Hy4Heat

demonstrating
hydrogen for heat

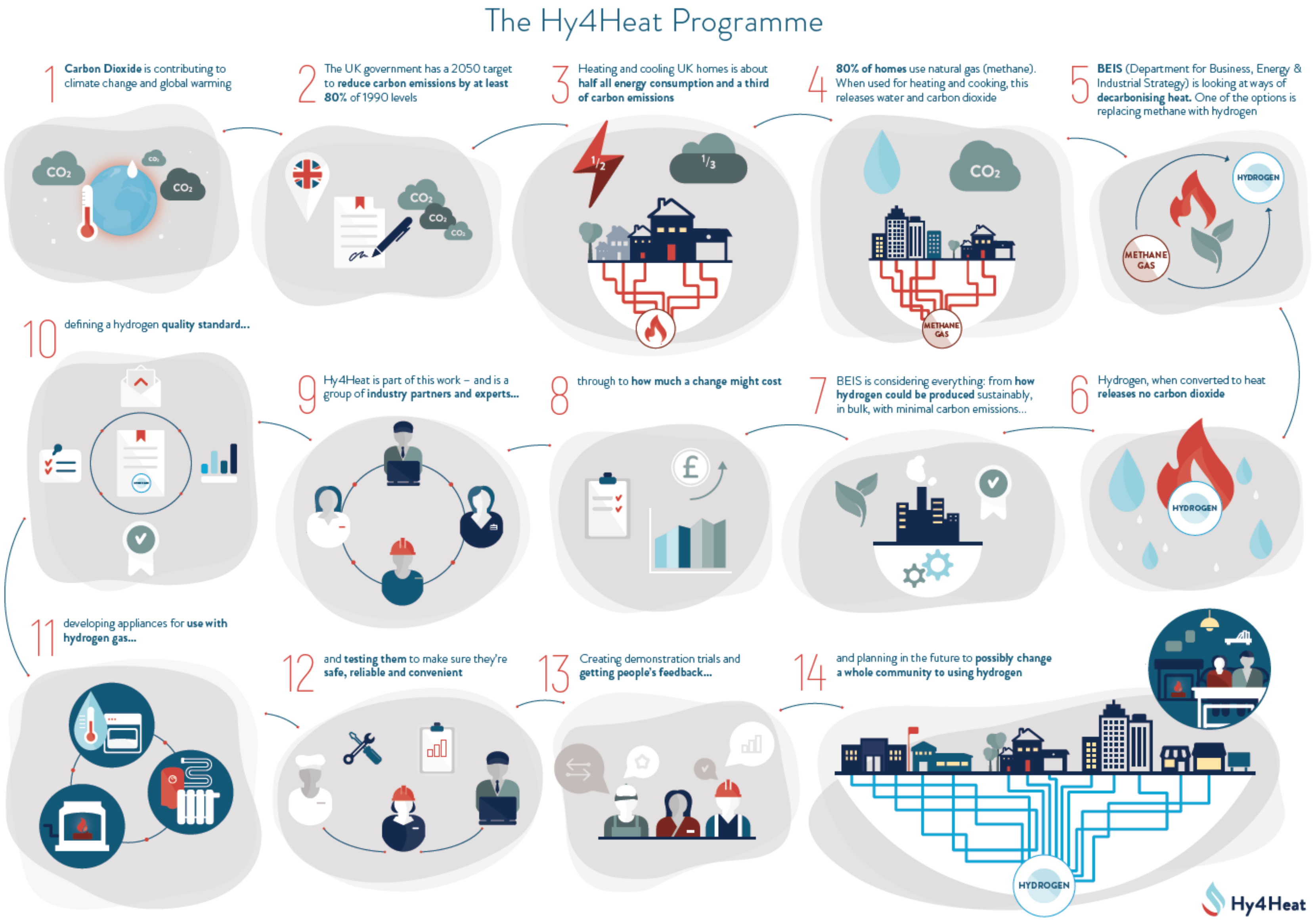
Presentation of the Hy4Heat Hydrogen Purity Report

Agenda

Welcome and introduction	**Jeremy Few**, Hy4Heat Work Package Manager
Developing a Hydrogen Purity Specification	**DNV-GL**
Break	**All**
Production and purification cost benefit analysis	**Element Energy**
Q&A	**All**
Networking lunch	**All**

Jeremy Few

Hy4Heat Work Package Manager



www.hy4heat.info

@Hy4Heat

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- Quarterly Newsletter
- Progress Reports
- Updates
- Documents/ITTs etc

Developing a Hydrogen Purity Specification

Colin Heap & Martin Brown – DNV GL

24 July 2019

Hy4Heat WP2 Objectives

Hydrogen Purity

To evaluate the varying hydrogen purity levels available in the UK and the potential impacts and cost effectiveness of introducing hydrogen at these quality levels into the wider distribution network and to recommend a purity level for use by the Hy4Heat programme.

Flame Colourant

To determine if there is a requirement for adding a colourant to hydrogen to ensure safe burning and user acceptance is achieved. Investigate the optimum solution if a colourant is required.

DNV GL

12,000 employees

150+ years

100+ countries

100,000+ customers

5% R&D of annual revenue

MARITIME

OIL & GAS

ENERGY

BUSINESS ASSURANCE

DIGITAL SOLUTIONS

Technology & Research

Global Shared Services

DNV GL - History

- Advantica, now part of DNV GL, and the Gas Networks have shared origins as they all were de-merged from British Gas
- The legacy KEMA part of DNV GL brings expertise in electricity

1963 – Establishment of integrated gas company (Gasunie)

1972 / 1996 – Establishment of British Gas ('72) and British Gas R&D ('96)

1997 – Demerger of British Gas Corporation in BG Group and Centrica

2000 – Demerger of National Grid, BG Group and Advantica (R&D)

2005 – Unbundling of transport & trading activities

2007 – Germanischer Lloyd acquires Advantica

2009 – Gasunie Research is bought by KEMA

2011 – KEMA merges with DNV to form DNV KEMA

2013 – DNV and GL merge to form DNV GL

Today DNV GL works extensively across European and global markets and regulatory regimes

Our Partners

- The **NPL** Gas and Particle Metrology Group supports the UK's energy industries with their existing and future measurement needs and has become a centre of expertise for standards for hydrogen as a fuel.
- **Element Energy** has worked in the hydrogen sector for over 15 years and has gained a deep understanding of the techno-economics of hydrogen technologies including generation, transport, storage and end-use appliances.
- **HSL** is one of the UK's leading health and safety research facilities. For over 15 years, HSL has been involved in understanding and communicating the safety aspects of emerging hydrogen energy technologies
- The Low Carbon Technology group at **Loughborough University** specialises in energy conversion through combustion and fuel cell technology with a focus on Hydrogen as a fuel source, additives and their effect on appliances.

NPL National Physical Laboratory

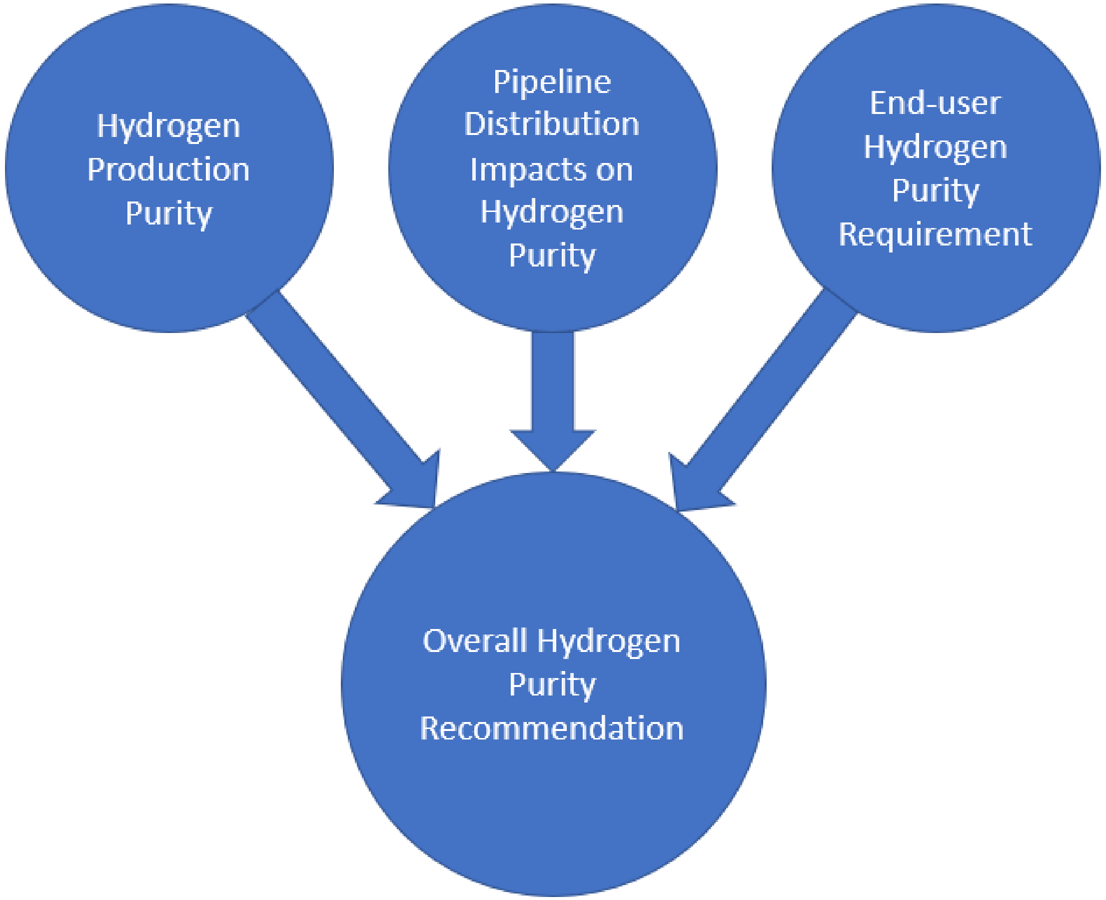
elementenergy

HEALTH & SAFETY LABORATORY

Loughborough University

Hydrogen Purity

- Hydrogen can be “super” pure but this comes at an increased cost
- Traditional end users (boilers, cookers and fires) don’t need “super” pure hydrogen
- Experience on natural gas and town gas suggests they will be able to operate efficiently and effectively with small concentrations of trace components
- Pipeline networks require limits on some trace components but could also be a source of some trace components



