# UKRI Co-ordinator for Research Challenges in Hydrogen and Alternative Liquid Fuels

UK-HyRES

# Report on Workshop findings: Storage & Distribution

Aug 2022

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The University Of Sheffield.

UNIVERSITY OF BATH

WARWICK THE UNIVERSITY OF WARWICK

UK Research and Innovation

# 1. Background and Objectives

Workshop 3 took place on the **16th June 2022** and was conducted online via Zoom 13:30-16:30 with **68 attendees** (~ 60% >2hrs). Building on the success of the UK-HyRES launch event, Workshop 3 focused on the **Storage and Distribution of Hydrogen** and followed the Production of Hydrogen (Workshop 2) event in the morning.

The purpose of the workshop was to bring together key and **diverse stakeholders** from across the hydrogen community to debate and **distil the key storage challenges** preventing the adoption of hydrogen and alternative liquid fuels.

The workshop was strategically framed around the **Theory of Change** (Figure. 1), which allows for a systematic unpacking of the key research challenges, opportunities and outcomes, guided by the strategic drivers and the added value of change. The workshop was facilitated by *The Collective,* and was delivered in three separate breakout sessions, with small (< 6) randomly assigned groups. The agenda (Appendix A) was distributed to the attendees prior to the workshop and consisted of three breakout discussions, **Challenges and Unmet Needs, Future Vision and Impact**, and **Opportunities for Research**. The workshop was also summarised in an illustrative output by Scriberia (Appendix B).

Principal investigator Professor Tim Mays (University of Bath) outlined the motivation and vision of the project and provided context to the workshop, both in terms of national Net-Zero strategy, and the UKRI "Become a hydrogen research co-ordinator" call from which this 6-month project is funded. Co-investigator Professor Rachael Rothman (The University of Sheffield) gave an introduction to the Theory of Change and discussed the scale of the challenge as well as the scope of the workshop, highlighting the need for interdisciplinary collaboration.

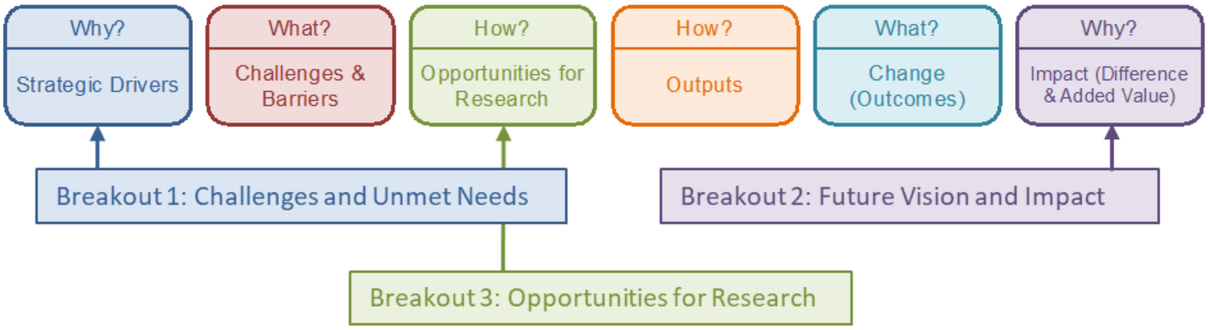



*Figure 1: The theory of change framework adopted for the UK-HyRES project, and the location of each breakout session within it.*

# 2. Insight Talks

Engaging insight talks were delivered during the workshop by industry and academic leaders active in the Hydrogen arena. **Prof. David Book (*University of Birmingham*)** and **Chris Manson-Whitton (*Progressive Energy*)** set the landscape with their strategic drivers for change talk before the first breakout discussion. We also heard from **Prof. Gavin Walker (*University of Nottingham*)** and **Shubi Mukherjee (*Ceres Power*)**, who also delivered their future vision for storage before the second breakout discussion.

Narrated slides for all four insight talks are available to download on the UKHyRES.co.uk website at https://ukhyres.co.uk/workshop-3.

# 3. Breakout Discussions

For each breakout discussion. delegates were tasked with debating the question posed and producing notes about their discussion on an online collaborative working environment. Following the workshop, the UK-HyRES research team analysed all the comments and grouped the responses accordingly.

## 3.1 Challenges and Unmet Needs

The first breakout discussion on challenges and unmet needs followed the first two insight talks. Comments were grouped by theme, as shown in Figure. 2.

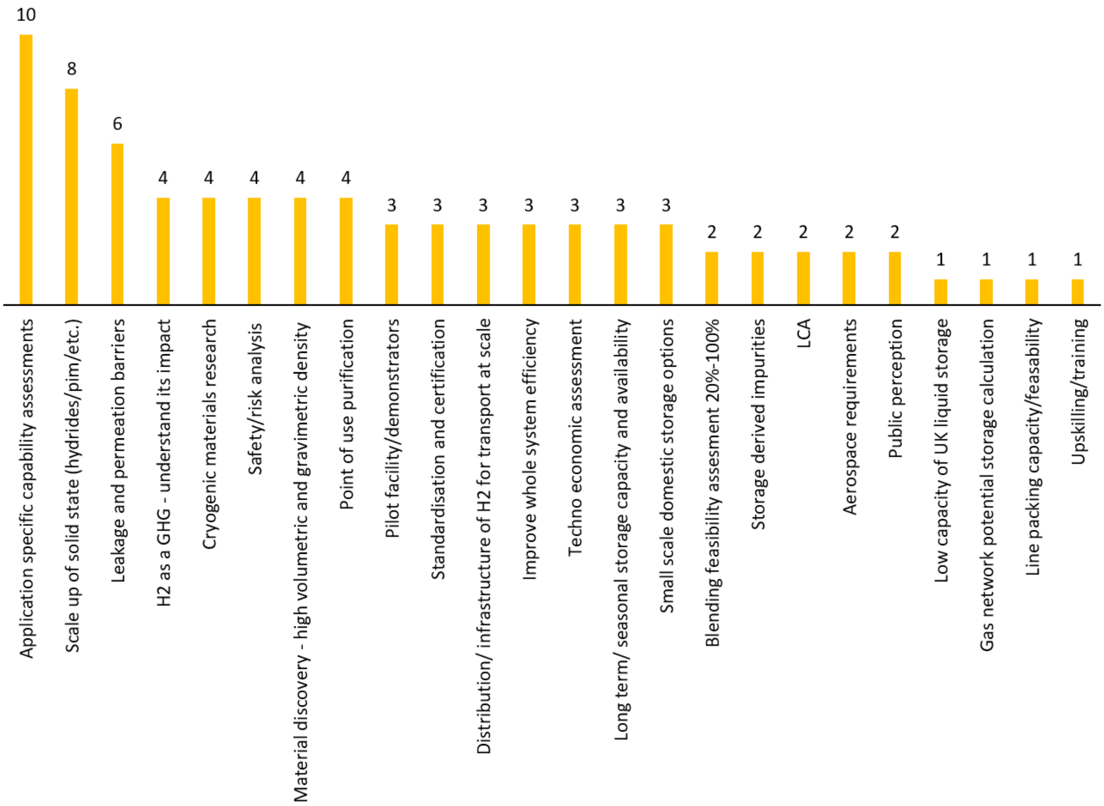



*Figure 2: Collated responses to "Thinking of how hydrogen is stored and the strategic drivers for change –From your perspective what are the challenges/unmet needs that need to be overcome?", grouped by theme. A larger version is available in Appendix C and the raw data with categorisation tags is in Appendix F.*

### Summary

- Attendees frequently mentioned that the specific capabilities of storage options and technologies needs to be recorded in a central knowledgebase and demonstrators and pilot studies could signpost for others "Demonstrate technology at scale". This also included responses that discussed how specific challenges were dependent on the end use "The storage technology is very specific to the end use".
- Scale up of solid state technologies was also well discussed. Several people discussed the need to conduct specific research in this area. "Physisorption storage: Existing materials

have poor storage capacity, fundamental research required in materials with high volumetric and gravimetric storage capacity and durability at high pressure. The materials should also be easily processed and manufactured at large scale". This was also picked up in the feedback session where it was noted that these materials must be demonstrated at scale. There was also discussion about the possibility of improving polymer storage to exceed the performance of compressed gas.

