H-delivery WP 3 – Task 3.2: Characterisation of prospective technologies

Sustainable Hydrogen Delphi Survey Round 2 – Participant Report.

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Contents

Introduction

A Delphi survey on the production of sustainable hydrogen has been conducted as part of the work of the EPSRC funded SUPERGEN XIV consortium "Delivery of Sustainable Hydrogen" (Dosh). The survey explores expert views on the following topics over the time period 2020-2050:

- Sustainable Development and Hydrogen
- Hydrogen Production
- Hydrogen Production Technologies and Feedstock
- Safety, Risk and Public Perception

The Delphi survey is an anonymous multi-round survey which allows experts to consider the responses of their peers without being unduly influenced by the responses of key individuals. The technique is particularly appropriate in this case as many of the relevant technologies are still in the research stage. As a result their expected performance is not well characterised and hence they are not included in many current models. Although views were sought for the period 2020-2050, the aim of this survey was to inform the future, not to forecast it.

This report summarises the findings from the second round of the Delphi survey carried out in October 2011.

A final round, comprising a small deliberative stakeholder workshop, was subsequently held in London in March 2012. A subsequent paper detailing overall findings from the Delphi process will be produced in due course.

Participant Information

From the responses to the first round of the Delphi survey (Stevenson 2011) it was evident that many hydrogen experts are specialists in very particular fields but that relatively few people have an overview of hydrogen developments as a whole. For this reason, it was necessary to increase the number of respondents to the second round survey by widening the group of experts invited and refining the questionnaire to reduce the time required to respond. This resulted in 347 responses for the second round survey compared with 52 for the first round.

Forty countries were represented, with more than eight responses each from Canada (16), China (34), Germany (11), India (12), Italy (25), Japan (8), Russia (9), Spain (15), The Netherlands (10), Turkey (10), UK (31) and USA (77).

The majority of responses were from participants working in non-industrial research functions (e.g. university or other publicly funded research institutes) (249), together with strong responses from National Government (30) and Industrial Research (41). This was considered to appropriately represent the population of hydrogen experts. The experts represented a wide range of expertise including Bioenergy (24), Chemistry (30), Combustion (10), Electrochemistry (26), Fuel cells (50), Hydrogen Production (51), Materials (13), Policy (10), Renewable energy, Safety (11), Storage (38) and Transport (9).

Where appropriate the responses were analysed for subgroups which included country, function, field of expertise and confidence level.

Sustainable Development and Hydrogen

Key Sustainability Issues

In order to understand the motivation of respondents when they responded to questions about sustainability of hydrogen, it is important to understand the aspects of sustainability which they consider to be important. In round 1, respondents were requested to specify the aspects of sustainability which they consider to be important. In round 2, respondents were asked to rank the aspects which were identified in round 1, on a scale from 1 to 7 (where 1 is considered to be the most significant aspect of sustainability and 7 the least). The mean ranking of all responses to each aspect is listed in Table 1.

Table 1 Mean Ranking of Sustainability Aspects (All Respondents)

Sustainability Aspect	Mean Ranking
Job Creation	5.39 (lowest ranking)
Retaining Living Standards	4.71
Cost of Fuel	4.61
Minimising Energy Poverty	4.61
Minimisation of Greenhouse Gases	2.91
Minimisation of Pollution	2.91
Use of Renewable Energy	2.66 (highest ranking)

The tendency to value environmental factors above social and economic factors was common throughout the respondents. However, the Russian respondents were (on average) less concerned by the minimisation of greenhouse gases and more concerned about retaining living standards. The Dutch respondents (on average) ranked minimising energy poverty similar to environmental factors. While the Turkish respondents showed moderate concern for all aspects apart from job creation which was not considered important.

One Round 2 respondent also added Security of Energy Supply as a key sustainability issue.

Hydrogen Production Feedstock

The sustainability of hydrogen production is closely linked to the feedstock used. In round 1, respondents were requested to specify what hydrogen production methods they considered to be sustainable. In round 2, respondents were asked to rank the sustainability of the feedstocks identified in round 1 on a scale from 1 to 12 (where 1 is considered the most sustainable feedstock and 12 the least). The mean ranking of all responses to each feedstock is listed in Table 2.

Table 2 Mean Ranking of Hydrogen Feedstock Sustainability (All Respondents)

Sustainability Aspect	Mean Ranking
Fossil fuel (without Carbon Capture and Storage)	9.63 (lowest ranking)
Heat (nuclear)	8.14
Alcohol	7.87
Fossil fuel (with Carbon Capture and Storage)	7.87
Microbes	7.76
Electricity (Nuclear)	7.10
Electricity (Marine)	6.06
Biomass	5.07
Electricity (Photovoltaic)	4.98
Solar (not electricity)	4.32
Electricity (Hydro)	4.05
Electricity (Wind)	3.89 (highest ranking)

The results indicate that there is stronger support for renewable energy as a sustainable feedstock for hydrogen production than for nuclear power or fossil fuels. A number of Round 2 respondents were keen to note that the sustainability has to be considered in terms of the local circumstances.

Nuclear vs fossil fuel
Canadian and Chinese respondents were less concerned about sustainability issues relating to nuclear energy generation than those from other countries. Despite the explosion at Fukushima nuclear plant and the resulting debates on the safety of nuclear energy generation, our Japanese respondents still considered fossil fuel with or without carbon capture and storage to be less sustainable than nuclear energy generation. Notably, our German and Turkish respondents considered fossil fuel without carbon capture and storage to be more sustainable than fossil fuel with carbon capture and storage.

The respondents whose first sustainability priority was economic ranked nuclear energy as more sustainable than the respondents whose first sustainability priority was environmental or societal.

Biomass
Perhaps unsurprisingly those respondents who identified themselves as bioenergy experts considered biomass to be more sustainable than other renewable energy options, more surprisingly this view was shared by reforming specialists.

Despite general support for renewable energy supplies, Dutch respondents considered the sustainability of biomass as a feedstock to be similar to that of nuclear energy generation. This finding may reflect the high profile of debates over the sustainability of biofuels in the Netherlands more broadly.

Hydrogen Production as an Energy Vector

Amount of Hydrogen Produced as an Energy Vector

In round 1, respondents were requested to predict the worldwide production of hydrogen (for use as an energy vector) for the years 2020, 2030, 2040 and 2050. Figure 1 shows their responses with a dashed red line indicating the amount of hydrogen (2 922 million standard tonnes) equivalent to the 2008 global final energy consumption of 8 428 million tonnes of oil equivalent (IEA 2010) and the solid blue line represents 42.7 million standard tonnes of hydrogen which is equivalent to the total 2009 hydrogen production (US Department of Energy).

The respondents can be considered in three groups which are represented by the shaded ovals. The bottom (blue) oval represents respondents who believe there will be less than 1 000 standard tonnes of hydrogen produced by 2050, this approximates to enough fuel to run 5 000 cars and indicates that hydrogen would play only a trivial role in future energy use. The middle (green) oval represents respondents who believe there will be between 1 million to 40 million standard tonnes of hydrogen produced by 2050, indicating a trend of increasing hydrogen use as an energy vector which by 2050 will be equivalent to current hydrogen production for chemical applications. The top (orange) oval represents respondents who believe that by 2050 hydrogen as an energy vector will be able to meet a demand equivalent or greater than 2008's total global energy consumption.

