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

UK-HyRES

Report on Workshop findings: End Use

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The University Of Sheffield. University of Bath. Warwick The University of Warwick. UK Research and Innovation

1. Background and Objectives

The Co-ordinator for Research Challenges in Hydrogen and Alternative Liquid Fuels project (UK-HyRES, https://ukhyres.co.uk/) is funded by the UKRI for six months from 1 April 2022. UK-HyRES is engaging nationally with academic, industrial and policy stakeholders to discuss and identify research challenges the solutions to which will accelerate the deployment of sustainable H&ALF technologies to help the country achieve its legally binding net zero carbon emissions target by 2050 and hence contribute to mitigating disastrous global heating. One of the main engagement routes is via facilitated workshops which are promoted widely in H&LF and associated communities in the UK. The outcomes from these workshops will inform and shape the development of a UKRI Centre of Research Excellence in HA&LFs to start in 2023.

UK-HyRES held the third themed workshop on the **5th July 2022**, which was conducted online via Zoom at 13:30-16:30 with **45 attendees** (~ 80% >2hrs). Building on the success of the UK-HyRES launch event and the previous two themed workshops, this workshop focused on the **End Use of Hydrogen**. This is a summary report of the workshop compiled by UK-HyRES researchers Rajan Jagpal (Bath), Diarmid Roberts (Sheffield) and Mengfei Zhang (Warwick) and reviewed and approved by the project investigator and management teams.

The purpose of the workshop was to bring together key and **diverse stakeholders** from across the hydrogen community to debate and **distil the key challenges** preventing the adoption of hydrogen and alternative liquid fuels, with particular focus on end use. 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 breakout sessions. The agenda (Appendix A) was distributed to the attendees prior to the workshop and focused on, **Challenges and Unmet Needs, Future Vision and Impact**, and **Opportunities for Research**. The workshop is also summarised in an illustrative output by Scriberia (Appendix B).

Principal investigator 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. Highlighting that hydrogen is about balancing supply and demand. Co-investigator Shanwen Tao (University of Warwick) set out some of the strategic drivers for end users and elaborated on the context of the workshop. Co-investigator 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.

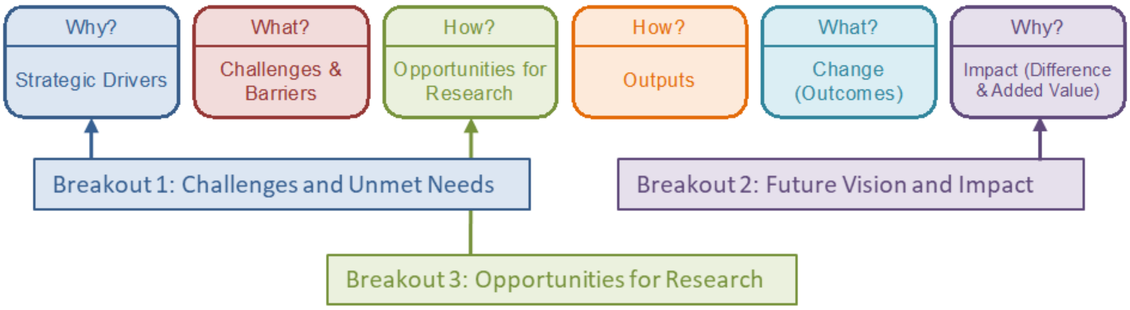


Figure 1: The theory of change framework mapped to each breakout session.

2. Insight Talks

Hydrogen is often discussed from the perspective of fuel cells, but many other end users rely on hydrogen, from ammonia, methanol and steel production, to power generation, oil and metal refining, and synthetic fuels. The end use of hydrogen is crucial to accelerating the uptake of hydrogen and alternative liquid fuels in pursuit of net zero. In the workshop an insight video, recommended by **Nigel Holmes (*CEO, Scottish Hydrogen and Fuel Cell Association*)** and produced by Ben Burman, summarising the motivation and challenges in hydrogen uptake was delivered prior to the first breakout discussion.

Later in the workshop, **Anthony Kurcernak (*Imperial College London*)** delivered an insight talk on the strategic drivers for change, highlighting the many end users with a stake in the hydrogen economy. **Qiong Cai (*University of Surrey*)** gave the final insight talk, with her perspective on the future vision for hydrogen fuel cell technology, such as cheaper and more durable catalysts.

Recordings of all four insight talks are available to download on the UKHyRES.co.uk website at https://ukhyres.co.uk/workshop-4/

3. Breakout Discussions

For each breakout discussion delegates were randomly assigned to groups of six or fewer. In each breakout discussion they 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.

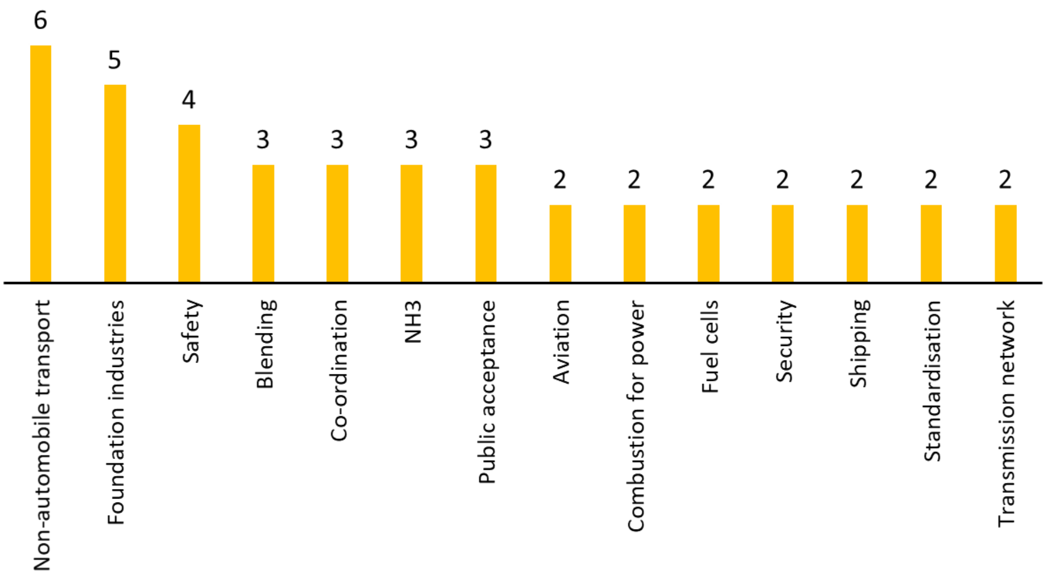


Figure 2: Collated responses to "Thinking of the end use of hydrogen and the strategic drivers for change –From your perspective what are the challenges/unmet needs that need to be overcome?", grouped by theme. Larger version available in Appendix C and all recorded comments and categorisation in Appendix F.

