PLATAFORMA TECNOLÓGICA ESPAÑOLA DEL HIDRÓGENO Y DE LAS PILAS DE COMBUSTIBLE

GRUPO DE TRABAJO DE ESTRATEGIA Y PLANIFICACIÓN

ALMACENAMIENTO Y DISTRIBUCIÓN DE H2

Elaborado por:

12 de Abril de 2006

Borrador

1. Resumen Ejecutivo

Tabla de Contenidos

2. Objeto y Alcance

El Grupo de Estrategia y Planificación tiene por objeto el desarrollo de la estrategia que debe seguir España para posicionarse adecuadamente a todos los niveles en las tecnologías del hidrógeno y de las pilas de combustible; su análisis se efectuará tanto desde el punto de vista de la aplicación (transporte, estacionaria, portátil), como desde el punto de vista de las tecnologías involucradas (pilas de combustible, sistemas de almacenamiento de hidrógeno, etc.). A su vez, se subdivide en Subgrupos de Trabajo, en una Matriz por temas y un Subgrupo de Financiación.

El objeto de este documento es establecer la contribución del Subgrupo de Almacenamiento y Distribución al documento bajo la responsabilidad del Grupo de Estrategia y Planificación (GEP), cuyo contenido e índice se fijó en la reunión de coordinadores de 18 de enero, y consistente en:

1. Análisis DAFO
2. Agenda para la PTE-HPC: a corto (-2010) y a medio plazo (2010-2020), para investigación básica, desarrollos tecnológicos, y proyectos de demostración e infraestructura.
3. Acciones transversales (Incluyendo en este punto las posibles sinergias entre diferentes grupos)
4. Estimación de costes de las acciones propuestas.

El alcance del presente documento es contribuir a la versión 1 del documento del GEP, previsto para Junio de 2006.

3. Análisis DAFO

Cursiva: cuestiones específicas de H2.

4. En rojo: se precisan aclaraciones.

Fortalezas	**Debilidades**
Existencia de grupos consolidados de I+D. Gran potencial de las energías renovables en España. Existencia de una red robusta de transporte y distribución energética / Empresas españolas muy fuertes en distribución de hidrocarburos y gas / Red de Gas Natural amplia Versatilidad. *Dos estaciones de servicio de H2 del proyecto CUTE, una de ellas realizada con tecnología de empresas nacionales* *Proyecto HyChain, con despliegue de vehículos especiales y dispensadores de botellas de CGH2* *Producción actual de H2 en varios puntos del territorio, logística de CGH2 bien desarrollada, con tecnólogos propios.*	Escasa implicación empresarial en I+D aplicado al almacenamiento. Baja coordinación de los grupos de investigación / Insuficiente dedicación de centros de investigación. Falta de mercado. Lejanía de las zonas de europa más pobladas Territorio poco poblado en promedio y con vacíos poblacionales *Ausencia de instalaciones y tecnólogos en licuefacción de H2 y electrolizadores* *Ausencia de redes industriales de H2*
Oportunidades	**Amenazas**
Existencia de fondos europeos. Potenciación de las redes de transporte y distribución de energía del país. Iniciativa de coordinación de los grupos de investigación. Fuerte apuesta del país por el transporte por carretera. *Integración con técnicas renovables de generación energética para suplir la variabilidad de estas / Visión original del despliegue de infraestructura: producción descentralizada por renovables para atender población dispersa.* *Creación de una infraestructura desplegada en torno a las estaciones actuales y los productores industriales*	Percepción social de peligro. Pérdida de oportunidades y liderazgo tecnológico frente a otros países / *Imposibilidad de liderazgo en LH2 y producción on-site por electrolisis* *Fuera de la primera fase de la red de autopistas de H2 europeas* *Barrera para el despliegue de vehículos con almacenamiento LH2*

5. Agenda a Corto Plazo (-2010)

Investigación básica

Almacenamiento en estado líquido

- Investigación básica aplicada a la mejora de sensores

Almacenamiento por adsorción en sólidos porosos

- Mantener la investigación en nuevos materiales, para aumento del porcentaje de H2 en peso, mejora de la cinética mediante el uso de nuevos catalizadores y reproducibilidad de resultados.

Almacenamiento por adsorción en hidruros metálicos

- Métodos de desorción a menores temperaturas.
- Aplicación a bajas temperaturas.
- Estudio de hidruros complejos.

Almacenamiento por reacción química

- Mejora de la cinética mediante el uso de nuevos catalizadores
- Aumento del porcentaje de H2 en peso.
- Aplicación a bajas temperaturas.

Desarrollos tecnológicos

Almacenamiento en estado líquido

- Ingeniería aplicada a un mayor control y seguridad

Almacenamiento del gas comprimido

- Diseño de tanques y materiales, sistemas de compresión (hasta 700 bar)

Almacenamiento por adsorción en hidruros metálicos

- Seguridad en el empleo de magnesio.

Distribución para aplicaciones portátiles y de transporte de pequeña potencia:

- Apoyar el desarrollo industrial de este almacenamiento y del modelo de negocio del punto de venta

Proyectos de demostración e infraestructura

Distribución para aplicaciones estacionarias:

- Apoyar experiencias en gestión de microrredes de H2 para usos residenciales

Distribución para aplicaciones de transporte:

- Apoyar la estandarización de las estaciones de servicio, para conseguir una reducción en los costes de instalación. Por ejemplo, fomentando la creación de uno o varios consorcios, cada uno con tecnología y modelos de negocio diferenciados y complementarios.

