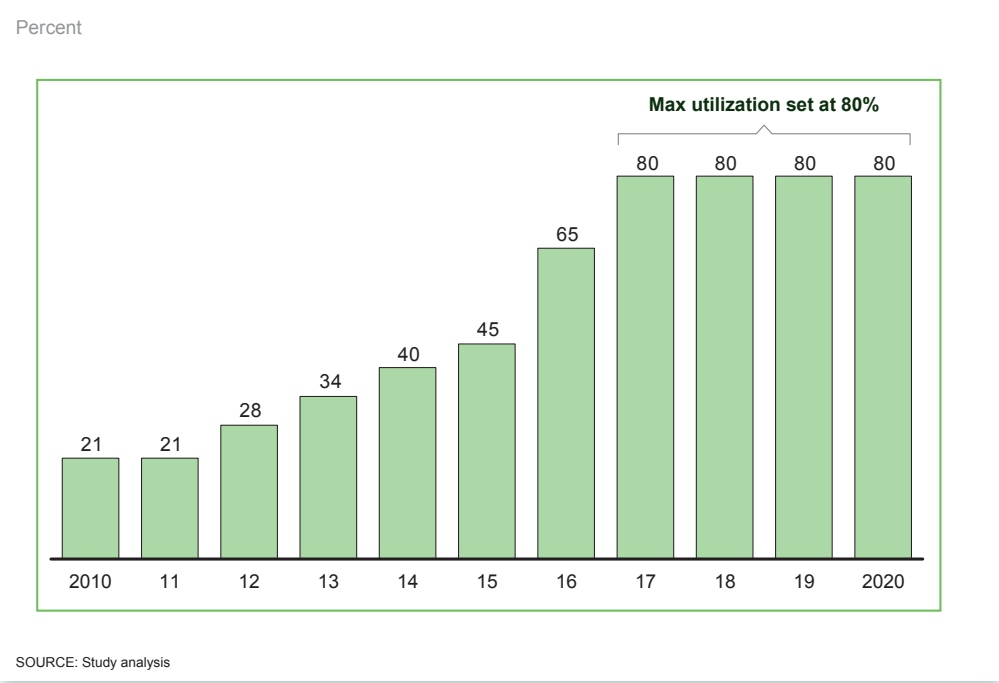


Exhibit 49: Average utilisation rate of hydrogen refuelling stations

