

R&D Programs for Hydrogen: US and EU

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Abstract

The possibility of a future economy based on H₂ and fuel cells is both promising and uncertain. As a consequence, in the US and in the EU significant actions, with similarities as well as differences, related to hydrogen R&D are being undertaken. Efforts are focused in both cases primarily on applied research, development and demonstration. Some striking differences result from the leading role of the Department of Energy (DOE) in the US, as opposed to the more unstructured, nation-based approach in the EU. R&D activities conducted both in America and Europe are reviewed and compared, and some tentative conclusions are advanced.

The case for hydrogen

Hydrogen (H₂) is, among other things, an energy carrier very abundant in nature in combination with other chemical elements. Molecular hydrogen (H₂) can be synthesized by energy intensive processes. H₂ must then be stored, distributed and finally utilised for energy generation. Internal combustion engines (ICE), in the form of reciprocating machines or gas turbines (GT), as well as electrochemical devices, known as fuel cells (FC), can convert H₂ into mechanical energy and/or electricity.

Possible incentives for the development of hydrogen technologies are related to either the potential to store electricity from intermittent renewable energy sources or to provide an alternative fuel for transportation.

At present only three approaches seem plausible for powering cars and trucks without oil and without significant CO₂ emissions: (1) hydrogen, (2) batteries, and (3) biofuels. Each of these encompasses a number of distinct possibilities depending on the primary energy source. Hydrogen can be derived from natural gas, coal, fossil-generated electricity, or non-fossil electricity; if a fossil fuel is the energy source, it must be used with carbon sequestration to achieve significantly reduced CO₂ emissions. Batteries offer similar options. Biofuels are more restrictive, and only advanced biofuels, such as cellulosic ethanol, would have a large impact on the emissions problem

Of course efficiency improvements to current internal combustion designs provide a partial forth alternative, although there are physical limits. The National Research Council (NRC) of the National Academies finds efficiency improvements more promising than Hydrogen Fuel Cell Vehicles (HFCVs) through about 2040. However, in combination with Plug-in Electric Vehicles (PEVs) the possibilities are striking¹.

¹ For instance, General Motors is currently hoping to begin selling PEVs with a 40 mile range in 2010. A 40-mile range is sufficient to cover 75 percent of the light-vehicle driving in the United States. Because the PEV is a hybrid, it will have increased efficiency; and, if used with a diesel engine, a doubling of efficiency should be easily achievable with present technology. This would result in roughly

Taking a longer view, the complete elimination of fossil fuel use is eventually inevitable. At that point, trucks and automobiles will be powered by electricity—from batteries or fuel cells—and by biofuels. Electricity will likely be produced by wind turbines, solar energy and nuclear power. HFCVs will then require the production of hydrogen by electrolysis, or a high-temperature process with advanced nuclear reactors. Assuming 70% efficiency for electrolysis or a high temperature process, and 70% efficiency for the fuel cell, the latter being a rather optimistic value, yields 49% efficiency for the conversion of bulk electricity to on-board electricity. Of course this ignores the need to pressurize and transport the hydrogen. By contrast, charging and discharging a battery is over 90% efficient. For this reason, the long-run dominance of HFCV technology over battery technology looks unlikely. However, this conclusion could be reversed by the development of cheap artificial photosynthesis for the production of hydrogen.

In the medium term, say between 2050 and 2075, hydrogen could possibly, although by no means certainly, dominate a combination of batteries, efficiency and biofuels². It should, however, be remembered that, unlike cellulosic ethanol and engine efficiency improvements, HFCVs will not automatically do much to reduce CO₂ emissions. There must be an additional policy requiring carbon capture when hydrogen is produced from fossil fuels.

At present, there is no case for tipping the balance towards a hydrogen transition. As the NRC explains, there is a “downside risk of pushing HFCVs (or any other specific technologies) before they are really ready or if they turn out not to be the best option, which could be extremely expensive and disruptive.”

There is also no proof that hydrogen is the most likely long-run solution. There exists, however, an excellent case for the present R&D effort in hydrogen technology. There is a modest chance that it could provide an enormous payoff. For example, it is possible that batteries and cellulosic ethanol will remain too expensive to be practical, and that breakthroughs in fuel-cell and hydrogen storage technologies will bring HFCVs to market sooner and more profitably than expected. And perhaps recent breakthroughs in artificial photosynthesis will eventually make solar-hydrogen the fuel of choice.