Summary

- The most frequent response in the first breakout was "Non-automobile transport". There was clear indication from the participants that "heavy transport" sectors including "aviation, trains, lorries, trucks, and shipping" represented an end use challenge and would require specific research and industrial input to understand the unmet needs. This included comments that the maritime industry could be a significant user of H_2, but this sector appears to have less collaboration and funding, but also that ammonia vs. hydrogen decisions need to be made. Aviation was also signposted as a key industry as volumetric density improvement is critical to their success.
- Attendees frequently mentioned "Foundation industries" which includes chemical, steel, cement and other difficult to abate sectors. Importance was placed on developing collaborations and engaging with these key industrial sectors to understand the specific challenges. One participant remarked that "Decarbonisation of steel in hydrogen use - emissions need to fall by more than 50%". It was also noted that we must identify further hard to electrify industrial sectors.
- As in all of the themed workshops, "Safety" also featured highly. Challenges were identified in producing a skilled workforce for servicing and implementation to ensure safe working practices. Specific safety considerations of natural gas and hydrogen blending was also discussed, as well as the challenge in designing safe technologies from the outset. This precedes another highly scoring category of "Public acceptance".
- "Co-ordination" was also of note. Participants discussed the need for an "overarching board" with specific discussion centred around the need for co-ordination between various industries, clusters and centres. This was repeated in the feedback session where policy co-ordination was also demanded.

The "other" category included: *Application specific technology comparison, Certification, Batteries vs. hydrogen, Behavioural change, Domestic, Duplication, Energy requirement, Fertiliser, H2 as GHG, Import/export/self-sufficiency, Industry input, Influence policy, Info campaign, Infrastructure, Large scale, Life cycle assessment, NOx, Purity, Recyclability, Refuelling stations, Remote power generation, Sector prioritisation, Techno-economic analysis, Training, Urgency, Materials compatibility, Net zero 2050*

3.2 Future Vision and Impact

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

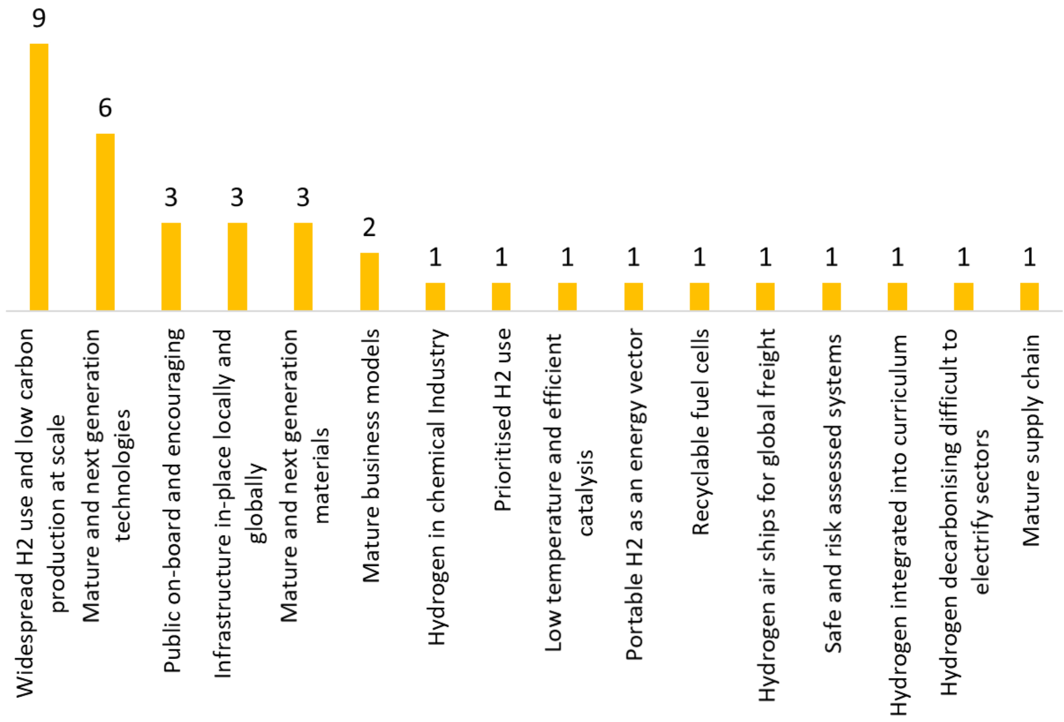


Figure 3: Collated responses to "Thinking ahead – what difference or change would you like to see in H_2 end use by 2050?" Larger version available in Appendix D and all recorded comments and categorisation in Appendix G.

Summary

- Participants vision for 2050 first focused on the need for "Widespread H_2 use and production at scale" as a key driver for the hydrogen economy. This included the desire for "hydrogen for all" and development of new market sectors and the inclusion of smaller end user groups. Access equality and scaled up UK production was seen as key challenges towards the transition. This included comments in the feedback session that hydrogen must become a commodity by 2050 and available in portable devices, in small scale and large scale volumes and that fuel cells, storage materials and catalysts must be manufactured at scale
- "Mature and next generation technologies" was the second most frequent response. This included development of new fuel cells that are designed for low cost, large scale manufacture, recyclability and from sustainable materials. Consideration of next generation technologies to enable wider product choices for emerging end user groups was also highly discussed.
- Similarly, to the other themed workshops, "Public on-board and encouraging" featured highly. It was recognised that the public play a key role in the transition and encouraging further engagement was vital. It was commented that the public had begun to understand the need for hydrogen, but it was the responsibility of the industry and academia to further educate and upskill. In the feedback session there was further discussion of the inclusion and integration of hydrogen and sustainable technologies into academic curriculums. It was added that it would require policy changes to achieve it and it should target all disciplines from phycology to physics and primary schools to universities.
- It was also noted, in the feedback session, that by 2050 we must fully understand and identify all difficult-to-electrify sectors. Developing, deploying and prioritising hydrogen technologies to effectively decarbonise.

3.3 Opportunities for Research

The final breakout discussion focused on the opportunities for hydrogen end use 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.

