SUPERGEN DoSH$_2$

Delivery of Sustainable Hydrogen

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

Sustainable Hydrogen Workshop Report.

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Contents

Introduction

This report summarises the findings from the stakeholder workshop carried out in March 2012, which was based on responses to two rounds of a Delphi survey on the production of sustainable hydrogen conducted as part of the work of the EPSRC funded SUPERGEN XIV consortium "Delivery of Sustainable Hydrogen" (DoSH$_2$). 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

Although views were sought for the period 2020-2050, the aim of the survey was to inform the future, not to forecast it.

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 the exploration of "Delivery of Sustainable Hydrogen" as many of the technologies are still in the research stage, are not yet well characterised and hence are not included in many current models.

The survey was followed by a UK-based stakeholder workshop which aimed to more fully discuss the following topics over the time period 2020-2050:

- Hydrogen (Energy Vector) Production Volumes
- Sustainable Feedstock and Processes

- Commercial Development

An additional aim was to derive an indication of the likely use of hydrogen production technologies in the period up to 2050 through the discussion arising from the stated topics.

Responses from the Delphi survey were presented to the participants to initiate discussion. The discussion was followed by questions focussed on the topics already stated. A real-time voting system was used to record the responses of the workshop participants. The workshop discussion was also recorded.

Participant Information

Participants were chosen to represent several of the aspects present in hydrogen related activities. These included:

- A - an industry representative familiar with hydrogen production and applications
- B - an industry representative familiar with hydrogen production and storage
- C - an academic familiar with energy policy and technology
- D - an academic familiar with the sustainable production of hydrogen, in particular utilising waste products as a feedstock
- E - an academic familiar with energy materials
- F - an academic with previous industrial experience of hydrogen production who is familiar with hydrogen production from biomass.
- G - a policy maker

Unfortunately, due to unforeseen circumstances, the policy maker was not able to attend on the day.

Hydrogen (Energy Vector) Production Volumes 2020-2050

The future use of Hydrogen as an energy vector should be considered in the context of global energy consumption.

Global Energy Consumption 2020-2050

Figure 1 represents the Delphi Survey respondent view of global final energy consumption. It shows anticipated consumption for 2020 to 2050 as a percentage of a benchmark (2008). Forecasts of 2050 global final energy consumption and primary energy demand were found in a variety of sources [1-6] and extend from 52% to 320% as a percentage compared to 2008 data.

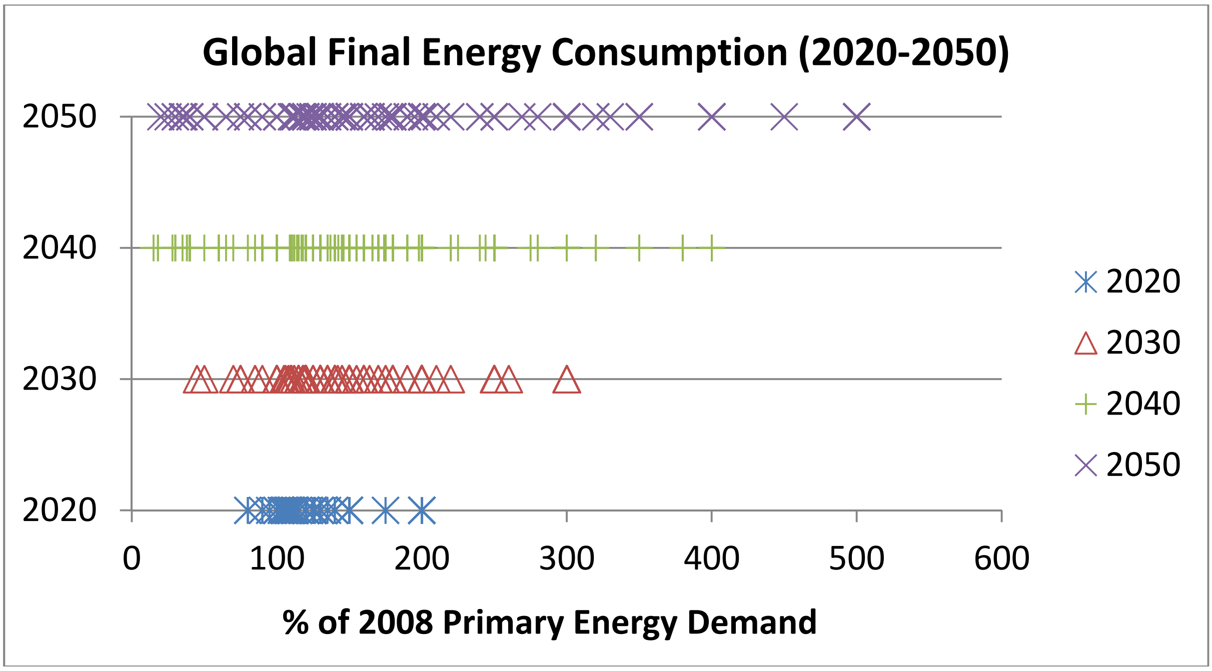

Figure 1 Global final energy consumption (2020-2050): Delphi Survey Response

The workshop participants were asked to predict the global final energy consumption for 2020, 2030, 2040 and 2050. These predictions were made as a percentage of the 2008 global final energy consumption benchmark and took the form of votes in the categories <50%, 50-94%, 95-105%, 106-149%, 150-200%, >200%.

The results of these predictions are illustrated in Figure 2.