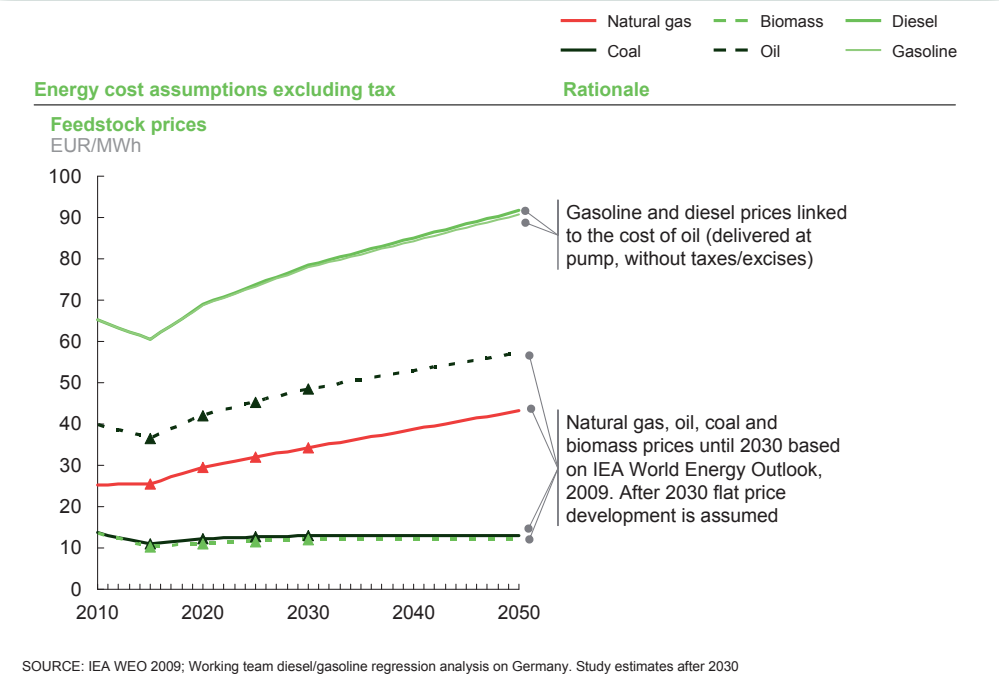


Exhibit 50: Feedstock price assumptions up to 2050 and corresponding gasoline and diesel prices (version 1)

