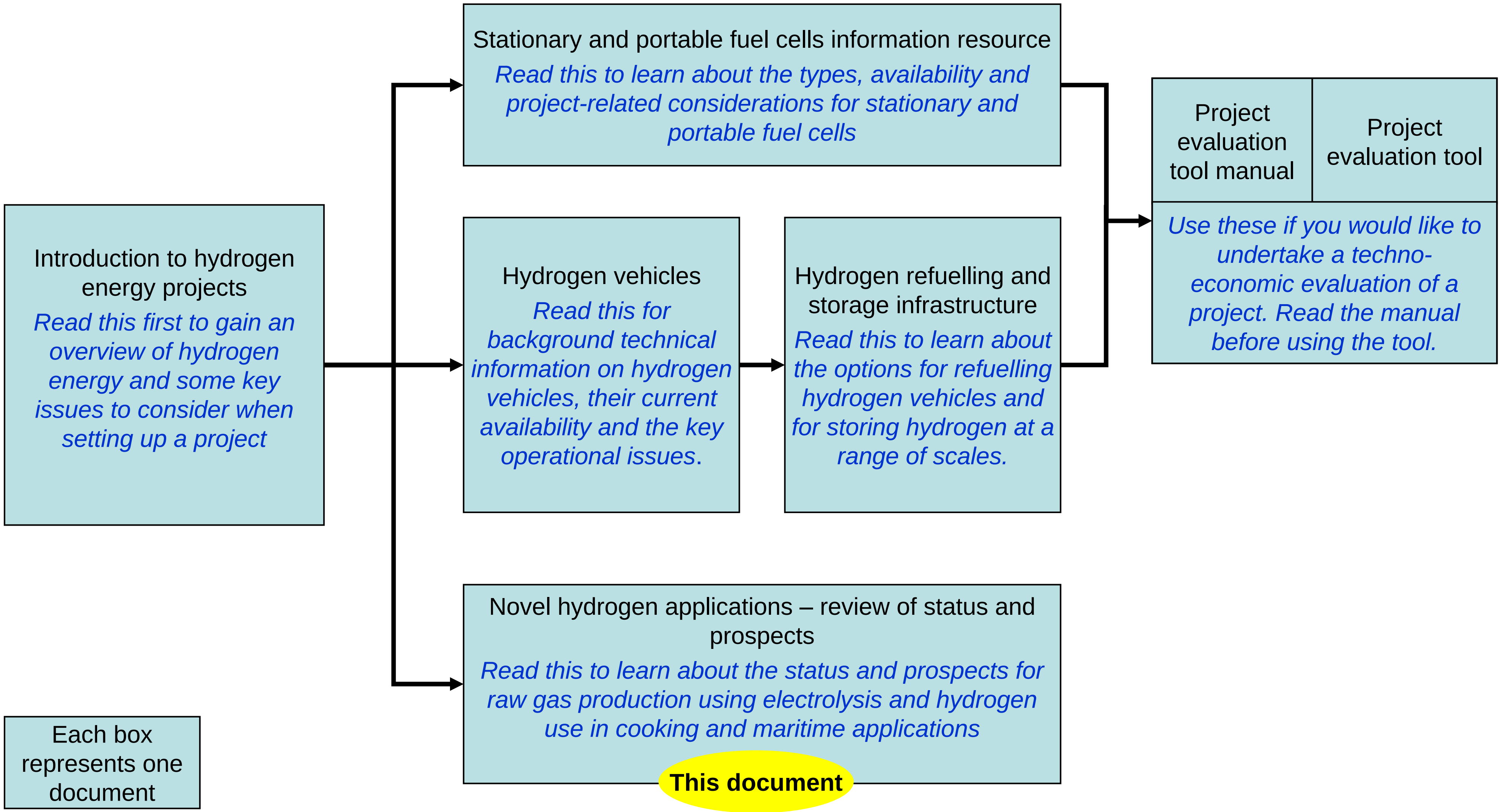
Novel hydrogen applications – review of status and prospects