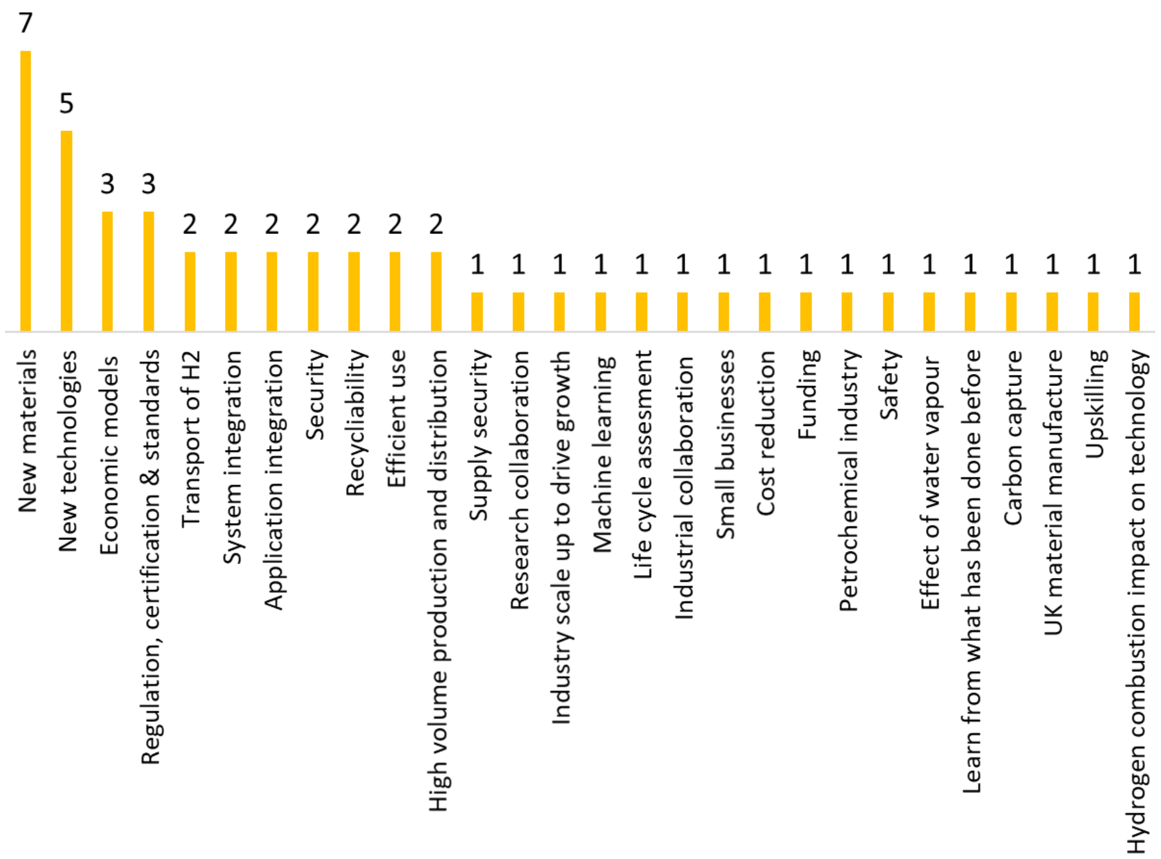


Figure 4: Collated responses to the questions: "Considering the discussions we have had today -What are the opportunities for research that will lead to and make the step change in H_2 end use? - What are the fundamental research questions that we need to think about? Larger version available in Appendix E and all recorded comments and categorisation in Appendix H.

Summary

- "New materials" featured heavily in the final breakout discussion. This included comments such requesting "Fundamental electrochemistry, catalysis and material research" and replacing expensive platinum group metal (PGM) catalysts and ensuring recyclability and design for X. There was also discussion around the need for high temperature materials and materials resistant to H_2 degradation and permeation.
- Opportunities to develop "New technologies" for green hydrogen production, and purification, compression, electrolysers and fuel cell technologies. It was noted that these must consider life cycles, high capacities, cost, improved performance and efficiency, but also enabling smaller end user sectors.
- In enabling more end users, it was also recognised that developing new "Economic models" was critical. Participants discussed the needs for new financial models taking into account

the cost and lifespans of H_2 implementation. This included the proposition of digitally twinning industries or sites and creating incentives for further investment.

- Expedited “Regulation, certification & standards” was deemed as crucial in developing the hydrogen economy and take-up. Development of new standards with industrial collaboration was seen as a key next step to drive further research opportunities.

4. Concluding remarks

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

1. A need to further understand the challenges in hard to abate transport sectors and foundation industries was identified as vital. It is noted that UK-HyRES plans to hold 1-to-1 interviews with key industrial stakeholders to further distil key opportunities for research and develop the findings from the workshops.
2. Development of new technologies and materials was also keenly discussed, with the requirement to consider a range of end users in terms of scale and requirement. Specific research in new materials and technologies that must consider recyclability, scalability, efficiency, resource security, cost and life cycles was requested, with development of non-PGM catalysts one example.
3. There was a clear demand for more co-ordination amongst the industry and a central overarching board to steer development. It was noted that there are many consortiums, centres and groups being set-up, but that co-ordination was lacking. It is noted that this may also precede demands for expedited regulations, certification and standards, with clear pathways for future business models.

