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

UK-HyRES

Report on Workshop findings: Production

Aug 2022

Diarmid Roberts, Rajan Jagpal, Mengfei Zhang

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 Workshop 2 took place on the **16 June 2022** and was conducted online via Zoom at 09:30-12:30 with **104 attendees** (~ 60% >2hrs). Building on the project launch event in May 2022, Workshop 2 focused on the **Production of Hydrogen**. This is a summary report of the workshop compiled by UK-HyRES researchers Raj 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** that must be overcome to achieve hydrogen production on the scale of the 10 GW by 2030 targeted by the UK government.

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. Facilitation was provided by *The Collective*, and the agenda (Appendix A) was discussed and agreed by the project teams prior to the workshop.

UK-HyRES Principal investigator Tim Mays (University of Bath) welcomed the participants and provided context to the workshop, both in terms of national Net-Zero strategy, and the original UKRI "Become a hydrogen research co-ordinator" call. Next Co-investigator Rachael Rothman (University of Sheffield) gave an overview of anticipated research challenges. In addition to cost reduction in the three main production areas (electrochemical, thermochemical and biochemical) she emphasised that social science and supply chain research is likely to be required. She also introduced the rationale for the three breakout sessions that would take place during the workshop, which fit into the Theory of Change stages, Figure 1. The workshop is also summarised in an illustrative output by Scriberia (Appendix B).

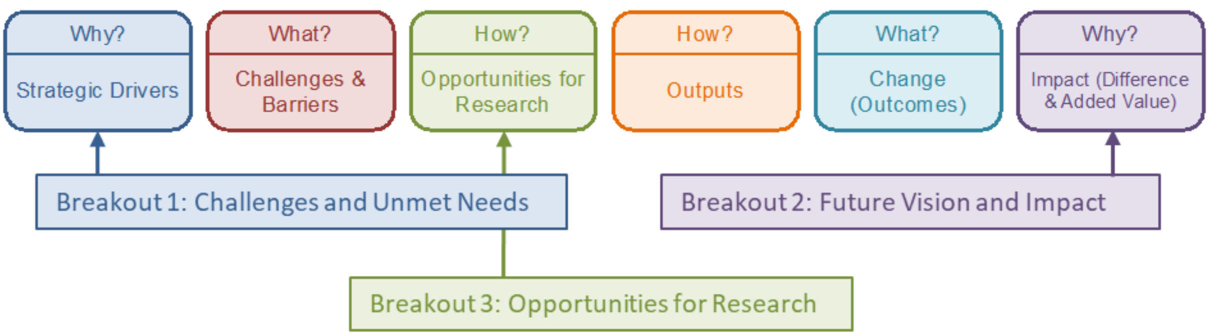

***Figure 1**: The Theory of Change framework adopted for the UK-HyRES project and the location of each breakout session.*

2. Insight Talks

Engaging insight talks were delivered during the workshop by academic, public and industry leaders in the hydrogen arena. **Anton Orpin-Massey (Senior Policy Advisor, Hydrogen Production Strategy, BEIS)** and **Richard Sulley (Net Zero project director at the South Yorkshire Mayoral Combined Authority)** set the landscape with their strategic drivers for change talk before the first breakout discussion. We also heard from **Marcus Newborough (Development Director at ITM Power**) and **Patricia Thornley (Director Supergen Bioenergy Hub)** who delivered their future vision for hydrogen production before the second breakout discussion. Recordings of all four insight talks are available to download on the UK-HyRES website at https://ukhyres.co.uk/workshops-2-3/.

3. Breakout Discussions

For each breakout session the delegates were randomly assigned to groups of six or fewer. They were tasked with debating the questions posed and recording notes about their discussion via the 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**.

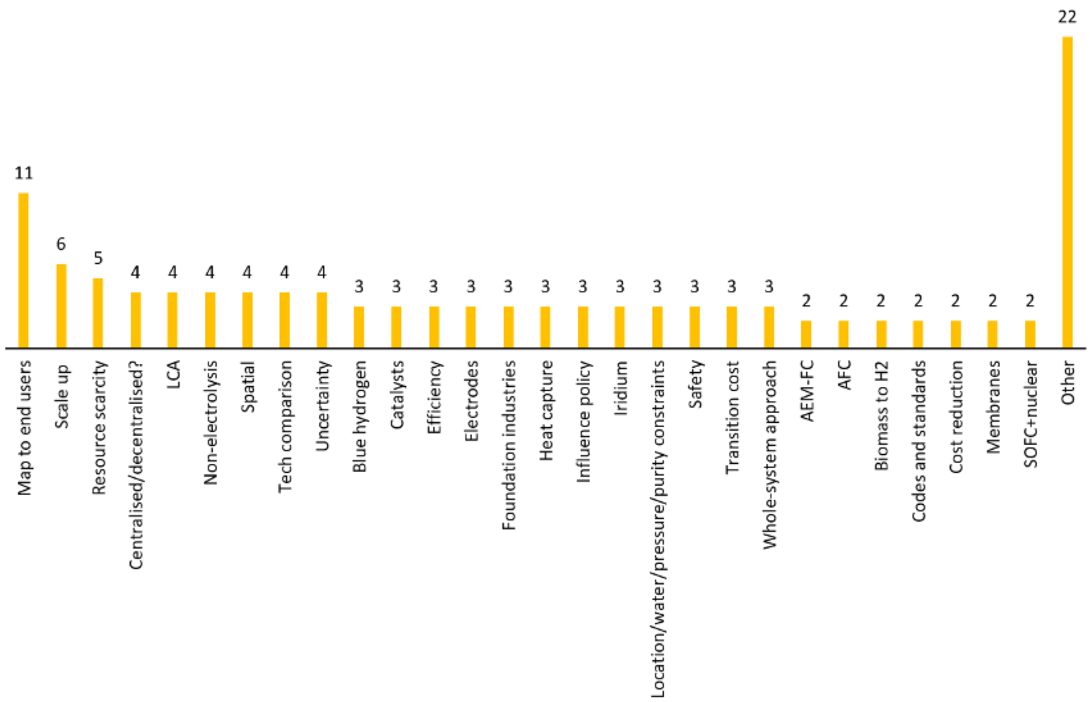

Figure 2: *Collated responses to "Thinking of how hydrogen is produced and the strategic drivers for change –From your perspective what are the challenges/unmet needs that need to be overcome?", grouped by theme. A larger version is available in Appendix C and the raw data with categorisation tags is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

Summary

- The theme that covered the most responses in this breakout was "Map to end users". There was a clear desire from the participants for better understanding of the current and near future market for hydrogen. In the feedback session after the breakout, participants also highlighted the importance of understanding the market, with comments including "if there is no usage we will miss the opportunity" and "if we don't have clear certainty this is going to inhibit investment into the sector". A related technical theme is "Location/water/pressure/purity constraints", as purity and pressure are both downstream concerns. The foundation industries received several mentions as a key market, as this sector is unlikely to have its needs met by electrification.
- The next most important themes were "scale up" and "Resource scarcity". Participants were clearly concerned with the scalability of PEM electrolysers, particularly availability of the iridium catalyst. In the feedback session it was remarked that 40 years of Iridium supply would be required for 1 TW of PEM electrolyser capacity, but that this could be used more efficiently. As alternatives to PEM electrolysers, anionic membrane and alkaline electrolysers were also discussed, as were non-electrolysis routes.
- LCA was also mentioned several times, with participants recognizing that this is an important method (alongside techno-economics) for understanding scalability.