Funding such high-risk advanced R&D is something the market does poorly. Because of this, the government should support hydrogen research, and quite likely at a higher level than the current one. That is the case for hydrogen. It is also the case for funding all of hydrogen’s competitors, or as the NRC (2008b) says, taking a “portfolio approach.”

an 87% reduction in gasoline use. That is considerably better than what the NRC predicts could be achieved by HFCVs by 2050 under its optimistic Case 1.

² The situation does not seem to be clearer in the short run, between now and 2050. For instance, the NRC’s (2008b) Conclusion 14 states that “advanced conventional vehicles and biofuels—have the potential to provide significant reductions in projected oil imports and CO₂ emissions. ... [but] the deepest cuts in oil use and CO₂ emissions after about 2040 would come from hydrogen.” But this conclusion has been weakened by assuming that the future will bring only advanced conventional vehicles or biofuels, but not both. In fact the NRC (2008b) reports (see Figures 6.29 and 6.30) what happens if both improvements are realized. In this case HFCVs do not provide deeper cuts in either oil or emissions until after 2050. This conclusion only includes on what the NRC considers “evolutionary” technology.

R&D needs

R&D opportunities appear along every stage of the H₂-chain. As already mentioned, if the hydrogen-containing molecule includes carbon as a component or the energy to be supplied is generated from fossil fuels or from a “mix” including them, the H₂-production process emits CO₂, unless a carbon separation and storage (CSS) technology is incorporated; all these methods leave plenty of room for innovation and energy consumption minimization. Stationary and on-board storage demands high energy density materials. Distribution pipeline materials must be protected against the brittleness that H₂ can cause. The end use of H₂ in ICE requires high temperature process adaptation and materials, while its utilization in FC needs important materials research in order to increase durability, robustness and significantly lower their costs.

Feeding FC with conventional fuels such as coal, gasoil, gasoline, methanol or natural gas seems appropriate for stationary energy generation plants, to which a CSS technology can be added. For vehicle on-board FC applications H₂ is the adequate energy carrier.

A hypothetical economy for transport, based solely on H₂, would require its massive production. Several thousands of nuclear power plants or, alternatively, a gigantic penetration of renewable energies (in Europe) or possibly coal-based hydrogen synthesis plants (in the USA) would be necessary to supply the future fleet of vehicles. The H₂ storage and supply would demand rather expensive infrastructures for transport and distribution. On the other hand, from an efficiency standpoint, only the unmanageable electricity/energy supply (due to intermittency and unpredictability of wind and sun resources) should be used for H₂ generation, thus viewing H₂ as a storage method of electricity surplus. The previous remarks, added to the poor well-to-wheel efficiency as well as the elevated total (fuel production chain plus vehicle) emissions, as noticed by Wald (2004), would make FC, originally conceived for powering automobiles, a more suitable technology for stationary distributed CHP generation.

Determinants of the Transition to Hydrogen

Most analyses of the hydrogen transition rest on what is referred to in this literature (for example, NRC 2008b) as the “chicken-and-egg problem.” This alludes to the popular puzzle: “which came first the chicken or the egg?” Applied to the hydrogen transition, this is interpreted to mean that HFCVs must come before hydrogen fueling stations, and fueling stations must come before HFCVs.

This problem is, in fact, the central justification for a planned massive intervention by the U.S. Department of Energy in the HFCV market. But as daunting as this problem sounds, there are many historical precedents for its solution by market forces and without government intervention. For example, gasoline cars and gas stations suffer from an identical problem, as do diesel trucks and diesel stations, and TVs and TV stations, and many other technology pairs.

So how does the market solve chicken and egg problems? The most important answer is niche markets³. In fact, the first use of hydrogen vehicles in several countries appear to be buses. Their obvious advantage is that city buses never take long trips and always return to the same point at night. A whole fleet needs only one fueling station and that station is well utilized. There are also many fleets of delivery vans, government cars and so on with similar attributes. But the point is not to solve the transformation problem, but rather to understand why the market is so much better at solving it than is the government. Governments can miss the most obvious niche markets, while those with money on the table are extremely creative at finding niches⁴.

The second most important answer to the problem is “related markets,” and NRC (2008b) has identified such a “potential remedy to the ‘chicken-and-egg’ problem of ... investments in large-scale hydrogen production. ... The flexibility of gasification systems to provide electric power as well as hydrogen can significantly reduce the financial risks associated with large-scale hydrogen production during the scale-up phase of HFCV commercialization.”

