‘Redefining Testing across the H2 Value Chain’

Dr Mark Eldridge – HIL Conference 5th July, London, 2023

THE JOURNEY SO FAR

element

TESTING, INSPECTION AND CERTIFICATION FOR

55,000+ CUSTOMERS

- CONNECTED TECHNOLOGIES
- MOBILITY
- LIFE SCIENCES
- BUILT ENVIRONMENT
- AEROSPACE
- ENERGY & ENERGY TRANSITION

OUR PURPOSE

MAKING TOMORROW SAFER THAN TODAY

60%+ REVENUE HELPING CUSTOMER SUSTAINABILITY JOURNEYS

#1 ESG RANKING IN INDUSTRY VIA SUSTAINALYTICS

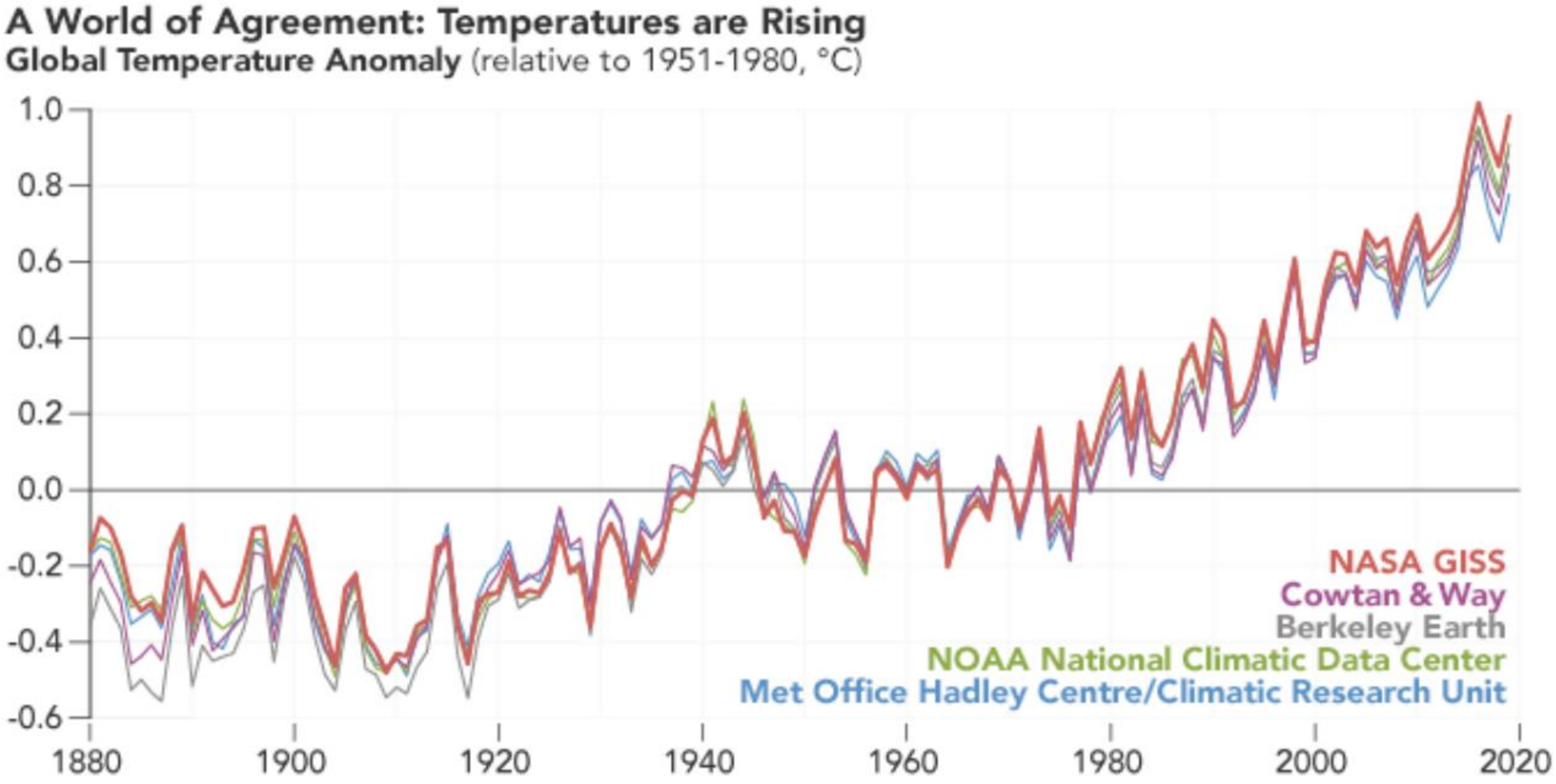
10x REVENUE GROWTH TO OVER $1.5B

47 ACQUISITIONS

REDEFINING TESTING

- Time, Hydrogen ,Other Options
- Redefining Testing
- Some Characteristics of Hydrogen
- Some Elements of Element
- From testing, to supporting problems
- How we are looking to help?

The Rapid Need to Decarbonise



Global temperature anomaly (relative to 1951-1980) Image: NASA: Earth Observatory

TIME ?

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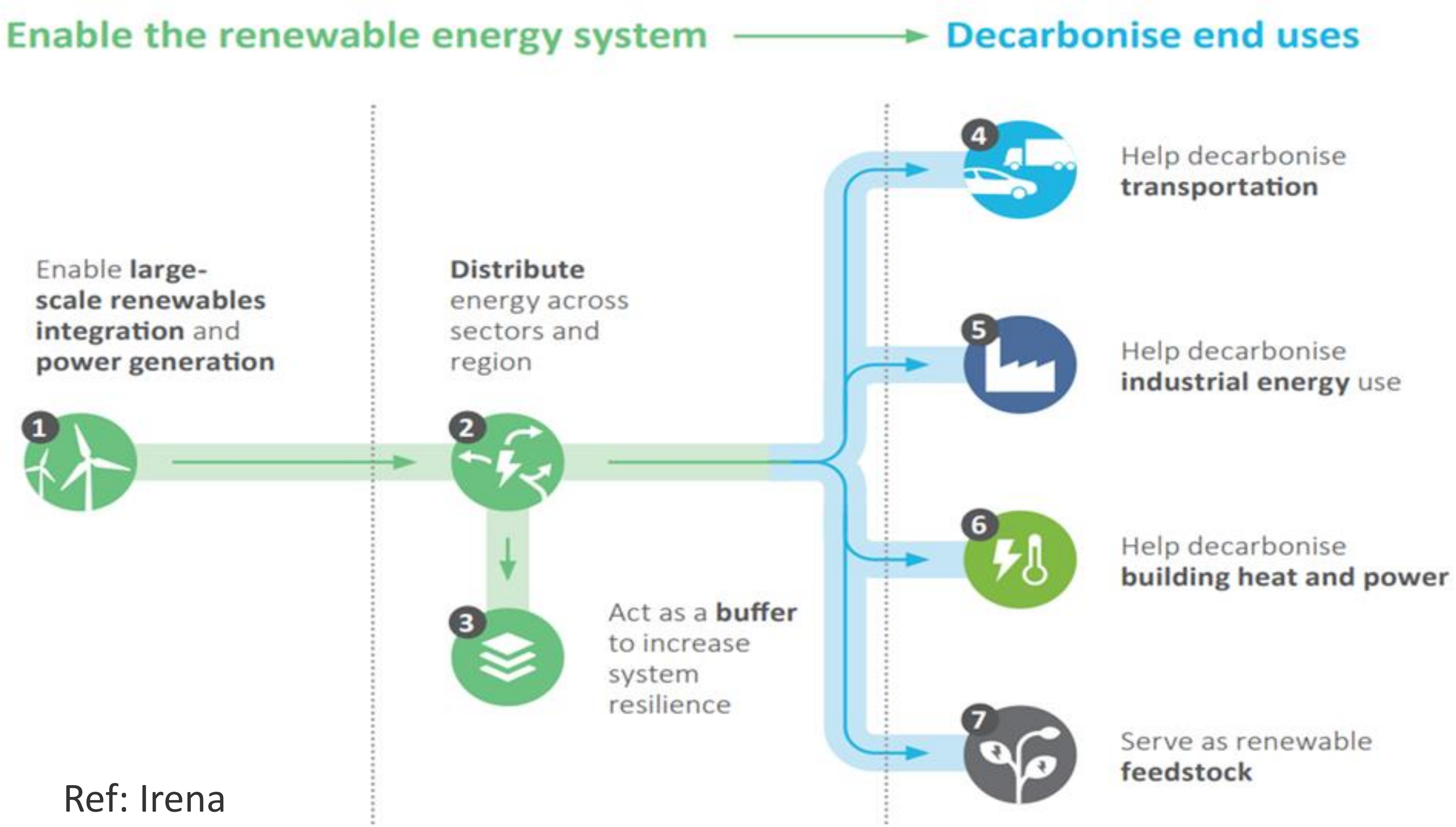
H2 is an elegant Energy Vector



Company	km	Miles
Air Liquide	1936	1203
Air Products	1140	708
Linde	244	152
Praxair	739	459
Others	483	300
World Total	**4542**	**2823**
U.S.	2608	1621
Europe	1598	993
Rest of World	337	209

https://h2tools.org/hyarc/hydrogen-data/hydrogen-pipelines

Ref: Irena

ITS NOT JUST HYDROGEN

Hydrogen <u>Must Always </u>be Considered as Complimentary in the Energy System based on Sound:

Economic
Thermodynamics and Metallurgy
Environmental
Alternatives
Specific Contexts
AND/OR – to Both?
Where is the system boundary