The "other" category in **Figure 2** contained: *Biomass to* H_2*, Blue hydrogen, Field trials, Improve efficiency, Industry feedstock, Insurance, Non-electrolysis, Pilot facilities needed, PV/wind integration, Recruitment problems (£), Roadmap, Supply chain, Use of oxygen*

3.2 Future Vision and Impact

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

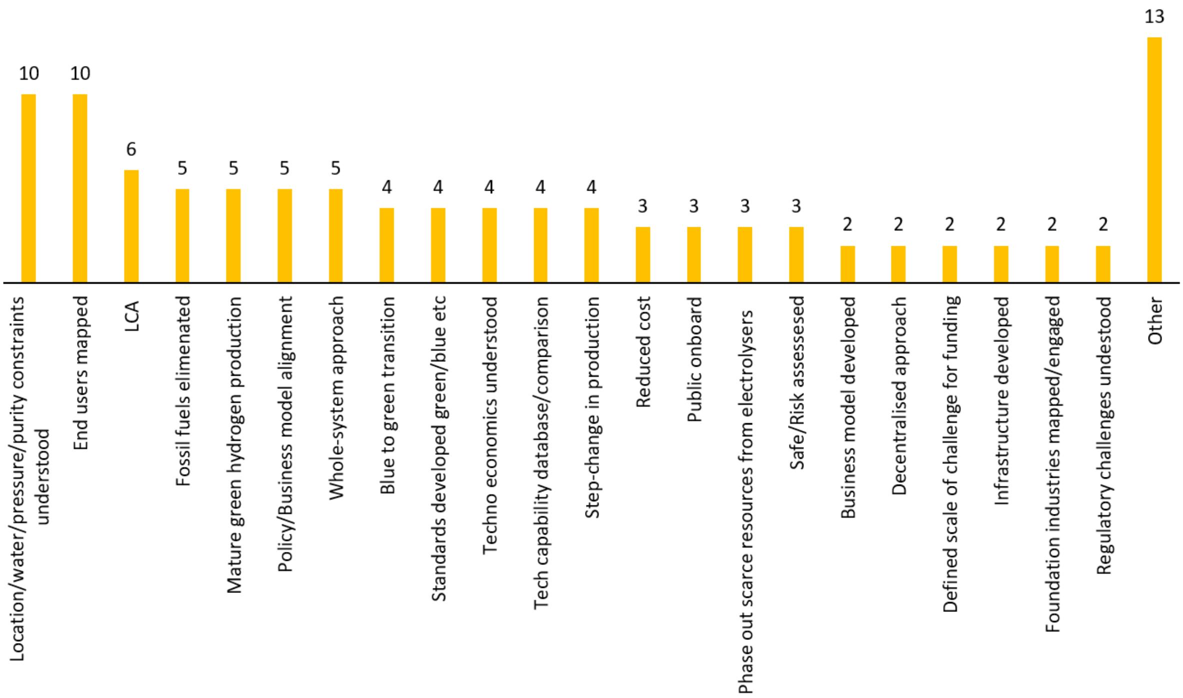

Figure 3: *Collated responses to "Thinking ahead – what difference or change would you like to see in H_2 production by 2050?". A larger version is available in Appendix D and the raw data with categorisation tags is in Appendix G.*

Summary

- In this session, the desire from participants to have greater understanding of both input and output constraints was marked. In the feedback session one participant noted the importance of understanding freshwater constraints in the context of climate change. The output compatibility issue is directly linked to the equally well represented desire to have end users mapped, and together these give a very clear signal from the community.
- The issue of blue hydrogen and its role in the eventual transition to green hydrogen was discussed in many breakout rooms. There was also a desire to see codes and standards implemented regarding the definition of each, with a goal of eliminating fossil fuels from the hydrogen supply. In the feedback session one participant wanted to avoid "the shift to hydrogen causing a perverse change to the market so that fossil fuels can still be used for electricity production"
- There was also some discussion around the framing of the question, with more than one participant pointing out that 2050 would be too late for many of the desired outcomes.

The "other" category in **Figure 3** contained: *Alternative feedstocks, Anode, Automation, Batolysers, Blending/deblending, Compatibility, Corrosion, Dynamic operation, Export, Fugitive emissions,* *Funding, Green hydrogen, NG blending, Oxygen use, Product separation, Roadmap, Scale-up, SOFC, Supply chain, TEA, Waste to H_2, Workforce training*

3.3 Opportunities for Research

The final breakout discussion focused on the opportunities for hydrogen production 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.

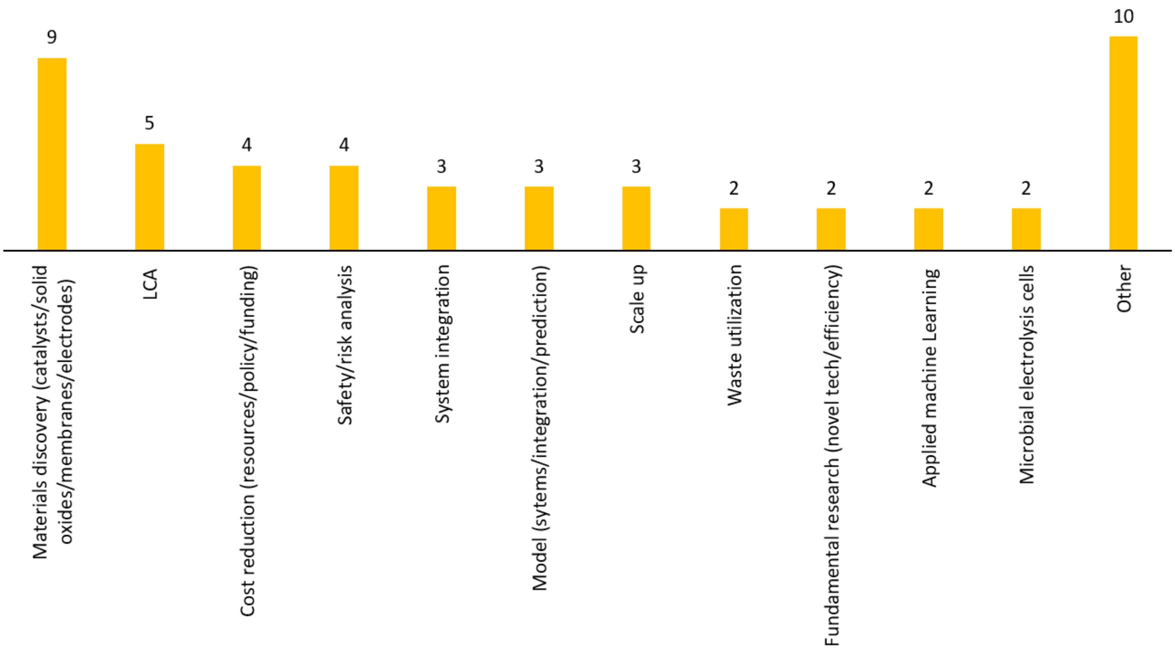

Figure 4: *Collated responses to the questions: "Considering the discussions we have had today -What are the opportunities for research that will lead to and make the step change in H2 production? -What are the fundamental research questions that we need to think about? A larger version is available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

