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RECOMMENDATIONS FOR THE FUEL CELL AND HYDROGEN RESEARCH AGENDA

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The European Commission is supporting the Coordination Action "HyLights" and the Integrated Project "Roads2HyCom" in the field of Hydrogen and Fuel Cells. The two projects support the Commission in the monitoring and coordination of ongoing activities of the HFP, and provide input to the HFP for the planning and preparation of future research and demonstration activities within an integrated EU strategy.

The two projects are complementary and are working in close coordination. HyLights focuses on the preparation of the large scale demonstration for transport applications, while Roads2HyCom focuses on identifying opportunities for research activities relative to the needs of industrial stakeholders and Hydrogen Communities that could contribute to the early adoption of hydrogen as a universal energy vector.

Further information on the projects and their partners is available on the project web-sites www.roads2hy.com and www.hylights.org

CONTRIBUTING AUTHORS

Chapter 1	Alexander Holleis *AVL List GmbH*
Chapter 2	Emmanuel Stamatakis *Centre for Renewable Energy Sources (CRES)*
Chapter 3	Manfred Klell *HyCentA Research GmbH* Marcel Weeda *ECN*
Chatper 4	Nick Owen and Matthew Keenan *Ricardo UK* Simon Vinot *IFP* Alexander Holleis *AVL List GmbH*
Chapter 5	Nick Owen and Matthew Keenan *Ricardo UK* Simon Vinot *IFP* Alexander Holleis *AVL List GmbH*
Chapter 6	Manfred Klell *HyCentA* Marcel Weeda *ECN* Raimund Bleischwitz *College of Europe* Alexander Holleis *AVL List GmbH*
Chapter 7	Simon Vinot *IFP*

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1. Introduction

Background

This report is a deliverable of the Roads2HyCom project, a partnership of 29 stakeholder organisations supported by the European Commission Framework Six programme. The project studied, technical and socio-economic issues associated with the use of fuel cells and hydrogen in a sustainable energy economy, with a focus on the situation in Europe.[1]

Roads2HyCom has created a comprehensive State of the Art encyclopaedia[2], as well as a comprehensive overview of targets and recommendations for research and technological development[3] [4]. Based on these project deliverables as well as the analysis of gaps and opportunities in Fuel Cell and Hydrogen research[5] an additional exercise was performed to select and priorities the recommended research actions. The results are summarised in this document.

Methodology

The aim of this document is to prioritise issues requiring further research in the field of hydrogen and fuel cells, on the basis of Roads2HyCom's outputs, in a manner complementary to strategic documents such as the New Energy World JTI's Multi-Annual Plan.

The research topics are divided in five main categories:

- Hydrogen production
- Hydrogen storage, Transport and Refuelling
- Transport Applications
- Stationary Applications
- Cross cutting issues

The Roads2HyCom experts have developed portfolio diagrams for each category (see Figure 1).

[1] More information about the Roads2HyCom project can be found on the project website www.roads2hy.com

[2] The Roads2HyCom Hydrogen & Fuel Cell Wiki (www.ika.rwth-aachen.de/r2h) contains comprehensive information on the State-of-the-Art of Fuel Cell and Hydrogen technologies, hydrogen infrastructure in Europe and profile of early adopters.

[3] "Socio-Economic conditions for Fuel Cell and Hydrogen Technology Development", Roads2HyCom report R2H6036PU, available to download from www.roads2hy.com/WP6.html, January 2009

[4] "R&D Topics and Expected Milestones for Hydrogen and Fuel Cell Technologies", Roads2HyCom Report R2H6034PU, January 2009

[5] "Analysis of Opportunities and Synergies in Fuel Cell and Hydrogen Technologies", Roads2HyCom report R2H4007PU, available to download from www.roads2hy.com/WP4.html, February 2009