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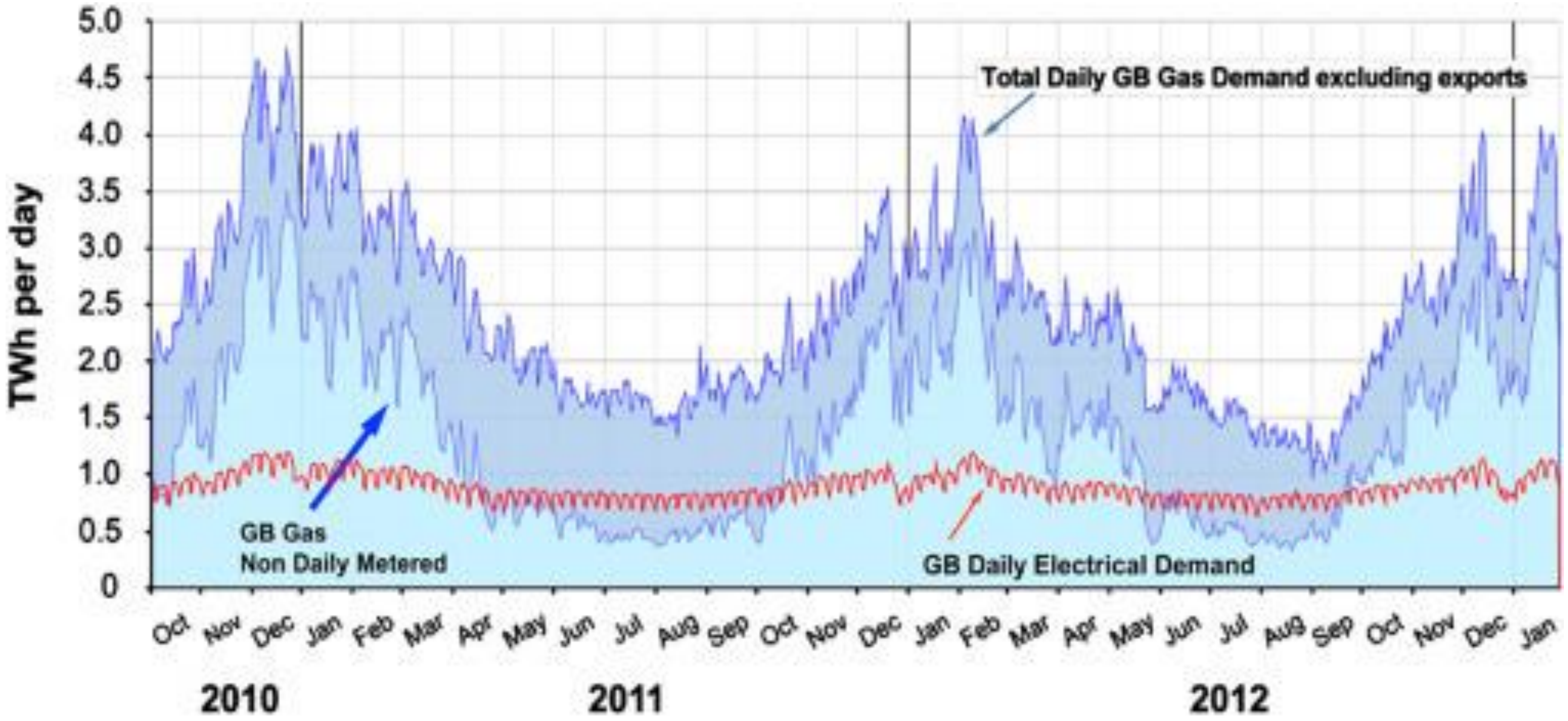
Blending and the Seasonal Effect of Heating



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H2 We need to look at the whole system

→ NEW
→ EXISTING

Resources
- Coal
- Natural Gas
- Biomass/Waste
- Nuclear
- Solar & Wind

Production
- Gasification
- Reforming
- Pyrolysis
- WATER: Electrolysis
- Photo and Bio Catalysis
- Thermochemical Cycles

Carbon Capture Use and Storage (CCUS)

BLUE HYDROGEN

GREEN HYDROGEN

Storage & Transport
- Compressed Gaseous H2
- Liquid H2
- Ammonia
- Liquid Organic Carriers
- Hydrides and Solids
- Pipelines
- Road
- Rail
- Shipping

Utilisation (End Use)
- Chemical Feedstock
- Aerospace
- Mobility
- Energy Plants & Storage
- Combined Heat and Power

CHANGE REQUIRMENTS
Element Offering: Full Life Cycle Service

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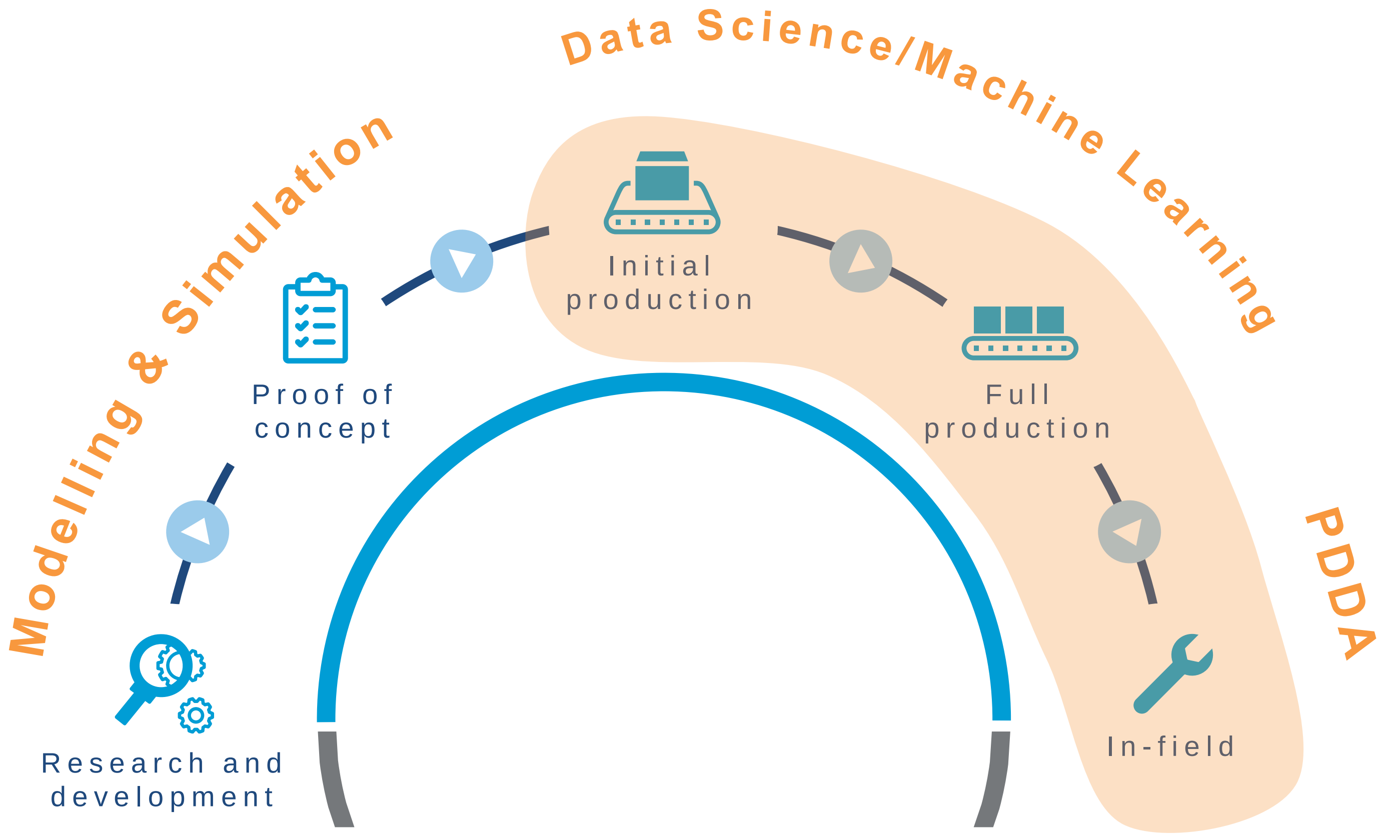
Digital Engineering
MODELLING | SIMULATION | DATA SCIENCE

Extension to core services

One stop shop for product development

Faster and cleverer R&D iterations



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Core Services
Production
Test & Validation
Inspection
Low Digital
Late TRL R&D

Digital production support
Digital asset management

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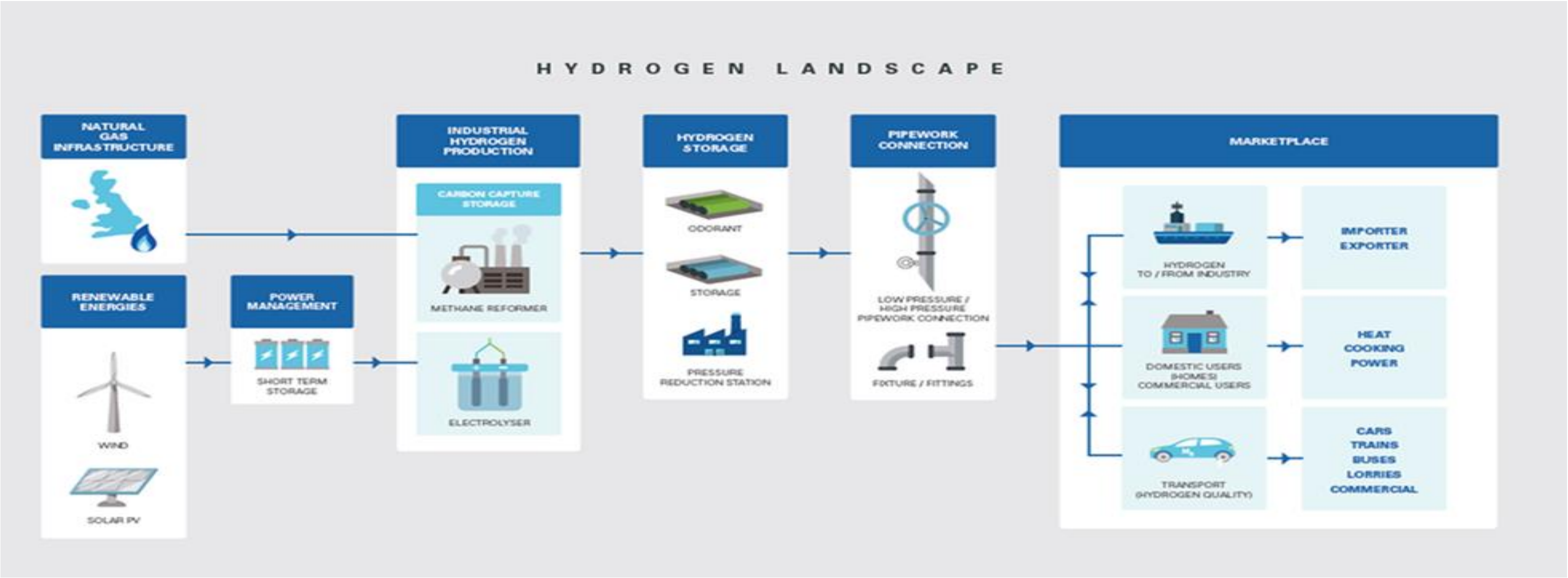
The H2 landscape

PRODUCTION

TRANSPORT AND STORAGE

UTILISATION



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Definition of Testing?

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Go to Market Strategy

Market Maturity

Lets Create The Future.....