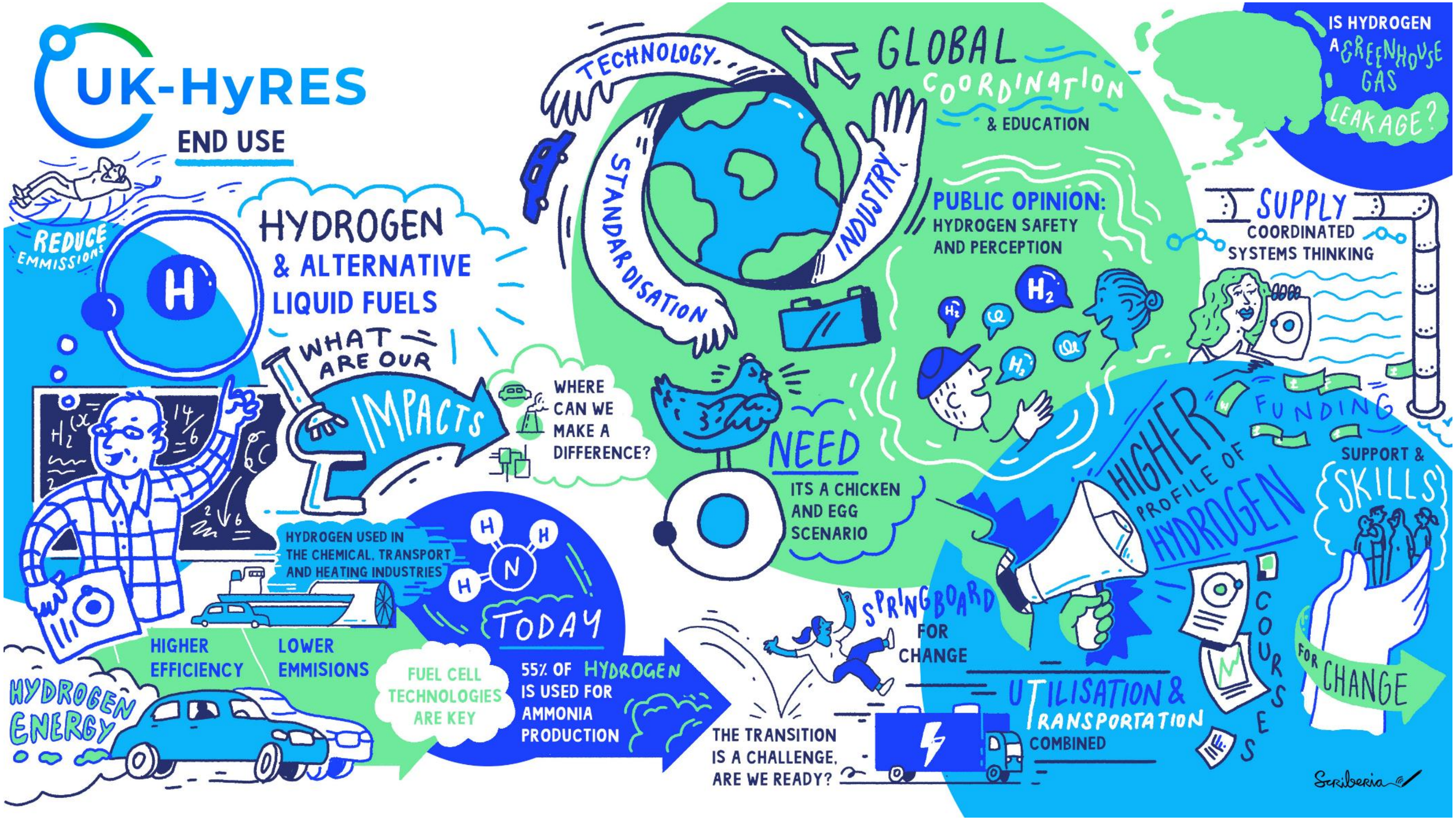
Appendix A: Attendee Agenda

UK-HYRES Project
Theme 3 Workshop 4: HYDROGEN - END USE
0930-1230 Tuesday July 5 2022

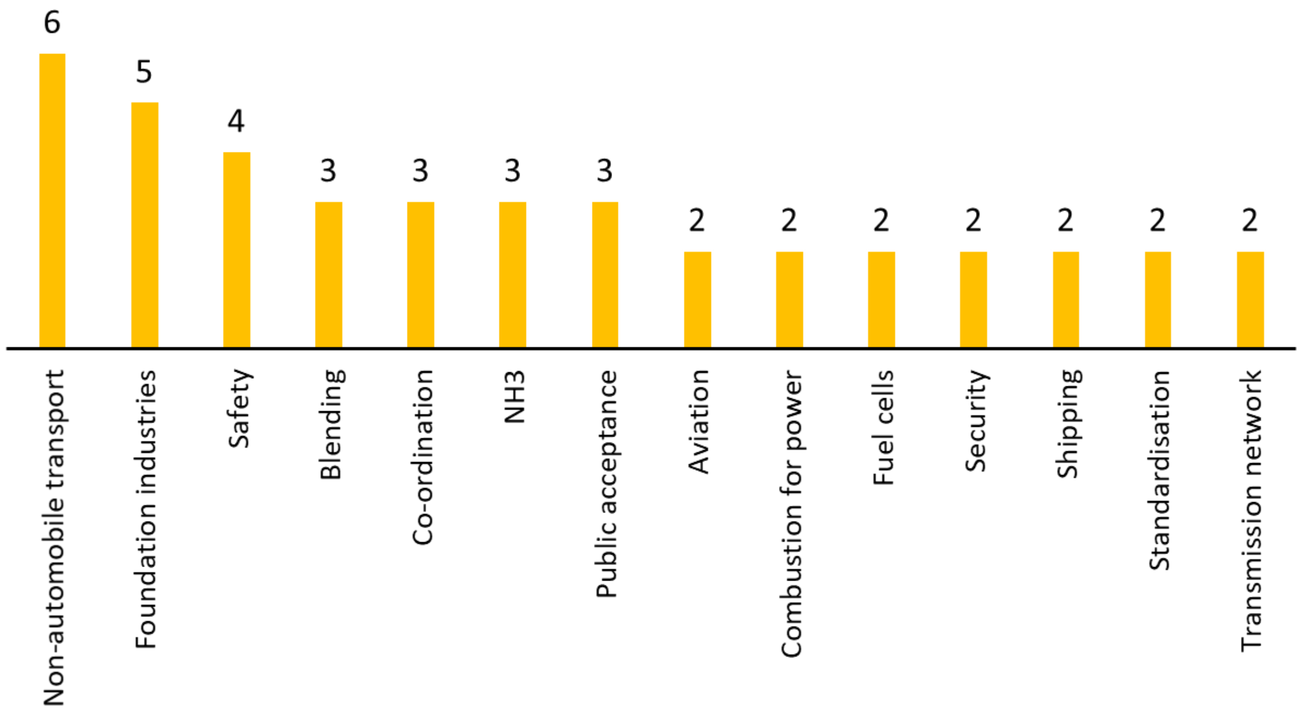
Zoom link
:https://us06web.zoom.us/j/88979766681?pwd=NEVadllzNzRGK2NyOFJDMG9xblprUT09

0915	**Waiting Room opens**
0930	**Welcome and Introductions**
	Setting the context for today's workshop • **UK-HyRES** • **End Use Theme** • **Theory of Change framework** ***Tim Mays*** ***Shanwen Tao*** ***Rachael Rothman***
	Strategic Drivers for Change - Insight Videos ***Hydrogen: Fuel of the Future Today***
	Breakout Discussion 1: Challenges and Unmet Needs **Followed by feedback in plenary**
1120	**COFFEE BREAK**
1130	**Future Vision - Insight Videos** ***Anthony Kucernak- Imperial College*** ***Qiong Cai -University of Surrey***
	Breakout Discussion 2: Future Vision and Impact **Followed by feedback in plenary**
	Breakout Discussion 3: Opportunities for Research **Followed by an open floor session**
	Next Steps ***Tim Mays***
1230	**CLOSE**

