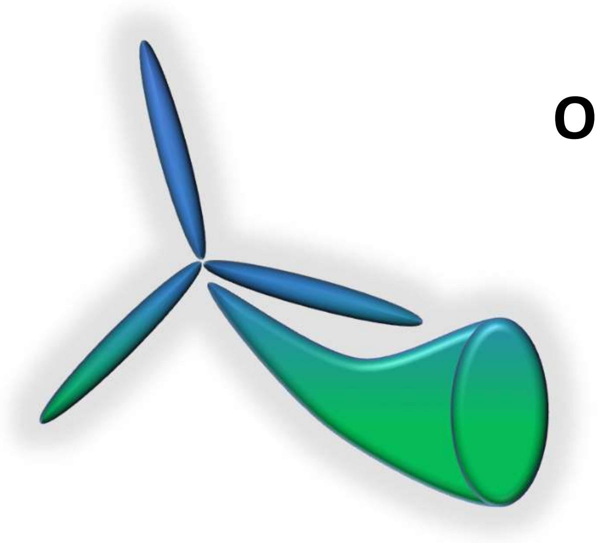
Engineering and Physical Sciences Research Council



Ocean-REFuel (Ocean Renewable Energy Fuel)

“Next generation Renewable Ocean Energy”

Cardiff University Prifysgol Caerdydd

Imperial College London

Newcastle University

University of Nottingham UK | CHINA | MALAYSIA

University of Strathclyde Glasgow

Inaugural Stakeholder Event - 06 September 2022

10:30 Ocean-REFuel Programme Overview, Professor Feargal Brennan

10:45 The Technical Workstreams

- Offshore structures, logistics and power generation, Professor Maurizio Collu.
- Power to Carbon-Free Fuel, Professor Mohamed Mamlouk.
- Carbon-Free Transportation & Storage, Professor Gavin Walker.
- Networks, Capability and Demand, Professor Robin Irons

11:45 Cross-cutting themes and Integration, Professors Nilay Shah and Karen Turner

12:15 Project Governance and Stakeholder Engagement, Professor Feargal Brennan and Dr Panagiotis Stavrakakis (HSE)

12:30 Open Discussion.

Ocean-REFuel (Ocean Renewable Energy Fuel)

“Next generation Renewable Ocean Energy”

Renewables Now

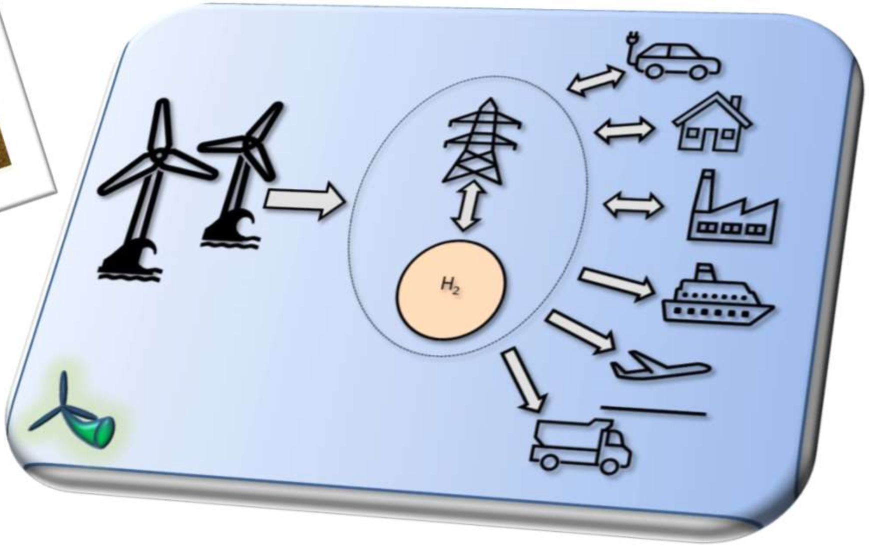
News Research Press Releases Events Advertising

Wind

UK project of GBP 10m to explore ocean energy-to-hydrogen conversion

July 26 (Renewables Now) - Glasgow's University of Strathclyde said on Friday it is leading a GBP-10-million (USD 13.8m/EUR 11.7m) research project to explore the potential of turning offshore wind and marine renewable energy into hydrogen and ammonia fuels for use in heating, energy storage and decarbonisation of transport.

The five-year Ocean Renewable Energy Fuels (Ocean-



The Context

- Tremendous success of early offshore wind spurring ambitious Government targets and investor confidence;
- The intermittency and curtailment of renewable energy resources coupled with vastly increased capacity makes energy storage increasingly important;
- There remains extremely large Ocean Energy potential which can never be fully utilised by the electricity network;
- Whereas enormous strides have been accomplished within the renewable power sector, the same can not be said for renewable heat and transport which account for more than 60% of UK energy demand;
- The Climate Emergency is being increasingly understood and the conventional Oil & Gas sector has begun to engage in the “Energy Transition”;
- **Ocean-REFuel** has the potential to establish the building blocks to ensure Ocean Energy to Fuel potential is developed to maximum effect ensuring safety, sustainability, resilience, affordability and environmental sensitivity.

Ocean-REFuel Vision: a whole Energy Systems Approach

- To establish **fundamental scientific and engineering understanding** for the conversion of Ocean Renewable Energy to liquid and gaseous fuels;
- To accelerate the development and unlock the potential of converting ocean energy into **new energy vectors** other than electricity; directly addressing challenges associated with energy storage, renewable heat and the decarbonisation of transport;
- To deliver a real **step-change** in our ability to harness offshore wind and marine renewable energy potential and contribute in a major way to the decarbonisation of the energy and transport sectors at a global scale;
- Positioning the **UK as a global leader** in Ocean Renewable Energy Fuels and developing exploitable technologies and methods for global markets.

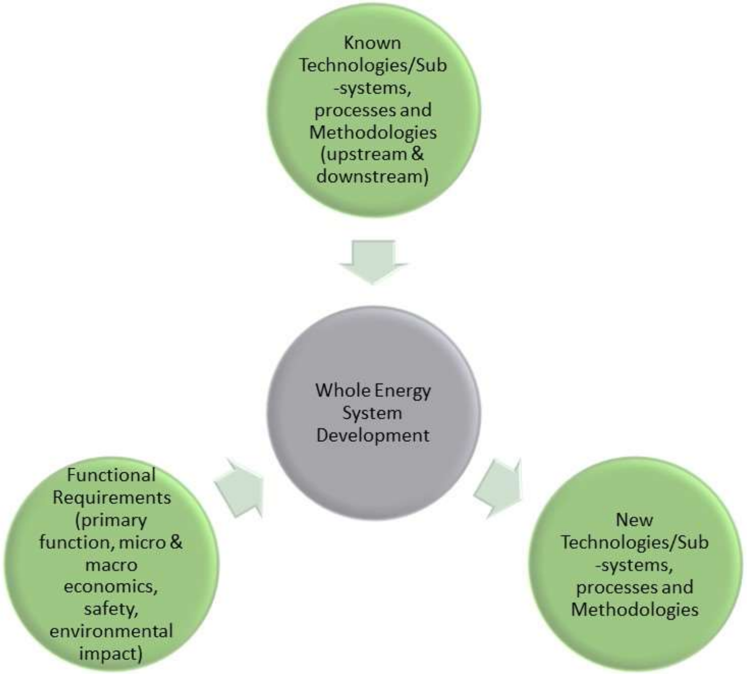
Ocean-REFuel

Cross cutting Themes

Research Workstreams	Materials	Safety	Socio Economics	Process Engineering	Environmental Impact
Offshore structures, logistics and power generation	●	●	●		●
Power to Carbon Free Fuel	●	●		●	●
Carbon Free Fuel transportation and storage	●	●	●	●	●
Networks, Compatibility and Demand		●	●		

Ocean-REFuel Deliverables

- Blueprint for the first integrated Ocean Renewable Fuel production facility;
- Solutions for flexible Ocean Renewable Energy Fuels strategies to decarbonise different sectors;
- Fully assess the opportunities and impact of Ocean Renewable Energy Fuels;
- Development of new technologies and sub systems, processes and methodologies.



Known Technologies/Sub-systems, processes and Methodologies (upstream & downstream)

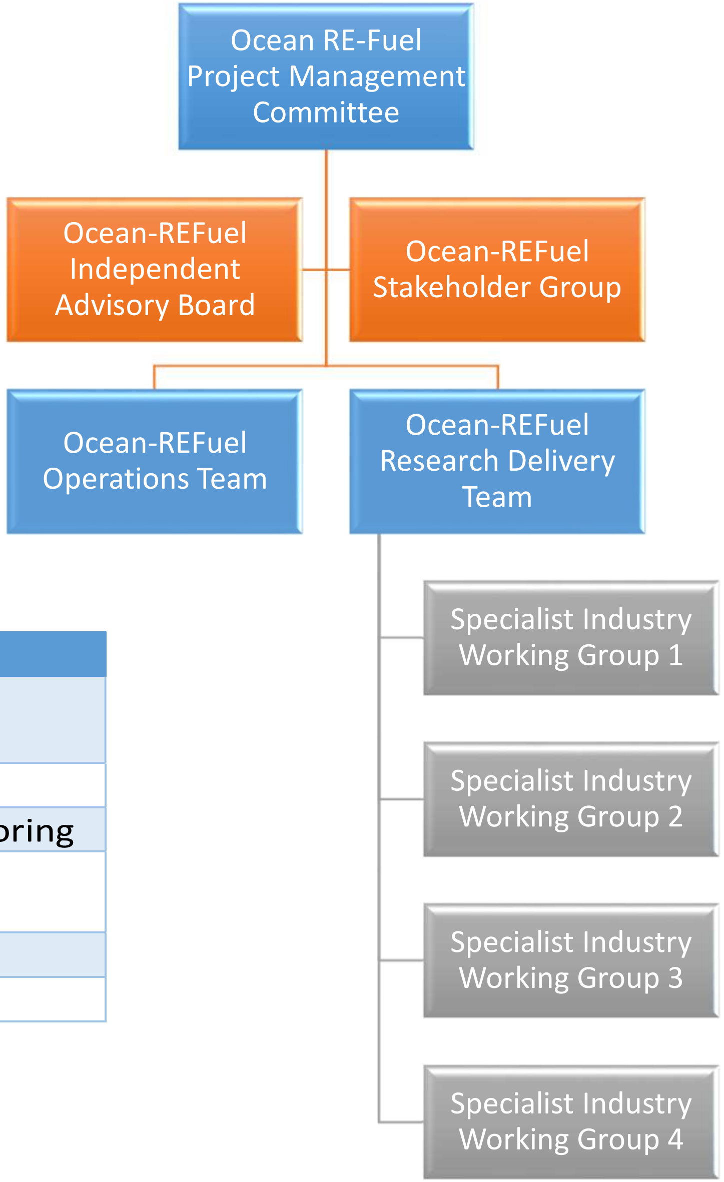
Whole Energy System Development

Functional Requirements (primary function, micro & macro economics, safety, environmental impact)

New Technologies/Sub-systems, processes and Methodologies

Ocean-REFuel Workstream Presentations

Management/Governance Structure



Investigator	Management Role
Brennan	PI, Chair of the Ocean-REFuel Management Committee, Stakeholder Engagement
Shah	Equality Diversity & Inclusion
Walker	Early Career Researcher Training and Mentoring
Valera Medina	Public engagement, advocacy, and media (including social media)
Irons	Impact Strategy
Mamlouk	Workshops, seminars & conferences

Ocean-REFuel Stakeholder Group

nationalgrid
ONE OPPORTUNITY NORTH EAST
OGTC
HSE Health & Safety Executive
SAMS
EDF
SCOTTISHPOWER
SIEMENS Gamesa RENEWABLE ENERGY
Cefas
equinor
DNV·GL
eni
PEEL PORTS GROUP
bp
MAINSTREAM RENEWABLE POWER
energy institute
eneus energy
Ørsted
TechnipFMC
CATAPULT Offshore Renewable Energy
orion Clean Energy Project
D2N2
mabe
ITM POWER Energy Storage | Clean Fuel
Supergen Offshore Renewable Energy
tfp H_2
HPGS Hydrogen Power Generation Solutions Ltd
evolve HYDROGEN
UKRI Engineering and Physical Sciences Research Council

- Research Organisations
- Government
- Owner/Operators
- Regulators/Certification Authorities & NGOs
- Investors
- Training Organisations
- OEMs, SMEs/supply base

Independent Advisory Board Members

1. Independent Chair (Chair of the Stakeholder Advisory Group), Dr Panagiotis Stavrakakis (HSE)
2. EPSRC Project Officer (Dr Isabella Panovic)
3. Project PI and University of Strathclyde Representative (Professor Feargal Brennan)
4. Partner University Representative 1 - Nottingham University Lead (Professor Gavin Walker)
5. Partner University Representative 2 - Newcastle University Lead (Professor Mohamed Mamlouk)
6. Partner University Representative 3 - Cardiff Universty Lead (Dr Agustin Valera Medina)
7. Partner University Representative 4 - Imperial College Lead (Professor Nilay Shah
8. International Academic Expert 1
9. International Academic Expert 2
10. International Academic Expert 3
11. International Academic Expert 4
12. Industry Expert 1
13. Industry Expert 2
14. Industry Expert 3
15. Industry Expert 4

Meeting Quorum: 10 with at least 50% independent members.
Meeting Frequency: Annual.
Diversity: Minimum 25% Female i.e. 4 members.
Chair and Membership reviewed periodically and appointed by the Project Management Committee.

Engage: Contacts

- Dr Panagiotis Stavrakakis, Stakeholder Group and Independent Advisory Board Chair) Panagiotis.Stavrakakis@hse.gov.uk
- Lynn O’ Brien, Ocean-REFuel Project Administrator
- Mark Robertson, Ocean-REFuel Project Manager mark.robertson.101@strath.ac.uk

X THE PLACE OF USEFUL LEARNING

University of Strathclyde
Engineering

Ocean REFuel

Workstream 1
Offshore structures, logistics, and power generation

6 September 2022, Stakeholder event
Prof Maurizio Collu, WS1 lead

www.strath.ac.uk/engineering

Workstream 1: the team

Prof Feargal
Brennan, PI

Prof Maurizio
Collu, WS1 lead

Dr Claudio
Rodriguez-Castillo,
Postdoc researcher

Dr Baran Yeter,
Postdoc researcher

Dr Shen Li,
Postdoc
researcher

Overview

1. Introduction to Workstream 1
2. First results
3. Coordination with other Workstreams
4. Next steps

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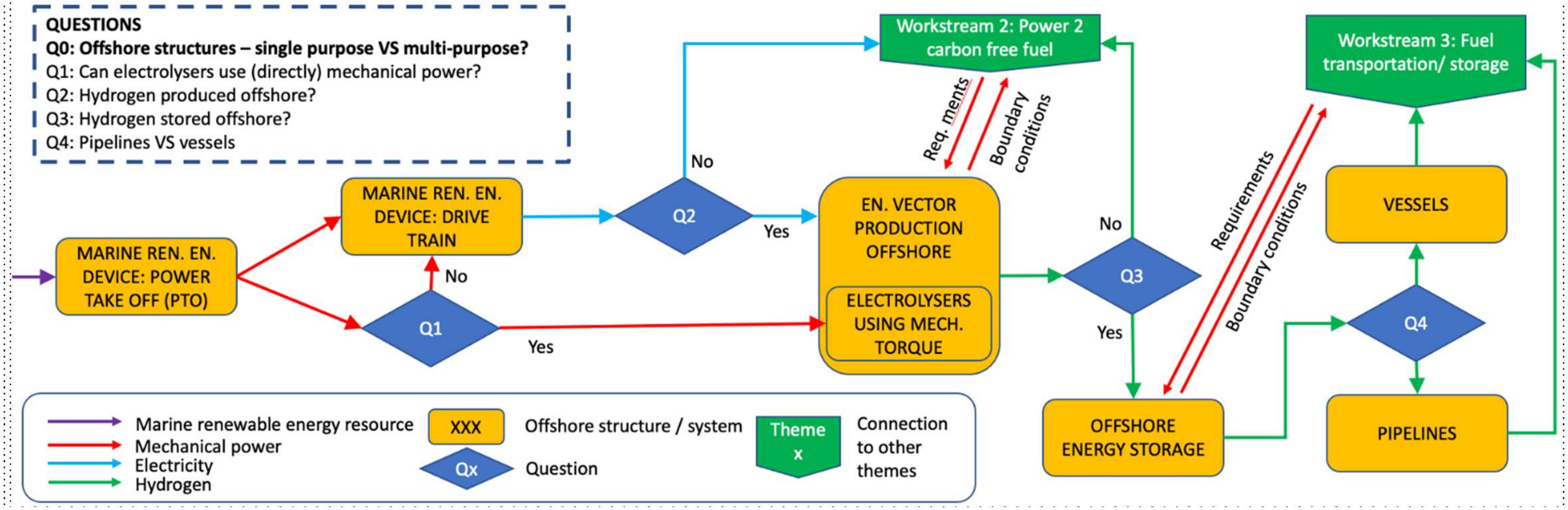
Introduction to Workstream 1

- Focus on ***Upstream***
- ***Questions*** to answer



QUESTIONS

Q0: Offshore structures – single purpose VS multi-purpose?

Q1: Can electrolysers use (directly) mechanical power?

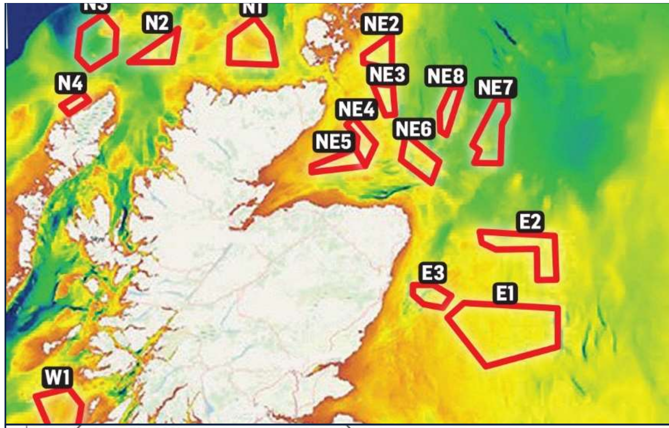
Q2: Hydrogen produced offshore?

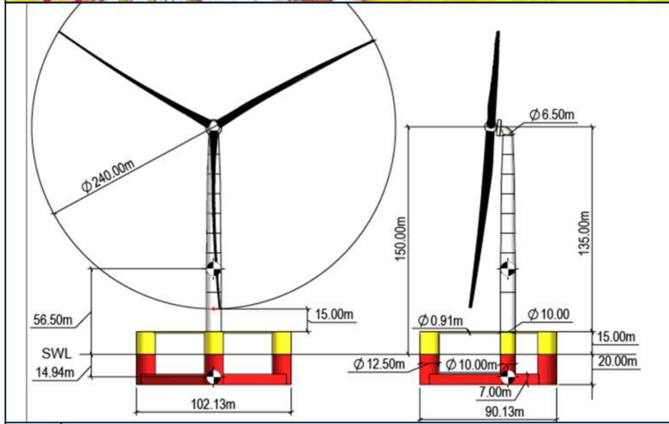
Q3: Hydrogen stored offshore?

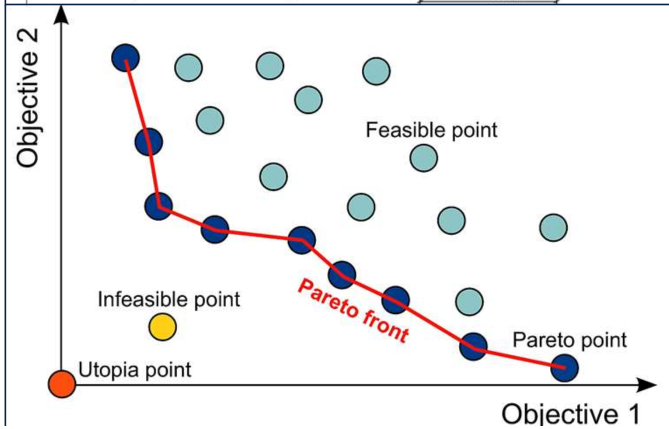
Q4: Pipelines VS vessels

Introduction to Workstream 1

WP1.1 Scenarios definition	T1.1.1 Locations? Metocean conditions?
	T1.1.2 Which ORE technologies?
WP1.2 Production of H_2 in offshore conditions	T1.2.1 Support platform: objectives, constraints
	T1.2.2 Support platform: MDAO analysis
	T1.2.3 Impact of offshore conditions on H_2 production
	T1.2.4 Offshore platform for H_2 **production**: optimum configuration
WP1.3 Storage of H_2 in offshore conditions	T1.3.1 Optimum materials for H_2 storage
	T1.3.2 Impact of offshore conditions on H_2 storage system equipment
	T1.3.3 Offshore platform for H_2 **storage**: optimum configuration
WP1.4 H_2 transportation to shore	T1.4.1 Materials and technologies for H_2 transportation
	T1.4.2 Damage modelling and mitigation solutions







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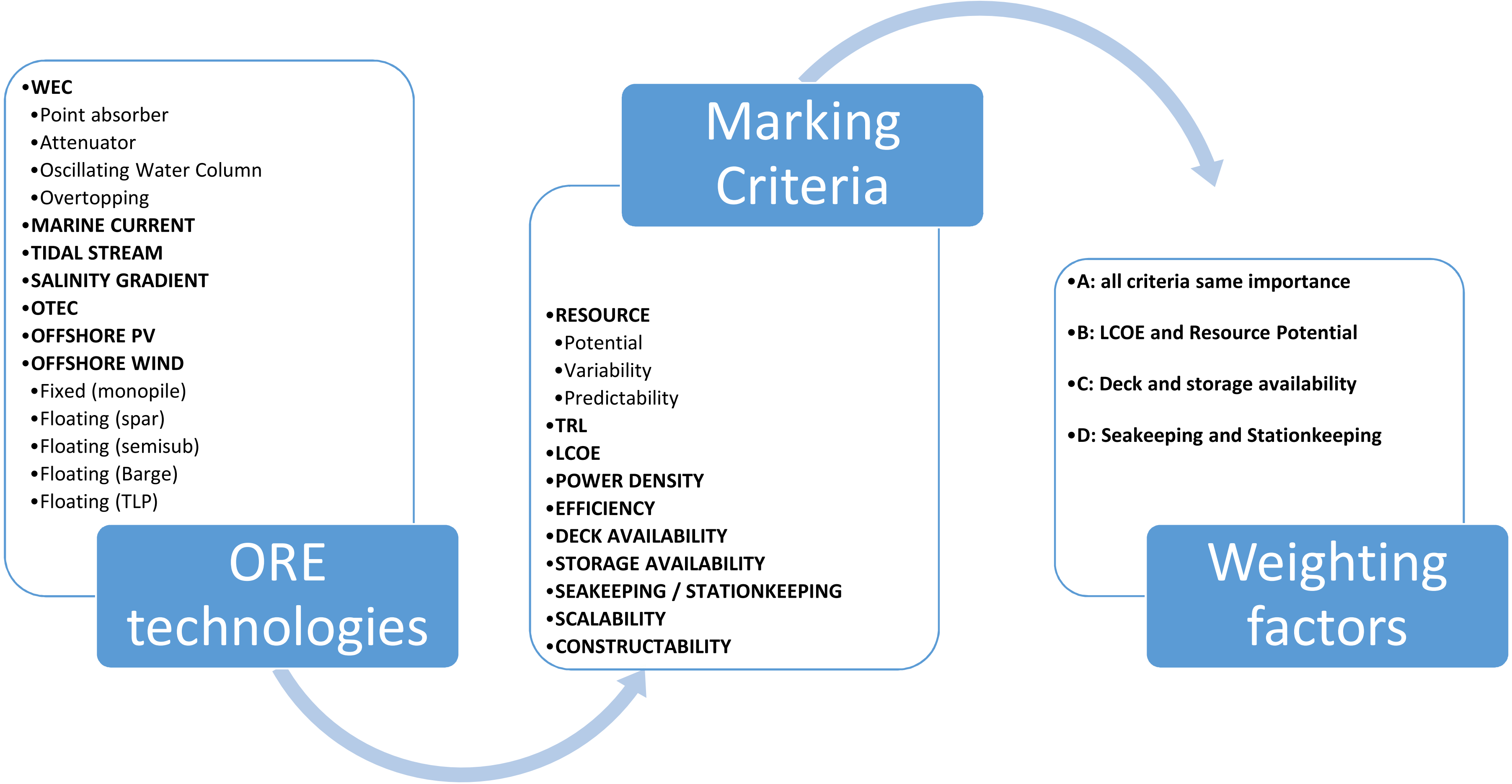
First results: which ORE technology?
Multi-Criteria Decision Analysis TOPSIS