One likely scenario, without government subsidies, is that HFCV costs will come down gradually, lagging behind politically determined goals. As this happens, fuel cells, hydrogen storage tanks and HFCVs will find high-value niche markets, exactly as expensive solar panels and \$98,000 plug-in electric cars have found high value niche markets. This is the general path to market transformations. But if there is a sudden breakthrough, and HFCV becomes the clearly dominant technology, there will be a rush to avoid being left behind as too many companies compete to become the market leader in fuel cells, hydrogen storage tanks and HFCVs. The market problem will prove to be a bubble of the internet variety, with over—not under—investment, followed by a shake out. Of course, if one asks the industry how much subsidy is needed to kick-start the market, as good businessmen, they will be obliged to name the highest plausible number.

³ By way of contrast, Gronich et al.’s approach to the transition is to look for a way to jump-start the final mass market from day one. Gronich (2008) suggest that because New York is compact it will be one of the easier mass-markets to jump start. This is probably correct, but it is likely not the solution that the market would choose without heavy guidance. The trouble with trying to jump-start a metropolitan area is that most people who buy a car want the option of taking the occasional longer trip. Under the Gronich plan, New Yorkers would have to wait eight years to visit Washington DC and much longer do visit relatives in upstate New York.

⁴ Since the chicken-and-egg school of thought offers no detailed theory of why the market cannot self-start, let us consider their claims concerning the consequences of this problem. Gronich et al. (2008), in Figure 16, shows that, without government support, the HFCV market would not achieve a 5% market share until 2048, while with \$8 to \$18 billion in subsidies it would achieve a 90% share by that date. Alternatively, this can be read as a 20 year delay if the government does not subsidize the transition. With \$18 billion in subsidies, the industry experiences essentially no cost during the transition. Is it plausible that the need for an \$18 billion dollar investment would delay the industry for twenty years from moving to a new dominant technology?

Consider that in the third quarter of 2007 GM posted a \$39 billion dollar loss. Falling behind the market can be quite risky. With hydrogen technology already developed by 2015 and waiting only for a solution to the chicken-and-egg problem so that high volume production levels can bring down the cost of HFCVs, every car company will live in fear that some other car company will move first and take over the new market. Once this market takes off, according to Gronich et al., it will, without benefit of subsidies, grown from a 5% to a 55% share of new car sales in nine years. The companies left behind will suffer fates similar to GM’s. That is why many are now researching hydrogen cars. They are not terribly optimistic, but they fear being left behind.

Another likely scenario, without subsidies, is that after a decade of slow progress on hydrogen, battery technology will surpass hydrogen technology fairly definitively, and only stationary fuel cells will remain in use. In this case, we will possibly have saved the cost of subsidies and hastened the adoption of the superior technology by not getting in its way.

R&D efforts in the US

Technology Goals

Most discussions of the federal hydrogen research initiative revolve around one or more of DOE's technology goals. The U.S. DOE, in conjunction with the auto industry, established the U.S. FreedomCAR Fuel Partnership. This partnership set technology goals for 2015 that were considered sufficient to bring about the commercialization of HFCVs. The most important of these goals are listed in Table 1.

Table 1. DOE's Hydrogen Technology Goals for 2015

Technology	Goal for 2015
Hydrogen	\$2/kg retail (by distributed methane reforming) ¹
Fuel-cell	\$30/kW at a volume of 500,000 units / year
Fuel-cell	80 kW
Fuel-cell	5,000 hrs life
Fuel-cell	60% efficiency (80 mpg equivalent)
Fuel tank	\$2 / kWh (= \$65.40 / kg H ₂)
Vehicle	300 mile range
Vehicle	80 miles/gasoline-gallon-equivalent

¹ DOE (2007, p. 19). Other goals are from NRC (2008b, p. S-4).

The first six of these goals, those concerning the cost of hydrogen and fuel-cells, can best be understood by comparison with other methods of generating electricity. After all, a fuel cell is just an electric generator and the market provides many types of generators for comparison. For a fuel cell meeting DOE's 2015 assumptions, the variable cost of electric power would be \$2/kg for hydrogen divided by 32.7 kWh per kg of hydrogen divided by 60% efficiency, or 10.2¢/kWh. If we assume a 100,000 mile life for the fuel cell, and use DOE's goal of 80 mpgge, and 32 kWh/gge, we find the fuel cell is expected to produce 41,250 kWh. At a fuel cell cost of \$2,400, this comes to a fixed cost of 6¢/kWh. This is fairly inexpensive for such a small-scale generator.

Such a fuel cell would be most competitive with peaking generators, which are those with the lowest capital costs. According to DOE (2008), the type of generator with the lowest capital cost is currently an advanced combustion turbine with a 230 MW capacity. The "overnight" capital cost of such a generator is \$450/kW, 15 times more than DOE's fuel cell.