- Leakage and permeation barriers also scored highly. This involved discussion of the end use of hydrogen and how this links to the storage option. Particular challenges were identified in geological storage and the effects of contamination. Understanding the impact and implications of H2 as a GHG was also identified as important. In the feedback session discussion highlighted the gas network industry is concerned about leakage and the need for climate science research to understand the GHG effects.
- Several people noted that point-of-use purification technology may be needed to deal with contamination and over-purifying before long term storage may not be efficient.
- It was also highlighted that public perception and acceptance of hydrogen and the locations for storage is vital. Discussion of safe, volumetrically and gravimetrically dense storage options are key for the aerospace and heavy transport sectors. With many research opportunities in liquid hydrogen research such as thermodynamics of systems, material behaviour and cryogenic behaviour.

## 3.2 Future Vision and Impact

The second breakout discussion focused on the future vision for hydrogen storage and followed a similar format to the previous discussion. Figure. 3 highlights the responses grouped by theme.

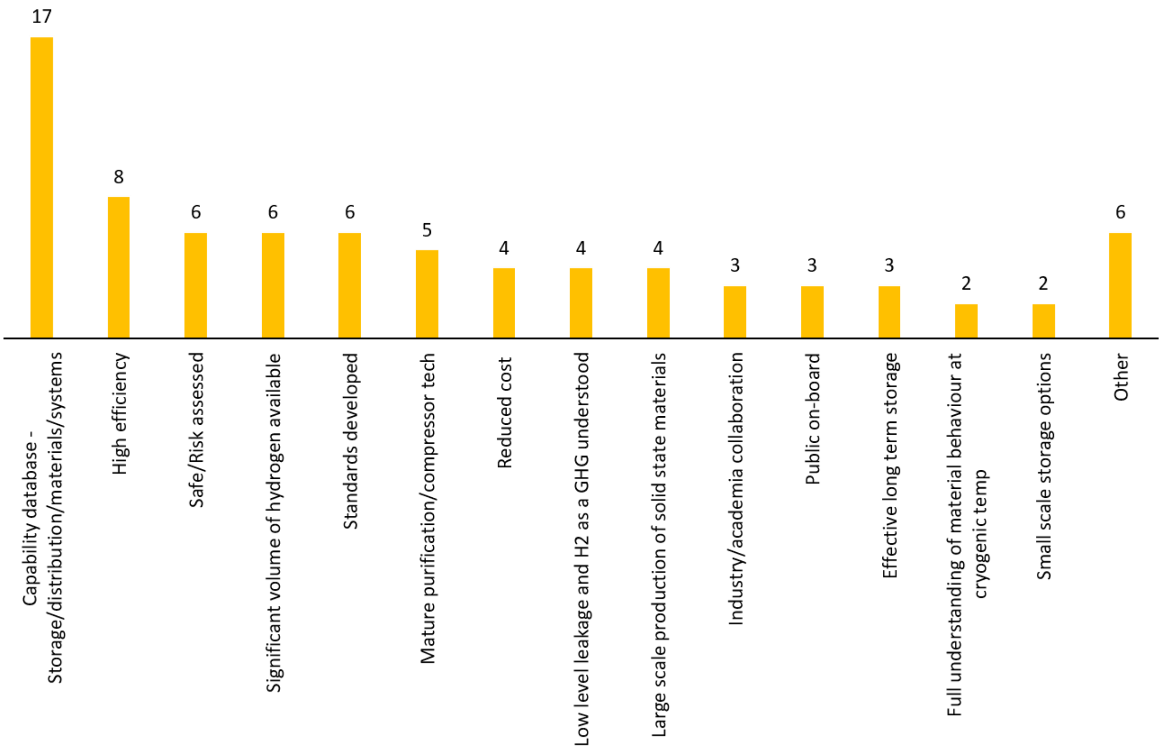



*Figure 3: Collated responses to "Thinking ahead – what difference or change would you like to see in H2 storage by 2050?". A larger version is available in Appendix D and the raw data with categorisation tags is in Appendix G.*

## Summary

- Attendees discussed use-case specific examples of storage and how that could help development. These were often grouped as a need for a capability database, so knowledge sharing can take place. Other delegates wanted “comprehensive materials property databases” with examples of “Purity and requirements for specific uses” for instance. This was picked up in the feedback session, where the need for comprehensive technology demonstrators to prove and test scalability was outlined.
- Efficiency was concluded to be a key future need, with Efficient storage materials/compressors/purification/use. “Improving efficiency - especially capturing heat”. Again this was repeated during the feedback session with the need for developed, highly efficient and stable storage materials.
- Common standards, modular technologies, regulatory frameworks, certification was also highly discussed, with the need for the entire sector to also use common language. “Clear design rules for structural materials for hydrogen storage” and “Standardisation and regulation - linking to future needs”
- Ensuring the public are on board and highly skilled contributors to the hydrogen economy by 2050 was also mentioned in the feedback session and will be important for the development of the industry. The need for small scale and low pressure storage options was also discussed, as well as storage flexibility for seasonal demands.

The “other” category included: *Sustainable storage available, Government funding increased, Storage linked to national grid, Mature technologies/novel technologies, Re-uptake of stranded assets, Understanding of pressure and temperature storage challenges, Volumetric density improvement, Workforce in-place/trained/skilled.*

## 3.3 Opportunities for Research

The final breakout discussion focused on the opportunities for hydrogen storage research. Figure 4 highlights the responses grouped by theme. This discussion had the least responses for the workshop, this may have been due to it being late in the afternoon and some attendees had already left, or that many of the points were already raised in the earlier breakouts.