Information Resource for Highlands & Islands Enterprise

About this document

- In 2006 the HIE Renewable Energy team commissioned a consulting team to assist with the identification and assessment of hydrogen energy opportunities across the region. As part of this work the project team conducted a workshop in each LEC area to introduce the hydrogen energy opportunity and identify potential project ideas. Over 80 individual ideas surfaced, at varying levels of ambition, detail and feasibility.
- The project team worked with HIE to identify several recurrent themes among the ideas:
  - What are all the issues that need to be considered when setting up a hydrogen project?
  - What different stationary and portable hydrogen applications are there?
  - How can hydrogen be used in road vehicles?
  - How can hydrogen be stored and what refuelling facilities would be required for hydrogen vehicles?
  - What are the prospects for hydrogen use in maritime applications or cooking? Could bottled hydrogen and oxygen be produced and sold?
  - How can developers undertake technical and economic evaluation of their ideas?
- HIE judged that the best way to provide value to the LECs would be through a suite of information resources and tools based on these themes, to enable ideas to be developed and assessed further. These tools fit together as shown overleaf.

Document Map



About the authors

Element Energy

- **Element Energy is an engineering consultancy specialising in the low carbon energy sector. It formed in 2003 as a spin off from larger engineering practice Whitbybird.**
- **Services:**
  - Engineering services for low carbon energy projects
  - Innovation in new energy technologies and storage solutions
  - Strategic advice and consultancy
  - Project management and funding assistance
  - Specialist knowledge in hydrogen and fuel cell projects

E4tech

- **E4tech is a sustainable energy business consultancy, based in the UK and in Switzerland (established 1997)**
- **Services:**
  - Business strategy
  - Organisational support and interim management
  - Technology and market review to assist financing
  - Policy input for local and national government
  - Support to technology startups
  - Focus on hydrogen energy, bioenergy and sustainable buildings

PURE Energy Centre

- **The Pure Energy Centre has one aim: to give you access to the most effective energy storage techniques in the world to grow your business/community and increase your energy independence**
- **Services/products:**
  - Renewable hydrogen training courses
  - Consultancy for energy and storage technologies
  - Sales of hydrogen production units
  - R&D contract work for third parties

Commonly used acronyms

AFC Alkaline Fuel Cell

C H2 Compressed Hydrogen

CHP Combined Heat and Power

CNG Compressed Natural Gas

CRES Centre for Renewable Energy Studies (Greece)

DoE United States Department of Energy

EC CUTE European Commission Clean Urban Transport for Europe

EC HyCom EC Hydrogen Communities

FC Fuel Cell

FP6&7 Framework Programmes 6&7 (EU instrument for funding research)

H&I Highlands and Islands

H2ICE Hydrogen Internal Combustion Engine

HAZOP Hazard and Safety Operational Studies

HHV High Heating Value

HIE Highlands and Islands Enterprise

HSE Health and Safety Executive

ICE Internal Combustion Engine

LCIP Low Carbon Innovation Programme (Carbon Trust)

LEC Local Enterprise Company

LHV Low Heating Value

LNG Liquid Natural Gas

LPG Liquid Petroleum Gas

MCFC Molten Carbonate Fuel Cell

MCPs Manifold Cylinder Packs

MEA Membrane Electrode Assembly

NOx Nitrous oxides (pollutants)

O&M Operation and Maintenance

OEM Original Equipment Manufacturer

PAFC Phosphoric Acid Fuel Cell

PE Primary Energy

PEM Primary Exchange Membrane/Polymer ion Exchange Membrane

PSA Pressure Swing Absorption

R&D Research and Development

ROCs Renewable Obligation Certificates (see Defra website)

SME Small to Medium Enterprises

SOFC Solid Oxide Fuel Cell

UPS Uninterruptible Power Supply

VSA Vacuum Swing Absorption

ZEMSHIPS Zero Emission Ships

Contents

This assessment addresses three areas that were raised in several LEC workshops

- Hydrogen from renewables and hydrogen use in vehicles and small fuel cells were dominant themes at the LEC workshops. Deliverables addressing these areas have been prepared.
- In addition, three other themes emerged at several workshops and were judged to merit further analysis:
  - raw gas supply
  - hydrogen cooking
  - maritime applications

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Could renewable hydrogen generation be used as a basis for raw gas supply?