6. Agenda a Medio Plazo (2010-2020)

Investigación básica

Distribución para aplicaciones estacionarias:

- Estudiar el transporte de H2 generado de manera descentralizada a través de la red de gas natural: barreras y economía.
- Estudiar la transición del gas natural al hidrógeno: compartir red o coexistencia de redes.

Desarrollos tecnológicos

Distribución para aplicaciones estacionarias:

- Apoyar experiencias en redes y líneas prototipo (nuevos materiales, condiciones extremas...)

Proyectos de demostración e infraestructura

Distribución para aplicaciones de transporte:

- Estudiar los posibles despliegues de parque móvil e hidrogeneras hasta 2020 para evaluar las necesidades.
- Apoyar la instalación de, o reducir las barreras para, al menos una unidad de licuefacción de H2, para servir a la península. Esto fomentará el libre mercado de los vehículos de H2 en España.

7. Acciones Transversales

Recomendaciones generales:

- Interacción de este grupo con el grupo de difusión, formación y percepción social.
- Alineamiento con el Plan de Fomento de Energías Renovables y el Plan de Ahorro y Eficiencia Energética, y con HY-net.
- Almacenamiento y distribución muy condicionados por aspectos de seguridad y la normativa al respecto.

Distribución para aplicaciones portátiles y de transporte de pequeña potencia:

- Hay que desarrollar normativa y reglamentación coherente con los países de nuestro entorno
- Hay que estar vigilante a la evolución de este mercado en otros países

Distribución para aplicaciones estacionarias:

- Se debe apoyar la participación en proyectos sobre estandarización, normalización, reglamentación, seguridad, tanto internacionales, como a nivel estatal entre administraciones, tecnólogos, usuarios...

Distribución para aplicaciones de transporte:

- Hay que crear la normativa y reglamentación específica de estaciones de servicio, con coherencia con los países del entorno, con el objetivo de integrarlas en la red existente de estaciones de servicio.

8. Estimación de costes

9. ANEXO: Análisis Diferencial con la Estrategia de Despliegue de la Plataforma Europea

Pag 35 y siguientes.

Distribución y Almacenamiento de hidrógeno para aplicaciones portátiles

"At present two technologies are competing for portable low-power applications such as notebooks or other electronic gadgets. The DMFC (direct methanol fuel cell) significantly simplifies the fuel distribution and storage issues, however the volumetric and gravimetric power density of state of the art PEMFC in the range of 20-100 Watts is at present roughly 50 times higher than for DMFCs25. This leads to the conclusion that a deployment of portable DMFC application is strongly dependent on the R&D results of increasing the power densities within the next year whereas the bottleneck for the market introduction of portable PEMFC application is besides cost issues the provision of an appropriate infrastructure.

Regarding the storage of pure hydrogen for portable low power application nonerefillable cartridges either being CGH2 or metal hydrides have been proofed to be the most suitable technology regarding cost, easy handling and safety issues26. Acknowledging that the gas industry is distributing since more than 50 years high pressure cylinders (steel, 200 bar) to customers with a relatively small hydrogen demand in the order of some 1 to 10 kg per week there is already a European wide hydrogen supply network in place that subsequently could be expanded with the growing demand for hydrogen fuelled portables. For a deployment strategy following two points are of interest:

§ Creating an interface to the customer: the process chain from recycling empty cartridges at existing sites of the gas industry and delivering them to filling centres (e.g. at big shopping malls or airport) where consumer can exchange their empty cartridges with new ones.

§ Preparing the legal framework: the usage of these hydrogen cartridges at all public places including airplane transport need to be ensured. Detailed proposals are expected by the Interest Group RCS (see also chapter 3.3.1)

Finally it should be mentioned to seek for synergies with other early markets or niche applications such as light traction (wheelchairs, micro cars for inner city traffic, power tools) that could be tied up with the same infrastructure in order to increase utilisation and sales volumes."

Comentarios a la distribución de metanol para aplicaciones portables, de hidrógeno para aplicaciones portables y aplicaciones de vehículos especiales ("tracción ligera")

La distribución de metanol no representa ningún problema técnico, sino de existencia de mercado, por lo que hay simplemente que estar vigilante. La distribución de hidrógeno en cartuchos de gas o de hidruros puede ser un nicho de mercado para industrias con tecnología similar (depósitos a presión, materiales compuestos, conectores para gases y racorería), aunque son productos que ya existen en el mercado (ver proyecto HyChain). Puede ser parte de un proyecto, asociado a un despliegue de aplicaciones portátiles o de transporte de poca potencia, poniendo en común al gasista, al desarrollador industrial, y a los órganos reguladores, con el objetivo de poner un producto de tecnología muy específica en un mercado global. El modelo de negocio del punto de venta también está por desarrollar. En algún momento antes de 2010 habrá que elaborar la normativa para permitir el uso de dichos dispositivos de almacenamiento y regular su distribución, de manera coherente con los países de nuestro entorno. Estos mercados pueden haber emergido ya en 2010.