Wind Offshore

Wind On-shore

Pipelines

Electrolyser

Duty Cycle

Reliability

Scale

Efficiency

Storage

System

Efficiency

Technology

A to B

Storage

Form

Liquefaction Gas

Demand

Duty Cycle

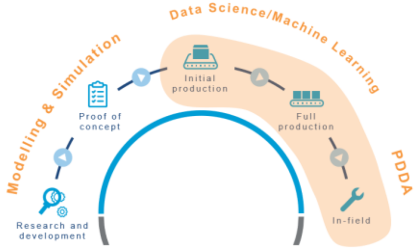
Reliability

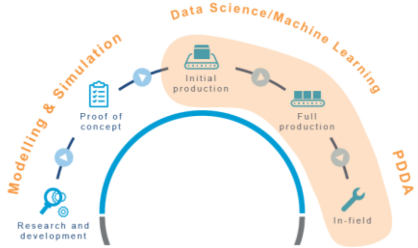
Technology

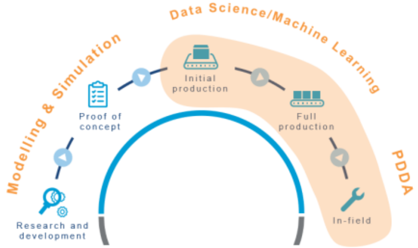
Efficiency

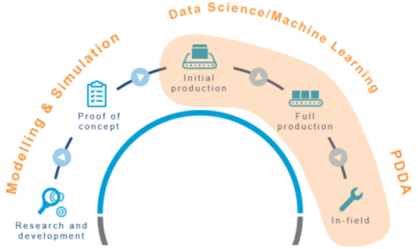
System

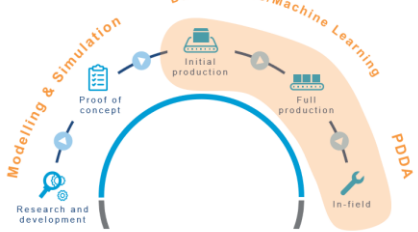
Scale





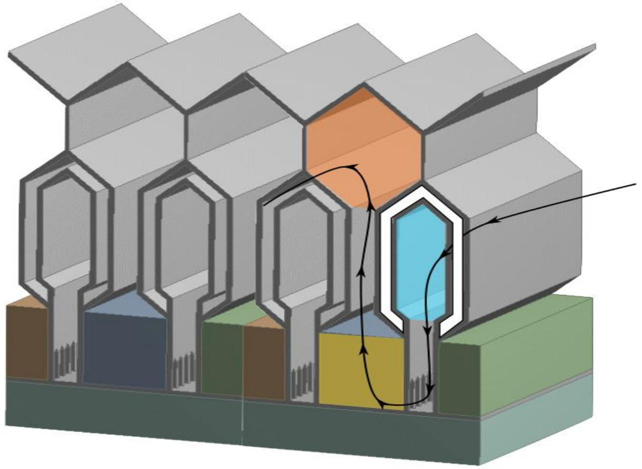






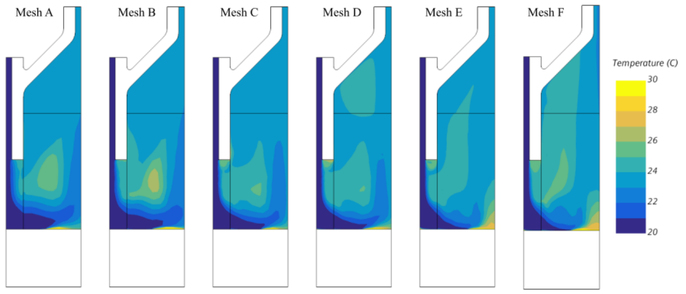
Design Exploration

Fusion Reactor Diverter HX



The STEP project aims to develop a fusion reactor that's in service by 2040. We were commissioned to design the diverter heat exchanger, deeply embedded within the hottest part of the torus.

- Microscale fluid dynamics simulation of flow paths
- Thermal modelling of structure
- Primary and secondary stress analysis
- Fatigue and creep assessment
- Design optimisation using HEEDS



Concept design and design exploration for a diverter heat exchanger for the UKAEA STEP programme. Teamed with additive manufacturing specialists HiETA to create high heat flux HX in a vacuum, high neutron flux environment

High-Voltage Cable Modelling

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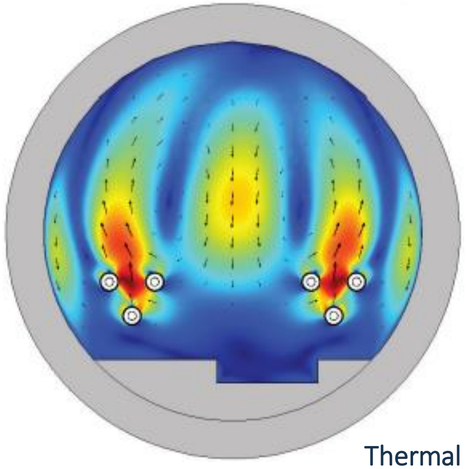
Digital Engineering



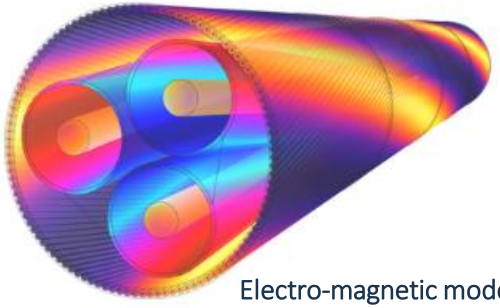
Thermal modelling

Challenges

Designing and managing the electrical grid to ensure it is capable of sustaining the demand, are fundamental for its reliability and minimising CAPEX. This becomes more complex as wind generation is highly variable which results in further challenges when predicting thermal ratings for different environments.

Our capability

To assist, we can simulate the cable performance using COMSOL Multiphysics software and IEC60287, which can include complex thermal environments and non-standard installations. Our consultancy team has conducted previous work in this area including cycling ratings which can be further explored in references provided.



Electro-magnetic modelling

1. R.D. Chippendale et al., Cyclic Load Profiles for Offshore Wind Farm Cable Rating, *IEEE Transactions on Power Delivery*, 2015.
2. R.D. Chippendale et al., Analytical Thermal Rating Method for Cables Installed in J-tubes, *IEEE Transactions on Power Delivery*, 2016.
3. R.D. Chippendale, Offshore Wind Cable Catalogue*, ORE Catapult*, 2016.

Outcome

Testing cables is not a trivial task and is expensive to conduct, as they are buried deep underground and do not exist as an isolated component but are part of a larger system.

The use of simulation to accurately predict the thermal ratings of cables within clear safety margins maximises throughput, ensures reliability and keeps costs as low as possible.

Safety:

Explosion modelling and structural response

Outcome

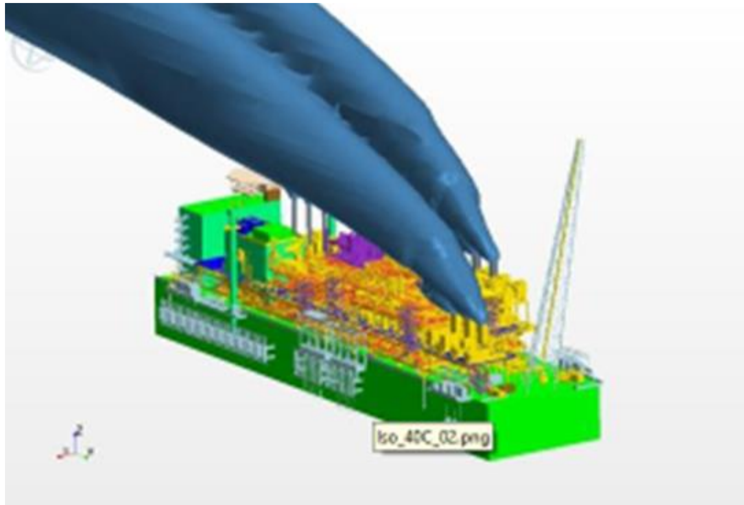
Explosion risk assessment generated, submitted and accepted by the safety authorities. The vessel is now in service.

Challenge

- Safety studies for FPSO
- Dispersion, helideck safety & blast response
- Simulation used to support FPSO design

Our work

- Simulation used to assess consequences of accidental gas releases and quantify blast over-pressures along with assessment of helideck safety and structural response



An experienced team

Our experts have been involved in major hazards consequence modelling for over 20 years. With unparalleled expertise and computational resources, we can provide support to projects and assets around the globe.

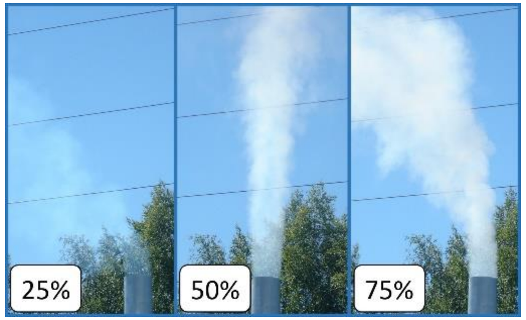
Other recent project examples

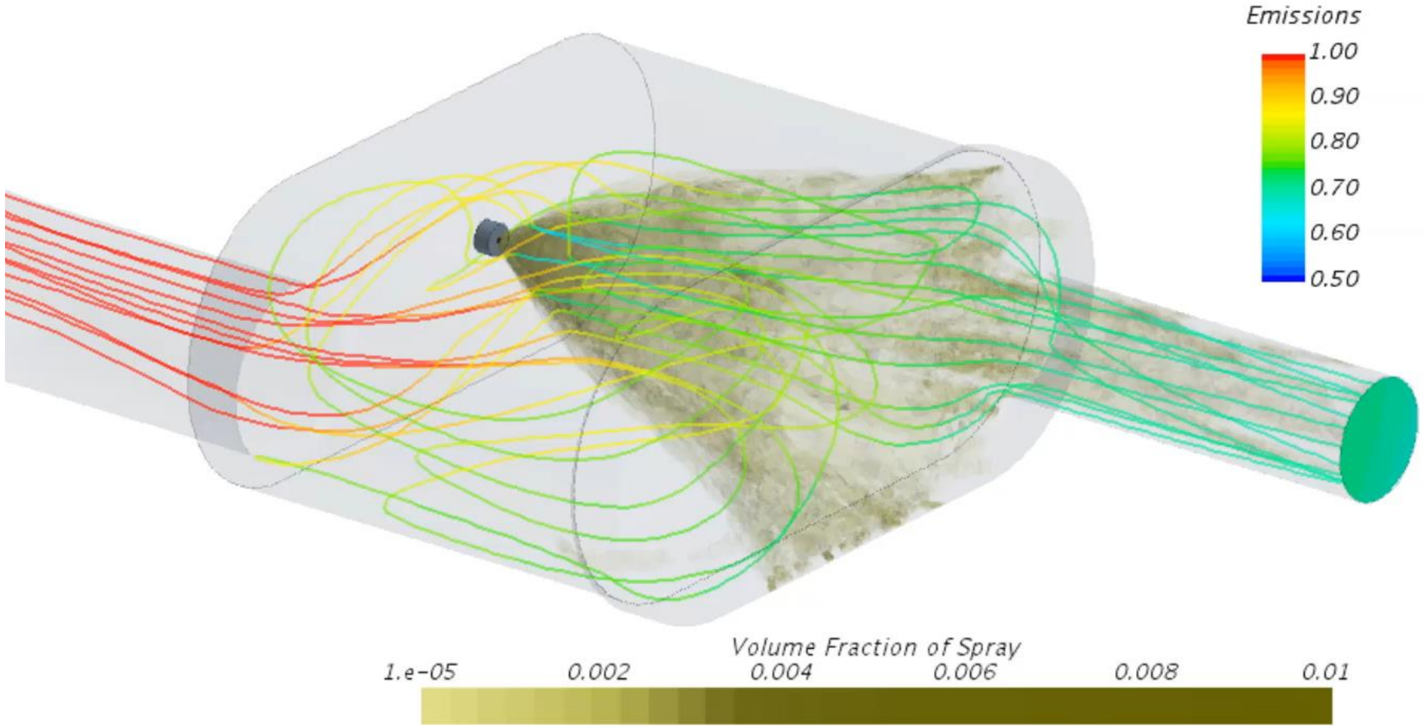
Operator	Project	Scope
Saipem	Jangrik	Ventilation, dispersion and explosion risk assessments
Premier Oil	Balmoral	ITA of cold vent gas dispersion
Petrobras	P67 & P70	Jet fire deflector performance assurance
Total	*West Franklin*	*TR integrity analysis*
Chevron	*Alba*	*H_2S dispersion risk assessment*
BP	*Flare Scrubbers*	*Blowdown event analysis*
Total	*Flare systems*	*Gas dispersion analysis*
Aker Solutions	*Sakhalin*	*Ice avoidance strategy development, including CFD studies.*
BP	*Jigsaw*	*Jigsaw project FRC performance analysis.*
Total	*Alwyn/Forvie*	*Blowdown J-T cooling risk analysis*
Petrobras	*Flange covers*	*Composite flange cover risk assessment*

element Digital Engineering

Emissions control technology development

Controlling the environmental emissions of industrial plants is critical in the fight against the climate crisis. However, it is oftentimes difficult to find alternative designs to reduce emissions using physical testing and experimentation alone. The use of **automated design-space exploration** together with **computational fluid dynamics simulations** can enable the discovery of solution options in a much shorter timeframe.