In fact, Oak Ridge National Laboratory (2008) reports that large-scale hydrogen generation costs only between \$1.00 and \$1.50/kg. At \$1.25/kg, DOE's fuel cells installed at these plants would generate power for only a little more than a conventional peaking unit, which is quite surprising given these fuel cells are so small and designed for the rigorous environment of driving.

How Much Progress?

With such optimistic goals, and no argument showing they should be attainable by 2015, the only means of judging them is by the rate of technical progress. DOE has issued annual progress reports from 2004 through 2007. These cover all aspects of hydrogen R&D, but one of the most closely watched is fuel-cell costs so it is informative to see what has been reported regarding this goal.

The introductions to the four progress reports give the following values for fuel-cell cost per kW of capacity. All assume a factory production level of 500,000 units per year. In the early 1990's the cost was approximately \$3,000/kW. In 2002, it was \$275/kW, followed by \$175 in 2004. In 2005 it was "approaching \$110," and in 2006 it was \$108, and in 2006 it was \$107. The duplicate final date reflects the unusual fact that the November 2007 progress report gives a new, slightly lower value for 2006, rather than reporting the value for 2007, as would have been customary.

Adding to the puzzle of the missing 2007 value, the 2007 report contains the subcontractor reports which in the past have provided DOE's cost estimates. The primary one, from TIAX LLC (Lasher, 2007), reports enormous cost reductions because of a reduced need for platinum. The other, from Argonne National Laboratory (Ahluwalia et al., 2007) reports the missing value. It reports, \$108 for 2006 and \$67 for 2007. Apparently DOE felt the new results were too good, or too shaky, to report.

Two problems with fuel-cell cost evaluation make progress difficult to judge. First, the choice of characteristics of the evaluated fuel cell changes frequently. Second, the estimates are based on very high production levels, even though no fuel cells of that year's assumed fuel-cell design may have ever been produced.

For example, the fuel-cell design in 2002 called for gasoline as a fuel and not hydrogen. The reported cost value has been partially adjusted for this change, but it does not appear that the \$100/kW drop in cost from 2002 to 2004 was primarily due to technical progress. On the other hand, the assumed fuel cell designs since 2004 appear to be increasing in performance. The 2007 cost of \$ 67/kW is based on a new design by the 3M Company, which utilizes 3M's nanostructured thin film (NSTF) catalyst support for the cathode (Lasher, 2007) (Ahluwalia et al., 2007). The cathode uses the bulk of the platinum. NSTF (apparently a "carbon fabric"), in conjunction with vacuum deposition of an iron-cobalt-carbon-nitrogen cathode catalyst followed by a heat treatment, has apparently been successful in cutting the platinum requirement by more than half while increasing performance (3M Company, 2007). The research team at 3M is also optimistic about production costs.

While the results sound promising, it appears difficult to estimate the per-unit cost of producing 500,000 units per year when not a single complete fuel-cell, never mind an 80 kW stack of them, has been produced. Although this estimation may be unusually heroic, which may explain why it was not reported by DOE in its summary, all fuel-cell cost estimates have been based on volume extrapolations that reduce estimated costs by more than an order of magnitude, and sometimes by two orders of magnitude from the low-volume costs with which there is actual experience.

Progress on hydrogen storage is even more difficult to pin down. Walsh et al. (2007) report that “Unlike other major technologies being pursued in support of [zero-emission vehicles], hydrogen storage technologies have advanced relatively little in recent years.” The NRC’s Case-1 scenario, which comes close to assuming DOE’s goals will be met, assumes hydrogen storage costs will be five times greater than DOE’s goal of \$2/kWh in 2015 (\$65/kg of hydrogen). But even this higher value is not an estimate of what will happen, but rather an optimistic possibility.

Because DOE’s on-board-storage-cost targets appear to be so wide of the mark, the discussion of storage research goals is quite ambiguous. Apparently, there is a presumption that the goals will be widely missed and manufacturers will use rather costly high-pressure storage. Meanwhile, the research emphasis has shifted to a wide range of alternative approaches that are in the early stages of development. These are based on advanced (not yet fully developed) materials, and generally operate at fairly low pressures and at temperatures far above that of liquid hydrogen.