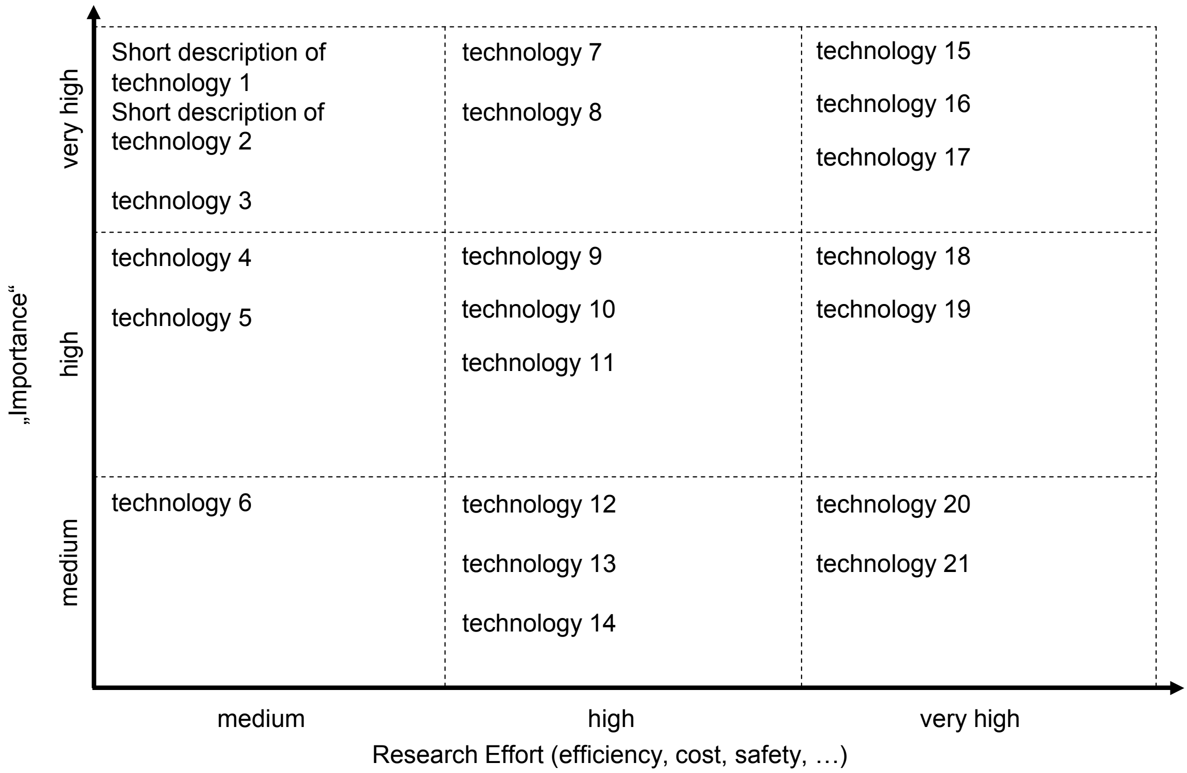

Figure 1: Example of a portfolio diagram

On these portfolio diagrams the (vertical) y-axis **"Importance"** is a measure of the added value of a FC&H2 application/technology for society. It shows the potential contribution of the selected technologies to meet the future hydrogen energy demand, the contribution to establishing a hydrogen infrastructure or the contribution to the market uptake of FC&H2 applications.

The "Importance" classification is on 3 levels:

- **Very high**: This technology/research in this field is a must for early adoption of FC&H2 applications
- **High**: High potential to early adoption of FC&H2 applications,
- **Medium**: This technology/RTD shows potential but is not seen as a critical breakthrough

The (horizontal) x-axis **"Research Effort Need"** anticipates the difficulty in achieving results. It summarises criteria such as the status of development and how difficult it is to progress the R&D in this area, what is the level of financial investment needed for R&D and for a successful implementation of the technology. In addition it considers issues such as whether the required competencies to achieve the objective are available in Europe, and the time horizon until successful implementation of the technology.

The “Research Effort Need” classification is on 3 levels:

- **Very high:** Need for basic research with high risk, to feed into applied research later before a product can be realised
- **High:** Need for basic and applied research, feeding into product development
- **Medium:** Need for applied research and policy schemes for “balanced/gradual“ deployment

This results in 3 x 3 = 9 fields, a prioritisation matrix, offering decision making support and acting as guidelines for future research planning.