Distribución de hidrógeno para aplicaciones estacionarias

"Most demonstration projects and field tests for pre-commercial stationary fuel cells in the range between some kWe to some 100 kWe are connected to the natural gas grid and are producing the hydrogen via reforming of natural gas and an integrated gas purification unit. Especially for high temperature fuel cells with their simplified reforming and good resistance against impurities this solution is very cost effective. Decentralised H2-production based on the existing NG-network allows a fast build up of early markets for a broad range of stationary hydrogen and fuel cell applications long before a competitive H2 infrastructure is build up.

For the usage of by-product hydrogen from chemical plants or from refinery a pipeline transport over short distances is the most efficient way if the utilisation is high right from the beginning. This applies to most industrial fuel cell installations in contradiction to the supply of hydrogen filling stations where the slow ramp up of vehicles cause a lower utilisation during a longer period.

A mid-term option is the installation of H2-microgrids to supply stationary fuel cells and filling stations with hydrogen. Advantage would be synergies of hydrogen demand pattern from stationary and filling stations, thereby an optimization of the hydrogen production and storage facility. Of course, in this case stationary fuel cells running on pure hydrogen (PEM) have to be developed. The operation of hydrogen pipelines has been performed by the chemical and gas industry since the 1930s as the example of the Leuna site (Germany) shows.

Comentarios a la distribución usando las redes de gas natural, de la distribución por gasoducto y de las microrredes.

Hasta 2010 habrá unicamente demostradores de pilas, con una potencia conjunta de pocas decenas de MW, conectadas a la red de gas natural, salvo que utilicen gas sintético o hidrógeno industrial residual por conveniencia. Es evidente que el hidrógeno industrial se transportará por tuberías dentro de la propia industria. También está claro que las industrias generadoras de hidrógeno son ubicaciones muy adecuadas para distribuir hidrógeno por gasoducto a consumidores estacionarios o de transporte en su entorno más próximo. La construcción de microrredes para usos no-industriales (esto es, generación de energía y transporte) vendrá determinado por los demostradores de pilas estacionarias y de vehículos que aprovechen hidrógeno industrial. Puede haber interés en la gestión de una red de H2 que atienda a varios consumidores residenciales (ver proyecto de Arnhem). Puede haber interés específico en construir redes prototipo, como en el caso del gasoducto a 1.000 bar construido para el proyecto Zero-Regio. Otra posibilidad que puede ser investigada, en un primer momento de manera teórica y con modelos, es el transporte de hidrógeno generado de manera descentralizada (renovables) inyectado a la red de gas natural, o alternativamente, estudiar la problemática específica de la logística de una producción y un consumo distribuidos. Si el transporte de mezclas de H2 y gas natural puede ser una solución de transición, en algún momento antes de 2050 se habría podido producir la sustitución completa del gas natural por el H2 al menos en parte de la red. En otro caso, habrá que optar por duplicar la red de distribución. Puede ser objeto de un estudio específico.

Distribución de hidrógeno para aplicaciones de transporte

"For transport application three different pathways and distribution regimes are generally considered as a viable option (taking into account the long term potential for CO2 emission

reduction and economic considerations):

§ central hydrogen production with pipeline transport to the filling station (only CGH2 fillings possible)

§ central production and liquefaction of hydrogen with tank trailer transport to the filling station (CGH2 and LH2 fillings possible)

§ on-site production of hydrogen with optional buffer storage for load levelling (only CGH2 fillings possible). An option that should be evaluated at large fuelling stations would be to add LH2 storage supplied by trailer to supply LH2 vehicles and cover peak loads and a buffer / backup supply for the on-site reformer.

The first option is often seen as the ideal long term option when high penetration rates of hydrogen will have been reached as e.g. suggested for a 2050 scenario. However this would imply a radical shift in technology at a point where a fairly high market penetration has been already reached. An example may be obtained for the post 2020 time frame from the HyNet Roadmap Report, assuming that more than 10,000 hydrogen fillings station would exist in the EU and therefore need to be fit with a new hydrogen pipeline network. Based on the results of the Transport Energy Strategy a rough estimate on the additional investment for the pipeline connection in the order of 10 billion € can be made. The initial investment for these 10,000 hydrogen stations using either an on-site production or a central liquid supply is in the order of 7 to 14 billion € (see Figure 8).

Regarding the investment figures given in Figure 8 it need to be stated that the ground area for the filling station including the area for on-site generatican differ from the figures given above since on-site production requires significant more footprint than pipeline supply or liquid underground storage. Hence an optimised distribution system will likely require an intelligent mix of technologies reflecting following issues:

§ Flexibility and transition friendly-ness

§ Footprint requirements

§ Cost issues

§ Emissions and energy balances

§ Safety and permitting issues

However this shall not prejudice a certain onboard the vehicle storage technology since all three potential storage technologies (liquid, high pressure compressed, low pressure technologies like nano-tubes) can be supplied by a filling station using a liquid storage tank."

Comentarios a los tres conceptos de distribución y a la construcción de estaciones de servicio.

Mientras en España no haya instalaciones de licuefacción de hidrógeno, dicha vía queda imposibilitada. Esto puede ser un obstáculo para el despliegue de vehículos con almacenamiento LH2. La elección posterior entre on-site y off-site dependerá unicamente de criterios económicos (transporte de CH2 por carretera frente a coste de equipos y energía para producción on-site). Hasta 2010 se construirán entre 5 y 10 estaciones de servicio de H2 en España para atender entre 20 y 50 vehículos. El escenario para 2020 podrían ser del orden de 1.000 hidrogeneras (dos órdenes de magnitud en diez años). La estandarización va a ser un factor clave, y el aspecto regulatorio, para poder reconvertir las actuales estaciones de servicio a H2. El despliegue de vehículos hasta 2010 será en flotas cautivas seguramente, por lo que no es prioritario crear una malla de hidrogeneras en la geografía, sino mejorar las prestaciones técnicas y económicas. Entre 2010 y 2020 habrá que crear la malla.