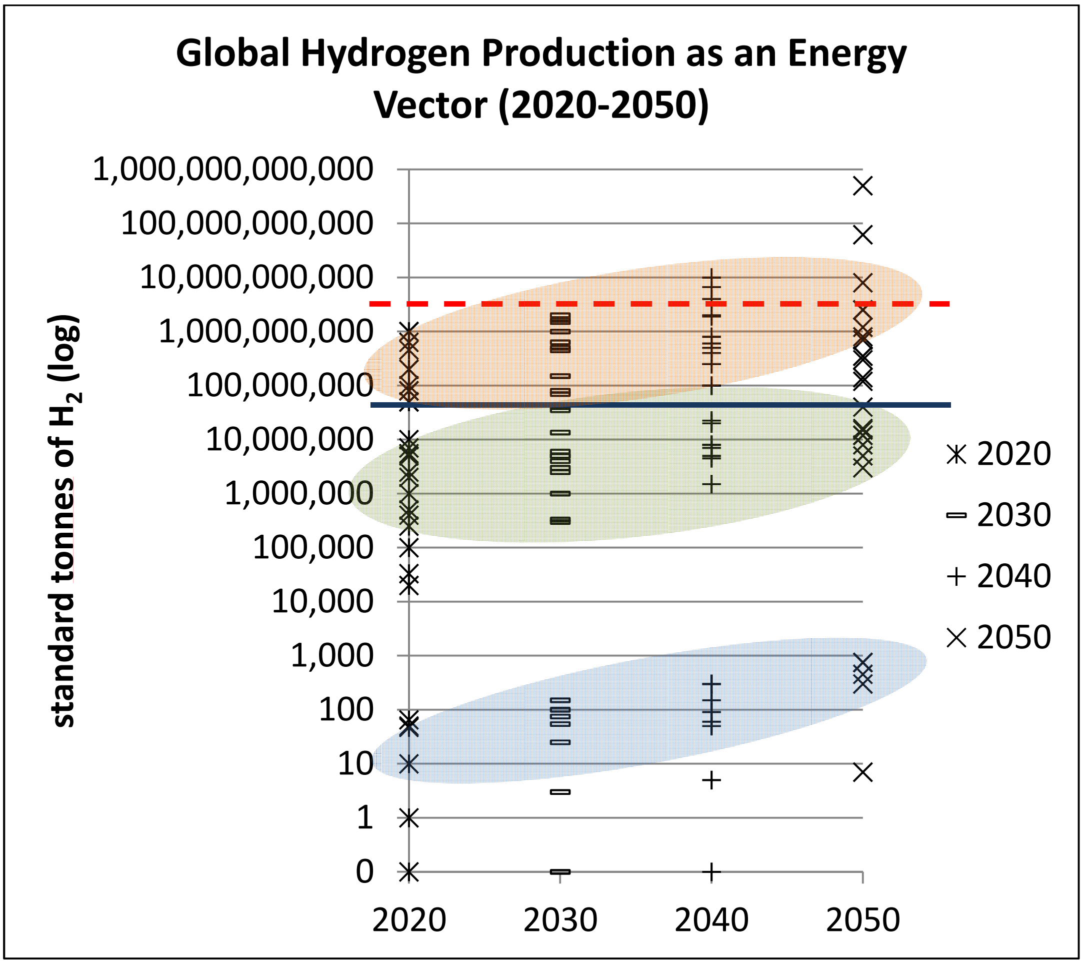

Figure 1 Global hydrogen production as an energy vector (2020-2050): Round 1 response

In round 2, Figure 1 was presented to the respondents who were again requested to predict the worldwide hydrogen production as an energy vector for 2020, 2030, 2040 and 2050. Their responses are presented in Figure 2, where the dashed red line again represents 2008 global final energy consumption and the solid blue line represents the total hydrogen production in 2009.

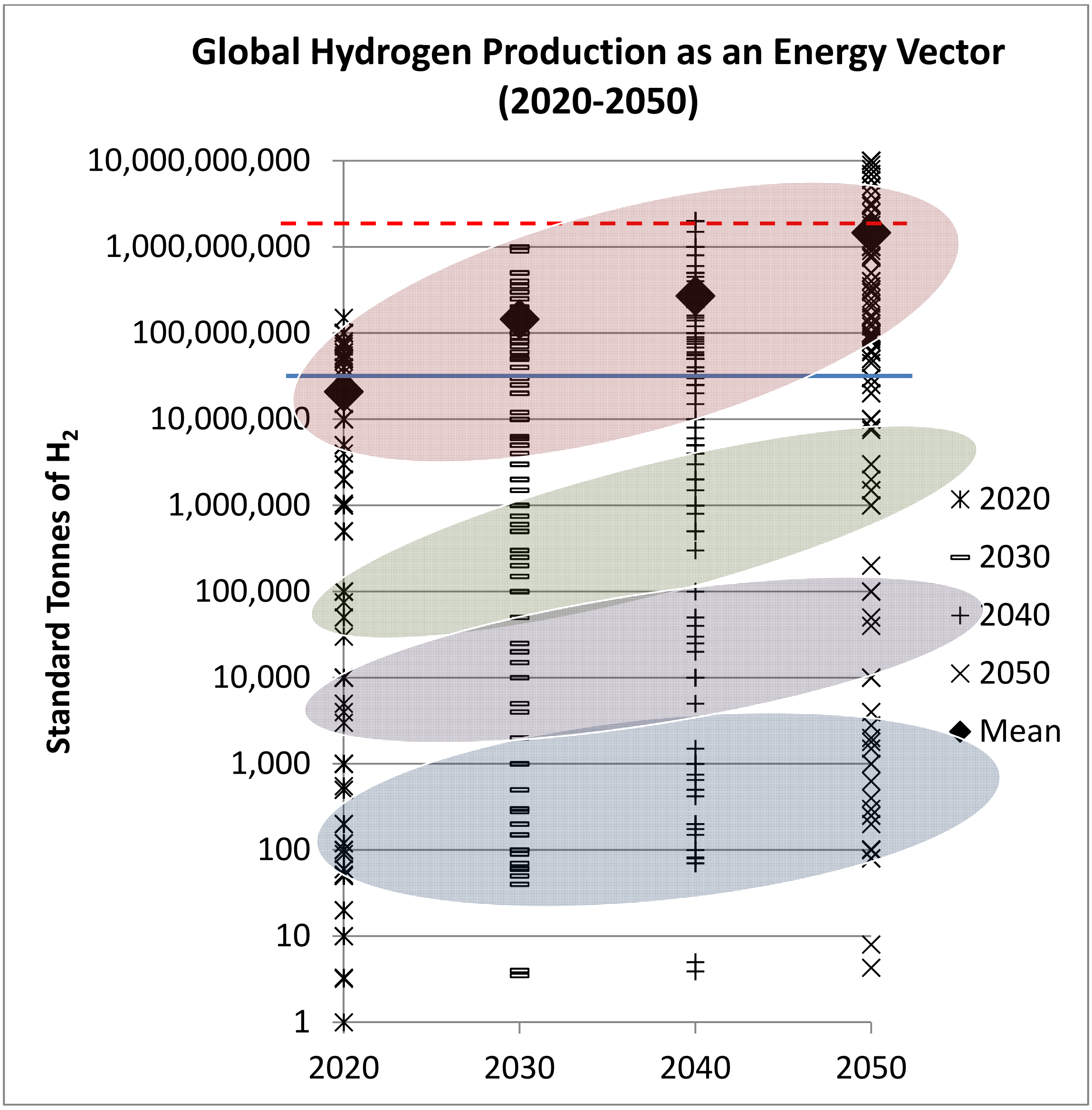

Figure 2 Global hydrogen production as an energy vector (2020-2050): Round 2 response

The mean forecast for each decade is 20 852 594 standard tonnes (2020), 144 850 374 standard tonnes (2030), 270 276 598 standard tonnes (2040) and 1 462 736 371 standard tonnes (2050).

Perhaps because of the increased number of respondents in round 2, there is not such a discrete grouping of responses on global hydrogen production as an energy vector; however, it is possible to consider the responses in four groups represented by the shaded ovals on Figure 2. The bottom (blue) oval represents respondents who believe there will be less than 4 000 standard tonnes of hydrogen produced by 2050 (approximately enough to run 20 000 cars) and indicates that hydrogen would play only a trivial role in future energy use. The second bottom oval (lilac) indicates 10 000 to 200 000 standard tonnes of hydrogen produced by 2050. The second top oval (green) represents

900 000 to 3 million standard tonnes of hydrogen produced by 2050, this is indicative of the forecasts by Renewable Energy experts. The top oval (orange) indicates that the global energy demand of 2008 could be met using hydrogen as an energy vector by 2050 and is indicative of the mean forecast by all groups analysed.

The mean forecast for 2050 by Policy experts, Electrochemistry experts, Dutch, UK and German respondents lie between 12 million and 750 million standard tonnes of hydrogen. The mean forecasts by all other groups lie between 1 000 million and 2 000 million standard tonnes of hydrogen.