Summary:

- The single most popular research theme was the discovery of new materials for water electrolysis, be it catalysts or membranes. This acknowledges the limitations of the existing electrolysis technologies, iridium scarcity (PEM), inability to operate dynamically (Alkaline) and unavailability of high-performing anionic membranes (AEM).
- LCA was also mentioned frequently in this session.
- A number of research opportunities were mentioned in the feedback session that had not been covered previously; security implications of hydrogen use,

manufacturability of electrolysers for recyclability and measurement of public awareness of hydrogen as an energy vector.

The "other" category in **Figure 4** contained: *Desalinising water, Device, Heat recovery, Location, Collaborative research, Facilities, Optimising systems, Reversible systems, Solar fuels, Electrolysis for* CO_2 *utilisation*

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 for better understanding of the likely end users of hydrogen, and the particular constraints these would place on output purity and pressure in order to be able to guide design/selection of production technology.
2. A need for fundamental research on the materials required for alternative hydrogen production technologies, particularly electrolysis.
3. There was a clear demand for techno-economic analysis and LCA in order to aid decision making. Across the feedback sessions, there were several comments regarding efficiency, and the difference between pure energy efficiency and cost efficiency of production. Although it falls more in the scope of the other hydrogen co-ordinator project, there was also interest in system integration and taking a "whole-system approach".
4. Safety was mentioned less frequently in this workshop than the launch workshop and the storage workshop, implying the community sees it as less of an issue in production.

Appendix A: Attendee Agenda

THE COLLECTIVE

UK Research and Innovation

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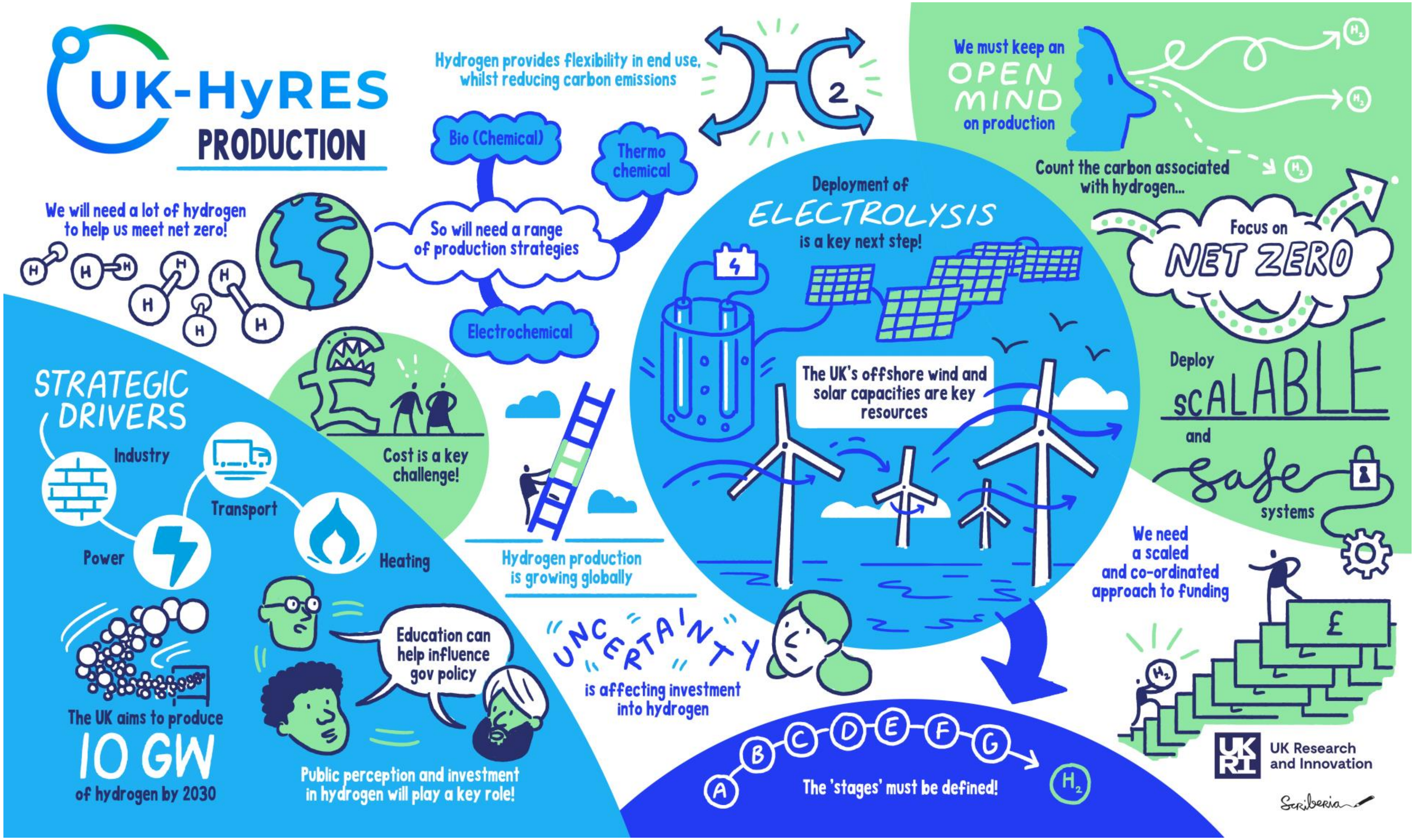
UK-HYRES Project
Theme 2 Workshop : PRODUCTION
1330-1630 Thurs 16th June 2022