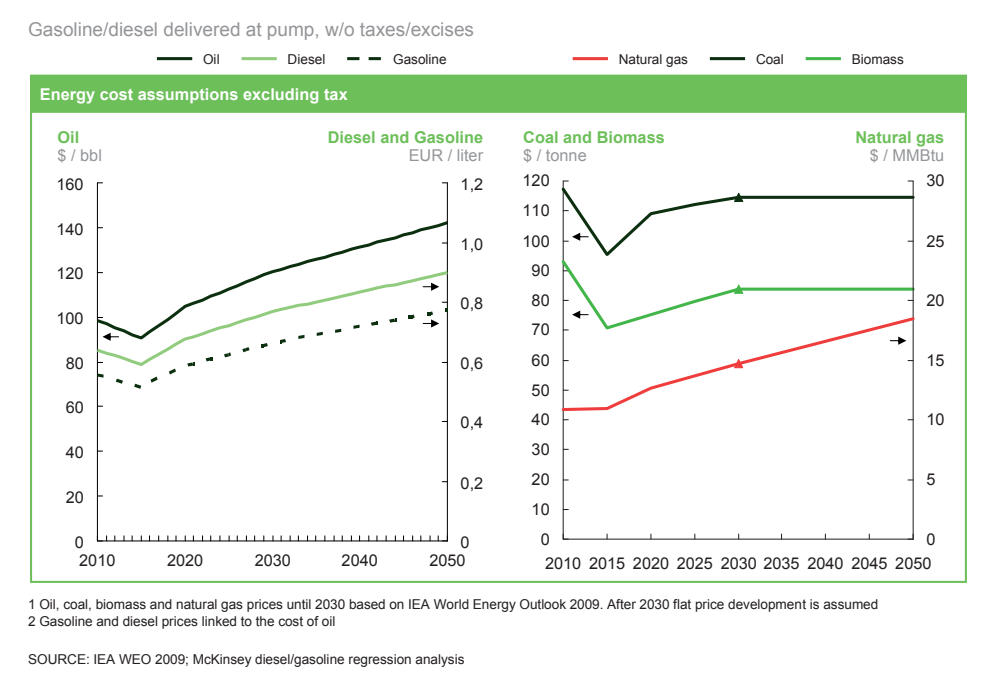
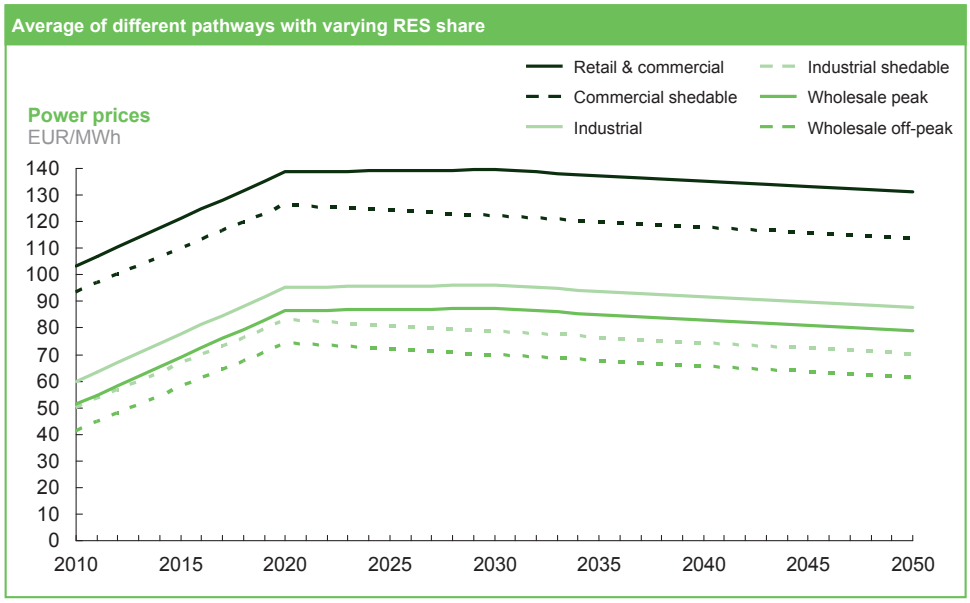
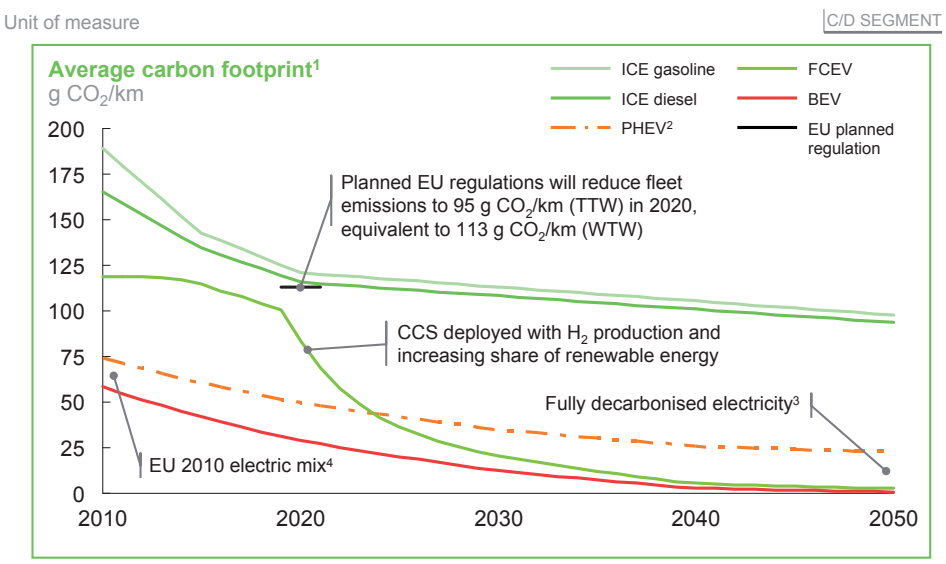