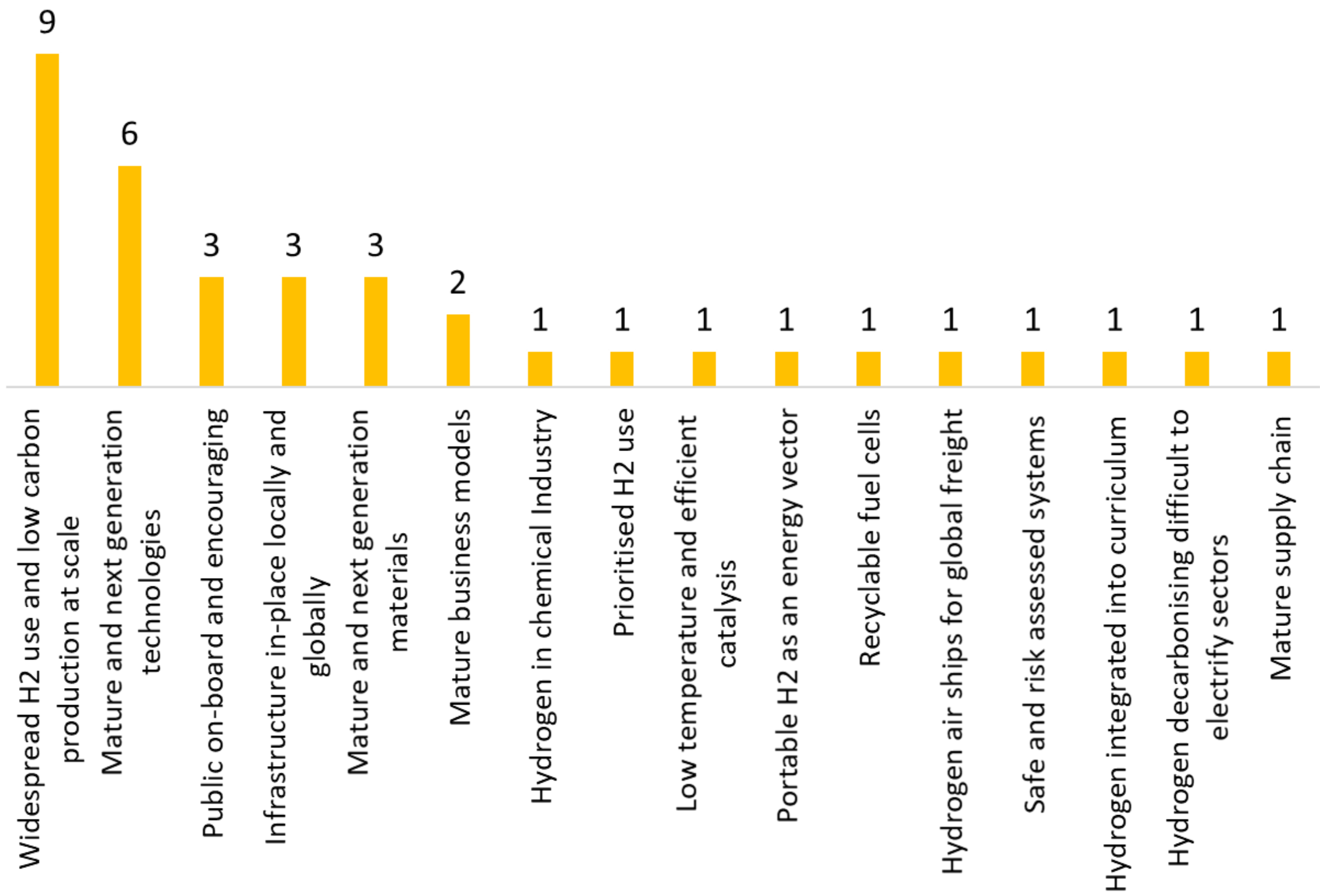
Appendix B: ***An illustrative summary of the workshop produced by Scriberia.***



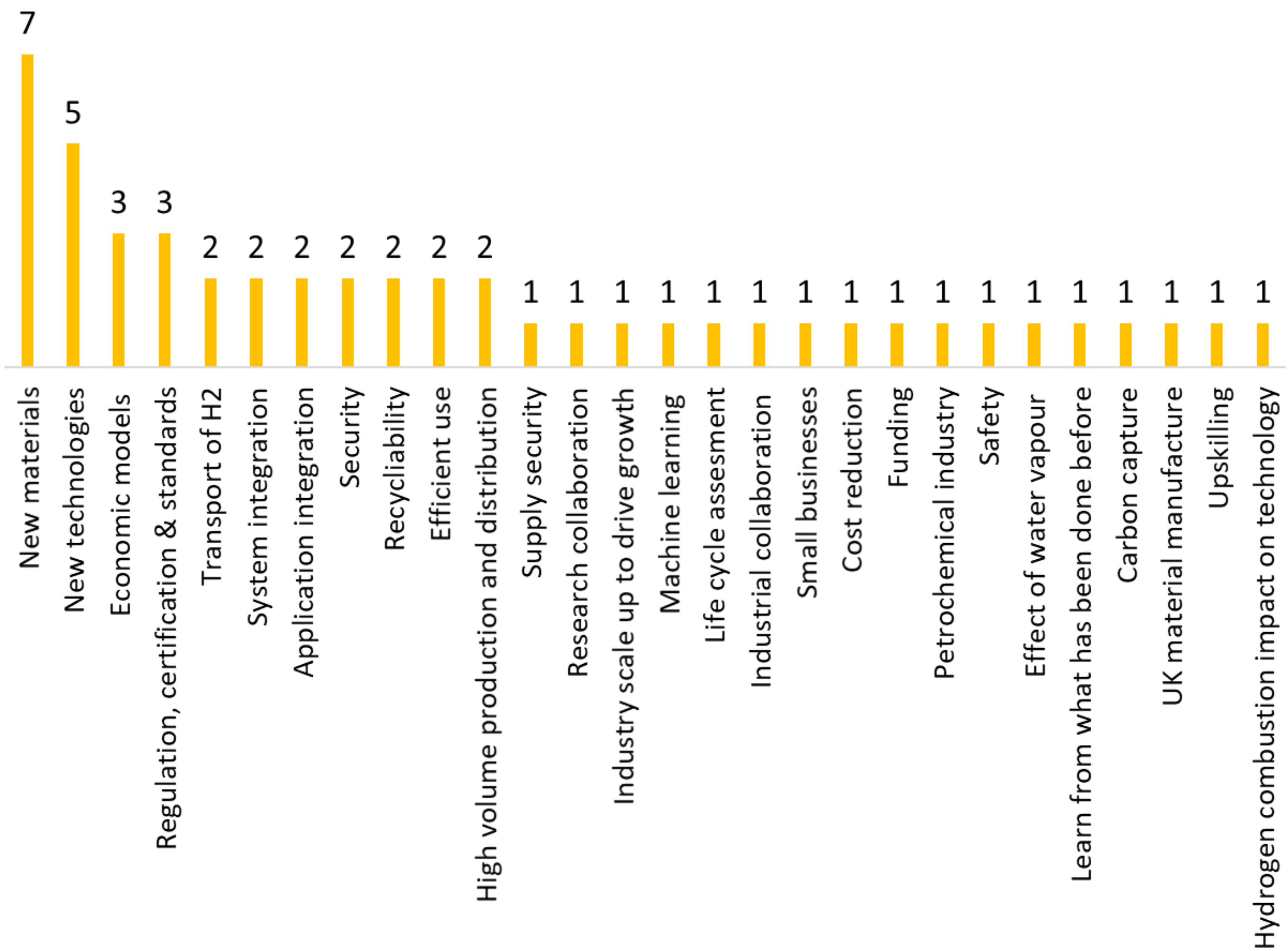
Appendix C: ***Responses to "What are the opportunities for research that will lead to and make the step change in H_2 end use? What are the fundamental research questions that we need to think about?", grouped by theme.***