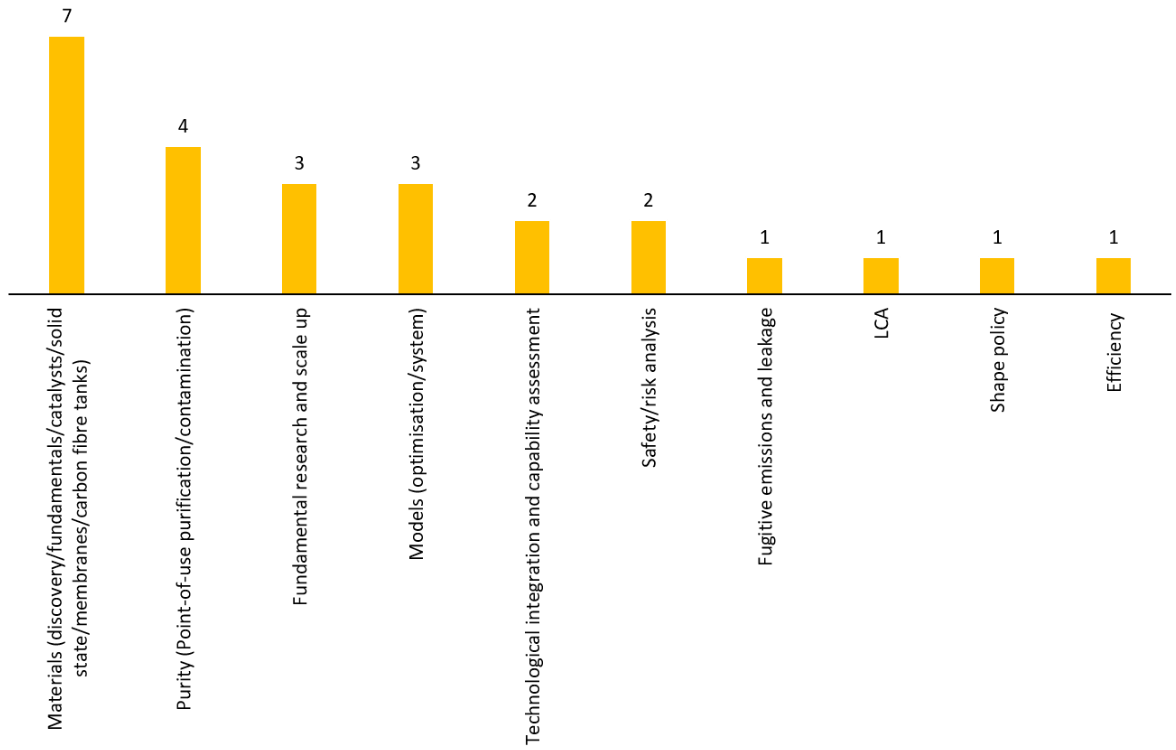



*Figure 4: Collated responses to the questions: "Considering the discussions we have had today -What are the opportunities for research that will lead to and make the step change in H2 storage? -What are the fundamental research questions that we need to think about? A larger version is available in Appendix E and the raw data with categorisation tags is in Appendix H.*

### Summary

- Materials featured heavily in the final breakout discussion. This included comments such as "Materials must withstand large numbers of cycles between cryogenic and ambient temperatures" and "containment materials that work well with cryogenic temperatures" which were centred around carbon fibre or other reinforced compression tanks. Discussion of solid state materials also featured, e.g. "Materials with high capacities are needed". Fundamental research and discovery of catalysts and permeation barriers was also requested, e.g. "new hydrogen permeation barriers" and "Development of highly efficient catalysts". This was mirrored in the feedback session, with super insulating materials, weld mechanics, hydrogen embrittlement and cheaper, recyclable materials were also discussed.
- Purity was the second most frequent comment, with contamination and its impact on purity, as well as novel point-of-use purification technologies identified as key opportunities. It was noted that the end-use of hydrogen would dictate purity demand, but purifying before and after storage would be inefficient
- Further comments in the feedback session asked for research into cyclic performance and increasing efficiency, with potential to maximise thermal energy management.

# 4. Concluding remarks

There were common themes that emerged throughout the workshop, identified here again as key challenges and opportunities for research.

1. Understanding of the fundamentals of hydrogen storage and mature knowledgebase of technologies and systems. Development of central database for comparisons, demonstrators, pilots and use case matching.
2. Upscaling of solid state/PIM/MOF/hydride storage, with large scale production consideration and production limits understood. Development of capabilities, including novel materials and maturation of technologies.
3. Leakage and $H_2$ as a greenhouse gas understood. This includes modelling to understand the limits (out of storage scope) and development of leakage sensors and permeation barriers.
4. Materials for cryogenic storage also featured across all breakout discussions. This involved not only carbon fibre pressure vessels, but also liners, sensors, and filters.
5. Research into contamination and purity was heavily discussed, with many areas lacking fundamental research. Contamination of geological stores, point-of-use purification and purity requirements were most commonly requested.
6. End use was also intrinsic to many of the storage discussions, with several comments application and context specific. Follow-up focus groups with domain or specific end user groups may be beneficial.
7. Important issues such as public perception, education, safety and security were also discussed, albeit less frequently. Focus groups could be beneficial to engage more social scientists and also to follow-up with specific industrial sectors.

## Appendix A: Attendee Agenda

THE COLLECTIVE

UK Research and Innovation

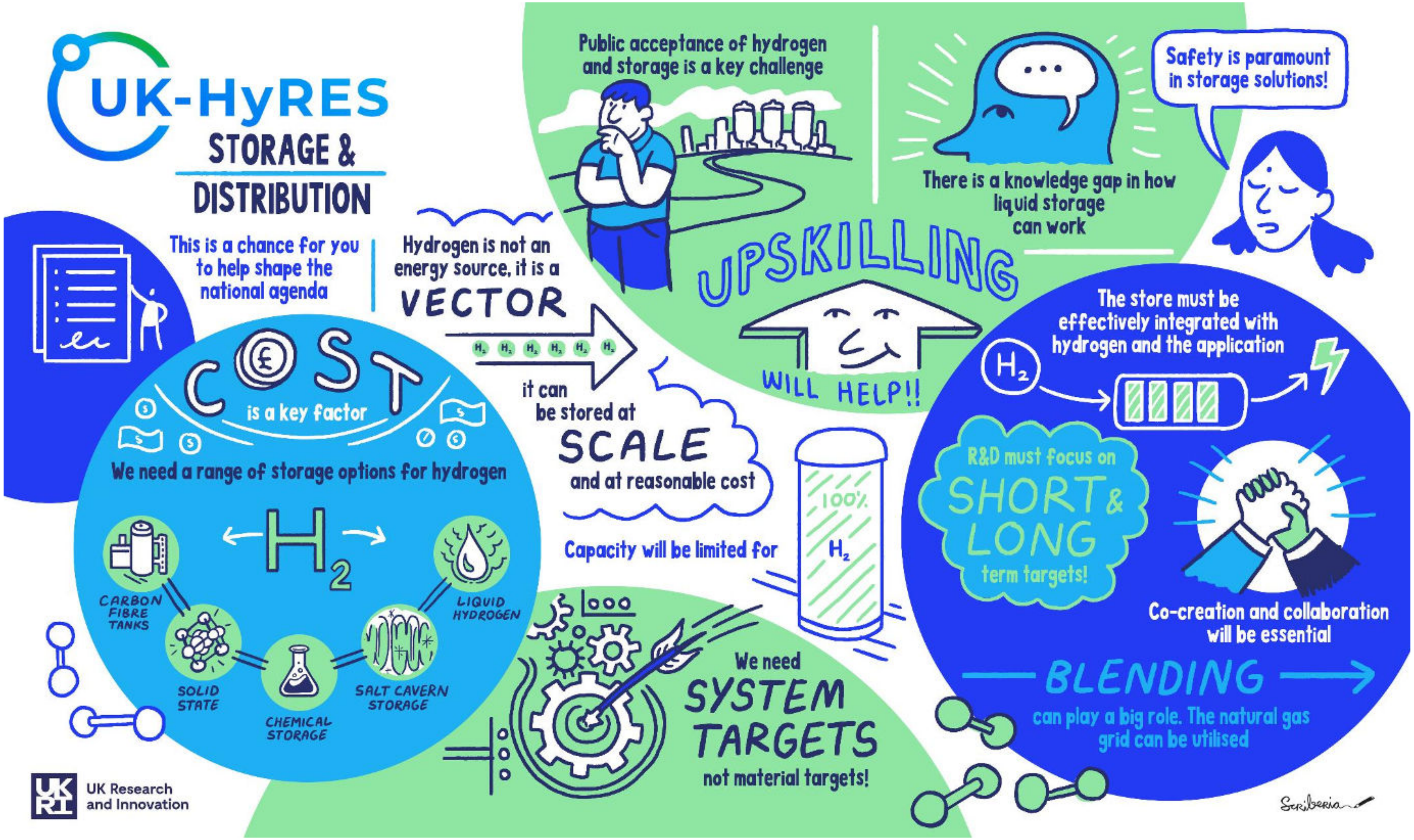
**UK-HYRES Project**
**Theme 2 Workshop : STORAGE**
**1330-1630 Thurs 16th June 2022**