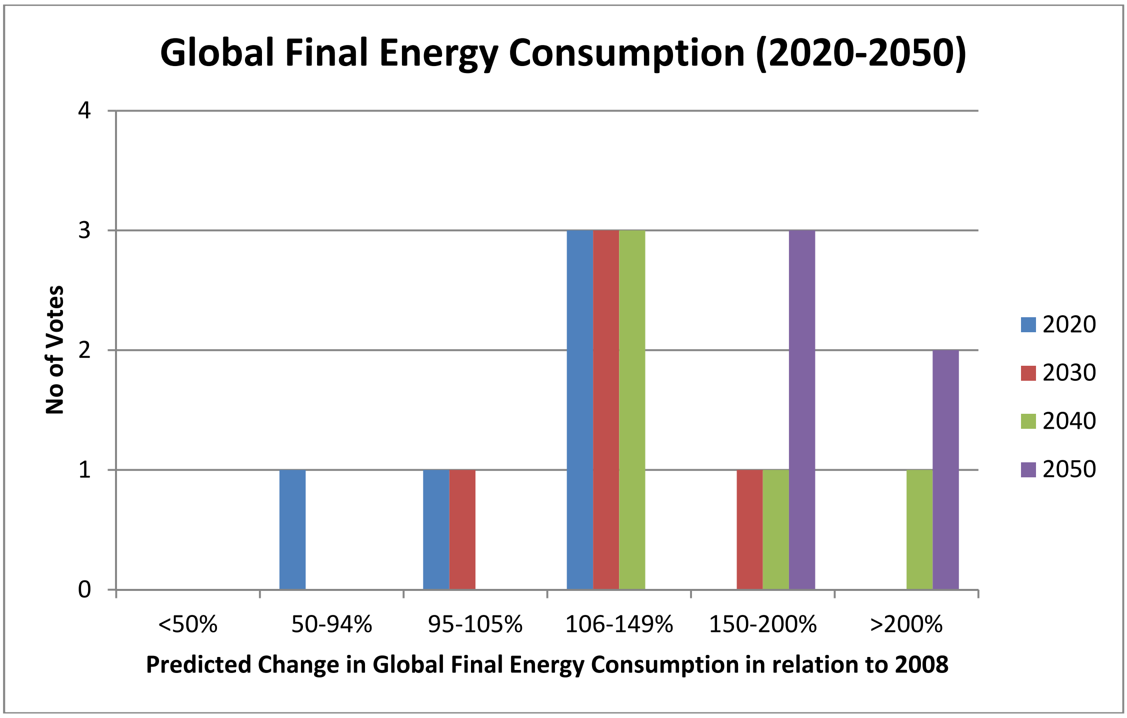

Figure 2 Predicted Global Final Energy Consumption (2020-2050): Workshop Response

This figure indicates that the workshop participants anticipate global final energy consumption to gradually rise until the level for 2050 energy consumption is just over double that of the 2008 consumption figure. This is within the published predictions [1-6].

Hydrogen (Energy Vector) Production Volumes

Hydrogen production as an energy vector – what counts?

During discussion, it was evident that people had different perceptions on what counted as “hydrogen production as an energy vector” rather than “industrial/chemical use of hydrogen”.   For the purpose of discussion of hydrogen (energy vector) production volumes during the workshop:

- hydrogen to refine petroleum feedstock was considered an industrial/chemical use,
- reformer conversion of natural gas to hydrogen for immediate use in a fuel cell was considered an energy vector use.

Hydrogen production as an energy vector – how much?

Figure 3 represents the Delphi Survey respondent view of hydrogen production as an energy vector for 2020 to 2050. The dashed red line indicates 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 [7] (not allowing for any wastage). The solid blue line represents 42.7 million standard tonnes of hydrogen which is equivalent to the total global 2009 hydrogen production [8].

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 1 million to 40 million standard tonnes of hydrogen produced by 2050, indicating a trend of increasing hydrogen use as an energy vector. By 2050 this would 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 global energy consumption.