The order of the technology in each box is not an indication of priority. No priority is given to technologies listed inside a box. Prioritisation is placing the technology in one of the nine boxes.

The prioritisation exercise was performed by a selected expert team from within the Roads2HyCom consortium, with justification of priority being linked to conclusions from the project outputs as described below.

2. Production

Roads2HyCom has performed a number of studies relating to the current and future supply of Hydrogen. High level critical issues are the build-up of a useable infrastructure, fuel cost, and the availability of low carbon energy sources relative to other demands such as de-carbonising the electricity grid. These issues are discussed in the project's final report, document R2H8500PU, and the detailed studies referenced therein.

In the early stages of infrastructure build-up, small reformers and electrolysers will provide hydrogen for small fleets alongside existing industrially-produced hydrogen. The next stage will include mid-sized community systems and large centralised hydrogen production facilities with fully developed truck delivery systems for short distances and pipeline delivery for long distances. As markets grow, Carbon Capture and Storage (CCS) and advanced direct conversion methods using photolytic renewable and nuclear technologies will be commercialised. It is therefore necessary that the research agenda should address these topics as the technologies become required for an infrastructure build-up. Challenges that need to be addressed are production cost, low initial demand, CO_2 emissions of current technologies, and the need for a new generation of advanced production technologies.

Carbon capture and storage (CCS) is identified as an area of high effort and priority, as other studies within Roads2HyCom have expressed concern that progress is insufficient to meet future demand. Alongside it are a number of improvements in electrolyser-based technologies that will improve the economic equation in fiscally challenging conditions such as peak-lopping production from intermittent renewables.

Development needs to continue regarding steam reforming, water electrolysis (by looking at high-temperature and high-pressure electrolysis) and other more advanced production technologies, like biological methods and nuclear (or solar) thermochemical water-spitting. More specifically, in the near term, water electrolysis looks more suitable. In the medium to long term, hydrogen production based on centralised fossil fuel production with CCS is feasible. Production from biomass needs additional focus on the preparation and logistics of the feed and will probably only be economical on a large scale. Photo-electrolysis is at an early stage of development and materials cost and practical issues have to be solved. Photo-biological processes are at a very early stage of development and have obtained only low conversion efficiencies so far. High-temperature processes need further material developments. For all hydrogen production processes, there is a need for significant improvement in plant efficiencies, for reduced capital costs and for better reliability and operating flexibility.

„Importance“: Potential to meet H2 demand / Research Effort (efficiency, cost, safety, …)	medium	high	very high
very high		• Increased size of electrolyser's cells and stack • Design and manufacturing of electrolyser equipment for mass production	• Improved carbon capture and sequestration technologies • Prevent degradation processes at the electrodes
high		• Material RTD for low temperature electrolysers • Electrolyser-based production synergy with intermittent renewables	• Material research for high temperature electrolysers • Improved high temperature processes for industrial scale
medium	• Process and catalyst improvement for reforming and gasification	• Central H2 production from non-fossil sources • Feedstock preparation and cleaning needs for biomass gasification	• Biomass fermentation including new bacteria for increased yield

Figure 2: Technologies for Hydrogen Production

3. Storage, Distribution and Refuelling

Storage, distribution and refuelling are key issues for the widespread use of hydrogen. To improve its very low volumetric energy density, hydrogen is stored as either a compressed gas at high pressures, as a liquid at very low temperatures or in solid storage systems as a physical or chemical compound. All of these storage methods involve high technical effort and sophisticated storage systems. The highest research effort and highest impact is expected from the reduction of weight, volume and costs of the storage systems, especially for portable and automotive applications.

Compressed storage of hydrogen at pressures between 350 bar and 900 bar in gas cylinders made of steel, aluminium, carbon and compounds allows moderate storage densities in relatively simple storage systems. Compression work has to be reduced. Key issues of research are material choice, component dimensioning and safety of the storage systems.