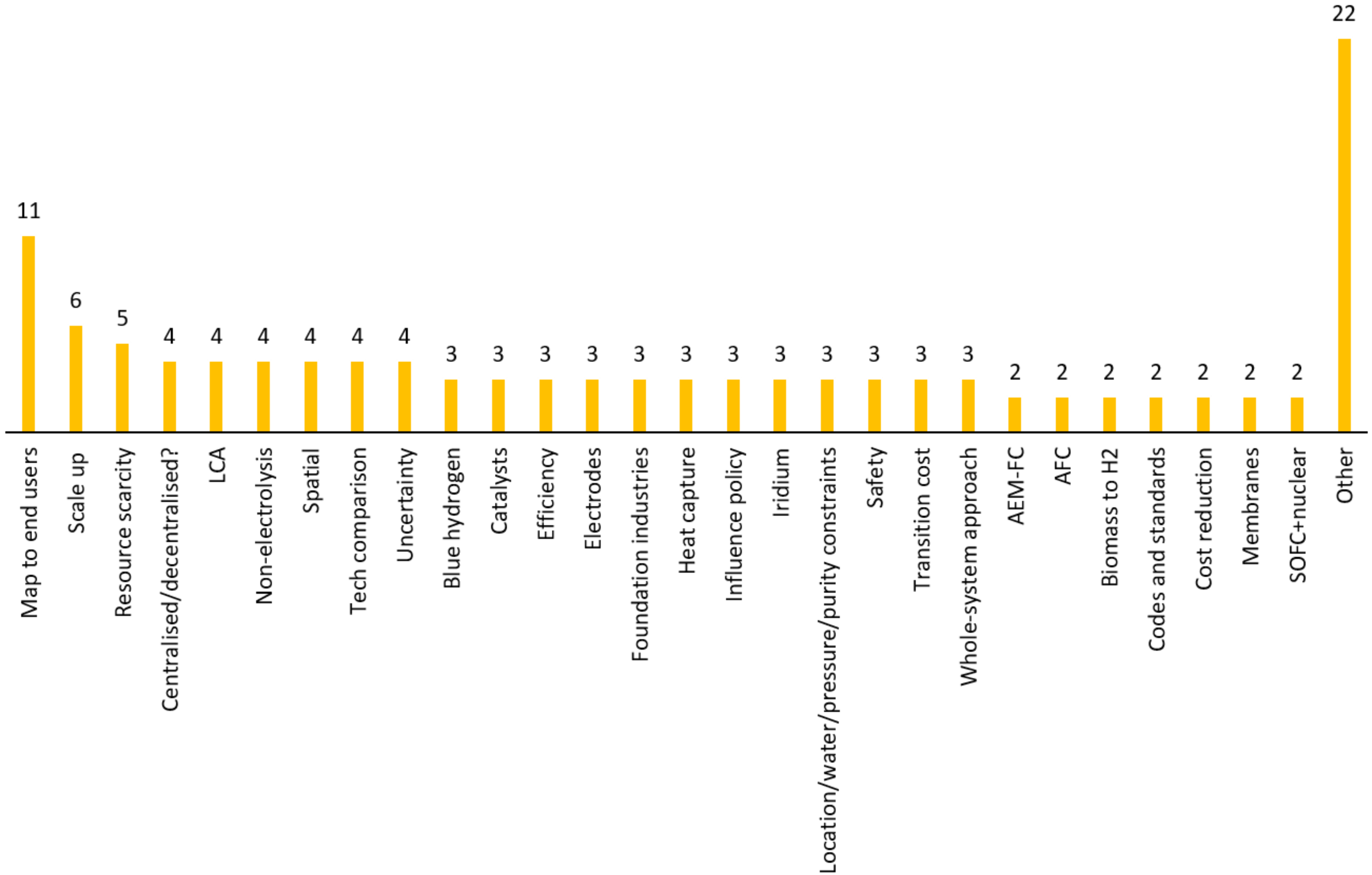
Zoom link
:https://us06web.zoom.us/j/88979766681?pwd=NEVadllzNzRGK2NyOFJDMG9xblprUT09

0915	**Waiting Room opens**
0930	**Welcome and Introductions**
	Setting the context for today's workshop • **UK-HyRES** • **Production Theme** • **Theory of Change framework** ***Tim Mays*** ***Rachael Rothman***
	Strategic Drivers for Change - Insight Videos • ***Anton Orpin-Massey*** **- Senior Policy Advisor, Hydrogen Production Strategy, BEIS** • ***Richard Sulley*** **- Net Zero project director at the South Yorkshire Mayoral Combined Authority**
	Breakout Discussion 1: Challenges and Unmet Needs **Followed by feedback in plenary**
1050	**COFFEE BREAK**
1100	**Future Vision - Insight Videos** • ***Marcus Newborough*** **- Development Director at ITM Power** • ***Patricia Thornley*** **- Director Supergen Bioenergy Hub**
	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
1230	**CLOSE**

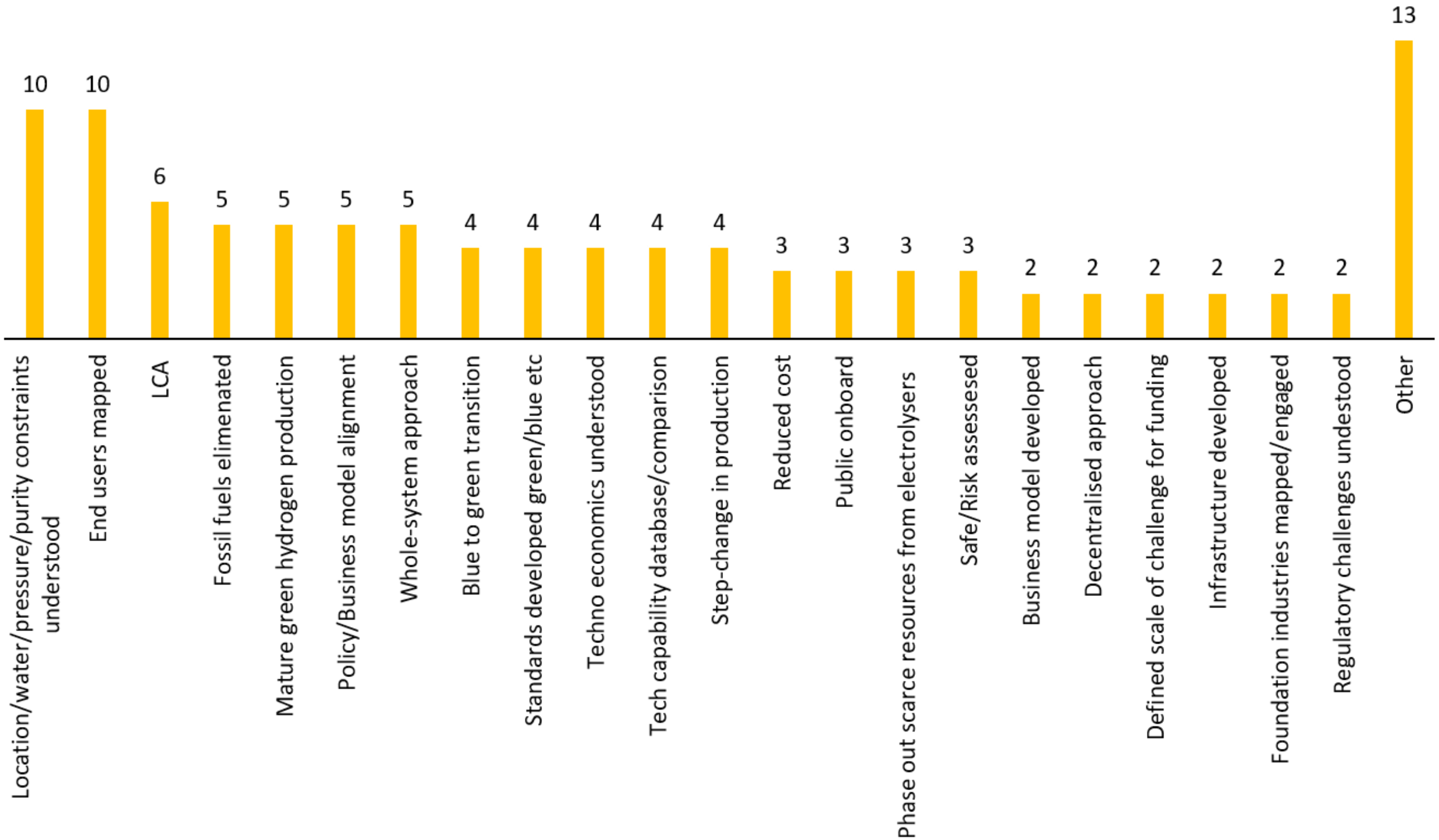
Appendix B: ***An illustrative summary of the workshop produced by Scriberia.***