- **WEC**
  - Point absorber
  - Attenuator
  - Oscillating Water Column
  - Overtopping
- **MARINE CURRENT**
- **TIDAL STREAM**
- **SALINITY GRADIENT**
- **OTEC**
- **OFFSHORE PV**
- **OFFSHORE WIND**
  - Fixed (monopile)
  - Floating (spar)
  - Floating (semisub)
  - Floating (Barge)
  - Floating (TLP)

ORE technologies

Marking Criteria

- **RESOURCE**
  - Potential
  - Variability
  - Predictability
- **TRL**
- **LCOE**
- **POWER DENSITY**
- **EFFICIENCY**
- **DECK AVAILABILITY**
- **STORAGE AVAILABILITY**
- **SEAKEEPING / STATIONKEEPING**
- **SCALABILITY**
- **CONSTRUCTABILITY**

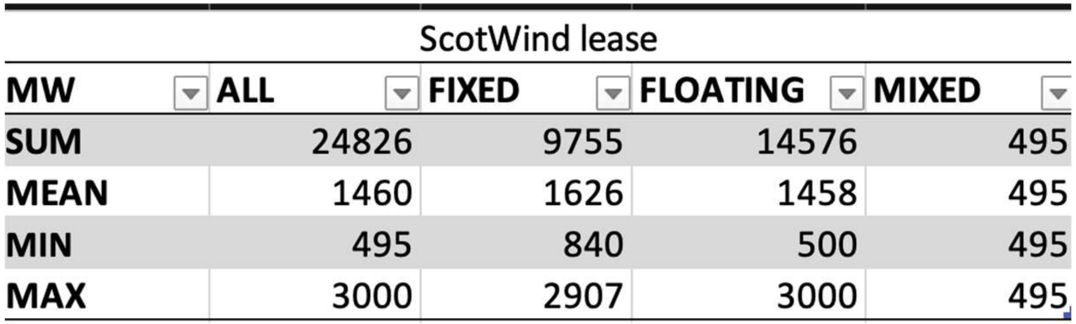
- **A: all criteria same importance**
- **B: LCOE and Resource Potential**
- **C: Deck and storage availability**
- **D: Seakeeping and Stationkeeping**

Weighting factors

First results: which ORE technology? Multi-Criteria Decision Analysis TOPSIS

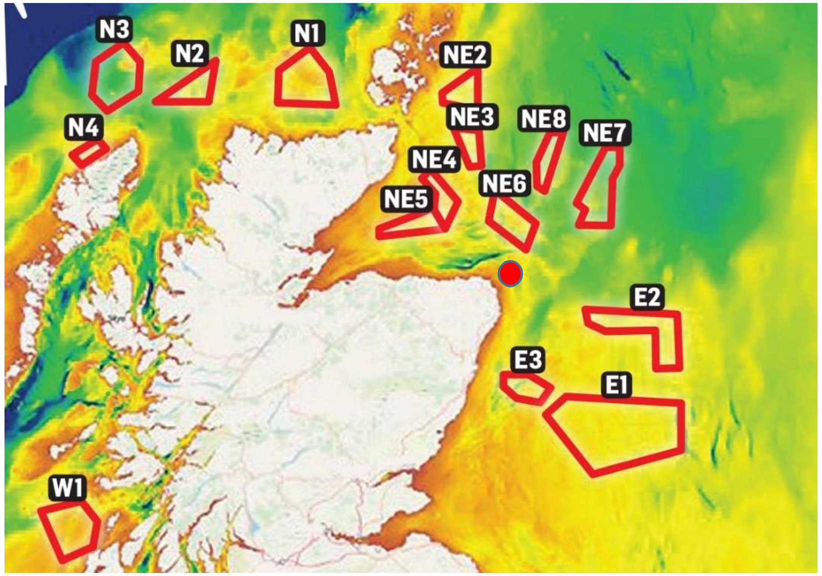
Scenarios →	**Baseline**	**Enhanced LCoE & Resource Potential**	**Enhanced Deck & Storage Availability**	**Enhanced Sea- & Station- keeping**
Alternatives ↓	**Closeness to ideal positive solution (1.00)**			
Wave-OB (PA)	0.31	0.36	0.23	0.25
Wave-OB (ATE)	0.49	0.47	0.55	0.48
Wave-OWC	0.59	0.54	0.62	0.69
Wave-OVT	0.36	0.38	0.41	0.33
Marine current	0.37	0.36	0.27	0.29
Tidal stream	0.34	0.35	0.25	0.27
Salinity gradient	0.60	0.51	0.66	0.68
OTEC	0.72	0.64	**0.79**	**0.78**
Offshore solar	0.41	0.38	0.38	0.37
OWT-fixed monopile	0.63	0.71	0.52	0.71
OWT-spar	0.65	0.71	0.59	0.73
OWT-semi	**0.73**	**0.76**	0.75	**0.78**
OWT-barge	**0.75**	**0.77**	**0.82**	0.76
OWT-TLP	0.67	0.69	0.71	0.74

First results: locations?



ScotWind lease				
MW	**ALL**	**FIXED**	**FLOATING**	**MIXED**
SUM	24826	9755	14576	495
MEAN	1460	1626	1458	495
MIN	495	840	500	495
MAX	3000	2907	3000	495

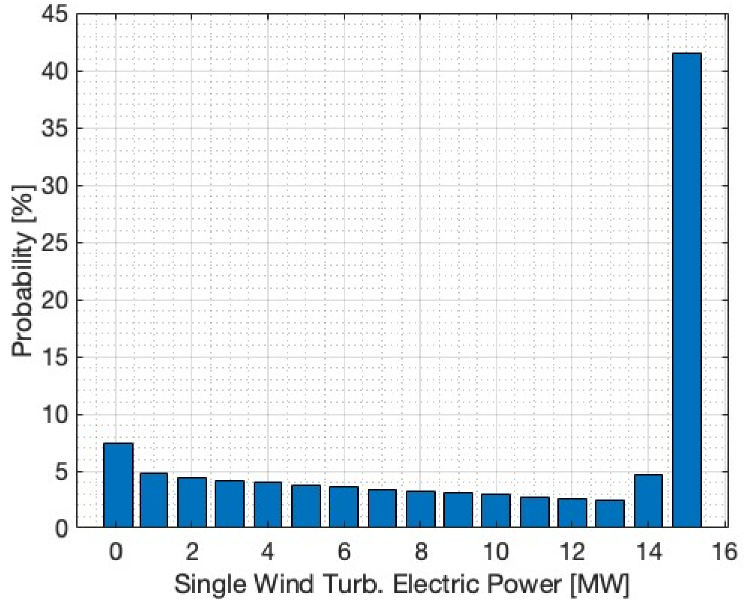
Zone	Type	MW	# turbines	AEY GWh (40%LF)
NE6	Floating	500	~33	~1700
NE7	Floating	3000	~200	~10512
NE8	**Floating**	**960**	**~64**	**~3360**

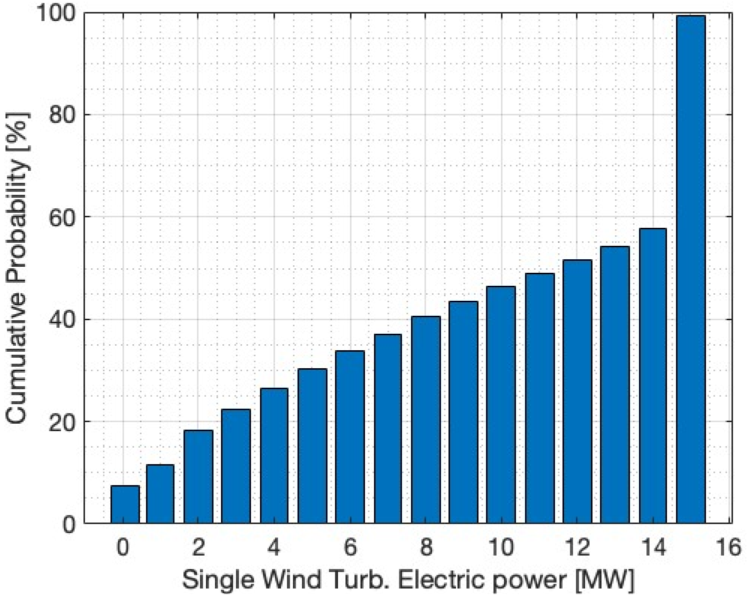


- Metocean conditions from hindcast databases (ERA5, Copernicus, etc) available for wind, waves, marine currents, sea level, air/sea temperatures, sea salinity)

First results: which ORE technology? Location? *“Strawman”* figures

Parameter	Value
Farm total power	~1000 MW
Farm Annual Energy Yield	~3500 GWh (40% L.F.)
Farm location	NE Scotland, near St. Fergus gas terminal (58.5 N, 1.25E)
Wind turbine power	15 MW (see distributions graphs →)
Wind turbine number	65 - 70
Wind turbine type	Floating, semisubmersible / barge
WT to WT distance	> 1.6 km (> 1 mile)
Wind turbine “deck space”	3x122m^2 – 3x650m^2





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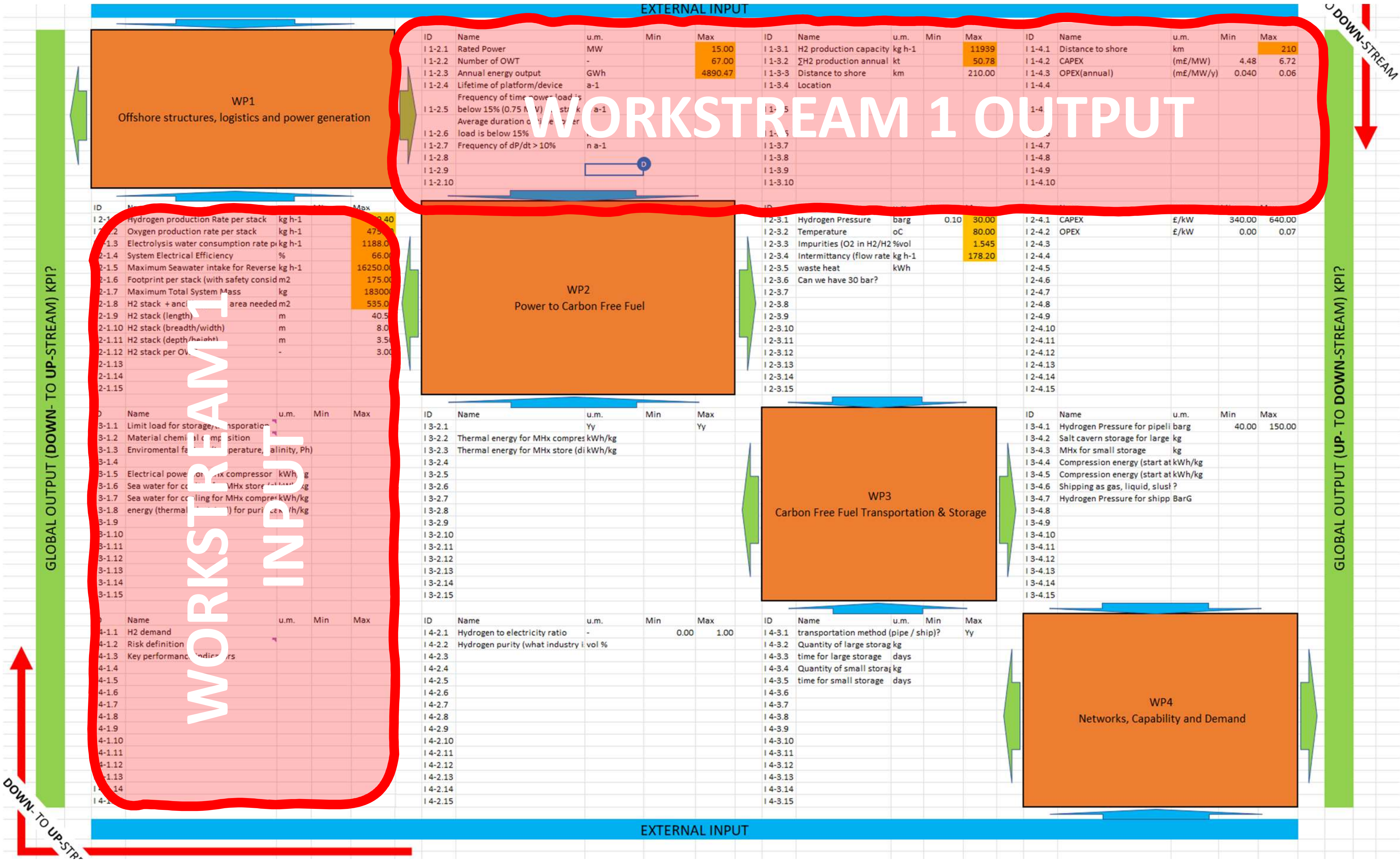

ID	Name	u.m.	Min	Max
I 1-2.1	Rated Power	MW		15.00
I 1-2.2	Number of OWT	-		67.00
I 1-2.3	Annual energy output	GWh		4890.47
I 1-2.4	Lifetime of platform/device	a-1		
I 1-2.5	Frequency of time [illegible] is below 15% (0.75 M[illegible]) [illegible]	[illegible] a-1		
I 1-2.6	Average duration o[illegible] load is below 15%	[illegible]		
I 1-2.7	Frequency of dP/dt > 10%	n a-1		
I 1-2.8				
I 1-2.9				
I 1-2.10				

ID	Name	u.m.	Min	Max
I 1-3.1	H2 production capacity	kg h-1		11939
I 1-3.2	∑H2 production annual	kt		50.78
I 1-3-3	Distance to shore	km		210.00
I 1-3.4	Location			
I 1-[illegible]				
I 1-[illegible]				
I 1-3.7				
I 1-3.8				
I 1-3.9				
I 1-3.10				

ID	Name	u.m.	Min	Max
I 1-4.1	Distance to shore	km		210
I 1-4.2	CAPEX	(m£/MW)	4.48	6.72
I 1-4.3	OPEX(annual)	(m£/MW/y)	0.040	0.06
I 1-4.4				
1-4.[illegible]				
[illegible]				
I 1-4.7				
I 1-4.8				
I 1-4.9				
I 1-4.10				

ID	N[illegible]	[illegible]	[illegible]	Max
I 2-1	Hydrogen production Rate per stack	kg h-1		[illegible].40
I [illegible].2	Oxygen production rate per stack	kg h-1		475[illegible]
[illegible]-1.3	Electrolysis water consumption rate p	kg h-1		1188.0[illegible]
2-1.4	System Electrical Efficiency	%		66.0[illegible]
2-1.5	Maximum Seawater intake for Reverse	kg h-1		16250.0[illegible]
2-1.6	Footprint per stack (with safety consid	m2		175.0[illegible]
2-1.7	Maximum Total System Mass	kg		18300[illegible]
2-1.8	H2 stack + anci[illegible] area needed	m2		535.0[illegible]
2-1.9	H2 stack (length)	m		40.5[illegible]
2-1.10	H2 stack (breadth/width)	m		8.0[illegible]
2-1.11	H2 stack (depth/height)	m		3.5[illegible]
2-1.12	H2 stack per OW[illegible]	-		3.0[illegible]
2-1.13				
2-1.14				
2-1.15				

ID	[illegible]	[illegible]	[illegible]	[illegible]
I 2-3.1	Hydrogen Pressure	barg	0.10	30.00
I 2-3.2	Temperature	oC		80.00
I 2-3.3	Impurities (O2 in H2/H2	%vol		1.545
I 2-3.4	Intermittancy (flow rate	kg h-1		178.20
I 2-3.5	waste heat	kWh		
I 2-3.6	Can we have 30 bar?			
I 2-3.7				
I 2-3.8				
I 2-3.9				
I 2-3.10				
I 2-3.11				
I 2-3.12				
I 2-3.13				
I 2-3.14				
I 2-3.15				

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
I 2-4.1	CAPEX	£/kW	340.00	640.00
I 2-4.2	OPEX	£/kW	0.00	0.07
I 2-4.3				
I 2-4.4				
I 2-4.5				
I 2-4.6				
I 2-4.7				
I 2-4.8				
I 2-4.9				
I 2-4.10				
I 2-4.11				
I 2-4.12				
I 2-4.13				
I 2-4.14				
I 2-4.15				

D	Name	u.m.	Min	Max
3-1.1	Limit load for storage/t[illegible]nsporation			
3-1.2	Material chemi[illegible] [illegible]sition			
3-1.3	Enviromental fa[illegible]perature, [illegible]alinity, Ph)			
3-1.4				
3-1.5	Electrical powe[illegible] compressor	kWh[illegible]g		
3-1.6	Sea water for c[illegible]MHx store [illegible]	[illegible]kg		
3-1.7	Sea water for c[illegible]ling for MHx compre	kWh/kg		
3-1.8	energy (thermal[illegible]) for puri[illegible]	[illegible]h/kg		
3-1.9				
3-1.10				
3-1.11				
3-1.12				
3-1.13				
3-1.14				
3-1.15				

ID	Name	u.m.	Min	Max
I 3-2.1		Yy		Yy
I 3-2.2	Thermal energy for MHx compres	kWh/kg		
I 3-2.3	Thermal energy for MHx store (di	kWh/kg		
I 3-2.4				
I 3-2.5				
I 3-2.6				
I 3-2.7				
I 3-2.8				
I 3-2.9				
I 3-2.10				
I 3-2.11				
I 3-2.12				
I 3-2.13				
I 3-2.14				
I 3-2.15				

ID	Name	u.m.	Min	Max
I 3-4.1	Hydrogen Pressure for pipeli	barg	40.00	150.00
I 3-4.2	Salt cavern storage for large	kg		
I 3-4.3	MHx for small storage	kg		
I 3-4.4	Compression energy (start at	kWh/kg		
I 3-4.5	Compression energy (start at	kWh/kg		
I 3-4.6	Shipping as gas, liquid, slusl	?		
I 3-4.7	Hydrogen Pressure for shipp	BarG		
I 3-4.8				
I 3-4.9				
I 3-4.10				
I 3-4.11				
I 3-4.12				
I 3-4.13				
I 3-4.14				
I 3-4.15				

D	Name	u.m.	Min	Max
4-1.1	H2 demand			
4-1.2	Risk definition			
4-1.3	Key performanc[illegible]rs			
4-1.4				
4-1.5				
4-1.6				
4-1.7				
4-1.8				
4-1.9				
4-1.10				
4-1.11				
4-1.12				
[illegible]-1.13				
I 4[illegible]14				
I 4-[illegible]				

ID	Name	u.m.	Min	Max
I 4-2.1	Hydrogen to electricity ratio	-	0.00	1.00
I 4-2.2	Hydrogen purity (what industry i	vol %		
I 4-2.3				
I 4-2.4				
I 4-2.5				
I 4-2.6				
I 4-2.7				
I 4-2.8				
I 4-2.9				
I 4-2.10				
I 4-2.11				
I 4-2.12				
I 4-2.13				
I 4-2.14				
I 4-2.15				

ID	Name	u.m.	Min	Max
I 4-3.1	transportation method (pipe / ship)?			Yy
I 4-3.2	Quantity of large storag	kg		
I 4-3.3	time for large storage	days		
I 4-3.4	Quantity of small storaį	kg		
I 4-3.5	time for small storage	days		
I 4-3.6				
I 4-3.7				
I 4-3.8				
I 4-3.9				
I 4-3.10				
I 4-3.11				
I 4-3.12				
I 4-3.13				
I 4-3.14				
I 4-3.15				

Overview

1. Introduction to Workstream 1
2. First results, and next steps
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Next steps

WP1.1 Scenarios definition	T1.1.1 Locations? Metocean conditions?
	T1.1.2 Which ORE technologies?
WP1.2 Production of H_2 in offshore conditions	T1.2.1 Support platform: objectives, constraints
	T1.2.2 Support platform: MDAO analysis
	T1.2.3 Impact of offshore conditions on H_2 production
	T1.2.4 Offshore platform for H_2 **production**: optimum configuration

Literature review paper on WP1.1 work

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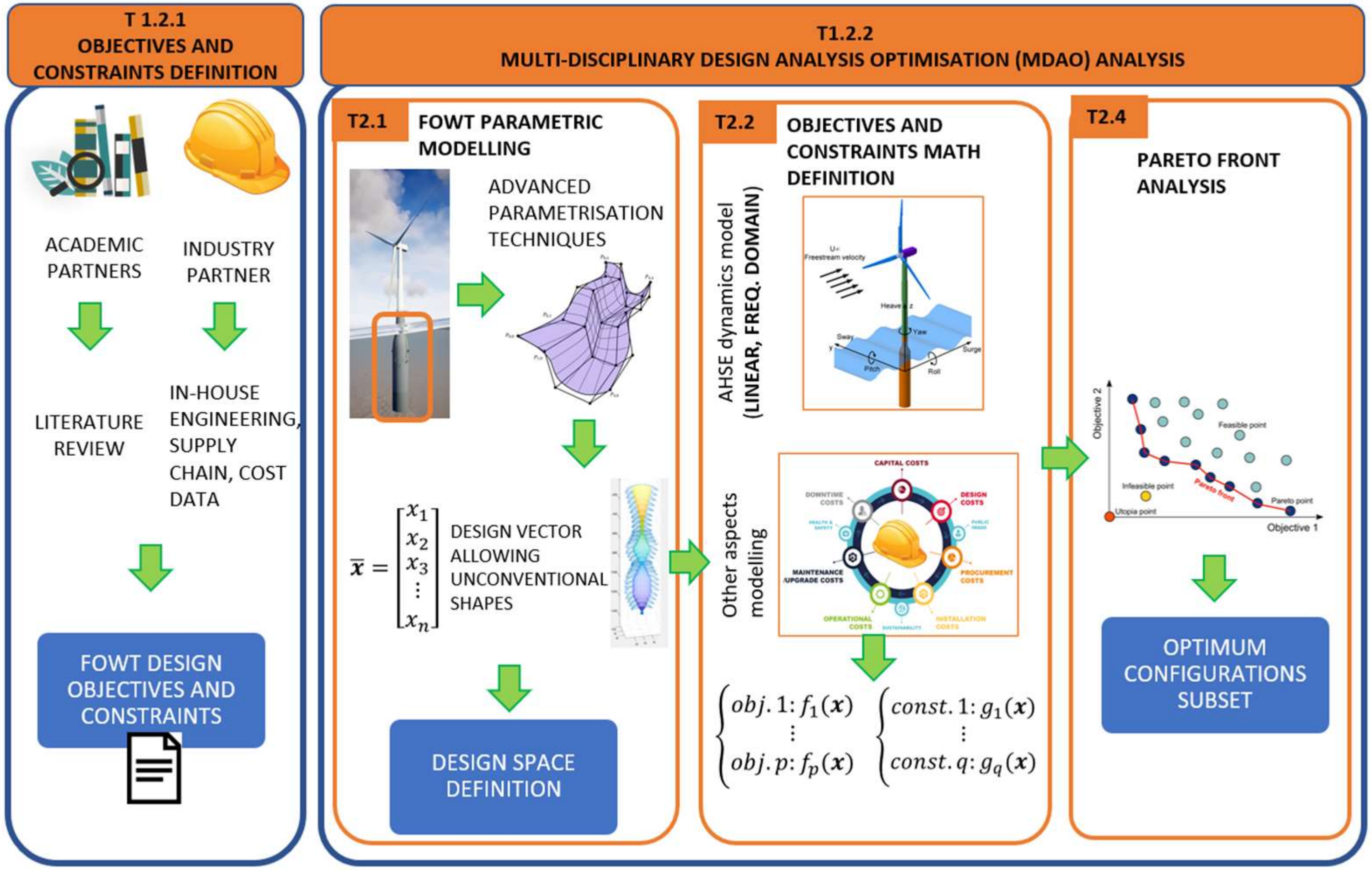
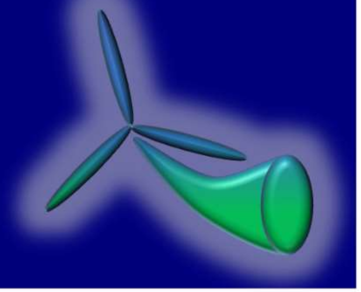


X THE PLACE OF USEFUL LEARNING

University of
Strathclyde
Engineering

Ocean-REFuel (Ocean Renewable Energy Fuel)

Workstream2: Power to carbon free fuel



Mohamed Mamlouk
School of Engineering, Newcastle University
06th September 2022, Hybrid Event

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

Imperial College London

Newcastle University

University of Nottingham UK | CHINA | MALAYSIA

University of Strathclyde Glasgow

Workstream 2 Team

Prof. Mohamed Mamlouk- Work Stream 2 Lead

Dr. Ramakrishnan Shanmugam- PDRA, Lead of WP 2.1 electrodes, electrocatalyst and support

Dr. Daniel Niblett- PDRA, Lead of WP2.2 Cell Design, Engineering and optimisation

Mostafa Delpisheh-PhD student, Thermofluids Engineer, responsible for Membrane-free cells experiments (WP2.2)

Overview

1. Introduction to Workstream 2
2. Coordination with other Workstreams
3. Initial results
4. Next steps

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4. Next steps

Introduction to WS2

1. Can seawater be used directly for efficient production of hydrogen or can seawater purifications be performed effectively offshore producing electrochemically chemicals for water treatment?