The forecasts illustrated in Figure 2 can also be compared to the size of the global hydrogen market reported in (Mansilla, Avril et al. 2012), where hydrogen as a fuel is expected to reach 0.9 million tonnes of hydrogen in 2030 and 67.1 million tonnes of hydrogen in 2050. This indicates a much steeper growth in hydrogen production from 2030 to 2050 than portrayed in Figure 2. It should be noted that the Mansilla et al figures exclude hydrogen use in processes such as biomass to liquid, oil refining, hydrogen injected into the gas network and hydrogen used to produce methanol. These figures would be affected by future fossil fuel and CO_2 prices.

Round 2 respondents have noted that estimates of future use of hydrogen as an energy vector can be influenced by the inclusion or non-inclusion of:

- hydrogen consumed in pre-combustion carbon capture and storage technology
- hydrogen used in the upgrading of oil sands and crude oil
- hydrogen generated as an intermediate for the storage of renewable electricity.

Hydrogen Contribution to Energy Demand

In round 1, respondents were requested to predict the percentage of global final energy demand delivered using hydrogen for 2020, 2030, 2040 and 2050. Figure 3 shows their responses.

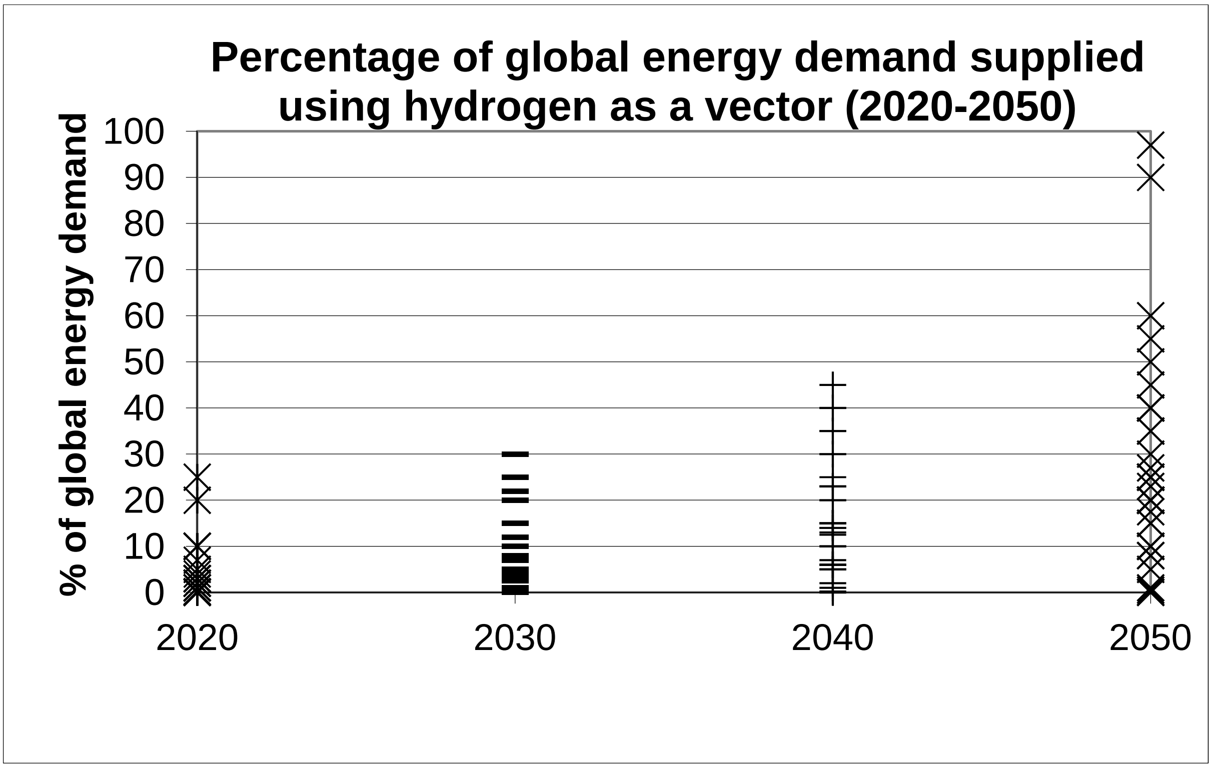

Figure 3 Percentage of global energy demand supplied using hydrogen as a vector (2020-2050): Round 1 response

In round 2, Figure 3 was presented to the respondents who were again requested to predict the percentage of global final energy demand delivered using hydrogen for 2020, 2030, 2040 and 2050. Figure 4 shows their responses.

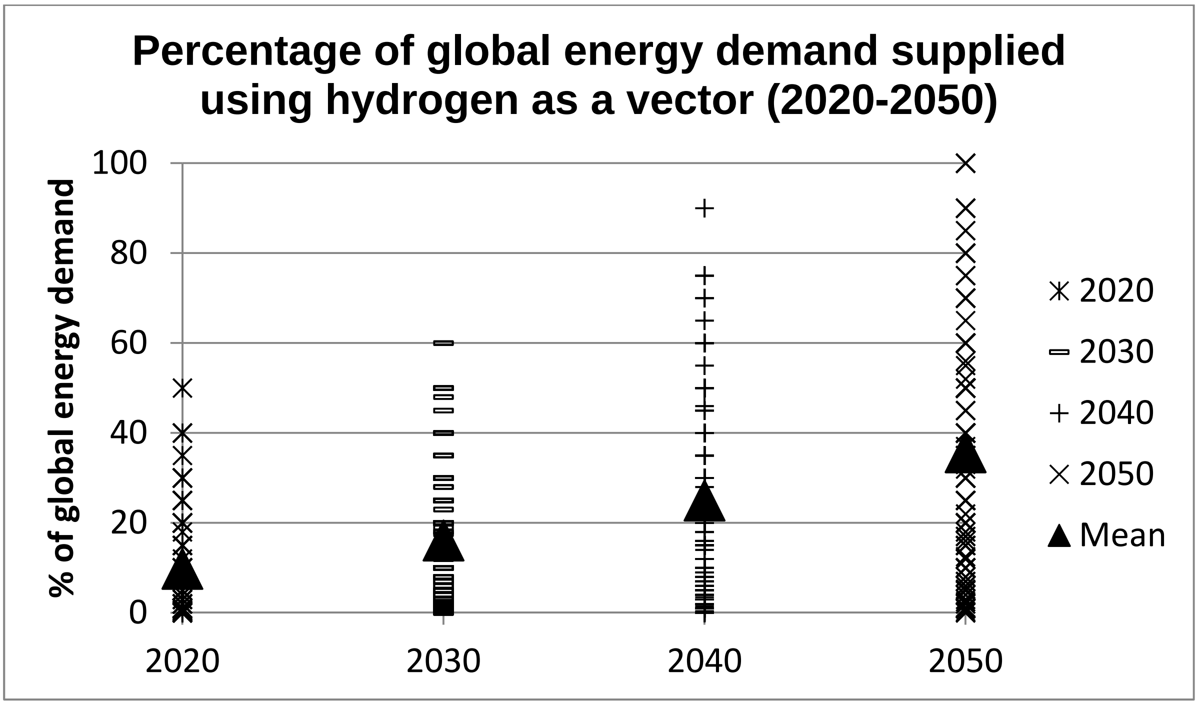

Figure 4 Percentage of global energy demand supplied using hydrogen as a vector (2020-2050): Round 2 response

The mean of the forecasts for each decade are 9.8% (2020), 16.1% (2030), 25.0% (2040), 35.7% (2050).

The groups who were (on average) least optimistic about the proportion of global energy demand which will be met using hydrogen as an energy vector were the Canadian , Dutch , Turkish , UK, Industrial Researchers, National Government, Policy experts and the respondents who were unsure in their responses. The most optimistic groups were (on average) the Chinese , Chemistry experts, Material experts, Storage experts and those respondents who were particularly confident in their responses.