Appendix C: **Collated responses to *"Thinking of how hydrogen is produced and the strategic drivers for change –From your perspective what are the challenges/unmet needs that need to be overcome?"***

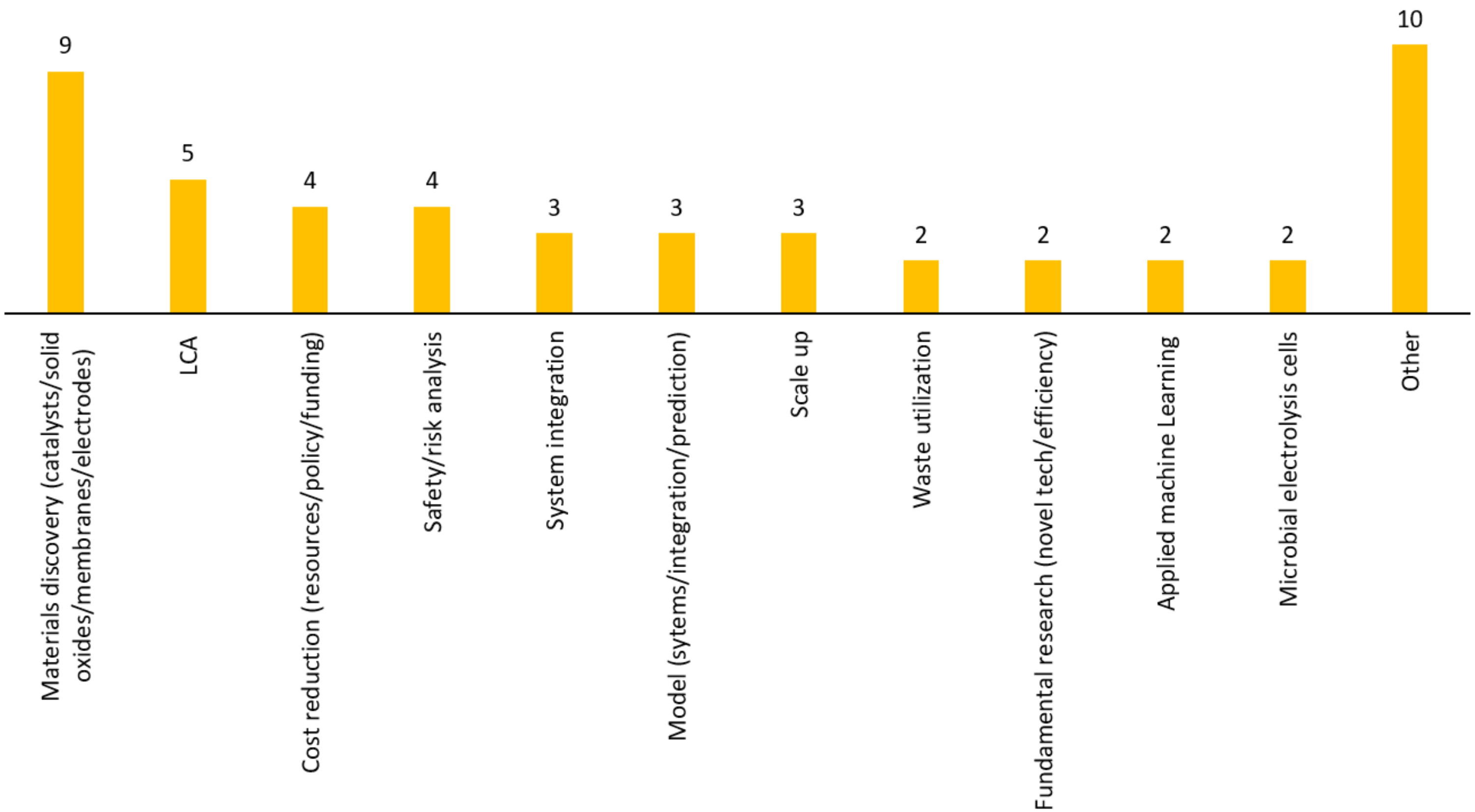


Appendix D: **Responses to *"Thinking ahead – what difference or change would you like to see in H_2 production by 2050?"* Should this be changed to 2030**



Appendix E: **Responses to "*Considering the discussions we have had today -***

What are the opportunities for research that will lead to and make the step change in H2 production?
What are the fundamental research questions that we need to think about?"



Appendix F: **All responses to *"Thinking of how hydrogen is produced 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 produced 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**
1	Integration of different generation technologies and uncertainties (nuclear, solar, wind)	Tech comparison	Uncertainty	
1	Life-cycle impact of complete systems	LCA	Whole-system approach	
1	Materials resource limitations meeting scale-up ambitions - e.g. iridium on oxygen electrode for PEM electrolyser	Resource scarcity		
1	Availability of low-carbon hydrogen to meet wide range of end-uses	Green hydrogen	Map to end users	
1	Timing of growth in production and demand	Roadmap	Map to end users	
1	System scale-up challenge (TW) - manufacture change from hand-crafted to automated	Scalability	Automation	
1	How can we build and buy 5GW electrolysers by 2030 (vs global 2GW shipment this year)	Scalability		
1	Extending existing safety understanding to cover use of hydrogen outside current context (refineries)	Safety		
1	Training for engineers - distribution and transmission network	Workforce training		
1	Inspection, test and verification protocols	Codes and standards		
1	Variety of purity requirements for different end-applications (transport fuel cells, heating, etc)	Location/water/pressure/purity constraints	Purity	Map to end users
1	Decision on blending and repurposing of natural gas network	NG blending		