UK-HyRES

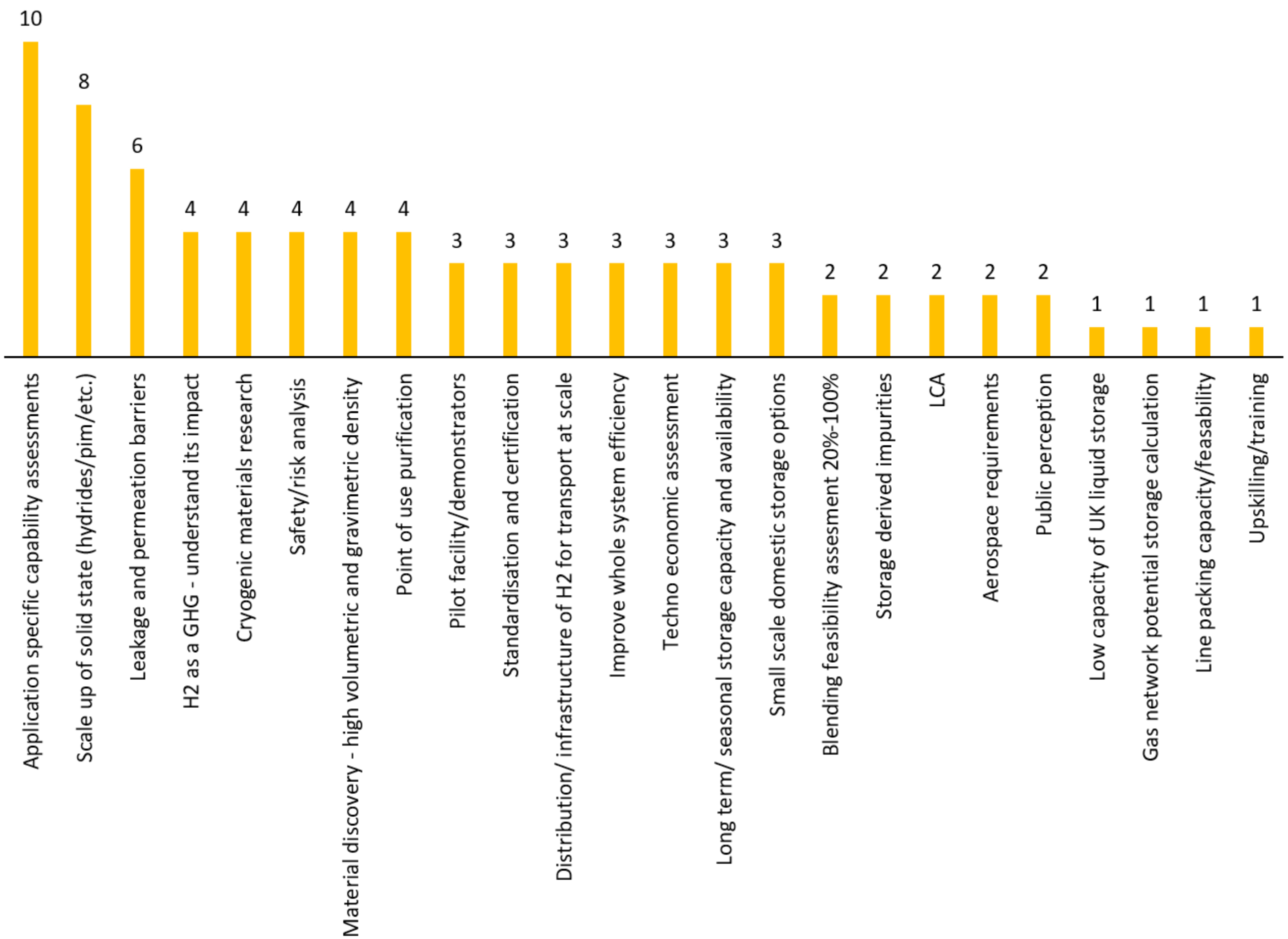
**Zoom link**
:https://us06web.zoom.us/j/88979766681?pwd=NEVadllzNzRGK2NyOFJDMG9xblprUT09

| | |
|---|---|
| **1315** | **Waiting Room opens** |
| **1330** | **Welcome and Introductions** |
| | **Setting the context for today's workshop**<br>● **UK-HyRES**<br>● **Storage Theme**<br>● **Theory of Change framework**<br><br>***Tim Mays***<br>***Rachael Rothman*** |
| | **Strategic Drivers for Change - Insight Videos**<br><br>● **David Book (University of Birmingham)**<br>● **Chris Manson-Whitton (Progressive Energy)** |
| | **Breakout Discussion 1: Challenges and Unmet Needs**<br><br>**Followed by feedback in plenary** |
| **1450** | **COFFEE BREAK** |
| **1500** | **Future Vision - Insight Videos**<br><br>● **Gavin Walker (University of Nottingham)**<br>● **Subi Mukherjee (Ceres Power)** |
| | **Breakout Discussion 2: Future Vision and Impact**<br><br>**Followed by feedback in plenary** |
| | **Breakout Discussion 3: Opportunities for Research**<br><br>**Followed by an open floor session** |
| | **Next Steps** |
| **1630** | **CLOSE** |

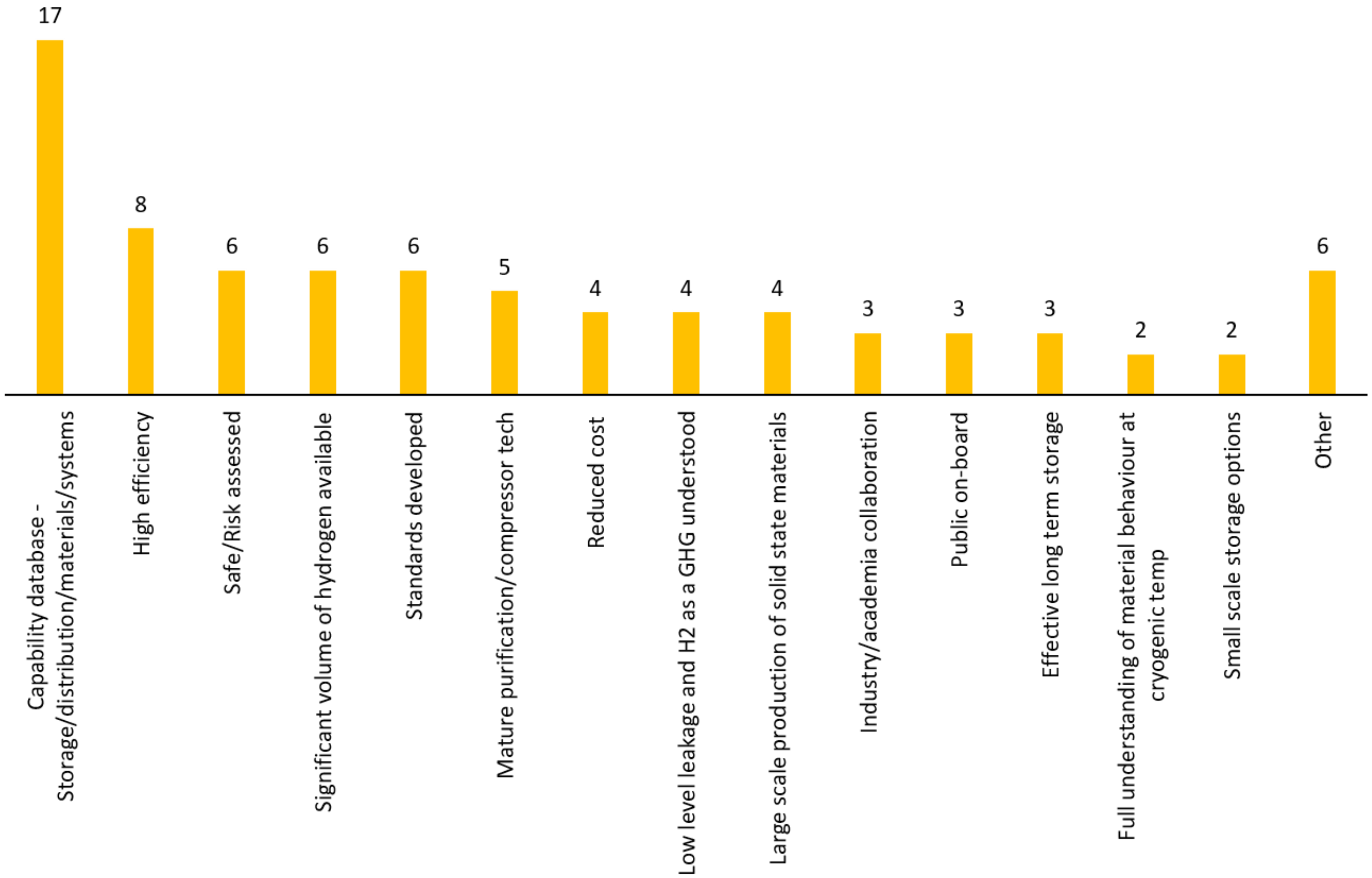
Appendix B: ***An illustrative summary of the workshop produced by Scriberia.***