Round 2 respondents also noted the following as factors which may affect the use of hydrogen as an energy vector:

- Limited supplies of copper to transmit electricity
- Production of Dimethyl Ether (DME) from electrolysis will be more feasible
- Application beyond automotive use
- The ability of the global population to deal with hydrogen technologies
- The development of alternatives such as alcohol and batteries
- The future cost of fossil fuels

Global Energy Consumption

The use of hydrogen production as an energy vector should be considered in the context of global energy consumption. Respondents were asked to predict the global final energy consumption for 2020, 2030, 2040 and 2050 as a percentage of 2008 consumption, which was 8 428 million tonnes of oil equivalent (IEA 2010). Their responses are presented in Figure 5. The shaded ovals on Figure 5 represent 2020, 2030 and 2050 forecasts of future global energy consumption and primary energy demand from a variety of sources including the International Energy Agency (IEA 2009), the World Energy Council (World Energy Council 2007), the US Energy Information Administration (US Energy Information Administration 2011), BP (BP 2011), Chevron (Chevron 2011) and others (Hawksworth 2006; Beretta 2007; Chefurka 2007; Roper 2011).

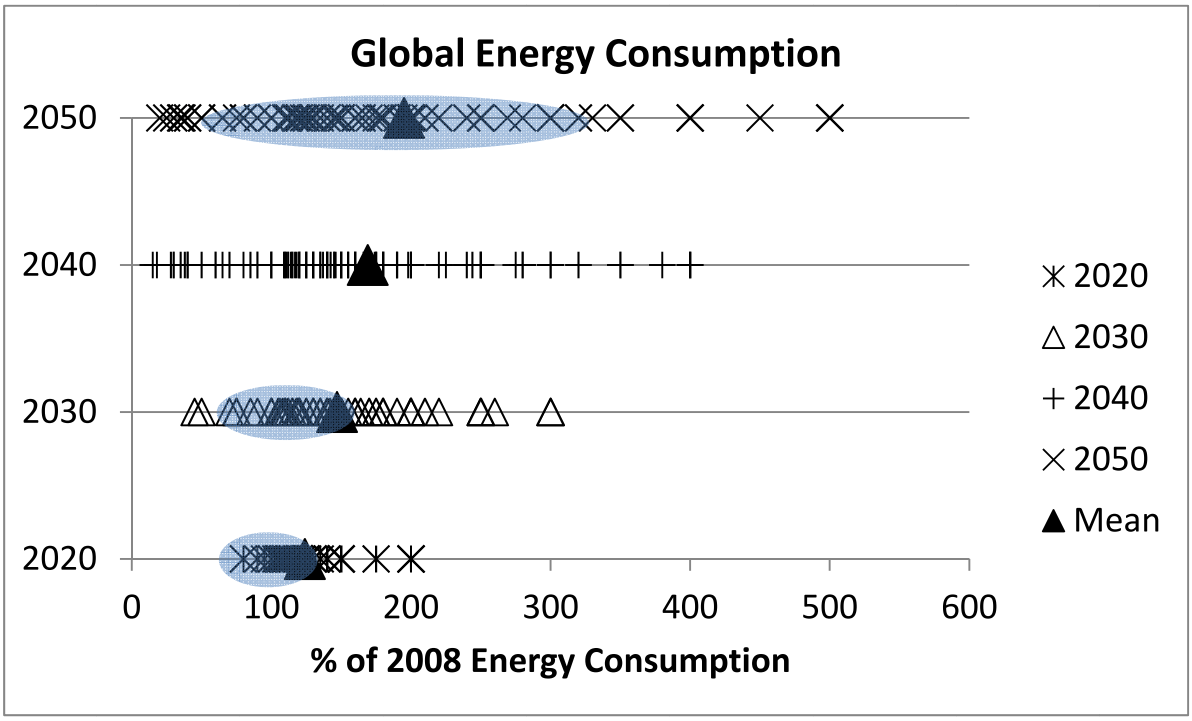

Figure 5 Global energy consumption (2020-2050): Round 2 response

The mean of the forecasts for each decade are 124% (2020), 147% (2030), 169% (2040), 195% (2050) of 2008 global energy consumption.

The groups who anticipate the least increase in global energy demand were (on average) the Indian and Japanese respondents and those identifying themselves as Safety experts. The groups who anticipate the greatest increase in global energy demand were the Chinese and Russian respondents and Fossil fuel experts.

Round 2 respondents noted the following factors which may affect future global energy demand:

- Increasing energy demand from developing countries
- Global economic performance
- Global population growth
- Energy efficiency initiatives
- Energy cost
- Decreased fossil fuel availability

No correlation was found between those respondents predicting high future global energy demand and those predicting significant future use of hydrogen as an energy vector.

Feedstock

Most Significant Feedstock

In round 1, respondents were requested to suggest the energy feedstock most likely to contribute to the bulk of hydrogen production for 2020, 2030, 2040 and 2050. In round 2, respondents were asked to rank the feedstock options in terms of significance for 2020, 2030, 2040 and 2050 (where 1 was considered to be the most significant feedstock and 11 the least). The mean ranking of all responses to each feedstock is listed in Table 3.

Table 3 Mean ranking of Feedstock Significance for 2020, 2030, 2040 and 2050 (All Respondents)

Feedstock	**Mean Ranking**			
	2020	**2030**	**2040**	**2050**
Electricity (Marine)	8.82 (lowest ranking)	8.47 (lowest ranking)	7.92 (lowest ranking)	7.36
Waste	7.94	7.68	7.02	6.86
Electricity (Solar)	6.42	5.60	4.51	3.75 (highest ranking)
Electricity (Nuclear)	6.40	6.23	6.16	5.96
Biomass	6.02	5.10	4.51	4.18
Electricity (Wind)	5.97	5.45	5.54	3.98
Oil	5.57	6.58	7.63	8.43 (lowest ranking)
Electricity (Hydro)	5.42	5.58	5.27	5.10
Electricity (Fossil)	4.77	5.61	6.57	6.92
Coal	4.54	5.21	6.31	6.84
Gas	2.65 (highest ranking)	2.91 (highest ranking)	4.27 (highest ranking)	5.40

The overall responses indicate that gas is expected to be the dominant hydrogen feedstock until 2030, after which there is expected to be less dominance by any single fuel. By 2050, the most significant feedstocks will be electricity sourced from solar, wind and hydro along with biomass. Marine electricity and waste are expected to slowly increase their significance between now and 2050, while oil, coal and fossil electricity are expected to decrease in significance. The ranking of nuclear electricity indicates a very slight decrease in significance by 2050.

Our Indian respondents did not (on average) anticipate a strong initial dependence on gas. Rather they expected a strong and enduring reliance on biofuel as well as solar and hydro generated electricity supporting fossil electricity from as early as 2020.

Japanese respondents considered nuclear electricity to have minimal significance throughout the time period.

Russian respondents showed some reliance on nuclear electricity which increases consistently until 2050. Wind sourced electricity was considered to have little significance initially, but to be more significant by 2050.

Transport experts considered that gas and nuclear sourced electricity would retain considerable significance right up until 2050, while acknowledging the increasing significance of wind and solar generated electricity by then.

Electricity Provision

In round 1, respondents were asked to identify the issues which might arise with obtaining adequate electricity provision in urban areas to generate hydrogen for transport refuelling. In round 2, respondents were asked to rank the significance of these issues for 2020, 2030, 2040 and 2050 (where 1 was considered to be the most significant issue and 7 the least). The mean ranking of all responses for each issue is listed in Table 4.

Table 4 Mean ranking of Electricity Provision Issues for 2020, 2030, 2040 and 2050 (All Respondents)

Issue	**Mean Ranking**			
	2020	**2030**	**2040**	**2050**
None	4.88 (lowest ranking)	4.94 (lowest ranking)	4.57 (lowest ranking)	5.14 (lowest ranking)
None if offpeak	4.39	4.43	4.19	4.59
Grid Stability	3.34	3.32	3.33	3.41
Grid Strength	3.31	3.43	3.51	3.74
Generating Capacity	2.96	3.01	2.88	3.23
Clean Sources	2.32	2.05 (highest ranking)	1.95 (highest ranking)	2.28 (highest ranking)
Cost	2.12 (highest ranking)	2.27	2.54	3.32

The mean responses indicate that clean sources are expected to be an issue throughout the time period, while cost and generating capacity are issues which become less important by 2050.

Canadian respondents did not consider generating capacity to be an issue for 2020, but were less confident about following decades.