1	Completely novel systems electro-thermochemical or direct from offshore wind	Non-electrolysis	
1	Compatibility with UK context - e.g. integration challenges - solar, offshore wind, gas distribution network	Location/water/pressure/purity constraints	Spatial
1	What technology will be able to deliver by 2030 - and what can scale to meet 2050 goals?	Scale-up	Tech comparison
2	Scalability from Lab to scale - links in with usage theme	Scalability	
2	How could it be funded for companies to invest?	Funding	Influence policy
2	Also the quantities required long term?		
2	Location/locality - Links in with Storage theme	Location/water/pressure/purity constraints	Spatial
2	Local production or central production	Centralised/decentralised?	
2	Compatibility with the existing infrastructure	Compatibility	
2	Mitigate fugitive emissions	Fugitive emissions	
3	different water electrolysis technologies suitable for energy sources (nuclear, solar, wind) (solid oxide electrolyser for high temperature processes such as nuclear and steel industry,, and low temperature electrolysis for renewable energy). require low cost materials, durability, and manufacturing.	SOFC+nuclear	Foundation industries
3	Qilei Song: Low-cost water electrolysis: low capital costs by replacing expensive PGM catalysts, low cost membranes, anion exchange membrane technology.	AEM-FC	Cost reduction
3	Efficient H2 separation for blue hydrogen and hydrogen blending.	Blending/deblending	
3	Thermochemical processes: natural gas reforming and CO2 capture.	Blue hydrogen	
3	scaling up of biomass gasification, combination with CO2 capture,, manufacturing.	Non-electrolysis	Biomass to H2
3	Green hydrogen efficiency loss in the electrolyser to produce hydrogen and the back-conversion to electricity through fuel cells (approximately 75% loss).	Efficiency	

3	: green hydrogen storage is a challenge either in the form of a compressed gas or in metal hydride.	Out of scope (storage)	
4	Hydrogen Demand - Uncertainty in the market	Uncertainty: market	Map to end users
4	Uncertainty inhibits investment	Uncertainty	
4	Bloomberg Report	N/A	
4	Difficulty optimising hydrogen production - large, centralised production co-located with renewable electricity generation or project specific hydrogen production?	Centralised/ decentralised?	Map to end users
4	Uncertainty in scale of distribution network needed	Uncertainty: scale	
4	Differing stages of hydrogen readiness	Scalability	
4	Cost of switching to hydrogen use	Transition cost	
4	Fuel poverty	Transition cost	
4	Who shoulders the cost?	Transition cost	
4	Green hydrogen vs blue hydrogen production	Blue to green transition	
4	How carbon efficient is blue hydrogen?	Standard definitions green/blue etc	
4	Necessary evil during a transition period	Blue hydrogen	
4	Possible incentives for producers to simultaneously ramp up blue production over grey, at the same time as developing green production	Blue to green transition	
4	Bottlenecks of rare materials	Resource scarcity	
4	Most hydrogen production methods rely on catalysts containing precious metals	Duplication	
4	Rolls Royce report (and others) highlight in particular the potential iridium shortfall if large-scale PEM electrolysis is implemented	Duplication	
4	Using alternative catalysts and materials is currently low TRL - research needs rapid advancement to make large-scale production practicable	Tech comparison	

4	High-temperature electrolysis and thermochemical cycles are promising alternatives, with higher efficiencies than conventional electrolytic methods - waste heat from nuclear plants can be utilised	Non-electrolysis	SOFC+nuclear	
5	Hydrogen DRI for use of H2	Out of scope (end users)		
5	Scaling up manufacture of electrolysers - globally	Scalability		
5	Capacity improvement of electrolysers and solar/wind	Duplication		
5	Efficiency	Efficiency		
6	- making H2 is easy, O2 generation is the problem, and nobody needs it. Alternative cathode side product.	Oxygen use	Alternative feedstocks	
6	Dani Strickland - avoid scarce materials, improve recyclability. Don't get hung up on efficiency.	Resource scarcity	LCA	Efficiency
6	storage, transport	Out of scope (storage)		
6	Glasgow university, can we add some thermal storage to improve the efficiency of the production process.	Heat capture		
6	effective separation of product gases	Product separation		
6	Alternative to PEM:	N/A		
6	Alkaline fuel cells - need to be continuously on otherwise	AFC		
6	SOFC - too expensive, and high losses	SOFC		
6	Batolysers - Lower cost, but lower efficiency, PbO2 side, materials challenges.	Batolysers		
8	*Geographic match of production and end use - government/regional policy drive*	Map to end users	Spatial	Influence policy
8	*Prioritisation of end-use demand sectors*	Map to end users		
8	*Framework on decarbonisation assessment agreed nationwide - pricing*	Map to end users		
8	*Independent body from government/industry for ranking of need*	Map to end users	Influence policy	
8	*Standards and safety - need for acceleration/support from UKRI*	Safety	Codes and standards	
8	*Co-location electricity generation capacity or connectivity - who drives location siting?*	Map to end users	Spatial	Centralised/decentralised
9	Replacing critical raw materials for the different technologies and increase/ensure their high efficiencies (esp. needed for low TRL technologies)	Resource scarcity	Efficiency	
9	Opportunities for heat integration with foundation industries eg steel	Heat capture	Foundation industries	

9	Reliable technologies that can work intermittently and how these can be integrated (incl. TEA)/controlled within an application (industrial/generation)	Dynamic operation	TEA
9	Scaling up of manufacture of devices, e.g. electrolysis and Fuel Cells	Scalability	

Category Counts

CATEGORY	COUNT
MAP TO END USERS	11
SCALE UP	6
RESOURCE SCARCITY	5
CENTRALISED/DECENTRALISED?	4
LCA	4
NON-ELECTROLYSIS	4
SPATIAL	4
TECH COMPARISON	4
UNCERTAINTY	4
BLUE HYDROGEN	3
CATALYSTS	3
EFFICIENCY	3
ELECTRODES	3
FOUNDATION INDUSTRIES	3
HEAT CAPTURE	3
INFLUENCE POLICY	3
IRIDIUM	3
LOCATION/WATER/PRESSURE/PURITY CONSTRAINTS	3
SAFETY	3
TRANSITION COST	3
WHOLE-SYSTEM APPROACH	3
AEM-FC	2
AFC	2
BIOMASS TO H2	2
CODES AND STANDARDS	2
COST REDUCTION	2
MEMBRANES	2
SOFC+NUCLEAR	2
ALTERNATIVE FEEDSTOCKS	1
ANODE	1
AUTOMATION	1
BATOLYSERS	1
BLENDING/DEBLENDING	1
COMPATABILITY	1
CORROSION	1
DYNAMIC OPERATION	1
EXPORT	1
FUGITIVE EMISSIONS	1
FUNDING	1
GREEN HYDROGEN	1
NG BLENDING	1
OXYGEN USE	1
PRODUCT SEPARATION	1
ROADMAP	1
SCALE-UP	1