Research Funding and Subsidies

The NRC has compiled federal funding data for prior years, 2004–2007, and has estimated likely necessary funding for future years, 2008–2023. The two sets of estimates use different funding categories, but these have been aligned to the extent possible in Table 2 below. The NRC has also estimated that an additional \$300 million per year will be needed for 2021–2023, when it believes HFCVs will break even and become self supporting. This brings their estimated total R&D funding for 2008 through 2023 to \$5 billion, although they say more will likely be needed, and that some funding will likely continue after 2023.

Table 2. DOE’s R&D Funding for Hydrogen Light-Duty Vehicles in Selected Years

	2004	2005	2006	2007	2011	2015	2020	2004– '20
H ₂ Production & Delivery	30	40	32	66	58	45	15	706
Production Demonstration					17	50	0	223
Fuel Cells and H ₂ storage	53	68	59	90	115	110	110	1721
Fuel-Cell Demonstration					50	20	10	355
Safety and Codes	8	6	5	16	25	10	5	232
Nuclear H ₂ Production	6	9	24	19				58
Renewable H ₂ production					30	30	30	404
System Analysis	1	3	5	10	10	10	5	146
Technology Validation	16	26	33	40				115
Science	0	29	33	50	60	60	60	892
Total	114	181	190	290	365	335	235	4852

All figures in millions of 2005 dollars. Data from the NRC (2008b), Tables 7.1 and 7.2. The year 2011 is listed because the NRC estimates it to be the peak spending year.

Besides federal spending on R&D, the NRC (2007b) reports that over \$2.5 billion was spent by the private sector through the end of 2006. Private spending was primarily by GM, Ford, Chevron/Texaco, United Technologies, GE and nine venture capital companies. The NRC also describes a survey conducted for the fuel-cell industry, which reports that combined federal and private R&D spending for the United States in 2005 was \$320 million. Subtracting federal spending of \$220 million leaves \$100 million in

privately funding research.⁵ Because the response rate of the survey was only 37%, the NRC inflates this number to \$700 million. Perhaps \$270 million would be a better guess, and because of likely self-selection bias in the survey responses, this value must be considered highly uncertain. In any case, the NRC estimates that there will be \$11 billion in privately funded R&D from 2008 through 2023. Anecdotal evidence, especially from GM and Toyota, indicates that interest in hydrogen may be waning as interest in plug-in hybrids accelerates.

Even if research funding achieves the goals set by the DOE, a widespread belief within the hydrogen-research community holds that the market will not adopt the new technology. Consequently significant effort is being expended to plan various ways to subsidize HFCVs and the fueling stations these will require. The authors of the NRC report judge that a “realistic estimate” of government subsidies is the “incremental cost of purchasing [producing] fuel-cell vehicles, plus about half the total cost of building and operating the [required] infrastructure.”

For Case 1, NRC estimates the cost of these subsidies at \$40 billion for the auto industry and \$8 billion for the fueling industry. Gronich et al. (2008) propose three subsidy-policy scenarios to support Case 1.⁶ These have a cumulative cost, through 2025 (at which time HFCVs are supposed to break even), of either \$8, \$14, or \$18 billion—considerably less than NRC’s \$48 billion. No explanation of the consequences of the different subsidy levels is provided by Gronich et al. (2008) other than a calculation showing that with less subsidy and the same production level and prices, the auto industry will have lower profits. Apparently these three “policy options” are all thought to be compatible with identical transitions to an HFCV future.

R&D efforts in the EU

Germany is the most advanced member state (MS) within the EU in H₂ and FC technologies; this vantage position is a consequence of significant R&D spending for over 20 years. The “National Organization for H₂ and FC Technology” (NOW) has been established in February 2008 as a component of the “National H₂ and FC Technology Innovation Programme” (NIP) in order to promote the development and commercialization of products and monitor the global Programme. 1000 M€ will be jointly spent by the Federal Government and the German industry over the next 10 years for development and demonstration activities.

The EU has been modestly investing in H₂ and FC R&D. 8 M€ funds under the Second Framework Programme (FP2) for the period 1986-1990 has yielded the way to 145 M€ and 320 M€ under FP5 (1999-2002) and FP6 (2003-2006), respectively. The latter dedicated 19.3 % of the budget to H₂ production, 8.1 % to storage, 14.6 % to basic research on FC, 19.3 % to transport applications and 8.0 % to stationary applications as depicted in Table 3. Several projects span over bioprocesses, biomimetics, photolysis, low and high temperature electrolysis as well as thermochemical cycles to produce H₂ with a target cost of 2.5-4.0 €/kg by 2015. The development of advanced materials (metal hydrides, carbon cones, nanomaterials) allowing the 2015 objectives of storing

⁵ The \$220 million figure includes \$40 million not shown in Table 2 because was earmarked by Congress for projects that were generally considered ineffective.