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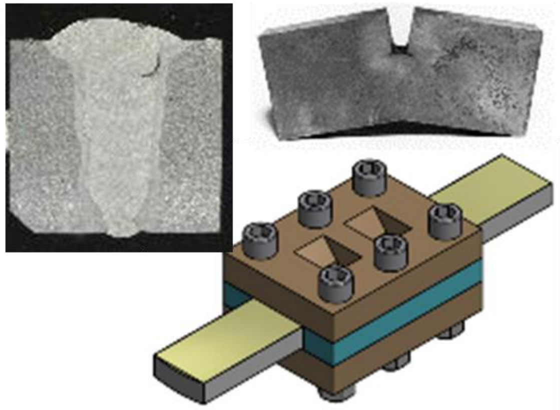
Physical Experience

PRODUCTION   TRANSPORT AND STORAGE   UTILISATION

Fracture mechanics & ECA

Pipeline installation & operation, input data, ECA analysis, In-situ fracture testing, Riser fatigue testing, Reeling, AUT validation



Corrosion

Weld & material integrity HPHT, Sweet & Sour operations, Full Ring Testing, Inhibitor Testing, Failure Analysis

Coatings

FJC, Chemical resistance, CD testing, Subsea insulation, HPHT testing, CUI, Electrochemical, Inspections, Failure Analysis

Polymers/Composites

Flexible pipes, Umbilicals, Elastomer seal testing, Composite ageing, HPHT: H_2S, CO_2, Hydrocarbon compatibility

Gas Turbine Technologies

Hydrogen Storage

Prod, Transport, Refueling Infrastructure

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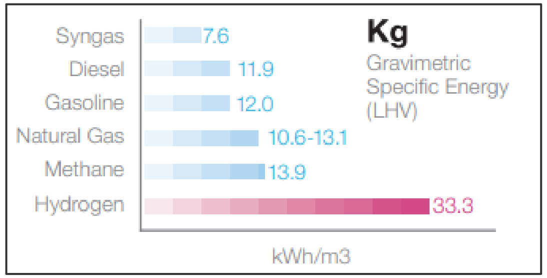
Start with something small and light..

90% of our Universe atoms are H2
10% of our Body
Common Water reference
Only element that can exist without neutrons



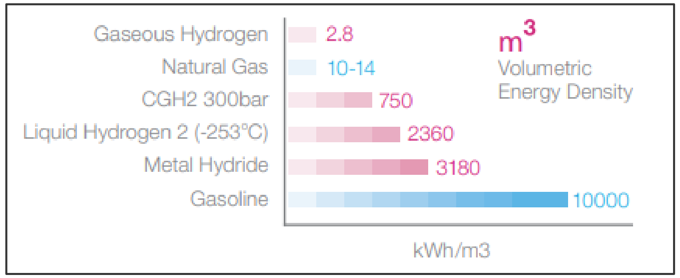


Table 1 - Characteristics of hydrogen, dry natural gas and gaseous propane

Property	Dry natural gas (methane)	LPG (propane)	Hydrogen
Density (Kg/m^3) *	0.65	1.88	0.090
Diffusion coefficient in air (cm^2/s) *	0.16	0.12	0.61
Viscosity (g/cm-s x 10^{-5}) *	0.651	0.819	0.083
Ignition energy in air (mJ)	0.29	0.26	0.02
Ignition limits in air (vol %)	5.3 – 15.0	2.1 – 9.5	4.0 – 75.0
Auto ignition temperature (C)	540	487	585
Specific heat at constant pressure (J/gK)	2.22	1.56	14.89
Flame temperature in air (C)	1875	1925	2045
Quenching gap (mm) *	2	2	0.6
Thermal energy radiated from flame to surroundings (%)	10-33	10 - 50	5-10
Detonability limits (vol % in air)	6.3-13.5	3.1 – 7.0	13-65
Maximum burning velocity (m/s)	0.43	0.47	2.6

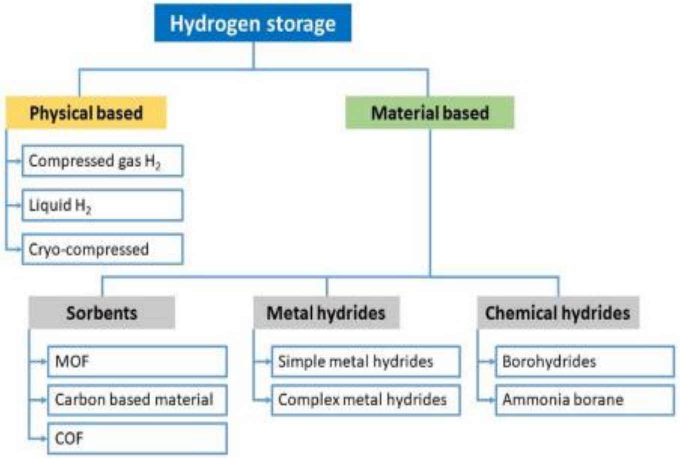
* at normal temperature and pressure – 1 atmosphere and 20°C

Propensity to leak
- Low Viscosity
- Very high diffusivity
- Likelihood of Embrittlement

Storage Volume
- Transportation
- Weight
- Technical Challenges

Propensity to Ignite
- Wide flammability range
- Very low ignition energy
- Spontaneous Ignition

Consequences of Fire and Explosion
- Invisible Flame
- Rapid Burning Rate
- Possibility of detonation



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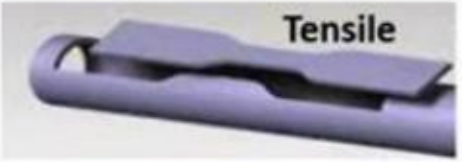
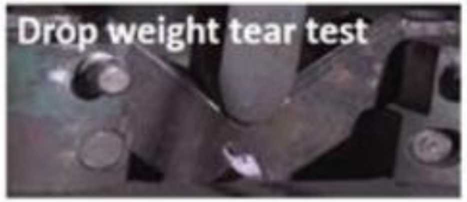
Examples for Metallics

MECHANICAL PROPERTIES - HYDROGEN EFFECT





Limited or no effect	Some effect	Significant effect	Unknown/ High strain rate

Generic property	Pipeline Steel Parameters	Effect of Hydrogen
Strength	Yield (0.2% or 0.5% proof stress)	Limited effect
	Ultimate tensile strength (UTS)	Limited effect
	YS/UTS ratio (Y/T)	Limited effect
	Young's Modulus (E)	No effect
	Poisson's ratio (ν)	No effect
Ductility	Elongation (Total)	Significant reduction
	Elongation (Uniform)	Limited effect
Charpy impact	Charpy impact energy	Limited data found, High strain rate
Crack propagation resistance	Drop weight tear test (DWTT)	No data found on DWTT, but possibly limited effect due to high strain rate
Fracture toughness	K/J/CTOD initiation fracture toughness	Some reduction
	J/CTOD ductile tearing resistance	Significant reduction
Fatigue	Fatigue threshold stress intensity factor range (ΔKth)	slight reduction in some cases
	Fatigue Crack growth rate	Significant increase: many variables
	S-N fatigue line	Effect observed more strongly in high stress LCF region

Source - UK HSE

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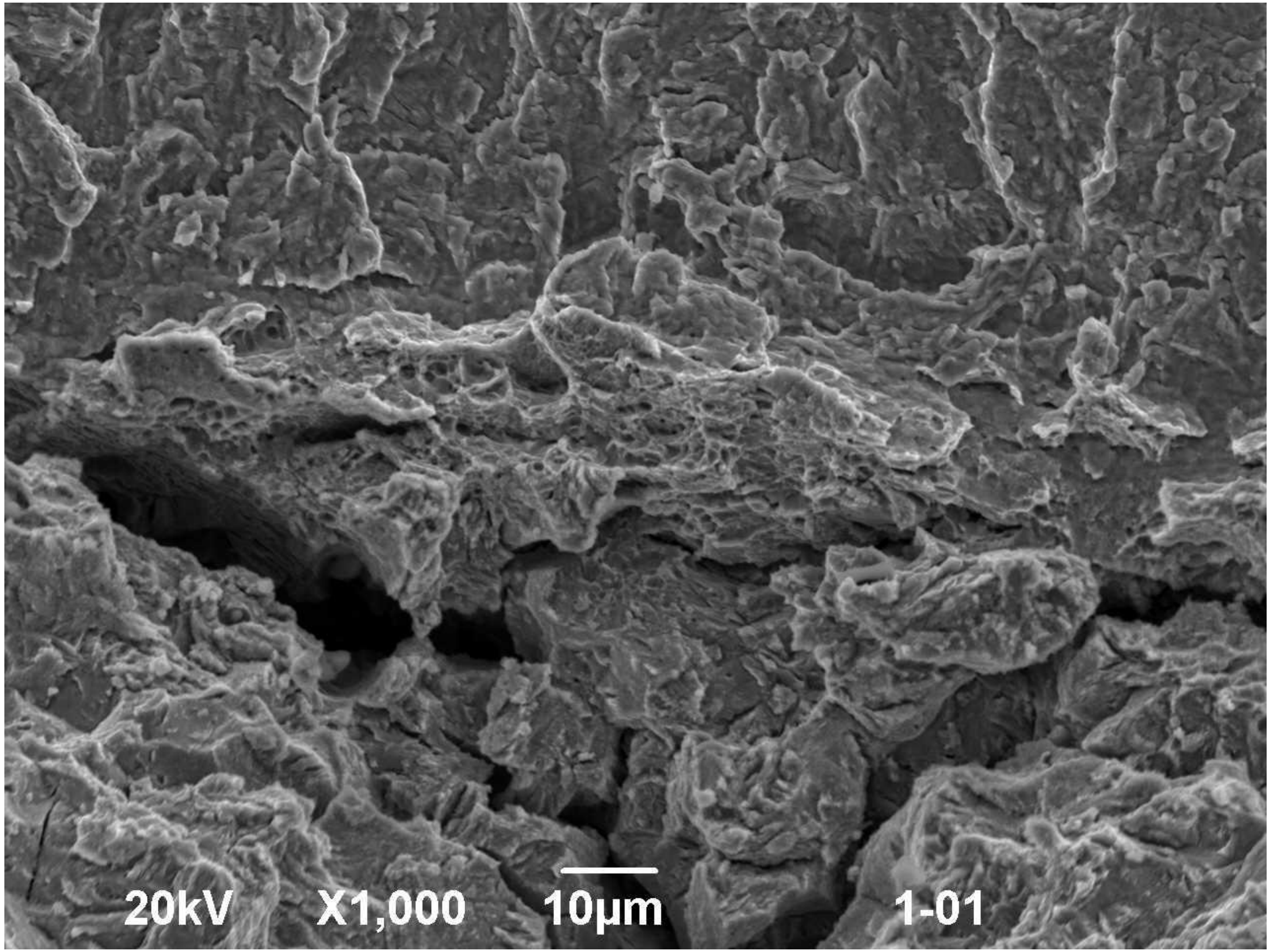
Like sand on the beach – it gets everywhere!!
HE Cracking Mechanisms