Hydrogen Purity Specification – Our Approach

Proposed Hydrogen Purity Specification

- What's achievable from a production point of view
- Key network requirements
- Stakeholder views on requirements for end users
- Overall Health & Safety concerns
- Robust technical approach linked to standards

Hydrogen Purity Specification – Our Methodology

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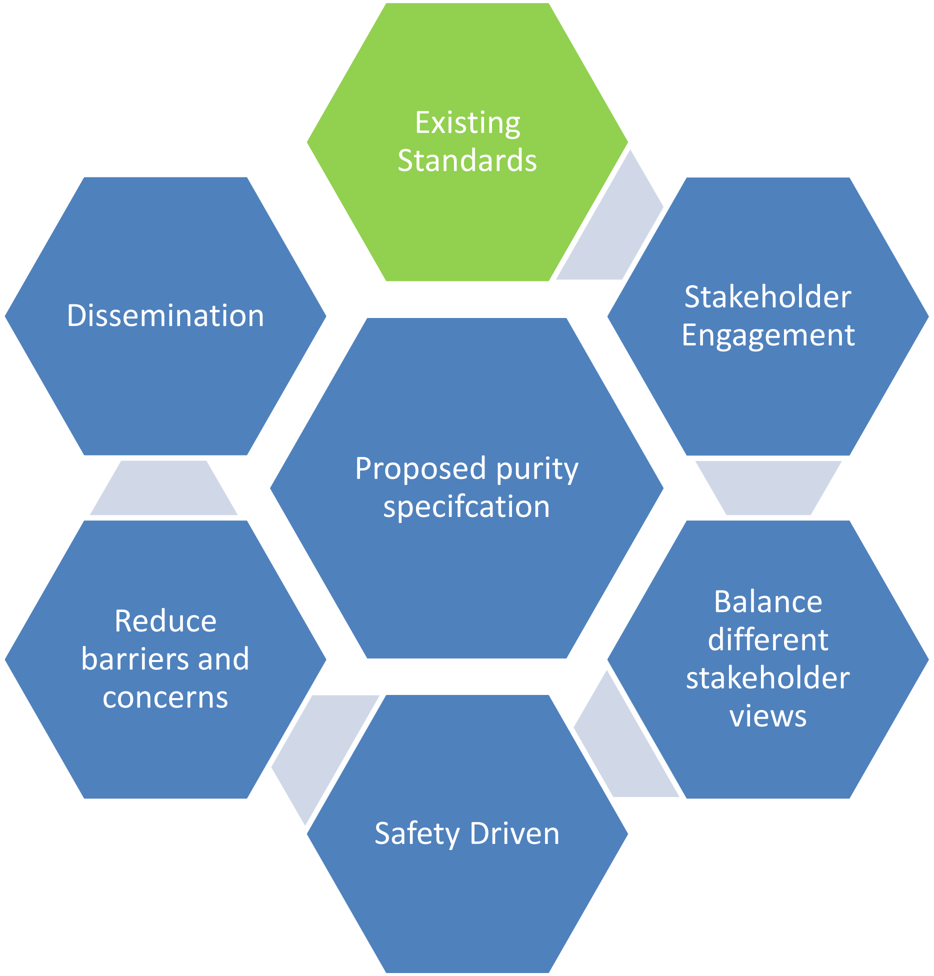
- Literature review undertaken on existing quality recommendations for hydrogen used for heating



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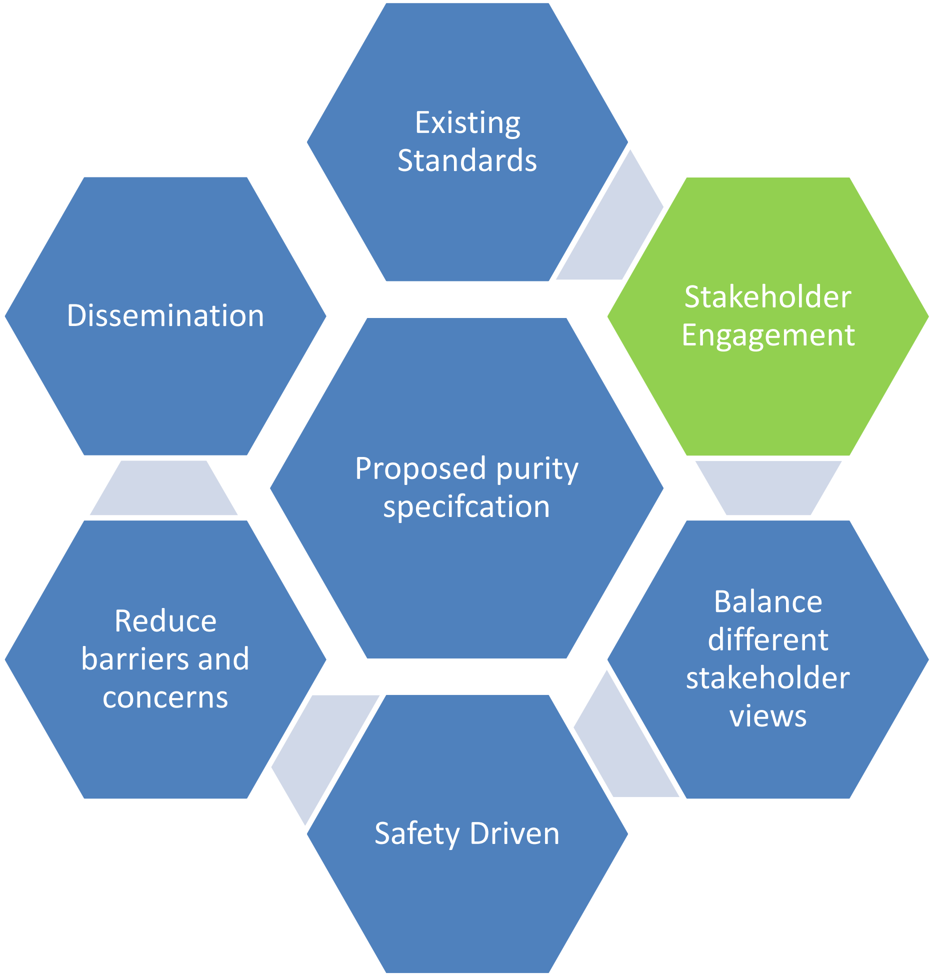

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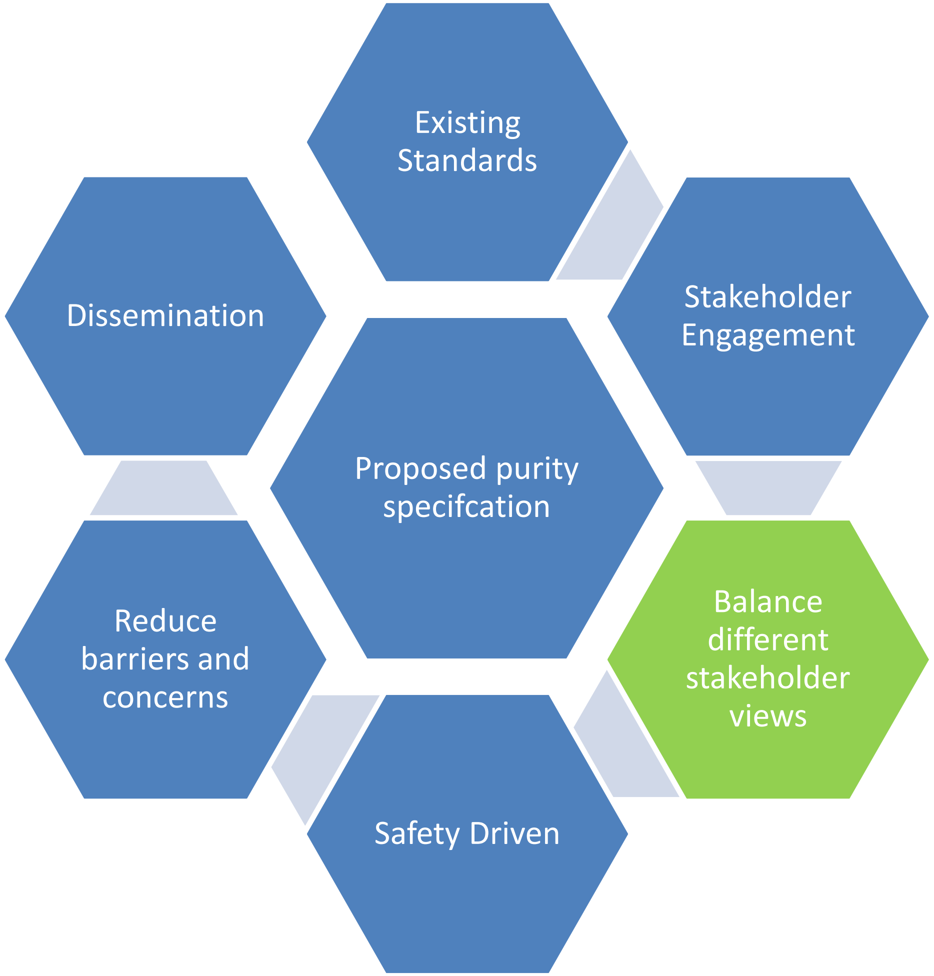