Chinese respondents were less concerned by cost, but considered grid stability and strength as issues which would become more dominant as time goes on.

German respondents considered cost to be an ongoing issue, and considered that grid strength and finding clean sources of electricity would become stronger issues leading up to 2050.

Japanese respondents were less concerned by generating capacity and cost. Finding clean sources of electricity was considered a major issue throughout the time period, with grid stability and grid strength also causing concern.

Russian respondents considered that finding clean sources of electricity would be an issue which became more significant leading up to 2050.

Although Dutch respondents considered that generating capacity was likely to be an issue up until 2040 and cost would be an increasing issue up to 2050, no issues for offpeak electricity were considered by 2050.

Renewable energy experts considered that grid strength and stability would be the major issues for 2040 and 2050.

One area which was not touched upon by respondents is the capability of the distribution network, which has been identified as an issue for the installation of electric vehicle charging equipment. A 6.3kW electrolyser operating for eight hours a day to produce 1kg of hydrogen per day could be considered a similar electrical load to a fast domestic electric vehicle charging station. The IET Code of Practice for Electric Vehicle Charging Equipment Installation has noted

> "Increasing numbers of collecting point clusters lead to a greater likelihood of voltage fluctuations of sufficient magnitude to affect neighbouring properties." (IET Standards Ltd 2012)

For this reason, in the UK, installation of any electric vehicle charging equipment at a site with less than 100A supply capacity has to be automatically reported to the appropriate distribution network operator. The operator will assess the impact in terms of the voltage drop, losses and potential overload of equipment in the area. A similar requirement may become necessary for domestic electrolysers if they became sufficiently popular or if they were installed in an area which already had electric vehicle charging stations installed. Although this information has been presented based on UK information, similar issues are expected in other countries.

Drivers and Barriers

Key Drivers

In round 1, respondents were requested to identify key drivers to a hydrogen economy. In round 2, respondents were asked to rank the drivers (where 1 is considered to be the most significant driver and 15 the least. The mean ranking of all responses to each driver is listed in Table 5.

Table 5 Mean ranking of Drivers to a Hydrogen Economy (All Respondents)

Driver	Mean Ranking
High Population	11.14 (lowest ranking)
Living Standards	10.88
Public Perception	9.75
Improving Cost Effectiveness	8.42
Hydrogen Market Establishment	8.34
Green Economy and Employment	8.30
Transport Fuel Alternative	7.51
Sustainable Development	7.43
Renewable Energy Storage	6.88
Energy Efficiency	6.88
Pollution Reduction	6.63
Hydrogen Technology Development	6.41
Fossil Fuel Cost	6.15
Fossil Fuel Availability	5.82
Greenhouse Gas Reduction	5.11 (highest ranking)

Although there is no perceived key driver for a hydrogen economy, there are a number of milder drivers including decreasing fossil fuel availability, increasing fossil fuel cost along with environmental considerations such as pollution and greenhouse gas reduction, energy efficiency and storage of renewable energy; however, the respondents acknowledge that these are also drivers for other technologies.

Fossil fuel availability and cost were perceived as less of a driver for the hydrogen economy by Japanese and Dutch respondents as well as by Bioenergy experts.

Greenhouse gas reduction was perceived as less of a driver by Japanese, Russian and Dutch respondents as well as by Bioenergy and Materials experts. Pollution reduction was perceived as less of a driver by Japanese, Russian, Dutch and Industrial Researcher respondents as well as by Bioenergy experts. Energy efficiency was perceived as less of a driver by UK, Indian, Spanish and National Government respondents as well as by Combustion and fossil fuel and Renewable energy experts. Renewable energy storage was perceived as less of a driver by Italian respondents, Combustion and fossil fuel and Transport experts.

Key Barriers

In round 1, respondents were requested to identify key barriers to a hydrogen economy. In round 2, respondents were asked to rank the drivers on a scale from 1 to 9 (where 1 is considered to be the most significant driver and 9 the least). The mean ranking of all responses to each driver is listed in Table 6.

Table 6 Mean ranking of Drivers to a Hydrogen Economy (All Respondents)

Driver	Mean Ranking
Safety	7.09 (lowest ranking)
Lack of Renewable Energy	6.48
Public Perception	6.42
Policy	5.64
Lack of Investment	4.77
Incumbent Technology	4.70
Technical Barriers	4.48
Lack of Infrastructure	3.61
Cost	2.49 (highest ranking)

Two key barriers have been identified as cost and lack of infrastructure; however, these were not perceived as barriers by Indian respondents.

Technological and Commercial Capability of Hydrogen Production

Technological Capability of Hydrogen Production

In round 1, respondents were requested to predict the year in which hydrogen production technologies would be technologically capable (suitable for demonstration project). Figure 6 shows the range of their responses, where the green triangle represents the median response. There was evident agreement that steam reforming and low temperature electrolysis were already considered to have reached Technological Capability.

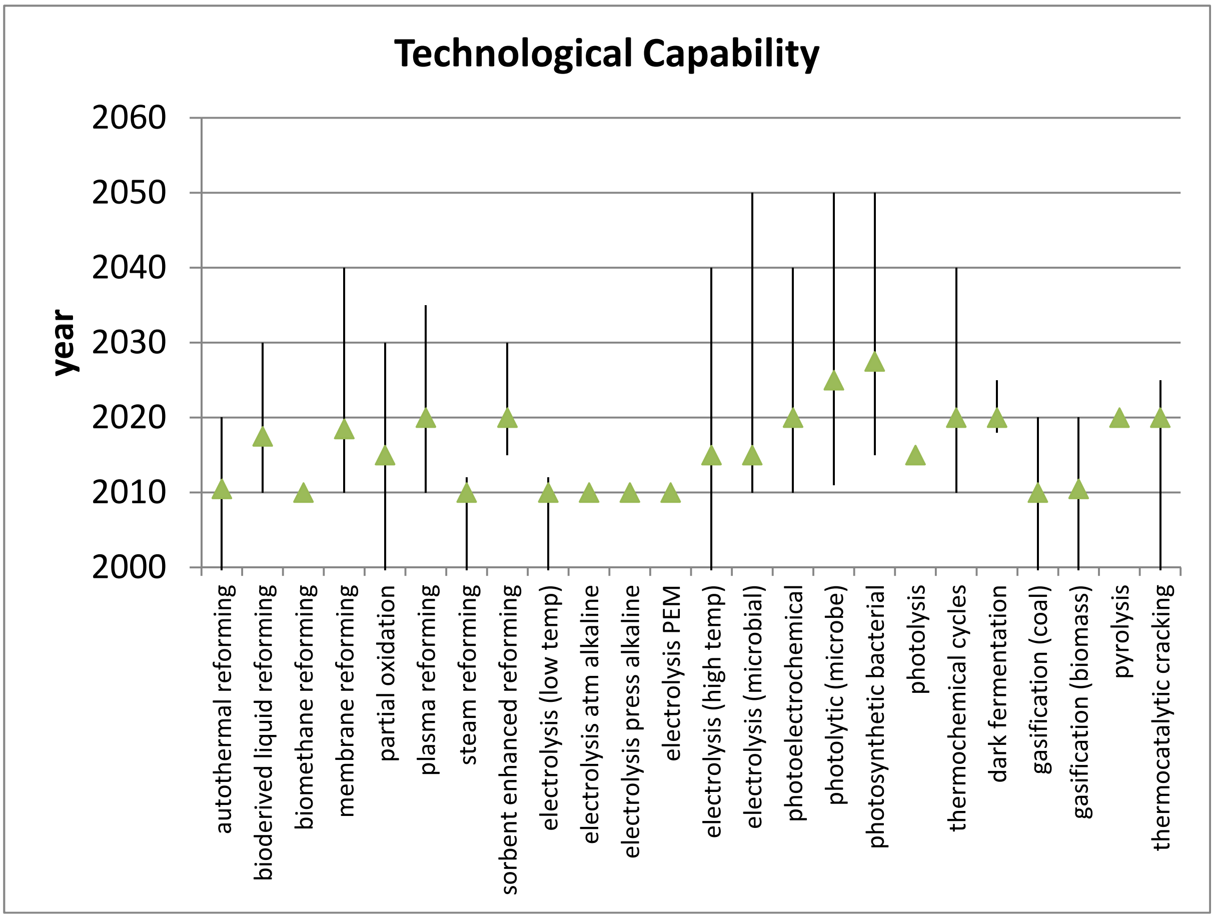

Figure 6 Predicted Technological Capability (demonstration) of Hydrogen Production Technologies: Round 1 response

In round 2, Figure 6 was presented to the respondents who were again asked to predict the technological capability of hydrogen production technologies. Figure 7 shows their responses.