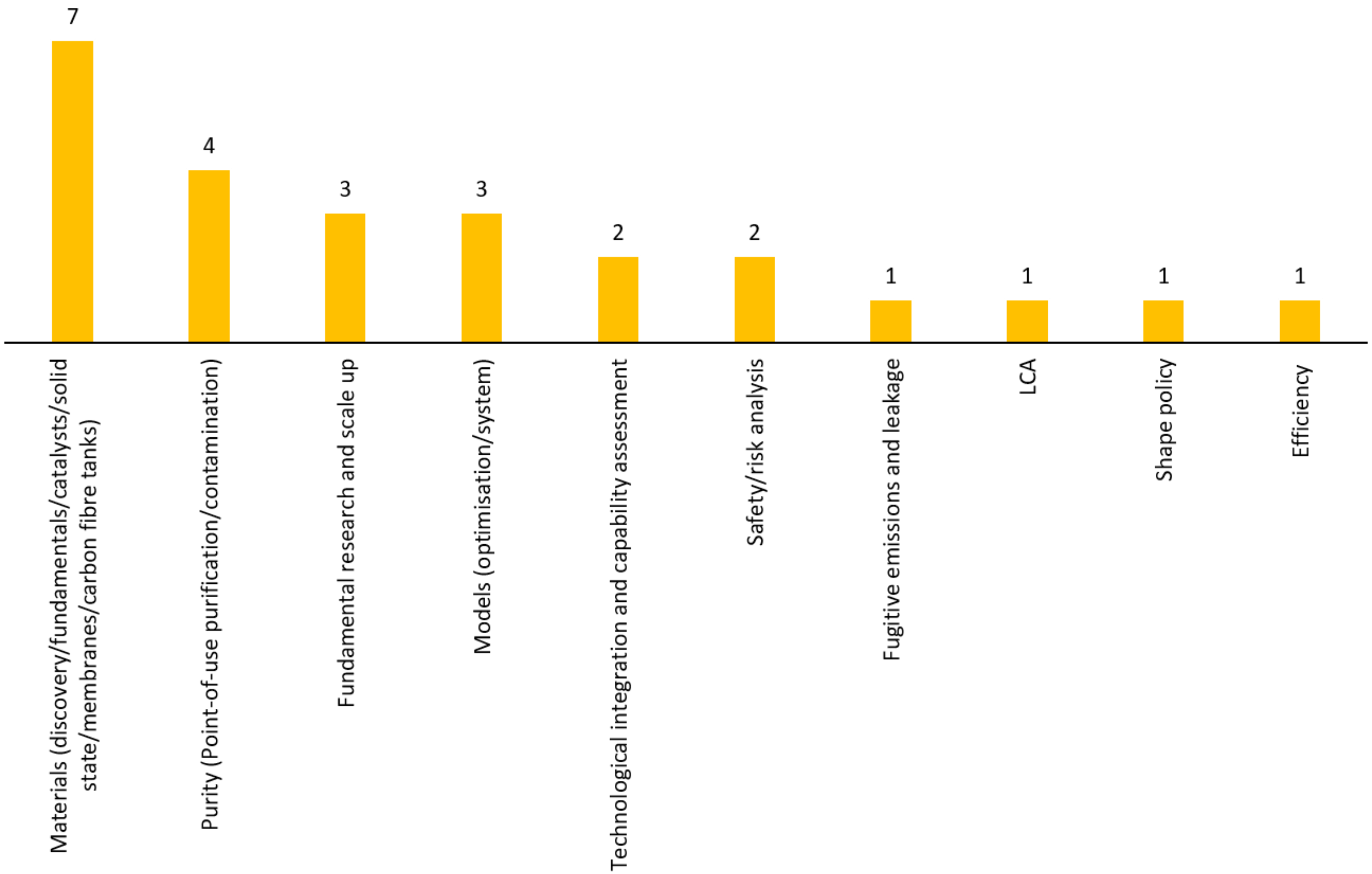
Appendix C: ***Responses to "Thinking of how hydrogen is stored and the strategic drivers for change – From your perspective what are the challenges/unmet needs that need to be overcome?", grouped by theme.***



Appendix D: ***Responses to "Thinking ahead – what difference or change would you like to see in H2 storage by 2050?", grouped by theme.***



## Appendix E: **Responses to "What are the opportunities for research that will lead to and make the step change in H2 storage? What are the fundamental research questions that we need to think about?", grouped by theme.**



## Appendix F: **All responses to *"Thinking of how hydrogen is stored and the strategic drivers for change – From your perspective what are the challenges/unmet needs that need to be overcome?"*, with primary, secondary and tertiary categorisation and the counts for each category.**

### All Comments

| **THEME:** | **STORAGE** | | | |
|---|---|---|---|---|
| **BREAKOUT** | **1** | | | |
| **QUESTION** | **Thinking of how hydrogen is stored and the strategic drivers for change – From your perspective what are the challenges/unmet needs that need to be overcome?** | | | |
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| **ROOM #** | **Comment** | **Primary** | **Secondary** | **Tertiary** |
| **1** | Is there a pilot facility for hydrogen storage? | Pilot facility needed | | |
| **1** | From gas network perspective - in the long term there would be 100% hydrogen in gas networks, though short term would be 20% as of next year. Plan is to go through a cluster route. The problem is that it might cause relocation of industry. Coastal based clusters. Can gas networks provide level of hydrogen required for industry. Store the energy within the actual network for use whenever. | Industry/skills geographical location assessment | Gas network potential storage calculation | |
| **1** | Blending 20% by volume and 4% by energy - is pointless. 20% is the level at which gas network does not require change in infrastructure. | Blending feasibility assessment | | |
| **1** | Is there a requirement to go through a blue hydrogen transition- Redcar has gone straight to green Hydrogen | | | |
| **1** | Drivers for different storage- blend of options dependent on the industry and end users. Hydrogen brings flexibility from an energy sector perspective multiple storage options are good. | Application specific capability assessments | | |
| **1** | Complex metal hydrides-gap in knowledge on the implementation of these at scale. Price is high | Scale up of solid state (hydrides/pim/etc.) | | |