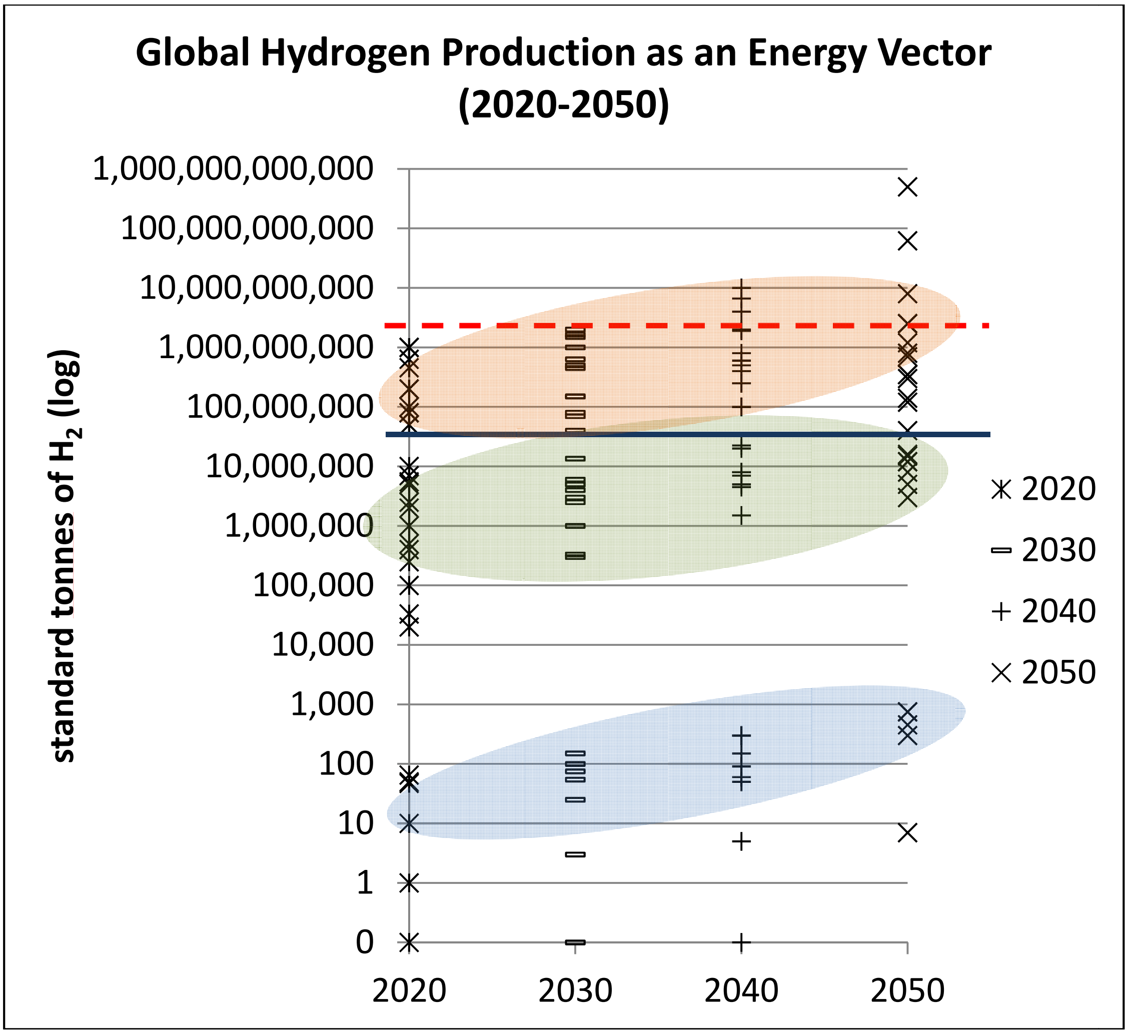

Figure 3 Global hydrogen production as an energy vector (2020-2050): Delphi Survey Response

Figure 4 represents hydrogen production as an energy vector for 2020 to 2050 when considered as a percentage of global final energy consumption for 2008.

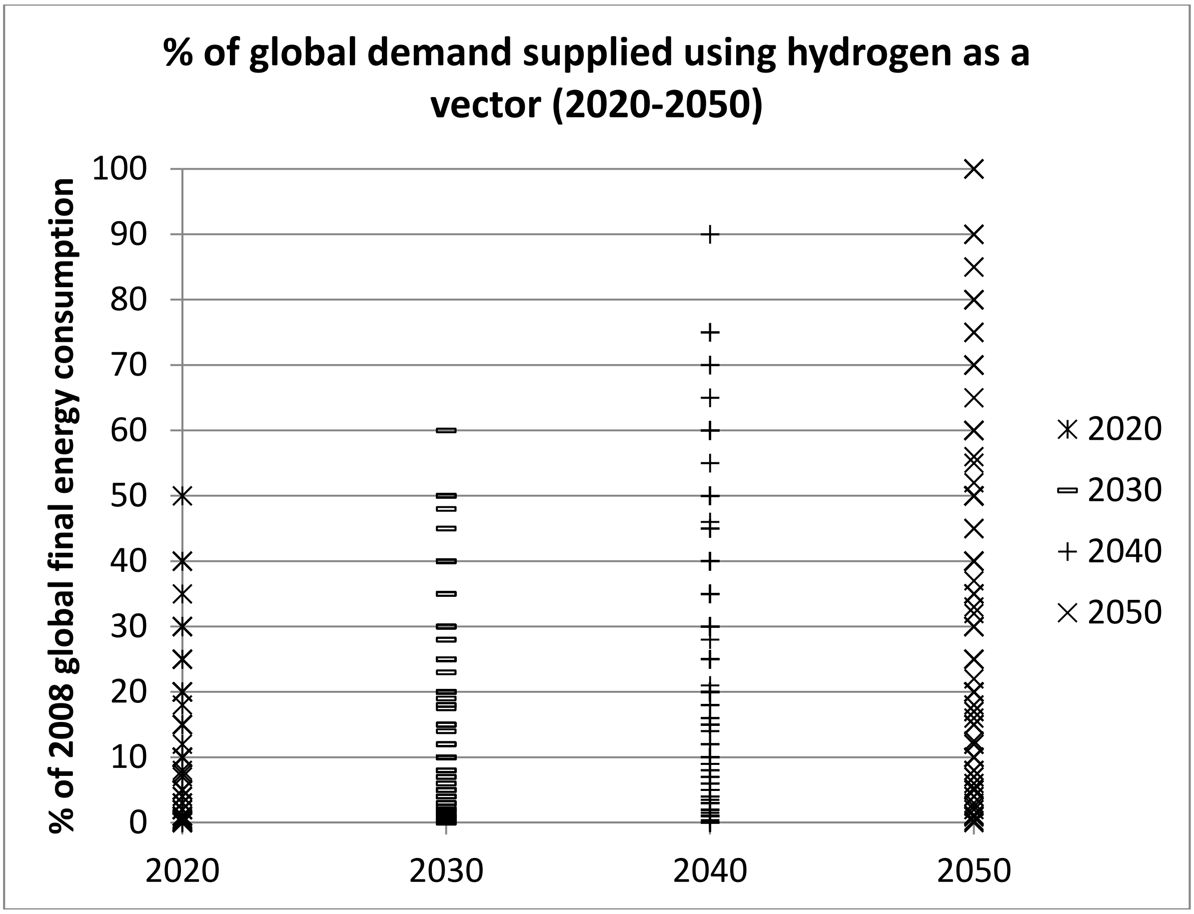

Figure 4 Percentage of global final energy demand supplied using hydrogen as a vector (2020-2050): Delphi Survey Response

The workshop participants were asked to predict the global hydrogen production as an energy vector for 2020 to 2050. These predictions were made as a percentage of 2008 global energy consumption and took the form of votes in the categories <65%, 66-135%, 136-200%, 201-300%, 301-450%, 450-600%, >600%.

These bands were very wide to allow for the wide range of predictions for future global energy demand depicted in Figure 1 and the expectation of some respondents that hydrogen could meet 100% of global energy demand by 2050 as illustrated in Figure 4. The result of the workshop participants' predictions is thus illustrated in Figure 5.