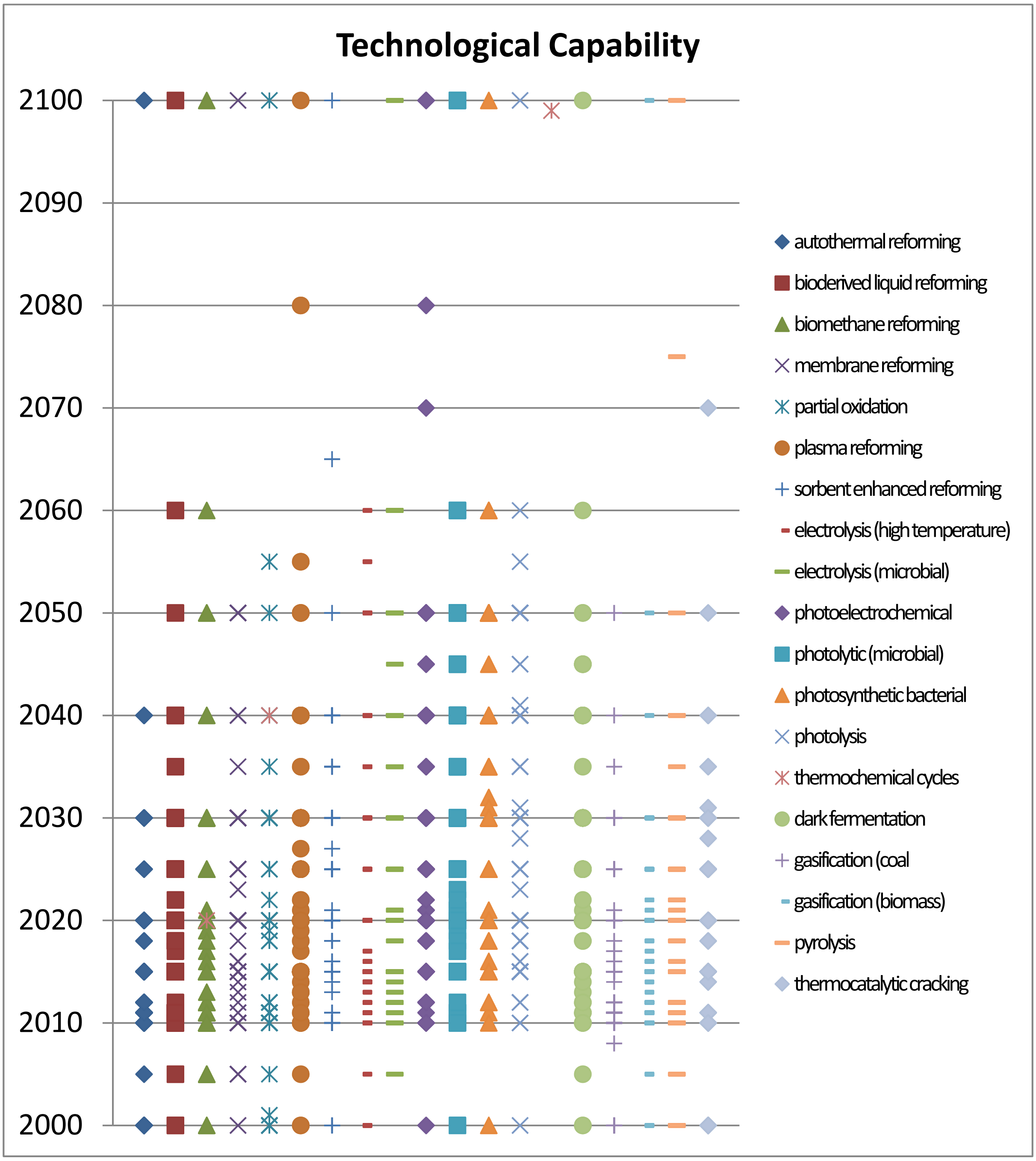

Figure 7 Predicted Technological Capability (demonstration) of Hydrogen Production Technologies: Round 2 response

Although there are a few dates predicted beyond 2100 (not shown on Figure 7), the majority of forecasts fall before then. The mean predicted year of Technological Capability for each technology is shown in Table 7.

Table 7 Mean Predicted year of Technological Capability

Technology	Predicted Year of Technological Capability	
	Mean	Standard Deviation
Photosynthetic (bacterial)	2031	17.0
Photolytic (microbial)	2030	14.4
Photolysis	2029	15.2
Plasma Reforming	2027	20.1
Electrolysis (Microbial)	2027	14.7
Photoelectrochemical	2027	14.6
Dark Fermentation	2026	19.6
Thermochemical Cycles	2024	12.6
Sorbent Enhanced Reforming	2023	11.4
Membrane Reforming	2022	11.6
Bioderived Liquid Reforming	2021	10.8
Electrolysis (High Temperature)	2020	12.3
Thermocatalytic Cracking	2020	17.0
Pyrolysis	2018	18.1
Biomethane Reforming	2017	12.9
Gasification (Biomass)	2017	10.9
Partial Oxidation	2016	11.7
Autothermal Reforming	2015	10.6
Gasification (Coal)	2013	20.4
Steam Reforming	Existing*	
Electrolysis (Low Temperature)	Existing*	

* - unambiguous responses from round 1 which did not need to be explored in round 2

The mean responses from the different categories of respondents were generally within one standard deviation of the mean; however, the exception to this was the “very unsure” response which indicated that autothermal reforming, bioderived liquid reforming, biomethane reforming, membrane reforming, partial oxidation and gasification (biomass) would not be technologically capable until significantly later than represented in Table 7.

Several respondents considered that one or more of the technologies would never prove technologically capable. The two respondents who considered that none of the technologies would prove technologically capable had expertise in transport science and in microbial biotechnology and ecology; however, both candidates had little confidence in their responses. Respondents who considered that few reforming technologies would ever be technologically capable had expertise in electronics (very unsure) and photovoltaic assisted electrolysis (very confident). It should be noted that steam reforming was not included in the options. Respondents who considered that high temperature and microbial electrolysis would never be technologically capable had expertise in metal hydrides (very confident), electronics (very unsure) and photovoltaic assisted electrolysis (very confident). Respondents who considered that photo assisted technologies (e.g. photoelectrochemical) would never be technologically capable had expertise in hydrogen separation processes (very confident), metal hydrides (very confident) and electronics (very unsure). Respondents who considered that coal and biomass gasification would never be technologically capable had expertise in metal hydrides (very confident) and hydrogen production from methane decomposition (fairly confident). Respondents who considered that dark fermentation and pyrolysis would never be technologically capable had expertise in metal hydrides (very confident) and electronics (very unsure).

Round 2 respondents noted that commercial capability is considered more important than technological capability.

Commercial Capability of Hydrogen Production

In round 1, respondents were requested to predict the year in which hydrogen production technologies would be commercially capable (saleable product, possibly in a niche market). Figure 8 shows the range of their responses, where the green triangle represents the median response.