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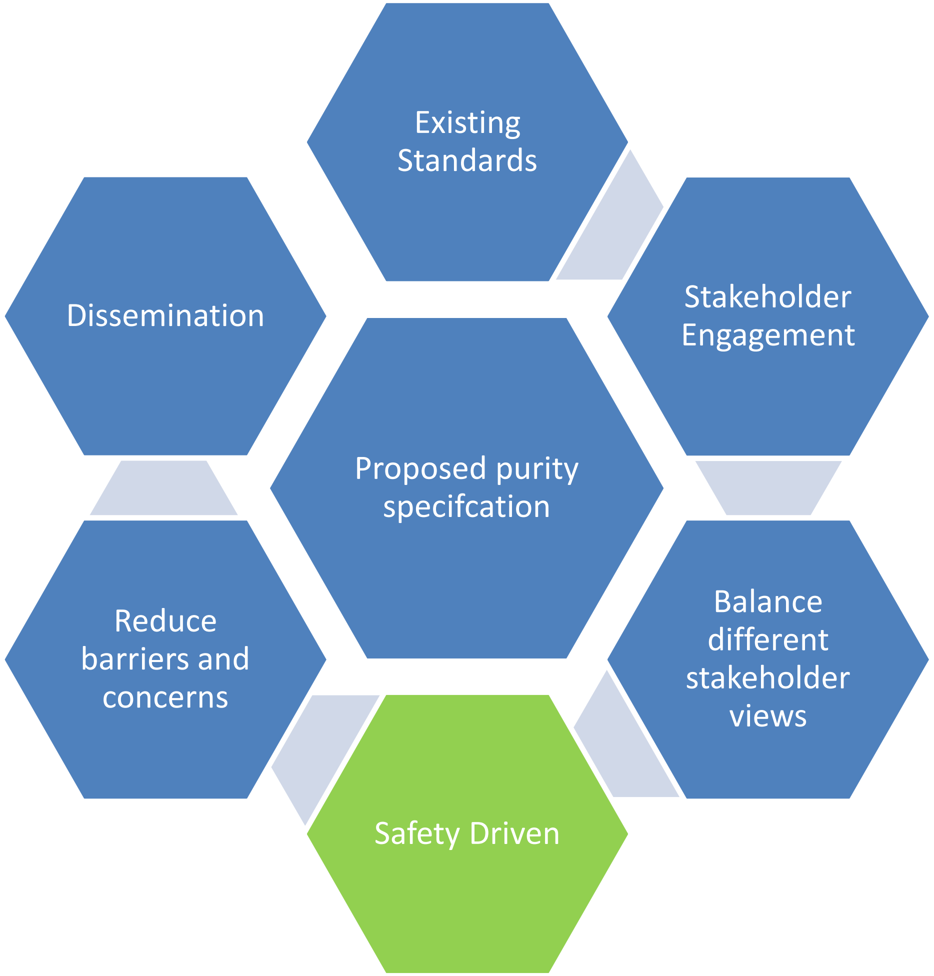

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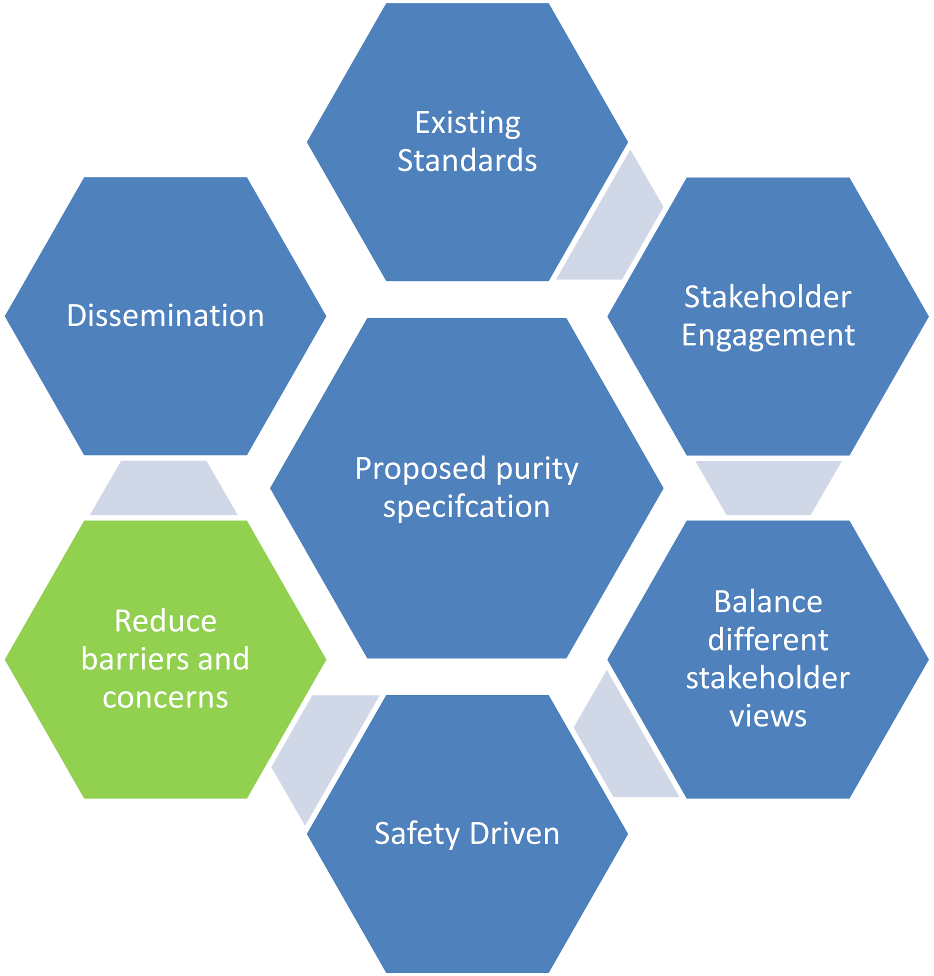

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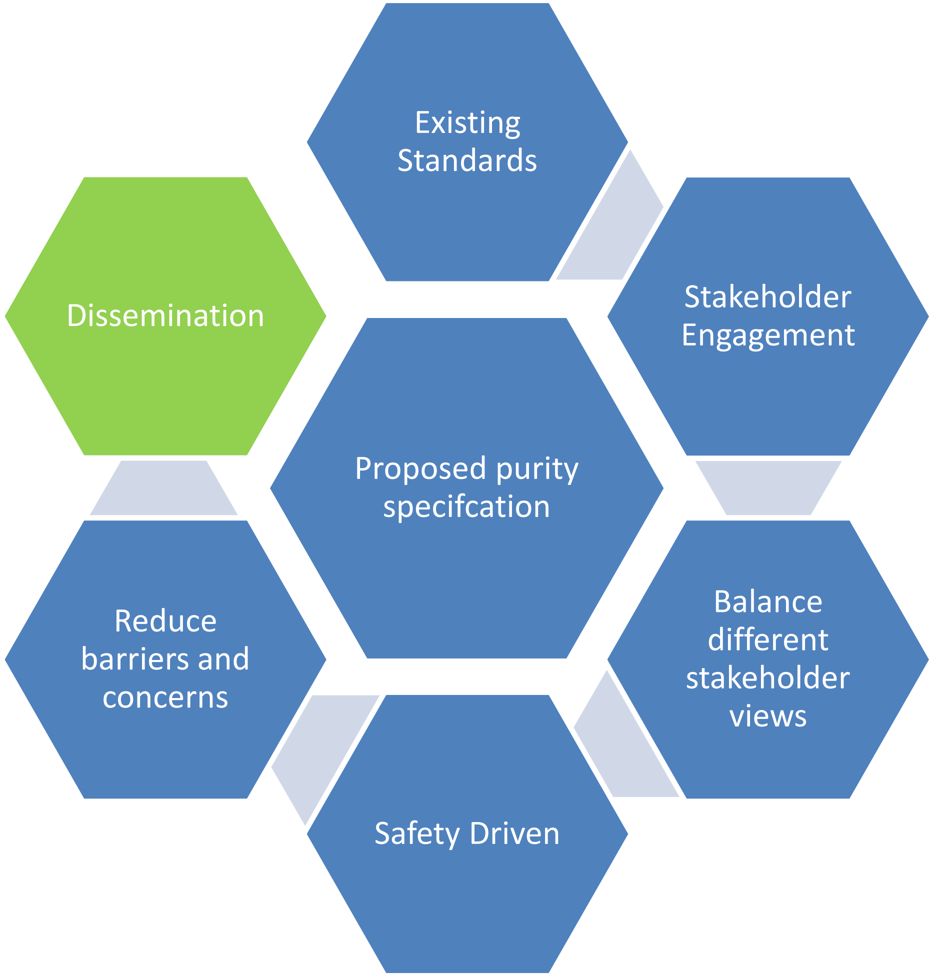
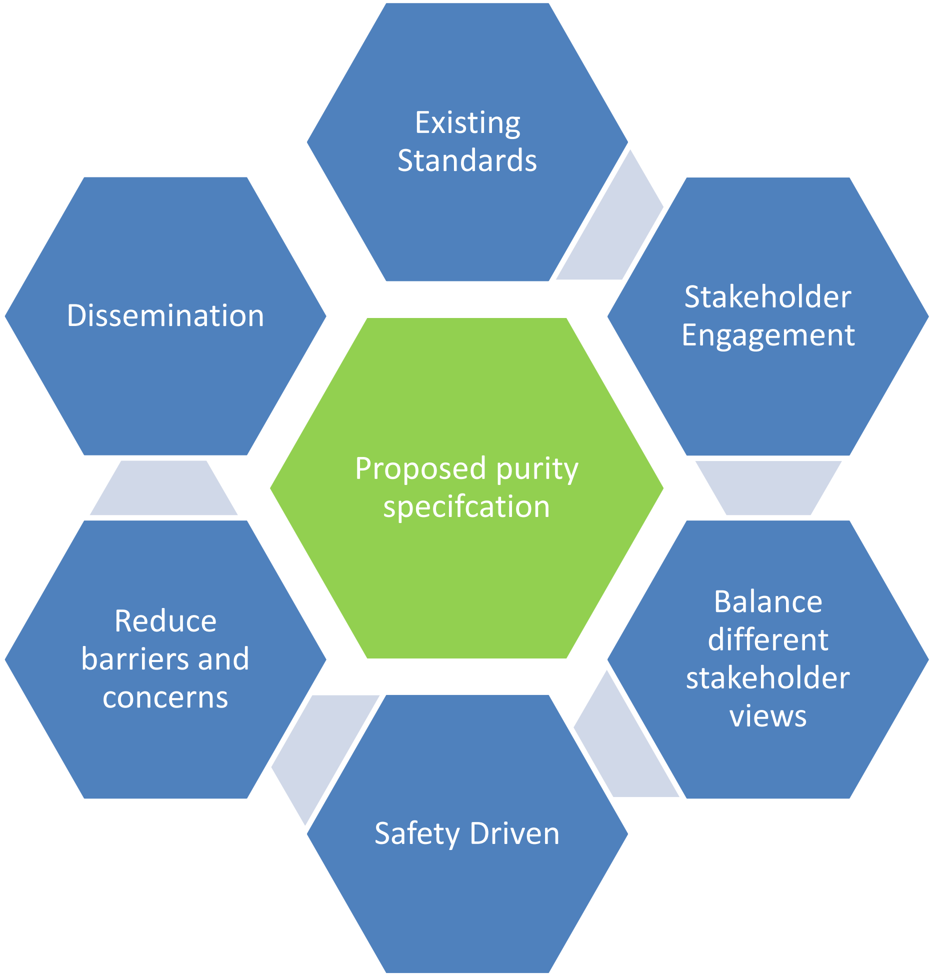
- Challenge and review – focus is on domestic utilisation
- Purity table sent out to industry contacts and presented today