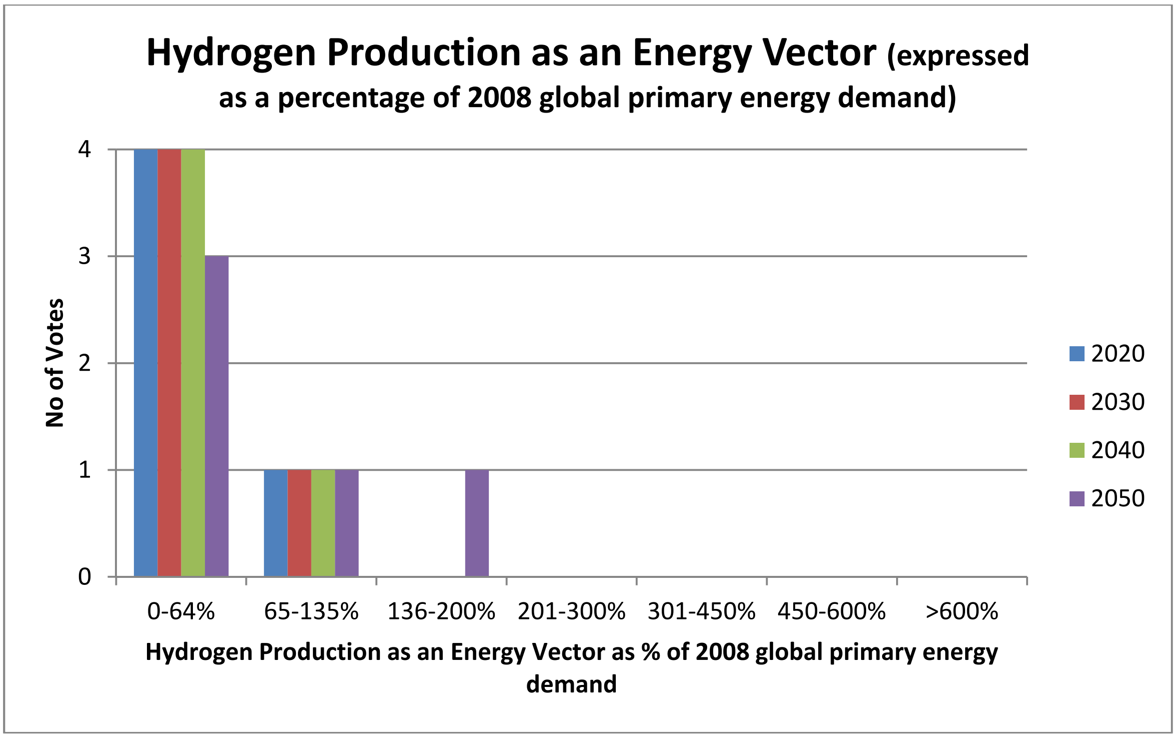

Figure 5 Predicted hydrogen production as an energy vector (2020-2050) as a percentage of 2008 global final energy consumption: Workshop Response

Respondent F noted that the majority of projects which will result in hydrogen generation by 2020 are already being thought about. From this perspective, he believes that the energy vector hydrogen generation in 2020 will be relatively modest, but will be followed by more significant growth. Respondent C expressed optimism for the prospects of hydrogen in the long term, but didn't anticipate more than 2.9 billion tonnes by 2050. Respondent D was in agreement, but felt that the competing applications for hydrogen (e.g. in fertilizer production) must be accounted for when considering the amount of hydrogen which would be available as an energy vector in the future.

Respondents noted that safety, lack of ownership and distribution were barriers to hydrogen becoming a more significant energy vector.

Safety

There were two views on safety, with participant D concerned that progress on safety in the utilisation of hydrogen was not keeping pace with progress in other aspects of hydrogen research and seeing this as a key area to convincing the public to use hydrogen. Whereas respondent C was happy that there was sufficient work on safety standards but had some concerns that the development of codes and standards was delaying deployment.

Lack of Ownership

Participant B was concerned that there was a lack of ownership (in a metaphorical sense rather than a financial one) to hydrogen amongst the public, industry and government, with nobody pushing it. To him this leaves a situation where unless people fall in love with fuel cell vehicles, it would take a significant event (e.g. war in the Middle East or oil prices escalating rapidly) to precipitate some nations to take the lead in subsidising vehicle and infrastructure costs to facilitate the transition. He felt it was unlikely that normal forces could bring hydrogen into a major position within the energy sector in a short time frame. Participant C was concerned that in such an event, the demand for transport fuel could push people to base hydrogen production from coal, but added that hydrogen technology had made such progress in the last decade that he considered that the transition to hydrogen as an energy vector now depended on being able to compete in the market place, adding that for any market solution that hydrogen provides, there are other solutions. He also considered that any significant use of hydrogen as an energy vector by 2050 would require strong links between Government and Industry, this type of industrial policy is more evident in South Korea and Japan than in the UK.

Distribution
Participant F considered that many hydrogen production methods (particularly from biomass) were likely to produce mixtures of bio hydrogen and bio methane, which could be processed to enable the hydrogen fractions to be separated and distributed; however, an alternative would be to feed the mixture to a natural gas grid, with customers who require hydrogen using on-site reformers or electrolysers.

Sustainability of Hydrogen

The responses to a context setting question in round 2 indicated that the majority of Delphi respondents rated environmental factors as more significant than economic or social factors when considering sustainability.

The sustainability of hydrogen production is closely linked to the feedstock used. In round 1, respondents were requested to specify the 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 1.

Table 1 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)

Participant F was concerned that microbes had been considered separately from biomass in this question, as he considered them either as wet biomass or as a process for deriving hydrogen from biomass.

Participant D was also concerned that alcohol had been considered separately from biomass, It was acknowledged that the lower sustainability ranking for alcohol considered separately from biomass may be due to efficiency issues related to converting biomass to alcohol then converting the alcohol to hydrogen rather than making a direct conversion.

The difference in sustainability ranking between nuclear-based electricity and nuclear-based heat was discussed. One possible explanation was considered to be related to the heat availability in the types of nuclear plant which will be available in the future (Participant E); another suggestion was the perceived requirement for hydrogen production to take place in close proximity to the nuclear plants.

Concern was expressed that the sustainability rankings were based on people's perceptions rather than on actual analysis of sustainability.