2. Which electrolyser technology and conditions are most suited to meet performance, cost and hydrogen purity requirements for offshore storage and hydrogen pumping?

3. Can electrolysers operate effectively and safely on offshore moored and floating platforms?

4. Can offshore electrolyser technology deliver stack performance target <48 kWh/kg (82% electrical efficiency) and costs of system < £800/kW?

Structure of WS2

Work Packages

WP 2.1 Electrodes, electrocatalyst and support (M1-30)

WP 2.2 Cell Design, Engineering and optimisation for membraneless operation (M1 - M48)

WP 2.3 Electrolyser scale-up and testing under offshore conditions (M25 - M60)

1. Introduction to Workstream 2
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4. Next steps

Inputs

WS1

- Rated Power
- Power Characteristics/dynamics
- Available space/volume
- Platform dynamics/oscillations

WS4

- % of generated power conversion to H2
- H2 purity and pressure
- O2 or other chemicals need
- Levelised cost of energy

Outputs

WS1

- Number of stacks, dimensions and weight
- Energy consumption and efficiency
- Water consumption

WS3

- H2 flowrate dynamics, temperature, purity and pressure
- Waste heat available

WS4

- CAPEX and OPEX of electrolyser

1. Introduction to Workstream 2
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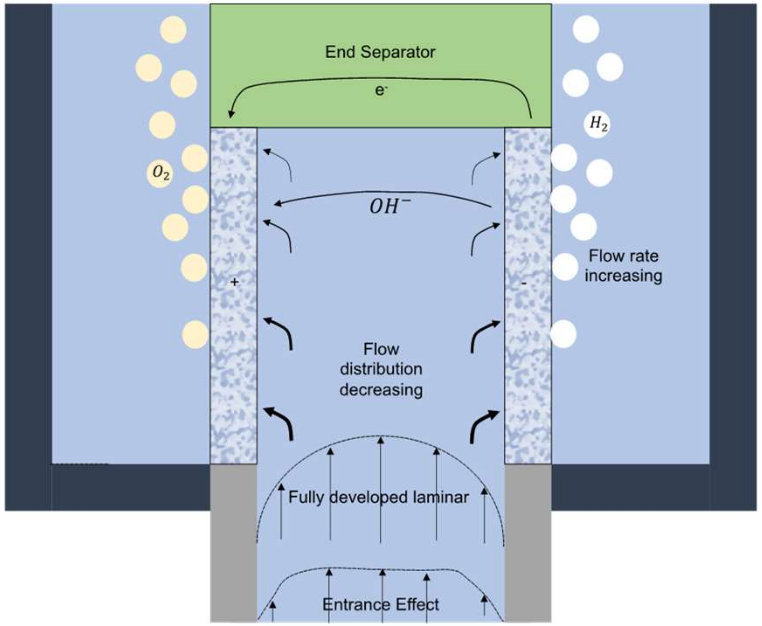
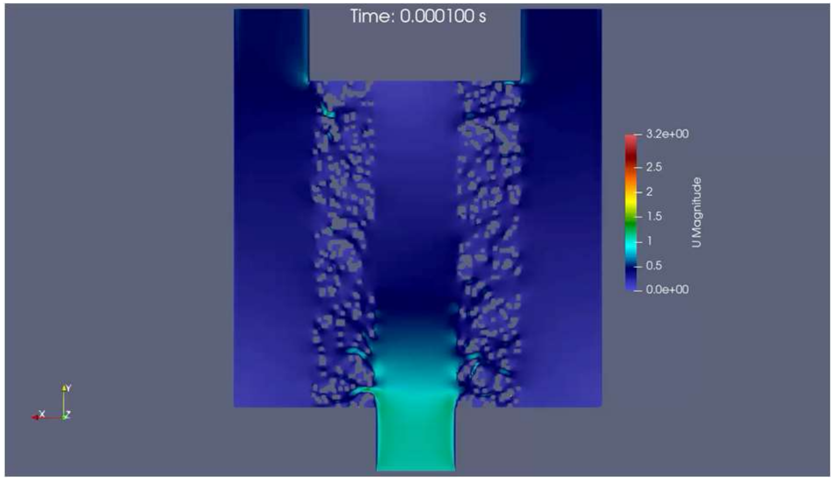
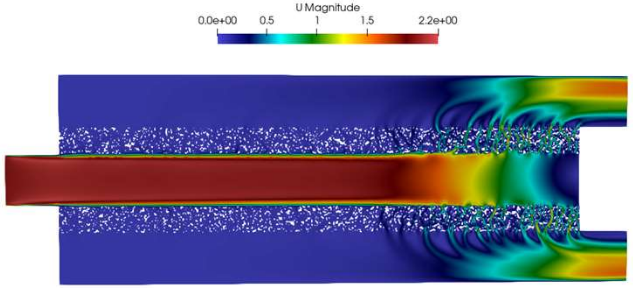
Flow through membraneless (1)

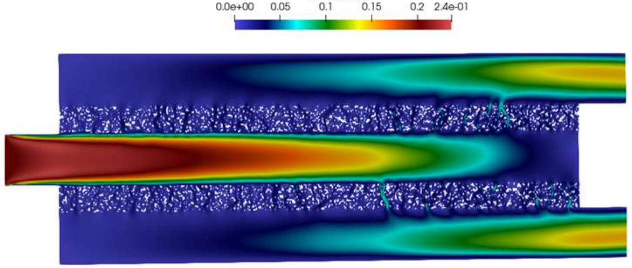




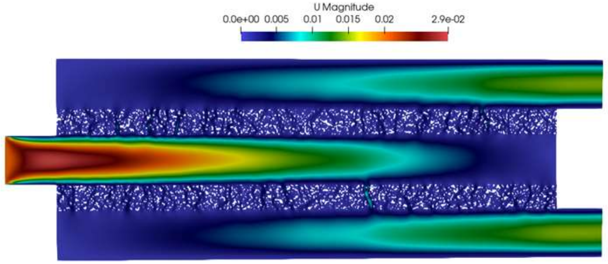
Flow through membraneless (2)



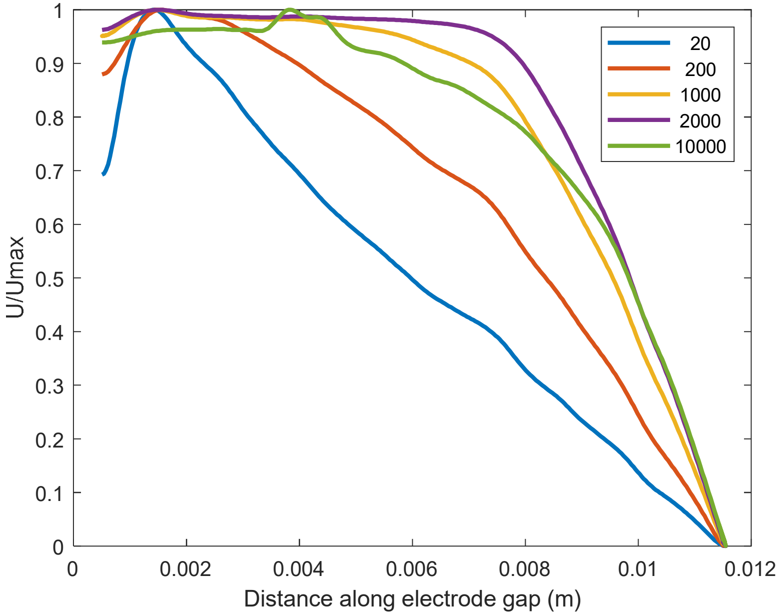
2 m/s, 0.5 A cm-2, **Re=2000**



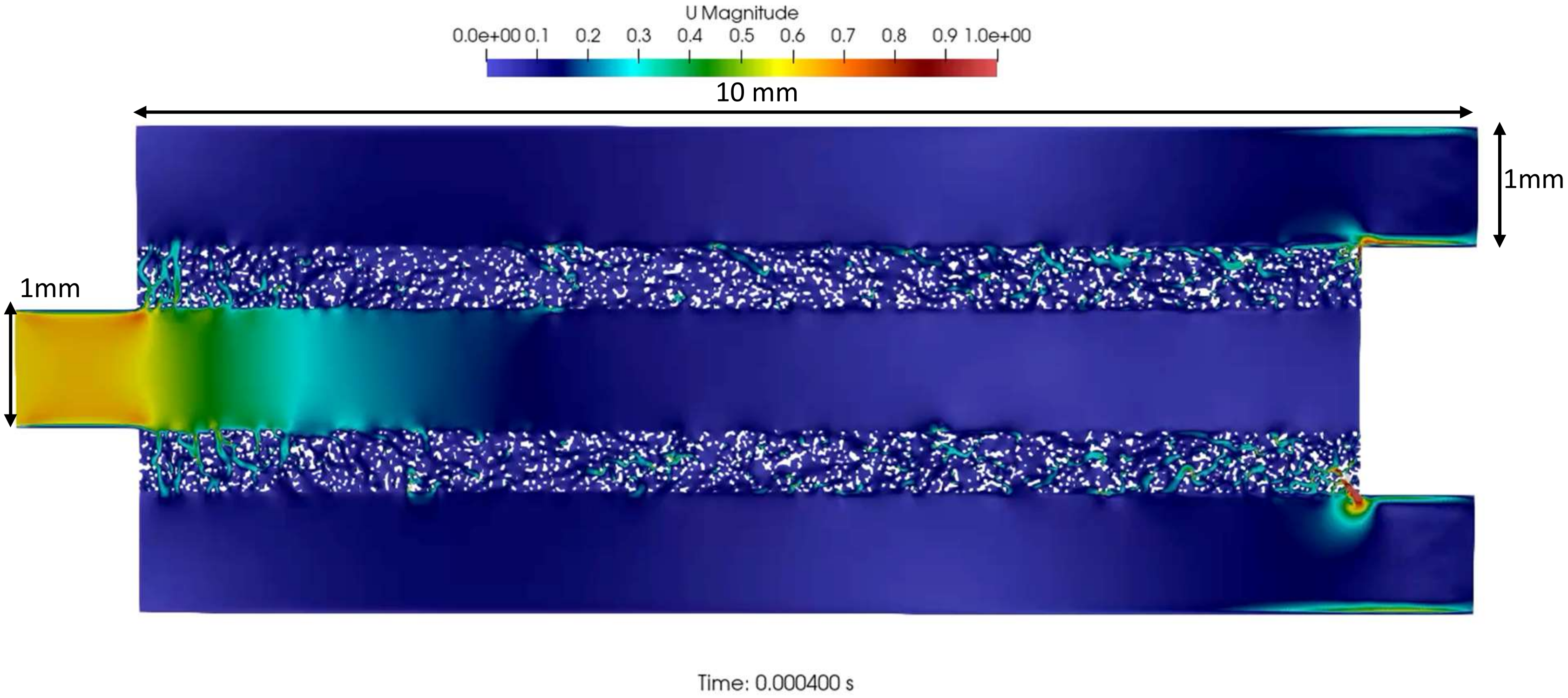
0.2 m/s, 0.5 A cm-2, **Re = 200**



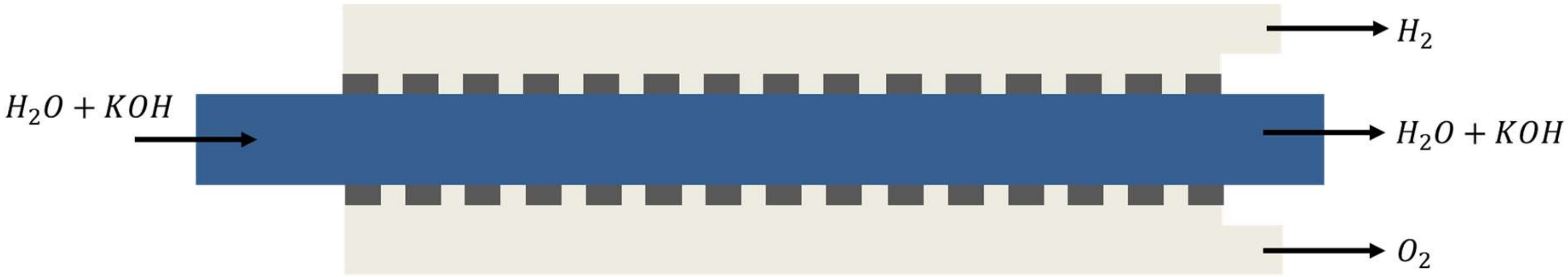
0.02 m/s, 0.5 A cm-2, **Re=2**

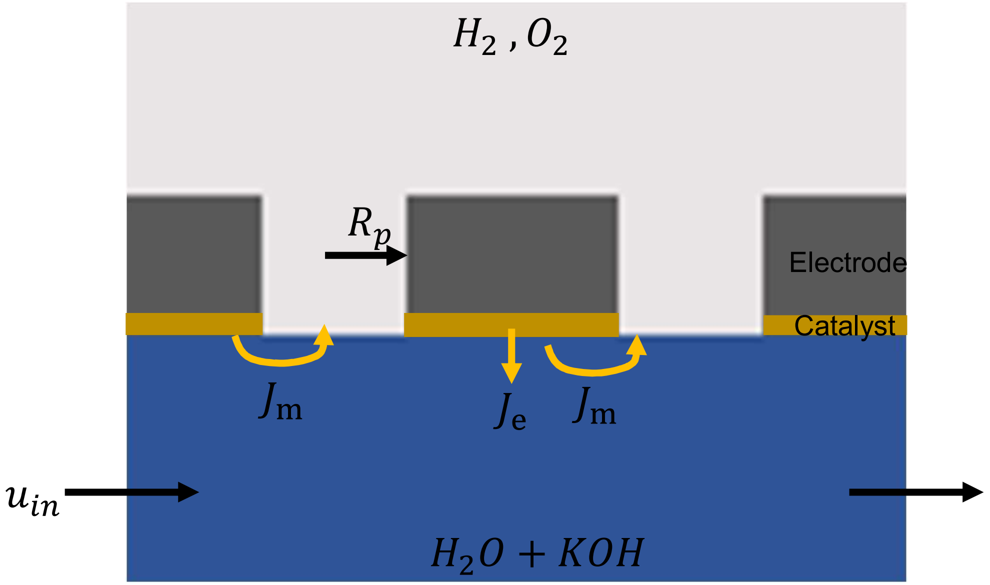


Flow through membraneless (3)



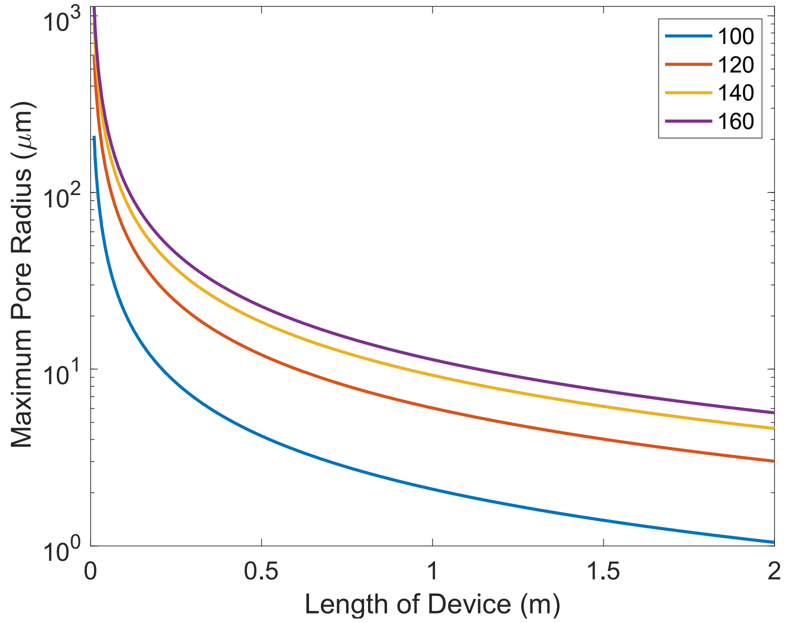
Membraneless contactor design(1)



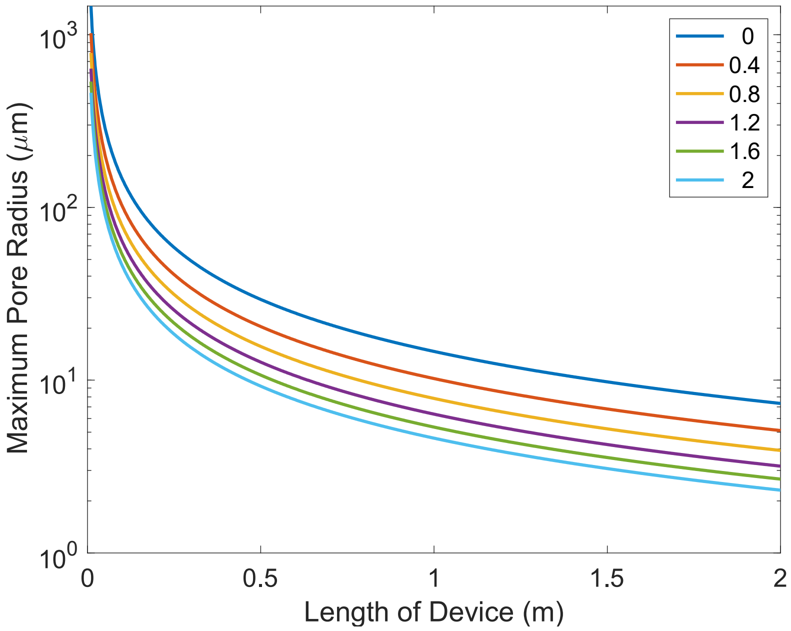


Membraneless contactor design(2)

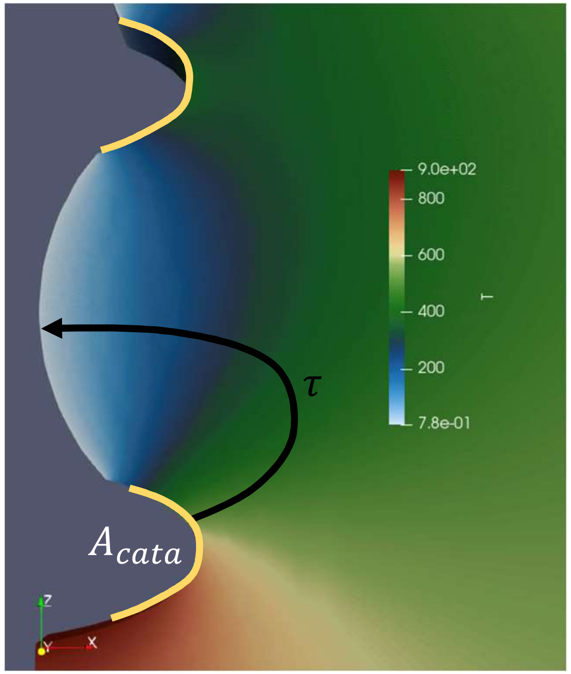
Effect of length of device and contact angle (100 – 160°)

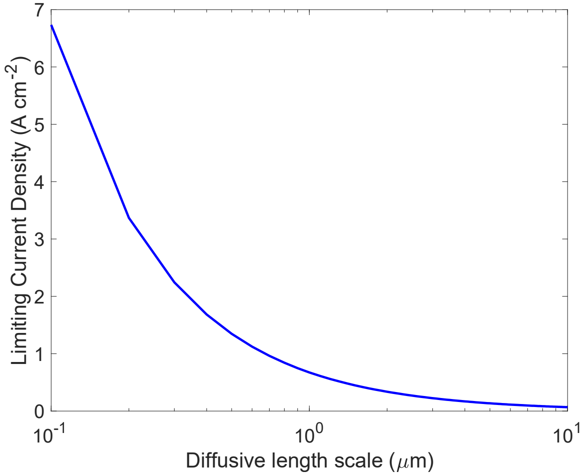


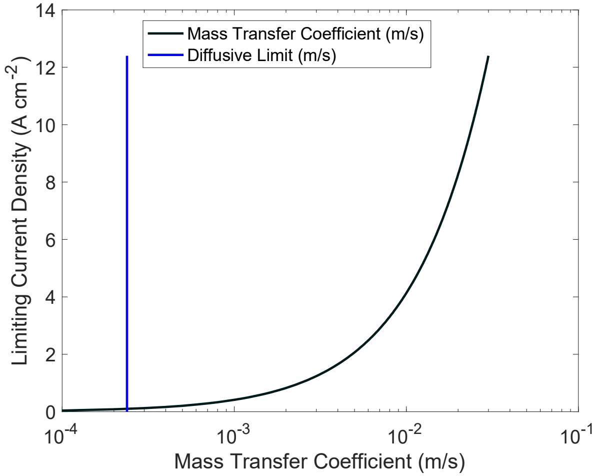
Effect of length of device and flow rate (0 – 2 m s^{-1})



Membraneless contactor design(3)







1. Introduction to Workstream 2
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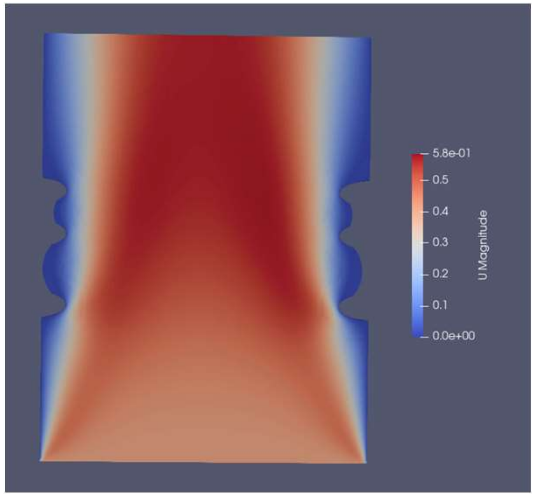
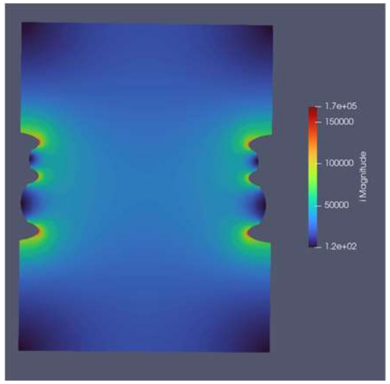
Modelling work