Hydrogen Purity Specification – Our Methodology

AIM

- Looking to establish an agreed specification that the next stages of the Hy4Heat programme can endorse and use.



Existing Standards

Document number	Title	Year of publication	Author	Comments
GSMR 1996	Gas safety (management) regulations 1996	1996	Health and safety executive	Technical specifications for natural gas quality in the UK
EIGA IGC Doc 15/06/E	Gaseous hydrogen stations	2006	EIGA	No specific purity requirements are specified although the use of gas purity analysers is mentioned
E10064-TB10.25	EASEE-gas – Gas quality specification	2010	EASEE-gas	This document provides a proposal for natural gas quality in Europe
EIGA IGC Doc 121/14	Hydrogen pipeline systems	2014	EIGA	Appendix I includes something on purity
EN 16726	Gas infrastructure - Quality of gas - Group H	2015	CEN TC 234	Provides quality of gas for Group H gas which has a Wobbe Index between 45.7 MJ m^{-3} and 54.7 MJ m^{-3}
SAE J2719	Hydrogen fuel quality for fuel cell vehicles	2015	SAE Fuel Cell Standards	US standard - hydrogen purity specifications for fuel cell vehicles (aligned with ISO 14687-2)
KIWA 20686	DECC Desk study on the development of a hydrogen-fired appliance supply chain	2016	KIWA / E4tech	Provides purity requirements for the Giacomini hydrogen boiler
H21 final	H21 final report	2016	H21	Information is provided on recommended purity for hydrogen in the grid
BCGA CP 41	The design, construction, Maintenance and operation of filling stations dispensing gaseous fuels	2016	BCGA	Recommendations are provided for fuel quality for hydrogen and natural gas at refuelling stations
EN 16723	Natural gas and biomethane for use in transport and biomethane for injection in the natural gas network - Automotive fuels specification	Part 1 – 2016 Part 2 - 2017	CEN TC 408	Guidance on quality requirements on biomethane for fuelling vehicles and injection to the grid (including additional impurities specific to biogas such as siloxanes)
EN 17124	Hydrogen fuel - Product specification and quality assurance - Proton exchange membrane (PEM) fuel cell applications for road vehicles	2018	CEN TC 268 WG5	Guidance on purity specifications and quality control for hydrogen refuelling stations
ISO 14687 (Previously ISO 14687-1, 2 & 3)	Hydrogen fuel quality - Product specification	(2019)	ISO TC 197 WG27	Hydrogen purity specifications for fuel cell vehicles, stationary fuel cells and non-PEM fuel cell applications such as hydrogen boilers and cookers

Starting point - ISO 14687 (Type 1 Grade A)

Type	Grade	Category	Applications
I Gas	A	-	Gaseous hydrogen; Internal combustion engines for transportation; Residential/commercial combustion appliances (e.g. boilers, cookers and similar applications)
	B	-	Gaseous hydrogen; Industrial fuel for power generation and heat generation except PEM fuel cell applications
	C	-	Gaseous hydrogen; Aircraft and space-vehicle ground support systems expect PEM fuel cell applications
	D	-	Gaseous hydrogen; PEM fuel cells for road vehicles
	E	PEM fuel cells for stationary appliances	
		1	Hydrogen based fuel; High efficiency/low power applications
		2	Hydrogen based fuel; High power applications
		3	Gaseous hydrogen; High power/high efficiency applications
II Liquid	C	-	Aircraft and space-vehicle on-board propulsion and electric energy requirements; Off-road vehicles
	D	-	PEM fuel cells for road vehicles
III Slush	-	-	Aircraft and space-vehicle on-board propulsion

Key

PEM: Proton Exchange Membrane

Note 1 – Grade D may be used for other fuel cell applications for transportation including forklifts and other industrial trucks if agreed upon between supplier and customer.

Note 2 – Grade D may be used for PEM fuel cell stationary appliances alternative to Grade E category 3.

Note 3 – It should be recognised that biological sources of hydrogen can contain additional constituents (e.g. siloxanes or mercury) that can affect the performance of the various applications, particularly PEM fuel cells, however these are not included in most of the following specifications due to insufficient information.

Hydrogen fuel index (minimum mole fraction, %)	98.0 %
Para-hydrogen (minimum mole fraction, %)	Not specified
Total gases	20 000 $\mu mol\ mol^{-1}$
Water (H_2O) (mole fraction, %)	Non-condensing at all ambient conditions
Total hydrocarbon	100 $\mu mol\ mol^{-1}$
Oxygen (O_2)	b
Argon (Ar)	b
Nitrogen (N_2)	b
Helium (He)	
Carbon dioxide (CO_2)	
Carbon monoxide (CO)	1 $\mu mol\ mol^{-1}$
Mercury (Hg)	
Sulphur (S)	2.0 $\mu mol\ mol^{-1}$
Permanent particulates	g
Density	

[b] Combined water, oxygen, nitrogen and argon; maximum mole fraction of 1.9 %.

[g] The hydrogen shall not contain dust, sand, dirt, gums, oils or other substances in an amount sufficient to damage the fuelling station equipment or the vehicle (engine) being fuelled

Stakeholder Engagement

Examples of stakeholder feedback …

"There is no merit in mixing reactive gases with non-reactive gases, or non-reactive gases with water"

We agree, the hydrogen content should be high (as the CV is relatively low already)

"Should calorific value and specific density be included?"

Hydrogen content between 98% and 100% doesn't impact the CV to any great extent but Wobbe Number (or density) can change significantly.

"Carbon monoxide should be set at 200 ppm for health considerations"

Need to balance purification ability (cost) and safety of users/engineers who may come into contact with "neat" gas – 200 ppm is high though.

"It should be noted that Grade A is actually the old PEM fuel cell grade, so is massively overkill for hydrogen combustion"

We agree – we would not suggest taking ISO 14687 Grade A directly, as we need to consider domestic appliance use and pipeline delivery

GS(M)R 1996 – use the key factors from an established UK gas supply

Content or characteristic	Value
Hydrogen sulphide content	≤ 5 mg m^{-3}
Total sulphur content (including H_2S)	≤ 50 mg m^{-3}
Hydrogen content	≤ 0.1% (molar)
Oxygen content	≤ 0.2% (molar)
Impurities	Shall not contain solid or liquid material which may interfere with the integrity or operation of pipes or any gas appliance (within the meaning of regulation 2(1) of the 1994 Regulations) which a consumer could reasonably be expected to operate
Hydrocarbon dewpoint and water dewpoint	Shall be at such levels that they do not interfere with the integrity or operation of pipes or any gas appliance (within the meaning of regulation 2(1) or the 1994 Regulations) which a consumer could reasonably be expected to operate
Wobbe number (WN)	47.20 MJ m^{-3} ≤ WN ≤ 51.41 MJ m^{-3}
Incomplete combustion factor (ICF)	≤ 0.48
Sooting index (SI)	≤ 0.60

Hydrogen Purity Specification

Content or characteristic	Value	Rationale
Hydrogen fuel index (minimum mole fraction)	98 %	Aim is to have a threshold value that meets user requirement.
Carbon monoxide	20 ppm	A practical engineering limit based on achievable production limits and to meet long term exposure limits HSE EH/40)
Hydrogen sulphide content	≤ 3.5 ppm	These values are taken from GS(M)R:1996 as any detrimental effects would be similar for hydrogen and natural gas.
Total sulphur content (including H_2S)	≤ 35 ppm	
Oxygen content	≤ 0.2 % (molar)	
Hydrocarbon dewpoint	-2 ^{o}C	Complies with GSMR:1996 and EASEE-gas
Water dewpoint	-10 ^{o}C	
Sum of methane, carbon dioxide and total hydrocarbons	≤ 1% (molar)	No combustion impacts and to reduce carbon emissions
Sum of argon, nitrogen and helium	≤ 2% (molar)	To avoid transporting inert gases and to limit the impact on Wobbe Number
Wobbe Number range	42 – 46 MJ m^{-3}	Range and percentage variation based on natural gas range in GS(M):R1996
Other impurities	Shall not contain solid, liquid or gaseous material that might interfere with the integrity or operation of pipes or any gas appliance, within the meaning of regulation 2(1) of the Gas Safety (Installation and Use) Regulations 1998, that a consumer could reasonably be expected to operate	

Hydrogen Content

- The **hydrogen content** in the purity specification has been discussed with stakeholders

- 98% minimum hydrogen content is viewed as a reasonable and pragmatic value.

