SUPERGEN HDelivery

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

Sustainable Hydrogen Delphi Survey Round 1 – Participant Report.

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Introduction

This is a summary of the data generated from Round 1 of the "Sustainable Hydrogen Delphi Survey".

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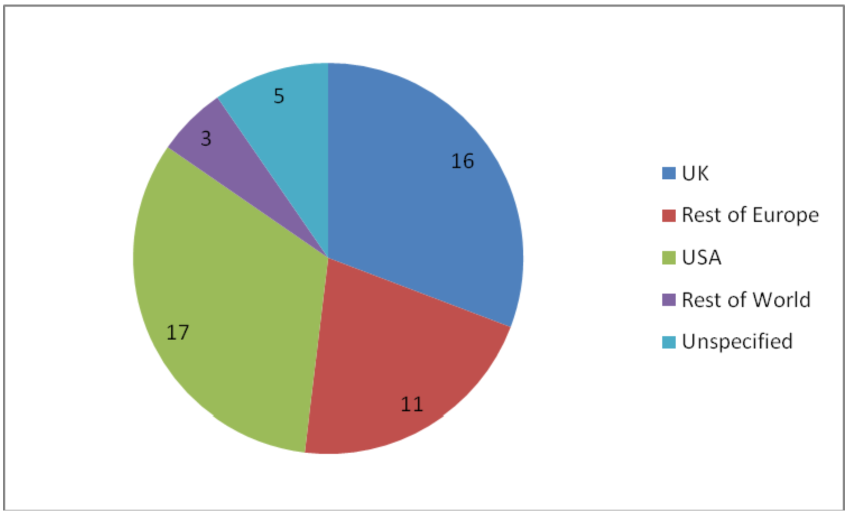
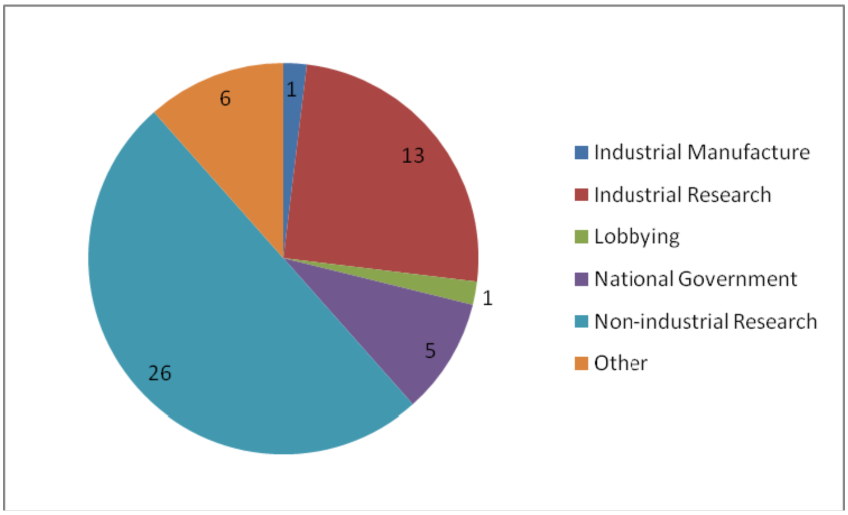
Participant Information

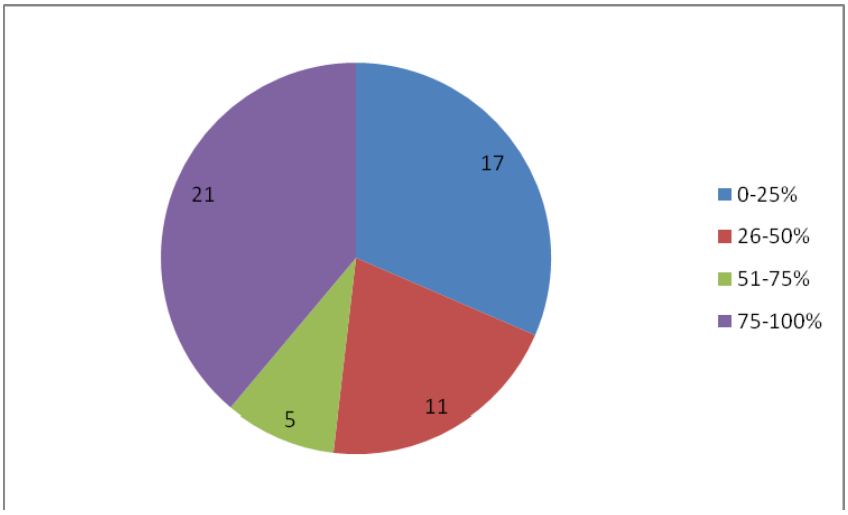
Q1 – Please state which geographical region or country you are primarily considering when responding to these questions



Q2 – Please select your main job function:

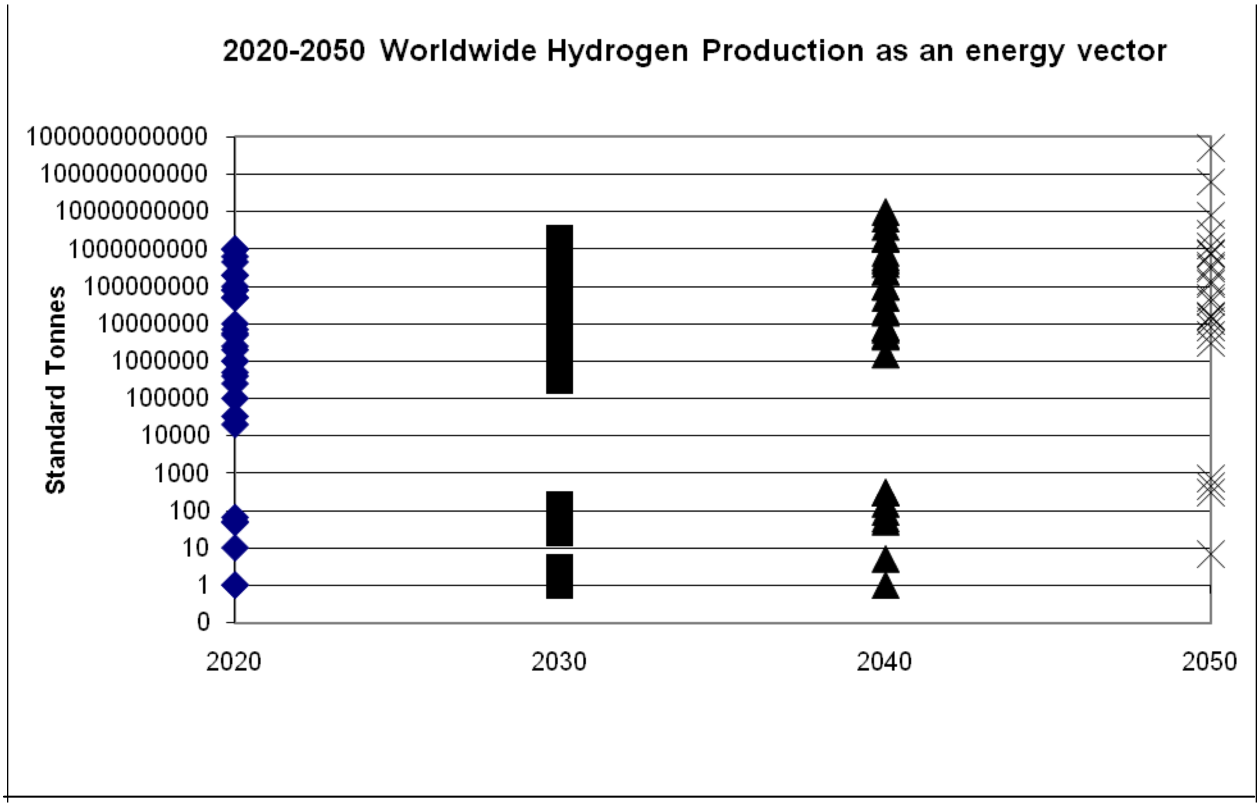


Q3 – What percentage of your job is involved primarily with hydrogen?



Hydrogen Production

Q4 – Predict the worldwide hydrogen production used as an energy vector (standard tonnes) for 2020 to 2050:

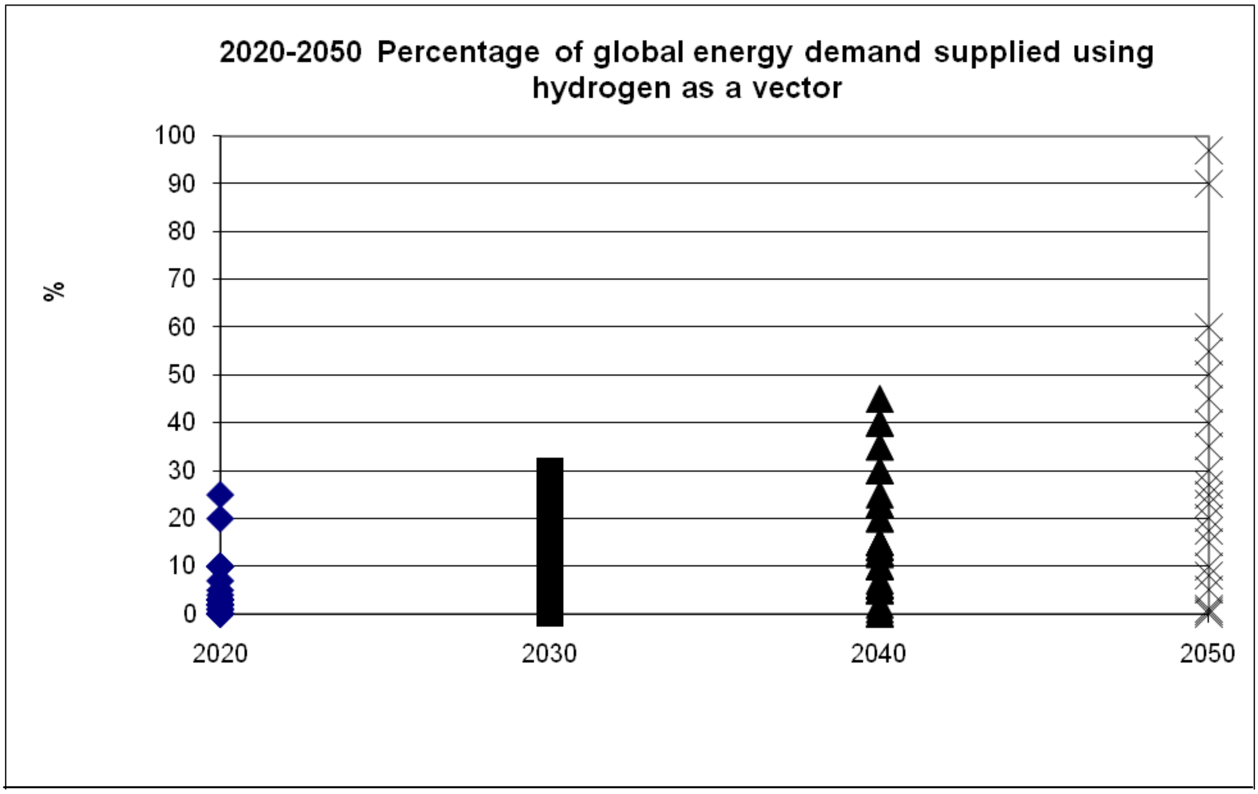


The median response indicates that the worldwide hydrogen production as an energy vector will steadily rise from 2.5 million standard tonnes in 2020 to 50 million standard tonnes in 2050. However, the chart above shows that a significant number of people don't expect more than 1000 standard tonnes of hydrogen to be available as an energy vector by 2050.

This question will be explored further in round 2 of the survey.

Q5 –The 2008 global final energy consumption was 8 428 Million tonnes of oil equivalent (Mtoe)*, this is equivalent to 2 922 million standard tonnes+ of hydrogen. What percentage of global energy requirement do you think hydrogen could be used to deliver in the time periods:

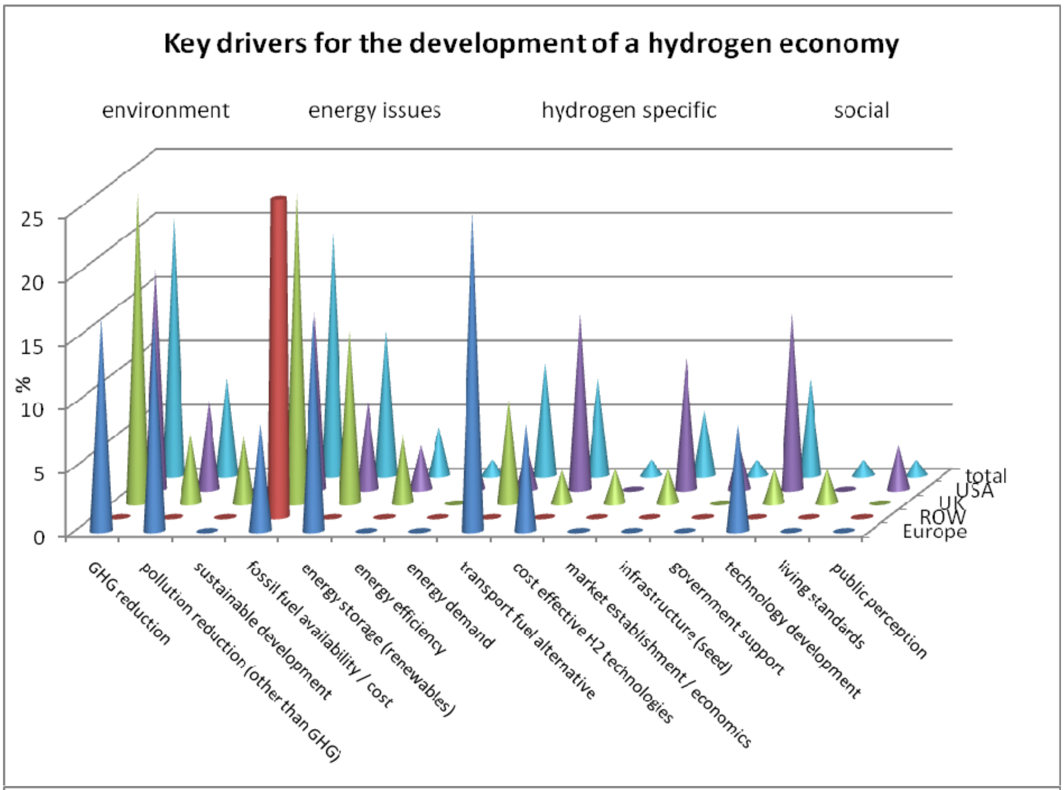
* Data from IEA (2010). Key World Energy Statistics
+ this is the same as 2.922 trillion gallons of gasoline equivalent (gge), 32.7 trillion cubic meters or 1 156 trillion cubic feet of hydrogen

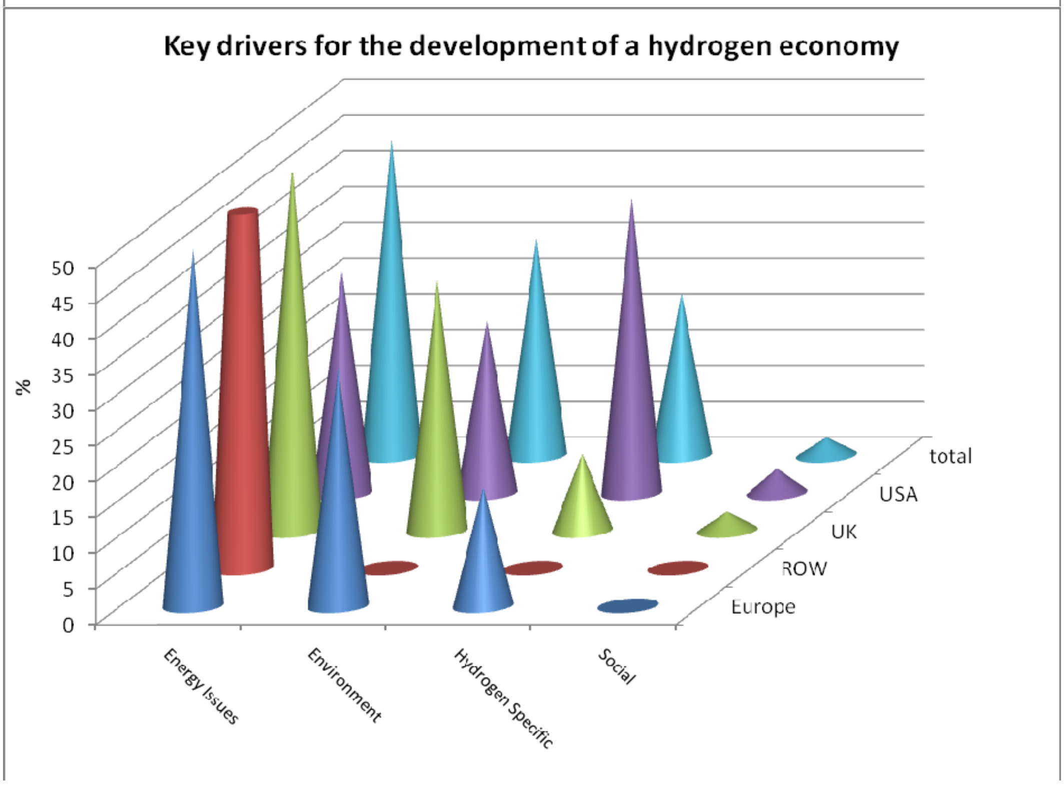


The median response indicates that the percentage of energy demand met using hydrogen as a vector would rise from 2% in 2020 to 20% in 2050.