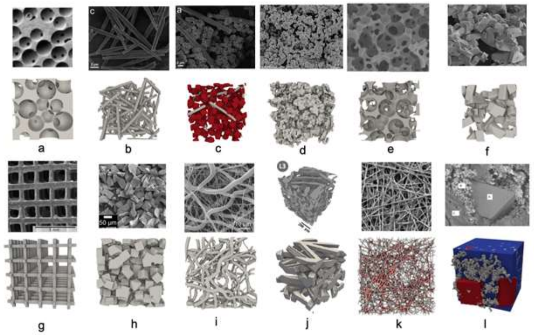
Potential/Current distribution

Velocity distribution

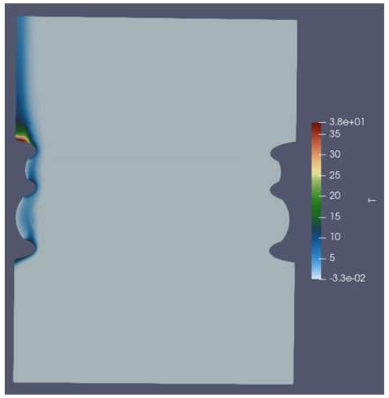




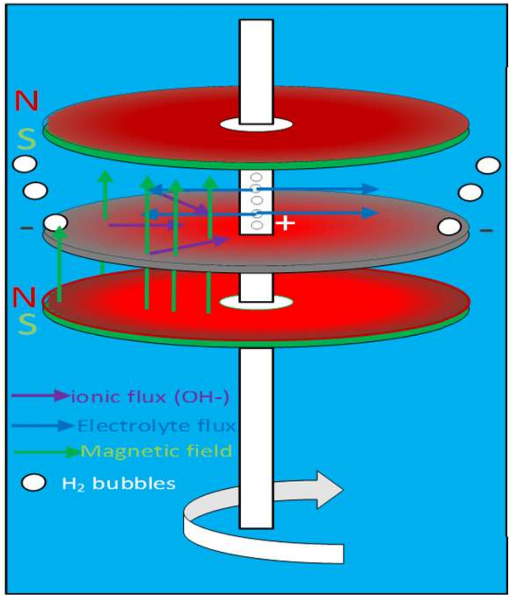
Machine Learning



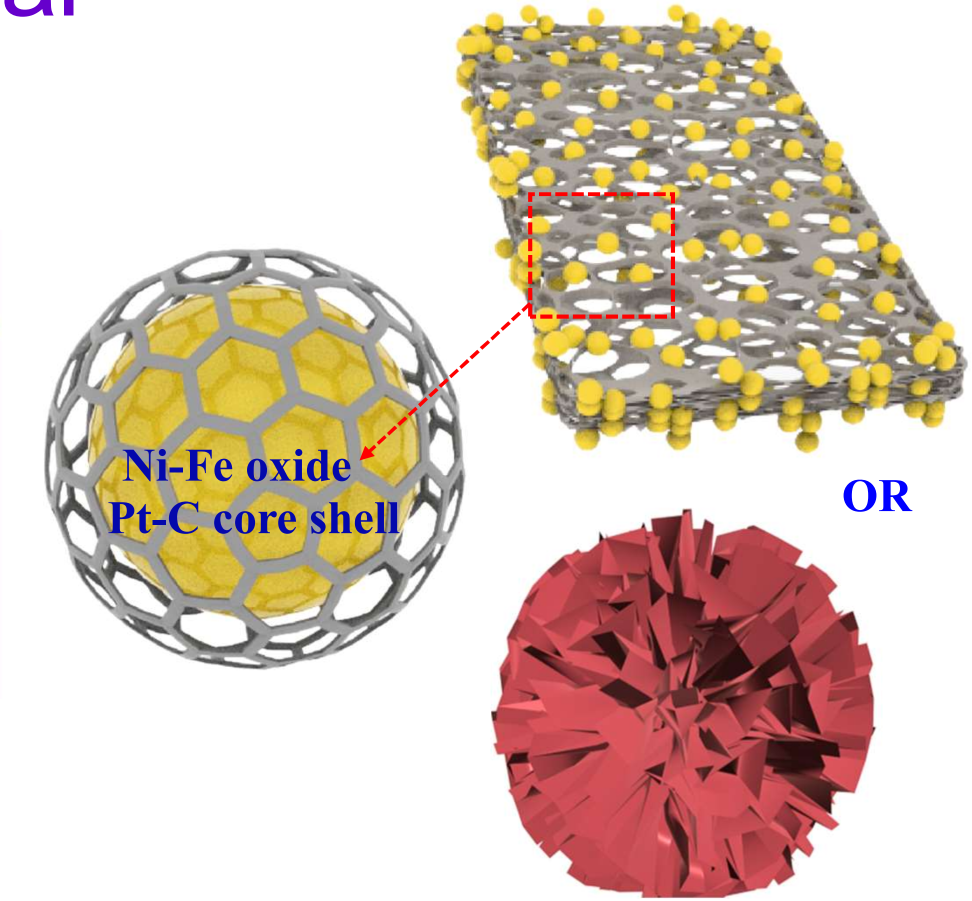
Dissolved species conc



Experimental



Rotating cells



Electrocatalyst/electrodes

Newcastle University

Thank you for your attention

UK Research and Innovation

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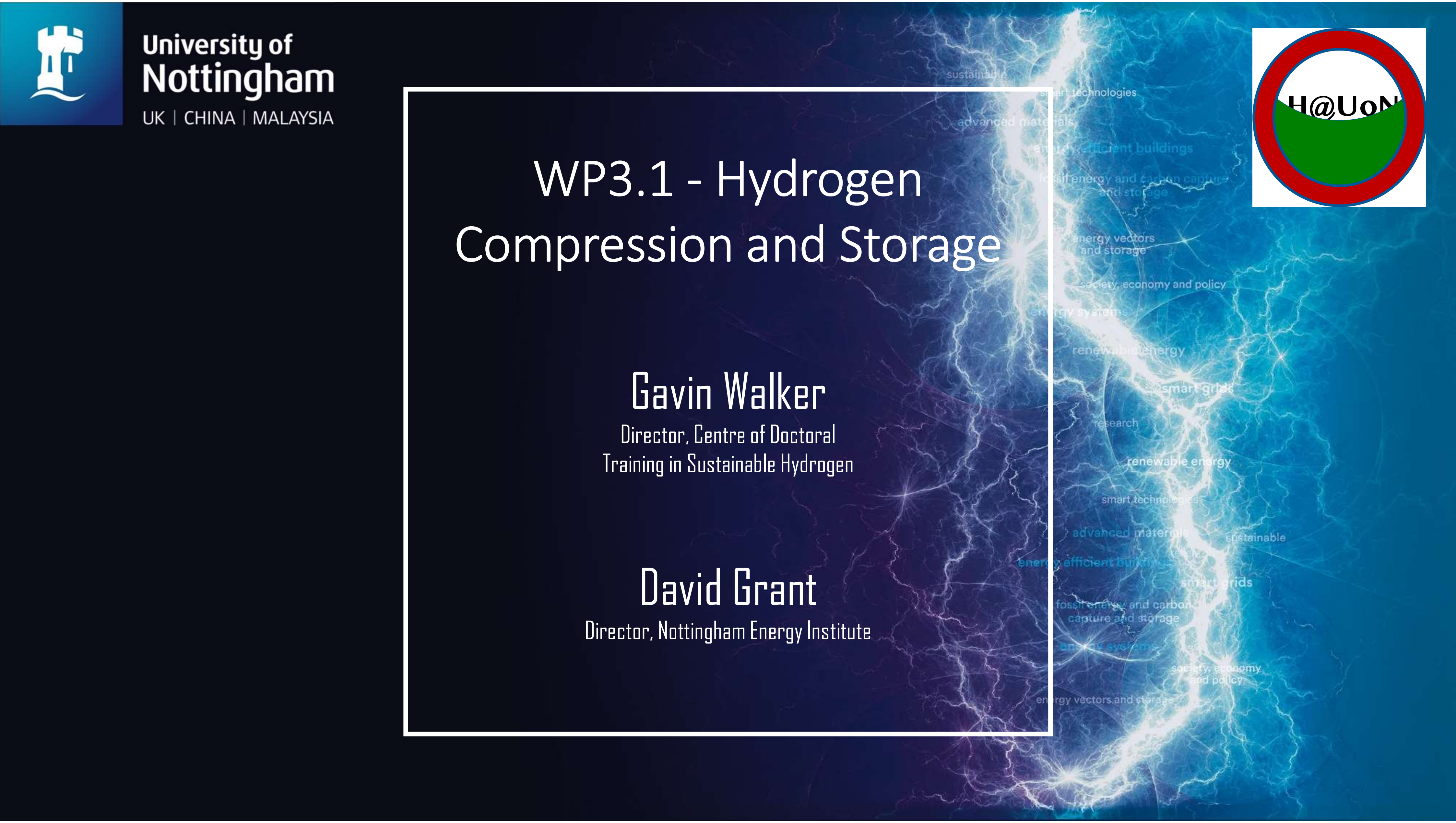


WP3.1 - Hydrogen Compression and Storage

Gavin Walker

Director, Centre of Doctoral
Training in Sustainable Hydrogen

David Grant

Director, Nottingham Energy Institute

University of
Nottingham
UK | CHINA | MALAYSIA

H@UoN

Hydrogen Group

David Grant
Director, Nottingham Energy Institute

Gavin Walker
Director, Centre of Doctoral Training in Sustainable Hydrogen

Dr Sanliang Ling
Nottingham Research Fellow

Dr Alastair Stuart
Research Associate

Dr Kandavel Manickam
Research Associate

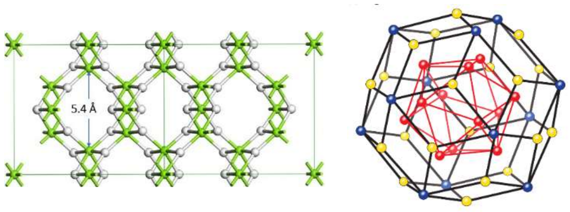
Dr Siow Loh
Research Associate

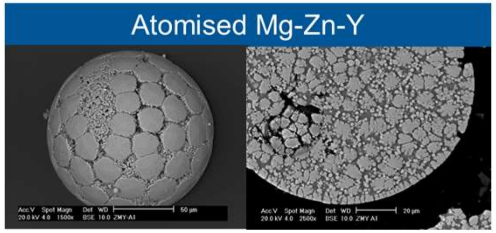
Dr Marcus Adams
Research Associate

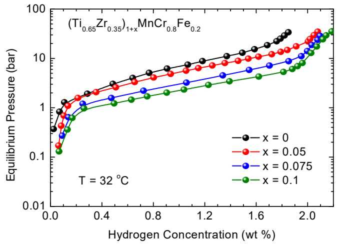
Dr Matt Wadge
Research Associate

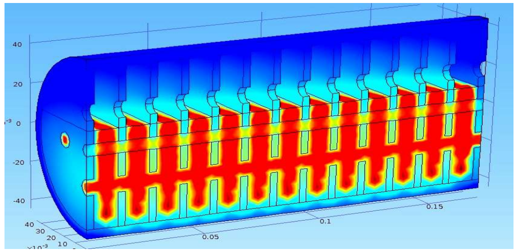
HYDROGEN RESEARCH @ NOTTINGHAM

- Materials research- new materials, modelling, machine learning characterisation and scale up
- Metal hydrides-room temperature and elevated temperatures, complex hydrides, high entropy alloys
- Stationary storage applications
- Solid state hydrogen compressors
- Hydrogen based thermal batteries and storage
- Facilities- Hydrogen storage laboratories
- Demonstrators and integration




Atomised Mg-Zn-Y





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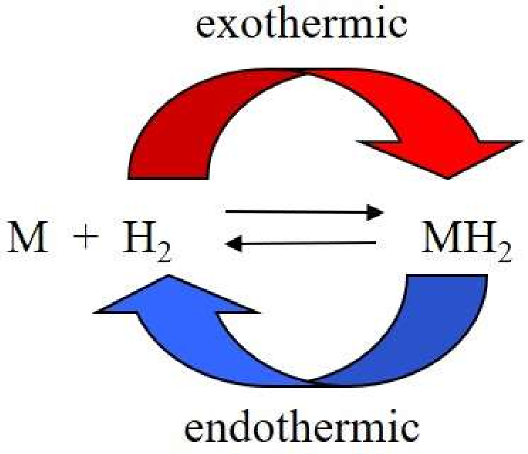
Metal Hydride Basics

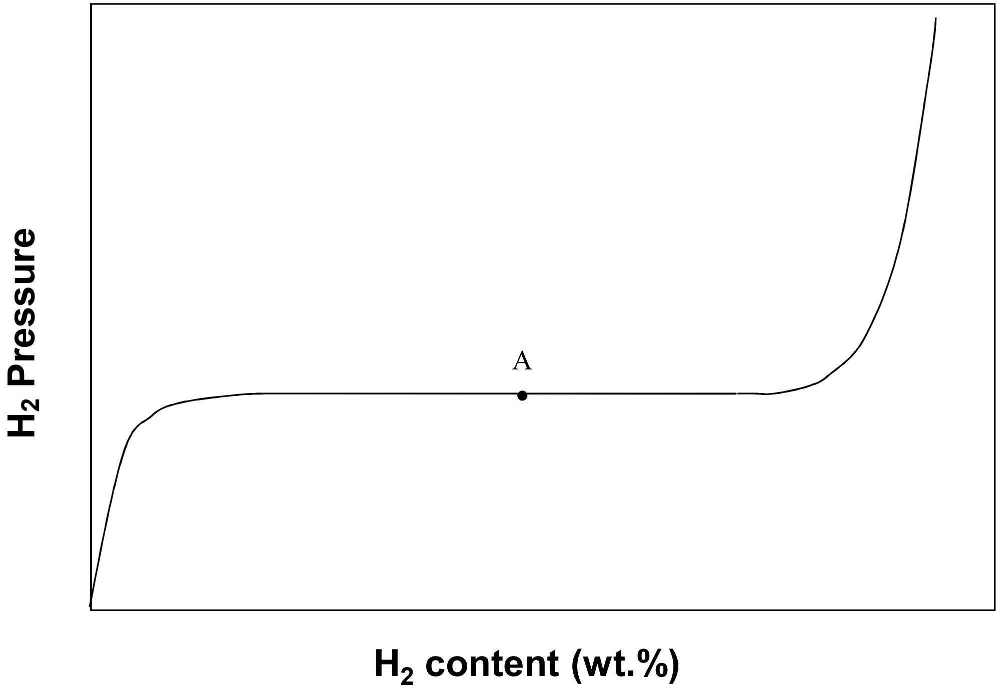
Thermodynamics of MHx



$$\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$$

$$\Delta G^\circ = -RT \ln K$$

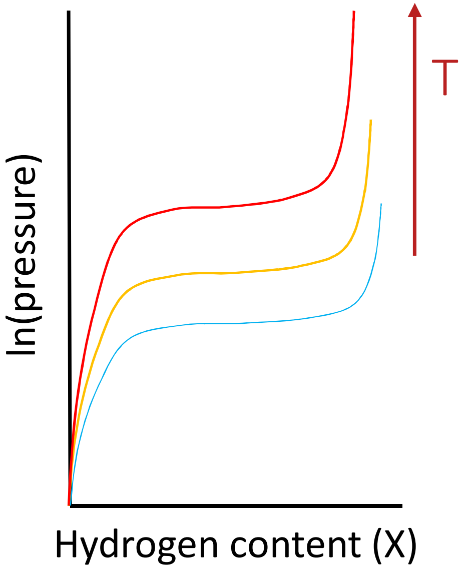
$$K_p = p(H_2)$$

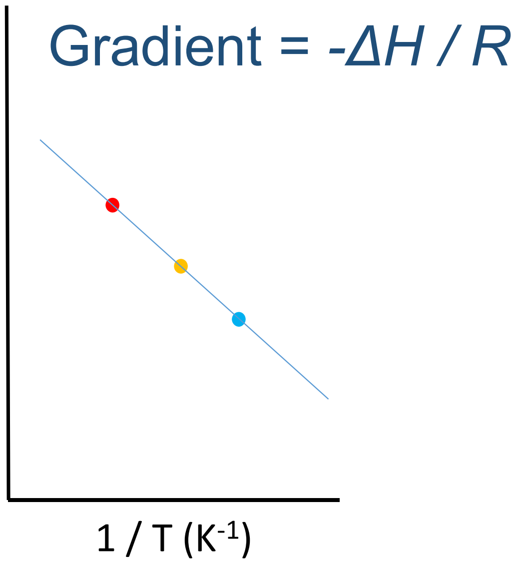


- Pressure Composition Isotherm (PCI)
- Equilibrium data
- Effect of pressure on the amount of H_2 stored
- Point A denotes the plateau pressure

Thermodynamics of MHx

- The equilibrium is affected by temperature





$$\Delta G^\circ = -RT \ln K$$

$$\Delta H^\circ - T\Delta S^\circ = -RT \ln K$$

$$\ln K = \frac{-\Delta H^\circ}{RT} + \frac{\Delta S^\circ}{R}$$

- van’t Hoff
- Linear relationship between ln(p) and 1/T.

- Calculate thermodynamic data from PCIs

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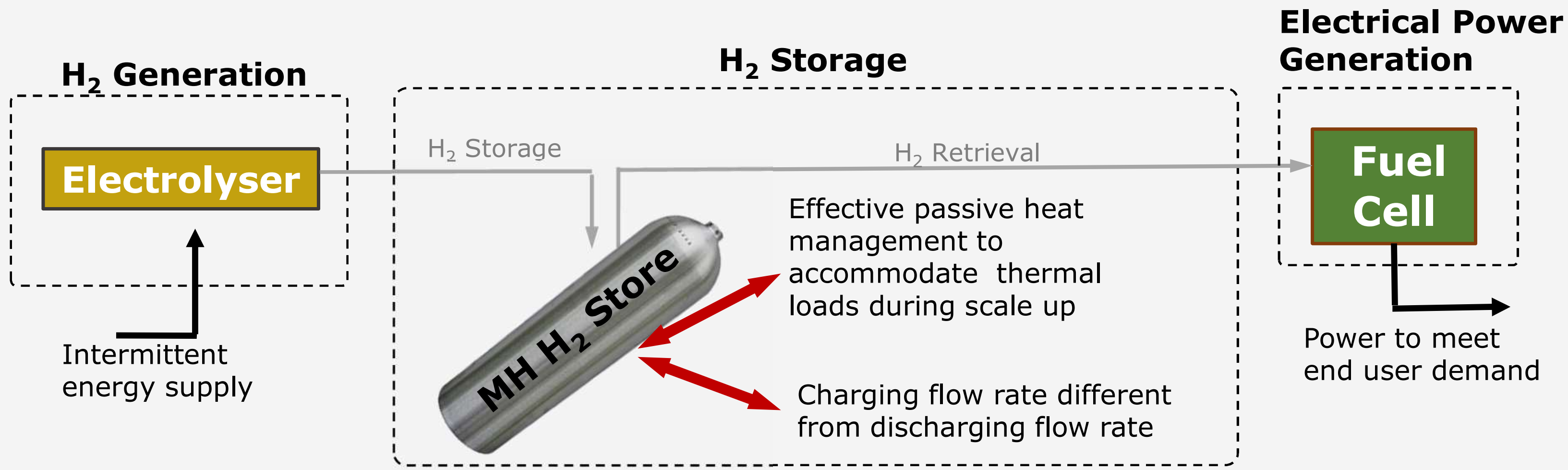
Hydrogen stores

Stationary Applications for the Storage of H_2

Gavin Walker, David Grant

‘Compression free’ concept for H_2 storage for off-grid renewable energy and micro grid applications.



H_2 Generation

Electrolyser

Intermittent energy supply

H_2 Storage

H_2 Storage

H_2 Retrieval

MH H_2 Store

Effective passive heat management to accommodate thermal loads during scale up

Charging flow rate different from discharging flow rate

Electrical Power Generation

Fuel Cell

Power to meet end user demand

Advantages

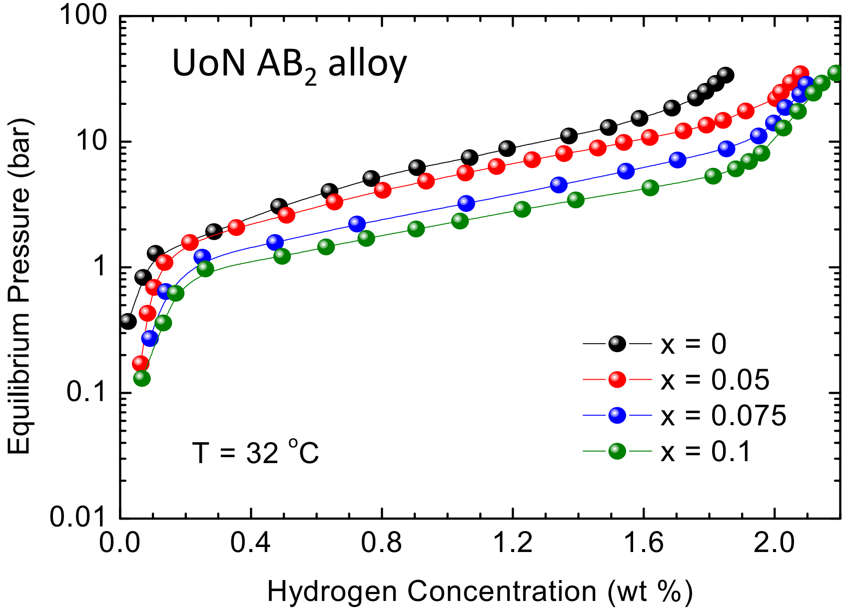
- Mechanical compression is not required
- Superior volumetric energy density is achieved
- System operates at relatively low pressures, < 3 MPA.

	Volumetric Energy Density [kg/m^3]
MH H_2	33
Compressed H_2 (20 MPa)	16

Hydrogen Energy Storage

AB_2 materials development

Pressure – Composition Isotherms



Working capacity: 1.8 wt %
ca. 30 % higher than commercial alloy.

- Low pressure storage (<30 bar) with densities equivalent to H_2 at 800 bar.
- We can tailor the operation pressure and working capacity for the material.
- H_2 storage capacities currently up to 2.2 wt% at 35 bar and 32 °C.
- For an operating pressure range of 1-30 bar the working capacity is 1.8 wt % at 32 °C; cf. the commercially available Hydralloy C which is only 1.4 wt % at 32 °C.
- Aim to reduce the cost of energy storage.

UoN AB_2 alloy:	£9/kg;	£13/kWh
Hydralloy C:	£45/kg;	£81/kWh

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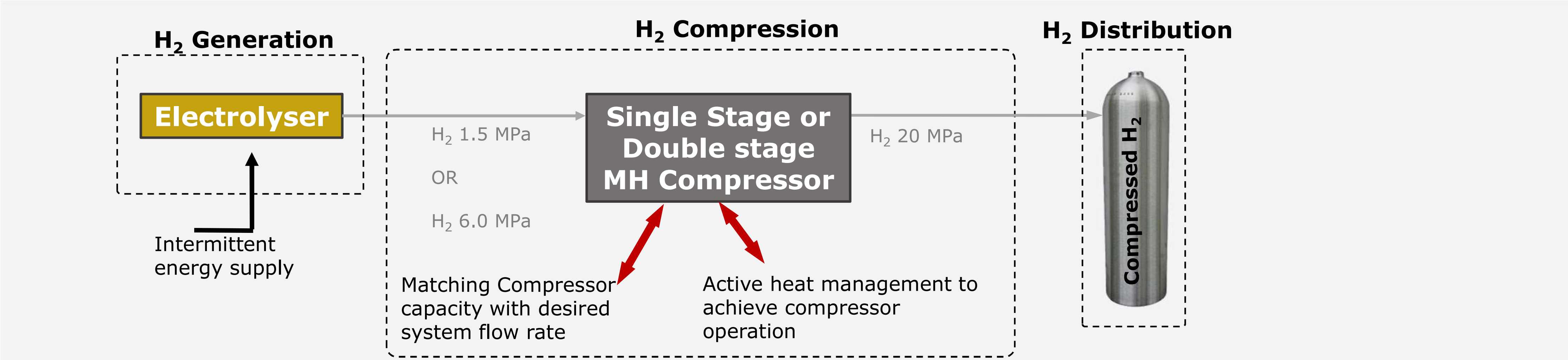
Solid state compressors

Compression for distribution of H_2

MH Compression concept for H_2 storage for off-grid renewable energy and micro grid applications.



Advantages

- MH compressor can utilise available low-grade heat to achieve desired H_2 compression up to 20 MPa.
- MH compressor has no moving parts so will provide reliable maintenance free operation. (unlike mechanical compression which is als0 energy intensive)

Solid State Hydrogen Compressors

H_2 gas compression is achieved by the reversible hydrogenation/dehydrogenation of AB_2 alloys.

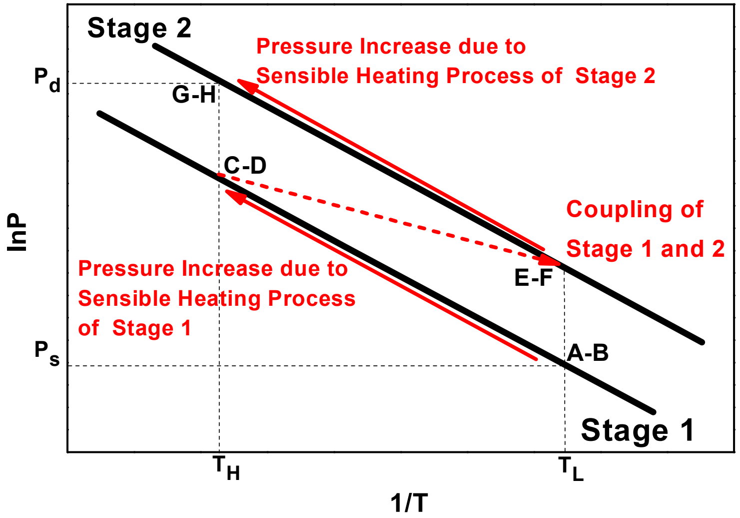
Step A: Hydrogenation of 1st stage reactor, at 30 bar (P_s) and ambient temperature (T_L).