- The range and quantity of trace components reflects those from existing hydrogen standards and natural gas quality requirements.

- The overall view is that
  - large scale hydrogen production systems can produce hydrogen purity to meet these limits
  - the concentration of trace components will not impact on the overall hydrogen fuel utilisation in traditional domestic appliance designs

Total Sulphur Content

- **Total Sulphur content** is akin to that for the current natural gas pipeline limits (as set out in the GS(M)R and includes
  - consideration of the sulphur content of odorant
  - the sulphur that may be adsorbed onto internal pipe walls and
  - any sulphur introduction through the hydrogen production process.

- As the current limit is achievable for natural gas, it is not anticipated to be a barrier for hydrogen pipeline networks.

- The proposed specification for sulphur content at 35 ppm means that the hydrogen gas is not directly suitable for solid oxide fuel cell CHP (SOFC CHP) or PEM fuel cell CHP (PEMFC CHP) which require less than 1 ppm and 4 ppb of sulphur compounds respectively.

Carbon Monoxide

- **Carbon Monoxide** has received the most stakeholder feedback and a limit of 20 ppm is proposed for the Hy4Heat trials.

- The rationale for this limit is a balance between:
  - the practicality of achieving the desired purity and the impact on cost (and maintaining several purification technology options)
  - ensuring that exposure to carbon monoxide is within the current HSE EH/40 occupational health guidelines.

- The EH/40 long term exposure limit (in the recently revised document) is 20 ppm and this is proposed as the appropriate upper limit in hydrogen

Oxygen

- The **Oxygen** content limit relates to the management of internal corrosion of the pipe and ensuring pipeline integrity.

- Although it is recognised that for accelerated corrosion the presence of both water and oxygen is required, it is deemed appropriate to adopt a current natural gas limit for oxygen content.

- This limit does not impact on hydrogen production costs and can be met readily.

Hydrocarbons and Inert Gases

- The **sum of hydrocarbons** limit focuses on the carbon content of the hydrogen fuel.
- This should be minimised to ensure that the maximum carbon emission reduction is obtained, and also hydrocarbons could impact on some utilisation processes.

- The **sum of inert gases** limit has been included to avoid significant impact on the Wobbe Number and transportation of gas with no calorific value that has no benefit to the end user.
- The limits have been proposed based on achievable levels from production processes.

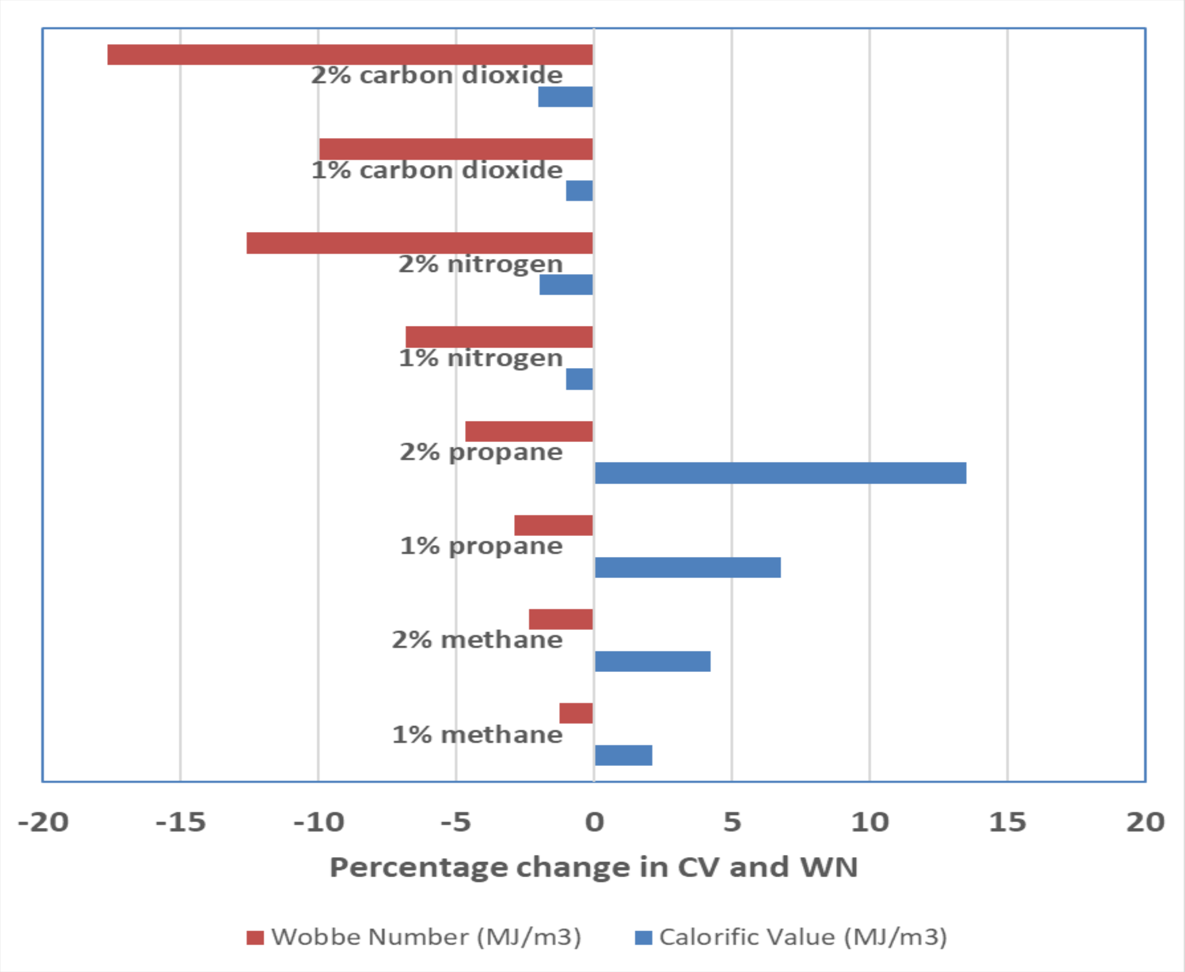
Dewpoint

- **Dewpoint** limits for water and hydrocarbons are included in the specification to avoid formation of a liquid phase in the pipe
- Water promotes pipe corrosion, especially when there is carbon dioxide & hydrogen sulphide present
- Two phase flow in pipelines must be avoided and the limits for natural gas in the UK are proposed as suitable values for hydrogen networks
- Water dewpoint is a key factor as water is used in many hydrogen production processes. Dehydration technologies are available so meeting the proposed specification should not impact significantly

Wobbe Number

- Wobbe Number has been included in the Purity Specification to meet the requirements from traditional burner manufacturers

- Wobbe Number is an important aspect as the variation can be significant if heavier trace components like carbon dioxide are present
  - Addition of small quantities of hydrocarbon increases the CV but decreases the WN
  - Addition of small quantities of nitrogen or carbon dioxide decreases both CV and WN
  - A decrease of 10% in the WN is significant



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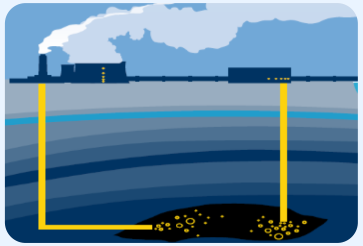
Production & Purification cost Benefit Analysis

Louis Day & Sam Foster – Element Energy

24 July 2019



Hy4Heat Purity specification

Production and purification cost benefit analysis

24/07/2019

Element Energy Ltd

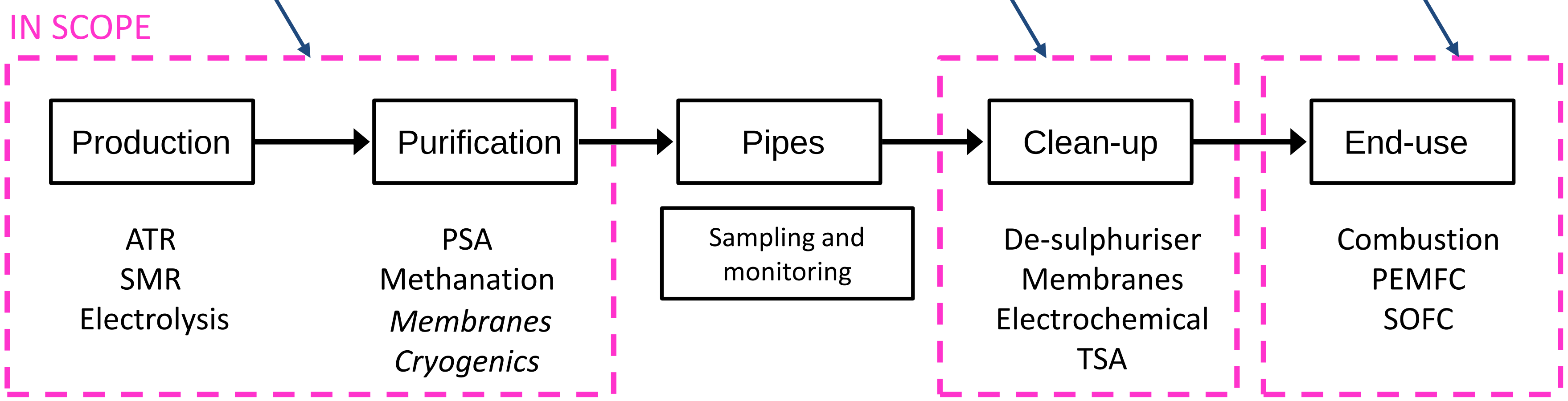
Louis Day louis.day@element-energy.co.uk
Sam Foster sam.foster@element-energy.co.uk