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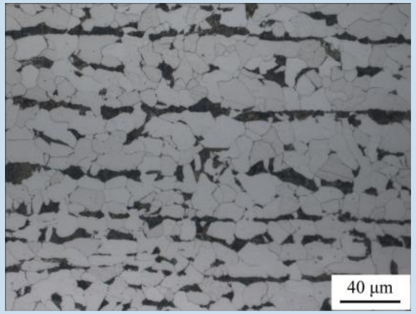
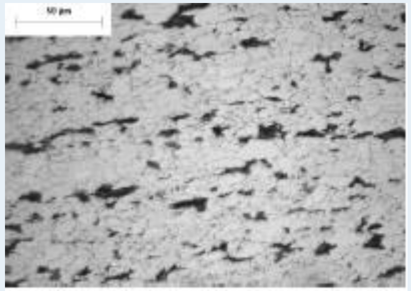
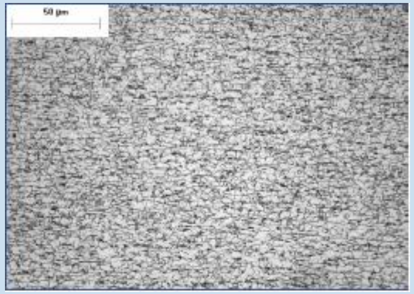
Pipe History and Availability?

1. Pipe homogeneity?

2. Network evaluation – date, range of steel, characteristics?

3. Age vs type (Operators vs Manufacturers) – MUST BE BOTH?
   - Microstructure is key…

4. What is the best steel to use:
   - Typical of ISO 3183 Annex A
   - Non sour, enhanced toughness, low temp – e.g. Offshore steel
   - Modern lean steel – enhanced toughness and weldability

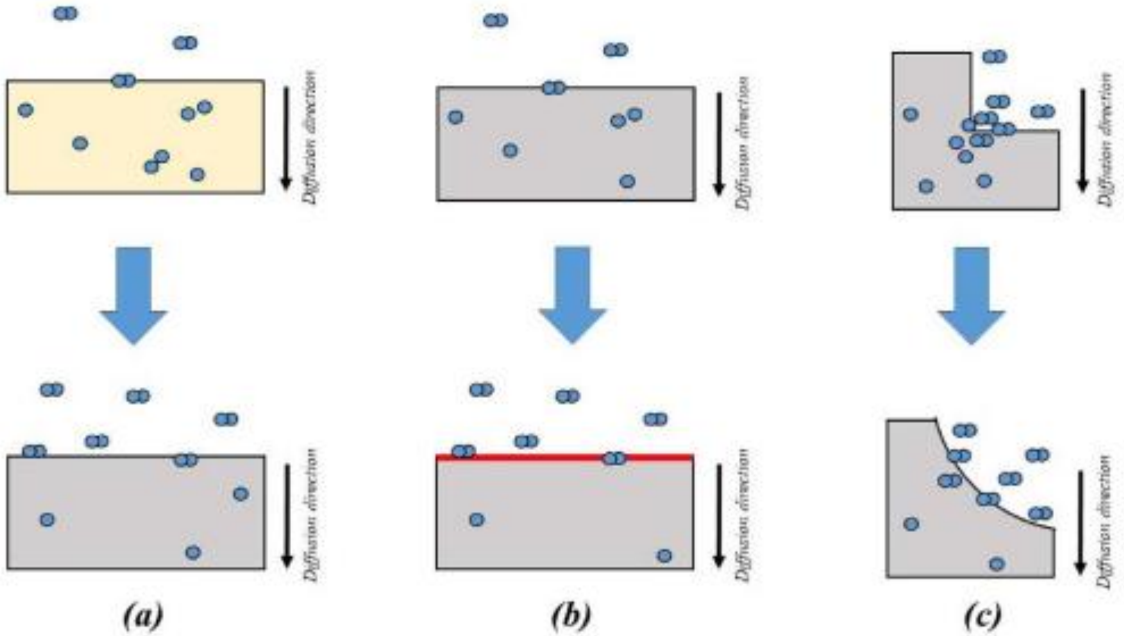
Type Of Steel	Typical Microstructure
<u>Light TMCP with high C</u> • Ferritic/pearlitic • Higher C, not as clean, banded • Typical of onshore Europe for last 50yrs	
<u>TMCP with moderate C</u> • Ferritic/ pearlitic • Finer grain, cleaner, but still with pearlite banding • Better weldability/fracture properties than above	
<u>TMCP with low C</u> • Ferritic/bainitic • Limited or no pearlitic banding • Finer grain • Typically offshore from mid 90s onwards	

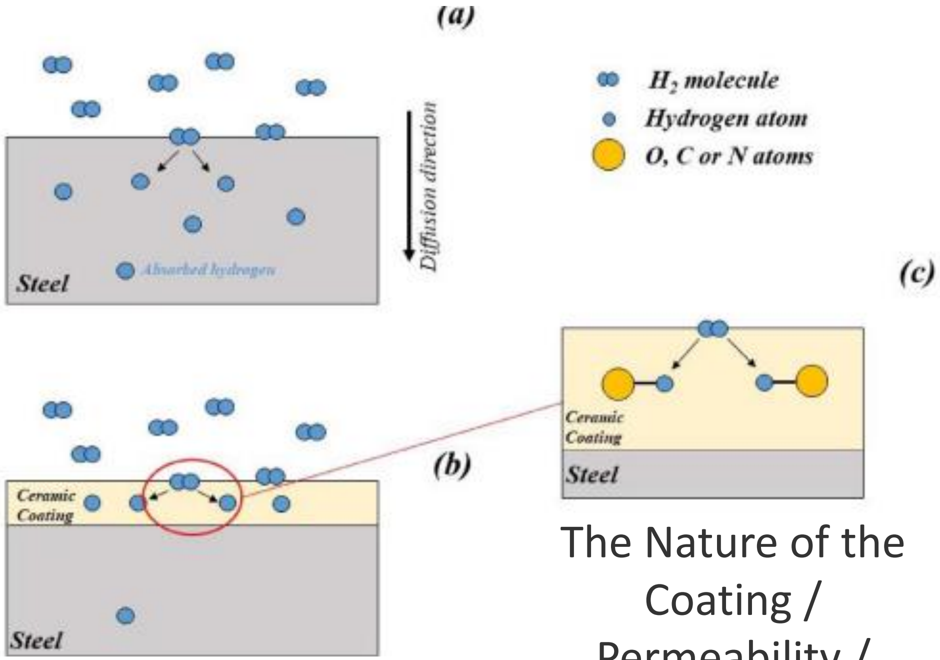
Protection Mechanisms

Material

Barrier Coatings

Edge Effects





The Nature of the Coating / Permeability / Mechanical Properties

International Journal of Hydrogen Energy
Volume 47, Issue 76, 5 September 2022, Pages 32707-32731

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Where do we make Hydrogen and Where and How Should it Get there?