Exhibit 51: Feedstock price assumptions up to 2050 and corresponding gasoline and diesel prices (version 2)



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

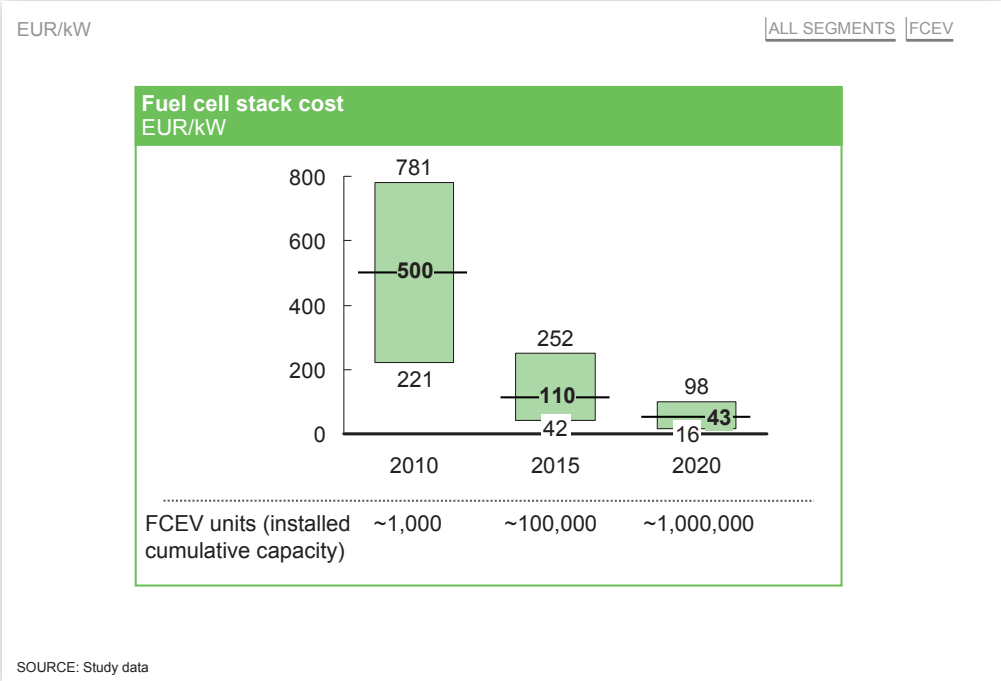


Exhibit 54: The cost of the fuel cell stack, based on data submitted by participating car manufacturers and suppliers

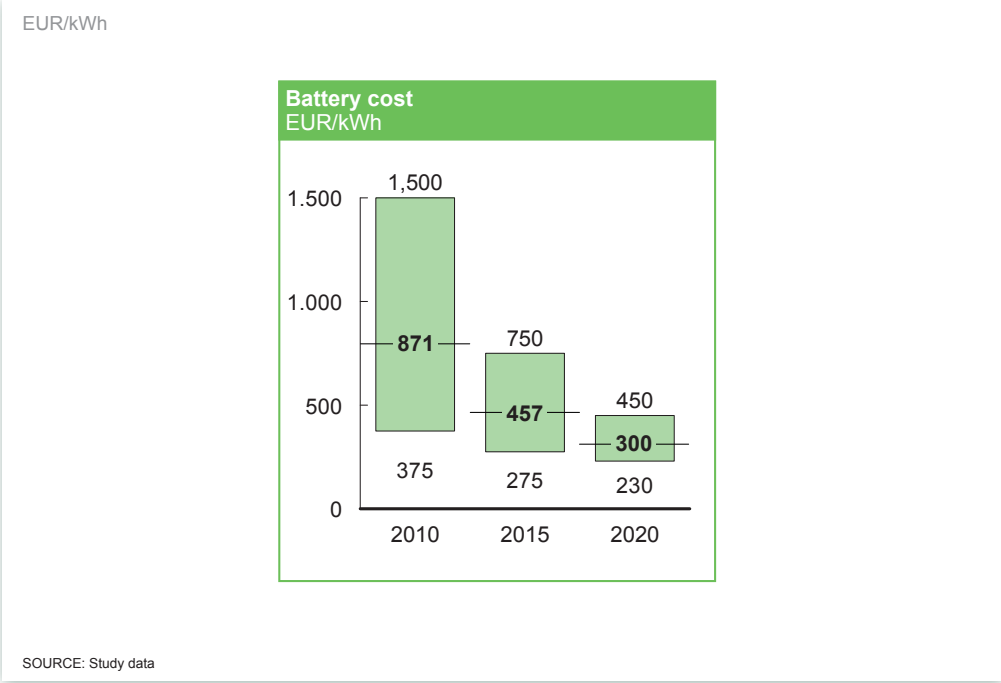


Exhibit 55: The cost of the battery, based on data submitted by participating car manufacturers and suppliers