- The H&I has an excellent wind resource which can be used to generate renewable electricity. Using an electrolyser to convert this electricity to hydrogen is one option for overcoming the supply variability and export constraints of wind power. The hydrogen can then be converted back to electricity using a fuel cell.
- An electrolyser uses electricity to convert water into gaseous hydrogen and oxygen – the oxygen is often vented to the atmosphere but, along with hydrogen, could be used in industrial applications.
- Both hydrogen and oxygen are used by businesses in the H&Is which is supplied compressed in cylinders. The expense of transporting cylinders to the H&Is can add significantly to the cost of the gases.
- Hydrogen and oxygen generated using an electrolyser running on renewable electricity (e.g. wind power) could be a more cost effective option.

Hydrogen and oxygen are used in a broad range of industries

Market	Oxygen	Hydrogen
Metals	To enhance combustion temperatures in industrial process	Mixed with inert gases to obtain a reducing atmosphere
Chemicals, pharmaceuticals & petroleum	Feedstock; combustion enhancer; catalysis enhancer	Feedstock; purification
Glass and ceramics	Combustion enhancer	To prevent oxidation
Pulp and paper	Bleaching agent (replacing chlorine); combustion enhancer	
Health care	Respiratory aid	
Environmental	Enhance biological waste treatments; replacement for chlorine	
Aquaculture	To increase oxygen content of water and therefore increase yields of fish	
Breathing apparatus	Diving	
Fitting and turning	Combined with fuel gas for welding, gas cutting etc	Aluminium welding; underwater cutting and welding
Rockets	Fuel	Fuel
Food and beverages		Unsaturated fatty acid hydrogenator
Semiconductor manufacture		Carrier gas for active trace elements
Electricity generation	Oxy-Fuel Combustion, Gasification	Coolant for generators; protective atmosphere for nuclear fuel rod fabrication

Five of these industries are present in the H&Is, however, the focus will clearly be on oxygen

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The volume of raw gas which could be supplied will limit which industries are potential markets

- An example of a gas generating system to give a sense of scale:
  - A 1 MW wind turbine, operating at 30 percent load factor
  - Providing electricity for an electrolyser producing hydrogen and oxygen
  - Would produce approximately 470 thousand m^3 H_2 (99.9% purity) and 235 thousand m^3 O_2 (99.5% purity) every year[1,2]
  - Most of the hydrogen would be used to generate electricity, however some could be used in industrial applications
- For comparison:
  - A world-scale petrochemical refinery uses approximately 40 million m^3 H_2 per year
  - A medium sized fish farm might use 38 thousand m^3 O_2 per year
  - A small boat builder would probably use less than 200 m^3 O_2 per year

1 – assuming the electrolyser produced 0.18 m^3 H_2 per kWh

2 – all m^3 of gas given for normal temperature and pressure

Based on the potential quantity of raw gas which could be supplied, there are four potential markets for renewable raw gas supply

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The healthcare industry may present a small market for oxygen in the H&Is

- There are around 15 hospitals in the H&Is (including around 4 on the Islands)
- Oxygen is used during surgery, intensive care treatment and to enhance quality of life (e.g. inhalation therapy)
- Oxygen supplied to hospitals in the UK is at least 99.5% pure, home oxygen generators produce oxygen as low as 90% purity. The nature of the contaminants is very important – e.g. carbon dioxide can be tolerated but sulphur compounds cannot.
- The oxygen would normally be supplied to hospitals through bulk liquid deliveries, however, this route is unsuitable for small and remote hospitals which are generally supplied with compressed oxygen (gas) in manifold cylinder packs (up to ~7 nm^3/cylinder)
- On-site oxygen production is also commercially available via turn-key medical pressure swing adsorption (PSA) oxygen systems – those systems however can not reach oxygen purity beyond 95%. Hospitals could use on-site electrolysers instead in combination with fuel cells making use of the hydrogen and providing back-up power.