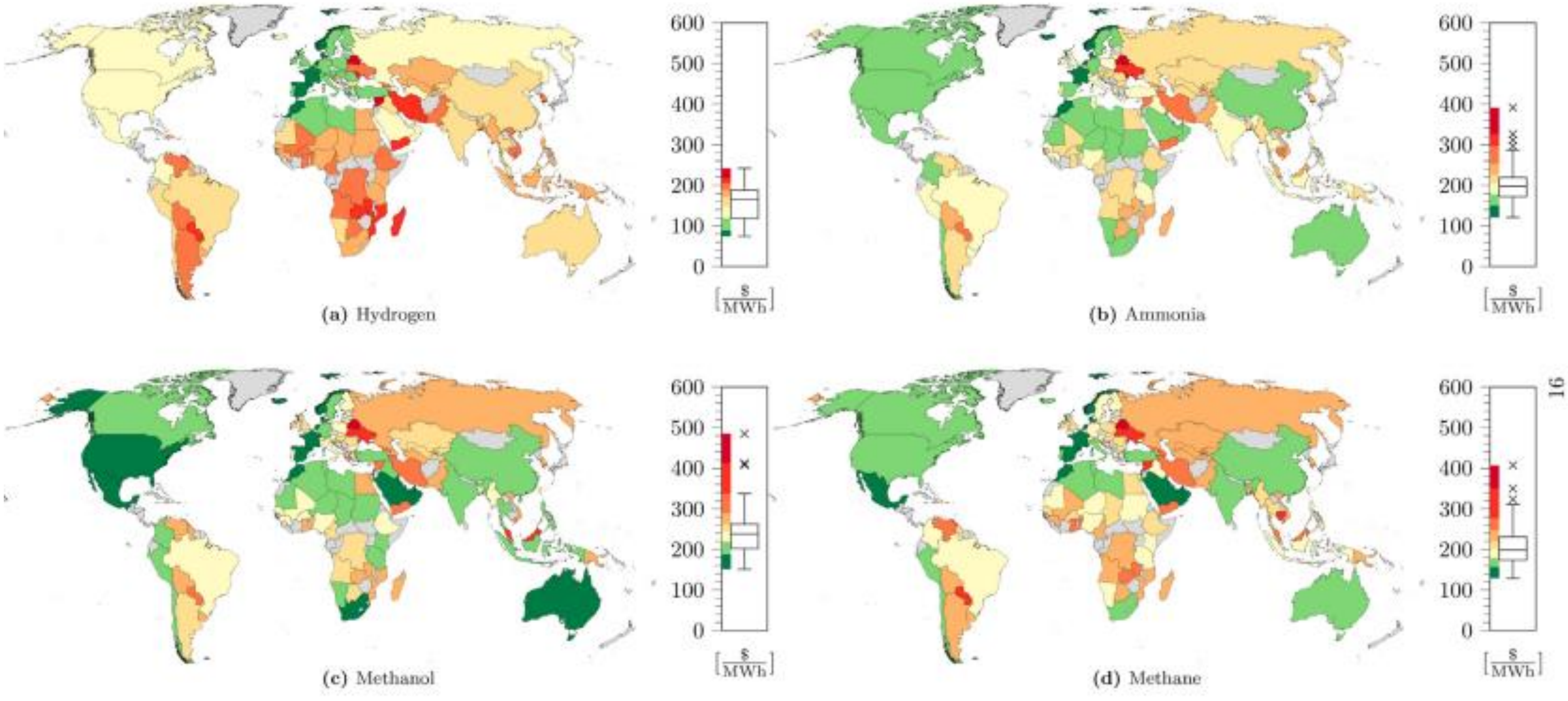
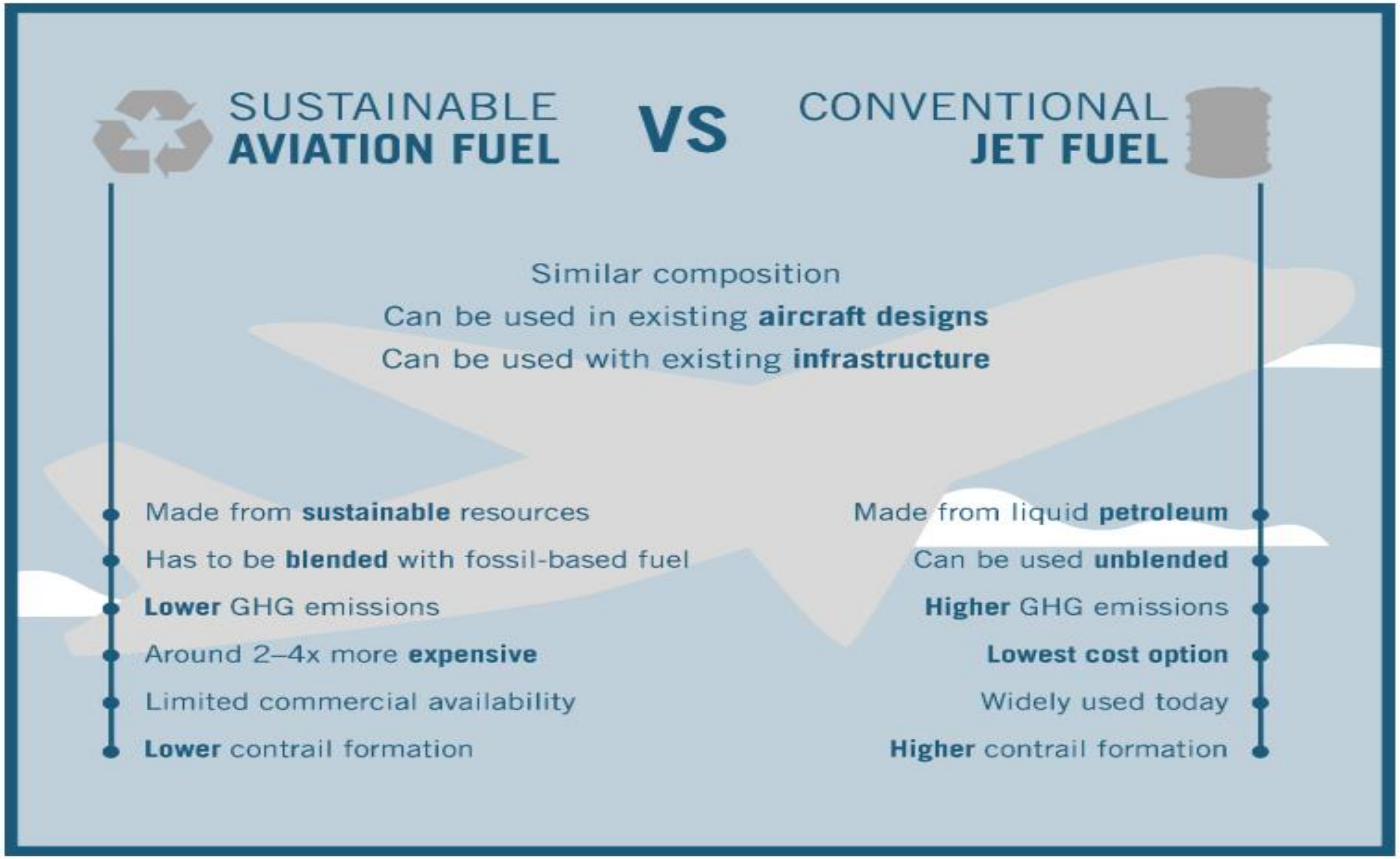


Fig. 6 — Supply cost to Germany for an import volume of 100 TWh/a in the baseline scenario and the year 2030.

Estimating global production and supply costs for green hydrogen and hydrogen-based green energy commodities

Michael Moritz [a,], Max Schönfisch [a], Simon Schulte [b]*

SAF – Where does the H2 come from and get there?



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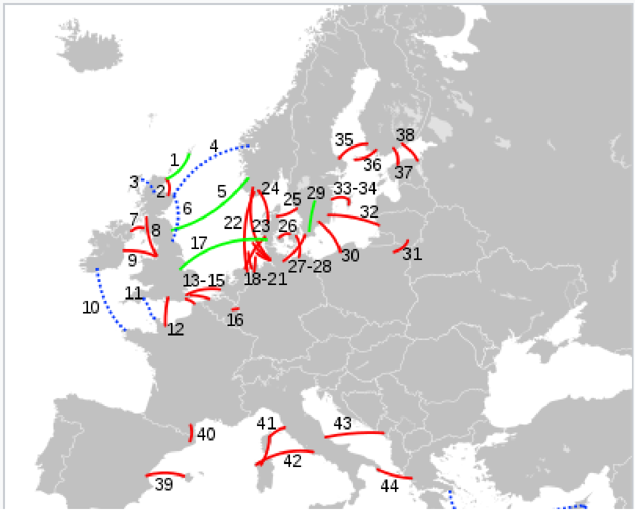
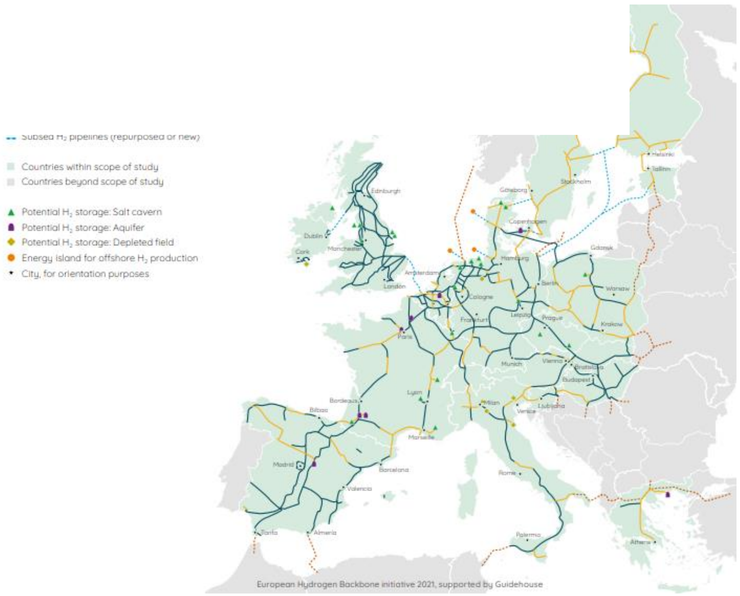


(H2 AND CO2) For just H2: 39,700 km across 21 European countries

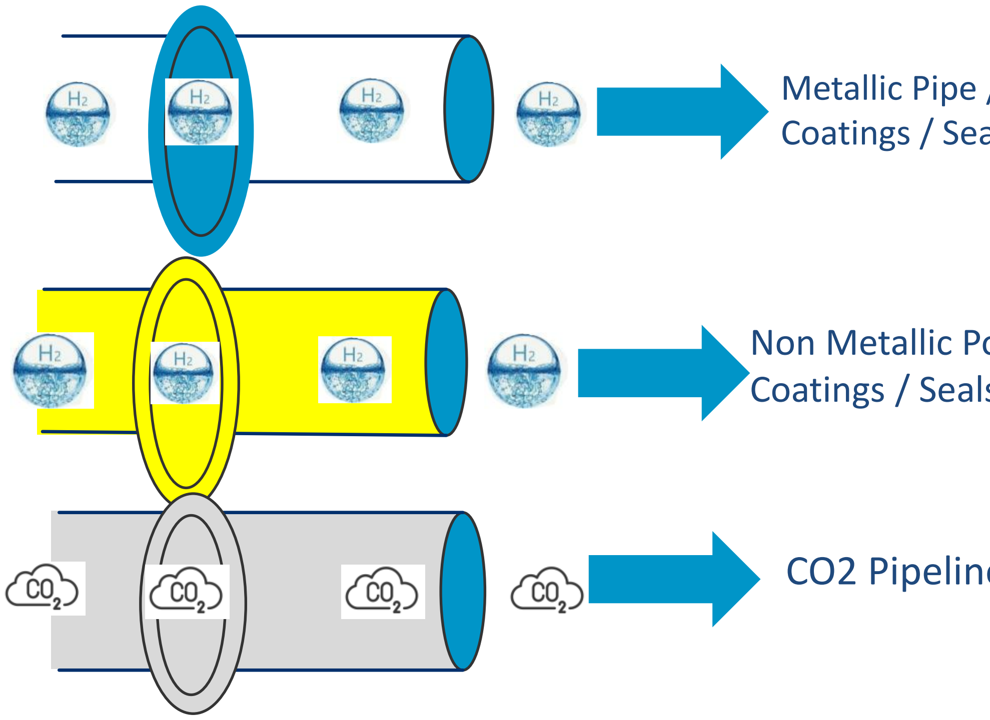
69% Repurposed pipe networks

31% New build



H2 Piping – Evolving Infrastructures

New / Old?

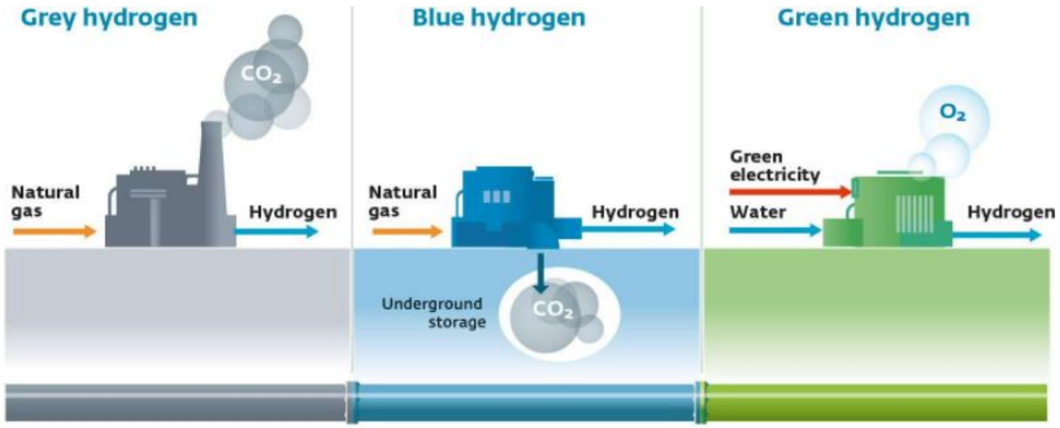


Metallic Pipe / Welds / Fittings / Jointing / Coatings / Seals

Non Metallic Polymer/composite Pipe / Joints / Fittings / Coatings / Seals / Permeation