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| **1** | Accreditation of materials for hydrogen adoption particularly cryogenic materials-there is not a standard way of measuring 'capacities' of hydrogen. Consistent methods for measuring for comparison of hydrogen storage. | Certification of cryogenic materials | Standardisation and certification |
| **1** | Gas networks concerned about leakage which could have impacts on indirect GHG emissions. Climate science for hydrogen economy is really important | H2 as a GHG - understand its impact | Leakage |
| **1** | -Sensing technology for hydrogen is not mature. | Develop hydrogen leakage sensors | Leakage |
| **1** | -purging of gas networks necessary for hydrogen which would have impacts of GHG emissions | H2 as a GHG - understand its impact | |
| **2** | Lack of liquid hydrogen production and storage in UK | Low capacity of UK liquid storage | |
| **2** | Lack of research on cryogenics e.g. for aerospace and potentially maritime industries including handling and refuelling. | Cryogenic materials research | safety/ risk analysis |
| **2** | Lighter weight and more conformable cryogenic storage | Reducing mass of cryogenic storage | Cryogenic materials research |
| **2** | Potential entrainment of water and impurities from storage into distribution network | Storage derived impurities | |
| **2** | Round-trip energy efficiency of hydrogen carriers | Full LCA understanding | |
| **2** | Meeting transport storage needs at point of distribution e.g. retail sites | Distribution/ infrastructure of H2 for transport at scale | |
| **2** | Physio-sorption storage: Existing materials have poor storage capacity, fundamental research required in materials with high volumetric and gravimetric storage capacity and durability at high pressure. The materials should also be easily processed and manufactured at large scale. | Scale up of solid state (hydrides/pim/etc.) | Material discovery - high volumetric and gravimetric density |
| **3** | Infrastructure for hydrogen distribution - fuelling sites, Push from the governments needed, Transport and energy company support also needed | Distribution/ infrastructure of H2 for transport at scale | |
| **3** | Efficiency improvements needed | Improve efficiency | |
| **3** | Lower infrastructure costs | Distribution/ infrastructure of H2 for | |

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| | | transport at scale | | |
| **3** | Use of waste heat and compression - heat from metal hydrides | Scale up of solid state (hydrides/pim/etc.) | Waste heat potential | Improve efficiency |
| **3** | Heat use from hydrogen storage in salt cavern | Waste heat potential | | |
| **3** | Storage cost depends on details if low pressure is needed, then compressed hydrogen is cost-effective. | Application specific capability assessments | Techno economic assessment | |
| **3** | Biological action in geological hydrogen storage - Particularly depleted oil and gas fields offshore - How this impacts quality of gas storage, storage loss, biochemical action and production of other gases by microbes | Biological impurity impact | Storage derived impurities | |
| **3** | Long term seasonal storage?? Depleted reservoir | Long term/ seasonal storage capacity and availability | | |
| **3** | -> Can aquifers play a role in seasonal storage | | | |
| **4** | Operability of geological storage - safety and reliability risks | Geological storage safety and risks | safety and risk analysis | |
| **4** | Cryogenics within aerospace, what about local generation | Cryogenic material research | Aerospace requirements | Local generation at point of use |
| **4** | Regulatory compliance for localised storage | Regulatory challenges | Standardisation and certification | |
| **4** | Public perception of hydrogen safety | public perception | safety/ risk analysis | |
| **4** | Increasing volumetric energy density for transport, i.e. aerospace and maritime | Aerospace requirements | Material discovery - high volumetric and gravimetric density | |
| **4** | How to deal with fugitive emissions? | H2 as a GHG - understand its impact | Leakage | |
| **4** | Production process for storage - e.g. Metal Hydrides | Scale up of solid state (hydrides/pim/etc.) | | |

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| **4** | When showing energy density figures, we should not show the gross figures but the net figures, i.e. show the in tank energy densities. | standardisation | |
| **5** | Strategic drivers-for transport H2 carriers, liquid fuels such as ammonia, liquid H2, methanol etc | Application specific capability assessments | Techno economic assessment |
| **5** | Cost is the key, purity, size and weight, distance/time scale , safety, compression of H2, efficiently and effectively, | Application specific capability assessments | Techno economic assessment |
| **5** | Transport applications - size and weight of storage is critical | Application specific capability assessments | Increasing volumetric density |
| **5** | Alternative geological forms storage | Long term/ seasonal storage capacity and availability | |
| **5** | Integrity of increased fluctuation of pressures in dynamic use of geological stores | Geological storage pressure fluctuation | safety and risk analysis |
| **5** | Deblending and purification | Point of use purification | |
| **5** | Public knowledge & acceptance | public perception | |
| **5** | Demonstrate technology at scale | Application specific capability assessments | scale up |
| **6** | PIM - polymer storage, Solid state materials research needs to exceed performance of pressurised tanks. | Scale up of solid state (hydrides/pim/etc.) | Increasing volumetric density |
| **6** | do we want to store H2 locally or in larger centralised sites. Oil fields off Scotland not necessarily suitable for hydrogen storage | Long term/ seasonal storage capacity and availability | |
| **6** | reiterated this point, and mentioned that political considerations of siting industry will also be important. | Regulatory challenges | political |
| **6** | if storage is offshore with wind, then we have a water purity issue. | Point of use purification | |
| **6** | most of UHS storage issues could be considered solved, it’s the economics that are challenging | techno economic analysis | |
| **6** | depleted gas reservoir storage may suffer from a minimum scale problem | Long term/ seasonal storage capacity and availability | |

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| **6** | modelling impacts of releases from safety perspective. | H2 as a GHG - understand its impact | |
| **6** | small scale storage options for domestic usage of hydrogen. | small scale domestic storage options | |
| **7** | Challenges in the gas grid - compatibility of compressors, valves/throttles, pipes and tanks to 100% hydrogen | Blending feasibility assessment | |
| **7** | Purity - no point in making very pure hydrogen if the storage introduces impurities. | Point of use purification | |
| **7** | The storage technology is very specific to the end use. | Application specific capability assessments | |
| **7** | Purification needed at the end use, to the appropriate level. | Point of use purification | |
| **7** | Loss of storage capacity due to hydrogen's low density. When using salt caverns or line packing in the gas grid, the storage capacity is only ⅓ as large in energy terms compared to natural gas (but gas flow rate is still good dues to hydrogen's low viscosity) | leakage | |
| **7** | Lack of storage technology for off-grid or remote and small scale applications. Especially low pressure (<50bar) and very low pressure (<50 millibar) to replace biogas for micro-grids. | small scale domestic storage options | |
| **7** | Research to be done on leak rates through materials for storage of hydrogen | leakage | |
| **8** | 10 point plan - driver | | |
| **8** | Feasibility of gas network conversion | 20%-100% Blending feasibility assessment | Blending feasibility assessment |
| **8** | Time scales for change | roadmaps/timescales | |
| **8** | Solid state for storage hydrides/mofs/pim | Scale up of solid state (hydrides/pim/etc.) | |
| **8** | Understanding the full life time of storage media | Full LCA understanding | |
| **8** | Where are we storing - how decentralised | Application specific capability assessments | geographic |
| **8** | demonstrators/ use cases | Application specific capability assessments | demonstrators |

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| **8** | Movable modular transportable storage tech | small scale domestic storage options | |
| **8** | Leakage rupture and failure to detect (liners) develop hydrogen barriers | leakage | permeation barriers |
| **8** | Issues with line packing | line packing capacity/feasibility | |
| **8** | Material behaviour and failure - carbon fibre tanks  not much understanding at cryogenic temps | cryogenic material research | |
| **8** | conditions (storage environment) dictate the storage tech | Application specific capability assessments | |
| **8** | Upskilling across the board - training/skill level | Upskilling/training | |