The aquaculture industry might be a significant market for on-site oxygen generation

- There are around 330 Atlantic salmon and 170 freshwater salmon farms in Scotland, the majority of which are in the H&Is.[1]
- One 1000m^3 farm might require 50 tonnes of oxygen (approx 38,000 nm^3) per year.
- The oxygen is added to the water in fish farms to increase dissolved oxygen concentration of the water. Higher dissolved oxygen concentration (e.g. 75-90% for intensive farms) promotes fish growth and increases yield.
- Oxygen purity not key market requirement – for example, 90% purity might be acceptable.
- Demand for oxygen is seasonal – peaking in summer.
- Compressed oxygen in cylinders is considered too expensive – liquid oxygen or on-site production are favoured. On-site production typically uses PSA, VSA[1] or membrane technology.
- On-site renewable oxygen supply may be a viable option for the aquaculture industry, particularly if there is an un-met need for electricity nearby.

PSA = pressure swing absorption; VSA = vacuum swing absorption.

1 – HIE (2004). *Aquaculture economic update – March 2004*. http://www.hie.co.uk/sectoralprofiles-aquacultu.pdf (Downloaded 16/08/06)

The scuba diving industry may present a small market for oxygen in the H&Is

- Approximately 20 companies involved in scuba diving (recreational or technical) in the H&Is
- The majority of recreational divers use compressed air, NOT oxygen.
- For deeper and/or longer diving – some recreational but also technical diving – oxygen is used in mixtures with air or helium.
- Common mixtures: nitrox (e.g. 32% O_2, 68% compressed air), trimix (10% O_2, 70% helium, 20% nitrogen) and heliox (21% O_2, 79% helium).
- These gases are either mixed on-site (e.g. dive shop) or purchased direct from gas supplier.
- On-site blending requires compressed oxygen in cylinders – which is decanted into the dive cylinder along with the other gases in the mixture.
- Renewable oxygen supply would meet the requirements of the diving industry, however, other markets for compressed oxygen would be required in order for raw gas supply to be economic. Dive companies would still have to source helium from a conventional gas supplier.

Metal workshops and boat builders might present a small market for gases in the H&Is – oxygen and hydrogen

- There are approximately 30 industrial workshops and 15 boat builders in the H&Is
- Oxygen is used in these workshops, in combination with a fuel gas (e.g. acetylene, propane and hydrogen) for cutting metals, gas welding, brazing etc.
- Using oxygen increases the temperature of the flame significantly above what would be achieved using only atmospheric oxygen.
- "Oxy-hydrogen" welding and cutting is typically used when working with aluminium or when cutting and welding underwater.
- Both oxygen and hydrogen used must be very pure – at least 99.5% or 99.995% respectively. A 1% reduction in purity increases oxygen consumption by 25% and reduces the cutting speed by a similar amount.
- Both oxygen and hydrogen are supplied compressed in cylinders – typically between 140 and 200 bar and up to 11 nm^3 / cylinder for oxygen and 7 nm^3 / cylinder for hydrogen.
- Renewable hydrogen and oxygen supply would meet the requirements of this industry, however, other markets for compressed oxygen would be required in order for raw gas supply to be economic. Businesses would still have to source acetylene and propane from conventional suppliers.

Hydrogen produced via electrolysis is likely to be expensive but may have potential applications in the H&I area.

- Existing costs:
  - Alkaline Electrolysers producing up to 20 Nm3 per hour of hydrogen at pressure (30Bg), and which can accommodate an intermittent variable electrical supply from a renewable source, currently cost around £4,000 p/kW or £20,000 p/Nm3 p/hr. However, these electrolysers have a projected lifetime of 20 years.
  - Grid connected Electrolysers producing hydrogen and oxygen at low pressure (c. 1 Bg) can cost as little as £1200 p/kW and companies such as Norsk Hydro produce Electrolysers of 1MW and above.
- Cost of H2 from electrolysis
  - PURE Project Example: A 15 kW electrolyser producing 3.55 Nm3 H2 p/hr is producing over 20,000 Nm3 per year at 80% of its capacity. The delivered price of a K-Class bottle of commercially supplied hydrogen in Shetland is £71 for 7.2Nm3. Thus the local value of hydrogen produced by the PURE Project electrolyser is approximately £150k per annum – considerably more than the capital cost of the plant.