Almacenamiento de Hidrógeno para aplicaciones estacionarias

In this context generally two different basic requirements need to be covered. First of all the hydrogen storage for island or remote applications requires the storage of high energy contents over a long period of time and external hydrogen delivery is required. Secondly for load-levelling requirements that could occur for instance at a hydrogen filling station with onsite production the hydrogen is stored internally at the plant for a short time only.

For remote applications due to the need of a delivery either by road or ship a liquid distribution and delivery system is most likely the most economical solution. State of the art technology is cylindrical tanks that can either be mounted above ground (standing, lying) or under ground having usually volumes from some m³ up to around 100 m³. Refilling of such tanks via trailer causes transport cost in the range of 0.2€/kg30 and is a standard operation in the gas industry, based on standard cryogenic equipment also used for the delivery of liquid nitrogen or oxygen.

Regarding the need for having an intermediate buffer storage in most case compressed gaseous hydrogen storage will be foreseen. Smaller installations can utilise either commercial pressure cylinders that are mass-produced today for the gas industry (200 bar, steel) and maybe in future also for the automotive industry (350 or 700 bar, composite fibres). Larger installations can also utilise tailored tube storage systems based on steel piping tubes that are produced for instance for large gas pipelines and commercially available for pressures up to 100 bar and diameters up to 1,400 mm. Very large scale storage of hydrogen (in the order of 10.000 m³ at about 1.000 bar) would be required at sites near large wind farms to store fuel for centralised power stations to provide grid stability. In addition it is recommended to examine whether the design pattern of town gasometers could be used for new hydrogen storage facilities.

Comentarios:

Almacenamiento de Hidrógeno para aplicaciones de transporte

Since conventional cars offer ranges between 500 km to around 1000 km often the lacking range of today's available semi-commercial storage solutions hinders the market success of hydrogen-powered vehicles. Due to the physical properties of hydrogen even liquid hydrogen, which offers the best physical storage, density (fuel property only!) needs roughly four times the volume than the same energy equivalent of gasoline. Furthermore cryogenic or high-pressure vessels also reduce the gravimetric advantage of hydrogen in comparison to gasoline, which is in theory (fuel Property only!) 3 times better. However existing liquid or compressed hydrogen storage vessels deliver today gravimetric densities far below 10% which means that more than 90% of the weight of the full tank system are related to the containment whereas today's plastic gasoline tank have roughly 10% of the weight of the stored fuel.

Besides the today in prototypes and early fleets test utilised liquid and compressed solutions the following hydrogen storage solutions are recognised to be available for a serial development process in 2015 and therefore relevant for market introduction strategies in 2020 and beyond:

Table 7: Hydrogen Storage Performance expected for 2015

	Usable H mass fraction (2015 perspective)[1]	Remarks
LH2	12%	Ongoing fleet tests
CGH2 700 bar	9%	First fleet test (ongoing with 350 bar)
Complex metal hydrides (alanates)	7%	Laboratory phase
Chemical hydrides ($NaBH_4$)	9%	Demonstrator in USA, requires not only refilling but also draining of hazardous chemical liquid; recycling process not reasonable

[1] Strategic Research Agenda Report (draft!), table 2.2-1

The results from Table 7 indicate that for the frame of a deployment strategy only LH2 and CGH2 storage systems can contribute to large-scale vehicle demonstration programmes and preparatory activities of a market introduction in the time frame until 2015. It also needs to be stated that the "onboard vehicle storage problem" is also related to the fact that due to cost reasons all automotive companies use up to now for their hydrogen development programmes a converted conventional body which is designed for a flexible mouldable gasoline tank but not for accommodating a more particular for Lighthouse Projects is the creation of an initial demand that is big enough to allow the automotive companies designing first small series of some thousand dedicated units each. With these dedicated hydrogen cars having a range in the order of 400 to 500 km and full functionality of conventional cars the demand of fleet and private customers will be stimulated much better than with today's converted vehicles.

For some heavy duty vehicles such as public transport buses the hydrogen storage problem has already been solved regarding range requirements with actual available liquid or compressed systems. Most common solution for buses are roof mounted compressed tanks where even the commercial available 350 bar tanks offer a range capable of at least one day's service. Hence for this segment the most urgent issue for a deployment strategy is lowering the cost for storage systems by utilising economies of scale in the production, leading enforcement programmes for the reinforced usage of fuel cell buses for public inner city transport.