CO2 Pipelines

- H2 Blends
- Impurities
- 100% Hydrogen
- Cryogenics



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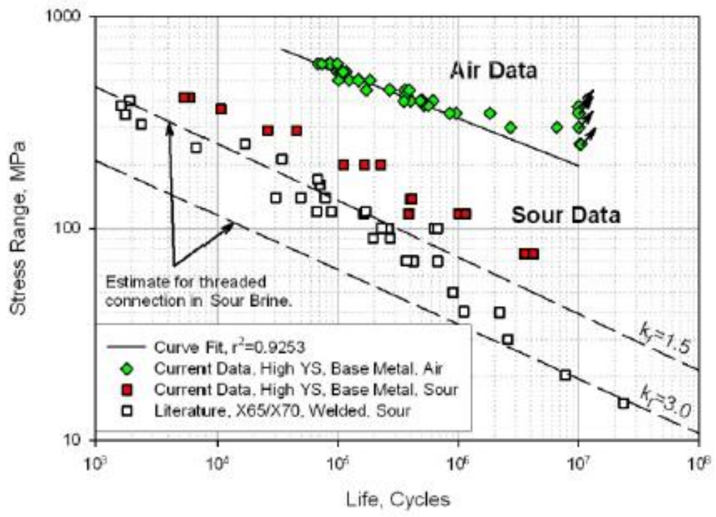
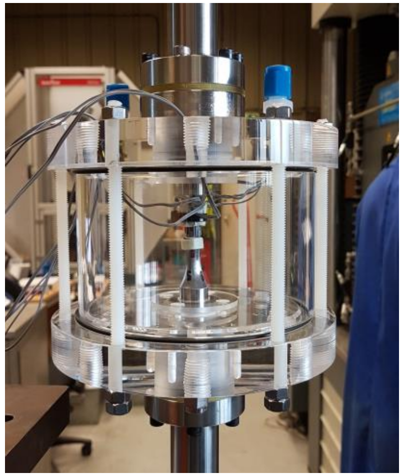
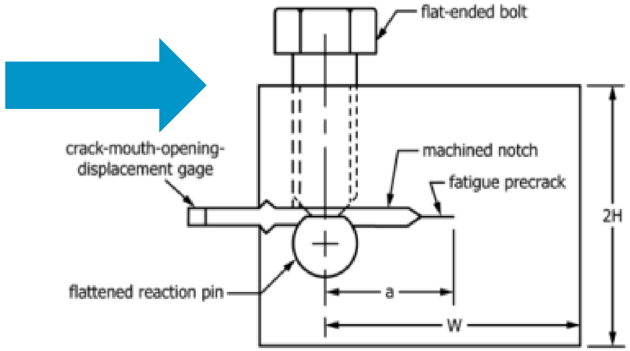
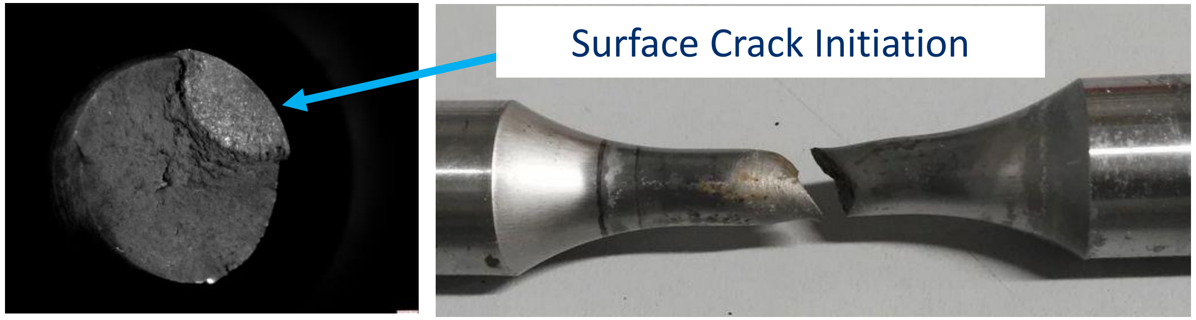
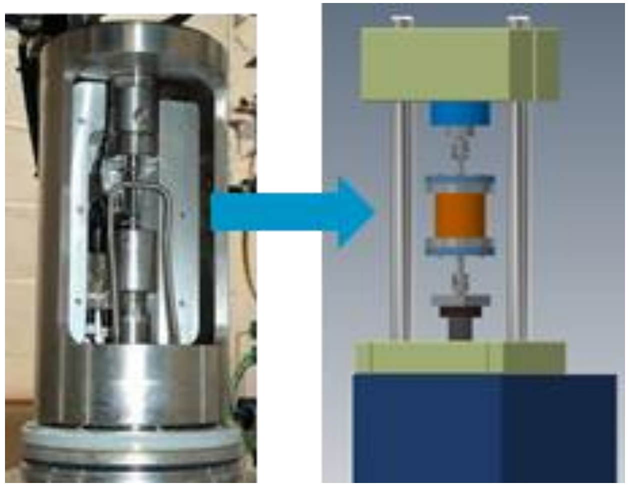
Fatigue Endurance - in-situ









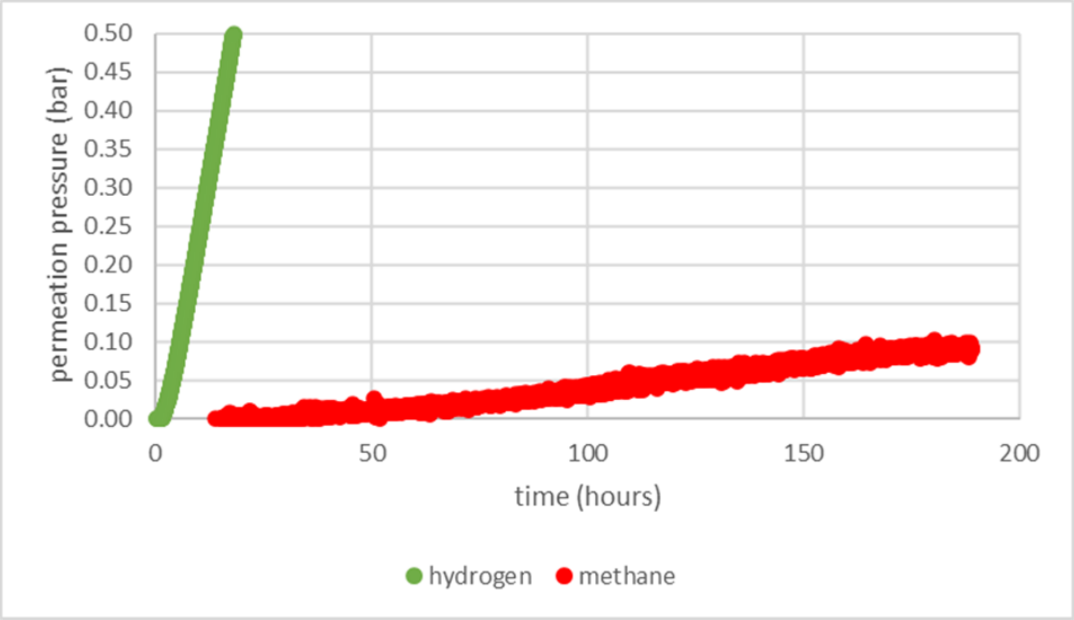


ASME B31.12 Standard on Hydrogen Piping and Pipelines contains requirements for piping in gaseous and liquid hydrogen service and pipelines in gaseous hydrogen service.

Non-Metallic Effects of H2

Permeation

Thermoplastic hydrogen 40 bar 40 °C:



Rapid Gas Decompression with H2

❑ Carbon dioxide has for years caused RGD damage:

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H2: Context is Key

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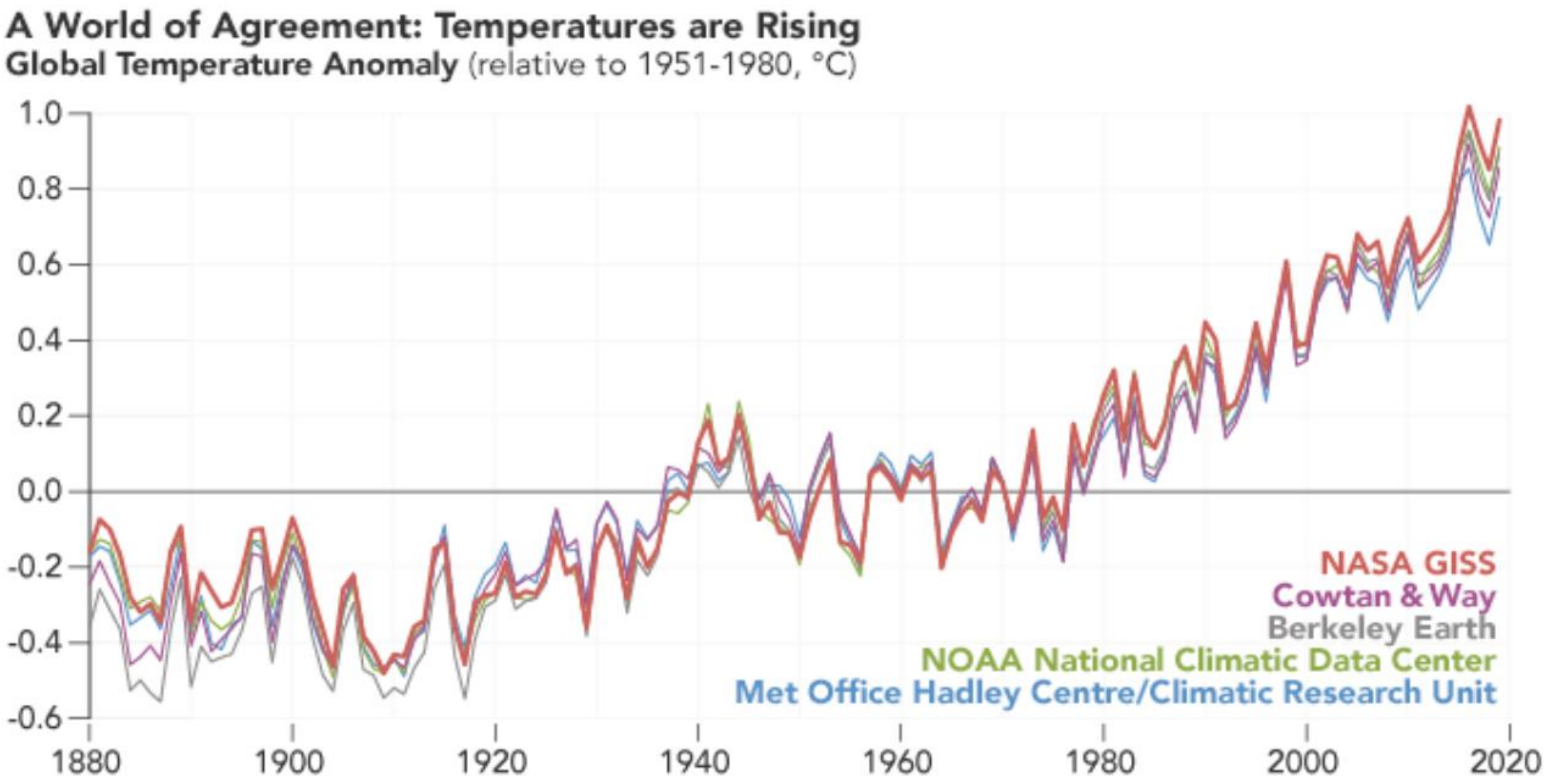
But we cant do it how we used to?



Global temperature anomaly (relative to 1951-1980) Image: NASA: Earth Observatory

TIME ?