Conclusions and next steps for renewable raw gas supply in the H&Is

- The aquaculture industry is the most attractive potential market for renewable oxygen supply in the H&Is. On-site oxygen generators are however likely to remain a preferred option versus electrolysers if a viable market for co-produced hydrogen can not be identified.
- This opportunity could be further investigated by way of a detailed feasibility study investigating the relative cost of different oxygen supply routes in a variety of different fish farms (e.g. Atlantic / freshwater). The aquaculture industry would need to be engaged in order to establish the operational feasibility.
- Depending on the results of this study one or more sites could be selected to trial the technology.

- For other industries: establish technical considerations of storing and filling H2 and O2 gas bottles for off-site supply, and
- Review the technology and market developments which might lead to significant reduction in the costs of suitable small scale electrolyser systems.

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Could hydrogen be used as a cooking fuel?

- Propane (LPG) is used extensively for cooking in the H&I.
- Anecdotal evidence suggests some households spend £100-200 per year on cooking (using LPG), while small businesses such as hotels might spend up to £6,000 per year.
- Could on-site renewable hydrogen be used as a substitute for LPG?

There are several technologies available for hydrogen cooking…

- Hydrogen stoves
  - Stoves can be specially adapted to burn hydrogen instead of LPG – a completely new burner unit is required.
  - Hydrogen burners prevent air from mixing with the hydrogen before it burns (unlike conventional LPG/natural gas burners) and would have very small burner "ports" from which the fuel is released (~0.5 mm)
- Catalytic hydrogen burners
  - Air and hydrogen are mixed in the presence of a catalyst, causing them to oxidise at a lower temperature than normal.
  - Catalytic burners are flameless
- Hybrid systems
  - Blending a very small amount of hydrogen with LPG might remove the need for new burners (but would require gas blending equipment)
  - Flame-assisted catalytic burning would combine conventional burner technology with catalytic burning – lowering temperatures and, therefore, NOx emissions

…However, there are currently no hydrogen cooking technologies available commercially

- Hydrogen stoves
  - While the technology has been proven (at least for outdoor use) there are currently no manufacturers retailing hydrogen stoves, or burners which can be retrofitted into existing stoves.
  - One US company retailing a hydrogen BBQ is no longer operating
  - The technology is very simple and trial versions could be made by a qualified gas technician.
- Catalytic hydrogen burners
  - There are currently no catalytic hydrogen burners available commercially
  - Demonstration examples have been developed, for example, by the Fraunhofer Institute for Solar Energy Systems in Germany.
  - Catalytic burning is fundamentally a very simple technology which has been in use since the 19th century.
- Hybrid systems
  - There are no known demonstration or commercial examples of stoves using LPG blended with hydrogen, and the cost of blending equipment may outweigh any potential benefit.
  - Flame-assisted catalytic burning has been demonstrated, but there are no known commercial examples

Key considerations

- The primary barrier to hydrogen cooking in the H&Is is the lack of a safe, simple, reliable and viable technology.
  - The principal safety concern for hydrogen burners is the invisible flame (burning hydrogen cannot be detected with the naked eye) – a significant hazard in both domestic and commercial kitchens. This is not an insurmountable barrier, but will require some innovation to overcome and is likely to add to the cost and simplicity of the technology.
  - Hydrogen stoves which are suitable for use in the H&Is would need to be serviceable with local skills.
  - Hydrogen stoves would need to be as reliable as existing LPG stoves.
  - Commercial viability needs to be demonstrated
- Any hydrogen burner technology would need to be "retrofit-able" if it was to achieve meaningful market penetration in the short to medium term.
- A hydrogen burner technology developed locally could have significant export potential (e.g. to the developing world).
- Hydrogen is much less dense than LPG and would therefore require cylinders to be changed more frequently. An alternative, decentralised, approach using a small scale wind turbine and electrolyser might be a more appropriate solution in particularly remote locations.

What next steps are required to pursue this in H&I?

- Hydrogen cooking will not proceed until a proven technology is available.
- The H&I could wait for this technology to be developed elsewhere, OR,
- Steps could be taken to develop a suitable technology locally.
- For example, a competition could be held between local companies to develop a safe, simple and reliable hydrogen burner which could be retrofitted into an existing stove.
- Once a technology is available, a small scale trial could be undertaken to develop operational experience and assess the relative merits of decentralised hydrogen generation and cylinder hydrogen.