The workshop participants were asked to choose their first, second and third most sustainable hydrogen feedstock groups from the options of biomass, electricity (nuclear), electricity (renewable), fossil fuel (CCS) and solar (not electricity). One participant abstained from this process. The responses of the other participants are presented in Figure 6.

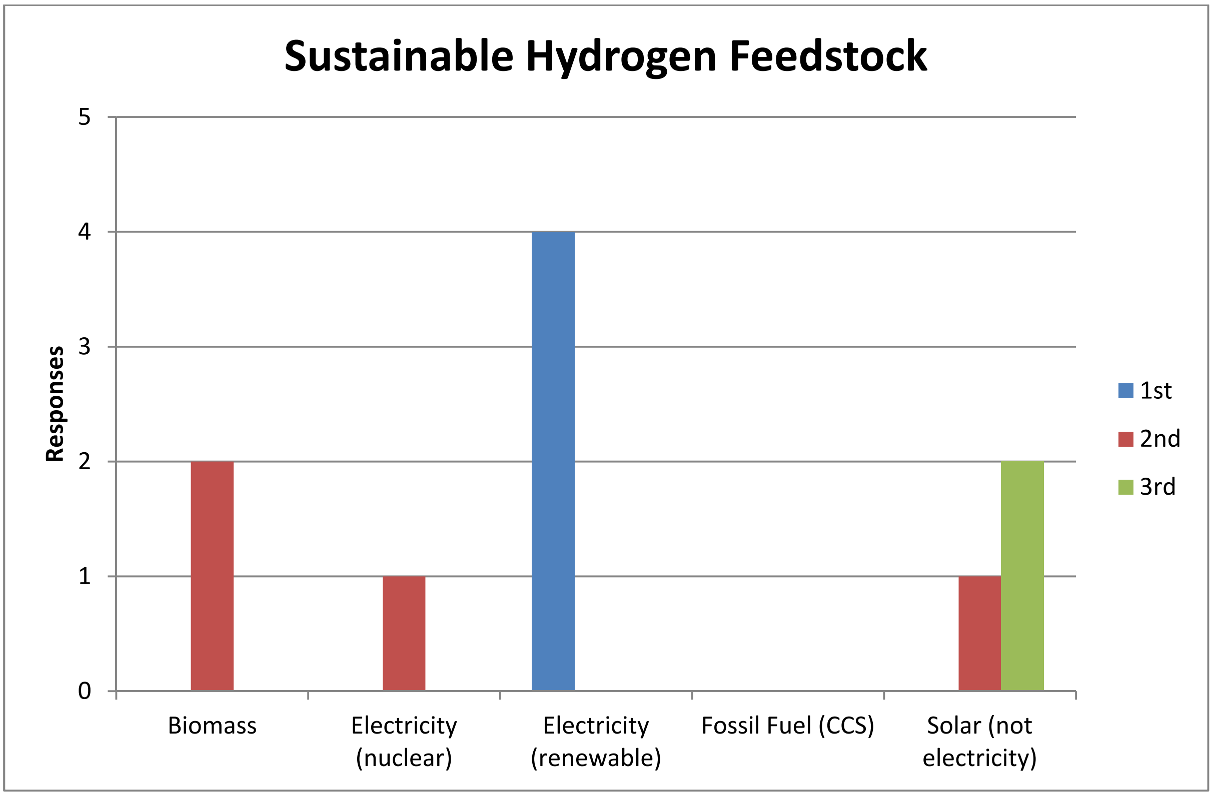

Figure 6 Sustainability ranking of Hydrogen Feedstock

Participant B qualified the rationale behind his choices as "is it expandable as an option globally … does it liberate CO_2 anywhere? … does it use finite fossil fuel or not?"

All participants considered renewable electricity as their most sustainable hydrogen feedstock. Participant C qualified this with the assumption that such electricity was not being displaced from more appropriate uses where it would result in lower carbon emissions.

The hydrogen feedstock ranking second in terms of sustainability had a broader response including biomass, nuclear generated electricity and solar (not electricity). Participant C selected solar (not electricity) and qualified his choice with the assumption that such use of solar energy was not being displaced from more appropriate uses where it would result in lower carbon emissions.

Only two participants felt able to select a third most sustainable feedstock, in both cases this was solar (not electricity). A comment which appeared to be indicative of the collective view at this point was that any choice would simply be selecting the "least bad of the rest".

A discussion about the sustainability of hydrogen production processes reinforced the view that the feedstock was the most significant factor when considering the environmental aspect of sustainability, although the maturity of the process would have an impact on the economic aspect of sustainability and while the social aspect of sustainability remained unknown. Aspects which could affect the environmental aspect of sustainability relating to hydrogen production processes would be:

- the requirement for external electricity or fuel to provide heat required in the process
- the capability of the process to make use of waste as a feedstock
- the proportion of the output which is hydrogen and the amount of post processing required to get usable hydrogen.

Commercialisation of the Technology

The initial discussion[1] considered factors which would affect the commercialisation of all hydrogen production (i.e. intrinsic to the market environment rather than to individual hydrogen producing technologies). These include:

- oil and gas price - as the fuel for incumbent technologies, the cost of these commodities is considered to have a significant effect on the potential utilisation of hydrogen (F)
- taxation rate on fuel – particularly if there was a lower rate of tax for hydrogen compared to other fuels (D), or a tax in relation to the carbon footprint of all fuels (B)
- energy subsidies (A)
- consumer pull – which is seen as mainly being influenced by cost, but could be influenced by other factors as illustrated by the use of hydrogen fork lift trucks in preference to battery fork lift trucks (B)
- the existing infrastructure for manufacturing and distributing hydrogen for the chemical industries which would allow hydrogen to be produced as an energy vector as an incremental step, rather than requiring a complete brand new infrastructure (F)
- future decarbonisation targets with an associated impact on the energy system (potentially a significant increase in renewable energy generation) (C)
- government commitment (or lack of) to hydrogen in a future energy system, perhaps as part of a policy to control the future carbon footprint of fuel by incentivising energy generation