There is a trade-off in purity between costs to the producer and end user

Additional production costs with increasing purity calculated using:
- Hydrogen producer consultation
- Literature values

Indicative **cost of downstream clean-up** calculated using:
- Appliance supplier consultation
- Target costs of prototype projects

Impacts on end-user of impurities evaluated using:
- Appliance supplier consultation
- Literature review



CO, H_2O and S are the key impurities with a significant impact on end-users at the levels found in production -> some purification is needed to address these

Reformation reactions:

$$1 - CH_4 + H_2O \rightleftharpoons CO + 3H_2^{*}$$

$$2 - CO + H_2O \rightleftharpoons CO_2 + H_2$$

Impact of impurities found at levels present after production

Group	Impurity	Combustion	SOFC	PEMFC
Impurities intrinsic to **reformation** produced hydrogen	CO	Unsafe	Unsafe	Catalyst poison
	CO_2	Hydrogen dilution	Hydrogen dilution	Hydrogen dilution
	CH_4		Potential carbon deposition	Hydrogen dilution
	H_2O	No condensation in pipes at -10°C	No condensation in pipes at -10°C	No condensation in pipes at -10°C
Impurities in **natural gas** and introduced in ATR O_2 source	N_2	Hydrogen dilution	Hydrogen dilution	Hydrogen dilution
	Ar	Hydrogen dilution	Hydrogen dilution	Hydrogen dilution
Impurities in **natural gas**, reduced to 50 ppb before **reformer**	S compounds		Catalyst poison (no impact at this level)	Catalyst poison
Electrolysis impurities	O_2			Degradation
	H_2O (electrolysis)	No condensation in pipes at -10°C	No condensation in pipes at -10°C	No condensation in pipes at -10°C

*ATR reaction differs slightly in stoichiometry. Trace reformation impurities such as formaldehyde, ammonia and formic acid removed during amine wash and in condensate.

PSA and methanation are the main options to remove water and carbon monoxide from reformer-produced hydrogen

PSA

- A PSA can remove all impurities found with varying strengths.
- A PSA is the industry standard for purifying hydrogen and can reach the 99.97% required by PEMFC.

RELATIVE STRENGTH OF ADSORPTION

+	++	+++	++++
He	Ar	CO	C_3H_6
H_2	O_2	CH_4	C_4H_8
	N_2	CO_2	C5+
		C_2H_6	H_2S
		C_2H_4	NH_3
		C_3H_8	H_2O

- Strength +
Alumina
Carbon Prefilter
Activated Carbon
Molecular Sieve

Strengths with which molecules are adsorbed to a PSA[1]

- A PSA uses 10% of the hydrogen product to purge its adsorbents – this can be used elsewhere.

Methanation

- Methanation can reduce CO levels to a safe level for heating applications, but drying is also needed
- H_2 is reacted with CO and CO_2 to produce methane:

$$CO + 3H_2 \rightleftharpoons CH_4 + H_2O \qquad \Delta H = -206 \text{ kJ/mol}$$

$$CO_2 + 4H_2 \rightleftharpoons CH_4 + 2H_2O \qquad \Delta H = -165 \text{ kJ/mol}$$

- CO levels of 10 ppm are achievable
- Drying is needed to remove the water produced in the process.

Note on electrolysis:

Electrolyser with de-oxygenation and drying (sometimes called TSA), is the current industry standard and meets the PEMFC ISO/DIS 14687 standard.

[1] Consonni et al. 'Decarbonized hydrogen and electricity from natural gas'. Int J Hydrogen Energy 2005;

The quality of data on production and purification costs is greater than on the downstream costs

	Quantity	Data notes	Data quality
Production costs	Basic reformer costs	Based upon H21 North of England report.	
	PSA capital and operating costs	H21 values, multiple industrial stakeholders.	
	PSA trade-off of cost with purity	Peer review literature data, with some assumption based upon stakeholder conversations.	
	Methanation capital and operating costs	Single data point from industry consultation. Drying costs estimated.	
	Methanation cost variation with purity	Not examined.	
Downstream costs	Costs of de-sulphuriser	Industry consultation.	
	Point of use clean-up (all impurities)	Uncertain costs based upon targets of prototype projects.	
	Impact of impurities on end-user	Impacts based upon review of literature and industry consultation.	

[1] Consonni et al. 'Decarbonized hydrogen and electricity from natural gas'. Int J Hydrogen Energy 2005;

Additional cost of reducing CO levels below 250 ppm are up to around £5/yr for low-carbon ATR H_2 and up to around £55/yr for SMR H_2

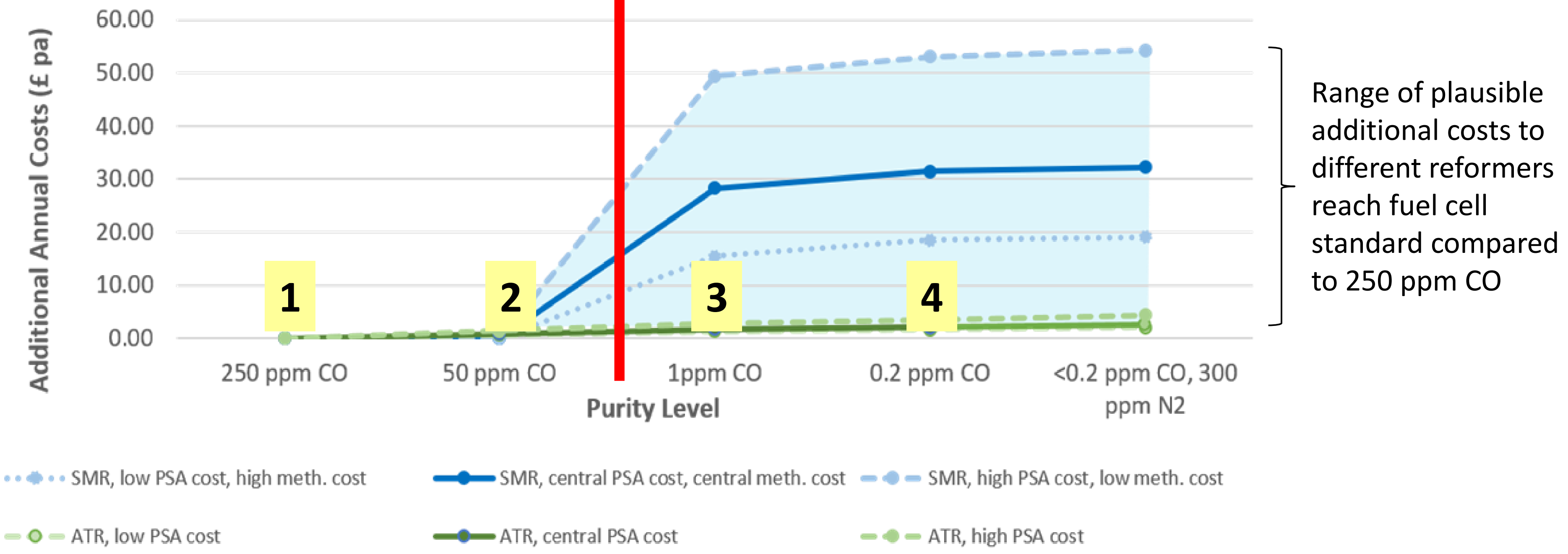
1 250ppm used as reference point

Purification:

SMR	Methanation
ATR	PSA

2 Additional PSA costs to a low-carbon ATR are small

For an SMR methanation is assumed to have negligible additional cost with purifying to 250 or 10ppm*



3 Below 10 ppm a PSA is used in place of methanation, leading to a step increase in cost for an SMR. There is no such step change for the ATR, since PSA is used at all purity levels.

4 At still lower impurity levels, for both the SMR and ATR cases, the increase in production cost is associated with the cost of using a PSA to reach increasing purity.

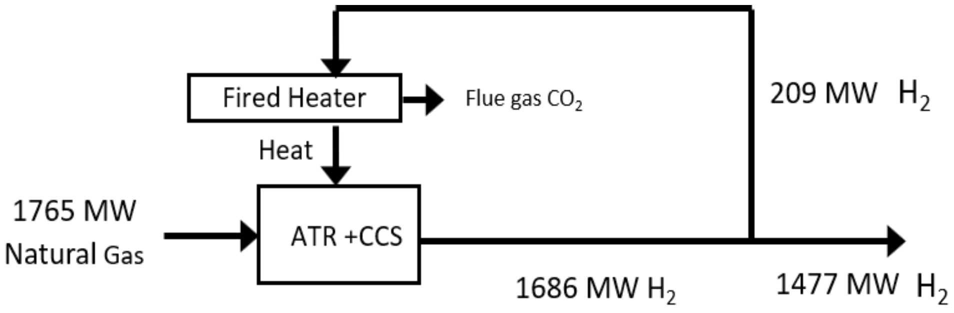
*Assuming heating end users for whom methane is usable

The two reformer options studied (ATR and SMR) produce H_2 at different carbon intensities and are impacted in different ways by PSA and methanation

- Natural gas and hydrogen flows for the two reformers considered here are displayed below.
- They are considered due to the different impacts that purification steps have on them.