⁶ The NRC’s Case 1, and Gronich et al. (2008) Case 1 are both derived from Gronich (2007).

0.025 kgH₂/l as a compressed gas or 0.040 kgH₂/l in the liquid state. Research on PEMFC and SOFC is aimed at reducing the cost by a factor of 10 by 2015 to figures of the order of 300 €/kW; materials for membranes, bipolar plates, anodes and cathodes, catalysts with no platinum, development of new manufacturing processes, and operation at lower temperatures in the case of SOFC are among the research topics covered. Some demonstration projects under the heading of transport applications intend to show the viability of increasing PEM efficiencies well above 40 % and lifetimes of up to 5000 hrs for cars and 10000 hrs for buses. Projects related to stationary applications mostly concentrate on MCFC and SOFC and aim at demonstrating efficiencies above 40 % with less than 10 % degradation and costs in the range of 1500 to 6000 €/kW as well as over 12000 hrs of operation for the residential sector and more than 30000 hrs for industrial uses.

R&D Topics

Source:(European funded Res H2&FC, H2&FC Review Days, EC Brussels, Oct. 2007)

TECHNOLOGY	% € FP6	2015 TARGETS	FP6 PROJECTS	Research
H2 Production	19.3	2.5 €/kgH ₂	R: HYDROSOL-II, SOLREF, HYVOLUTION, SOLARH O: DYNAMIS, NEMESIS, HYTEC, INNOHYP, GENHYPEM, HI2H2 Distrib: NATURALHY	Bioprocess Biomimetics Photolysis L&HT Electroly Th-Ch Cycles Materials/Proc
H2 Storage	8.1	CG: .025 kgH ₂ /l L: 0.040 kgH ₂ /l	STORHY, COSY, HYCONES, NESSHY, HYTRAIN	Comp/Cryog, Metal Hydrides Carbon cones Nanomaterials
H2 Infrastruct			HyWAYS, Roads2HyCom, DYNAMIS,	
Bas.Research FC	14.6	2-3000€/kW → 300 €/kW	PEM: FURIM, APOLLON-B, AUTOBRANE, CARISMA, FCANODE SOFC: Real-SOFC, SOFC600 GENFC	PEM:Membran € Catalyst no Pt, HTElectroly mem SOFC:Material: bipol plates, ano, cat, el.LT→600°C, manufact(screen print, tape cast)
Transport Appl.	19.3	Car: 40%/100€/kW/5000h Bus: 40%/100€/kW/10000 APU:35%/500€/kW/5000	HYFLEET-CUTE, HYCHAIN-MINITRANS, ZERO-REGIO, HYICE, HYTRAN, HYSYS, HOPE, FELICITAS, CELINA, MC-WAP	DEMOS
Stationary Appl.	8.0	Res: 40%, 6000€/kW, >12000h(10%) Ind: 40%, 1500-5000 €/kW, >30000 h (10% degradation)	BICEPS, FlameSOFC, NextGenCell, LargeSOFC, MOREPOWER	DEMOS

Table 3. R&D topics and projects under the European Commission 6th Framework Programme and 2015 EU targets.

A High Level Group (HLG) on H₂ and FC was created in 2003 by Ms Loyola de Palacio, EC Vice-President and Commissioner for Energy and Transportation, with the assignment of producing some recommendations on possible approaches to a hypothetical H₂ future economy. A report, "Hydrogen Energy and Fuel Cells: A vision of our future", proposed a roadmap and the creation of a European Technology Platform (HFP). The latter started operation in 2004, with a management structure composed by an Advisory Council (AC), a MS Mirror Group (MG) and representatives from the EC. The AC, composed by major EU H₂ and FC industrial stakeholders and research community members, and its Executive Group constitute the governing board of the

HFP. The interests of the MS are conveyed through the MG. Between 2005 and 2007 the HFP has produced several key documents (Strategic Research Agenda, Deployment Strategy, Strategic Overview and Implementation Plan), apart from conducting several projects and initiatives, as well as holding an annual General Assembly. A reasonable “Snapshot 2020” (Table 4) considers a realistic initial penetration of portable FC, portable generators, stationary FC and road transport FC.