This question will be explored further in round 2 of the survey.

Q6 – What do you consider to be the key drivers for the development of a hydrogen economy?

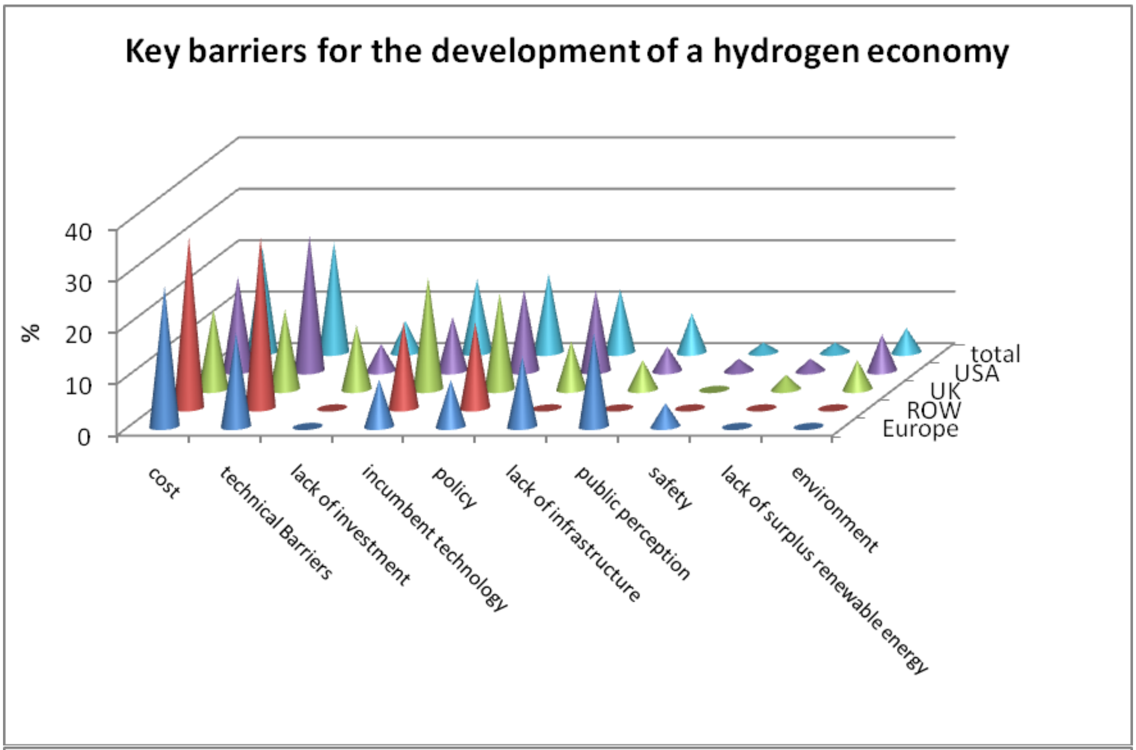


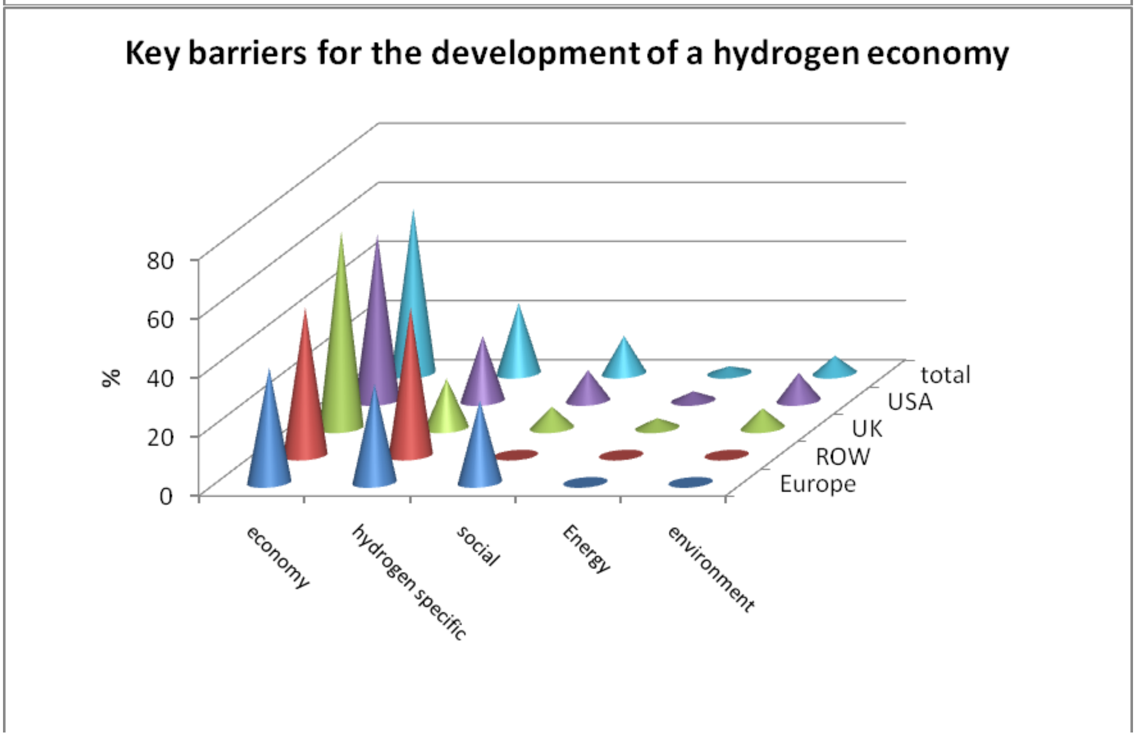


The most frequently cited drivers for the development of a hydrogen economy related to concerns about future fossil fuel availability and cost, the requirement to reduce greenhouse gas emissions and other pollutants, the requirement for alternative transport fuels and the requirement for storage of electricity generated from renewable technologies along with increased energy efficiency. This will be assisted by the development hydrogen technologies, their increased cost effectiveness and the establishment of seed infrastructure.

This question will be explored further in round 2 of the survey.

Q7 – What do you consider to be the key barriers slowing or preventing the development of a hydrogen economy? Bullet points or text acceptable in answer

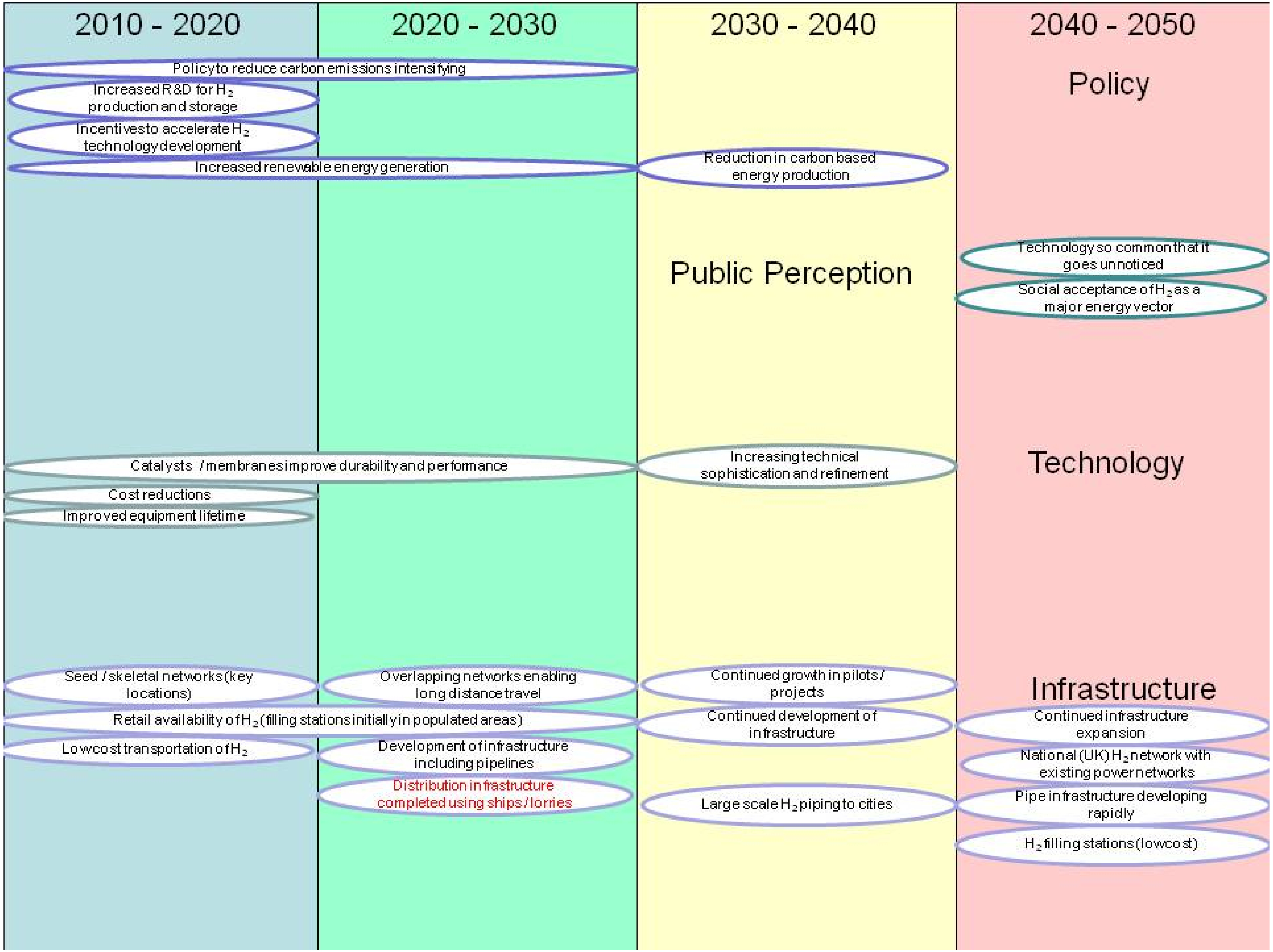


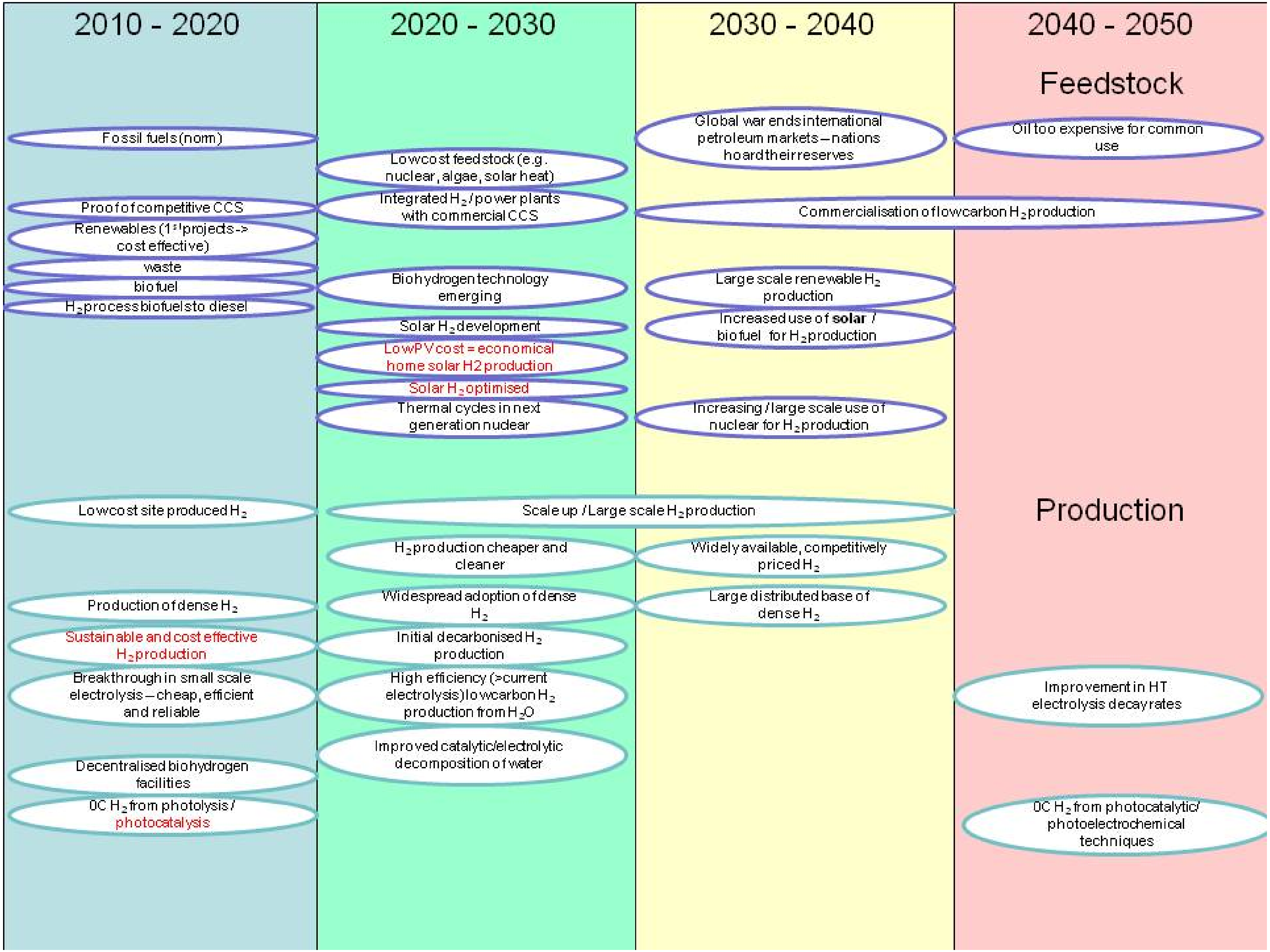


The most frequently cited barriers for the development of a hydrogen economy related to the cost and technical barriers of implementing the new technology as well as the existence of incumbent technology. It was considered that policy, lack of infrastructure, lack of investment and public perception were also significant barriers.