Comentarios:

Recomendaciones en Almacenamiento y Distribución de Hidrógeno

In an initial phase – in the near and mid-term future – following activities regarding hydrogen distribution and storage should further be deployed:

** An infrastructure for portables (mainly notebooks and telecommunication devices with < 100W) and early or niche markets applications (power generators, forklift trucks, back-up power systems, …) with hydrogen cylinders needs to be developed in close collaboration with the gas industry and application developers.*

** The ongoing improvements of LH2 and CGH2 storage systems as well as eventually available alternatives need to be further deployed under large scale demonstration programmes such as Lighthouse Projects with the aim to agree on industry standards in the 2010 time frame.*

**Large-scale hydrogen-production and liquefaction and subsequently trucking of liquid hydrogen to the re-fuelling stations, to offer flexible hydrogen supply for early and time critical demonstration purposes. In this case the delivery of liquid hydrogen and the demand side need to be well synchronized in order to avoid boil-off hydrogen. Re-liquefaction units or concurrent operation of stationary heat and power production could be used to overcome this problem.*

** In parallel to the large-scale liquid production build up, the deployment of onsite pathways (see chapter ¿?.) should be performed with same intensity in order to lay the basis for final commercialisation decisions around the 2015 time frame.*

Comentarios:

10. ANEXO: Análisis Diferencial con la Agenda Estratégica de Investigación de la Plataforma Europea

Página 31 y siguientes:

Visión a medio plazo hasta 2030

After 2015 hydrogen will be supplied to the customers progressively via pipelines and decreasingly by making use of road, rail and water transport. Besides the delivery of liquefied hydrogen, also steam methane reformers (SMR) can supply hydrogen on-site at the fuelling station. In parallel with the hydrogen-adapted natural gas grid, the network of hydrogen pipelines will be significantly extended from its original base in Northern Europe and in the Ruhr area as well as the Leuna area in Germany. Liquefaction units and supply by liquefied hydrogen tanks will be established. Networks of a few thousand compressed gaseous hydrogen (CGH2) and liquefied hydrogen (LH2) fuelling stations coexist in the main urban areas.

Comentarios:

Añadir que la eólica se apoyará progresivamente en el hidrógeno, conforme las exigencias de los operadores de sistemas eléctricos sean más severas, y las tecnologías de electrolizadores más asequibles, de forma que habrá excedentes de H2 en zonas de potencial eólico, que pueden ser empleados para transporte.

From experience gained with first fleets of vehicles before 2015, the storage of gaseous pressurised hydrogen in composite tanks will have been validated at 700 bar with a usable hydrogen mass fraction 30 between 4 to 6 %. Prototypes of a second generation of on-board gaseous or liquid hydrogen or hydride storage systems with a larger usable hydrogen mass fraction and volumetric energy density 31 (kWh/l), and increased safety will be available and tested on a large scale. From today's perspective, hydrogen mass fraction reaching 9 % can be expected in 2015 based on ultimate achievement for gaseous or liquid hydrogen storage on a laboratory scale. This expectation is further backed by the fact that some solid or liquid hydrides contain an intrinsic hydrogen mass fraction exceeding 10 %32, cf. Table 2.2-1.

Besides pressurised hydrogen storage, on-board cryogenic liquid hydrogen storage may be adopted, provided solutions have been proven and optimised in terms of safety, reduction of hydrogen gas boil-off as well as prospects for the mass production of such tanks. The price level for a hydrogen tank will be higher by a factor of more than 10 compared with gasoline tanks (125 EUR/tank).

Replacing the first generation of hydride tanks already available in the early 2000s, a second generation of tanks or cartridges for stationary and portable applications will penetrate the market. This innovation will be based on novel materials.

Auxiliary technologies for safe hydrogen management will be available. This refers particularly to hydrogen management at distribution nodes, refuelling stations and filling centres and end-use applications. Critical components like hydrogen sensors, high-pressure valves, micropumps for liquid hydrogen will need further development.

Comentarios:

Visión a largo plazo hasta 2050

"Between 2030 and 2050 increasing market penetration of hydrogen will require a dedicated infrastructure for production, storage and distribution. Road transport of gaseous hydrogen in tube trailers and of liquid hydrogen will serve to meet the demand for market introduction. Large liquefaction units will be in operation with a capacity beyond > 100 tons/day. Liquid hydrogen will be transported by road, rail or ship. For serving mass demand, a network of pipelines and related facilities will be established connecting new large-scale production sites. It will be increasingly expanded and will include decentralised production facilities also based on renewable energy sources Main stationary systems, filling centres, fuelling stations, and domestic, commercial and industrial end-users will be connected. The pipeline grid will take advantage of the existing natural gas infrastructure which will have been adapted to hydrogen."

Comentarios:

Aunque la producción centralizada llegue a imponerse, existirá la producción descentralizada, que habrá que llevar al punto de consumo, bien por una logística especial, bien como se hace hoy en día con el Régimen Especial (vertiendo a red en condiciones más favorables).

"Satisfactory solutions and processes for hydrogen storage in novel materials will have been identified and demonstrated. A dedicated industry that produces, distributes, and recycles these novel materials needs to be fostered. The main materials issues and concepts for manufacturing pipes, tanks, as well as storage media, will have been solved. Standardised technical devices will be widespread. Consequently, the research effort should evolve towards mass production and constant improvement of materials for storage systems."

Comentarios:

Estrategia de investigación para 2005-2015

"Prototypes of a next generation of on-board gaseous hydrogen or hydride storage systems with a larger usable hydrogen mass fraction and volumetric energy density 33 (kWh/l), and increased safety have to be available and tested on a large scale. From today's perspective, a hydrogen mass fraction reaching 9 % can be expected in 2015 based on the ultimate achievement for gaseous or liquid hydrogen storage on the laboratory scale."