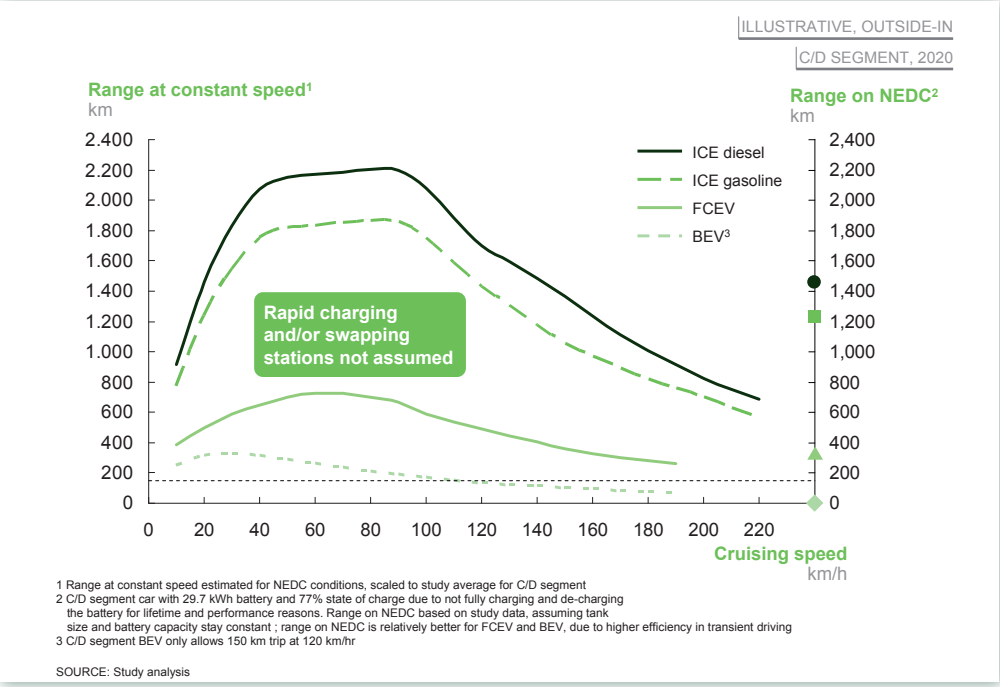


Exhibit 56: FCEVs have sufficient range at higher cruising speed, while BEVs are restricted on range

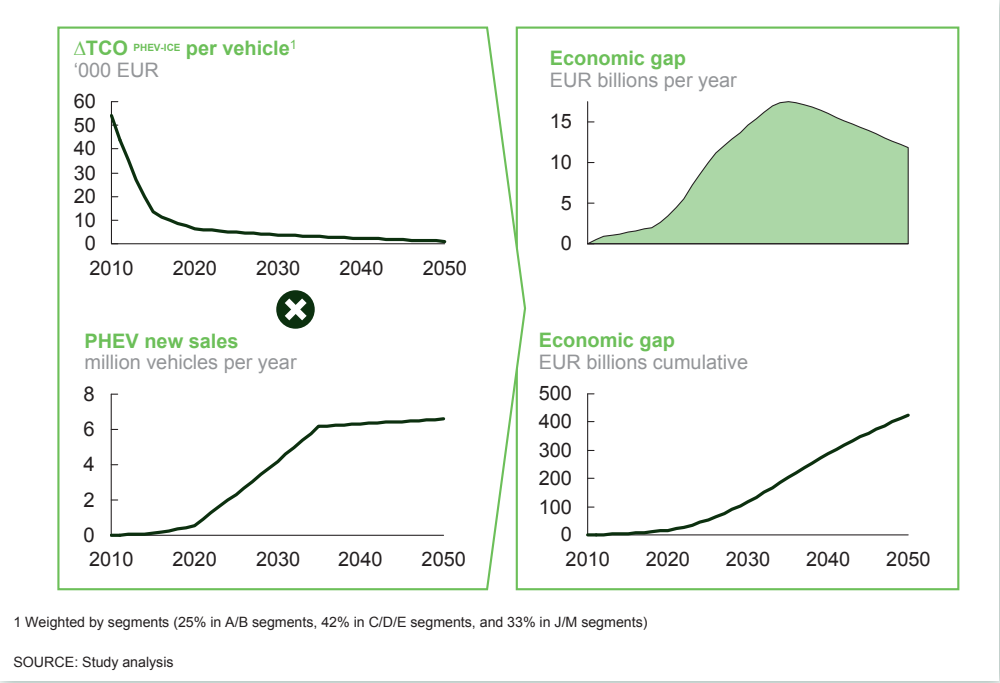


Exhibit 57: PHEVs face an economic gap of €420 billion by 2050

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:
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Att: Ms Alexandra Reis
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Letter of Understanding

on the Development and Market Introduction of Fuel Cell Vehicles

To: Oil and Energy Companies, Government Organizations and NOW GmbH

From: Daimler, Ford, GM/Opel, Honda, Hyundai/KIA, the Alliance Renault/Nissan, Toyota