Figure 1: “Snapshot 2020”: Key assumptions on Hydrogen & Fuel Cell Applications for a 2020 Scenario

	Portable FCs for handheld electronic devices	Portable Generators & Early Markets	Stationary FCs Combined Heat and Power (CHP)	Road Transport
EU H ₂ / FC units sold per year projection 2020	~ 250 million	~ 100,000 per year (~ 1 GW _e)	100,000 to 200,000 per year (2-4 GW _e)	0.4 million to 1.8 million
EU cumulative sales projections until 2020	n.a.	~ 600,000 (~ 6 GW _e)	400,000 to 800,000 (8-16 GW _e)	1-5 million
EU Expected 2020 Market Status	Established	Established	Growth	Mass market roll-out
Average power FC system	15 W	10 kW	<100 kW (Micro HP) >100 kW (industrial CHP)	80 kW
FC system cost target	1-2 €/ W	500 €/kW	2000 €/kW (Micro) 1.000-1.500 €/kW (industrial CHP)	< 100 €/kW (for 150.000 units per year)

Table 4. “Snapshot 2020” with key assumptions on H₂ and FC applications for a 2020 Scenario

The interconnection of EU H₂ communities between 2015 and 2020 allowing to travel from Madrid to Stockholm in a FC vehicle (HFCV) and the completion of the full H₂ infrastructures by 2050 are contemplated as ambitious targets. Four innovation and development actions (IDA) on “H₂ Vehicles and Refuelling Stations” (2661 M€), “Sustainable H₂ Production and Supply” (759 M€), “FC for CHP and Power Generation” (2853 M€) and “FC for Early Markets” (1110 M€) were established (the estimated budgetary needs between 2007 and 2015 appear within parenthesis) and subdivided into well defined tasks within the Implementation Plan (IP).

The HFP proposed the creation of a Joint Technology Initiative (JTI) to overcome the fragmentation of R&D activities by fostering the cooperation among industrial stakeholders; a consistent execution of the long term strategy outlined at the IP was aimed at ensuring well defined R&D programmes matching industrial needs. 58 companies from 15 different MS initially established in 2007 the Industry Grouping (IG) as a legal entity, leading the steps towards the JTI; over 10 M€ have been invested by the IG stakeholders for the JTI preparation. The companies participating at the IG, both large corporations and SME, represent 90 % of the total industrial investment on H₂ and FC and share 50 % of the JTI Program Office running cost. By the end of 2007 the JTI proposal was adopted by the EC and the project FCHInStruct was launched as a part of the JTI formal preparation; the latter was a Coordination and Support Action, co-funded by the EC and the IG. The creation of a Research Grouping (RG) was initiated in the second half of 2007; by January 2008, 49 participants from every MS had expressed interest in joining the RG to be integrated within the JTI. The JTI FCH received the approval of the Council on February 26, 2008, and that of the European

Parliament on May 20, 2008. A stakeholder General Assembly in October 2008 will formally launch the JTI operation.

The JTI Governing Board will be composed of 6 members from the IG, 5 from the EC and 1 from the RG, and will receive advice from a Scientific Committee and from the FCH States Representatives Group. The head of the JTI Programme Office will be the Executive Director; Projects as well as coordination and cooperation with Regional and International Programmes will be the responsibility of this Office. The FCH Joint Undertaking (JU) will be the legal entity coordinating the use and efficient management of funds committed to the JTI; it will be established under Article 171 of the EC Treaty and will operate from 2008 to 2013, with a possible extension to 2017. The Stakeholders General Assembly of members from IG, EC, RG, MS, Regions, International Organizations, NGOs and other industrial and research groups will provide input to the JTI governance.

50 % of the JTI budget will come from industry, while 50 % will be provided by the EC, MS and the European Regions. For the FP7 (2007-2013) the EC has allocated 470 M€ under Energy, Transport, Materials and Environment Programmes; a matching budget of at least 470 M€ will be supplied by the private sector. Additional contributions of about 200 M€ from non EC public entities and private groups are expected. The IDA, defined by the IP with an overall budget of 7383 M€ for the period 2007-2015, will be streamlined and the different tasks prioritized and adapted to a reduced funding of about 1100 M€ for the period 2007-2013.

Comparison between UE (DGTREN & DGRES) and USDOE

As it has already been mentioned, Germany is the leading EU MS in H₂ and FC R&D. H₂ funding reached its peak in 1991 and it has been reduced by a factor of 20 over 10 years' time. FC investment had its maximum in 1995 and declined by 30 % until 1999. During the same period the USDOE funding has more than doubled for both H₂ and FC starting from about 100 M\$/yr in 1992; that year the H₂ spending in the USA was more than twice that in Germany, while the FC investment in the USA was near 20 times that of Germany. That situation was even less favourable to Germany in 1996 with the previous figures being approximately 30 and 10, respectively.