Liquid storage of hydrogen at -253°C allows higher energy densities, systems are more sophisticated to cope with the pressure built up and boil-off of hydrogen. Liquefaction work has to be reduced. Key issues of research are material choice, component dimensioning and shape.

While these two (mature) technologies exhibit storage densities that are limited by the physical state of hydrogen (compressed gas or liquid, respectively), solid storage of hydrogen holds promise for higher energy densities and increased safety. Conditions for charging and decharching of the systems (pressure, temperature and time) are crucial issues of research. New materials and new systems like hydrogen slush or cryocompressed storage are interesting topics of research.

For distribution and refuelling scale up of the infrastructure is vital, transport in gas pipelines and underground storage is of interest.

„Importance“: Potential contribution to market uptake of FC&H2 applications (reliability, affordability, consumer acceptance, …) \ Research Effort (efficiency, cost, safety, …)	medium	high	very high
very high	• Scale up of manufacturing composite pressure systems • Unify safety requirements and standardisation	• Material research for lightweight and freeform systems • zero loss system for liquid storage avoiding boil-off	• Reduce storage system weight, volume and costs
high	• Improve compressors and cryogenic pumps • Improve liquefaction efficiency • safety and standard requirements	• Material research for higher energy density of physical and chemical storage • Scale up of infrastructure for distribution and refuelling • Investigate H_2 underground storage	• Develop new technologies with higher storage density (slush, cryo-compressed) • Improve charging and decharching process for physical and chemical solid storage
medium		• Improve isolation with liquid storage systems	• Reduce costs and improve efficiency of distribution and refuelling infrastructure • Distribute H_2 in (natural) gas pipelines

Figure 3: Technologies for storage, distribution and refuelling of hydrogen

4. Energy Conversion – Transport

Prioritisation has been given to the research needs regarding transport and stationary fuel cell and hydrogen activities. The research needs are rated as functions of importance and research effort required. Therefore, research recommendations in the top left of the chart require industrialisation whereas, the recommendations in the top right require more fundamental research. The order of each recommendation in a box does not represent a ranking, the analysis has not determined which research recommendation is more critical inside a box.

As expected (and as indicated repeatedly in the outputs of other parts of the project) cost reduction, durability and new materials are of highest importance.

- Cost remains a critical issue, despite the significant progress highlighted in other Roads2HyCom studies [2]. Analysis conducted by the project [5] indicates that the current State of the Art, projected forward in terms of progress and increasing product volumes, remains challenging for early market uptake in Transport applications. For this reason, topics that address cost through better system integration and the thrifting or deletion of costly materials are ranked as highly important – as this will require basic research ideas to be brought through to product, these topics are also ranked as very high difficulty.

- As highlighted by some recent demonstrations [2], tolerance of Impurities remains a key challenge, as fuel cell poisoning has costly consequences. Again, dealing with it is critical to mass uptake, and requires basic research at cell level to be translated to a market-ready product, hence the topic is rated "very high" on both axes.

- Realising reliable, safe products manufactured from mass-production processes (not as prototypes) remains critical to early uptake, as there is absolutely no industry experience of mass-produced product in service. Significant progress by leading players [2] indicates that the "high" category for research effort is generally appropriate.

Standardisation of components, and development of international standards, remain important to allow the transport sector to develop higher volumes. Although as the knowledge exists to do both, they are deemed appropriate of more moderate research effort. This is a task, which industrial partners are more used to delivering, since it is a matter of understanding the breadth of components and their use in a product portfolio.

Maintenance and diagnostics are important enablers to sustain the growth of early markets. The relative lack of field experience means that a high effort is required to realise trustworthy processes; topics such as smart diagnosis and accelerated lifetime testing require a fundamental understanding of the underlying scientific processes, indicating the highest category of effort.

Those research recommendations with high research effort and very high importance such as "scale up to mass production capability of FC" fit in the applied research arena and are very critical to develop processes and tooling for large scale quality production.

Medium research effort and importance recommendations, those in the bottom left, are deemed not necessary in developing a transport hydrogen and fuel cell market.