SOFC	1
SUPPLY CHAIN	1
TEA	1
WASTE TO H2	1
WORKFORCE TRAINING	1

Appendix G: **All responses to *"Thinking ahead – what difference or change would you like to see in H2 production 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 production by 2050?**			
ROOM #	**Comment**	**Primary**	**Secondary**	**Tertiary**
1	Need to consider different technologies (not just electrolysis), biomass.	Biomass to H2	Non-electrolysis	
1	Map to end users.	Map to end users		
1	Infrastructure	Infrastructure		
1	To accelerate legislation and regulation processes in the UK to allow pilot plants and venturing firms to get involved.	Regulatory challenges	Pilot facilities needed	
1	Allowing small scale field trials to find out real-world obstacles and problems in the hydrogen consumption.	Map to end users	Field trials	
1	Engineering improvement hand-in-hand with Scienctific advancements.	Science to engineering		
2	Existing technology scalability problem - raw material requirement	Resource scarcity		
2	Alternative production technology - how to determine viable options	Tech comparison	TEA	
2	Need to shift from blue to green	Blue to green transition		
2	Determination of purity required - determines production method	Location/water/pressure/purity constraints	Map to end users	
3	Hydrogen production integrated with PV and Wind using sustainable low cost processes	PV/wind integration		Map to end users
3	No fossil fuels used for power generation	Fossil fuel elimination		

3	Legislation and policy aligned so that there is clarity in the hydrogen market to make sure that hydrogen production occurs efficiently and ensure that fossil fuels do not continue to be used for electricity generation.	Fossil fuel elimination	Influence policy
3	Systemic change to the way society work so that it is more energy efficient	Out of scope	
3	Chemical industry no longer uses fossil resources for feedstocks (e.g. no natural gas used)	Fossil fuel elimination	Foundation industries
3	Scale from renewable resources (TW scale of production worldwide)	Green hydrogen	
3	Skilled workforce to manufacture, install, service and operate system	Workforce training	
3	Working, regulated market for hydrogen distribution	Regulatory challenges	
3	Society comfortable with use of hydrogen	Public perception	
4	All hydrogen production in 2050 to be green / carbon neutral. Minimise the need for methane-blue	Blue to green transition	
4	Optimised system - which technology works with which renewables at which sites, considering costs and feasibility in water supply, electricity supply, storage and transportation of H2.	Tech comparison	TEA
4	Sustainable electrolysis manufacturing & recycling of materials.	LCA	
4	Established policy and business models for hydrogen economy	Influence policy	Business models
4	Established supply chain for hydrogen production within the UK	Supply chain	
4	Match production with appropriate storage and transport	Map to end users	
5	Decentralised hydrogen generation	Decentralise d	
5	Production in commercial sectors (where solar/wind is possible)	Too general	
5	Hydrogen as a service (app!?)	Business models	
5	2050 too late, move on at speed to make a difference	Urgency/agg ressive	

5	Different production technologies can be optimised/scaled to achieve target	Tech comparison	TEA
5	Green hydrogen production extensive	Fossil fuel elimination	
5	Sustainable solution - materials use	LCA	
5	Efficiency of production is mass market - effects cost/competitiveness	Improve efficiency	
5	Geographic dependency solution in place	Location/water/pressure/purity constraints	
5	Holistic look at whole system - full green hydrogen economy	Whole-system approach	
5	Recyclability of embedded materials - need a solution for material recovery	LCA	
5	price/cost of hydrogen technologies must be accessible	Cost reduction	
5	Safety - safe systems - domestic safety - risk analysis all needs to be in place	Safety	
6	Meihong: Blue hydrogen + CCS	Blue hydrogen	
6	Fernando: large scale H2 production using renewable energy	Green hydrogen	
7	A logical, geographically specific plan Asap - that prioritizes uses and technologies	Location/water/pressure/purity constraints	Urgency/aggressive
7	An enabling infrastructure for the whole system that works with constraints/limitations on pressure, purity, distances etc.	Location/water/pressure/purity constraints	Whole-system approach
7	A framework for hydrogen that incentivizes genuine carbon reductions	Whole-system approach	LCA
7	Reduction in cost of producing hydrogen - cheaper than other energy carriers	Cost reduction	
7	100% green hydrogen production - what do you mean by “green”?	Standard definitions green/blue etc	
7	Great point! I mean 0 carbon emissions (or as low as possible)	Standard definitions green/blue etc	
7	Good! - or maybe less than a certain level if truly zero cannot be achieved because fo embodied emissions etc.	Duplicate	

7	Clear definitions of Green, Blue and other colours for hydrogen production - standards for hydrogen production	Standard definitions green/blue etc		
7	Less use of ,critical minerals	Resource scarcity		
8	Would like it to be inexpensive -improvements in catalysts (abundant materials based), consider potential for subsidy support	Cost reduction	Resource scarcity	
8	Infrastructure available to distribute at scale - utilise existing natural gas grid? Ensure it is low carbon	Infrastructur e	Green hydrogen	
8	Address public perception around hydrogen - have resources to make it safe and acceptable	Public perception	Safety	
8	Green hydrogen predominantly by 2050 - different hydrogen production options globally eg utilisation of blue hydrogen in fossil fuel rich regions, realistic to shift to blue hydrogen globally in 205o timescale	Blue to green transition		Efficiency
8	Water usage globally and challenge it presents - greater use seawater and competition with drinking water, agriculture etc	Location/wa ter/pressure /purity constraints		
8	Match supply with demand and understanding of the implications for different end uses - volume and purity related	Location/wa ter/pressure /purity constraints		
9	H2 funding is tiny in UK compared to e.g. Germany. Need something like Faraday for funding	Define scale of challenge for funding		
9	co-ordinated approach, with large training component.	"Faraday type approach"		
9	define the funding requirement for a programme of this scale.	Define scale of challenge for funding		
9	Need to highlight and define the scale of funding required given the size of the challenge. Part of this is having the scale and money to be able to attract good quality researchers (CDT plus i.e. better funded/higher rate studentships). (DR: this is a summary)	Recruitment problems (£)		
9	Mechanism to collaborate and develop things effectively. Aggressive policy, with gating and oversight.	Urgency/agg ressive		
10	Sustainable, affordable array of technologies (solar, wind and nuclear)			Influence policy
10	Diverse uses of H2 - industry, power, transport, heating - prioritised according to sustainability of alternatives	Map to end users	Fossil fuel elimination	
10	Synergies with industry, making effective use of waste materials, and oxygen and other co-products of H2 production	Use of oxygen	Foundation industries	
10	Minimise transport and storage needs by producing close to point of use where possible	Decentralise d		