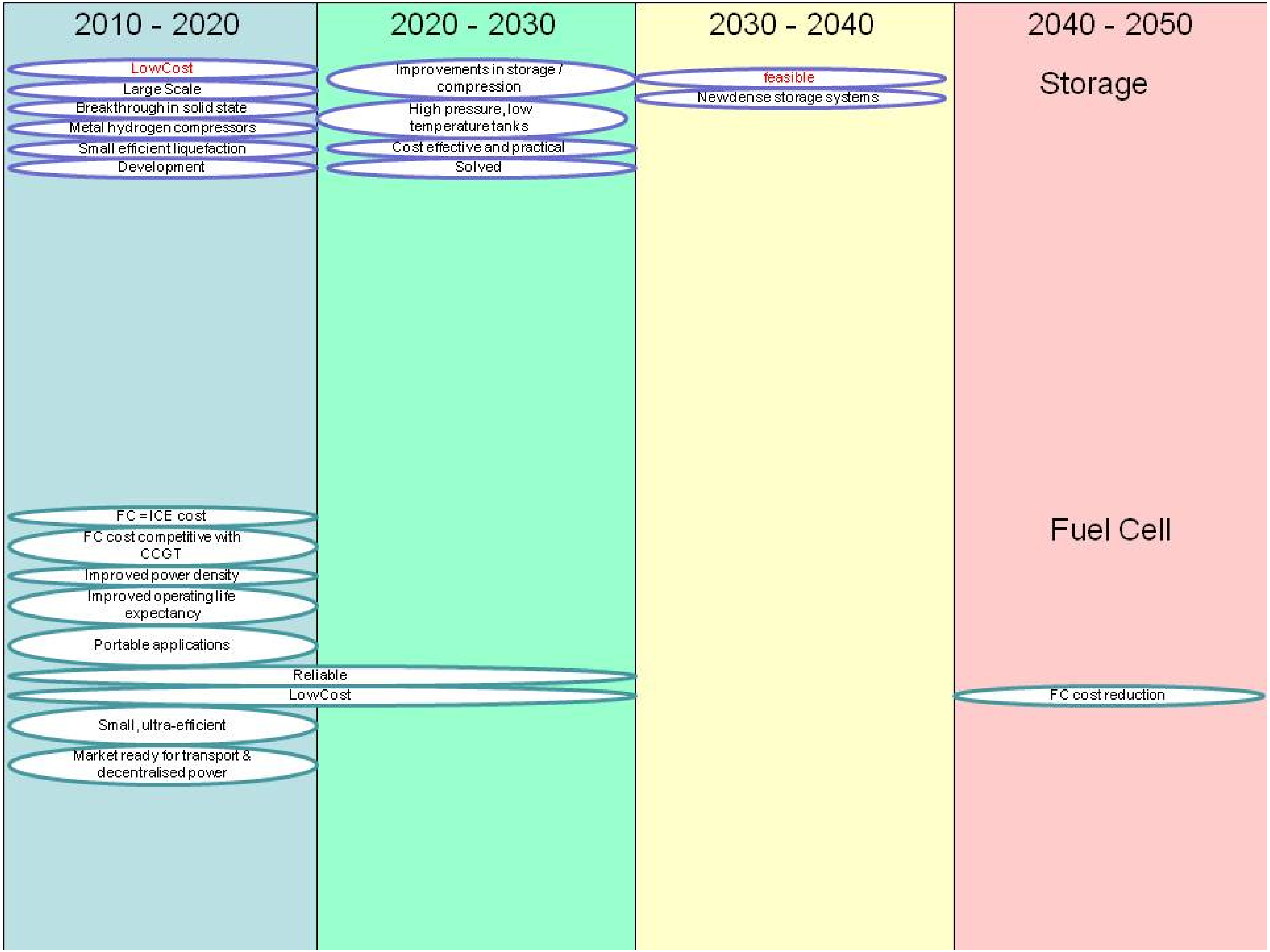
This question will be explored further in round 2 of the survey.

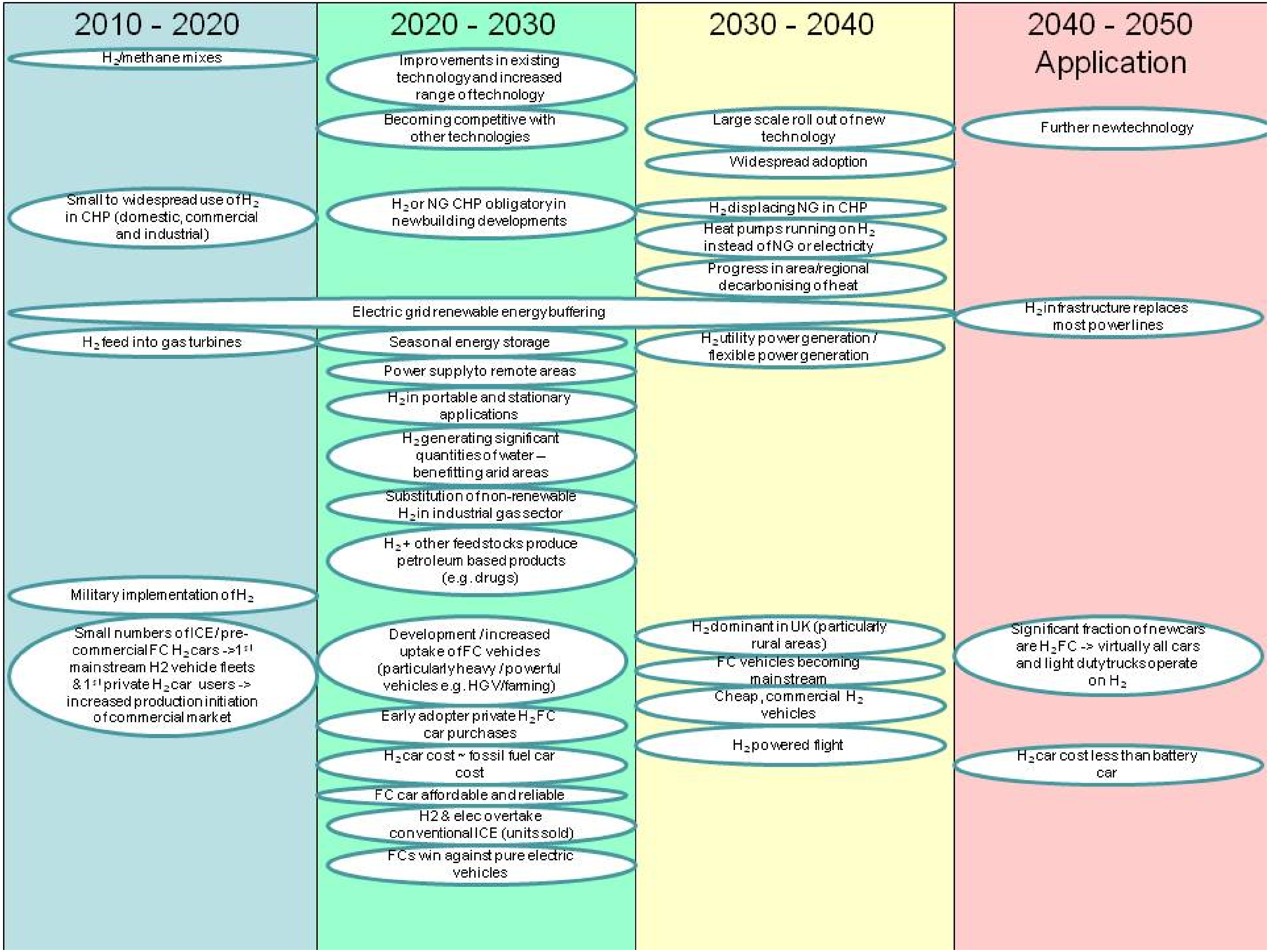
Q8 - Indicate the key developments in the hydrogen economy which you anticipate in the next 40 years:

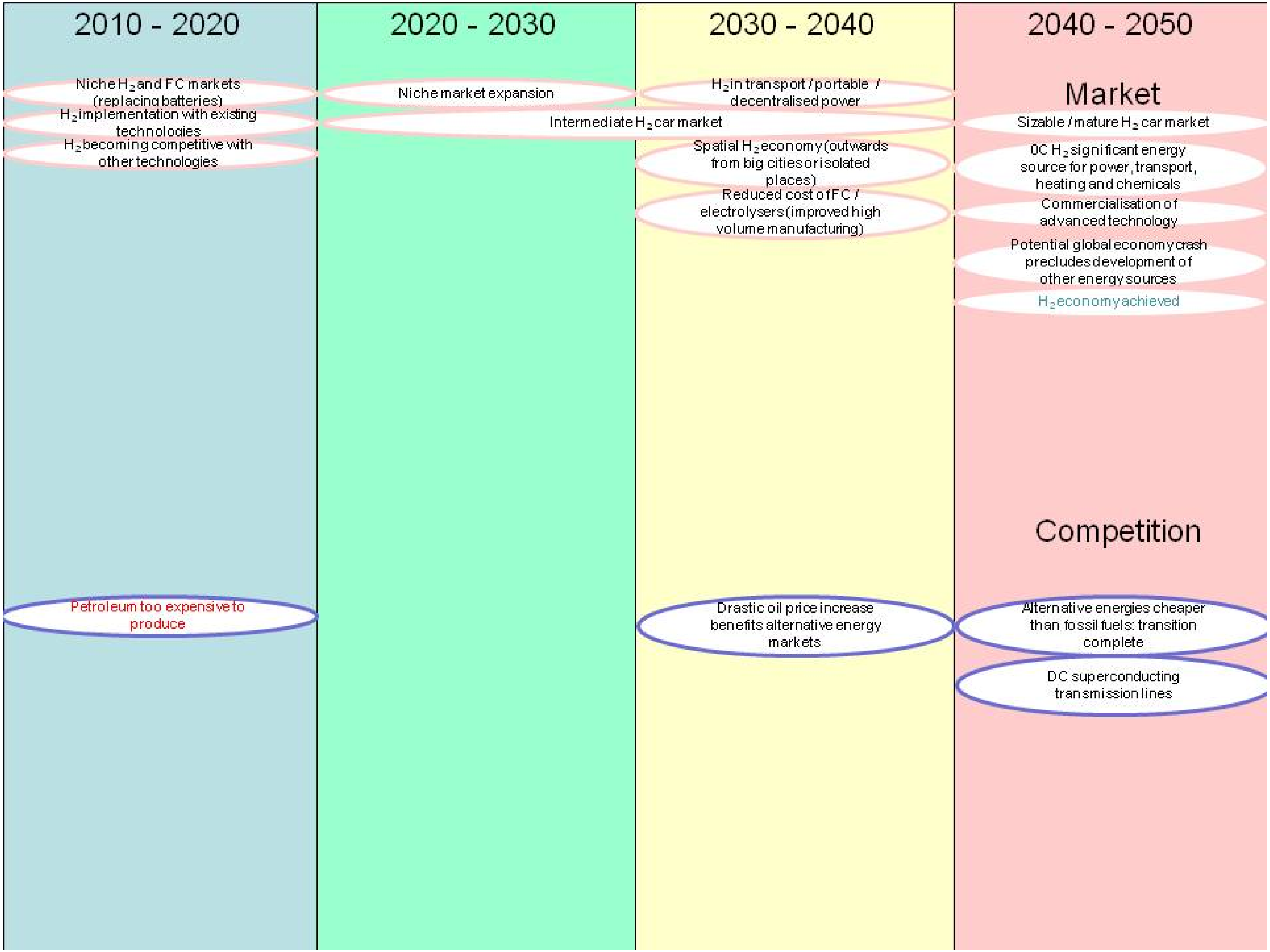




2010 - 2020
2020 - 2030
2030 - 2040
2040 - 2050
Feedstock
Fossil fuels (norm)
Low cost feedstock (e.g. nuclear, algae, solar heat)
Global war ends international petroleum markets – nations hoard their reserves
Oil too expensive for common use
Proof of competitive CCS
Integrated H_2 / power plants with commercial CCS
Commercialisation of low carbon H_2 production
Renewables (1st projects -> cost effective)
waste
bio fuel
H_2 process biofuels to diesel
Biohydrogen technology emerging
Large scale renewable H_2 production
Solar H_2 development
Increased use of **solar** / bio fuel for H_2 production
Low PV cost = economical home solar H2 production
Solar H_2 optimised
Thermal cycles in next generation nuclear
Increasing / large scale use of nuclear for H_2 production
Production
Low cost site produced H_2
Scale up / Large scale H_2 production
H_2 production cheaper and cleaner
Widely available, competitively priced H_2
Production of dense H_2
Widespread adoption of dense H_2
Large distributed base of dense H_2
Sustainable and cost effective H_2 production
Initial decarbonised H_2 production
Breakthrough in small scale electrolysis – cheap, efficient and reliable
High efficiency (>current electrolysis) low carbon H_2 production from H_2O
Improvement in HT electrolysis decay rates
Improved catalytic/electrolytic decomposition of water
Decentralised biohydrogen facilities
0C H_2 from photolysis / photocatalysis
0C H_2 from photocatalytic/ photoelectrochemical techniques


2010 - 2020
2020 - 2030
2030 - 2040
2040 - 2050
LowCost
Large Scale
Breakthrough in solid state
Metal hydrogen compressors
Small efficient liquefaction
Development
Improvements in storage / compression
High pressure, low temperature tanks
Cost effective and practical
Solved
feasible
Newdense storage systems
Storage
FC = ICE cost
FC cost competitive with CCGT
Improved power density
Improved operating life expectancy
Portable applications
Reliable
LowCost
Small, ultra-efficient
Market ready for transport & decentralised power
Fuel Cell
FC cost reduction


2010 - 2020
2020 - 2030
2030 - 2040
2040 - 2050 Application
H2/methane mixes
Improvements in existing technology and increased range of technology
Becoming competitive with other technologies
Large scale roll out of new technology
Widespread adoption
Further new technology
Small to widespread use of H2 in CHP (domestic, commercial and industrial)
H2 or NG CHP obligatory in new building developments
H2 displacing NG in CHP
Heat pumps running on H2 instead of NG or electricity
Progress in area/regional decarbonising of heat
Electric grid renewable energy buffering
H2 infrastructure replaces most powerlines
H2 feed into gas turbines
Seasonal energy storage
H2 utility power generation / flexible power generation
Power supply to remote areas
H2 in portable and stationary applications
H2 generating significant quantities of water – benefitting arid areas
Substitution of non-renewable H2 in industrial gas sector
H2 + other feed stocks produce petroleum based products (e.g. drugs)
Military implementation of H2
Small numbers of ICE / pre-commercial FC H2 cars -> 1st mainstream H2 vehicle fleets & 1st private H2 car users -> increased production initiation of commercial market
Development / increased uptake of FC vehicles (particularly heavy / powerful vehicles e.g. HGV/farming)
H2 dominant in UK (particularly rural areas)
FC vehicles becoming mainstream
Cheap, commercial H2 vehicles
Significant fraction of new cars are H2FC -> virtually all cars and light duty trucks operate on H2
Early adopter private H2FC car purchases
H2 car cost ~ fossil fuel car cost
H2 powered flight
H2 car cost less than battery car
FC car affordable and reliable
H2 & elec overtake conventional ICE (units sold)
FCs win against pure electric vehicles


2010 - 2020
2020 - 2030
2030 - 2040
2040 - 2050
Market
Niche H_2 and FC markets (replacing batteries)
H_2 implementation with existing technologies
H_2 becoming competitive with other technologies
Niche market expansion
Intermediate H_2 car market
H_2 in transport / portable / decentralised power
Spatial H_2 economy (outwards from big cities or isolated places)
Reduced cost of FC / electrolysers (improved high volume manufacturing)
Sizable / mature H_2 car market
0C H_2 significant energy source for power, transport, heating and chemicals
Commercialisation of advanced technology
Potential global economy crash precludes development of other energy sources
H_2 economy achieved
Competition
Petroleum too expensive to produce
Drastic oil price increase benefits alternative energy markets
Alternative energies cheaper than fossil fuels: transition complete
DC superconducting transmission lines