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Marine propulsion

- Ferries and other boats (e.g. fishing and recreational boats) account for a significant amount of energy use in the H&Is.
- They operate in highly sensitive marine environments which are valuable for their biological diversity and the tourism revenue which they can generate.
- All boats use marine hydrocarbon fuels which produce emissions that can be visually polluting and harmful to human health and the biosphere.

There are three segments of the market, defined by size and length of journey

Market Segment | **Requirements**

Large – Medium haul ferries

- e.g. to the Shetlands or Outer Hebrides
- 120 cars, 700 passengers
- Approximately 8,000 kW

- Low cost operation
- Reliability, simplicity and lifetime
- Flexibility and propulsion system availability
- Power density (including fuel storage system)

Medium – Short haul ferries

- e.g. to Mull or within the Orkneys
- 30 cars, 90-100 passengers
- Approximately 3,000 kW

- Power density (including fuel storage system)
- Economic operation
- Reliability and propulsion system availability

Small – Recreation & work boats

- E.g. dive boats, small fishing boats,
- Up to 100 kW

- Very high power density (including fuel storage system)
- Reliable & safe

Hydrogen could be used in either a fuel cell or in an internal combustion engine

- Hydrogen fuel cell powered boats or ships
  - Hydrogen can be used in a fuel cell to generate electricity for electric drive systems – completely replacing existing internal combustion engines.
  - These ships would emit less local air pollution be quieter and have less vibration.
  - Navies are interested in fuel cell powered boats for their "stealth" capabilities and efficient electrical generation efficiency. Local governments in harbour cities are interested because of their better emissions performance.
- Hydrogen internal combustion engine boats or ships
  - Hydrogen cannot be used in a conventional diesel engine, because its auto-ignition temperature is too high
  - However, this can be overcome by fitting diesel engines with spark plugs or by using a small amount of diesel (e.g. 10-15% of fuel requirements) to ignite the gas (known as "pilot ignition")
  - Hydrogen and diesel co-combustion

Neither hydrogen technology is currently competitive for application in marine propulsion

- Hydrogen fuel cells
  - Currently have significantly lower power density than medium and high speed diesels, however, they have the technical potential to perform significantly better.
  - They are also significantly more expensive than diesels
  - The low density of hydrogen means refuelling is required far more frequently – as a result, much technology development is focusing on converting existing hydrocarbon fuels to hydrogen with on-board reformers or to directly run appropriate fuel cell technology on naval liquid fuels (after desulphurisation).
- Hydrogen in internal combustion engines
  - Still being developed and no known trials for marine applications

Primary propulsion	Cost (£ per kW)	Power density – kW per kg (projected)	Power density – kW per m^3 (projected)
Medium-speed diesel	0.2	Up to 0.2	50-70
High-speed diesel	0.3	Up to 0.3	55-75
Fuel cell	1 – 1.2	~0.05 (0.2 – 0.4)	~10 (120-180)

However, there are research and demonstration projects trying to prove the viability of hydrogen fuel cells for marine propulsion

- ZEMSHIPS project (zero emission ships)
  - Hamburg
  - 100 passenger tourist boat with 60 kW fuel cell
  - Conventional Alster vessel with on-board compressed hydrogen storage
- New-H-Ship project
  - Assessed technology barriers to hydrogen fuel cell power ships
  - Defined research agenda
  - Aimed to establish demonstration project, however, this was not awarded funding

What next steps are required to pursue this in H&I?

- Hydrogen for primary propulsion power in ships is currently not viable in the H&Is:
  - Hydrogen fuel cells do not meet performance criteria for boats/ships yet – in particular power density, life time and cost must be improved
  - Hydrogen internal combustion engines for boats/ships have not yet been technically proven
- HIE and its industrial partners should stay aware of opportunities to become involved in research projects (e.g. at the EU level) which are attempting to make technological breakthroughs in the area of hydrogen marine propulsion. A competitive advantage that the H&I can offer in this area is the diversity of ships and, potentially, low cost renewable hydrogen.
- Monitor the activities of the recently founded Marine Hydrogen and Fuel Cell Association.