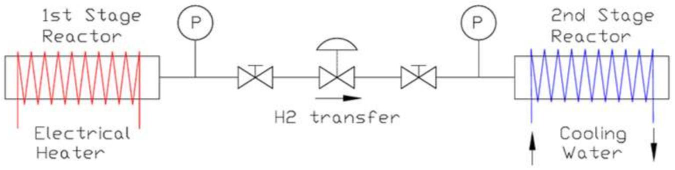
Step B-C: Sensible heating of 1st stage reactor accompanied by pressure increase.

Step D-E: Coupling process between 1st stage (dehydrogenation at T_H) and 2nd stage reactors (hydrogenation at T_L).

Step F-G: Sensible heating of 2nd stage reactor accompanied by pressure increase.

Step H: Dehydrogenation at 120 °C (T_H) of 2nd stage reactor H_2 released at 350 bar (P_d).

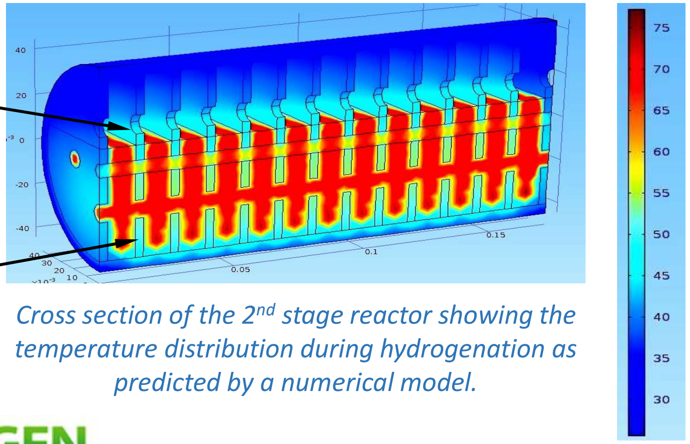




Simplified schematic of solid state compressor illustrating the coupling process of Step D-E

Head space to accommodate bed breathing

Equally spaced internal fins to provide heat management



Cross section of the 2nd stage reactor showing the temperature distribution during hydrogenation as predicted by a numerical model.

Loughborough University
The University of Nottingham
University of Birmingham
Energy Programme
H2FCSUPERGEN
THE HYDROGEN AND FUEL CELL RESEARCH HUB

Solid State Hydrogen Compressors

Mechanical compressors are known to be unreliable increasing cost of ownership and leading to plant downtime. The advantages of a solid state H_2 are:

- **Less energy intensive and therefore less expensive to run.** Energy costs can be reduced to fraction of that of a mechanical compression by utilising waste heat to drive the compressor.
- **Lower maintenance costs.** No moving parts means that there is no dynamic seals or bearings that need ongoing maintenance.
- **High gas purity.** There is no contamination of hydrogen.
- **Silent operation.** Relative to a mechanical compression there is no noise.

- **Hydrogen vehicle refuelling infrastructure** – an improvement in hydrogen compression technology quieter and potentially improve the cost-performance (improved further if their operation can be coupled with a waste heat source).
- **Renewable energy storage** – the ability to efficiently compress H_2 gas can potentially provide a significant improvement in the operational efficiency as an energy store.

Offshore storage

Offshore hydrogen storage

Compare offshore options:

- Salt caverns
- Depleted gas fields or aquifers
- Underwater containment vessels
- Compressed vessels (100 – 700 bar)
- Solid-state H_2 (metal hydride)
- Liquid hydrogen

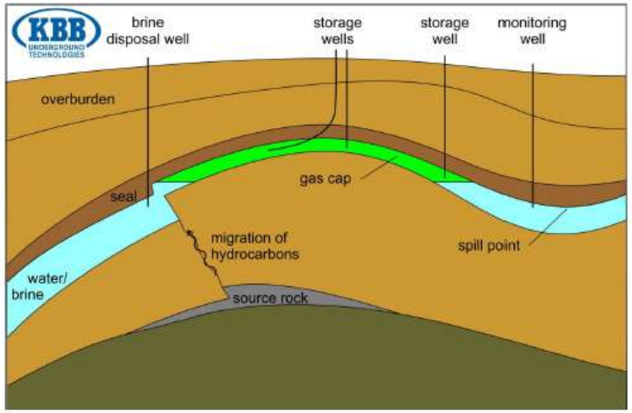


Figure 4-1: Schematic diagram showing a typical setup of a hydrocarbon reservoir

Space Applications of Hydrogen and Fuel Cells (2021)
https://www.nasa.gov/content/space-applications-of-hydrogen-and-fuel-cells

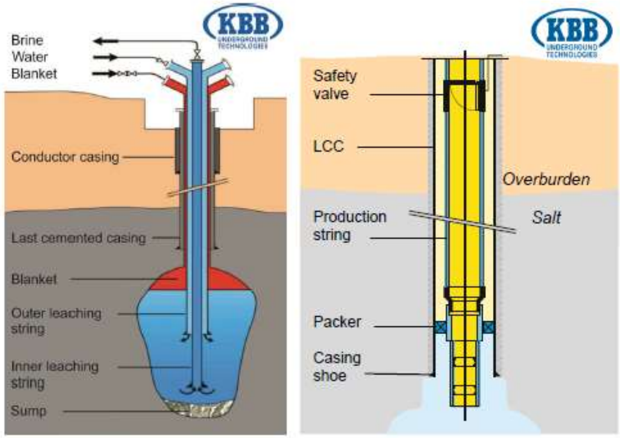


Figure 2-1: Salt cavern with installed leaching string and blanket during leaching (left) and gas completion (right)

HyUnder Report (2013), D(4) – Overview on all known underground storage technologies for hydrogen

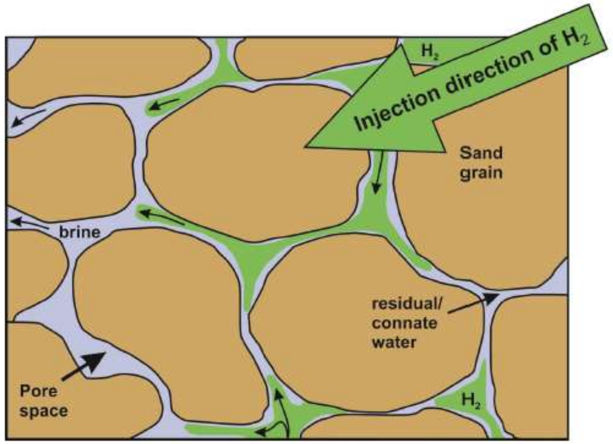
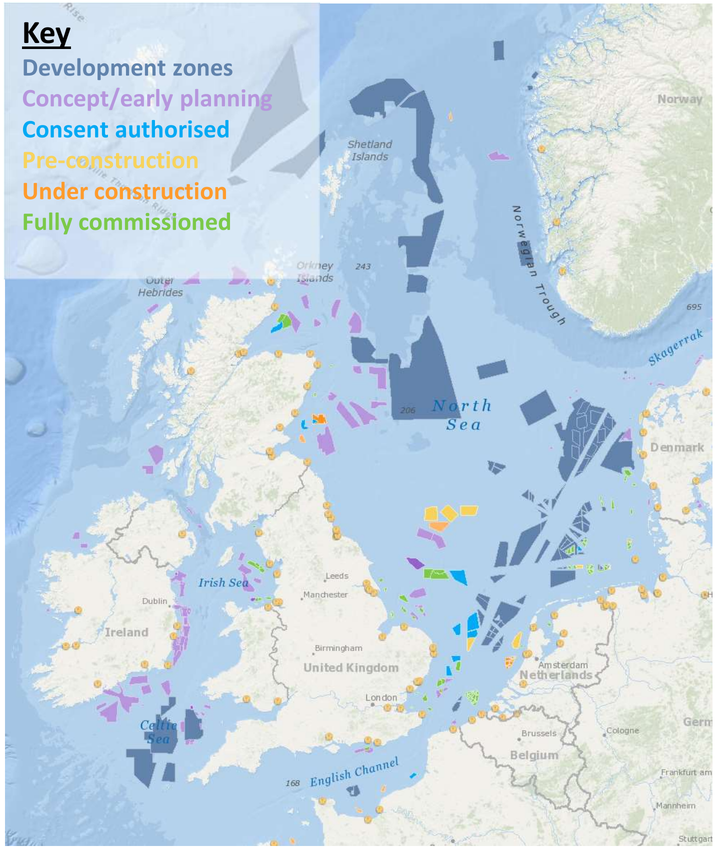


Figure 3-2: Gas migration in a water filled pore space.

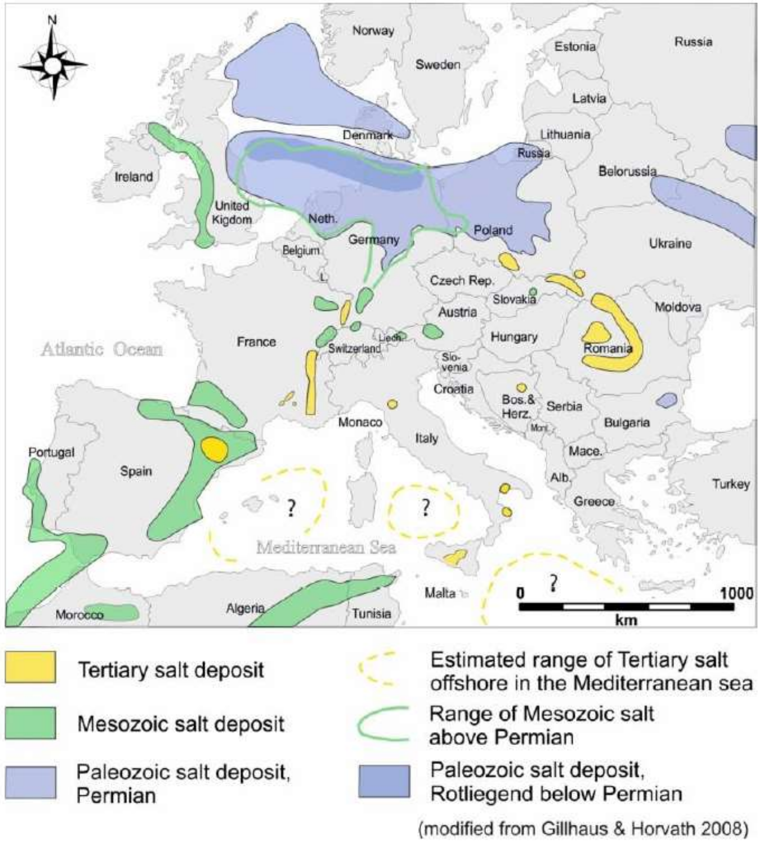
HyUnder Report (2013), D(4) – Overview on all known underground storage technologies for hydrogen

Offshore hydrogen storage

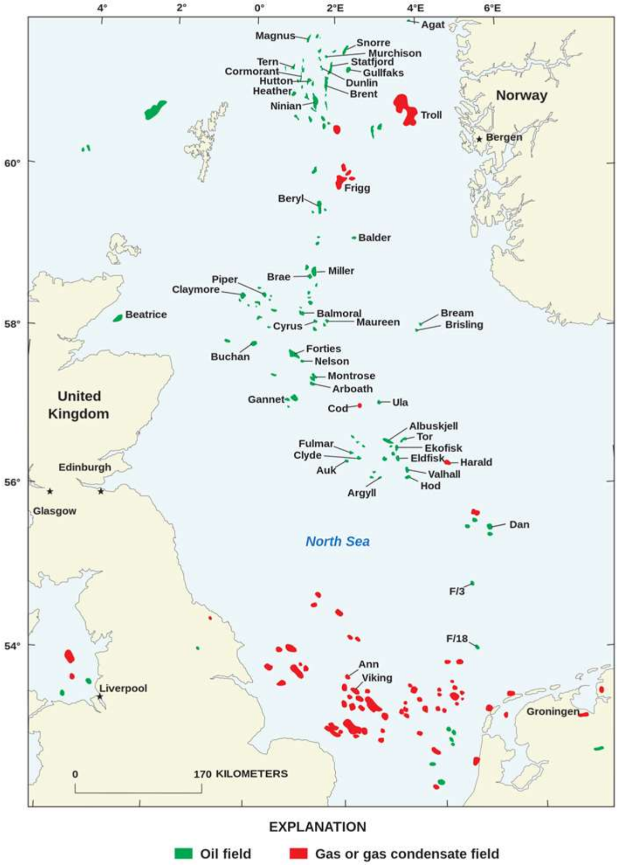
Offshore wind farm locations (North Sea) with gas field and salt cavern deposits



4C Offshore, a TGS Company, https://map.4coffshore.com/offshorewind/



HyUnder Report (2013), D(4) – Overview on all known underground storage technologies for hydrogen



By Gautier, D.L. - US Dept. of Interior USGS Bulletin 2204-C, Public Domain, https://commons.wikimedia.org/w/index.php?curid=106453503

Offshore hydrogen storage

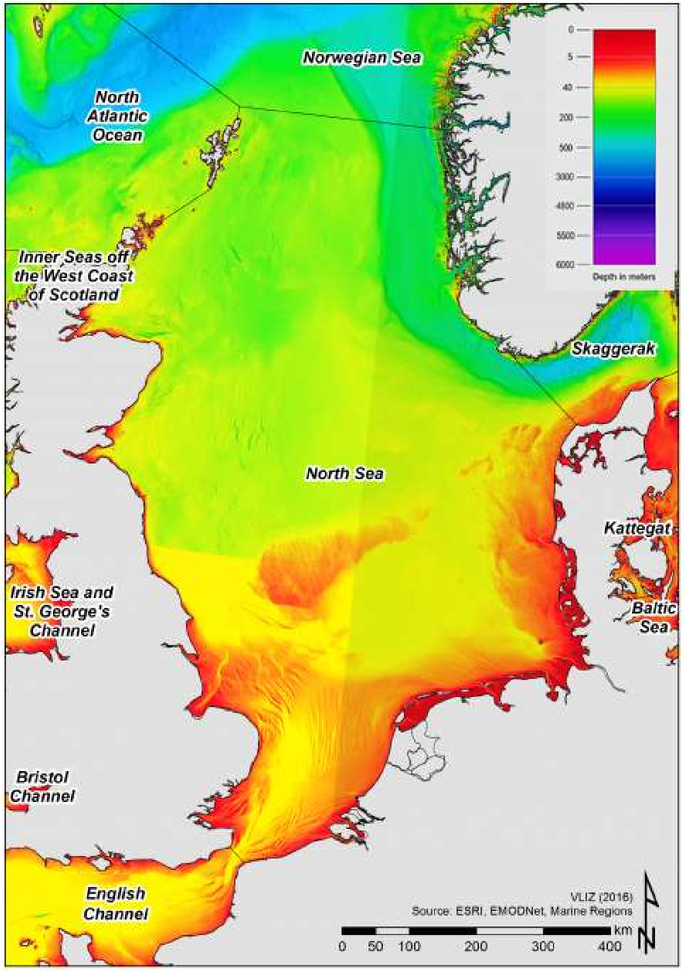
Underwater isobaric containment vessels

- Energy bags
- Spheres

Pimm (2014) Design and testing of Energy bags for underwater compressed air energy storage.

Fraunhofer's 3m concrete sphere
Andrews (2018) A review of underwater compressed air storage

				Energy bags		Spheres			
						Lower	Higher	Lower	Higher
Depth	Pressure (bar)	Density (kg/m3)	kg H2	€/kg H2	€/MWh	€/kg H2	€/kg H2	€/MWh	€/MWh
20	2	0.17	229	£37	£927	0.32	1.6	8.2	41
40	4	0.35	457	£18	£464	0.16	0.81	4.1	21
100	10	0.87	1138	£7.3	£186	0.07	0.33	1.7	8.3
200	20	1.72	2263	£3.7	£94	0.03	0.16	0.8	4.2
400	40	3.40	4471	£1.9	£47	0.02	0.08	0.4	2.1
500	50	4.23	5555	£1.5	£38	0.01	0.07	0.3	1.7
600	60	5.04	6625	£1.3	£32	0.01	0.06	0.3	1.4
700	70	5.8465	7682	£1.1	£28	0.01	0.05	0.2	1.2



De Hauwere, Nathalie (2016) Bathymetry of the North Sea, https://www.marineregions.org/maps.php?album=3747&pic=115811

Summary

Summary

The compression and storage requirements are dependant on wind farm location

- Optimal energy transportation (offshore-onshore); which affects:
- Delivery and Storage Pressure
- Storage time
- Charging frequency
- Suitability of site for geological storage
- Phase: solid, slurry, liquid H, or gas
- Gas impurities

Electrolyser technology determines

- Output pressure
- Compression requirement for storage / transportation
- Gas impurities purity

Advantages of MHx technologies

- Utilising waste heat for compression
- Compact storage of hydrogen at atmospheric pressure

Cost influenced by all of the above

Thank You

gavin.walker@nottingham.ac.uk

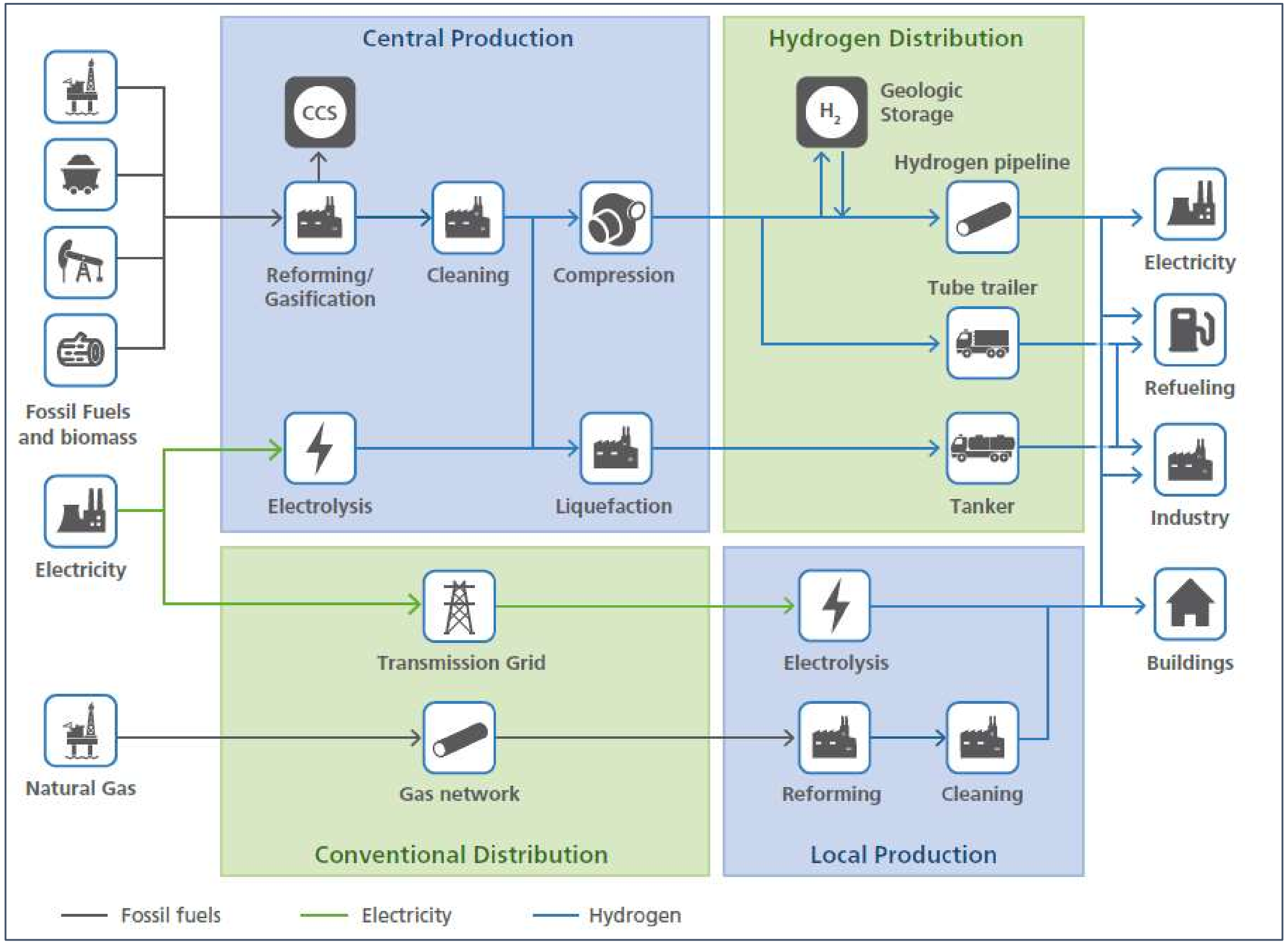
Ocean-REFuel (Ocean Renewable Energy Fuel)

WP4 - Networks, Compatibility and Demand

WP4 - Networks, Compatibility and Demand

- The techno-economics of the conversion of the H_2 to an alternative energy vector (if used).
- The performance of the energy vector during its transportation and storage
- The compatibility of the energy vector used with end-user technologies and whether there is a need for reconversion at or near the point of use.
- How industry, public and regulators/politicians perceive the technology solutions themselves, and the wider economy impacts of developing, deploying and using the technology. This is crucial in informing policy narratives around which consensus can build.

Systems view



Future low carbon systems need low carbon energy vectors:

- Electricity
- Hydrogen
- Biofuels
- Synthetic fuels

Different regions will have different proportions…

New service: negative emissions

How might ocean-derived fuels be used?

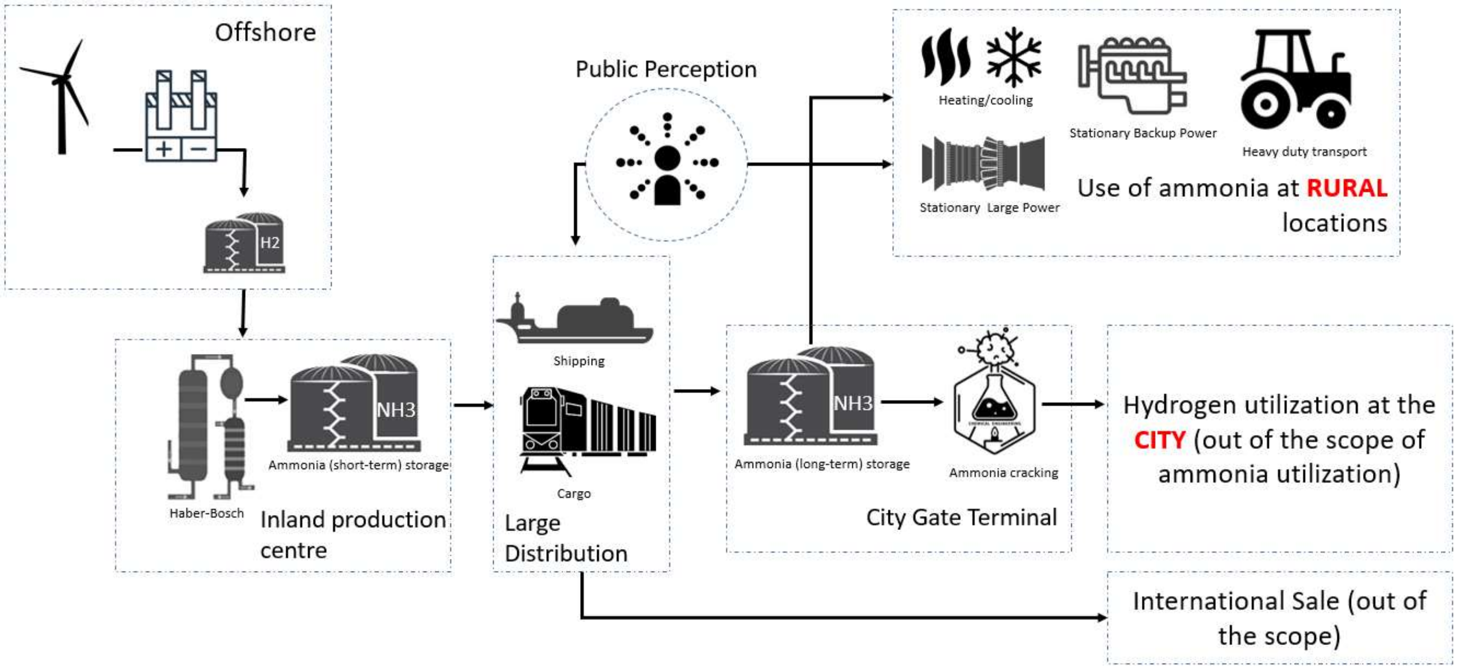
- Directly as H_2
  - Industrial feedstock/heating
  - Transport fleets
  - Grid injection for domestic/commercial heating
  - Energy storage (longer term)
- As other fuels – shipping, aviation, HGVs, ….
  - Conversion location is relatively flexible as fuel is fungible
    - NH_3
    - MeOH
    - Hydrocarbons
  - Convert H_2 near shore?