10	Integrated mix of sustainable energy sources, overcoming challenges and limitations of intermittency	Green hydrogen		
10	Forecast and be prepared for changes due to climate change, including freshwater availability	Location/water/pressure/purity constraints		Centralised/decentralised
10	Green hydrogen as a whole system approach	Green hydrogen	Whole-system approach	
10	End to end cost effectiveness, recycle, re-use and circular economy	TEA	LCA	
10	Recognising where H2 is and is not the best solution - work in harmony with other technologies	Map to end users		
10	Why are we looking to such a distant date of 2050? May be beneficial to have a vision for this and then work backwards and see how we could get there	Roadmap		
10	Effective transition as blue hydrogen makes way to green hydrogen	Blue to green transition		
11	2050 seems too late??	Urgency/aggressive		
11	Cannot grow hydrogen production in isolation- how does the whole system align and grow at the same rate to ensure we meet the 2050 targets. Problem is changing social/public acceptance of adopting the new technologies - safety aspects/land management. This is the bigger challenge.	Whole-system approach	Public perception	Safety
11	Putting battolyser on wind farm-here pressure is the challenge- low pressure storage is the ideal	Map to end users	Location/water/pressure/purity constraints	
11	Ideal is lots of different hydrogen production methods and storage solutions.	Tech comparison		
11	Batterlyser technology requires clean-up of seawater	Location/water/pressure/purity constraints		
11	Recycling chain is required/Circular economy	LCA		
11	Lots of aspects around hydrogen uses needs to be understood/mapped	Map to end users		
11	Clarity on local/regional/national hydrogen production- . how will we overcome challenges associated with regional boundaries.	Influence policy		
11	Large scale end-users will require hydrogen transportation	Map to end users		
11	Skills pool at all level are able to pivot to technology developments as they arise	Workforce training		
11	Legislation and Policy	Influence policy		
11	Insurance	Insurance		

Category Counts

CATEGORY	COUNT
LOCATION/WATER/PRESSURE/PURITY CONSTRAINTS UNDERSTOOD	10
END USERS MAPPED	10
LCA	6
FOSSIL FUELS ELIMENATED	5
MATURE GREEN HYDROGEN PRODUCTION	5
POLICY/BUSINESS MODEL ALIGNMENT	5
WHOLE-SYSTEM APPROACH	5
BLUE TO GREEN TRANSITION	4
STANDARDS DEVELOPED GREEN/BLUE ETC	4
TECHNO ECONOMICS UNDERSTOOD	4
TECH CAPABILITY DATABASE/COMPARISON	4
STEP-CHANGE IN PRODUCTION	4
REDUCED COST	3
PUBLIC ONBOARD	3
PHASE OUT SCARCE RESOURCES FROM ELECTROLYSERS	3
SAFE/RISK ASSESSESED	3
BUSINESS MODEL DEVELOPED	2
DECENTRALISED APPROACH	2
DEFINED SCALE OF CHALLENGE FOR FUNDING	2
INFRASTRUCTURE DEVELOPED	2
FOUNDATION INDUSTRIES MAPPED/ENGAGED	2
REGULATORY CHALLENGES UNDESTOOD	2
BIOMASS TO H2	1
BLUE HYDROGEN	1
FIELD TRIALS	1
IMPROVE EFFICIENCY	1
INDUSTRY FEEDSTOCK	1
INSURANCE	1
NON-ELECTROLYSIS	1
PILOT FACILITIES NEEDED	1
PV/WIND INTEGRATION	1
RECRUITMENT PROBLEMS (£)	1
ROADMAP	1
SUPPLY CHAIN	1
USE OF OXYGEN	1

Appendix H: All responses to "What are the opportunities for research that will lead to and make the step change in H2 production? 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 production? What are the fundamental research questions that we need to think about?**			
ROOM #	**Comment**	**Primary**	**Secondary**	**Tertiary**
1	Reduction in noble metals	materials		
1	Study of membranes/ electrodes/ degradation mechanisms	mechanisms		
1	whole life cycle assessments	life cycle		
1	Desalinising water direct use of sea water	Desalinising water		
1	gradually building domestic use	domestic use		
2	direct solar energy conversion	solar fuels		
2	water splitting	thermochemical way		
2	thermochemical processes	durable materials		
2	Low-cost water electrolysis technology	price		
2	membranes and catalysts	MEA		
2	Use of both photons and direct use of solar energy into Hydrogen production	Suitability of material		
2	Utilisation of stranded assets	oil and gas sites and facilities		
2	Waste to hydrogen both chemical and biological processes	waste utilization		
3	conversion of ammonia to hydrogen	Addressing toxicity impacts		
3	SOFC	heat recovery		

3	integration around overall systems	system integration
3	academia and industry	sensible funding solutions
3	Whole life cycle assessment	assessment
3	structure- property relationships	Materials
3	available materials	Long term testing
4	materials	Catalyst discovery
4	economic manufacturing processes	Scalable
4	methods to reduce risk	safety
4	materials	Machine Learning
4	supply chain, electrolyser simplicity, replaceable components	system integration
4	Conversion of waste into hydrogen	gasification to syngas
4	Electrolysis for CO2 utilisation	chemical/fu el production (syngas)
4	Biological systems	microbial electrolysis cells
4	hydrogen market and taxation/incentivisation	price
5	integration of temperature regulation	system integration
5	electrolysis and fuel cell	reversible systems
5	onshore/offshore/near industry	ideal locations
5	cyber security and infrastructure inherent safety	security
5	quick start-up shut-down	technology
6	Catalysts and supports for electrolysers	materials
6	scale-up production	low permeability to O2
6	from fundamental materials, to systems	Model
6	Production of porous transport layers at scale	bubble dynamics
6	Circular use of materials	(reuse and remanufactu re

6	allowing “overdriving system” for short periods	Optimising systems
7	mechanism of new technologies	Fundamenta l research
7	Circular economy associated with the life cycle of hydrogen production technologies	assessment
7	membrane	New materials
8	reduce/eliminate iridium use	price
8	Stable, low cost alkaline membrane for alkaline electrolysers	materials
8	electricity system based on understanding of level of renewable electricity available and utilisation for hydrogen competing areas	
8	challenge of utilisation of waste heat	waste
8	High temp solid oxide	materials
9	Develop materials and devices for photosynthesis of H2 using solar energy	materials
9	minimise the use of critical raw materials such as Ir for electrolysers	price
9	Scale up of materials for the different devices for H2 production	Scale up
9	Develop devices that work intermittently and tolerate impurities	Develop devices
9	Recyclable and durable materials and devices	materials
10	Working together rather than competing	Mixed research
10	when the economic benefits are clear, funding should soon follow	business case

Category Counts

CATEGORY	COUNT
MATERIALS DISCOVERY (CATALYSTS/SOLID OXIDES/MEMBRANES/ELECTRODES)	9
LCA	5
COST REDUCTION (RESOURCES/POLICY/FUNDING)	4
SAFETY/RISK ANALYSIS	4
SYSTEM INTEGRATION	3
MODEL (SYTEMS/INTEGRATION/PREDICTION)	3
SCALE UP	3
WASTE UTILIZATION	2
FUNDAMENTAL RESEARCH (NOVEL TECH/EFFICIENCY)	2
APPLIED MACHINE LEARNING	2
MICROBIAL ELECTROLYSIS CELLS	2
DESALANISING WATER	1
DEVICE	1

HEAT RECOVERY	1
LOCATION	1
COLLOBORATIVE RESEARCH	1
FACILITIES	1
OPTIMISING SYSTEMS	1
REVERSIBLE SYSTEMS	1
SOLAR FUELS	1
ELECTROLYSIS FOR CO2 UTILISATION	1