„Importance“: Potential contribution to market uptake of FC&H2 applications (reliability, affordability, consumer acceptance, …) / Research Effort (efficiency, cost, safety, …)

Importance \ Research Effort	medium	high	very high
very high	• Component standardisation	• Increased safety and reliability • Scale up to mass production capability of FC • Optimise durability and reliability for early market product	• Precious metal free FC • Improved durability and impurity tolerance of FC(CO, sea water etc) • FC Component and system cost reduction to automotive industry levels
high	• Development of international regulation, codes and standards for manufacture, use and recycling / disposal • Truck APU system optimization	• Establishing maintenance procedures • Efficiency improvements of BoP components • Fuel reformers for APU	• Precious metal thrifting • Diagnostics and life time prediction techniques
medium	• Develop purpose-built FC vehicle • Cost and size reduction of the H2 ICE drive train		

Figure 4: Technologies for Transport Applications

5. Energy Conversion, Stationary

Although the actual technologies used are very different, the two portfolio diagrams for transport and stationary are similar in their recommendations and their placement. Therefore, as with transport research recommendations, durability and cost are deemed the highest importance and research effort requirement, with the comments of Section 4 above being applicable here too. These are fundamental issues with fuel cells and require more coordinated and smart research, while supporting players in early markets that are starting to emerge in this sector.

Regulations, codes and standards need to be developed internationally. These are important to the uptake of both transport and stationary applications but require limited research effort. However, this does not imply that the need for regulations, codes and standards is diminished.

„Importance“: Potential contribution to market uptake of FC&H2 applications (reliability, affordability, consumer acceptance, …) / Research Effort (efficiency, cost, safety, …)	medium	high	very high
very high	• Component standardisation • Scale up to mass production (larger products with lower production numbers)	• Scale up to mass production (small scale / high volume products)	• Improved system durability • Tolerance to impurities, both in stacks and fuel processing equipment • FC Component and system cost reduction
high	• Development of international regulation, codes and standards for manufacture, use and recycling / disposal • Fuel processing	• Establishing maintenance procedures • Enhancement of fuel flexibility	• Improved electrical efficiency • Accelerated lifetime testing • Diagnostics and life time prediction techniques
medium	• Strategies to lower start-up time • Remote diagnostics	• Tri-generation for buildings • Grid stabilization	

Figure 5: Technologies for Stationary Applications

6. Cross-cutting Issues

Compared to conventional fossil fuels and energy converters, hydrogen and fuel cells require more sophisticated technologies and thus are more expensive. In order to promote these technologies, apart from technical conditions, social-economic factors are of crucial importance:

- Early stages of finance and business development requires the increased and sustained use of public procurement programmes
- Socio-economic costs have to be scheduled to support early and niche markets
- Safety, standards and regulations adequate to users and producers have to be harmonised internationally
- Public perception and acceptance can be promoted by demonstration projects and education about the benefits of a CO_2 free energy cycle with hydrogen
- Education and training about hydrogen and fuel cells and their benefits from primary education up to university level is important
- A public policy framework to reduce green house gas emission could comprise havier taxation on CO_2 emission and tax reduction and benefits for CO_2 free technologies