## Category Counts

| CATEGORY | COUNT |
|---|---|
| **APPLICATION SPECIFIC CAPABILITY ASSESSMENTS** | 10 |
| **SCALE UP OF SOLID STATE (HYDRIDES/PIM/ETC.)** | 8 |
| **LEAKAGE AND PERMEATION BARRIERS** | 6 |
| **H2 AS A GHG - UNDERSTAND ITS IMPACT** | 4 |
| **CRYOGENIC MATERIALS RESEARCH** | 4 |
| **SAFETY/RISK ANALYSIS** | 4 |
| **MATERIAL DISCOVERY - HIGH VOLUMETRIC AND GRAVIMETRIC DENSITY** | 4 |
| **POINT OF USE PURIFICATION** | 4 |
| **PILOT FACILITY/DEMONSTRATORS** | 3 |
| **STANDARDISATION AND CERTIFICATION** | 3 |
| **DISTRIBUTION/ INFRASTRUCTURE OF H2 FOR TRANSPORT AT SCALE** | 3 |
| **IMPROVE WHOLE SYSTEM EFFICIENCY** | 3 |
| **TECHNO ECONOMIC ASSESSMENT** | 3 |
| **LONG TERM/ SEASONAL STORAGE CAPACITY AND AVAILABILITY** | 3 |
| **SMALL SCALE DOMESTIC STORAGE OPTIONS** | 3 |
| **BLENDING FEASIBILITY ASSESSMENT 20%-100%** | 2 |
| **STORAGE DERIVED IMPURITIES** | 2 |
| **LCA** | 2 |
| **AEROSPACE REQUIREMENTS** | 2 |
| **PUBLIC PERCEPTION** | 2 |
| **LOW CAPACITY OF UK LIQUID STORAGE** | 1 |
| **GAS NETWORK POTENTIAL STORAGE CALCULATION** | 1 |
| **LINE PACKING CAPACITY/FEASIBILITY** | 1 |
| **UPSKILLING/TRAINING** | 1 |

## Appendix G: **All responses to *"Thinking ahead – what difference or change would you like to see in H2 storage by 2050?", grouped by theme."*, with primary, AND secondary categorisation and the counts for each category.**

## All Comments

| **THEME:** | **STORAGE** | | |
|---|---|---|---|
| **BREAKOUT** | **2** | | |
| **QUESTION** | **Thinking ahead – what difference or change would you like to see in H2 storage by 2050?** | | |
| | | | |
| | | | |
| **ROOM #** | **Comment** | **Primary** | **Secondary** |
| 1 | How cost effective can storage methods become in 2050 timescale | Reduced cost | techno economic analysis |
| 1 | Addressing perceptions around hydrogen safety in a variety of end use scenarios | Safe/Risk assessed | |
| 1 | Understanding the properties of the materials at 20K - composites or metal systems and the impact on these | Full understanding of material behaviour at cryogenic temp | Composite/ Metals |
| 1 | Availability of significant volumes of hydrogen - quoting in kgs and tonnes rather than GW's | Significant volume of hydrogen available | Standards developed |
| 1 | Relate units (kg or tonnes) to mileage driven in transport (1kg produced requires 50kwh) | Standards developed | |
| 1 | Ensure low leakage from storage | Low level leakage and H2 as a GHG understood | |
| 1 | Storage method of hydrogen to match access needs in terms of timescale and link to production | Database of different storage/distributio n capabilities | |
| 1 | Ability to produce hydrogen storage materials at scale required | Large scale production of solid state materials | |
| 1 | Clear design rules for structural materials for hydrogen storage | Standards developed | |
| 1 | Sustainable storage solutions | Sustainable storage available | |
| 1 | Scale of storage in relation to what it is needed for and is it geographically in the right place - matching storage and distribution | Database of different storage/distributio n capabilities | |

| | | | |
|---|---|---|---|
| 2 | More government funding for projects | Government funding increased | |
| 2 | Industry collaboration to research | Industry/academia collaboration | |
| 2 | Connections to the national grid from storages with dynamic reaction times | Storage linked to national grid | |
| 2 | Improvement of technology vs development of new technology? | Mature technologies/Novel technologies | Novel technologies |
| 2 | Long term vs short term storage? | Database of different storage/distribution capabilities | |
| 2 | Expansion in consenting and utilisation of stranded assets | Re-uptake of stranded assets | |
| 3 | address temperature and pressure related challenges of storing hydrogen. | Understanding of pressure and temperature storage challenges | |
| 3 | efficiency and stability of h2 storage materials. | High efficiency | large scale production of solid state materials |
| 3 | Public perception: | Public on-board | |
| 3 | Public perception and safety | Safe/Risk assessed | Public on board |
| 3 | fire/explosion risk is perhaps overstated | Safe/Risk assessed | |
| 3 | echoed that people have negative perceptions re safety | | |
| 3 | Can we do public demos of safety? | Safe/Risk assessed | Public on board |
| 3 | ignition energy not worse than nat gas | | |
| 3 | Improving efficiency - especially capturing heat | High efficiency | High efficiency |
| 3 | Tom beard - improvements to volumetric energy density, e.g. liquid organic hydrogen carriers. AloHC, e.g. toluene <-> methyl cyclo-hexane. | Volumetric density improvement | large scale production of solid state materials |
| 3 | John Garside - one outcome is assessing system level benefits of techs that might not look as good in isolation. | Database of different storage/distribution capabilities | |
| 3 | Need to have a good handle on H2 as indirect GHG. | Low level leakage and H2 as a GHG understood | |

| | | | |
|---|---|---|---|
| 3 | Hydrogen loss through all components in the system needs to be overcome due to possible impact as indirect GHG. | Low level leakage and H2 as a GHG understood | |
| 4 | Decision on centralised vs decentralised system? | Standards developed | |
| 4 | Effective long-term storage | Effective long term storage | |
| 4 | More H2 storage, integrated into the system to support flexible access | Significant volume of hydrogen available | |
| 4 | Large scale geological storage of hydrogen in salt caverns - localised distribution - near existing chemical industries - Teesside, Cheshire, Easter Irish Sea | Effective long term storage | |
| 4 | Connections/proximity between renewable energy production and hydrogen storage [Scotland problematic here - high renewable, low site availability] | Effective long term storage | |
| 4 | Overcoming gas/mineral contamination of geo-storage | Mature purification/compressor tech | |
| 4 | Compressed gas storage - high pressure is a bottleneck for scaling | Database of different storage/distribution capabilities | |
| 4 | Overcoming unreliability of high use compressors - costs/downtime - improvements of mechanical compressors and looking at alternatives such as metal hydrides, chemical etc | Large scale production of solid state materials | Mature purification/ compressor tech |
| 4 | Switch to high capacity and low pressure storage - | | |
| 4 | Possibility of low pressure for small scale applications (e.g. 100 homes - off grid for LMICs - where used for cooking as replacement for LPG/biogas); Japan - 12 homes, metal hydride - v expensive - low pressure, low footprint | Database of different storage/distribution capabilities | small scale storage options |
| 4 | Mobile storage? | small scale storage options | |
| 4 | Communicating hydrogen using tonnage | Standards developed | |
| 4 | 20-35% final energy use - 40MT max per year | Significant volume of hydrogen available | |
| 4 | Different storage technologies to enable flexibility in the season to account for seasonal variability in use | Database of different storage/distribution capabilities | |
| 4 | Production limits | Significant volume of hydrogen available | |