Comentarios:

"Research should be done on gradually modifying the existing natural gas grid up to 100 % hydrogen. Hydrogen management at the refuelling or filling stations requires optimisation of components such as hydrogen dispensers and nozzles, hydrogen sensors, and sensing of hydrogen mass flows during refuelling. Moreover, basic engineering for rapid refuelling and energy

management in compression and gas cooling is important. Specific work has to be done in terms of safety, risk assessment and components for highpressure and high-volume transmission, medium-pressure distribution and low-pressure infrastructure at the end-user side. Regulation and standards must be defined and questions of public acceptance must be studied. Hydrogen in private customer use requires a new quality of handling, safety and acceptance which includes refilling procedures at special locations or in combination with fuelling stations for vehicles as well as operating small energy converters < 5 kW"

Comentarios:

Desde el punto de vista de desarrollo, son temas de tecnología convencional que debe ser adaptada, y que las empresas que tienen esta tecnología no están necesariamente al tanto de las oportunidades del hidrógeno. Hay que apoyar que las empresas nacionales con competencias en estos ámbitos puedan adaptar su tecnología, aunque la integren en sistemas desarrollados por empresas de otros países.

Gasoductos

"The results of large existing pipeline systems in Belgium, France, the Netherlands and Germany have to be evaluated. A strategy has to be found to use these systems for initial hydrogen infrastructures and to combine today's hydrogen production stations with those and new pipelines to create the first small hydrogen supply clusters. Engineering studies have to be done on how to make use of existing pipeline systems for hydrogen and natural gas, planning new pipelines in urban areas and distributing hydrogen from refineries and chemical plants to take maximum advantage of already existing lowest cost hydrogen sources.

After 2015, hydrogen will be supplied to the customers progressively via pipelines and decreasingly by making use of road, rail and water transport. Research should be done on gradually modifying the existing natural gas grid for hydrogen use. As biomass is envisaged to play a major role in the future there will still be the need for a methane gas pipeline grid, even in the long run. Specific work has to be done in terms of safety, risk assessment and components for high-pressure and high-volume transmission, medium-pressure distribution and low-pressure infrastructure at the end-user side. Regulation and standards must be defined and questions of public acceptance must be studied."

Comentarios:

Hay que estudiar los escenarios de transición respecto a la red de distribución (compartir o coexistencia). En zonas con potencial eólico, los gasoductos podrían servir para evacuar H2 producido por exceso de viento, lo que hay que estudiar de cara a mezclas no homogéneas del gas, y la distribución del mismo.

Almacenamiento Estacionario

"Stationary storage refers to central storage of gaseous or liquid hydrogen for industrial or further retail use. This can be secondary distribution centres, such as fuelling stations or cylinder filling centres, sites along pipelines, hydrogen production sites associated with offshore wind parks or stationary power applications above 10 kW which need larger hydrogen supplies. In any case, the storage technology is well known. Underground and underwater storage facilities are considered to

be of strategic importance to match hydrogen production and demand and to ensure energy reliability. Their deployment depends more on regulatory approval than on further research. However, more applied research is still needed to evaluate the long-term behaviour of hydrogen confinement. New procedures for regulation and standards are necessary.

For reasons of safety in the neighbourhood, stationary storage based on hydride materials needs to be investigated in terms of reactor design for relatively large hydrogen flows (several hundred or thousand Nm3/h). Moreover, management of the supply chain of hydride materials, including refilling or recycling of the dehydrogenated products, needs to be addressed.

Comentarios:

Hidrogeneras

"Based on the preliminary experience of the European Clean Urban Transport for Europe (CUTE) project and other national projects, the first fuelling stations have to be evaluated. New commercial standards should be derived from their non-commercial prototypes as hydrogen corridors or highways appear in some European regions. At this stage the local hydrogen demand will be met by local storage and/or on-site production. At the same time, pipeline interconnection between centralised production units and fuelling stations is expected to be starting in some areas.

A car must be refuelled with hydrogen within a few minutes and has to be safe enough for self-service operation by members of the public in various climates and operation conditions. This requires optimisation of components such as hydrogen dispensers and nozzles, hydrogen sensors, and sensing of hydrogen mass flows during refuelling. Moreover, basic engineering for rapid refuelling and energy management in compression and gas cooling (CGH2) is important. For cryogenic liquid technology, boil-off and heat transfer are crucial issues. This should be reflected in the specific hydrogen delivery cost to the user. Space requirements of fuelling stations and scalability of their hydrogen fuelling capacity have to be optimised and anticipated. This may require scalable on-site production units, such as electrolysers or reformers, and eventually small liquefaction units. All components of future fuelling stations must be more compact to avoid complex space requirements. Underground storage must be accepted for future infrastructure. Such important developments call for an evolution of hydrogen regulations and standards and should be driven by the Deployment Strategy. Specific aspects and requirements of hydrogen fuelling stations for boats and ships in harbours should be investigated simultaneously."

Comentarios:

Son temas de ingeniería que deben ser motivados por el despliegue de infraestructuras.