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[1] A - an industry representative familiar with hydrogen production and applications
B - an industry representative familiar with hydrogen production and storage
C - an academic familiar with energy policy and technology
D - an academic familiar with the sustainable production of hydrogen, in particular utilising waste products as a feedstock
E - an academic familiar with energy materials
F - an academic with previous industrial experience of hydrogen production who is familiar with hydrogen production from biomass.
G - a policy maker

techniques (including some hydrogen production techniques) which will contribute to a low carbon footprint (B), this is a policy which is only just being developed for electricity with a cap on the allowable carbon emissions for new electricity generation plant (C)

- events like the Fukushima disaster which has created a greater impetus for the deployment of PEM fuel cell CHP in Japan, which in turn has led to cost reduction in the technology which is presumed to increase the prospects of hydrogen commercialisation in the country (C)
- the launch of fuel cell vehicles which many major automotive manufacturers have committed to (B)
- UK specific
    - the method of distributing renewable energy resources in the UK, particularly in relation to the renewable electricity potential of Scotland in relation to its electricity demand, leading to the possibility of the surplus being exported as electricity or used to generate hydrogen for transport fuel (B).
    - the potential future market for hydrogen as an energy vector driving investment for new hydrogen production (in the UK) which would not be considered economic with the current decline in UK manufacturing (A)
- Korea specific
    - Natural gas or hydrogen feedstock which supplies a fuel cell receives an uplift of approximately 23 cents which is driving the indigenous fuel cell industry as well as imports. A critical factor in this example is that Korea has the capability to produce more hydrogen than it currently has demand for.
- Developing country specific
    - The energy route which countries like China and India take as they develop will have significant impact on other countries.

Technology-Specific Commercialisation

In round 1, respondents were requested to predict the year in which hydrogen production technologies would be commercially capable, where commercially capable has been defined as a saleable product, possibly in a niche market. The results from round 1 were presented in round 2 and the respondents again requested to predict the year that each technology would be commercially capable; however, electrolysis (low temperature), steam reforming and dark fermentation were omitted from round 2 as the results from round 1 were clear. The mean predicted year of commercial capability for each technology is illustrated in Table 2 along with the number of respondents who stated that the technology would never be commercially capable. It should be noted that the 136 respondents answered the question in round 2, so although the “never” respondents are a significant response, they are not a majority one.

Table 2 Mean Predicted Year of Commercial Capability (Delphi Round 1 & 2 responses)

Technology	Predicted Year of Commercial Capability	
	Mean	Never
Photolytic (microbial)	2036	15
Photosynthetic (bacterial)	2036	16
Photolysis	2035	13
Photoelectrochemical	2034	10
Electrolysis (Microbial)	2033	16
Plasma Reforming	2032	12
Thermochemical Cycles	2030	9
Sorbent Enhanced Reforming	2029	10
Membrane Reforming	2028	6
Dark Fermentation	2027*	
Bioderived Liquid Reforming	2026	10
Electrolysis (High Temperature)	2025	8
Thermocatalytic Cracking	2024	6
Pyrolysis	2023	8
Biomethane Reforming	2022	9
Gasification (Biomass)	2021	6
Partial Oxidation	2020	7
Autothermal Reforming	2018	7
Gasification (Coal)	2018	5
Steam Reforming	Existing*	
Electrolysis (Low Temperature)	Existing*	

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

There was concern about the number of responses indicating that technologies would never be commercially capable, even though examples indicating the opposite could be identified, particularly for coal gasification and partial oxidation plants. This issue can be related to the specialist nature of many of the respondents with relatively few people having an overview of hydrogen developments as a whole.

The workshop participants were asked to predict the date of commercial capability for hydrogen production technologies. The response is illustrated in Table 3.

Table 3 Mean Predicted Year of Commercial Capability (Workshop responses)

Technology	Predicted Year of Commercial Capability		
	Mean	**Never**	**Abstentions**
Photolytic (microbial)	2040		5
Photosynthetic (bacterial)	2040		5
Photolysis	2035		3
Thermochemical Cycles	2035	2	2
Photoelectrochemical	2033		2
Electrolysis (Microbial)	2031		5
Dark Fermentation	2027		4
Membrane Reforming	2026		2
Electrolysis (High Temperature)	2026		1
Thermocatalytic Cracking	2025	1	4
Sorbent Enhanced Reforming	2024		4
Pyrolysis	2024	1	3
Bioderived Liquid Reforming	2023		3
Plasma Reforming	2016		3
Gasification (Biomass)	2016		1
Autothermal Reforming	2014		2
Biomethane Reforming	2012		1
Partial Oxidation	Existing		2
Gasification (Coal)	Existing		1
Steam Reforming	Existing		
Electrolysis (Low Temperature)	Existing		

It should be noted that there were a large number of abstentions for some of the technologies explored in this exercise. In particular for Photolytic (microbial), Photosynthetic (bacterial) and Electrolysis (microbial) only one respondent felt able to predict a year of commercial capability. For Dark Fermentation, Thermocatalytic Cracking and Sorbent Enhanced Reforming two respondents gave predictions and three respondents gave predictions for Photolysis, Pyrolysis, Bioderived Liquid Reforming and Plasma Reforming. For all other technologies explored more than half of the workshop panel were able to give predictions.

Compared to the Delphi survey, the major differences expressed by the workshop participants were:

- Coal gasification and partial oxidation are known to be existing commercial technologies (as opposed to predicted year of commercial capability being 2018 with 5 to 7 people stating “never”)
- Autothermal reforming and biomethane reforming are expected to be commercially capable in the very near future, although answers ranged from “already commercially capable” to 2021.
- Biomass gasification, is expected to be commercially capable in 2016, rather than in 2022
- Plasma reforming is expected to be commercially capable in 2016, rather than in 2029
- Sorbent enhanced reforming is expected to be commercially capable in 2024, rather than in 2028
- Thermochemical cycles is expected to be commercially capable in 2035, rather than in 2030; however, two participants believed that this technology would never be commercially capable.