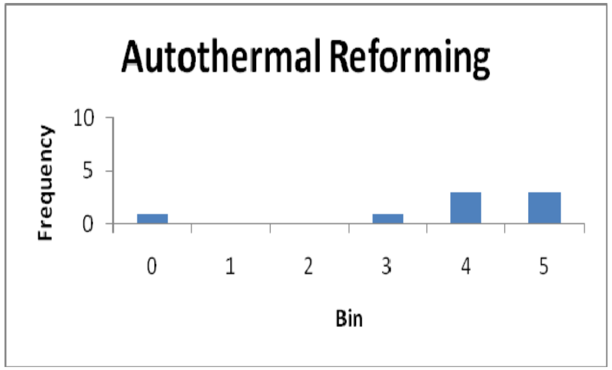
Hydrogen Production Technologies

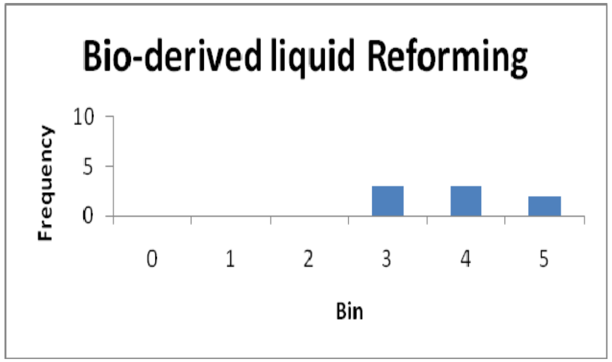
Q9/10/16 – For each of the Hydrogen Production Technologies listed:

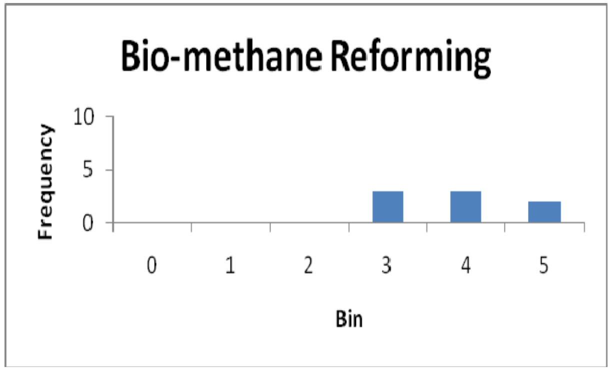
a) Indicate the scale of production to which the technology is best suited

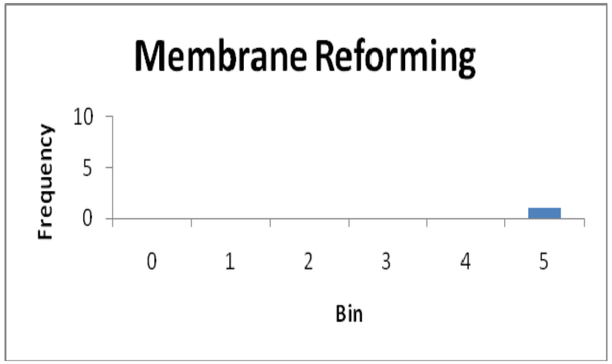
using a scale of 0 to 5 where:

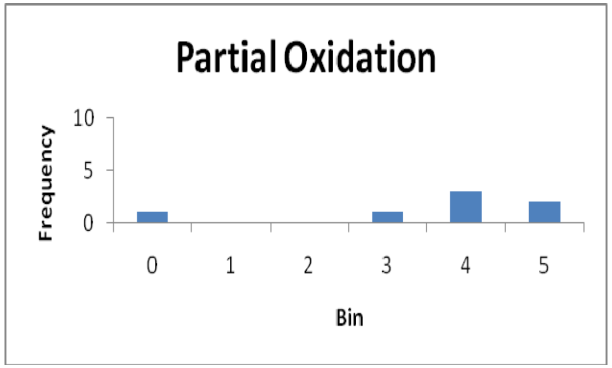
0 <200kg H_2 pa
1 200-1 000 kg H_2 pa
2 1 000-10 000 kg H_2 pa
3 10 000-30 000 kg H_2 pa
4 30 000-100 000 kg H_2 pa
5 > 100 000 kg H_2 pa

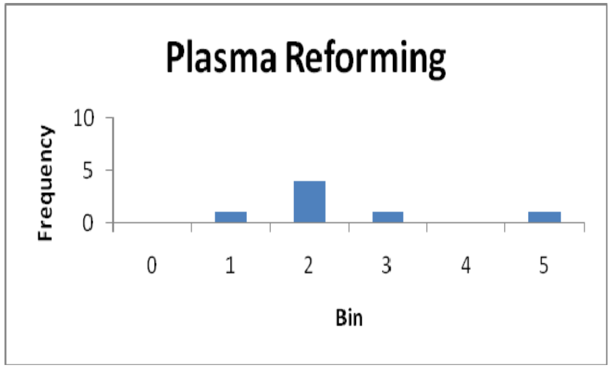


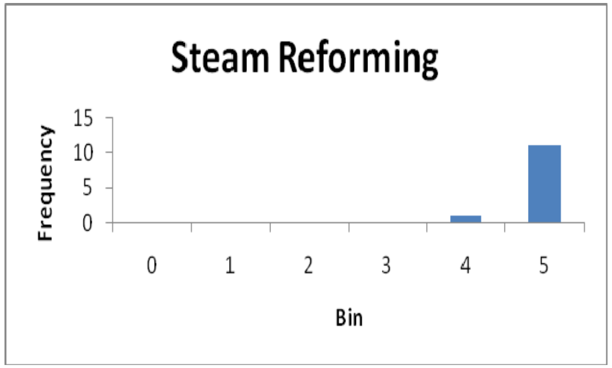


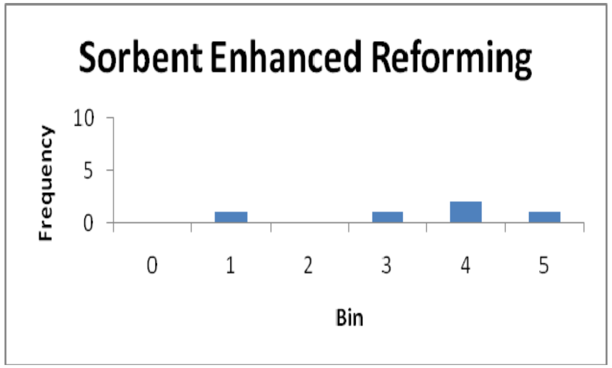


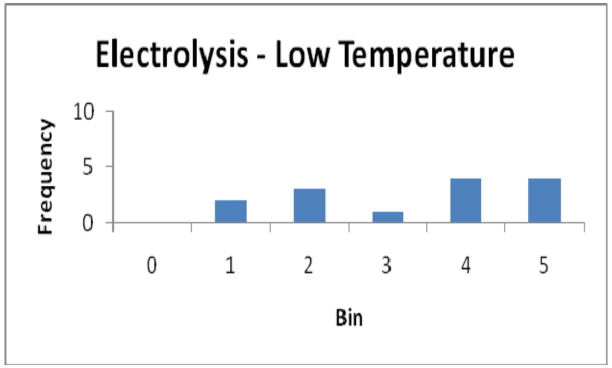









Sorbent Enhanced Reforming
Frequency
10
5
0
0
1
2
3
4
5
Bin


Electrolysis - Low Temperature
Frequency
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2
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4
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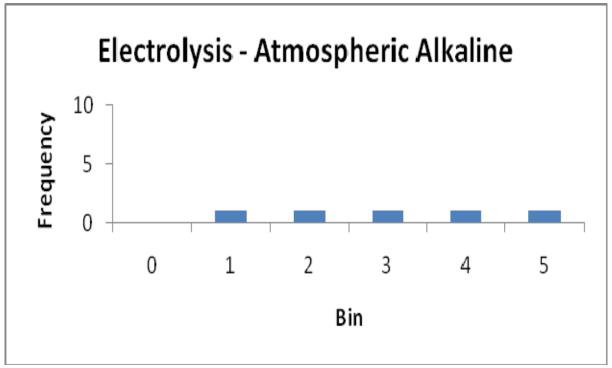
Bin


Electrolysis - Atmospheric Alkaline
Frequency
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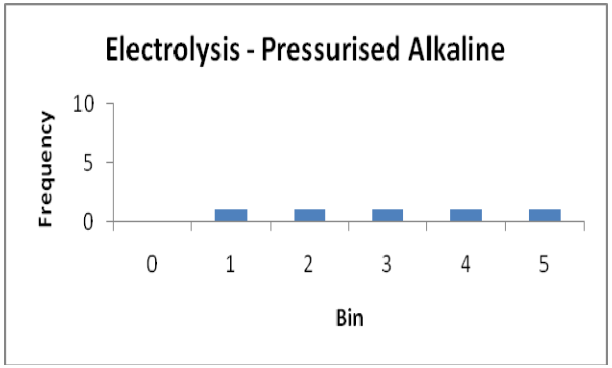
Electrolysis - Pressurised Alkaline
Frequency
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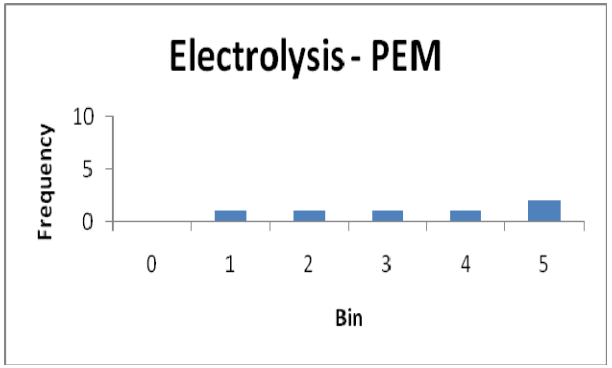
3
4
5
Bin


Electrolysis - PEM
Frequency
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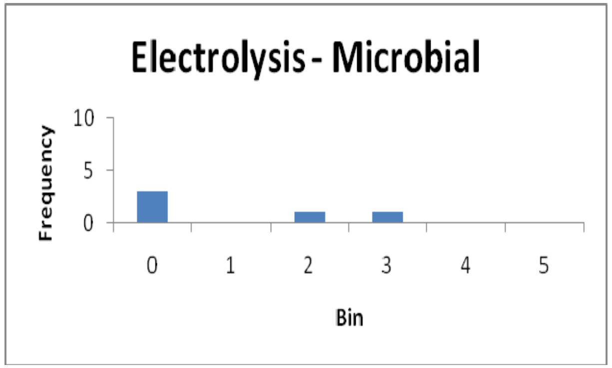
2
3
4
5
Bin


Electrolysis - Microbial
Frequency
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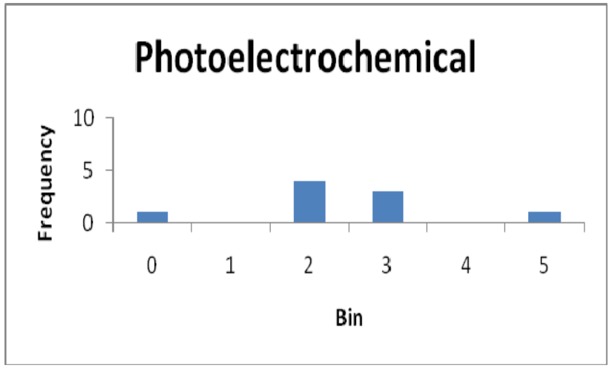
3
4
5
Bin


Photoelectrochemical
Frequency
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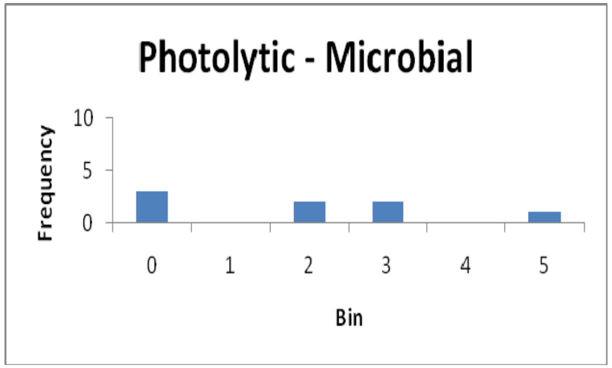
Photolytic - Microbial
Frequency
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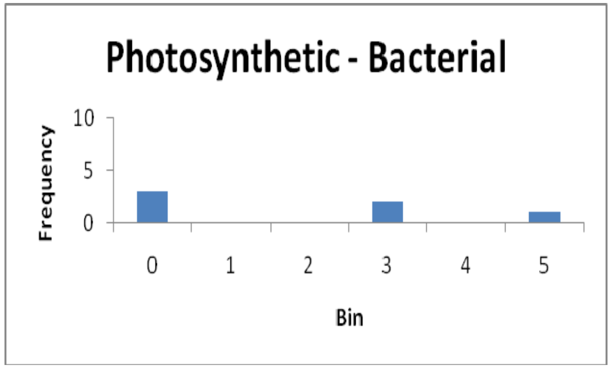
0
1
2
3
4
5
Bin


Photosynthetic - Bacterial
Frequency
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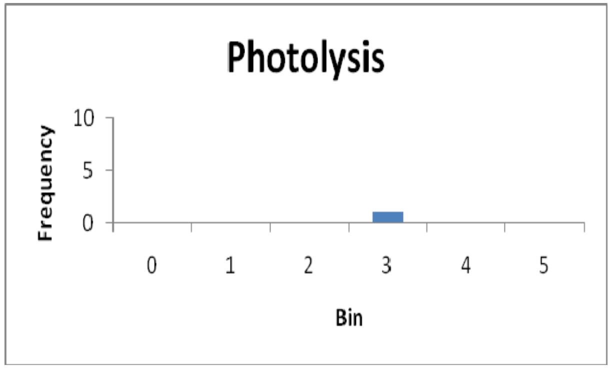
0 1 2 3 4 5
Bin


Photolysis
Frequency
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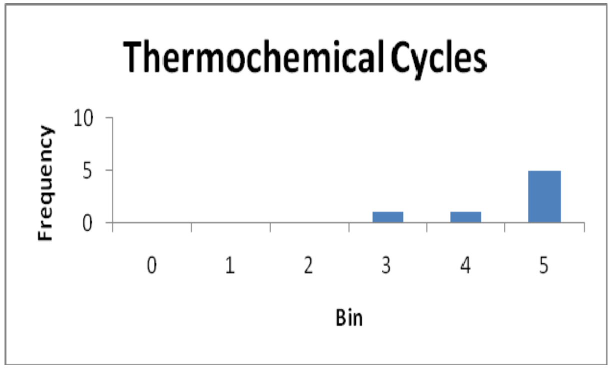
0 1 2 3 4 5
Bin


Thermochemical Cycles
Frequency
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0 1 2 3 4 5
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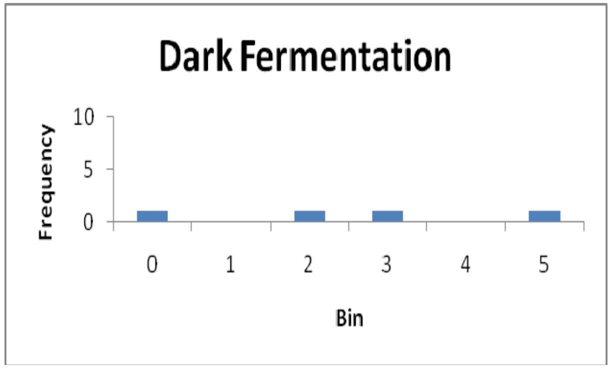
Dark Fermentation
Frequency
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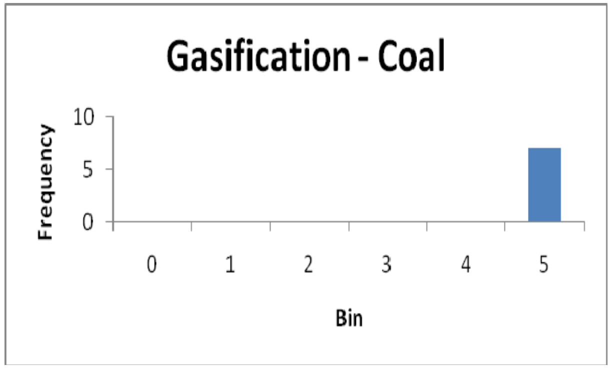
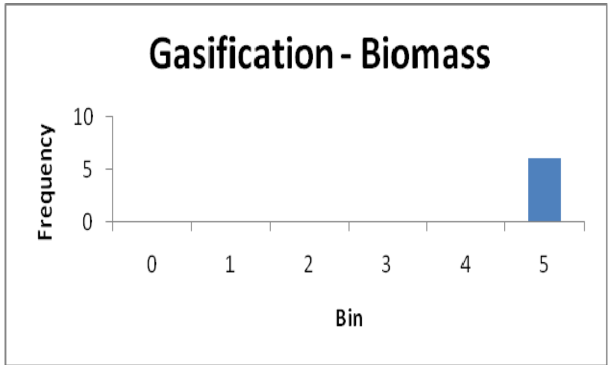
0 1 2 3 4 5
Bin