Appendix D: ***Responses to "Thinking ahead – what difference or change would you like to see in H_2 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 H_2 end use? What are the fundamental research questions that we need to think about?", grouped by theme.**



Appendix F: All responses to *"Thinking of the end use of hydrogen 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:	END USE			
BREAKOUT	**1**			
QUESTION	**Thinking of the end use of hydrogen and the strategic drivers for change –From your perspective what are the challenges/unmet needs that need to be overcome?**			
ROOM #	**Comment**	**Primary**	**Secondary**	**Tertiary**
2	Hydrogen fuel cells for heavy duty vehicles (buses, trains, lorries, trucks, boats, aeroplanes)	Non-automobile transport	Fuel cells	
2	Hydrogen fuel cells for portable power sources, and remote power generation when batteries face limitations	Remote power generation		
2	Chemical industry (steel industry, cement industry, glass industry, petroleum refinery, etc) - We need industry input to understand what the challenges are for using H2 in industry sectors.	Foundation industries	Industry input	
2	Hydrogen combustion for electricity generation (un-on-demand renewable electricity convert to hydrogen, and use combustion to generate electricity at high demand, could deal with H2 impurity but generate NOx, need to evaluate how this compares with fuel cells, and what type of fuel cells).	Combustion for power	Nox	Application specific technology comparison
2	Materials research challenges across different hydrogen end use (e.g. hydrogen embrittlement)	Materials compatibility		
3	How do you prioritise certain sectors an user groups	Sector prioritisation		
3	Transport - global consistency international cooperation. - infrastructure etc.	Standardisation		
3	Similar tech across user groups, eg. airports how do they standardise	Standardisation	Aviation	Non-automobile transport
3	Aviation as a user group	Aviation	Non-automobile transport	
3	Infrastructure - blending - changing current infrastructure-	Blending	Infrastructure	

3	Hydrogen refuelling stations - how do we stimulate investment?	Refuelling stations	
3	Will alternative tech eg batteries inhibit the hydrogen take up	Batteries vs.hydrogen	
3	Public onboard, how do you get public acceptance	Public acceptance	
3	Public behaviour change - how do we encourage the transition	Behavioural change	
3	Phased changes for blending preparing for switch	Blending	
3	Security considerations	Security	
3	Security of supply	Security of supply	
3	Agricultural sector, fertiliser demand for hydrogen - how do we replace	Fertiliser	
3	Ammonia burning - nitrous oxide emissions - has this been modelled?	NH3 Nox	
3	Emissions - hydrogen as a GHG	H2 as GHG	
3	Economics, new business models, investment		
3	Lack of standards for end users	Standardisat ion	
4	Driver for change - Net Zero 2050	Net zero 2050	
4	From point of view of transmission system, they are the service in the middle. From net zero perspective, everyone has their own timescales - difficult to pull together.	Transmissio n network	Co-ordination
4	Unmet need - working together! How much H? When? Where? Work together. Not just industrial clusters, also transport, heating etc.	Co-ordination	
4	Lack of steer/strategy from BEIS/government	Influence policy	
4	Do the UK want to be an importer? Exporter? Make what we need? Use what we have?	Import/expo rt/self-sufficiency	
4	Origin of use certification	Certification	
4	Public perception of hydrogen and willingness of public to pay for OfU certificates	Public acceptance	

4	Maritime sector has potential to be big H2 user but only little funding in that area	Shipping	Non-automobile transport	
4	Challenge - there isn't the reassurance of large scale production and where it comes from which means companies are less likely to commit to switch to hydrogen	Large scale		
4	Challenge - we will need a lot of energy to make large scale H2 - where will this energy come from?	Energy requirement		
4	We aren't moving fast enough - need to find a way to get out of the loop	Urgency		
4	Need - overarching board. Everyone wants to set up their own H2 centre - who is overseeing? In nuclear know who to go to	Co-ordination		
5	Overarching drivers:			
5	Reducing CO2 emissions			
5	Quality of service/product, and trade-offs with economics/cost, and both compared to alternatives	TEA		
5	Industry:			
5	Tackle hard-to-abate sectors:: developing hydrogen technologies in industry where electrification does not provide a good quality of product	Foundation industries	Non-automobile transport	
5	Decarbonisation of steel in hydrogen use - emissions need to fall by more than 50% - direct iron reduction	Foundation industries		
5	Use glass and electric arc furnaces	Duplication		
5	Redesign cement kilns	Foundation industries		
5	Synthetic high-value chemicals	Foundation industries		
5	Use in combustion or electrical generation	Combustion for power		
5	Ammonia safety	Safety	NH3	
5	Transport:			
5	Purification and grade of supply for fuel cells for different application on road and railway transport - hydrogen technologies and fuel cell technologies	Purity		
5	Aviation and shipping - ammonia or hydrogen?	Shipping	NH3 v H2	Non-automobi

				le transport
5	Hydrogen in homes:	Domestic		
5	Safety issues with mixes of natural gas and hydrogen, compared to using each separately	Blending	Safety	
5	Robustness of gas grid for hydrogen use	Transmission network		
5	Manufacturing:			
5	Continued reduction in cost of fuel cells through improved manufacture and reduced use of critical raw materials	Fuel cells cost reduction		
5	Large scale manufacturing - using latest manufacturing technology			
5	Training:			
5	Safety: production of trained workforce for servicing and implementation	Safety	Training	
5	Safety of new technologies	Safety		
5	Public perception -> information campaign across social media?	Public acceptance	Info campaign	
5	Life cycle assessment to demonstrate hydrogen technologies meet emission goals.	LCA		
5	Recyclability of hydrogen fuel cells / what do we do with waste ones? Can we design them with replacement/recycling in mind?	Recyclability		