- Photolytic (microbial) and Photosynthetic (bacterial) are expected to be commercially capable in 2040, rather than in 2034; however, there was only one response for these technologies.

Future Use of Hydrogen Production Technologies

The respondents were asked to indicate the hydrogen production technologies and feedstock which they considered were likely to be used in the decades ending in the year 2020, 2030, 2040 and 2050. Four respondents also indicated the proportion of the hydrogen likely to be generated by specific technologies in each decade. This information is illustrated in Figures 7a and 7b.

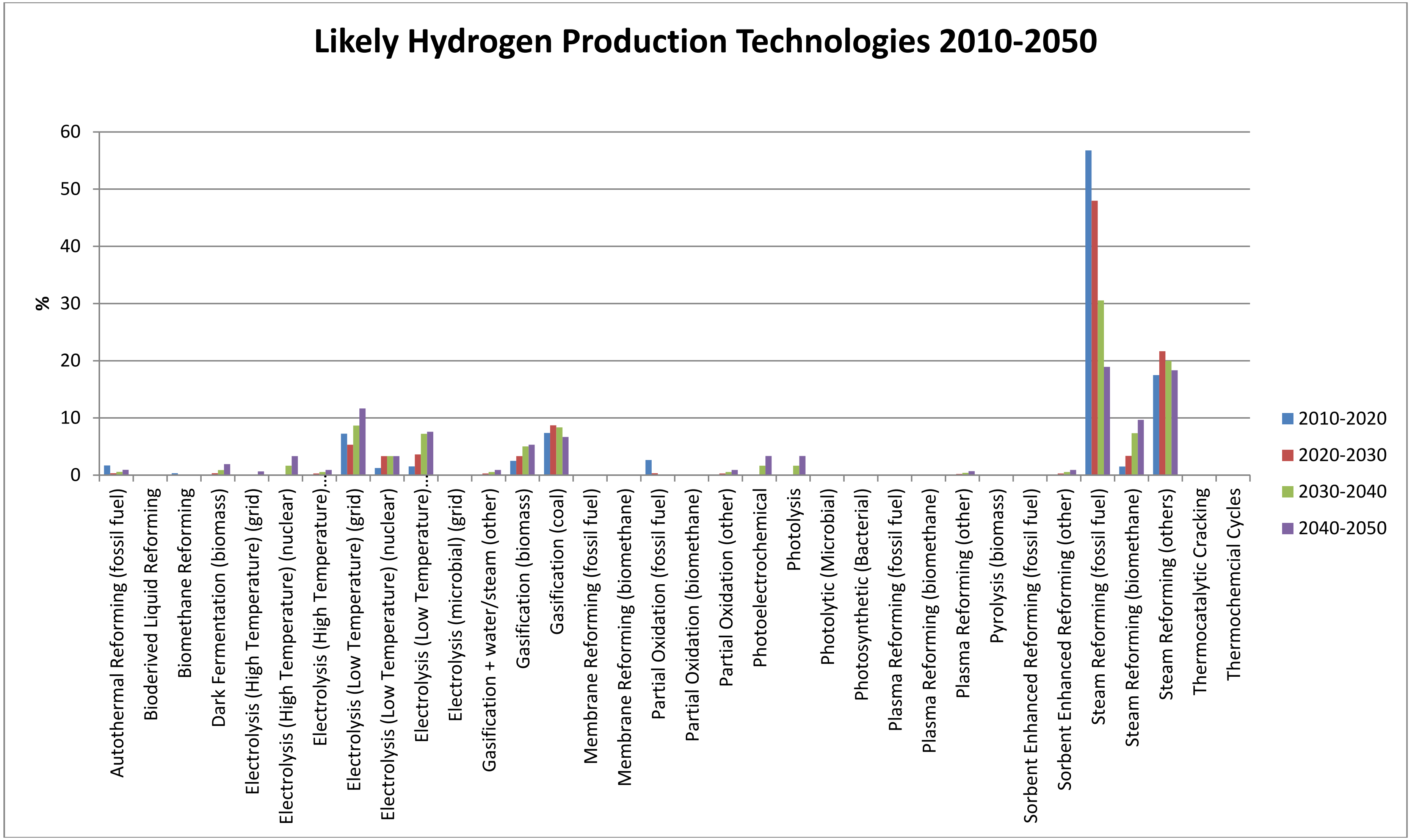

Figure 7a Likely hydrogen production technologies (2010 - 2050)