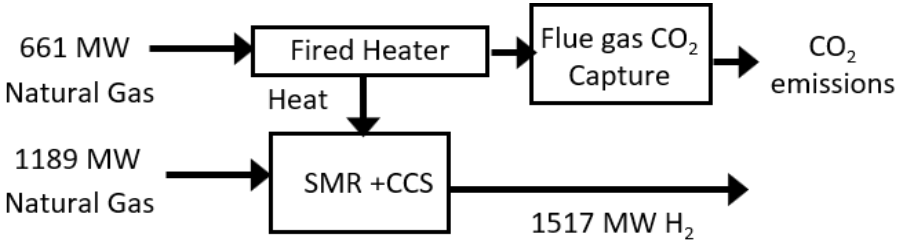
Low-carbon ATR – 8.2 g CO_2/kWh H_2

- H_2 used as fuel for fired heater
- PSA tail gas displaces H_2 product burnt
- >98% capture rate at high pressure from reformer



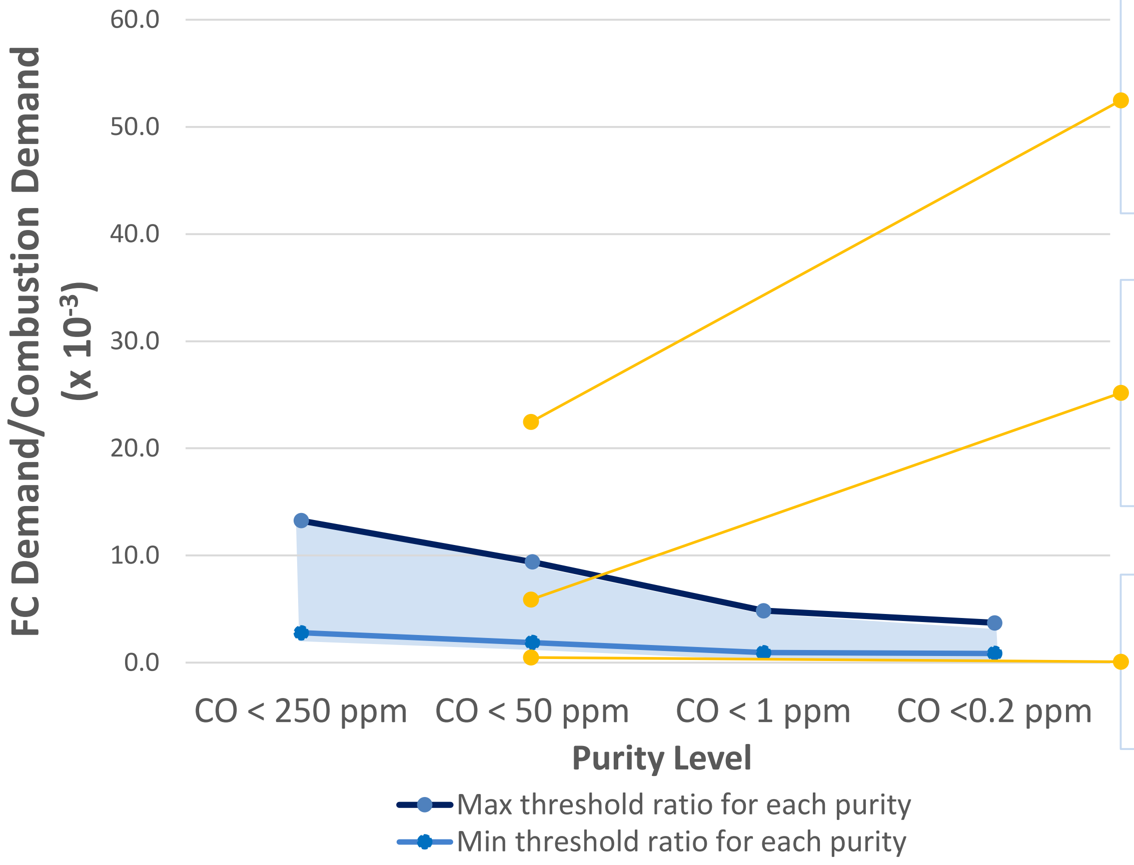
Low-carbon SMR – 20.5 g CO_2/kWh H_2

- Natural gas used as fuel for fired heater
- Significant CO_2 emissions produced at low pressure in fired heater
- Low pressure carbon capture assumed with 90% capture rate
- H_2 product amount and methane input reduced by PSA



Cost benefit trade-off with stringent emissions requirements of <9 g/kWh

- We identified a shortage of robust data on the dependence of downstream clean-up costs with purity. Fixed costs of 2-4 p/kWh were applied, based on the best-available data.
- We used the CBA to determine, under various assumptions, the ratio of FC demand / combustion demand above which producing to the PEMFC specification is lower cost than the chosen CO level[1]



Above max threshold (upper blue line)
High FC demand scenarios: overall system cost is lower when grid H_2 conforms to PEMFC standard

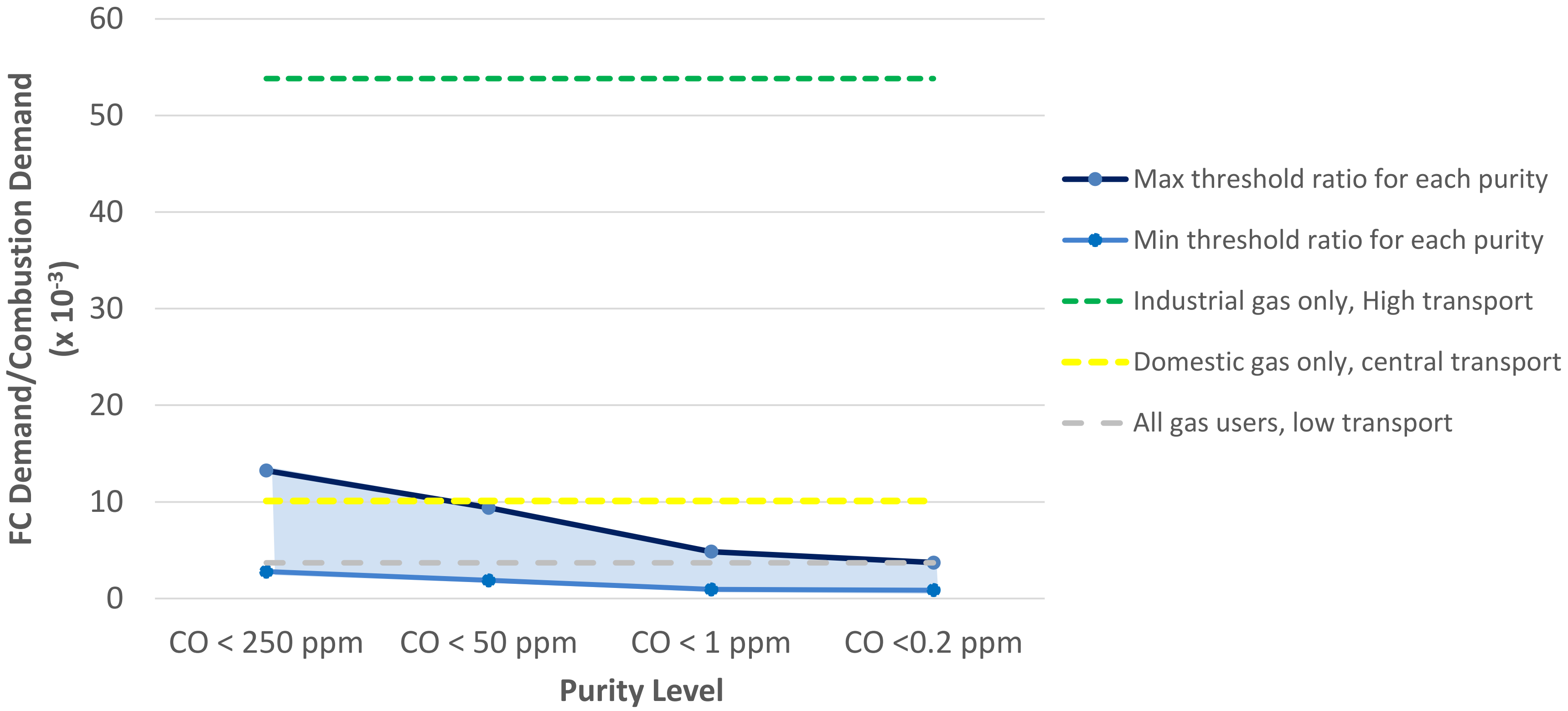
Between min and max thresholds
Scenarios within range of uncertainty: no clear conclusion on least cost H_2 standard

Below min threshold (lower blue line)
High combustion demand scenarios: system cost is lower for lower purity H_2

[1]Assuming no CO picked up in network, and impurities in network are removed using simple purification technology e.g. scrubbers and de-sulphurisers

Example H_2 scenarios with various FC to combustion demand ratios are studied for the highest emissions stringency (<9 g/kWh)