| | | | |
|---|---|---|---|
| 4 | Many affordable low cost electrolysers | reduced cost | Database of different storage/distribution capabilities |
| 5 | Educated and skilled personnel working in the sector | Workforce in place/ trained/skilled | |
| 5 | Knowledge sharing with engineers experienced in storing other cryogenic liquids, e.g. LNG | Industry/academia collaboration | Database of different storage/distribution capabilities |
| 5 | Comprehensive materials property database | Database of different storage/distribution capabilities | Full understanding of material behaviour at cryogenic temp |
| 5 | Sufficient quantity to meet the needs of all interested sectors | Significant volume of hydrogen available | |
| 5 | Efficient (volume, mass, energy of conversion) | Efficient storage | |
| 5 | Safe | Safe/Risk assessed | |
| 5 | Secure | Secure | |
| 5 | Affordable | Reduced cost | |
| 5 | Flexible | High efficiency | |
| 6 | Understanding geological impurities | Impurities understanding | Mature purification/ compressor tech |
| 6 | Dynamic cycling of salt caverns | | |
| 6 | Reduction of boil of in liquid storage - super insulation - | liquid storage boil off reduced | |
| 6 | Cryogenic material properties | Full understanding of material behaviour at cryogenic temp | |
| 6 | Leakage and how we reduce the effects | Leakage kept to low levels | |
| 6 | Metering - how do we manage the heat - thermal management | High efficiency | |
| 6 | Price per kg to store capex - compressed gas price reduction | Reduced cost | Database of different storage/distribution capabilities |
| 6 | Cheaper materials/ sustainable/ recyclable / full life cycle assessment | Reduced cost | |

| | | | |
|---|---|---|---|
| 6 | Innovative storage in regional demonstrators - integration of storage of power to x - when do we draw/when do we take (economics) maybe needs new business models - benefits | demonstrators | industry/academic collaboration |
| 6 | Solid state storage - cooling power - can we use the excess heat (overall system efficacy) thermal vectors | High efficiency | |
| 6 | multipurpose/function | Database of different storage/distribution capabilities | |
| 6 | Compression - thermal management issue to be overcome - | High efficiency | |
| 6 | Novel materials - possibility for integrating hydrogen storage ie. solid state integration | Large scale production of solid state materials | |
| 6 | What is the required pressure (use case specific) cascade distribution | Database of different storage/distribution capabilities | |
| 6 | Standardisation and regulation - linking to future needs | Standards developed | |

## Category Counts

| CATEGORY | COUNT |
|---|---|
| **CAPABILITY DATABASE -STORAGE/DISTRIBUTION/MATERIALS/SYSTEMS** | 17 |
| **HIGH EFFICIENCY** | 8 |
| **SAFE/RISK ASSESSED** | 6 |
| **SIGNIFICANT VOLUME OF HYDROGEN AVAILABLE** | 6 |
| **STANDARDS DEVELOPED** | 6 |
| **MATURE PURIFICATION/COMPRESSOR TECH** | 5 |
| **REDUCED COST** | 4 |
| **LOW LEVEL LEAKAGE AND H2 AS A GHG UNDERSTOOD** | 4 |
| **LARGE SCALE PRODUCTION OF SOLID STATE MATERIALS** | 4 |
| **INDUSTRY/ACADEMIA COLLABORATION** | 3 |
| **PUBLIC ON-BOARD** | 3 |
| **EFFECTIVE LONG TERM STORAGE** | 3 |
| **FULL UNDERSTANDING OF MATERIAL BEHAVIOUR AT CRYOGENIC TEMP** | 2 |
| **SMALL SCALE STORAGE OPTIONS** | 2 |
| **SUSTAINABLE STORAGE AVAILABLE** | 1 |
| **GOVERNMENT FUNDING INCREASED** | 1 |
| **STORAGE LINKED TO NATIONAL GRID** | 1 |
| **MATURE TECHNOLOGIES/NOVEL TECHNOLOGIES** | 1 |
| **RE-UPTAKE OF STRANDED ASSETS** | 1 |
| **UNDERSTANDING OF PRESSURE AND TEMPERATURE STORAGE CHALLENGES** | 1 |
| **VOLUMETRIC DENSITY IMPROVEMENT** | 1 |

## Appendix H: All responses to “What are the opportunities for research that will lead to and make the step change in H2 storage? What are the fundamental research questions that we need to think about?”, with primary, secondary and tertiary categorisation and the counts for each category.

### All Comments

| | | | |
|---|---|---|---|
| **THEME:** | **STORAGE** | | |
| **BREAKOUT** | **3** | | |
| **QUESTION** | **What are the opportunities for research that will lead to and make the step change in H2 storage? What are the fundamental research questions that we need to think about?** | | |
| | | | |
| | | | |
| **ROOM #** | **Comment** | **Primary** | **Secondary** |
| **1** | Novel materials for inter-day storage | materials | carbon fibre or materials to strengthen existing vessels in the same area of assets the gas distribution network currently has |
| **1** | Increase efficiency and reduce losses | economy | at point of use i.e membranes and PSA |
| **1** | potential entrainment issues from large scale storage | purity | |
| **1** | Impact mercaptans use on fuel cell applications and need to purify ahead of use | purity | |
| **1** | understanding on GHG effects of hydrogen leakage | fugitive emissions | |
| **2** | For small scale H2 storage for transport applications, fundamental research is required | fundamental research | |
| **2** | resolve the contamination of hydrogen purity from ground-based storage solutions | purity | |
| **2** | transport hydrogen from offshore to the city | influence policy | |
| **3** | Opportunity to optimise the utility of storage within a system | models | |

| | | |
|---|---|---|
| **3** | the large losses associated with re pressurising hydrogen for vehicular use. | vehicular use |
| **4** | new hydrogen permeation barriers | material compatibility |
| **4** | Database of material safety with H2 | safety |
| **4** | containment materials that work well with cryogenic temperatures | materials |
| **5** | Seek possibilities for collaboration between research teams and users of the technologies | technological integration |
| **5** | Efficient integration of individual technological developments/solutions into overall systems | technological integration |
| **5** | New business models for selling co-products including electricity back into the grid | New business models |
| **5** | Develop a detailed model | models |
| **5** | Materials for container walls need to be thin and light but also secure and stable | materials |
| **5** | Less expensive container materials are desirable | price |
| **5** | Materials must withstand large numbers of cycles between cryogenic and ambient temperatures | cycle |
| **5** | Materials with high capacities are needed | materials |
| **5** | Development of highly efficient catalysts | materials |
| **6** | improve H2 purity | purity |
| **7** | Balance between research and pilot scale rigs | fundamental research |
| **7** | carbon capture commercial | LCA |
| **7** | Liquid to gaseous conversion | safely |
| **7** | Carbon fibre tanks | materials |

## Category Counts

| CATEGORY | COUNT |
|---|---|
| **MATERIALS (DISCOVERY/FUNDAMENTALS/CATALYSTS/SOLID STATE/MEMBRANES/CARBON FIBRE TANKS)** | 7 |
| **PURITY (POINT-OF-USE PURIFICATION/CONTAMINATION)** | 4 |
| **FUNDAMENTAL RESEARCH AND SCALE UP** | 3 |
| **MODELS (OPTIMISATION/SYSTEM)** | 3 |
| **TECHNOLOGICAL INTEGRATION AND CAPABILITY ASSESSMENT** | 2 |
| **SAFETY/RISK ANALYSIS** | 2 |
| **FUGITIVE EMISSIONS AND LEAKAGE** | 1 |
| **LCA** | 1 |
| **SHAPE POLICY** | 1 |
| **EFFICIENCY** | 1 |
| **MATERIALS (DISCOVERY/FUNDAMENTALS/CATALYSTS/SOLID STATE/MEMBRANES/CARBON FIBRE TANKS)** | 7 |
| **PURITY (POINT-OF-USE PURIFICATION/CONTAMINATION)** | 4 |
| **FUNDAMENTAL RESEARCH AND SCALE UP** | 3 |
| **MODELS (OPTIMISATION/SYSTEM)** | 3 |
| **TECHNOLOGICAL INTEGRATION AND CAPABILITY ASSESSMENT** | 2 |
| **SAFETY/RISK ANALYSIS** | 2 |
| **FUGITIVE EMISSIONS AND LEAKAGE** | 1 |
| **LCA** | 1 |
| **SHAPE POLICY** | 1 |
| **EFFICIENCY** | 1 |
| | |