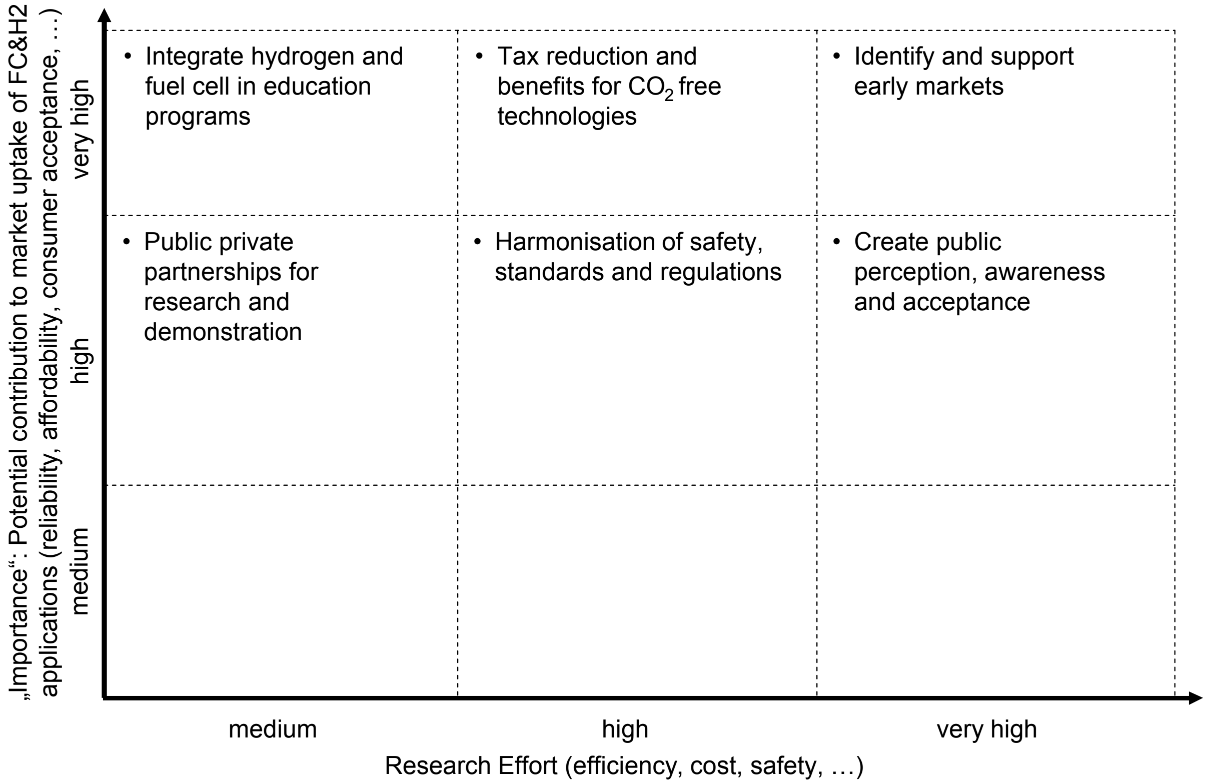

Figure 6: Cross-cutting issues

7. Conclusions

A number of recommendations and research priorities have been issued by the Roads2HyCom project. In this document, the priorities have been classified to clarify the level of difficulty faced in solving a particular issue and to indicate the impact of such an R&D breakthrough on the take-off of FC&H2 technology.

From the observation of the priority matrices, one should consider that the need for a scale up towards mass production through some component standardisation is currently the most important issue. For all the categories (hydrogen production, transport storage and refuelling, transport applications, or stationary applications) the axis of work has been selected as a factor of very high importance. Research effort does not have as great an importance. Gathering the large number of potential applications together could lead to synergies that increase the profitability of the research.

The second most influential factor would be the cost of the systems. Both for storage, transport and stationary applications, costs are still a major drawback. The achievement of lower costs systems would certainly be of high importance, since lower costs could increase the uptake of FC&H2 technologies across a range of markets.

On a parallel axis to costs the running costs should be tackled in the near future. On a research basis, efficiencies of all kind of hydrogen systems still offer huge potentials for improvement. From the long-term technology like biomass fermentation to existing systems like balance of plant or electric components and liquefaction, each can be improved efficiency-wise.

The lifetimes of systems are still to be addressed. This research priority has been seen as challenging, but the payback in terms of making hydrogen systems acceptable to a wider market makes it worth the effort.

The last common effort should be put on procedures, codes and regulations. This particular issue has been viewed as of high importance for all applications, no matter if they are in stationary or transport sector. There could also be benefits for hydrogen storage, distribution and refuelling.

More specifically on the production side, it is vital to develop technologies that allow hydrogen to be produced in a sustainable way, reducing the well-to-tank carbon dioxide emissions for the energy vector. Such technologies include coal gasification or fossil fuel-based production that can be used with carbon capture and sequestration.

For all production processes there is a need for significant improvement in efficiency, costs and reliability but high temperature electrolysers and high temperature processes are demanding high research effort to enter the industrial scale.