Almacenamiento a bordo

Storage tanks in current hydrogen vehicles are still too bulky. The need for an increased driving range of 500 to 600 km with a fuel cell propulsion system requires an estimate of 5 kg of hydrogen. This corresponds to a liquid hydrogen volume of about 75 l, or a gaseous volume of 120 l at 700 bar and ~20 °C. In order to confine this hydrogen quantity in an overall volume smaller than 150 l, developers have to achieve a volumetric energy density for the overall tank volume larger than 1.1 kWh/l36. Cryogenic liquid hydrogen tanks need further research to reduce size, cost and to minimize and manage boil-off (cf. Chapter 2.4.3.3.6)

Improved storage media may be necessary to significantly improve the net volumetric energy density (kWh/l) and usable gravimetric energy density (kWh/kg) or usable mass fraction of hydrogen (% kgH2/kgstorage), when the overall tank volume and weight is considered. This may be achieved by using alternative hydrogen storage media based either on hydrogen reversible physical or chemical hydrogen adsorption. Permeability to hydrogen is to be considered. Moreover, the storage system should match further criteria pertaining to automotive usage in terms of fuel stability:

** Operating temperature range from -40 °C to +60 °C*

** Minimum and maximum hydrogen delivery temperature from -40 °C and +85 °C*

** More than 1,500 cycles*

** Kinetics and transient response.*

Comentarios:

Suministro de Hidrógeno a sistemas portátiles de menos de 5 kW o 120 kg

Cylinders and cartridges

Hydrogen for use by private customers requires a new quality of handling, safety and acceptance that includes refilling procedures at special locations or in combination with fuelling stations for vehicles as well as operating small energy converters < 5 kW. The storage medium either consists of compressed gaseous hydrogen cylinders, or metal-hydride tanks, or chemical-hydride tanks. In this case, refilling and recyclability of the tank or the storage medium or product are crucial.

Improved storage systems are necessary for micro or mini fuel cells < 100 W, where nonrefillable cartridges can be used. These cartridges have special requirements regarding specific and volumetric energy density, kinetics, cycle life, temperature stability, interfaces, safety equipment, sensors and test procedures. Chemical hydrides or reversible adsorption/desorption systems based on metal hydrides may be preferred over gaseous hydrogen, which is basically applicable. Alternatively, reusable methanol cartridges are a solution for direct methanol fuel cells (DMFC).

Refilling and recycling centres

The development of a collection of specific stationary and portable applications requires the adaptation of existing industrial gas filling plants in order to manage the corresponding cylinder or cartridge logistics. This also needs engineering effort to optimise the refilling processes of reversible hydrogen adsorption/desorption systems based metal hydrides or on activated nano-porous carbon, as well as the recycling of chemical hydride by-products.

Comentarios:

Necesidades de investigación básica

Compressed hydrogen storage

Compressed hydrogen storage should be improved and verified in the following research areas:

** Development of novel strong, reliable, and low-cost materials for containers, i.e. fibrereinforced composites for storage containers using high-quality fibres and new strong binders impermeable to hydrogen*

** In-depth knowledge of the failure mechanisms of storage container materials, such as the atomic-level processes responsible for hydrogen embrittlement in candidate materials; this research is necessary in order to develop strategies to prevent failure resulting from long exposure to hydrogen*

** Smart sensors for hydrogen leakage detection and the corresponding safety feedback systems needed to ensure safe operation of CGH2 systems*

** Miniaturised, low cost, lightweight pressure regulators for portable and transport applications.*

Liquid hydrogen storage

Improvement of liquid hydrogen storage includes the following basic research and verification items:

** Lightweight, low-volume and low-cost materials with good heat resistivity properties, strength, integrity, leak tightness, and durability*

** Improvement of liquefaction processes in terms of energy efficiency and cost, e.g. by magnetic refrigeration 37*

** Identification of fail-safe methods to handle hydrogen boil-off safely and address other safety issues associated with liquid hydrogen.*

Novel storage materials

The development of novel materials for hydrogen storage involves many scientific and technical challenges. Fundamental research including verification is needed to understand the interaction of hydrogen in solid-state materials and identify suitable materials for hydrogen storage.

Research in solid hydrogen storage materials has to be focused on:

** Knowledge of the fundamental factors governing bond strength, kinetics, absorption and desorption behaviour, and degradation with cycling*

** Applying these principles to modify the performance of known hydrogen storage materials*

** Identifying new materials and new classes of materials whose properties can be tailored to meet targets required for different final uses. At present, most of the 2,000 storage materials known have not been explored yet in doped or nano form.*

These experiments will require some new developments in analytical and characterisation techniques such as neutron and x-ray scattering and imaging tools. Researchers will also need to develop a comprehensive theoretical model explaining the interactions between hydrogen and its storage materials, e.g. the nature of bonding and the role of structure and nanophase boundaries.

This fundamental research should be directed in two key areas that promise to meet the goals of *hydrogen storage: metal and complex hydrides and nanostructured materials.*

Research will take advantage of the revolutionary new properties and capabilities offered by nanoscience to further enhance storage capacity and to improve uptake/release kinetics. Improvements in today's metal and complex hydrides can be achieved by a careful design of two- and three-dimensional nano-architectures to improve the weight percentages of stored hydrogen and control of hydrogen storage/release. Advances in basic research also contribute to the development of intelligent storage tanks that predict and communicate performance attributes and warn of potential failure.

Computational approaches

Multi-scale computational approaches can be applied to model absorption and desorption in hydride storage materials. Computational approaches and experimental data should be used to identify mechanisms responsible for degradation of hydrogen storage materials, and limitation of the life spans of these materials, particularly with repeated hydrogen storage and release cycles. Experiments on model hydrogen storage systems should be benchmarked against calculations at all length scales. Taken together, this knowledge will allow the design of novel materials for optimum hydrogen storage and release and provide a means to control and maintain the structural properties of candidate hydrogen storage materials and improve their durability. Computational tools must be applied and developed in safety studies in order to simulate accidents and scenarios.