In 2003 the EC HLG recognized the need of a drastic action by the EU on H₂ and FC R&D in order to overcome its significant weakness in comparison with the USA and Japan. In some respects, the structural organization of the European JTI resembles that of the USDOE SECA (Solid State Energy Conversion Alliance), a public-private partnership (PPP), initiated in 1999, bringing together industry, research groups and government to foster the accelerated development of SOFC systems; however, the technical leadership of USDOE in SECA seems, in principle, more significant than that of the EC, through DGTREN and DGRES. The JTI IP bears some similarities to the Core Technology Program of SECA, supporting long-term research activities typically not prioritized by industry and with a dynamic annual Peer Review process.

It seems pertinent to remark that, while the operation of USDOE could be compared with that of an orchestra, with well trained musicians (15 National Laboratories, near 300 University research groups and powerful companies) actively coordinated by a

single conductor (USDOE and its body of scientific advisors), the coordination of DGTREN and DGRES at the European level is hampered by 27 orchestras with 27 conductors at the MS, which insist on playing their own scores, with inefficient spending of funds and not profiting from synergies. The EC JRC activities in support of EC policy measures are not comparable to those of the USA National Laboratories.

Research institutions, far from the standards of excellence, can be a part of joint European endeavours. The fragmented character of European R&D within several MS, with regional differential approaches not always well coordinated, compound the EC difficulties.

The way forward

The possibility of a future economy based on H₂ and FC is both promising and uncertain. The fate of these technologies might well be conditioned by the decisions of China and India on their commercialization and deployment.

However, due to low well-to-wheel efficiencies and to high fuel-chain plus vehicle emissions, H₂ and FC, originally conceived for automobile propulsion, might be better suited for stationary CHP applications.

Regarding H₂ production, natural gas is a precious fuel and should not be used for the production of H₂, while its generation from coal should include CSS technologies. Massive nuclear and renewable power should be the carbon-free energy sources for possible H₂ large-scale production processes. A rational approach, contributing to alleviate the intermittent and unpredictable nature of some renewable energy resources, would produce H₂ from the unmanageable electricity surplus, storing it and, subsequently using it, either in ICE or in FC, for electricity generation along periods of no wind and/or sun. The use of ICE to burn H₂, as well as fossil fuels or biomass, with CSS, should be carefully evaluated in comparison with the alternative utilization of FC. In any event, the development and demonstration of H₂-storage methods, as well as robust and inexpensive FC seems to be a top priority.

Research on materials and processes for H₂ production and on materials and innovative manufacturing for FC are the fields of vital interest. Industrial development and demonstration projects should be actively launched in the near and medium terms, before medium/long term deployment, commercialization and market penetration can follow. Well balanced funding strategies encompassing short, medium and long term R&D activities should be undertaken by Public-Private Partnerships. The allocated funds for H₂ and FC should be necessary and sufficient, in competition with alternative/promising fuels and conversion technologies. High quality management of programs and projects is essential and should include annual peer reviews and evaluations of performance and strategy; technical learning rates will equally depend on good funding, on excellent R&D and on quality management.

Temporary subsidies might be considered for penetration and deployment activities, while technology commercialization should be supported through rational and internationally homogeneous regulations, standards, procedures and licensing. However, it is likely that the market will find a cheaper path, through niche and related

markets, to complete the transition to hydrogen—if that proves to be the right solution. And that is the real reason to let the private sector lead the market transition. In other words, the great advantage of relying on market incentives, such as a cap-and-trade system or a carbon tax, is that it will allow the market to determine the correct timing and the correct direction for the transition. This is what markets are good at and bureaucracies notoriously fail at. On the other hand, markets are poor at conducting advanced research, and governments have the required deep pockets and risk tolerance. It would be best to let both sides do what they do best.

Conclusion

Research on and development of hydrogen technologies are reasonable and necessary activities, in spite of uncertainties related to the future of a “hydrogen economy” in competition with alternative solutions. However, it also entails important R&D spending. Therefore no single economy, neither the US nor the EU ones, can reasonably and profitably face the required efforts in isolation. Furthermore, experience shows that albeit its faults, the US centralized research approach has been much more successful than the less structured and fragmented EU pursuit.

In any event, the penetration of most hydrogen technologies is a long-term issue. A priori favouring of specific technologies for massive deployment can be an incorrect strategy and even detrimental to the long-term hydrogen future. Rather, proper economic public incentives should be established for different alternative competing technologies. Then entrepreneurs should look for the niche and related markets that could spawn earlier and wider applications of hydrogen.

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