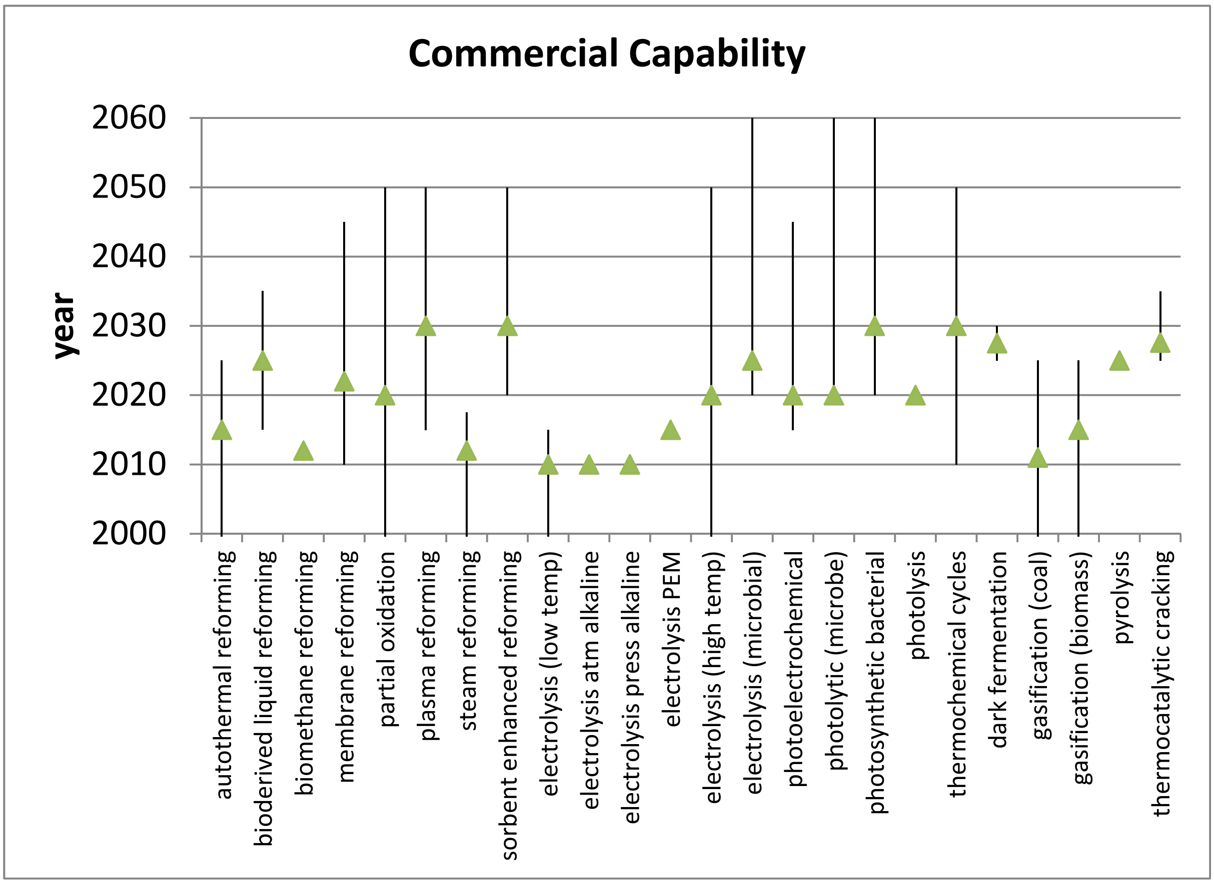

Figure 8 Predicted Commercial Capability (saleable, possibly in niche market) of Hydrogen Production Technologies: Round 1 response

In round 2, Figure 8 was presented to the respondents who were again asked to predict the commercial capability of hydrogen production technologies. Figure 9 shows their response.

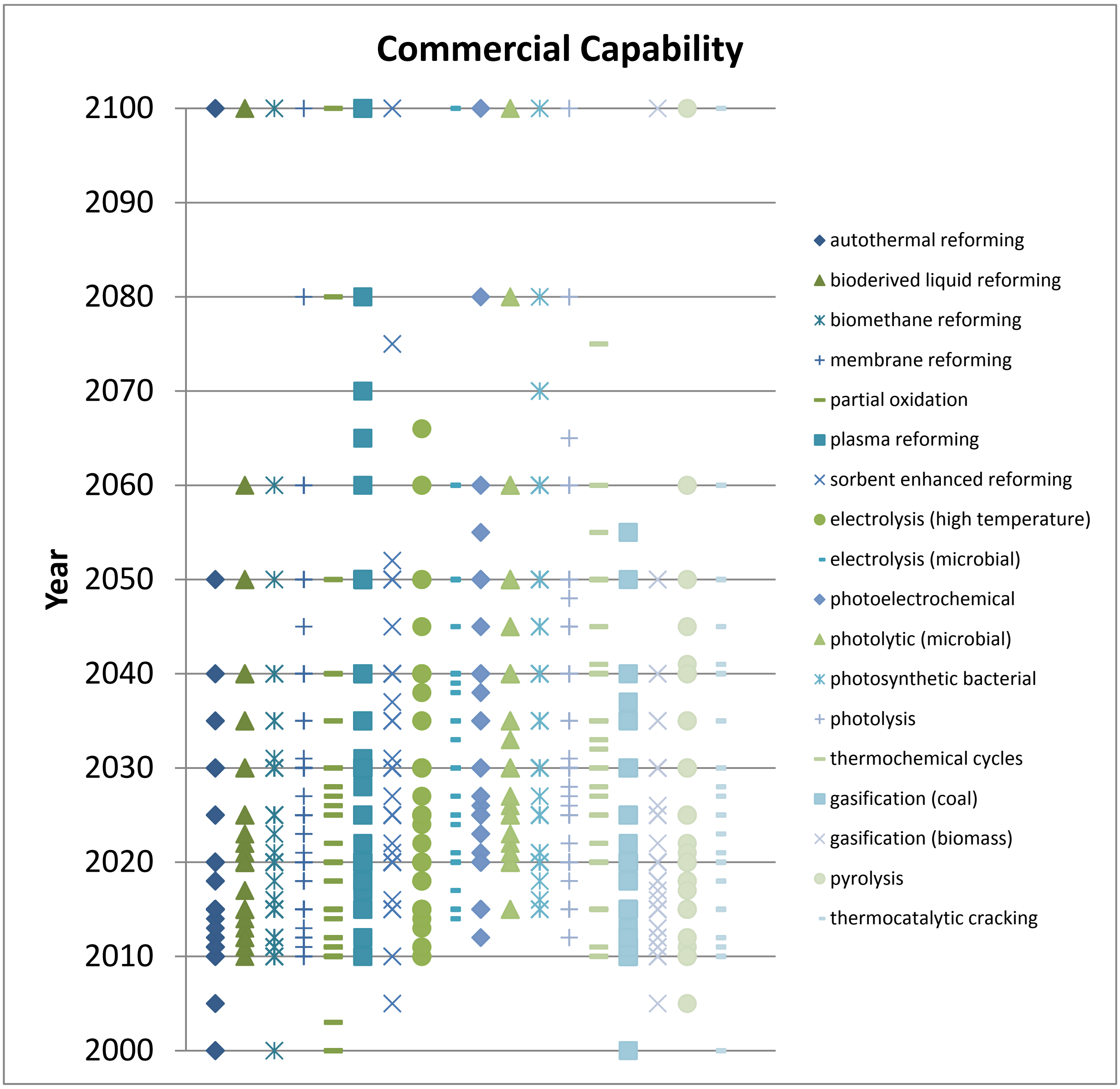

Figure 9 Predicted Commercial Capability (saleable, possibly in niche market) of Hydrogen Production Technologies: Round 1 response

Although there are a few dates forecast beyond 2100 (not shown on Figure 9), the majority of forecasts fall before then.

The mean predicted year of Commercial Capability for each technology is shown in Table 8.

Table 8 Mean Predicted year of Commercial Capability

Technology	Predicted Year of Commercial Capability	
	Mean	**Standard Deviation**
Photolytic (microbial)	2036	18.7
Photosynthetic (bacterial)	2036	13.2
Photolysis	2035	14.7
Photoelectrochemical	2034	17.3
Electrolysis (Microbial)	2033	17.6
Plasma Reforming	2032	14.9
Thermochemical Cycles	2030	18.4
Sorbent Enhanced Reforming	2029	12.4
Membrane Reforming	2028	13.3
Dark Fermentation	2027*	
Bioderived Liquid Reforming	2026	11.3
Electrolysis (High Temperature)	2025	13.6
Thermocatalytic Cracking	2024	22.8
Pyrolysis	2023	22.7
Biomethane Reforming	2022	12.9
Gasification (Biomass)	2021	15.5
Partial Oxidation	2020	17.7
Autothermal Reforming	2018	16.1
Gasification (Coal)	2018	30.0
Steam Reforming	Existing*	
Electrolysis (Low Temperature)	Existing*	

* - unambiguous responses from round 1 which did not need to be explored in round 2

The mean responses from the different categories of respondents were generally within one standard deviation of the mean; however, the exceptions to this were:

- "very unsure" response which indicated that autothermal reforming, partial oxidation and gasification (biomass) would not be commercially capable until significantly later than represented in Table 8.
- Bioenergy experts indicated that gasification (coal) would not be commercially capable until significantly later than represented in Table 8.
- Material experts indicated that thermocatalytic racking would not be commercially capable until significantly later than represented in Table 8.