WP4 - Networks, Compatibility and Demand

WP 4.1 Use of NH_3 as an alternative long-term/long-distance energy vector

- *Task 4.1.1. Numerical and experimental data on efficiency, energy, costs*
- *Task 4.1.2. Integration of systems for higher efficiencies to various sectors.*
- *Task 4.1.3: Study for the reconversion of ammonia to hydrogen at a larger "city-gate" scale.*

SCOPE OF THE USE OF AMMONIA AS A HYDROGEN VECTOR


Offshore

H2

Haber-Bosch

NH3

Ammonia (short-term) storage

Inland production centre

Public Perception

Shipping

Cargo

Large Distribution

NH3

Ammonia (long-term) storage

Ammonia cracking

City Gate Terminal

Heating/cooling

Stationary Backup Power

Heavy duty transport

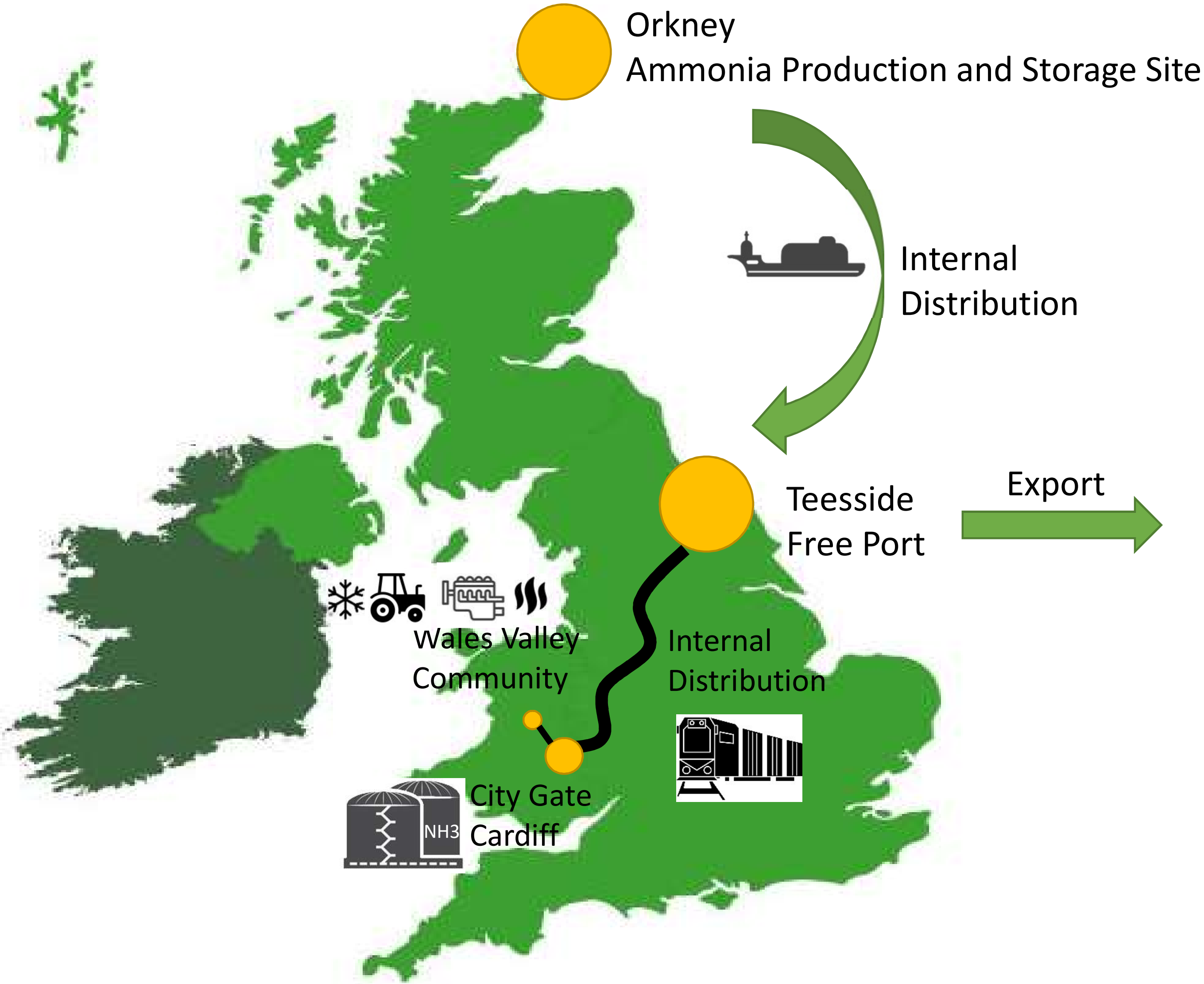
Stationary Large Power

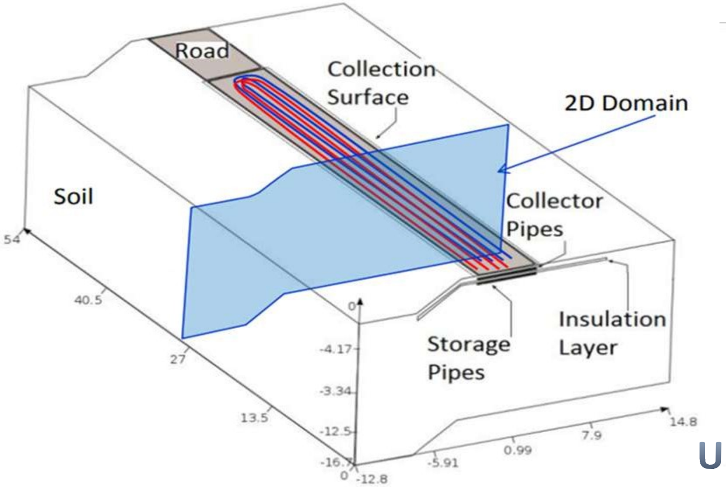
Use of ammonia at **RURAL** locations

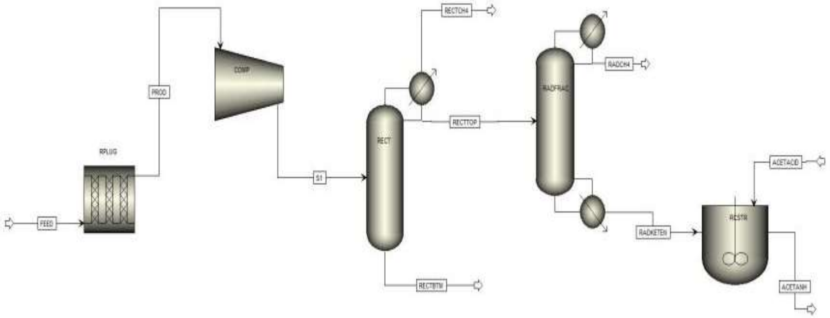
Hydrogen utilization at the **CITY** (out of the scope of ammonia utilization)

International Sale (out of the scope)

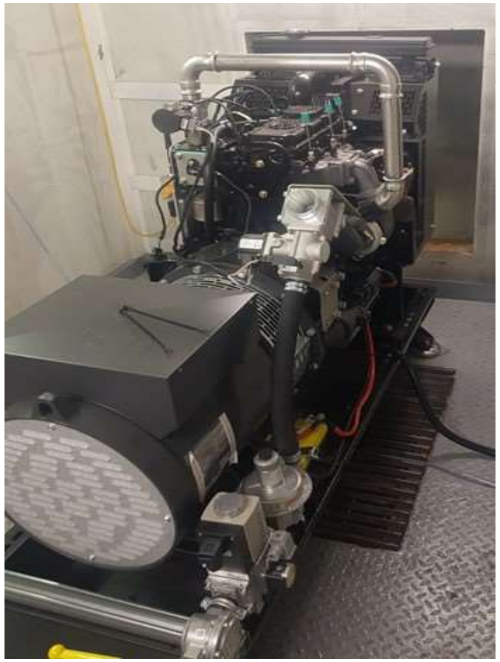
UK SCENARIO FOR AMMONIA UTILIZATION

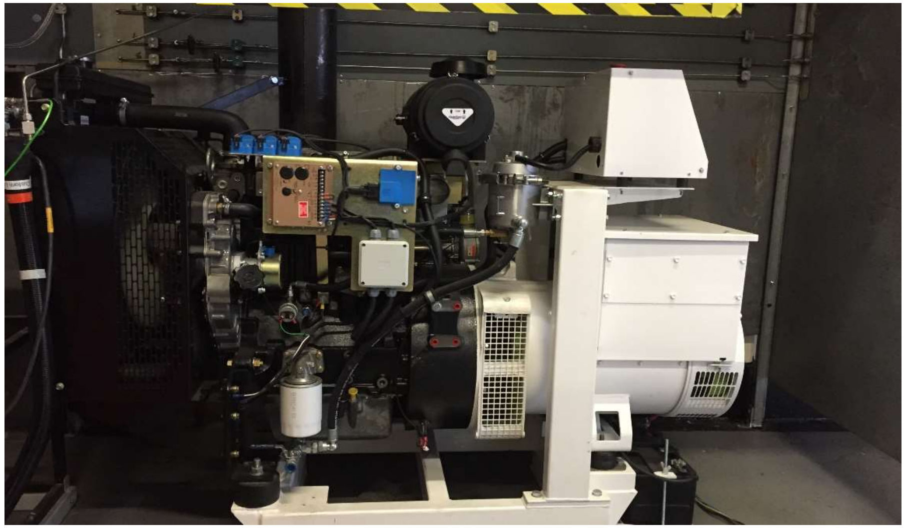






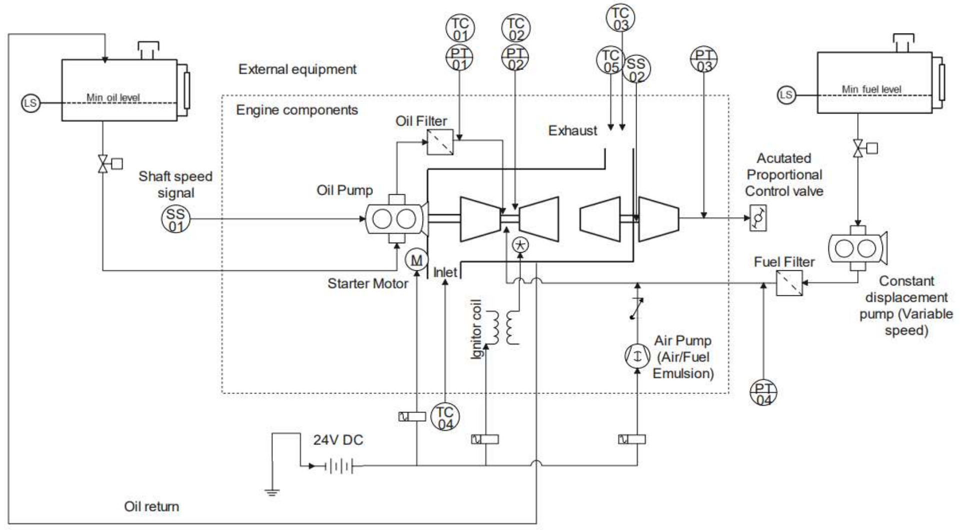
Underground Heat Pump modelling using ammonia as working fluid





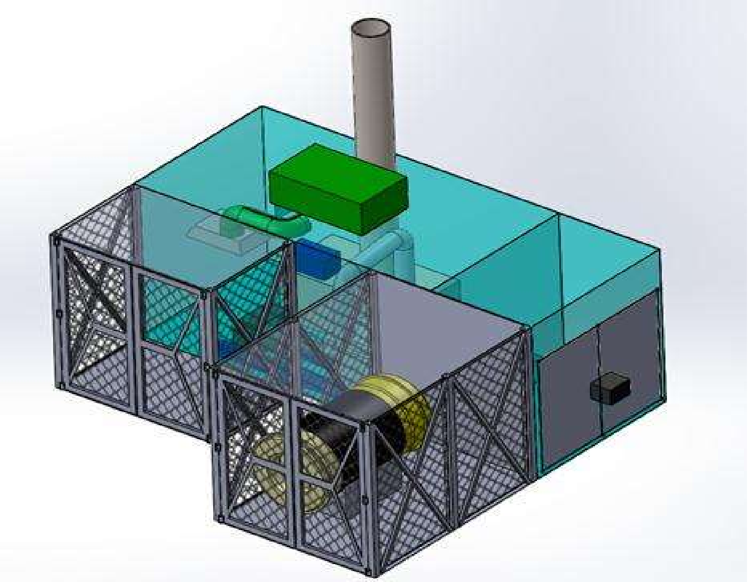
Performance, Injection strategies, Heat recovery, and Emissions (CO2 and NOx) using ICE-H2/NH3

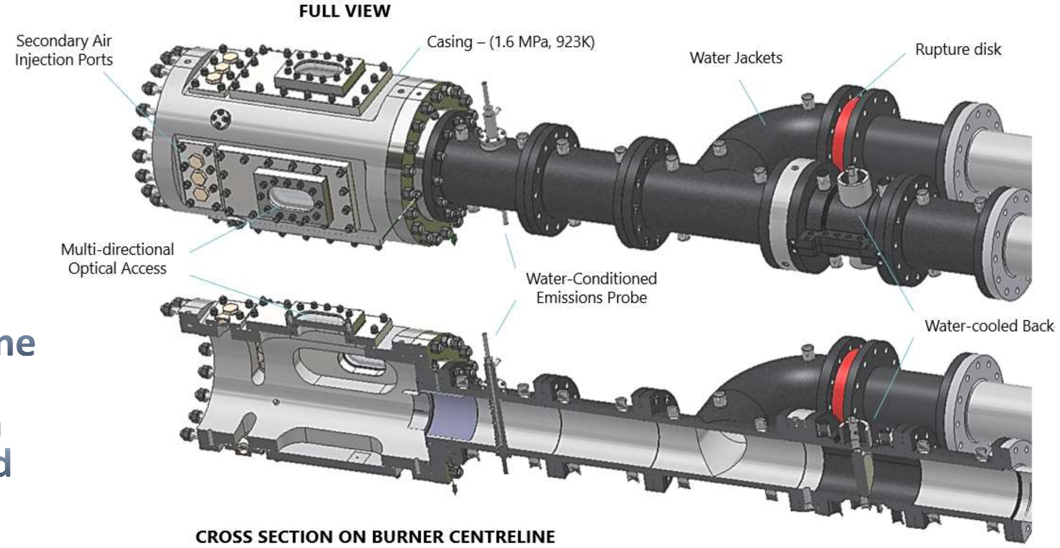
Ammonia Gas Turbine modelling using experimental data from SAFE-AGT and FLEXnCONFU



Shaft speed signal 1 - needs to be fitted to oil pump as engine does not have a speed sensor

Shaft speed signal 2 - needs to identify type of signal generated by sesnor on engine





WP4 - Networks, Compatibility and Demand

WP 4.2 ‘Carboniferous’ Hydrogen Supply

- *Task 4.2.1 Safety Assessment*
- *Task 4.2.2 End-use performance limitations* - what % of H2 is feasible in end-use technologies?
- *Task 4.2.3 Accurate (fiscal) flow measurement*

Projects such as Hy4Heat and Hynet have explored the suitability of several end-use technologies at relatively low H_2 contents but additional

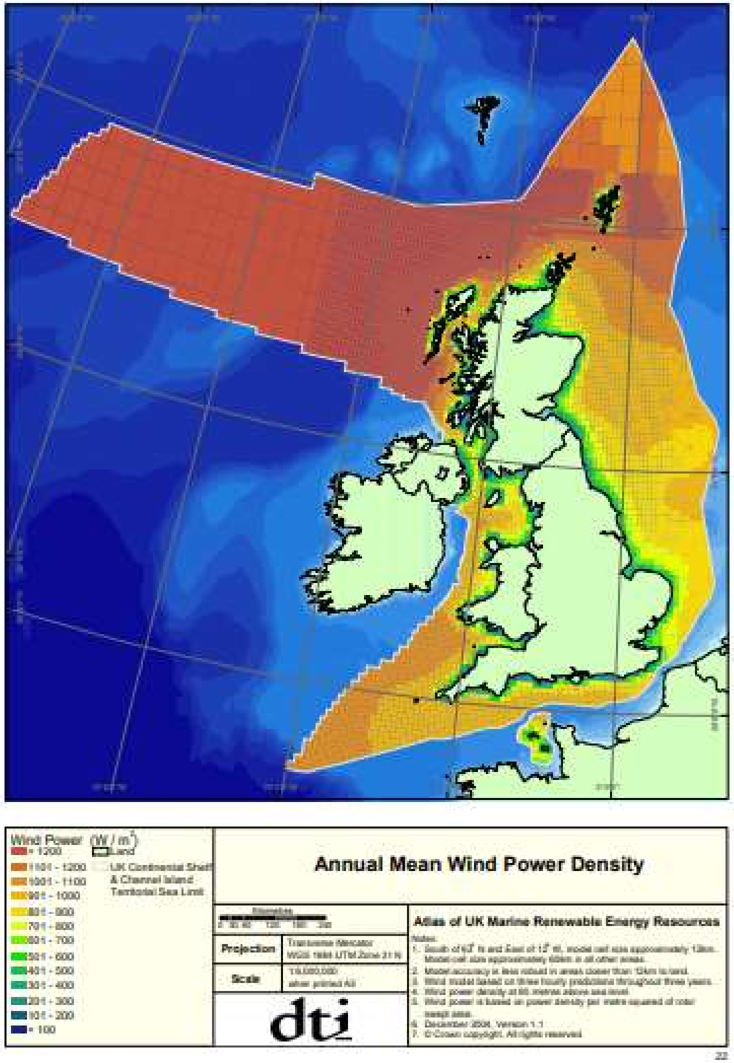
The move towards higher H_2 in the system may be limited either by H_2 availability or by the ability of end-users to accept pure H_2.

Green CO_2 from BECCS plus H_2 can reacted to make a CH_4/H_2 blend that is suitable for end users but still ‘net zero’.

Determining likely future operational limits for major system gas consuming technologies.

Proof of concept for gas flow measurement techniques.

Outline techno-economic analysis of one or two candidate technologies for $CO_2 + H_2$ conversion to CH_4 to create a suitable overall H_2/CH_4 blend.

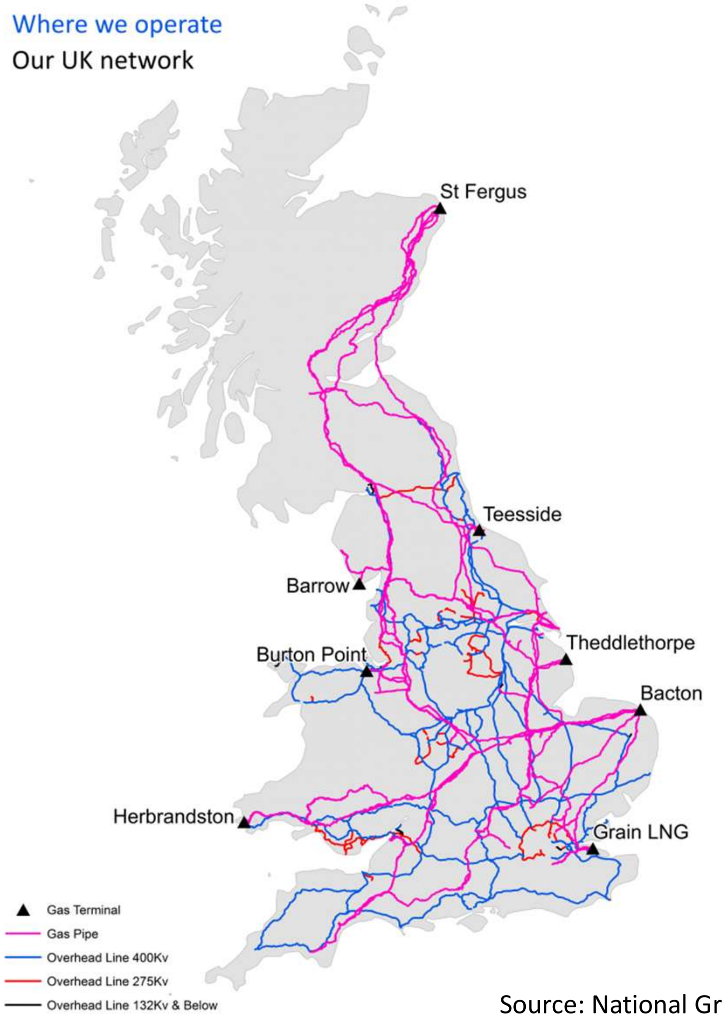


Annual Mean Wind Power Density

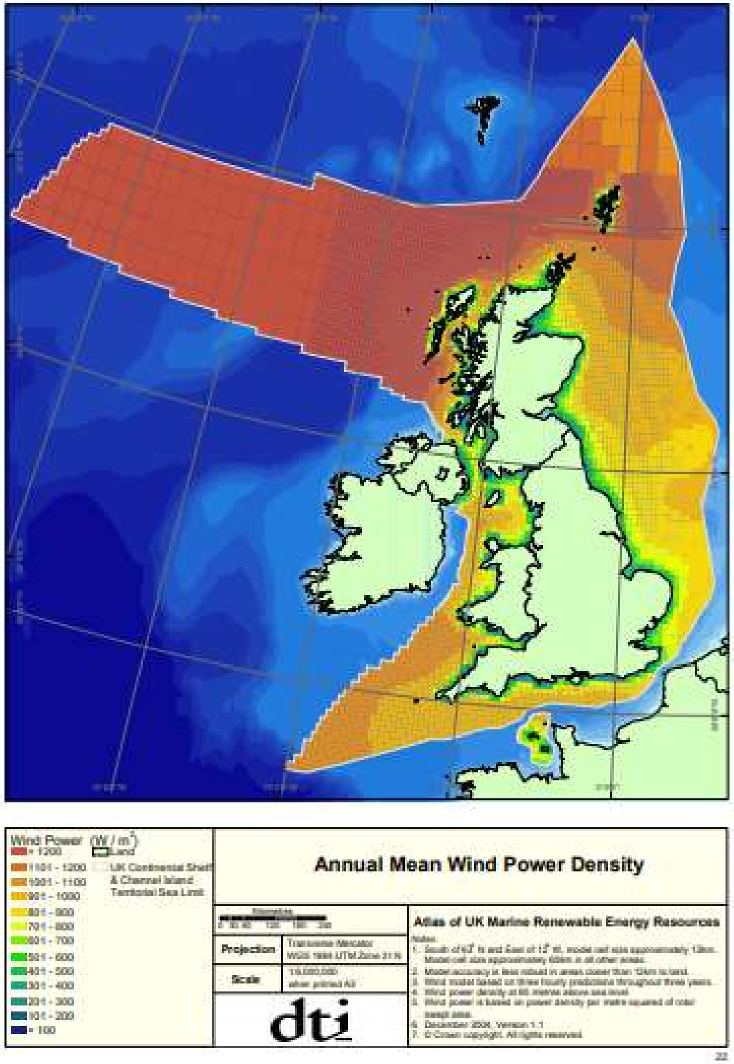
Notes:
1. South of 63° N and East of 12° W, model cell size approximately 12km. Model cell size approximately 60km in all other areas.
2. Model accuracy is less robust in areas closer than 12km to land.
3. Wind model based on three hourly predictions throughout three years.
4. Wind power density at 80 metres above sea level.
5. Wind power is based on power density per metre squared of rotor swept area.
6. December 2004, Version 1.1
7. © Crown copyright. All rights reserved.