Preamble

Road traffic has been steadily increasing in recent years and vehicle ownership is expected to grow. As a result, there will be increased priority on low and zero emission vehicles and an increase in overall CO_2 reduction goals. Over the last decade, governments, OEMs and the energy sector have given special attention to the introduction of hydrogen as a fuel for road transport as a priority option to reach several goals associated with emission management and CO_2 reduction.

Battery and fuel cell vehicles complement one another and can move us closer to the objective of sustainable mobility.

Development and Production Plan for Fuel Cell Vehicles

Based on current knowledge and subject to a variety of prerequisites and conditions, the signing OEMs strongly anticipate that from 2015 onwards a quite significant number of fuel cell vehicles could be commercialised. This number is aimed at a few hundred thousand (100.000) units over life cycle on a worldwide basis.

All OEMs involved will implement their own specific production and commercial strategies and timelines, and, as a consequence, depending on various influencing factors, the commercialisation of fuel cell vehicles may occur earlier than in the above-mentioned expected year.

Build-up of a Hydrogen Infrastructure

In order to ensure a successful market introduction of fuel cell vehicles, this market introduction has to be aligned with the build-up of the necessary hydrogen infrastructure. Therefore a hydrogen infrastructure network with sufficient density is required by 2015. The network should be built-up from metropolitan areas via corridors into area-wide coverage.

Key criteria for the hydrogen fuelling stations are:

- All hydrogen stations are publicly accessible and integrated into branded conventional fuelling stations,
- All hydrogen stations meet the requirements of SAEJ2601,
- All hydrogen stations are located smartly to enable customer access,
- The hydrogen is offered at a reasonable price to the customers.

The signing OEMs strongly support the idea of building-up a hydrogen infrastructure in Europe, with Germany as starting point and at the same time developing similar concepts for the market penetration of hydrogen infrastructure in other regions of the world, with one US market, Japan and Korea as further starting points.

In support of the above understanding, the parties hereof have signed this letter of understanding on the date(s) herein below indicated.

Letter of Understanding

on the Development and Market Introduction of Fuel Cell vehicles

Daimler AG
By:
Name: Dr. Thomas Weber
Title: Member of the Board
Date: 04.09.09

By:
Name: Prof. Dr. Herbert Kohler
Title: Vice President
Date: 04.09.09

Ford Motor Company
By:
Name: B. Mattes
Title: Chairman Ford-Werke GmbH
Date: 08.09.09

By:
Name: Dr. Franz-Josef Laermann
Title: Managing Director PD Ford-Werke GmbH
Date: 08.09.09

General Motors Corporation
By:
Name: Daniel M. Hancock
Title: GM Powertrain Vice President
Date: 04 SEPT 09

Honda Motor Co., Ltd.
By:
Name: Tsuneo Tanai
Title: Director, COO for Automotive Operations
Date: 7-Sep-09

Hyundai Motor Company / KIA Motors Corporation
By:
Name: Woong-chul Yang, Ph.D
Title: President R&D Division
Date: 07.09.2009

By:
Name: Hyun-Soon Lee, Ph.D
Title: Vice Chairman
Date: 07.09.2009

The Alliance Renault S.A / Nissan Motor Co., Ltd.
By:
Name: Minoru Shinohara
Title: Senior Vice President
Nissan Motor Co., Ltd.
Date: Sept. 8, 2009

Toyota Motor Corporation
By:
Name: Takeshi Uchiyamada
Title: Executive Vice President
Date: 4 Sep 2009