Several respondents considered that one or more of the technologies would never prove commercially capable. The respondents who considered that none of the technologies would prove commercially capable had expertise in fuel reforming (very confident), transport science (very unsure) and industrial safety (very unsure). Respondents who considered that few reforming technologies would ever be commercially capable had expertise in electronics (very unsure), electrolysis (fairly confident) and photovoltaic assisted electrolysis (very confident). Respondents who considered that high temperature and microbial electrolysis would never be commercially capable had expertise in hydrogen separation (fairly confident), metal hydrides (very confident) and electronics (very unsure). Respondents who considered that photo assisted technologies (e.g. photoelectrochemical) would never be commercially capable had expertise in hydrogen separation methods (fairly confident), metal hydrides (very confident), biomass gasification (slightly unsure), catalysis (slightly unsure), electronics (very unsure) and fuel cell materials (very unsure). The respondent who considered that coal and biomass gasification would never be commercially capable had expertise in metal hydrides (very confident).

Round 2 respondents have noted that some of the technologies are already commercially viable; however, local circumstances can affect commercial viability. It was also noted that storage, distribution and end use devices for hydrogen were more significant barriers to hydrogen as an energy vector than commercial production of hydrogen.

Commercialisation Assets

In round 1, respondents were requested to suggest the commercialisation assets related to hydrogen production technologies. In round 2, respondents were requested to rank the commercialisation assets identified in round 1, on a scale from 1 to 14 (where 1 is considered the most significant asset and 14 the least). The mean ranking of all the responses to each commercialisation asset is listed in Table 9.

Table 9 Mean Ranking of Commercialisation Assets (All Respondents)

Sustainability Aspect	Mean Ranking
Carbon Capture Potential	9.32 (lowest ranking)
Low Complexity	9.06
Use of waste / by products	8.87
High purity hydrogen (without significant post processing)	7.97
High volume production	7.61
Low risk	7.33
Easy to scale up	7.21
Zero CO_2 Generation	7.15
Capability (existing or soon)	6.61
Low Capital Cost	6.44
Renewable Feedstock	6.34
Reliable	6.08
Energy Efficient	5.97
Low Production Cost	5.87 (highest ranking)

The mean responses indicate that the most significant commercialisation assets are considered to be low costs, reliability, energy efficiency, use of renewable feedstock and existing or imminent capability.

German and Russian respondents as well as Bioenergy experts and Renewable energy experts perceived capital and production costs as less significant; while National Government respondents and Material experts considered capital costs as less significant.

Dutch and Turkish respondents as well as Safety experts considered reliability to be less significant; while US and Industrial researcher respondents as well as Materials experts and Safety experts considered the use of renewable feedstock to be less significant.

Commercialisation Barriers

In round 1, respondents were requested to suggest the commercialisation barriers related to hydrogen production technologies. In round 2, respondents were requested to rank the commercialisation barriers identified in round 1 on a scale from 1 to 17 (where 1 is considered to be the most significant and 17 the least). The mean ranking of all the responses to each commercialisation asset is listed in Table 10.

Table 10 Mean Ranking of Commercialisation Barriers (All Respondents)

Sustainability Aspect	Mean Ranking
Cost of Oxygen	12.71 (lowest ranking)
Not suitable for urban environment	11.30
Feedstock Inhomogeneity	11.11
Issues with fluctuating power input	10.19
Carbon emissions	10.14
Requires modified atmosphere (e.g. high temperature / low pressure)	10.10
Complex	9.74
Hydrogen output needs further processing	9.13
Feedstock availability	8.66
Needs constant operation	8.66
Unreliable	8.11
Poor energy efficiency	8.10
Difficult to Scale up	7.94
Durability	6.94
Needs development	4.87
High running cost	4.24
High investment cost	3.46 (highest ranking)

The mean responses indicate that the most significant commercialisation barriers are considered to be high costs, the requirement for further development and concerns about durability; however, Transport experts perceived durability to be less significant.

There is some mapping between commercialisation assets and barriers (i.e. high running costs and investment costs are perceived as barriers, conversely low production cost and low capital cost are perceived as assets).

Public Perception

Public Acceptability Barriers

In round 1, respondents were requested to suggest public acceptability barriers which they could foresee for hydrogen production in fuelling stations. In round 2, respondents were requested to rank those barriers on a scale from 1 to 7 (where 1 is considered to be the most significant and 7 the least). The mean ranking of all the responses to each public acceptability barrier is listed in Table 11.

Table 11 Mean Ranking of Public Acceptability Barriers (All Respondents)

Sustainability Aspect	Mean Ranking
None	6.85 (lowest ranking)
Lack of Environmental Concern	4.94
Lack of trust in decision makers	4.70
"not in my backyard" response	4.12
High pressure Storage	4.01
Lock in to Existing Technology	3.44
Unfamiliarity	3.29
Misconceptions about Safety	2.81 (highest ranking)

The mean responses indicate that the most significant public acceptability barriers are considered to be Misconceptions about safety and Unfamiliarity. Chinese, Japanese and Dutch respondents as well as Renewable Energy experts and Storage experts consider unfamiliarity to be less of a problem. Chinese and German respondents perceive high pressure storage to be a more significant barrier.

Public Support for Hydrogen Production

In round 2, respondents were asked the percentage of the population which they believe support, are neutral to, don't support and are unaware of the development of hydrogen technologies. The response is described in Table 12.

Table 12 Population support for and awareness of hydrogen technologies

Population Status	%	Standard Deviation
Support hydrogen technologies	27	22
Neutral about hydrogen technologies	26	17
Don't support hydrogen technologies	15	14
Unaware of hydrogen technologies	32	23

There was a wide range of responses (as indicated by the large standard deviations). The mean responses from the different categories of respondents were generally within one standard deviation of the mean apart from the response from Turkish respondents which exceeded the mean value for the percentage of the population unaware of hydrogen technologies. One US respondent based his response to this question on an informal survey of non-technical people in his local community.

Community Education

In round 2, respondents were asked the percentage of people who are not currently supportive of hydrogen technologies who are likely to be persuaded to support hydrogen technologies by community education. The mean response to this was 48%. The mean responses from the different categories of respondents were generally within one standard deviation of the mean apart from the response by Safety experts which considered that 80% of the currently non-supportive population could be swayed by community education.

Key Factors to Include in Community Education

In round 1, respondents were requested to identify key factors to include in any scheme aimed at community education regarding hydrogen production. In round 2, respondents were requested to rank those factors on a scale from 1 to 5 (where 1 is considered to be the most significant and 5 the least). The mean ranking of all the responses to each education factor is listed in Table 13.

Table 13 Mean Ranking of Community Education Factors (All Respondents)

Sustainability Aspect	Mean Ranking
Reducing Fossil Fuel Availability	3.26 (lowest ranking)
Real cost of hydrogen vs fossil fuel	3.22
Greenhouse Gas Avoidance	3.09
Familiarisation	2.87
Education on Safety of Hydrogen	2.34 (highest ranking)

The mean responses indicate that the most significant public education factor is considered to be the safety of hydrogen. However, Japanese and Dutch respondents considered that the Real cost of hydrogen versus fossil fuel would be a significant education factor; while Indian respondents and Renewable Energy Experts considered Greenhouse gas avoidance as a significant education factor.

Discussion

Many respondents commented that they were unable to give full answers to questions because their knowledge did not embrace all of the technologies under discussion; however, the number of responses received has allowed each question to be analysed despite this.

The information from both rounds of the Delphi survey and the follow on workshop will be discussed together in a future paper.

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