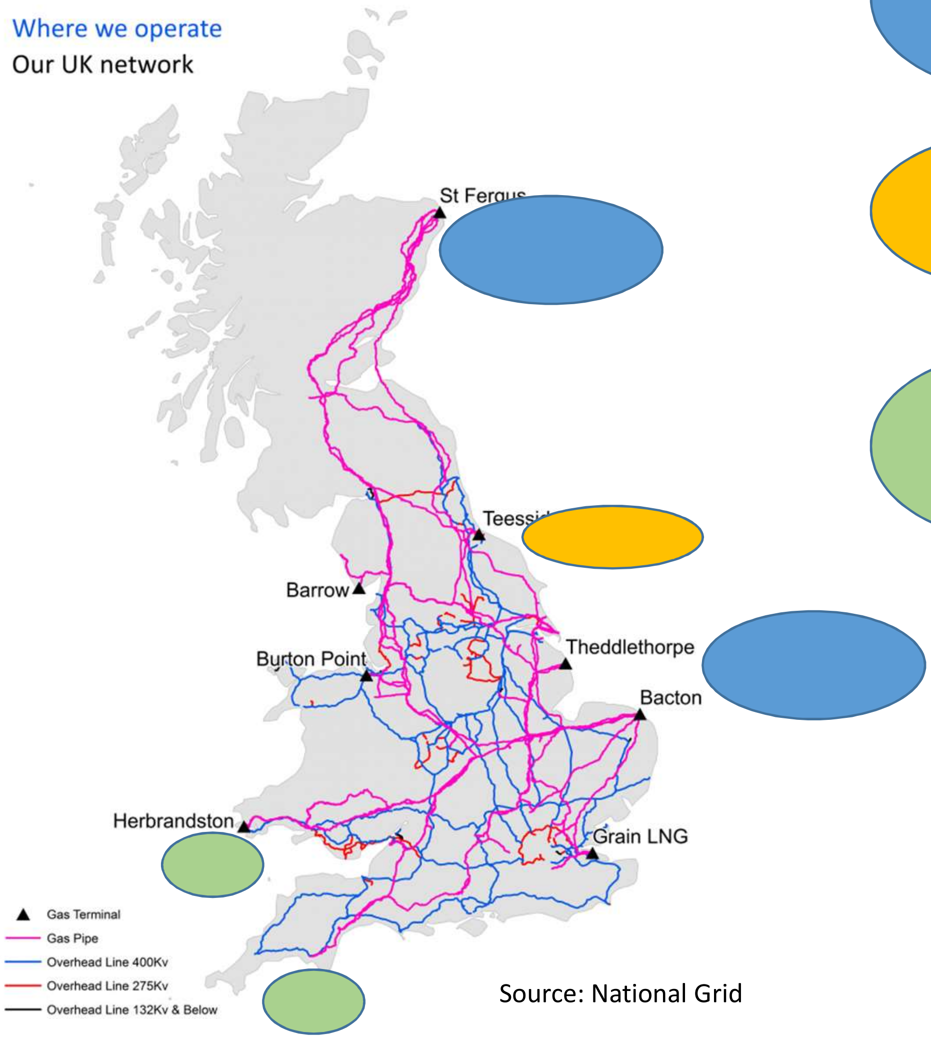
Where we operate

Our UK network



Source: National Grid





Source: National Grid

Multiple pipeline routes

Pure H2?

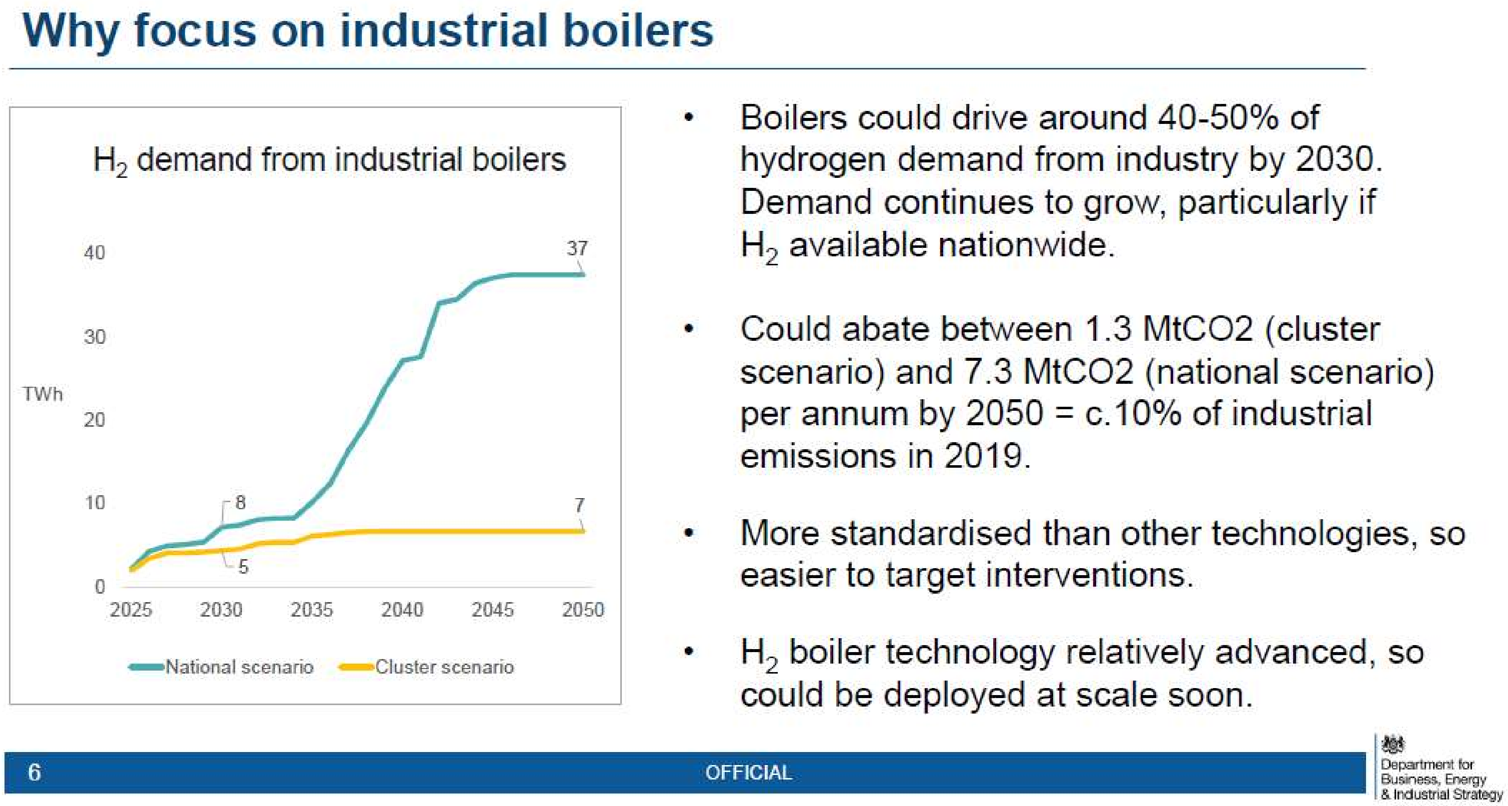
Limited pipeline capacity – CO2 available – 'net-zero' methane?

Single pipeline – transport as blend?

Possibilities

- Multiple gas connections – export as blend or pure H_2 – multiple lines gives optionality.
- Single gas connection – transport as H_2 blend only – or as ‘net-zero’ methane
- No adequate gas connection – transmit as power – H_2 Production elsewhere?
- No grid options – off-shore production and ship transfer?

Industry – clusters and national



Why focus on industrial boilers

- Boilers could drive around 40-50% of hydrogen demand from industry by 2030. Demand continues to grow, particularly if H_2 available nationwide.
- Could abate between 1.3 MtCO2 (cluster scenario) and 7.3 MtCO2 (national scenario) per annum by 2050 = c.10% of industrial emissions in 2019.
- More standardised than other technologies, so easier to target interventions.
- H_2 boiler technology relatively advanced, so could be deployed at scale soon.

Department for
Business, Energy
& Industrial Strategy

WP4 - Networks, Compatibility and Demand

WP4.3 Public Perception of technologies

*T*echnological development has been focused on achieving more reliable, efficient and safe energy vectors.

Social sciences studies have been analysing the role of attitudes – across governments, industry and consumers - to these developments

- secure a future for zero-carbon alternatives and
- ensure a just transition to mid-century net zero targets.

Public perception is a key element for the transition to renewable energies.

We focus on the importance of understanding these complex interactions between public and the development of new energy alternative technologies.

Work will be performed to build understanding of public perceptions and attitudes towards the use of NH_3 and H_2

WP4 - Networks, Compatibility and Demand

WP4.4 LCA and System Metrics (M1-M60)

- *Task 4.4.1 Technology level TEA and LCA assessments*
- *Task 4.4.2 Identify/analyse the wider economy impacts*
- *Task4.4.3 Assessment of key resource flows, waste generation and circular management*

Hydrogen and NH_3 energy systems based on offshore renewable electricity generation can be inherently low carbon, but risk introducing trade-offs in other sustainability metrics (safety, environmental, economics, thermodynamic, resource efficiency, and planetary boundaries).

- This work package will develop and deploy a suite of techniques to comprehensively evaluate candidate systems, linking technology-level assessments of key components to assess systems.
- Techno-economic and life cycle assessment models will be developed from technology-level assessments of key system components (offshore renewable energy; electrolysis; NH_3/carboniferous fuel production; H_2 and NH_3 storage and transport infrastructure; end use applications)
- These will be complemented by economic (Computable General Equilibrium (CGE) and scenario simulation models which will develop generic understanding of how the implications of deploying key system components, in terms of how these integrate with current energy supply and use sectors, may impact across the wider UK economy.
- Iterative work will be continuously updated with insights from technical work including cost, inefficiency, or environmental impact, as well as impacts on competitiveness, GDP, jobs, earnings, and potential for new economic activities, identifying the most promising system configurations to deliver fuels and feedstocks for downstream applications.
- Abundant materials can pose challenges, where end-of-life management is difficult (e.g., composite wind turbine blade materials; solid state H_2 storage alloys). Material flow analysis models will be developed to track stocks and flows of these key materials under illustrative deployment scenarios of the candidate systems.
- Other LCA metrics such as global warming potential, damages to resources and damages to human health and ecosystems will compare alternative systems and identify sustainability hotspots.

WP4 - Networks, Compatibility and Demand

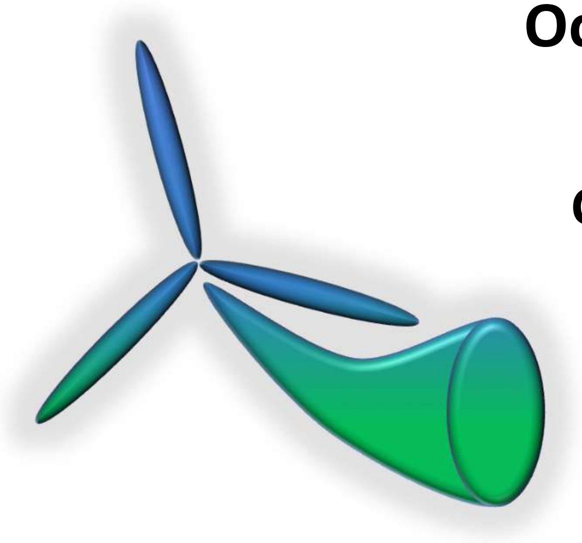
WP4.5 Overall System Optimisation

Task 4.5.1 Value chain definition
Task 4.5.2 Value chain model development
Task 4.5.3 Value chain optimisation

- In this WP, value chain superstructure models will be developed to capture the interactions between the different nodes of the system and embed technological detail (e.g. power generation, hydrogen production/fuel production, fuel transport and storage, end-use technologies) in the nodes of the value chain.
- Optimisation models informed by the technical details arising from the other work packages as well as the economic and environmental analyses of WP4.4 will be used to optimise whole system design against a range of metrics.
- These value chain optimisation models will be used for regional case studies which explore trade-offs between objectives and the values different technologies bring to the system and also to assess performance levels that technologies will need to meet for them to play a substantial role in the overall system.
- There will be considerable iteration between this WP and all the others since the contribution of each technology to the performance of the system as a whole and its sensitivity to technology parameters will be important in other WPs.

Contacts

Robin Irons (robin.irons1@nottingham.ac.uk)
Agustin Valera Medina (ValeraMedinaA1@cardiff.ac.uk)
Jon McKechnie (jon.mckechnie@nottingham.ac.uk)
Nilay Shah (n.shah@imperial.ac.uk)



Ocean-REFuel (Ocean Renewable Energy Fuel)

Cross-cutting: systems engineering

Cardiff University
Prifysgol Caerdydd

Imperial College London

Newcastle University

University of Nottingham
UK | CHINA | MALAYSIA

University of Strathclyde
Glasgow

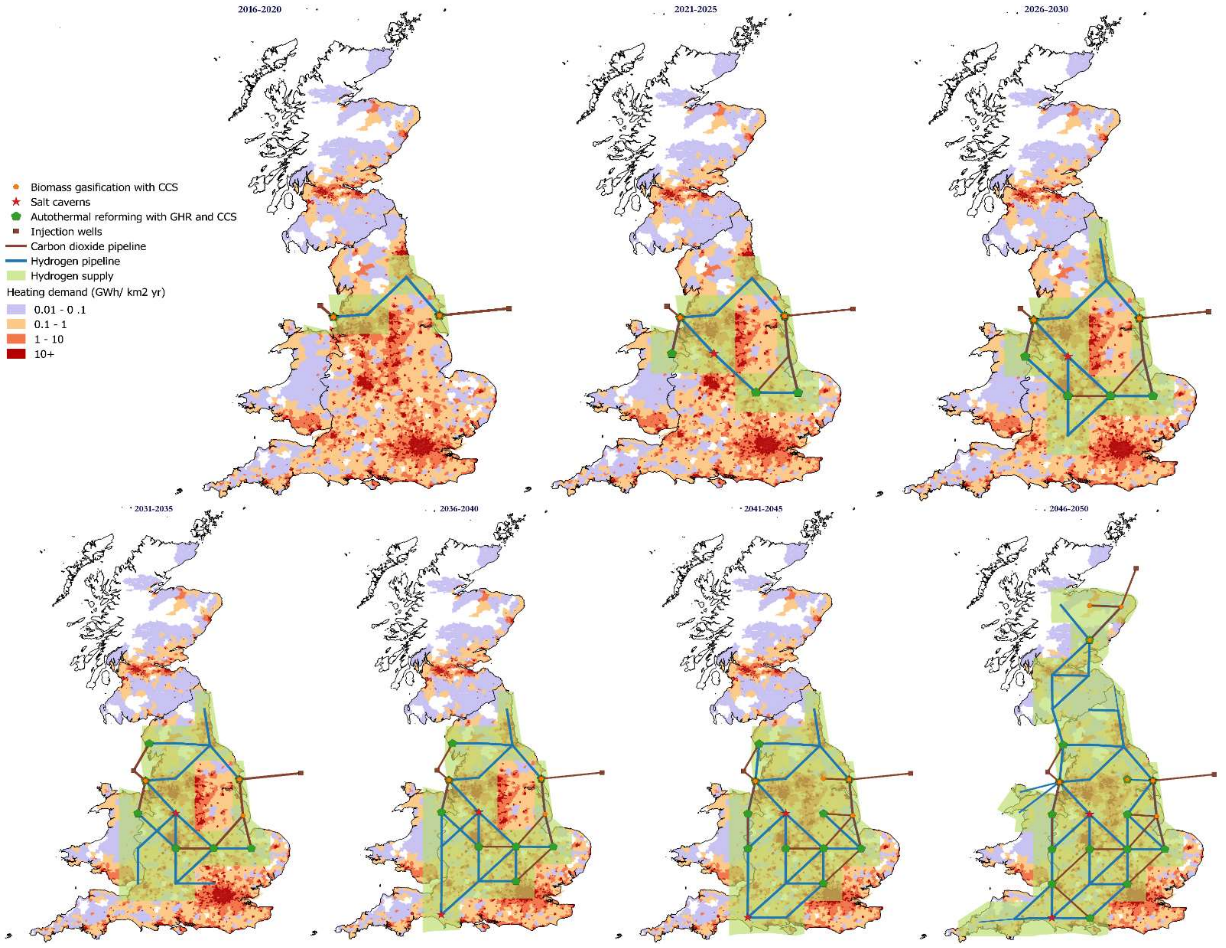
Systems questions

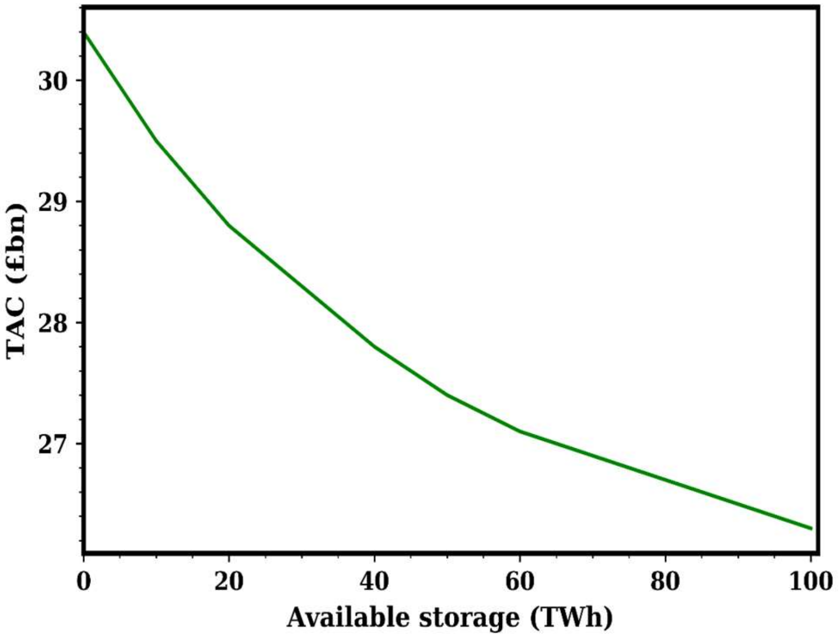
- Where to establish the system boundary (especially on the demand side)
  - How far onshore to explore infrastructure (in conjunction with WP4)
- Where will our fuels be most valuable?
- How does that compare with the most favourable supply location?
- Are there opportunity costs in the conversion process (displacement of useful renewable electricity)?
- What vectors are best to move between locations (electricity, H2, chemical fuels, …)?
- How to operate the system dynamically?
- How does the system dovetail with the UK’s energy (and hydrogen strategy) to 2030 and beyond?
- Where are the innovation and policy pinch-points in the system?

Context: Hydrogen – roles in the future energy system

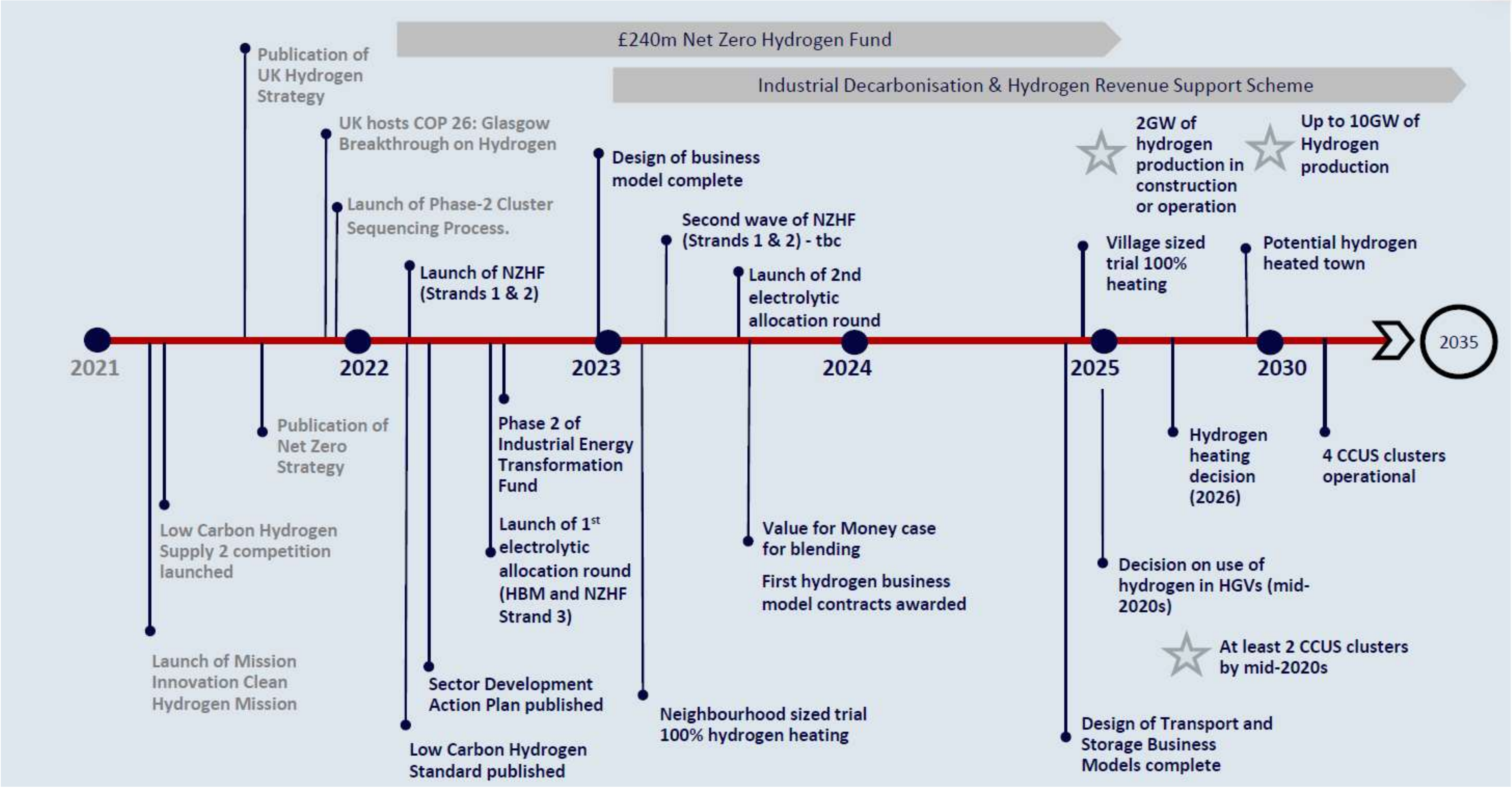
- Industrial feedstock and reductant
    - Existing and new processes (iron, synthetic fuels, …)
- Industrial, commercial and residential heating
- Low carbon power generation/CHP
- Transport
    - Heavier duty/longer range vehicles, trains, marine, aviation?
- Energy storage and renewables integration/cost reduction
- Long distance low-carbon energy transport
- …

Systems engineering: aim to establish how “best” the system evolves over time





Context: UK H2 roadmap



£240m Net Zero Hydrogen Fund

Industrial Decarbonisation & Hydrogen Revenue Support Scheme

2021

Publication of UK Hydrogen Strategy

UK hosts COP 26: Glasgow Breakthrough on Hydrogen

Launch of Phase-2 Cluster Sequencing Process.

Low Carbon Hydrogen Supply 2 competition launched

Launch of Mission Innovation Clean Hydrogen Mission

Publication of Net Zero Strategy

2022

Launch of NZHF (Strands 1 & 2)

Low Carbon Hydrogen Standard published

Sector Development Action Plan published

Phase 2 of Industrial Energy Transformation Fund

Launch of 1st electrolytic allocation round (HBM and NZHF Strand 3)

2023

Design of business model complete

Second wave of NZHF (Strands 1 & 2) - tbc

Launch of 2nd electrolytic allocation round

Neighbourhood sized trial 100% hydrogen heating

Value for Money case for blending

First hydrogen business model contracts awarded

2024

2025

☆ 2GW of hydrogen production in construction or operation

Village sized trial 100% heating

Design of Transport and Storage Business Models complete

Decision on use of hydrogen in HGVs (mid-2020s)

☆ At least 2 CCUS clusters by mid-2020s

Hydrogen heating decision (2026)

2030

☆ Up to 10GW of Hydrogen production

Potential hydrogen heated town

4 CCUS clusters operational

2035

System design: problem statement

Identify the best strategy of expansion planning for offshore wind power generation in terms of:

1. location of offshore wind farms,
2. Technology selection
   - 2.1. Electrolyzer type : turbine-integrated, wind farm hub, alkaline, PEM, or SOEC (centralised or decentralised)
   - 2.2. Energy transmission method: direct through cable , indirect through hydrogen carrier (hydrogen, ammonia, etc)
3. Dynamic operation and control
4. Integration with onshore infrastructure – what is required at port-side and what is assumed beyond?

What are the metrics to assess the system (e.g. system value, levelised cost of energy, ….)?

How to ensure effective integration (not competition) with onshore fuel production?