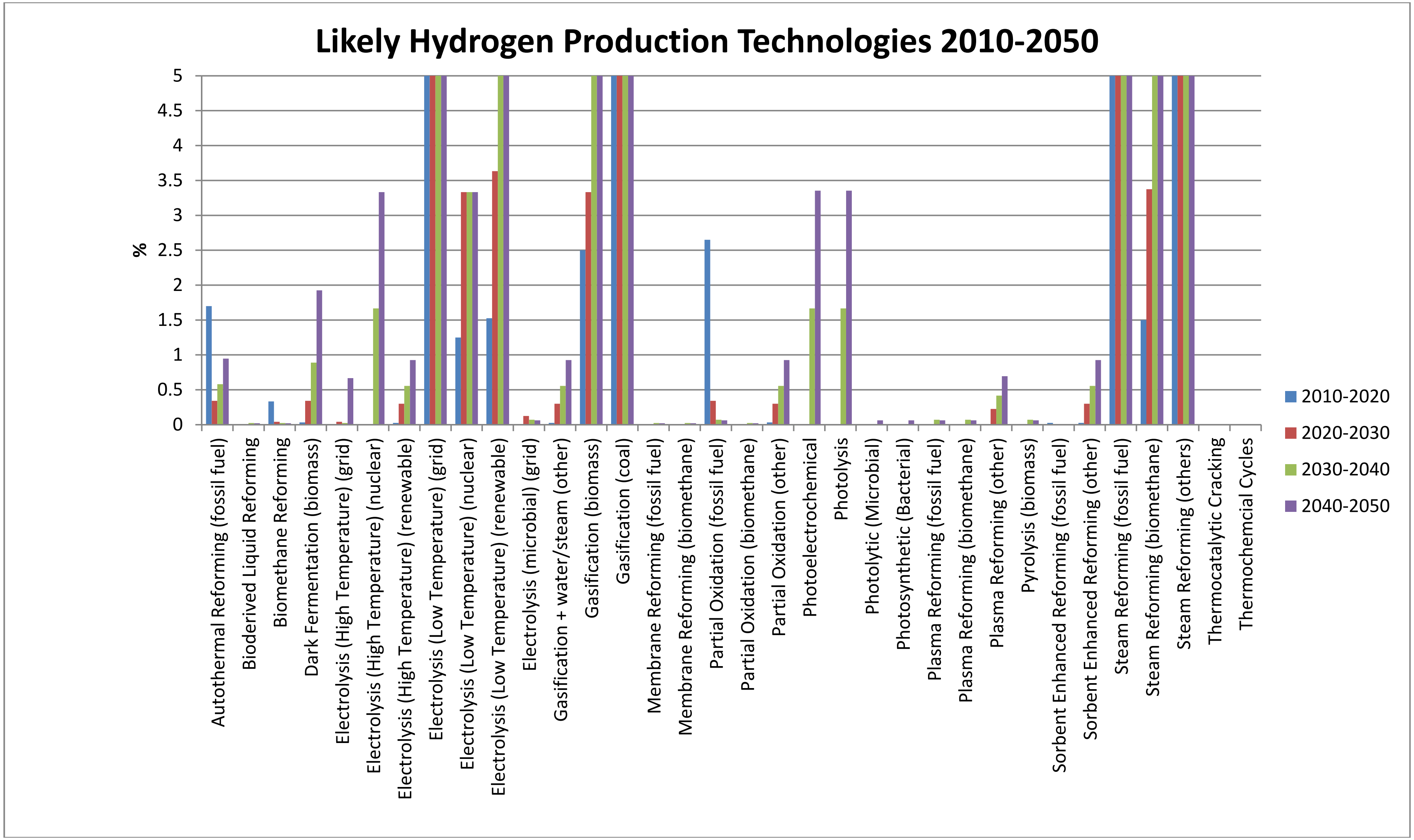

Figure 7b Likely hydrogen production technologies (2010 - 2050): detail of low use technologies

The participants indicate that steam reforming using fossil fuel and feedstocks other than biomethane are considered to be the major current sources of hydrogen. Reliance on steam reforming using fossil fuel is likely to decrease in future decades while steam reforming using biomethane is likely to increase. Gasification using coal is likely to remain stable over the time period considered, while gasification using biomass is likely to increase.

Over the period, low temperature electrolysis supplied from the electric grid and from renewable sources, is expected to increase. Low temperature electrolysis supplied from nuclear is expected to increase from 2020 to 2030, but then remain stable.

Steam reforming, gasification and low temperature electrolysis are expected to supply approximately 95% of the hydrogen required in 2010-2020. This value is expected to fall to 82% by 2040-2050. An increased number of technologies are expected to generate the remaining hydrogen required by 2050. These include (in decreasing order) photoelectrochemical (3.3%), photolysis (3.3%), high temperature electrolysis from nuclear (3.3%), dark fermentation from biomass (1.9%), autothermal reforming (0.9%), high temperature electrolysis from renewables (0.9%), partial oxidation (0.9%), sorbent enhanced reforming (0.9%), plasma reforming (0.7%) and high temperature electrolysis from the grid (0.7%). Other technologies which are expected to contribute less than 0.1% each are biodervied liquid reforming, biomethane reforming, microbial electrolysis, membrane reforming, partial oxidation from fossil fuel or biomethane, photolytic (microbial), photosynthetic (bacterial) and pyrolysis from biomass. Thermocatalytic cracking and thermochemical cycles are not expected to contribute to hydrogen production by 2050.

Summary

Information from two rounds of a Delphi survey on sustainable production of hydrogen was presented to appropriate industrial and academic experts in a workshop to discuss hydrogen production volumes, sustainable feedstock and processes and commercial development in the period up to 2050.

Hydrogen production volumes as an energy vector were considered within the context of future global energy consumption. Workshop participants expect global energy consumption to gradually rise until the level for 2050 is just over double that of the 2008 consumption figure, this is within the expectations of published predictions. Workshop participants considered hydrogen production volumes as an energy vector could rise gradually by 2020, then more sharply until 2050 hydrogen production could meet somewhere between 0% and 200% of the 2008 benchmark figure for global energy consumption. This range illustrates the uncertainties affecting future hydrogen use as an energy vector including competing applications for hydrogen and the lack of commitment the public and government have for hydrogen development. The required strong links between Government and industry for future hydrogen development are considered to be more evident in South Korea and Japan than in the UK.

The sustainability of hydrogen production was considered to have a strong link to the feedstock used. The workshop participants clearly prioritised the use of renewable electricity as a feedstock for sustainable hydrogen, with strong support for biomass and direct solar conversion technologies as well as the use of nuclear generated electricity. One participant qualified the rationale behind his choices as “is it expandable as an option globally … does it liberate CO_2 anywhere? … does it use finite fossil fuel or not?” Concern was expressed over the interpretation of “sustainable”, these concerns are reinforced by results from the Delphi survey which indicate that many respondents prioritise the environmental aspects of sustainability over the social and economic aspects.

Discussion on commercial development was focussed on factors which would affect all hydrogen production (i.e. intrinsic to the market environment rather than individual hydrogen technologies). These included the costs of oil and gas, taxation on fuel, future decarbonisation targets, government commitment, consumer pull, existing infrastructure for hydrogen in the chemical industries, launch of fuel cell vehicles and major events like the Fukushima.

The information from this workshop will be considered alongside the information from both rounds of the Delphi survey in a future paper.

Acknowledgements

The author gratefully acknowledges the assistance provided by Malcolm Eames and Nick Hacking.

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