Gasification - Coal
Frequency
10
5
0
0 1 2 3 4 5
Bin


Gasification - Biomass
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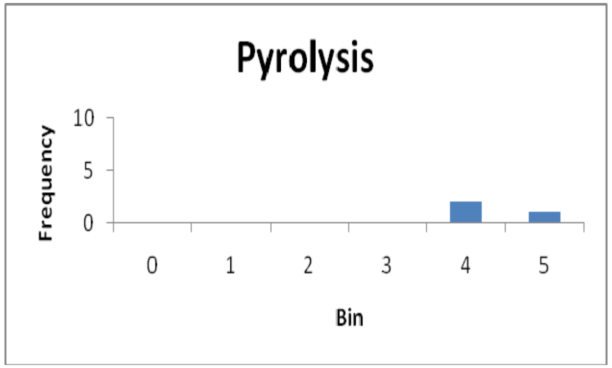
Pyrolysis
Frequency
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5
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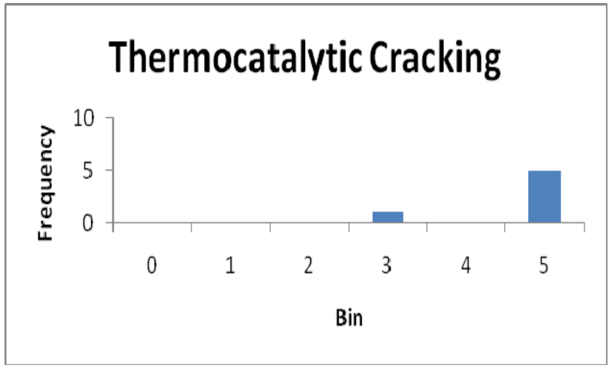
0 1 2 3 4 5
Bin


Thermocatalytic Cracking
Frequency
10
5
0
0 1 2 3 4 5
Bin

The technologies which appear to be best suited for small scale production (<1 000 kg H_2 pa) are:

- Microbial electrolysis

The technologies which appear to be best suited for medium scale production (1 000 – 30 000 kg H_2 pa) are:

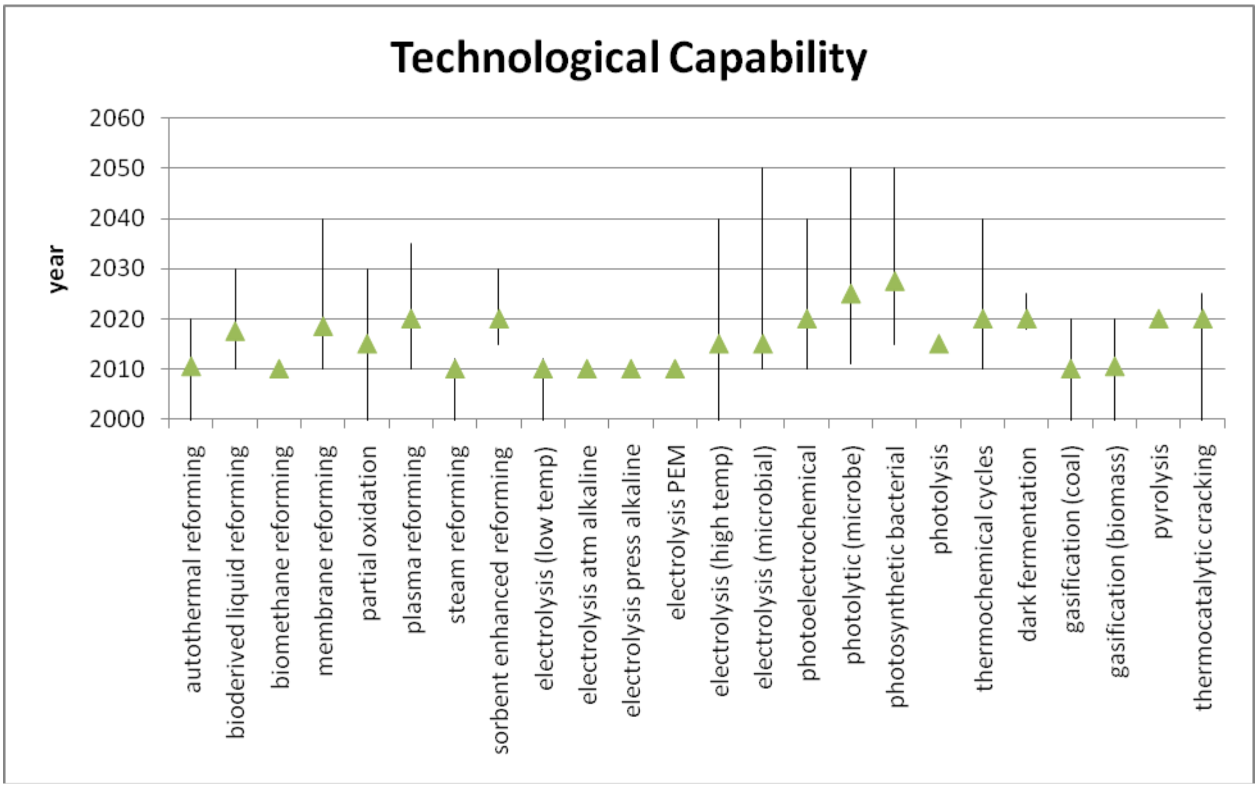
- Bioderived liquid reforming
- Biomethane reforming
- Plasma reforming
- Photoelectrochemical
- Photolytic (microbial)
- Photosynthetic (bacterial)
- Photolysis

The technologies which appear to be best suited for large scale production (>30 000 kg H_2 pa) are:

- Autothermal reforming
- Membrane reforming
- Partial oxidation
- Steam reforming
- Sorbent enhanced reforming
- High temperature electrolysis
- Thermochemical Cycles
- Gasification (coal and biomass)
- Pyrolysis
- Thermocatalytic Cracking

Low temperature electrolysis and dark fermentation appear to be suitable for a wide range of production scales.

b) Technological Capability



Many hydrogen producing technologies have already reached technological capability. These include:

- Autothermal reforming
- Biomethane reforming
- Steam reforming
- Low temperature electrolysis including atmospheric and pressurised alkaline as well as PEM.
- Gasification (coal and biomass)

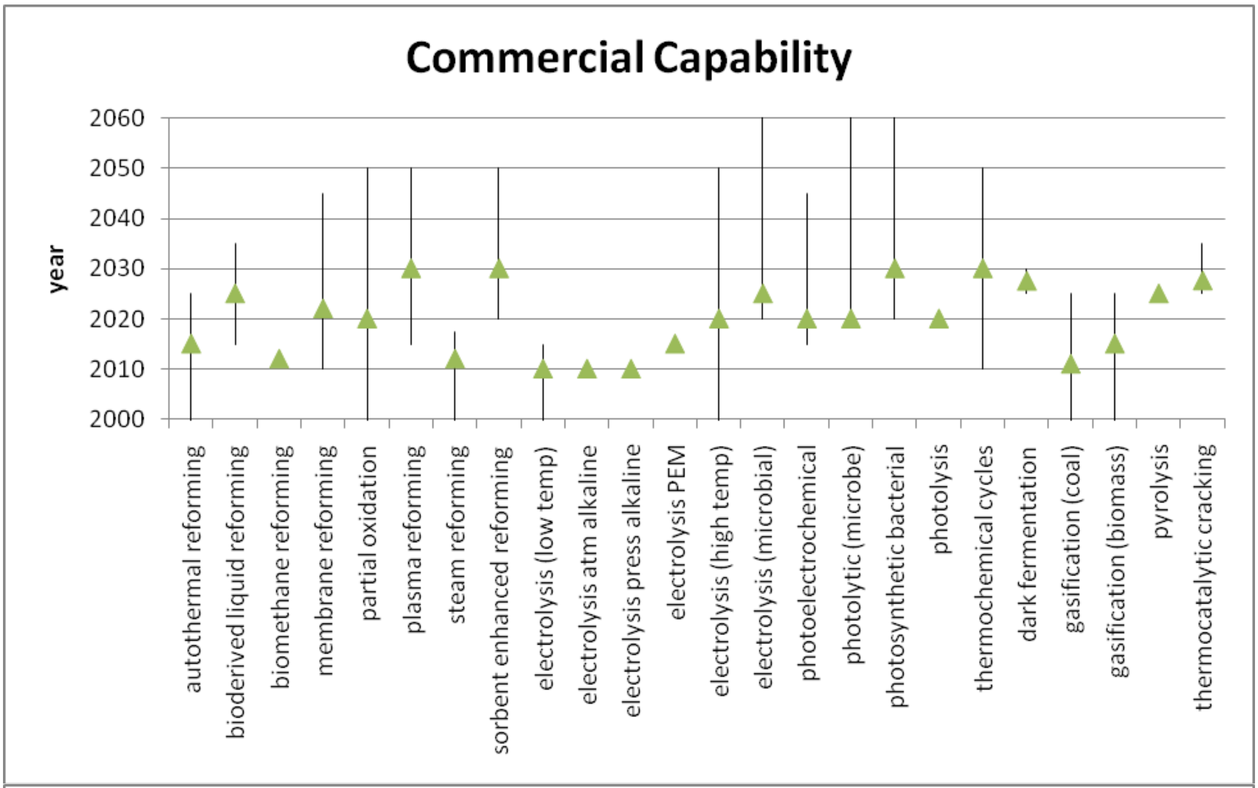
Those expected to reach technological capability by 2020 are:

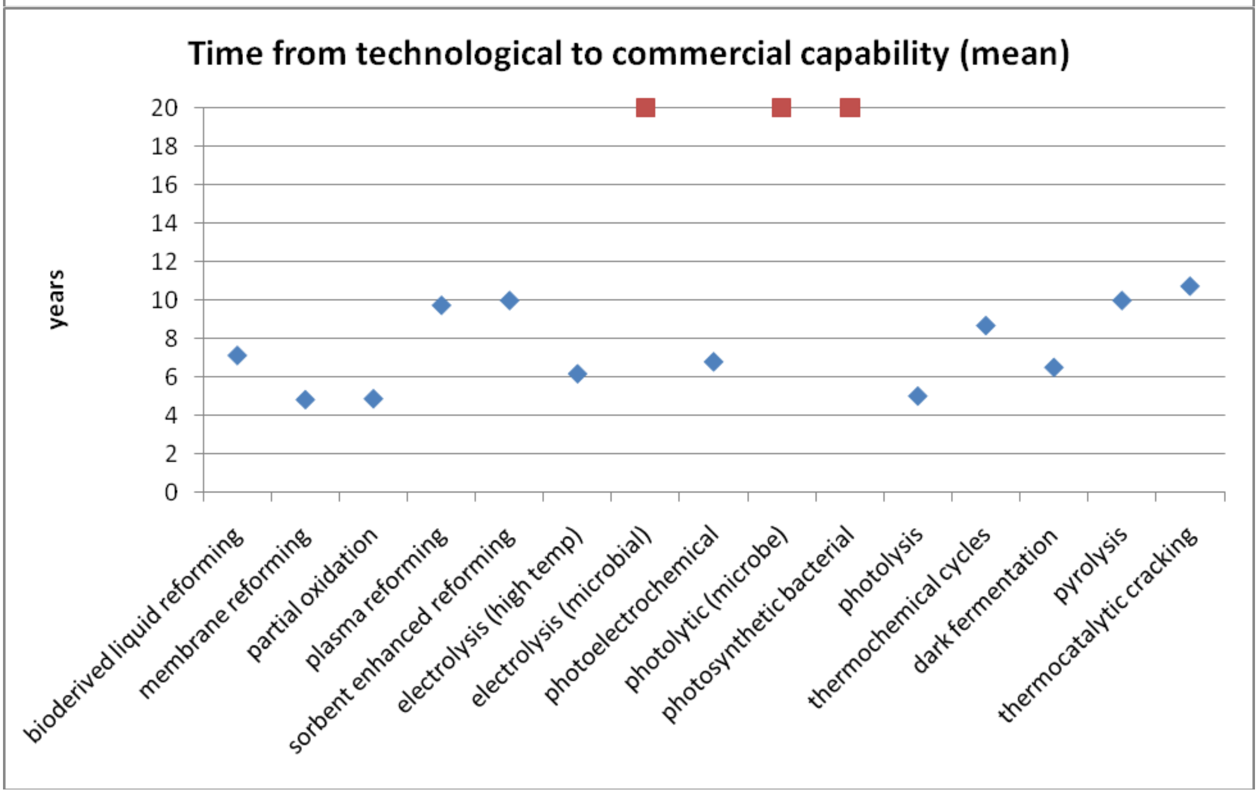
- Bioderived liquid reforming
- Membrane reforming
- Partial oxidation
- Plasma reforming
- High temperature electrolysis
- Microbial electrolysis
- Photolysis
- Thermocatalytic cracking

Those expected to require more time include:

- Sorbent enhanced reforming
- Photoelectrochemical
- Photolytic (microbial)
- Photosynthetic (bacterial)
- Thermochemical cycles
- Dark fermentation
- Pyrolysis

c) Commercial Capability





Hydrogen producing technologies which have already reached technological capability include:

- Biomethane reforming
- Steam reforming
- Low temperature electrolysis including atmospheric and pressurised alkaline
- Gasification (coal)

Those expected to reach technological capability by 2020 are:

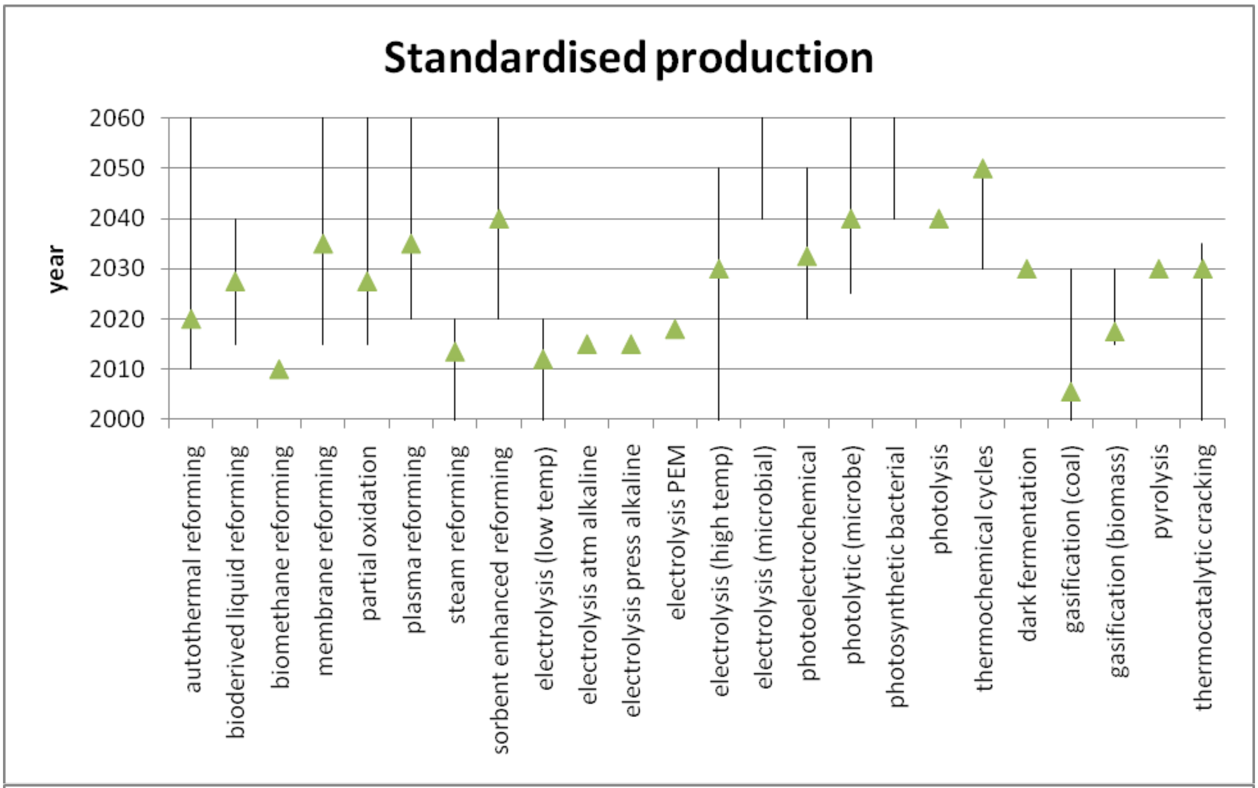
- Autothermal reforming
- Membrane reforming
- Partial oxidation
- PEM electrolysis
- High temperature electrolysis
- Photoelectrochemical
- Photolytic (microbial)
- Photolysis
- Gasification (biomass)

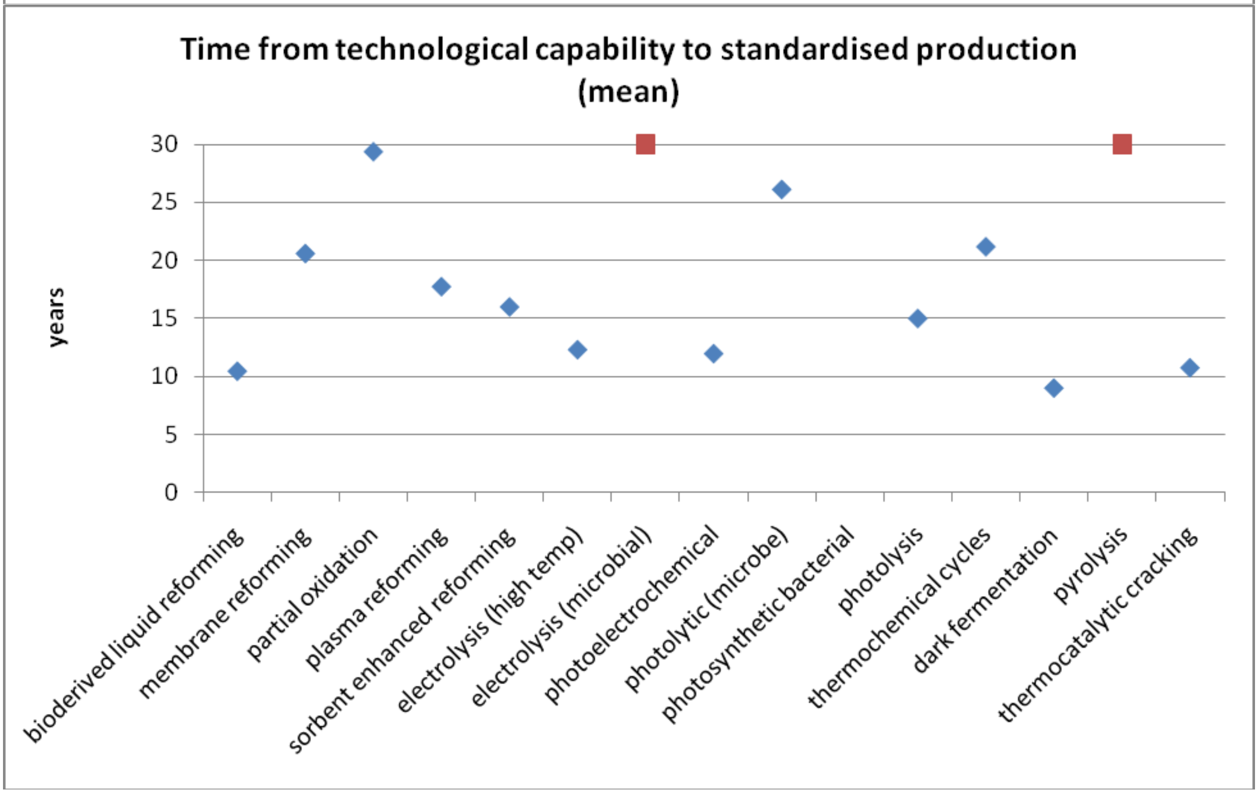
Those expected to require more time include:

- Bioderived liquid reforming
- Plasma reforming
- Sorbent enhanced reforming
- Microbial electrolysis
- Photosynthetic (bacterial)
- Thermochemical cycles
- Dark fermentation
- Pyrolysis
- Thermocatalytic cracking

In general, technologies are expected to move from technological to commercial capability within 5 to 10 years. However, microbial electrolysis, microbe photolysis and the use of photosynthetic bacterial are expected to take significantly longer (>20 years) to reach commercial capability.

d) Standardised production (>1 000 units per year)





The only hydrogen producing technologies which have already achieved standardised production are biomethane reforming and coal gasification.

Those expected to reach technological capability by 2020 are:

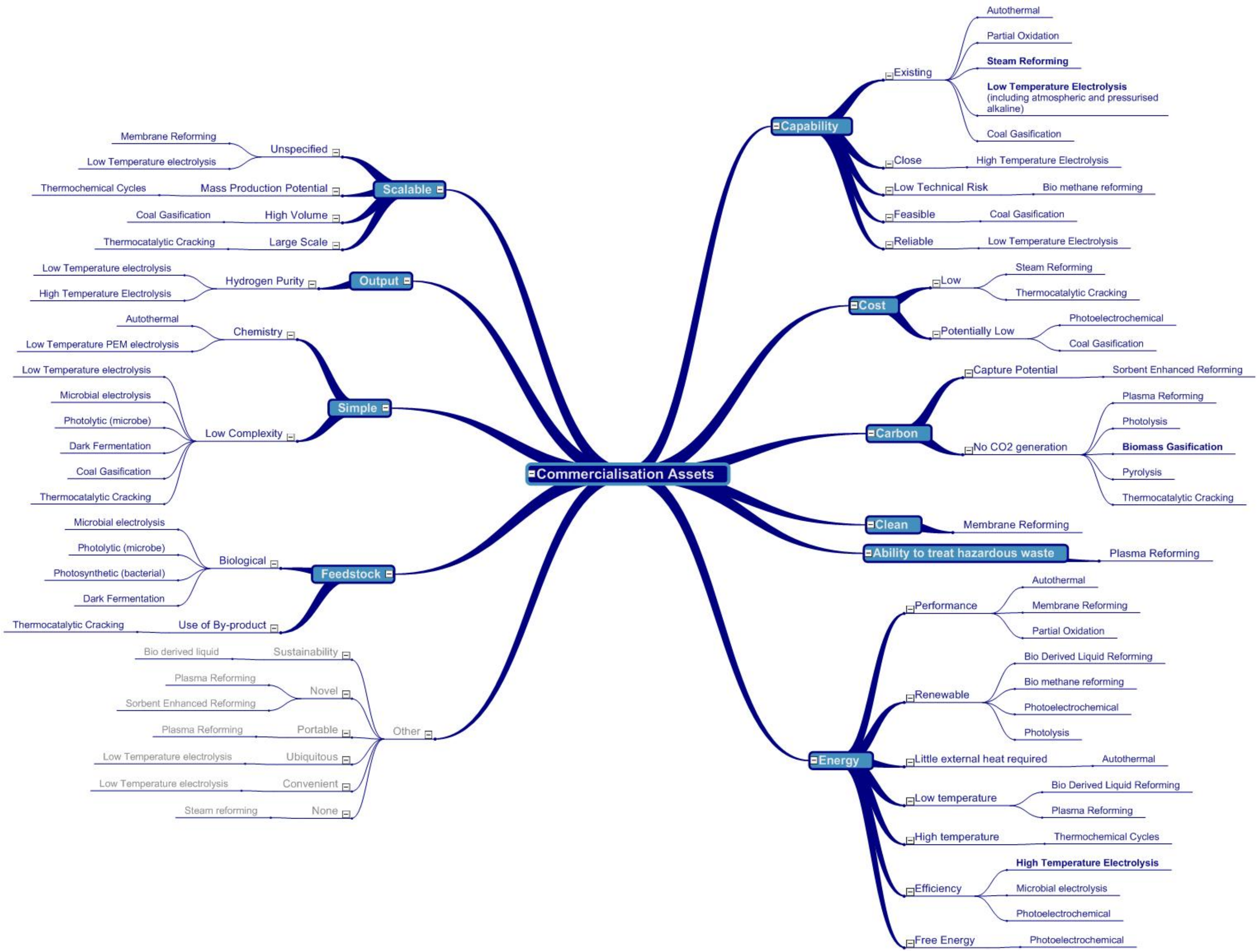
- Autothermal reforming
- Steam reforming
- Low temperature electrolysis including atmospheric and pressurised alkaline as well as PEM

- Gasification (biomass)

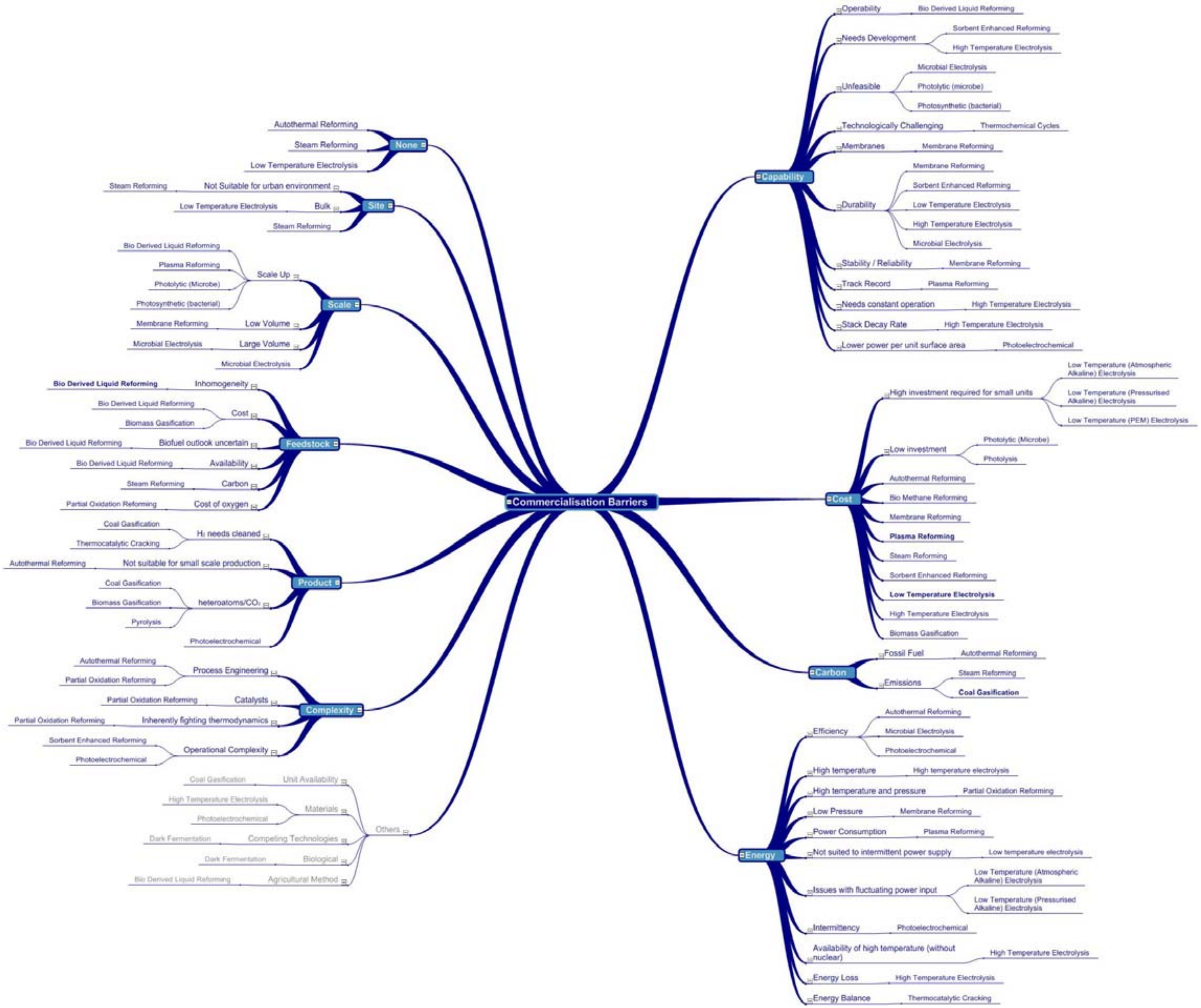
Those expected to require more time include:
- Membrane reforming
- Partial oxidation
- High temperature electrolysis
- Photoelectrochemical
- Photolytic (microbial)
- Photolysis
- Bioderived liquid reforming
- Plasma reforming
- Sorbent enhanced reforming
- Microbial electrolysis
- Photosynthetic (bacterial)
- Thermochemical cycles
- Dark fermentation
- Pyrolysis
- Thermocatalytic cracking

In general, technologies are expected to move from technological capability to standardised production within 30 years. However, pyrolysis and microbial electrolysis are expected to take significantly longer.

e) Greatest potential assets for commercialisation

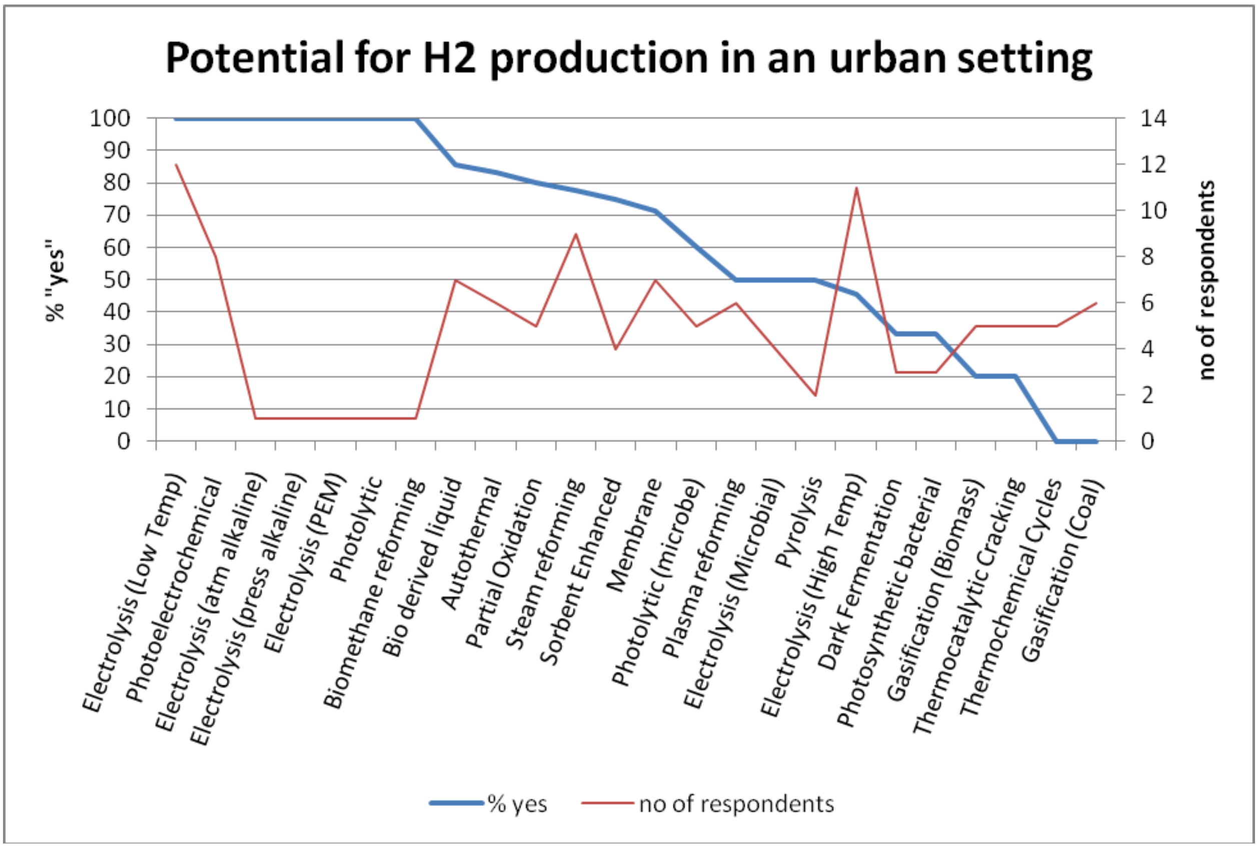


f) Greatest potential barriers to commercialisation



A wide range of assets and barriers to commercialisation of hydrogen production technologies have been reported by the participants. Where the technologies affected have been indicated by more than three participants, it has been represented with bold text.

g) potential of hydrogen production within an urban setting



Low Temperature Electrolysis and Photoelectrochemical are the technologies most widely accepted as being suitable for hydrogen production within an urban setting.