Model development

A mathematical optimization problem is being developed, by evaluating, justifying or rejecting the following assumptions:

- Operational strategy: even or independent distribution of the electricity load
- Considering the time horizon of 8 years (2022 -2030), or only a certain target year for the abovementioned expansion commitment of 40 GWs.
- Considering the interactions with onshore grid
- Considering utility-scale battery integration
- Considering the possibility of energy storage using hydrogen
- Temporal variations in the electricity price and opportunity costs

Ongoing research: Problem formulation

Objective function: levelized costs of hydrogen and electricity (LCOH & LCOE),

Constraints: Satisfying demand for electricity and hydrogen over the time horizon of 2023-2030,

Constraints: modelling economics, including capital costs and operational expenses,

Constraints: energy balance of electricity flows,

Constraints: mass balance of hydrogen flows,

Constraints: lean model (perform. curves) of electrolysers,

Constraints: lean model (perform. curves) of fuel cells,

Constraints: Electricity network model

Constraints: technical limitation of process equipment, and infrastructure

Source: ArcGIS – UK Offshore Wind Energy (Link)

Data requirements

The location of existing offshore wind farms,

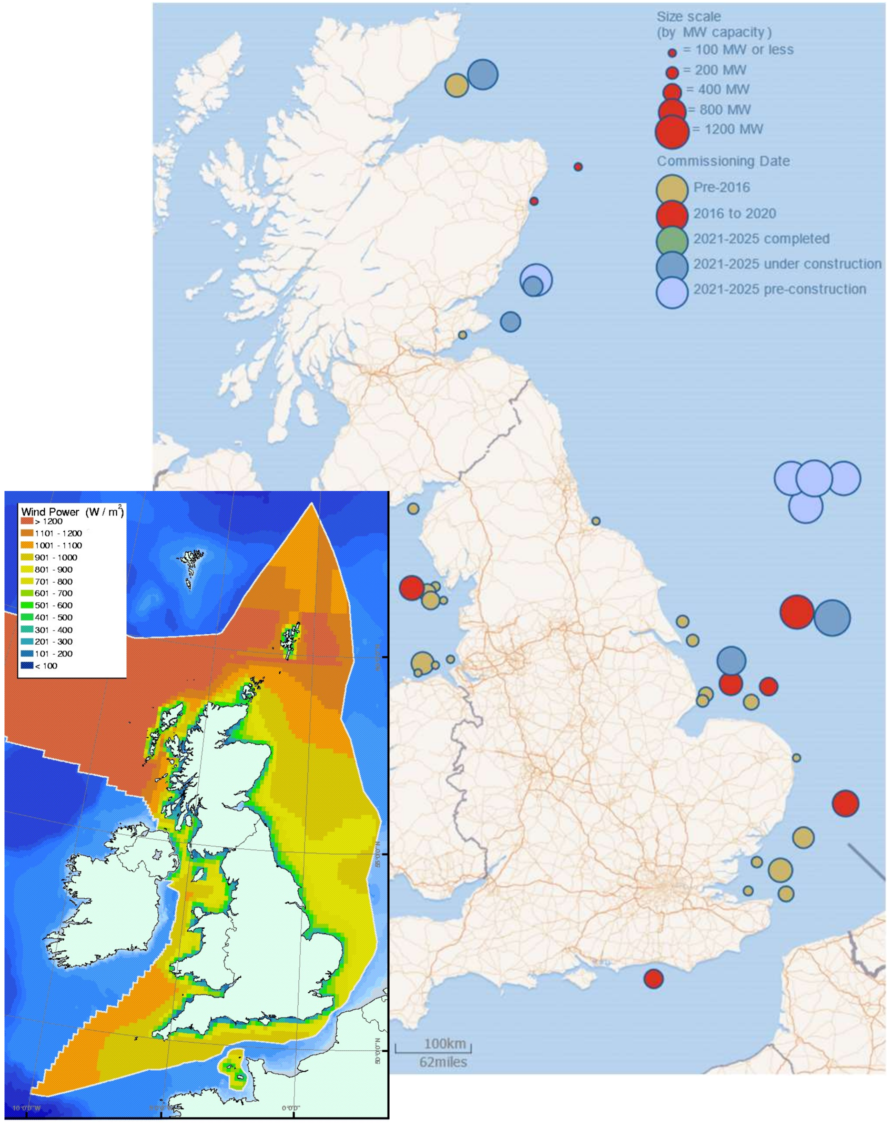
The potential location of future offshore wind farms,

The wind profile associated with the location of existing and potential wind farms

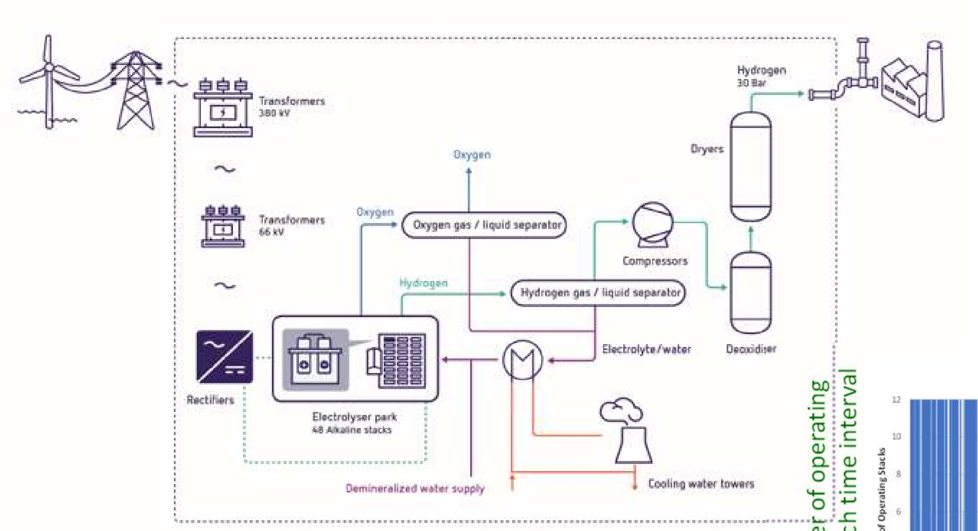
The potential of integrating electrolyser with future WTs

The temporal distribution of demand for hydrogen and electricity over 2023-2030 time horizon

The performance of the electrolyser technologies [PEM, AWE, SOEC, ….]

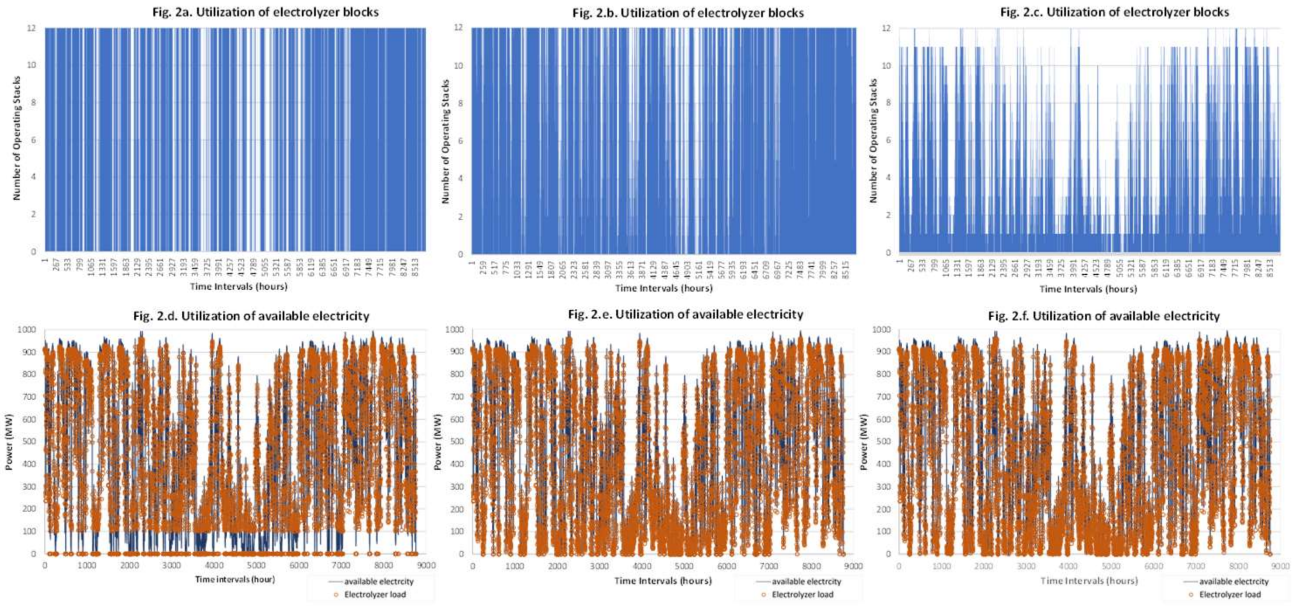


Previous related research: Integrated design and operation of 1GW facility

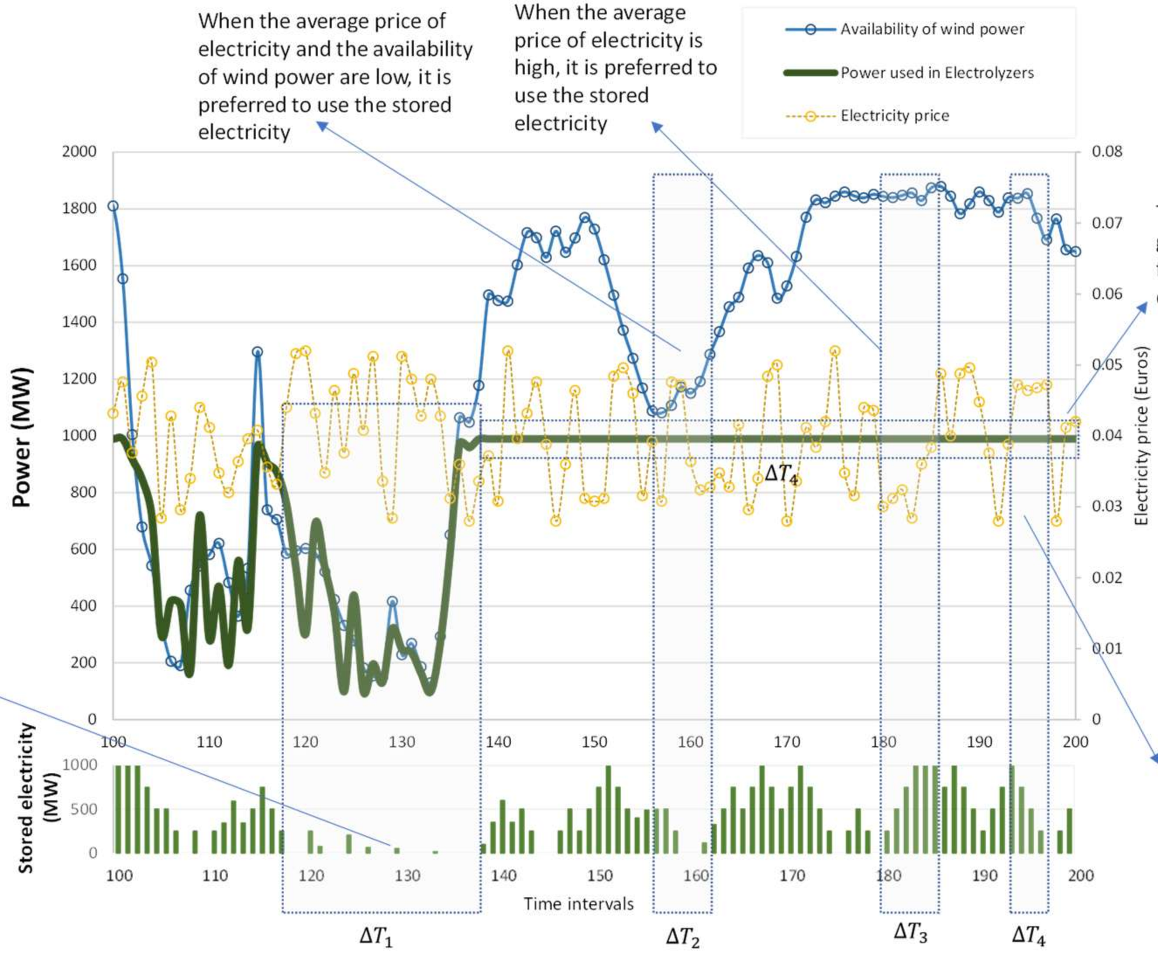


The number of operating stacks at each time interval

Electrolyzer utilization vs wind power



System dynamics



When the average price of electricity and the availability of wind power are low, it is preferred to use the stored electricity

When the average price of electricity is high, it is preferred to use the stored electricity

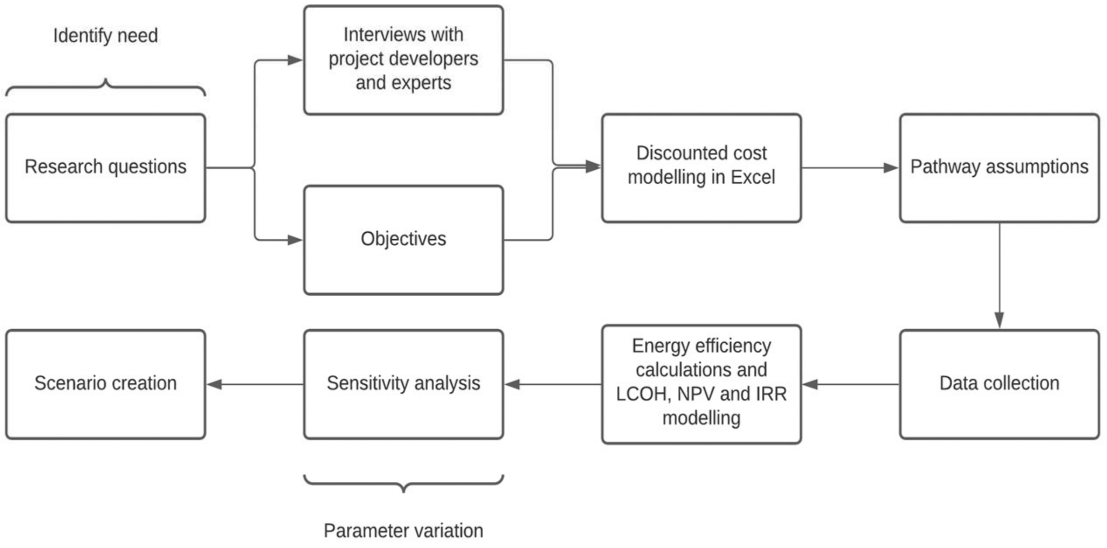
The highest priority is given to utilizing the full capacity of the electrolyzer stacks

In the absence of excess wind power less attempts is made to store electricity

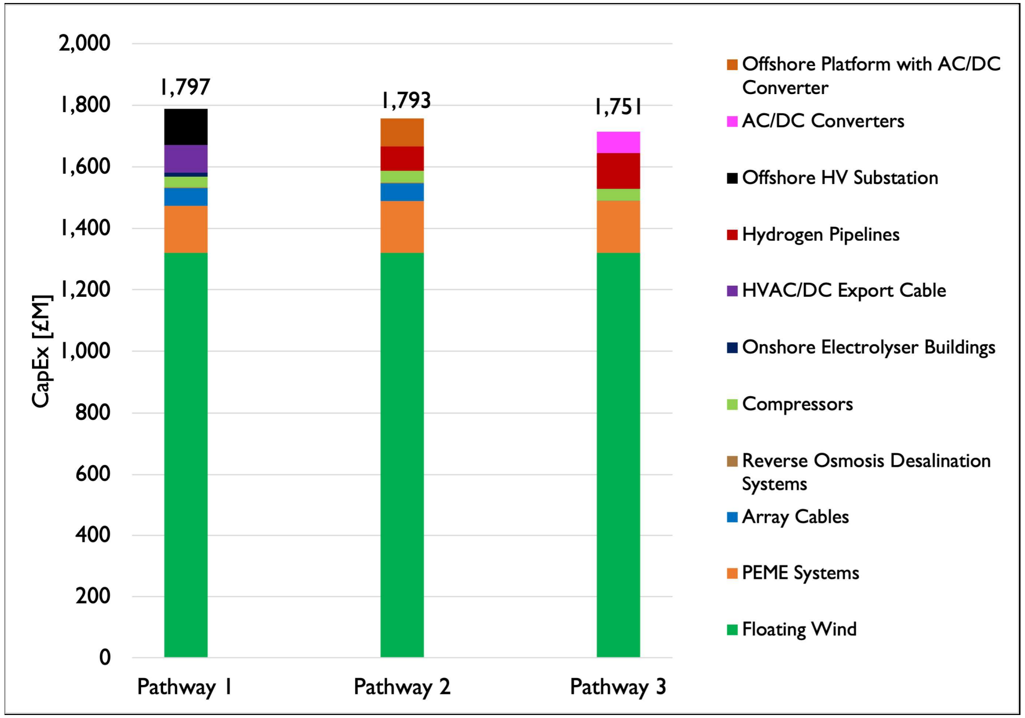
When the average price of electricity is low, it is preferred to also store electricity

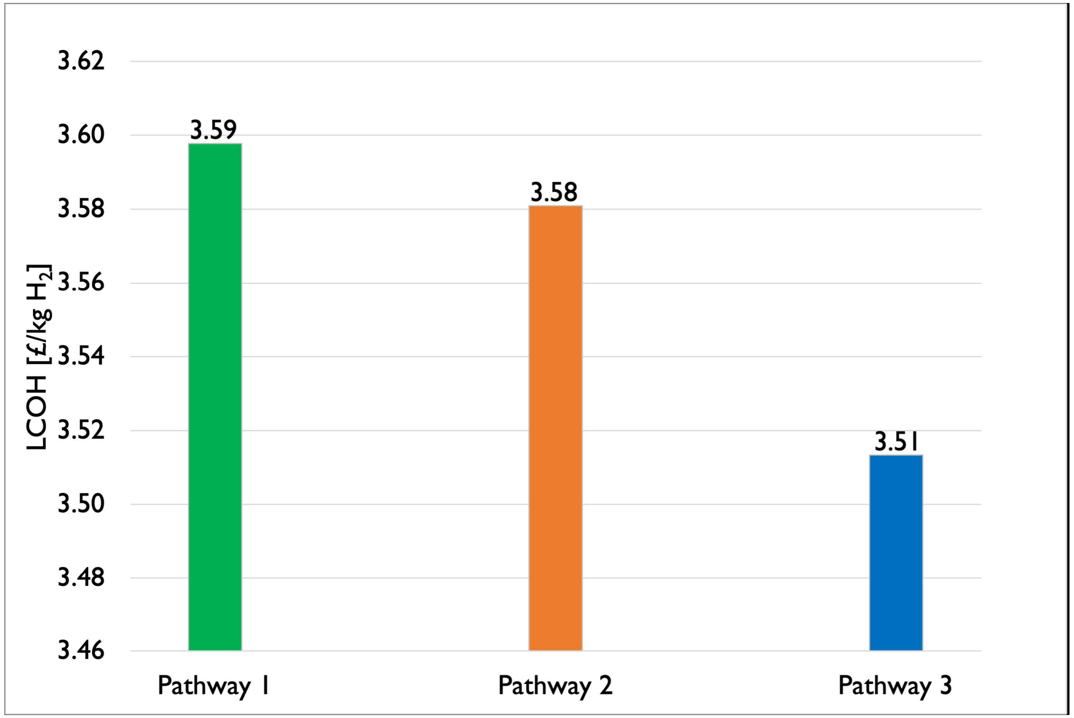
Current analysis: trade-offs

- Pathway 1: floating wind array, offshore electrical substation, HV export to onshore substation, PEME onshore
- Pathway 2: floating wind array; inter-array cables to a centralised PEME electrolysis off-shore platform. Hydrogen gas pipeline to shore.
- Pathway 3 integrated electrolysis at each floating turbine with inter-array hydrogen collectors and hydrogen pipeline to shore.


Identify need
Research questions
Interviews with project developers and experts
Objectives
Discounted cost modelling in Excel
Pathway assumptions
Data collection
Energy efficiency calculations and LCOH, NPV and IRR modelling
Sensitivity analysis
Scenario creation
Parameter variation

Preliminary results: CAPEX and LCOH





Ocean-REFuel Inaugural Stakeholder Event
Cross-cutting themes and Integration – the Economic System

6 September 2022

UNIVERSITY of STRATHCLYDE
CENTRE FOR
ENERGY POLICY

www.strath.ac.uk/humanities/centreforenergypolicy/

The energy system is part of the ECONOMIC system

Conditions and responses in the wider economic system are crucial in determining what happens *in*, and the impacts *of* activity in any part of the energy system

Ultimately, the political/economic feasibility of energy system solutions depends on issues such as:

- The outcomes in terms of choice and efficiency for different (household, business, other) users
- Net impacts on all elements of energy costs/price faced by different users
- Direct and indirect impacts on the cost of living and the inflationary process

- Transition of existing and creation of new jobs – set against replacement and displacement of others
- Impacts on real wage rates and incomes to worker – competitive labour costs for different UK sectors
- Overall impacts on competitiveness of UK producers – not limited to energy costs

- Value of infrastructure and capacity transitioned and created – focus on UK productivity
- Macroeconomic impacts extending to GDP, public budget, trade balance etc.
- Absolute and distributional impacts at regional, sectoral and household levels

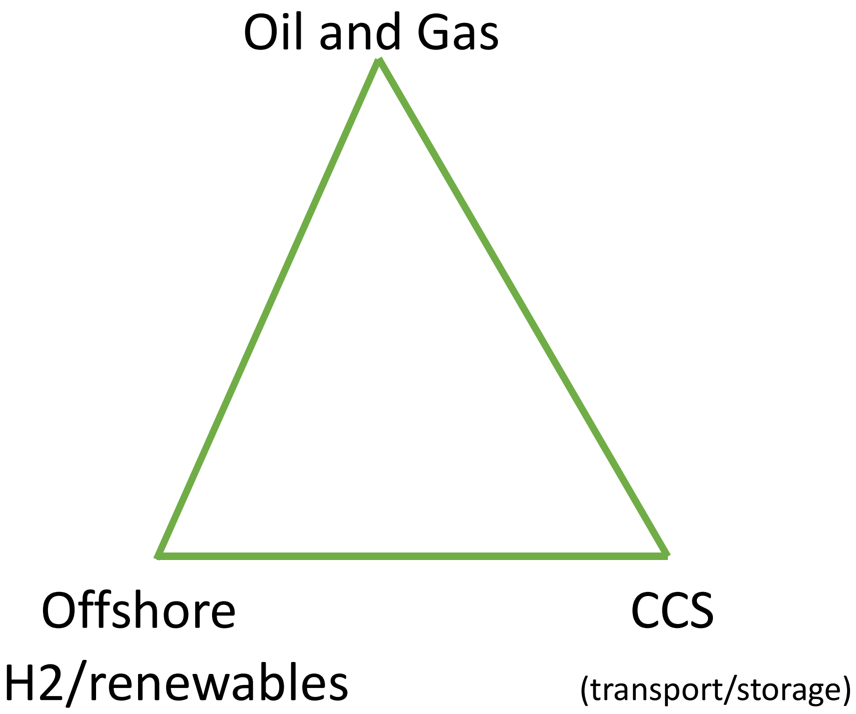
Integrating economic system analysis into Ocean-REFuel

1. **Integrating the new energy system activity identified in the engineering work into a multi-sector economy-wide model of the UK economy**
    - UKENVI, a computable general equilibrium (CGE) model previously developed to look at a wide range of energy, climate and economic policy issues
    - Including enabling and realising residential energy efficiency actions, the EV roll-out, introducing and deploying carbon capture and storage (CCS)
    - Understanding how carbon pricing and energy price shocks ripple across the economy

2. **Developing and running dynamic scenario simulations with focus on how implications and responses in different markets and sectors govern the wider economy outcomes and consequences**
    - ***How might different outcomes and consequences in different timeframes be affected by changes in how energy system projects are delivered, and/or by policy interventions?***

Conceptualising the nature and role of the offshore energy sector

- Effectively a new sector in the economy?
- Doesn't yet exist/report in economy-wide national accounts (input-output, IO, tables reported by ONS)
- Can we identify a benchmark/proxy from current IO?
  - Electricity, transmission and distribution?
  - Gas; distribution of gaseous fuels through mains; steam and air conditioning supply?
  - Extraction Of Crude Petroleum And Natural Gas & Mining Of Metal Ores?
- Enables initial 'what if' reporting and scenario simulation
- Including focus on benefits of retaining already established supply chain capacity
- But also need to investigate differences in what is produced, how valued and by whom
- Benchmark basis for consultation to ultimately refine to how new industry activity actually integrates into economy



A wide range of policy and research challenges

- The integration of new energy supply options into the economy is complex
- Once we've established what the new energy supply sector looks like, and what it is producing, just how is it deployed?
  - E.g., is there a need to initially over-size capacity – what are the capital expenditure implications, who pays, how and when, how can the process be de-risked?
- What demand does the new sector serve, what and how does it replace and/or integrate with via existing/new networks and markets?
  - E.g., industrial use of hydrogen may begin with continued purchase and 'in-house' reforming of natural gas, which will have (sunk?) investment and network implications for firms – how does hydrogen ultimately become a substitute for industrial users?
- Which actors (industry, regulator, government) are responsible, able and willing to act at what stages in the supply/demand process?
- How can/will the picture evolve over time and under different circumstances?