Category Counts

CATEGORY	COUNT
NON-AUTOMOBILE TRANSPORT	6
FOUNDATION INDUSTRIES	5
SAFETY	4
BLENDING	3
CO-ORDINATION	3
NH3	3
PUBLIC ACCEPTANCE	3
AVIATION	2
COMBUSTION FOR POWER	2
FUEL CELLS	2
SECURITY	2
SHIPPING	2
STANDARDISATION	2
TRANSMISSION NETWORK	2

APPLICATION SPECIFIC TECHNOLOGY COMPARISON	1
CERTIFICATION	1
BATTERIES VS.HYDROGEN	1
BEHAVIOURAL CHANGE	1
DOMESTIC	1
DUPLICATION	1
ENERGY REQUIREMENT	1
FERTILISER	1
H2 AS GHG	1
IMPORT/EXPORT/SELF-SUFFICIENCY	1
INDUSTRY INPUT	1
INFLUENCE POLICY	1
INFO CAMPAIGN	1
INFRASTRUCTURE	1
LARGE SCALE	1
LIFE CYCLE ANALYSIS	1
NOX	1
PURITY	1
RECYCLABILITY	1
REFUELLING STATIONS	1
REMOTE POWER GENERATION	1
SECTOR PRIORITISATION	1
TEA	1
TRAINING	1
URGENCY	1
MATERIALS COMPATIBILITY	1
NET ZERO 2050	1

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

All Comments

THEME:	**END USE**			
BREAKOUT	**2**			
QUESTION	**Thinking ahead – what difference or change would you like to see in H2 end use by 2050?**			
ROOM #	**Comment**	**Primary**	**Secondary**	**Tertiary**
1	Lots of fuel cells powered buses, lorries, train	Mature and next generation technologies		
1	Chemical plants using hydrogen	Hydrogen in chemical Industry		
1	Using existing system for whole hydrogen economy	Widespread H2 use and low carbon production at scale		
1	H2 as energy vector	Widespread H2 use and low carbon production at scale		
2	Shift change in public perception of hydrogen as a fuel source	Public onboard and encouraging		
2	How will we move hydrogen around?	Infrastructure in-place locally and globally		
2	Need to prioritise on how hydrogen is used (limited production)	Prioratised H2 use		
3	Large scale fuel production/manufacture	Widespread H2 use and low carbon production at scale		
3	drive down cost of fuel cell but also manufacturing equipment used to create fuel cells	Mature and next generation technologies		

3	Widescale acceptance / adoption of portable hydrogen fuels in all convenient technologies	Widespread H2 use and production at scale	Portable H2 as an energy vector	Public onboard and encouragin g
3	Development of low temperature catalysis to reduce energy demand for dehydrogenation	Low temperature and effcient catalysis	Widespread H2 use and low carbon production at scale	
3	Fuel cell design that is recyclable and dont generate a waste problem	Recyclable fuel cells	Mature and next generation technologies	
3	Bringing back hydrogen airships for freight travel	Hydrogen air ships for global freight		
3	H2 production on site by seawater electrolysis powered by wind power etc	Widespread H2 use and low carbon production at scale		
4	how can we have equality access by 2050 - hydrogen for all	Widespread H2 use and low carbon production at scale		
4	we must consider safety	Safe and risk assessed systems		
4	Public perception - public onboard embracing hydrogen now educate -	Public onboard and encouraging		
4	develop economic models	Mature business models		
4	Infrastructure across europe	Infrastructur e in-place locally and globally		
4	uni courses to include hydrogen/ lectrochemistry/cryogenics	Hydrogen integrated into curriculum		
5	Which sectors will benefit most/hardest to decarbonise without hydrogen	Hydrogen decarbonisin g difficult to electrify sectors	Widespread H2 use and low carbon production at scale	
5	applications: important to consider smaller end-use sectors as well	Smaller end-use sectors benifiting	Widespread H2 use and low carbon production at scale	

5	Transformational changes needed across supply chain	Mature supply chain	
5	Driving economics	Mature business models	
5	Wide range of technologies	Mature and next generation technologies	
5	applications	Widespread H2 use and production at scale	
5	materials systems	Mature and next generation materials	
6	Steel manufacture from coal to H2	H2 decarbonising steel	
6	Hydrogen and CO2 work together		
6	Hydrogen transport specifically designed materials	Mature and next generation materials	
7	Next generation of technologies in market testing	Mature and next generation technologies	
7	Wider products are available to offer different services to consumers	Mature and next generation technologies	Widespread H2 use and low carbon production at scale
7	Global hydrogen trade integration	Infrastructure in-place locally and globally	
1	Lots of fuel cells powered buses, lorries, train	Mature and next generation technologies	
1	Chemical plants using hydrogen	Hydrogen in chemical Industry	
1	Using existing system for whole hydrogen economy	Widespread H2 use and low carbon production at scale	

1	H2 as energy vector	Widespread H2 use and low carbon production at scale		
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3	drive down cost of fuel cell but also manufacturing equipment used to create fuel cells	Mature and next generation technologies		
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4	develop economic models	Mature business models	
4	Infrastructure across europe	Infrastructure in-place locally and globally	
4	uni courses to include hydrogen/ electrochemistry/cryogenics	Hydrogen integrated into curriculum	
5	Which sectors will benefit most/hardest to decarbonise without hydrogen	Hydrogen decarbonising difficult to electrify sectors	Widespread H2 use and low carbon production at scale
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6	Hydrogen and CO2 work together		
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7	Global hydrogen trade integration	Infrastructure in-place locally and globally	
7	Wider products are available to offer different services to consumers	Mature and next generation technologies	Widespread H2 use and low carbon production at scale