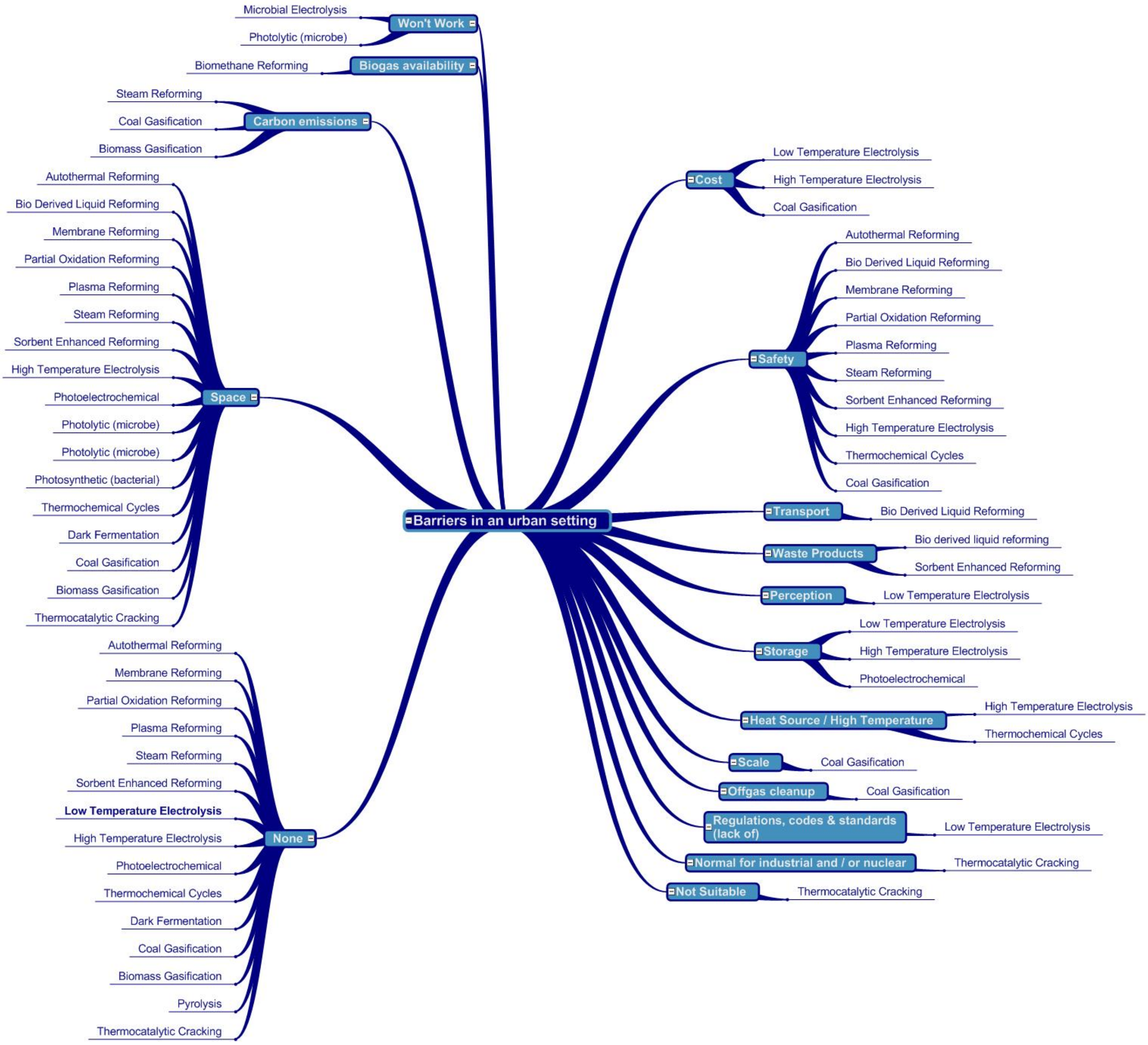
h) indicate the scale of production feasible within a forecourt situation (325m^2 or 3500ft^2)

using a scale of 0 to 5 where:

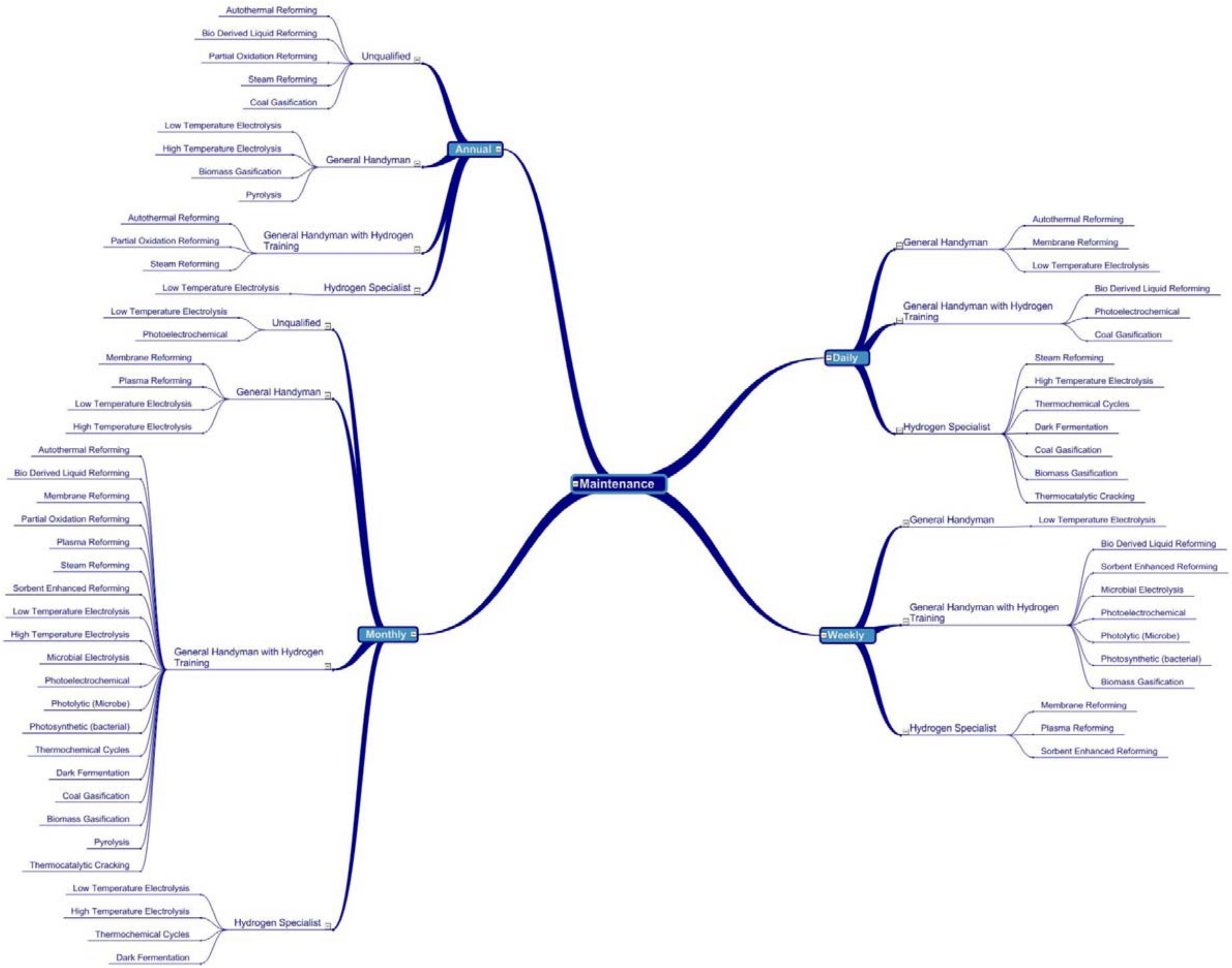
0 <200kg H_2 pa
1 200-1 000 kg H_2 pa
2 1 000-10 000 kg H_2 pa
3 10 000-30 000 kg H_2 pa
4 30 000-100 000 kg H_2 pa
5 > 100 000 kg H_2 pa

There were few responses to this question and some confusion as to the scale feasible in a forecourt situation.

i) Indicate the barriers forseeable in an urban setting



j) indicate the frequency and skill level of maintenance required



There was a spread of opinions about the frequency and skill level required for maintenance. In general, most technologies required at least a general handyman with hydrogen specific training on a monthly basis.

Electrolysis Production Priorities

Q11 – increased site surface area vs increased operating costs

Choice of increasing site surface area to incorporate larger storage tanks or increasing operating costs due to lack of capacity to take advantage of off-peak electricity rates.

Larger Site Surface Area generally favoured.

Q12 – increased use of solar / wind generated electricity vs reduced maintenance

Choice of increasing use of solar / wind generated electricity or reducing maintenance by allowing electrolyser to run without interruption.

Increasing use of solar / wind generated electricity should not be an issue if appropriate control systems are used. Varying current is a problem, but on/off operation is not.

Q13 – high electrolysis efficiency vs sellable oxygen production

Choice of increasing electrolysis efficiency or producing sellable oxygen as a by-product.

Increased electrolysis efficiency generally favoured – potential exceptions to this would be a hospital with a local requirement for oxygen.

Q14 – high electrolysis efficiency vs high hydrogen production rate

Choice of increasing electrolysis efficiency by operating with a very low current density or increasing hydrogen production rate by increasing the current density.

This was considered to be application dependent with no clear bias to one option or the other.

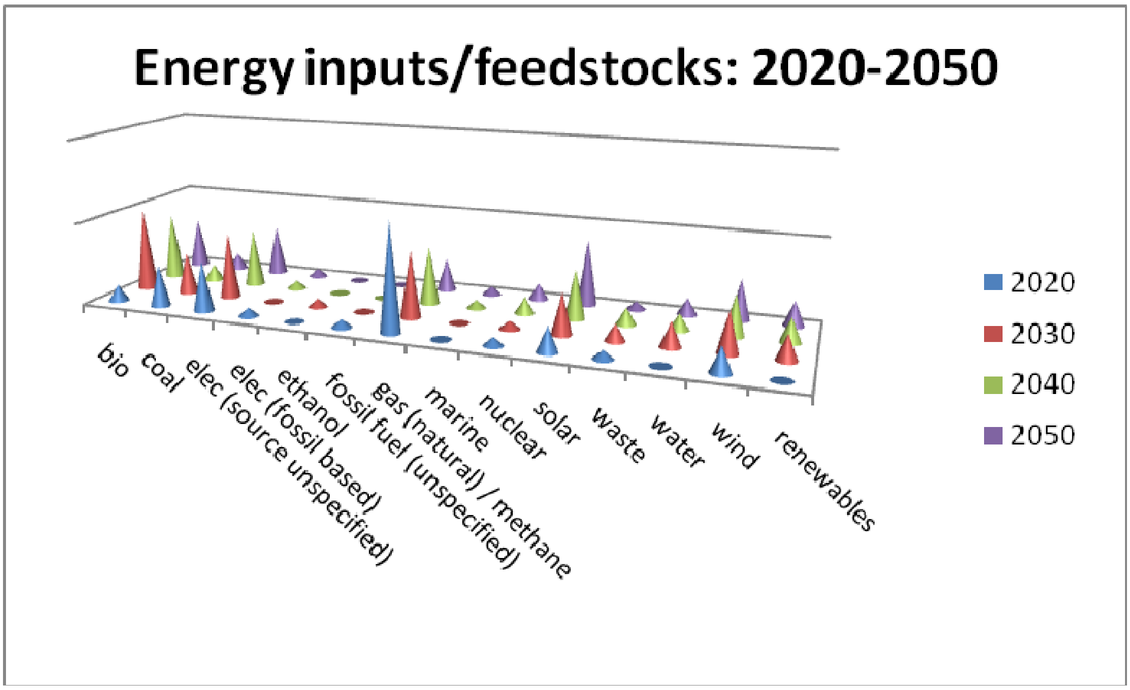
Q15 – high electrolysis efficiency vs higher capital/maintenance costs and restricted availability of high temperature process heat

Choice of using more electricity for low temperature electrolysis or using high temperature electrolysis with higher capital/maintenance costs and restricted availability of high temperature process heat

This was considered to be application dependent with no clear bias to one option or the other.