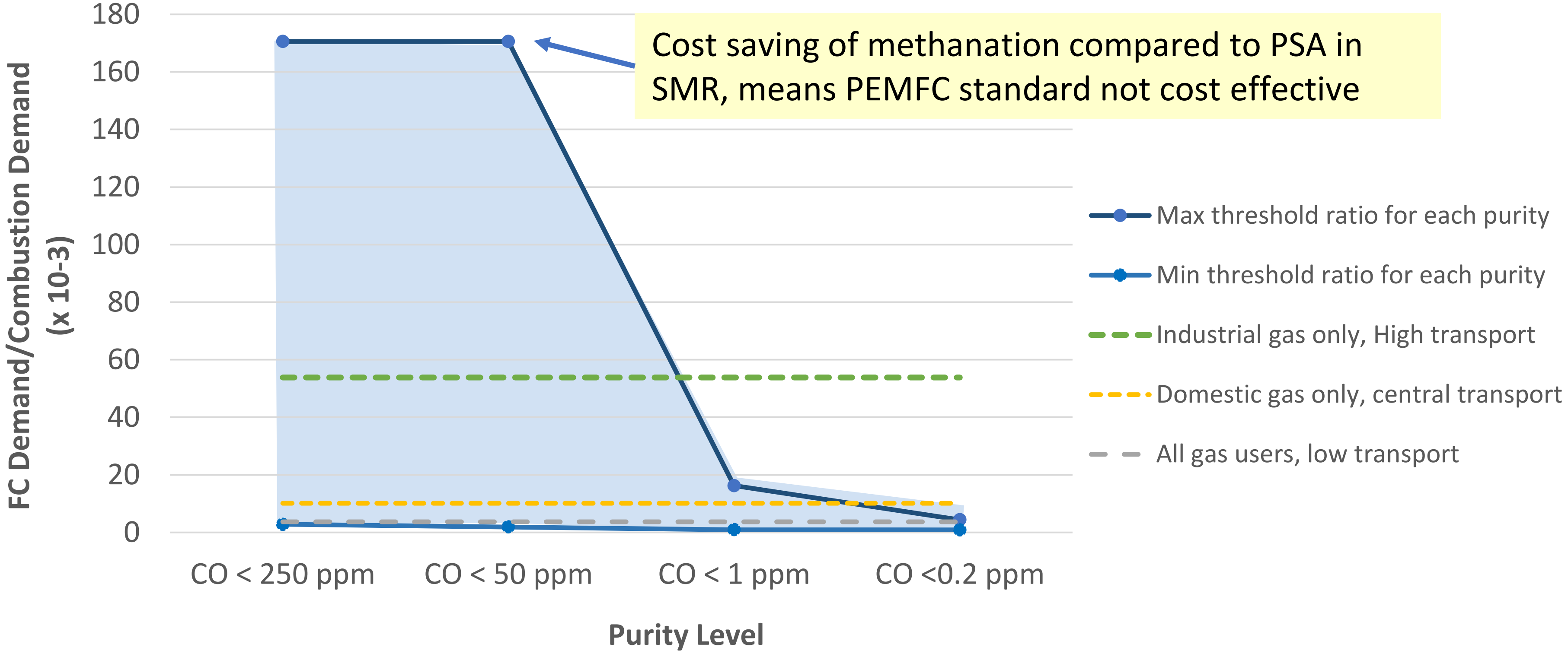
Scenario (UK-wide)	Heating demand (TWh)	2030 Transport demand (TWh)[1]
Industry only converts, high transport uptake	93	5
Domestic gas users only convert, central transport uptake	297	3
All gas users convert (incl. services), low transport uptake	483	1.8



[1] Calculated from EE industry verified UK H_2 mobility predictions for FC vehicle sales

The same analysis has been undertaken with a relaxed emissions intensity (<20 g/kWh) allowing an SMR to be used

Scenario (UK-wide)	**Heating demand (TWh)**	**2030 Transport demand (TWh)[1]**
Industry only converts, high transport uptake	93	5
Domestic gas users only convert, central transport uptake	297	3
All gas users convert (incl. services), low transport uptake	483	1.8



[1] Calculated from EE industry verified UK H_2 mobility predictions for FC vehicle sales

The Hy4Heat standard from a production and end-user perspective

Impurity	Level	Production/Purification Impact	End-user	Justification
CO	20 ppm	Both methanation and PSA can reach.	Not suitable for PEMFC	Meets HSE long term exposure limit without ruling out potentially cheaper purification option
Water dewpoint	-10 ºC	Met with PSA if CO standard met. Drying required with methanation.	Further purification required for PEMFC	Complies with GSMR:1996 and EASEE-gas
Total Sulphur	35 ppm	Met by production with no further purification.	Not suitable for PEMFC or SOFC	May be present at these levels initially in the grid. Used as a warning to be review with time.
Oxygen	≤ 0.2 %	Met by production with no further purification.	Not suitable for PEMFC	GSMR:1996
Sum of methane, CO_2, total hydrocarbons	≤ 1 %	Met with a PSA reaching CO spec. Rules out methanation with an SMR, but could be used with careful ATR design.	Not suitable for PEMFC and potential SOFC issues.	Restriction must be applied for boiler design. Lowest restriction applied
Sum of inerts	≤ 2 mol %	Met by SMR with no purification . Met with PSA meeting CO standard.	Small impact on PEMFC – could be managed	To avoid transporting inert gases with no calorific value in the and to limit the impact on Wobbe Number (see below)

Any Questions ?

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SAFER, SMARTER, GREENER

Appendix: Acronyms

ATR: Autothermal reformer

CBA: Cost benefit analysis

CCS: Carbon capture and storage

FC: Fuel cell

PEMFC: Polymer electrolyte membrane fuel cell

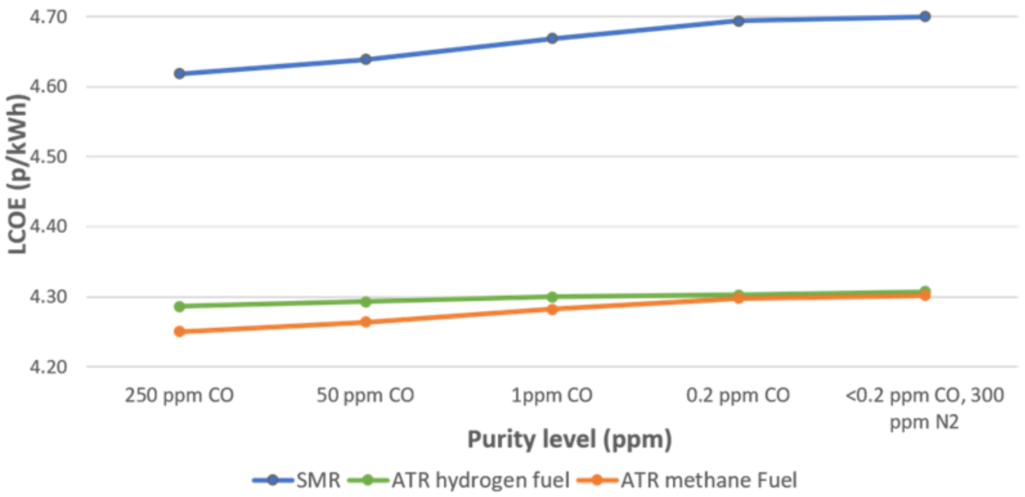
PSA: Pressure swing adsorption

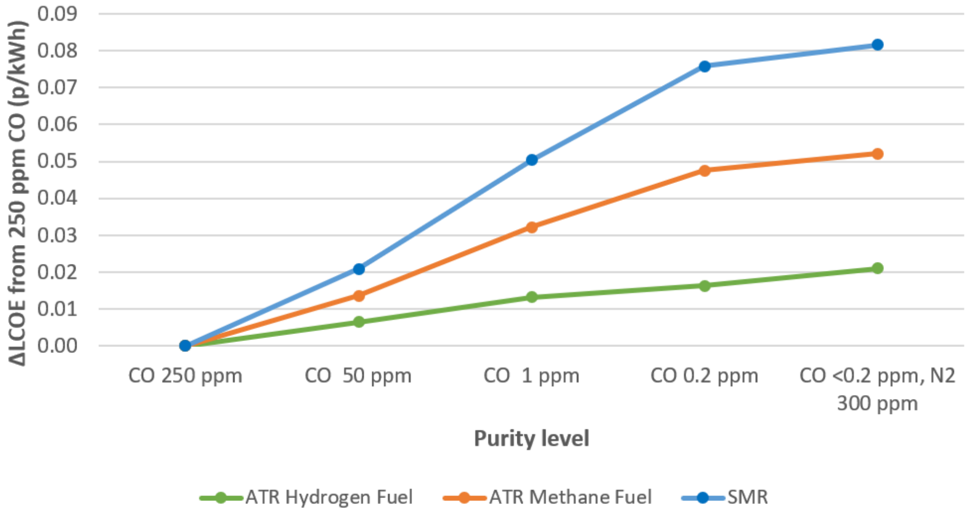
SMR: Steam methane reformer

SOFC: Solid oxide fuel cell

TSA: Temperature swing adsorption

Appendix 1 : Calculated hydrogen costs and additional costs with a PSA used to purify reformer produced hydrogen – based upon H21 reformer cost





Appendix 2 : Ranges of literature values for impurity levels produced by different production options without purification

Impurity	SMR (dry mol%)	Oxygen-Fed ATR (dry mol %)	Electrolysis (ppm)
CO	0.1-4	0.3-2	n/a
CO_2	0.35-0.7	0.7-1.7	0.2-5.4
CH_4	3.5-8	0.3-3	n/a
N_2	0-0.3	0.7	<100
Ar	n/a	0.6	n/a
H_2O	0.2– 0.4	0.2– 0.4	<100
O_2	n/a	n/a	18-500
H_2S	$< 50 \times 10^{-4}$	$< 50 \times 10^{-4}$	n/a

Here CO_2 levels are calculated assuming a capture rate of 98%