<u>Category Counts</u>

CATEGORY	COUNT
WIDESPREAD H2 USE AND LOW CARBON PRODUCTION AT SCALE	9
MATURE AND NEXT GENERATION TECHNOLOGIES	6
PUBLIC ON-BOARD AND ENCOURAGING	3
INFRASTRUCTURE IN-PLACE LOCALLY AND GLOBALLY	3
MATURE AND NEXT GENERATION MATERIALS	3
MATURE BUSINESS MODELS	2
HYDROGEN IN CHEMICAL INDUSTRY	1
PRIORITISED H2 USE	1
LOW TEMPERATURE AND EFFICIENT CATALYSIS	1
PORTABLE H2 AS AN ENERGY VECTOR	1
RECYCLABLE FUEL CELLS	1
HYDROGEN AIR SHIPS FOR GLOBAL FREIGHT	1
SAFE AND RISK ASSESSED SYSTEMS	1
HYDROGEN INTEGRATED INTO CURRICULUM	1
HYDROGEN DECARBONISING DIFFICULT TO ELECTRIFY SECTORS	1
MATURE SUPPLY CHAIN	1
WIDESPREAD H2 USE AND LOW CARBON PRODUCTION AT SCALE	9
MATURE AND NEXT GENERATION TECHNOLOGIES	6
PUBLIC ON-BOARD AND ENCOURAGING	3
INFRASTRUCTURE IN-PLACE LOCALLY AND GLOBALLY	3
MATURE AND NEXT GENERATION MATERIALS	3
MATURE BUSINESS MODELS	2
HYDROGEN IN CHEMICAL INDUSTRY	1
PRIORITISED H2 USE	1
LOW TEMPERATURE AND EFFICIENT CATALYSIS	1
PORTABLE H2 AS AN ENERGY VECTOR	1
RECYCLABLE FUEL CELLS	1
HYDROGEN AIR SHIPS FOR GLOBAL FREIGHT	1
SAFE AND RISK ASSESSED SYSTEMS	1
HYDROGEN INTEGRATED INTO CURRICULUM	1
HYDROGEN DECARBONISING DIFFICULT TO ELECTRIFY SECTORS	1
MATURE SUPPLY CHAIN	1

Appendix H: All responses to "What are the opportunities for research that will lead to and make the step change in H2 end use? 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:	END USE			
BREAKOUT	3			
QUESTION	What are the opportunities for research that will lead to and make the step change in H2 end use? What are the fundamental research questions that we need to think about?			
ROOM #	Comment	Primary	Secondary	Tertiary
1	Financial modelling and digital twinning of sites	Economic modelling		
1	Understanding best use (cost, CO2, etc) of hydrogen for power generation	Efficient use		
1	Green, large-scale hydrogen production technology	New technologies		
1	integration into different applications	application integration		
1	future petrochemical industry	Petrochemical industry		
1	connecting H2 production and supply of sustainable carbon	System integration & efficient use		
1	Purification & compression technologies for different applications	New technologies		
1	Recyclability of critical materials (e.g. PGMs)	New materials	Recycliability	
2	Reducing the cost of end-use devices:	Cost reduction		
2	Safety of these technologies need to be explored	Safety		
2	Developing enabling technologies for utilisation of hydrogen for different sectors	New technologies		
2	Regulation and certification will likely need to be expedited for hydrogen to be taken up effectively	Regulation, certification & standards		
2	What are the current standards and where might changes or new standards be needed in the future?	Regulation, certification & standards		

2	System integration for heavy-duty road and rail vehicles to optimise performance and reduce cost.	System integration & efficient use
2	if the cost is high and lifespan short, how will that impact economic models?	Economic models
2	What will this mean for circularisation of the lifecycle of these technologies?	Life cycle assesment
3	Using machine learning for optimising fuel cell design	Machine learning
3	How can H2 be stored in porous materials?	New materials
3	What water vapour will have effects on the environment in the H2 economy.	Effect of water vapour
3	How can we transport H2 on a large scale?	Transport of H2
4	Economic modelling	Economic modelling
4	strategy of delivery of h2 tech	New technologies
4	Better connection of physical sciences researcher with technoeconomical researchers	Research collaboratio n
4	Work with industrial companies to identify the need for use of hydrogen,	Industrial collaboratio n
4	new technology required to further improve the performance	New technologies
4	Development of low-cost manufacturing technology for delivering hydrogen tech	Transport of H2
4	High temperature+H2 environment resistant materials	New materials
4	Opportunities to learn from what has been done before	Learn from what has been done before
4	replace the expensive PGM catalysts	New materials
5	Negative carbon technology	Carbon capture
5	Demand on catalyst, polymer,	New materials
5	Electolysers and fuels cells - need large capacity	New technologies
5	Fundamental electrochemistry, catalysis and material research	New materials
5	Supply of materials and resources	Supply security
5	Recycling of raw materials	Recycliability

5	Material manufacture in the UK	UK material manufacture
5	Scale of end use to drive H2 supply chain	Industry scale up to drive growth
5	Balance and inclusiveness in funding strategy, funding mode	Funding
6	Skills and competencies in wider gas industry	Upskilling
6	small/one person businesses	Small businesses
6	security	Security
6	Foundation industries: fundamental understanding of effect of hydrogen combustion on product quality and production equipment	Hydrogen combustion impact on technology
6	What is needed to meet needs of range of end-use sectors: production, distribution	High volume production and distribution
6	cross-coupling between sectors and central versus distributed production	High volume production and distribution
6	Standardisation	Regulation, certification & standards
6	economic model for incentives for investment in infrastructure, end-use	Economic model

Category Counts

CATEGORY	COUNT
NEW MATERIALS	7
NEW TECHNOLOGIES	5
ECONOMIC MODELS	3
REGULATION, CERTIFICATION & STANDARDS	3
TRANSPORT OF H2	2
SYSTEM INTEGRATION	2
APPLICATION INTEGRATION	2
SECURITY	2
RECYCLIABILITY	2
EFFICIENT USE	2
HIGH VOLUME PRODUCTION AND DISTRIBUTION	2
SUPPLY SECURITY	1
RESEARCH COLLABORATION	1

INDUSTRY SCALE UP TO DRIVE GROWTH	1
MACHINE LEARNING	1
LIFE CYCLE ASSESMENT	1
INDUSTRIAL COLLABORATION	1
SMALL BUSINESSES	1
COST REDUCTION	1
FUNDING	1
PETROCHEMICAL INDUSTRY	1
SAFETY	1
EFFECT OF WATER VAPOUR	1
LEARN FROM WHAT HAS BEEN DONE BEFORE	1
CARBON CAPTURE	1
UK MATERIAL MANUFACTURE	1
UPSKILLING	1
HYDROGEN COMBUSTION IMPACT ON TECHNOLOGY	1