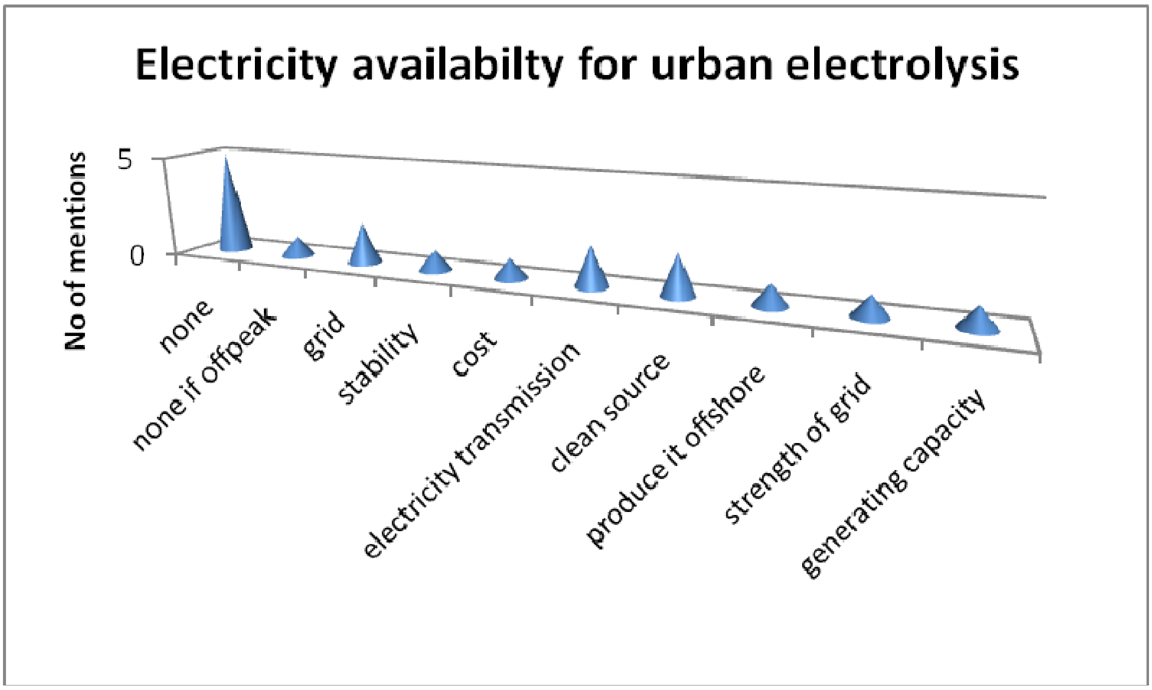
Feedstock

Q17 – Specify the energy inputs/feedstock most likely to contribute to the bulk of hydrogen production in 2020-2050

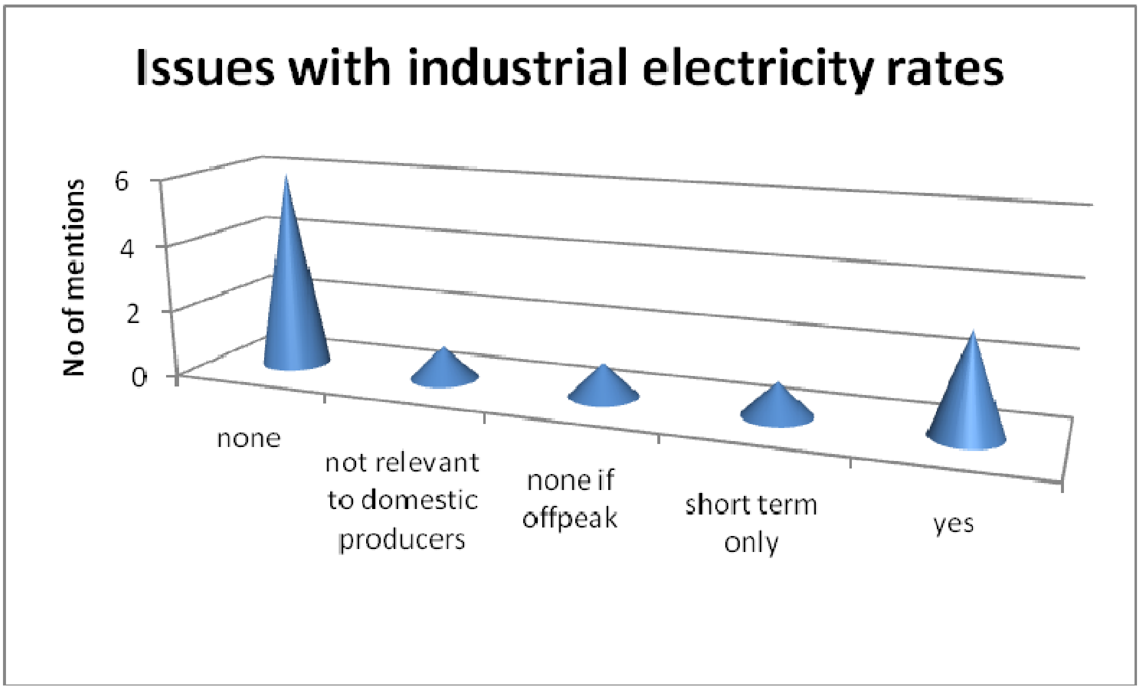


Carbon based feedstocks are expected to decline, with biomass sources peaking in 2030 then declining, while nuclear and other renewable sources increasing.

Q18a – For hydrogen produced through electrolysis, what issues might arise with electricity provision in urban areas for transport refuelling locations?



Q18b – What issues with industrial electricity rates might be faced?

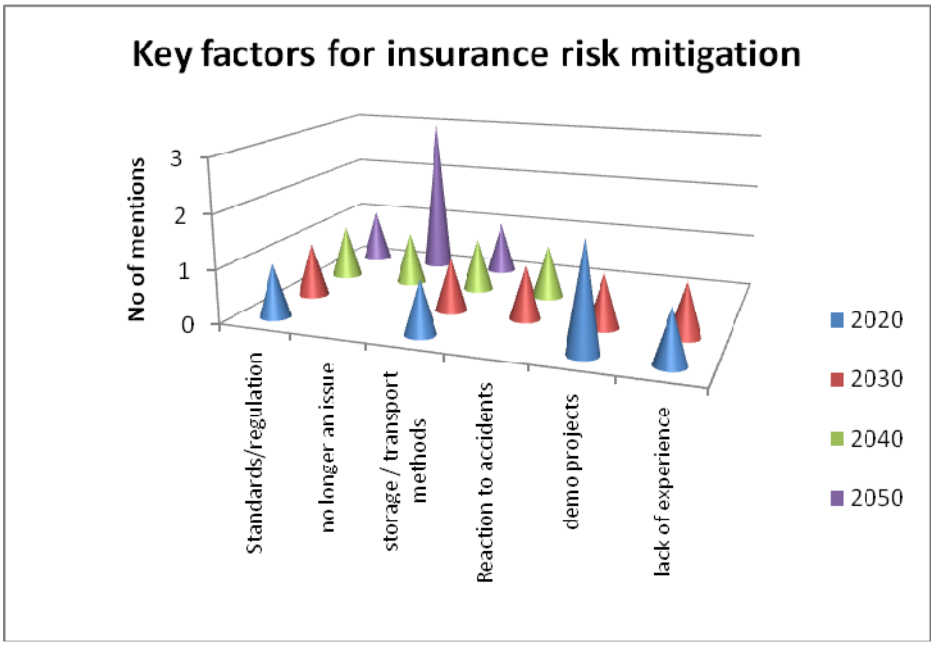


Safety Risk and Public Perception

Q19 – What opportunities do you forsee to develop global standards and safety regulations for hydrogen production?

General agreement that good progress has already been made

Q20 – What will be the key factors to cover insurance risk mitigation from 2020 to 2050?

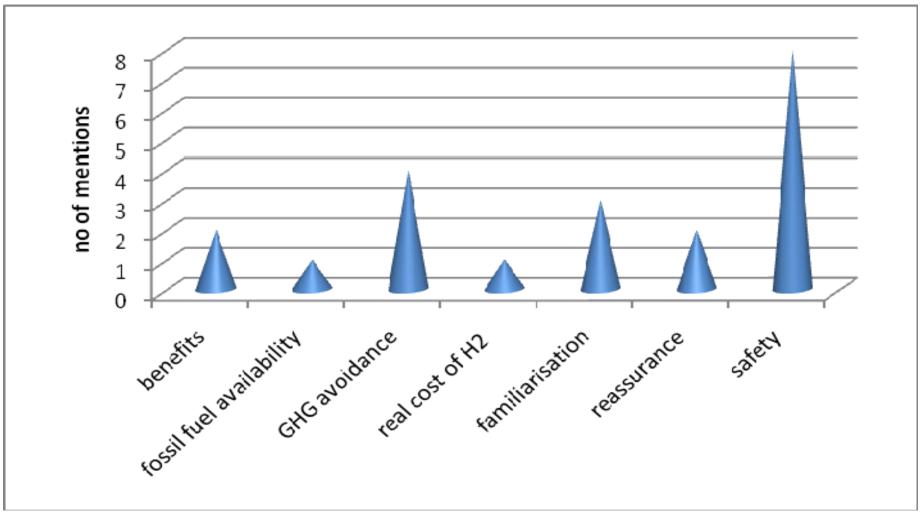


Initially standards/regulations and storage/transport methods need to be developed at the same time as demonstration projects are undertaken which will build up familiarity and experience.

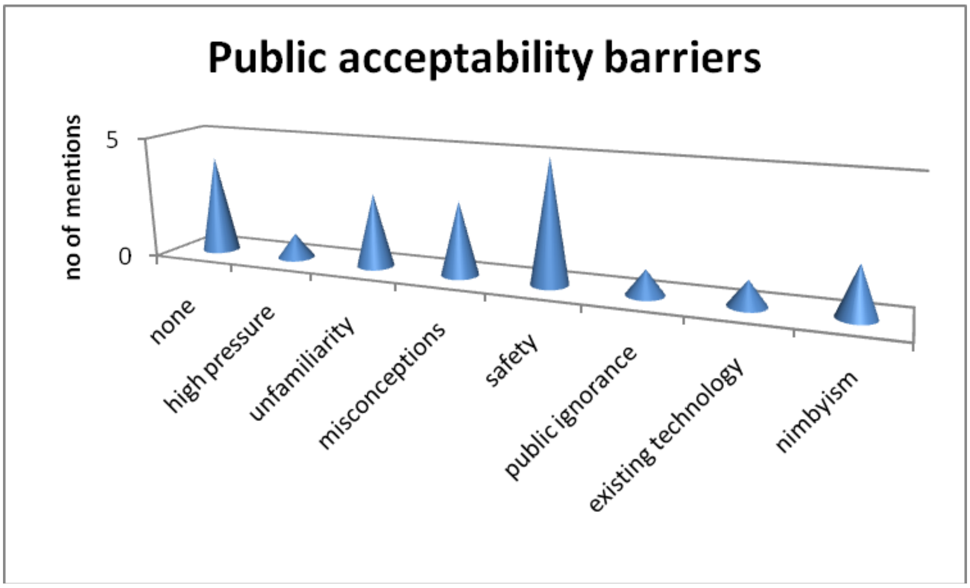
Q21 – Are there any safety issues which should be addressed when siting hydrogen production facilities near power plants (including nuclear) and high voltage lines?

General concensus that common sense be followed and that hydrogen production would be no more dangerous in this scenario than other energy sources or chemical plants.

Q22 – What are the key factors to include in any scheme aimed at community education regarding hydrogen production?



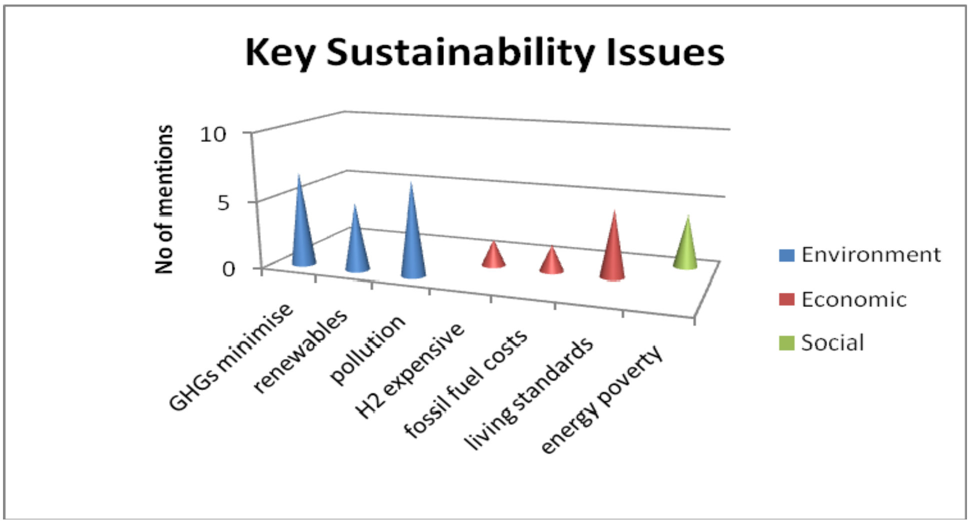
Q23 – What public acceptability barriers do you foresee for hydrogen production in fuelling stations?



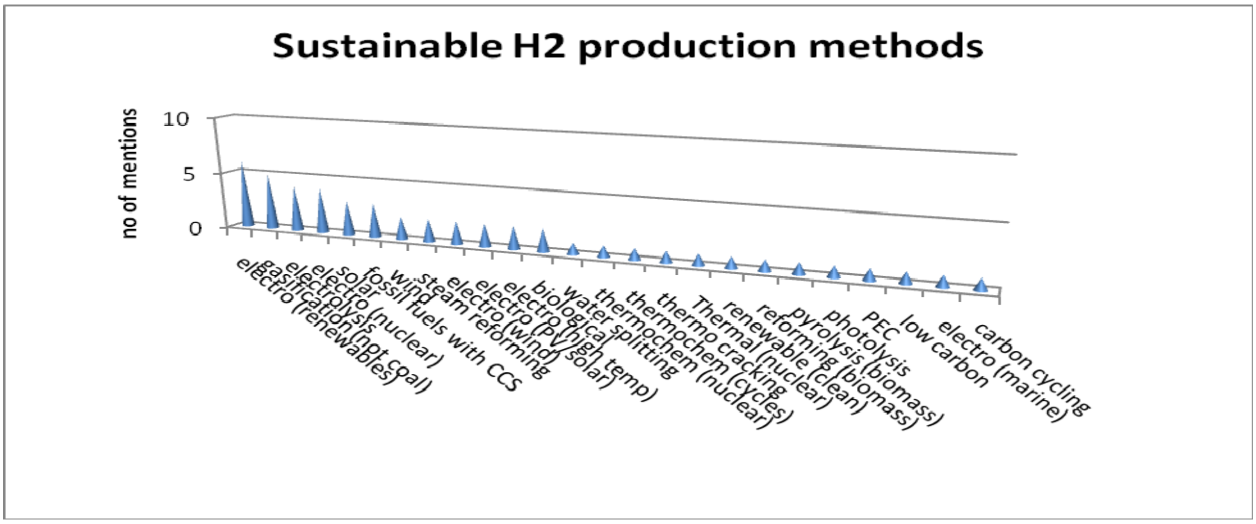
Safety is considered to be the main public acceptability barrier and as such is the key factor to include in any scheme aimed at community education.

Sustainable Development and Hydrogen

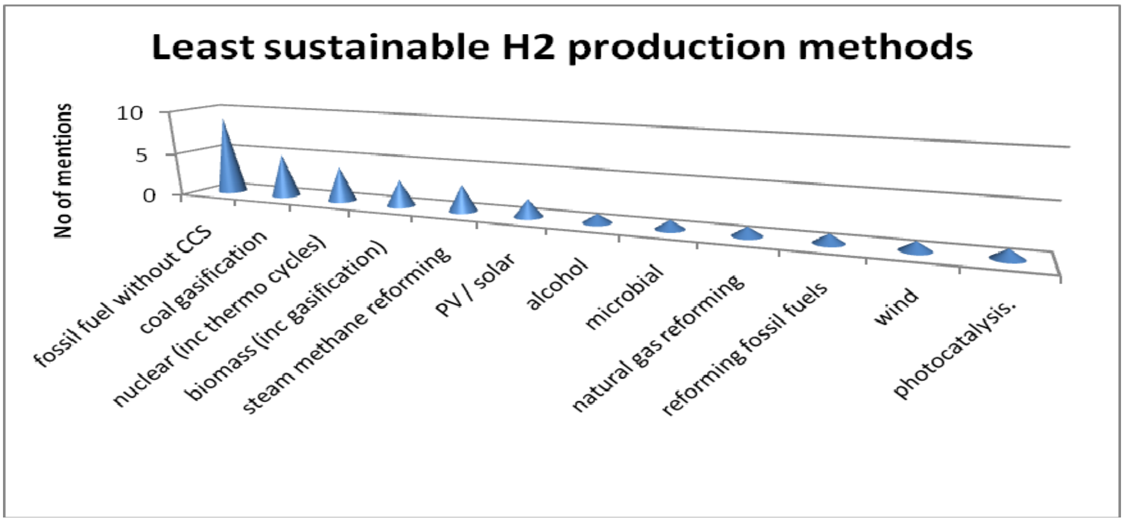
Q24 – most important aspects of sustainability (environmental / economic / social)



Q25 – most sustainable methods of hydrogen production



Q26 – least sustainable methods of hydrogen production



Although fossil fuel based technologies are generally regarded as the least sustainable, renewable methods including biomass, PV/solar and wind are also mentioned in this category, despite also being considered as sustainable methods in Q25.