Comentarios:

Recomendaciones en Investigación y Visión Estratégica

Basic research to achieve a commercially viable hydrogen economy requires an integrated approach, connecting progress in the critical areas of hydrogen production, liquefaction, transmission, storage and use. Lower cost, lighter weight, and higher density of hydrogen storage are the key technologies needed for a hydrogen economy. A breakthrough in hydrogen storage could have a great impact on the successful introduction of hydrogen as an energy carrier especially in automotive applications. It will, however, require highly innovative materials meeting hydrogen storage requirements, and not only incremental improvements of current technologies. Investments in fundamental research to develop and examine new materials and obtain an atomic- and molecular-level understanding of the physical and chemical processes involved in hydrogen storage and release and finally to present verification units will be necessary.

The hydrogen economy implies technical challenges that require interdisciplinary approaches involving physics, chemistry, materials science and engineering. Moreover, a strong integration of experiment and theory and modelling will be necessary not only to help researchers understand the experimental data, but also to allow them to identify key parameters which will facilitate major advances in hydrogen storage technology and guide subsequent experiments. This integrated research effort will probably lead to the discovery of new hydrogen storage materials.

Pipeline systems in urban areas will play an important role for future infrastructure growth. Dispensers of hydrogen need to be self-serviceable and refuel vehicles in only a few minutes and be fully safe for operation by the public. Underground stores will have to become part of the future infrastructure and need further development, with respect to safety and sensors.

Assessment of fuel delivery costs to the user needs to consider (i) different pathways, (ii) different filling station concepts and (iii) different hydrogen sources. External factors include life cycle costs, lifetime air pollutant and greenhouse gas emissions as well as primary energy issues and will also have to be considered in an appropriate way38. The European ExternE project can provide a viable methodology here.

Table 2.2-2: Research budget priorities for hydrogen storage and distribution

	Year 1 – 5	Year 6 – 10
Reversible storage systems for transportation	26 %	23 %
Hydrogen management at transfer, filling (cartridges) and fuelling (vehicles) stations	10 %	11 %
Hydrogen storage at production sites	10 %	10 %
Pipeline infrastructures	9 %	11 %
System analyses and network strategy	5 %	5 %
Reversible and non-reversible storage solutions for portable applications	15 %	15 %
Liquid hydrogen infrastructure components, reduction of boil-off	9 %	9 %
Basic research and cross-cuttings	16 %	16 %

Comentarios:

11. ANEXO: Revisión del Estado del Arte en Almacenamiento

Resultado de la reunión del Subgrupo de Almacenamiento (28 de septiembre de 2005)

ALMACENAMIENTO EN ESTADO LÍQUIDO (método físico)

Estado actual:

- Tecnológicamente madura

Líneas de mejora:

- Ingeniería aplicada a un mayor control y seguridad
- Investigación básica aplicada a la mejora de sensores

Nicho de penetración:

- Almacenamiento masivo a corto/medio plazo
- Aplicaciones con bajo “tiempo de dormitancia”
- Debido a su elevado precio, sólo sería competitivo en el campo de la aviación

ALMACENAMIENTO DEL GAS COMPRIMIDO (método físico)

Estado actual:

- Tecnológicamente madura

Líneas de mejora:

- Diseño de tanques y materiales
- Sistemas de compresión
- Requisito para hacer esta tecnología competitiva: compresión hasta 700 bar

Nicho de penetración:

- Almacenamiento masivo

ALMACENAMIENTO POR ADSORCIÓN (método físico-químico)

En sólidos porosos: nanotubos, carbón activo, zeolitas…

Estado actual:

- Tecnológicamente inmaduro

Líneas de mejora:

- Mantener la investigación en nuevos materiales
- Aumento del porcentaje de hidrógeno en peso
- Mejora de la cinética mediante el uso de nuevos catalizadores

- Reproducibilidad de resultados

Nicho de penetración:

- Almacenamiento para usuario final: sistemas estacionarios/portátiles

En hidruros metálicos

Estado actual:

- Tecnológicamente inmaduro.

Líneas de mejora:

- Métodos de desorción a menores temperaturas
- Aplicación a bajas temperaturas
- Estudio de hidruros complejos que permiten alcanzar mayores porcentajes de hidrógeno en peso
- Seguridad en el empleo del magnesio

Nicho de penetración:

- Almacenamiento para usuario final: sistemas estacionarios/portátiles (ventaja por su elevada densidad volumétrica)

ALMACENAMIENTO POR REACCIÓN QUÍMICA (método químico)

Estado actual:

- Escaso desarrollo tecnológico: no apto aún para su aplicación real

Líneas de mejora:

- Mejora de la cinética mediante el uso de nuevos catalizadores
- Aumento del porcentaje de hidrógeno en peso

Nicho de penetración:

- Almacenamiento para usuario final

La visión general del grupo en cuanto a la situación y prospectiva del mercado a corto plazo, para una aplicación determinada como es el almacenamiento en vehículos de hidrógeno, se decantó por la tecnología del hidrógeno comprimido o licuado. No obstante, se deja constancia de las posibilidades que ofrece el empleo de metanol mediante técnicas de reformado directo a bordo.