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System Scalability and Time

- Global H2 ~ 75 million tonnes per year - demand > projected to 621 million tonnes 2050.
- 75 Million Tonnes is Grey – without little or no CCUS infrastructure.

- e.g.Paris Orly Airport - filling up 30 percent of flights H2 - 270 tons of 'liquid' hydrogen per day.
- Largest single liquefier - 32 tonnes per day (TPD), global capacity is 350 tonnes per day.
- Liquifaction – energy losses (~40%), Safety, Scale….
- Hydrogen from Electrolysis - 18 gigawatt-hours every day - one typical nuclear plant 900 MW.
- The electricity is produced through solar power, 44 square kilometers of solar panels would be needed—a footprint representing three times the entire surface area of the airport.
- Largest hydrogen-electrolysis plants today ~20 megawatts of capacity - maximum production of just 0.5 gigawatt-hours a day—A growth factor of 50x.

Hydrogen Liquifaction (Review Article) *Energy Environ. Sci.*, 2022, **15**, 2690-2731

International Energy Agency (IEA), Energy Technology Perspectives 2020, Paris, France, 2020.

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Model the dynamics of complex stochastic systems

element Digital Engineering

Challenge

Model the behavior of an *entire* mining fleet powered mostly by hydrogen in a way that can inform business strategic decisions.

But how can one deal with the interaction of thousands of subsystems full of uncertainty?

Our work

We used a combination of discrete event simulation (DES), deterministic and probabilistic analysis, and Monte Carlo simulation along with Python to pressure-test the system (scheduling, routing, supply, failure, cost, …).

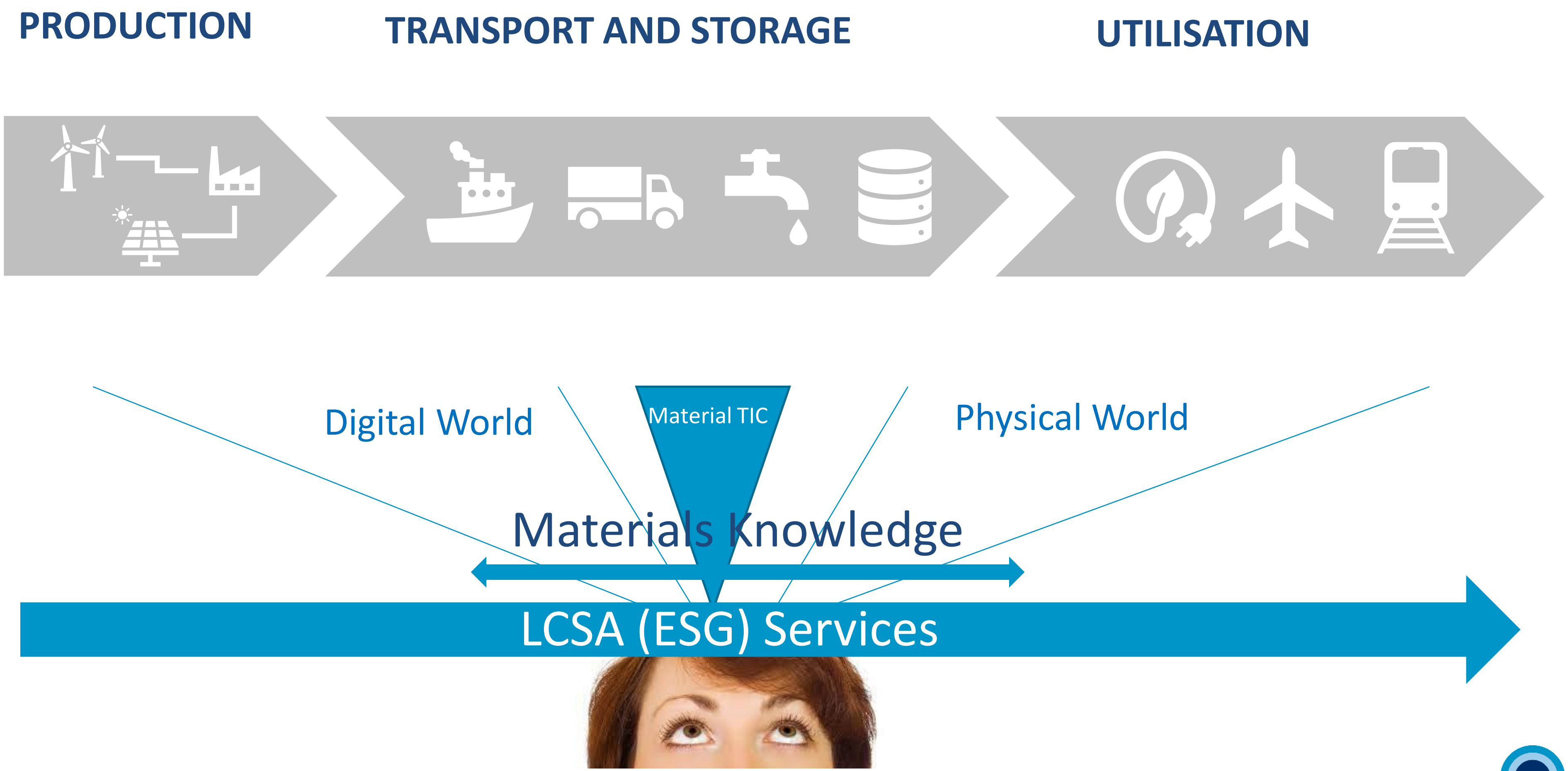
Our client brought the domain-specific knowledge to build the models.

Outcome

Our contribution has helped enable scenario playing and (in)validate assumptions, both of which have facilitated risk analysis and probabilistic design of the full system. The beginnings of a digital twin.

Client is well equipped to make a next generation energy efficient mining system a reality and at scale.

Element – Assuring Your Energy Transition



Condition Monitoring and Digital Twins

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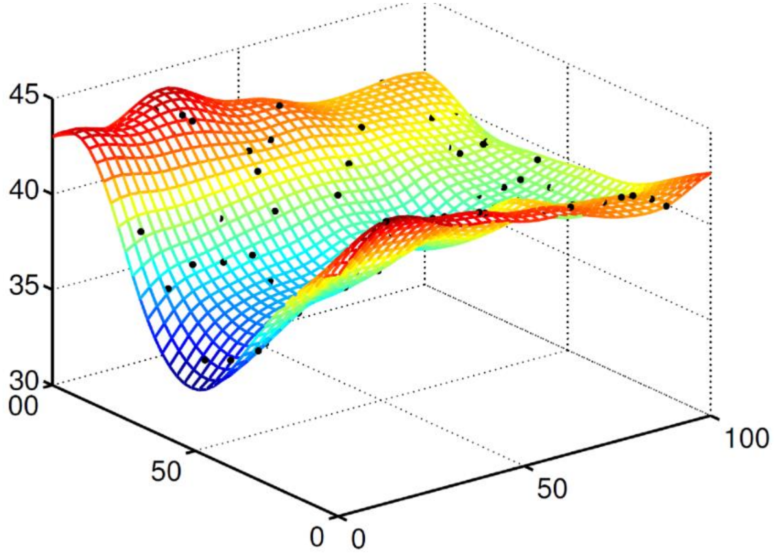
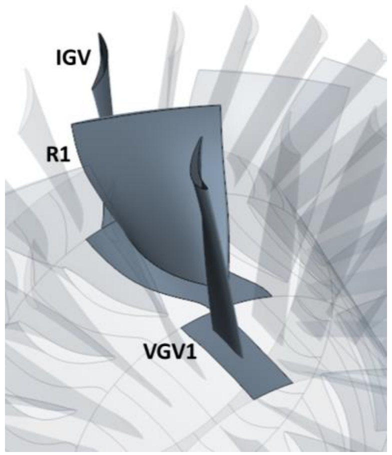


Challenge

An industrial turbine manufacturer wished to develop a predictive tool to determine how real-life variation of operating conditions affects component fatigue life which relates to maintenance schedules.

Our work

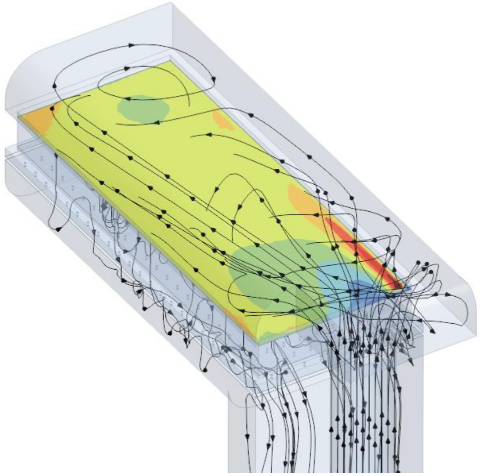
A limited number of high-fidelity simulations have been computed to determine component response surface. Using this data, a reduced-order model was calibrated. Component stress and fatigue damage could then be estimated by feeding the reduced-order model with real-life operating data.



Outcome

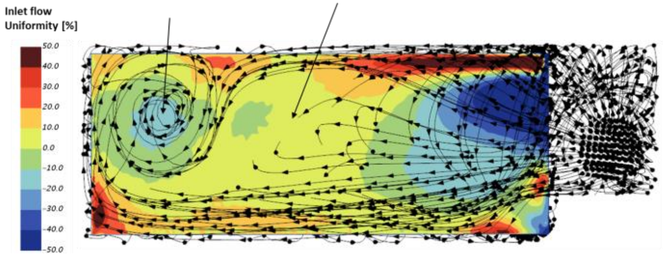
The resulting approach is a simplified analysis process that allows for fatigue damage to be rapidly estimated based on real-life operating data. This allows damage and failure to be tracked in close to real time based on actual operating history. In turn, this allows for service intervals to be extended.

Hydrogen fuel cell performance optimisation



Challenge

We have been approached by a fuel cell manufacturer to support the troubleshooting of in-service operation of their fuel cell.



Our work

Computational Fluid Dynamics models were built and used to predict flow distribution and characterize non-uniformity in the catalyst and the cell itself.

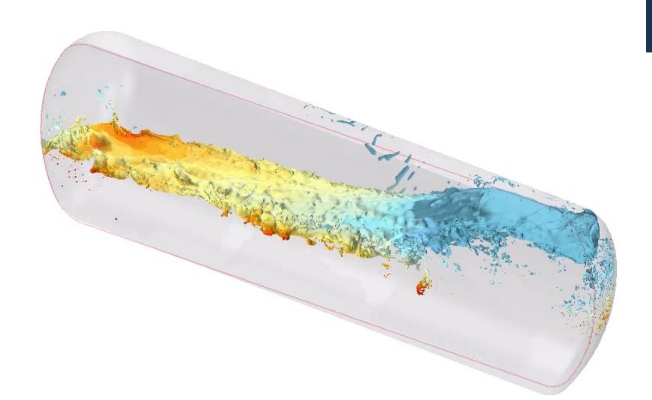
The team proposed a design modification consisting of porous strips used to improve flow uniformity within the fuel cell.

Outcome

The client received a solution which helped reduce wear of fuel cell whilst in operation saving costs of maintenance over time.

Sloshing of cryogenic hydrogen tanks

element
Digital Engineering



Challenge

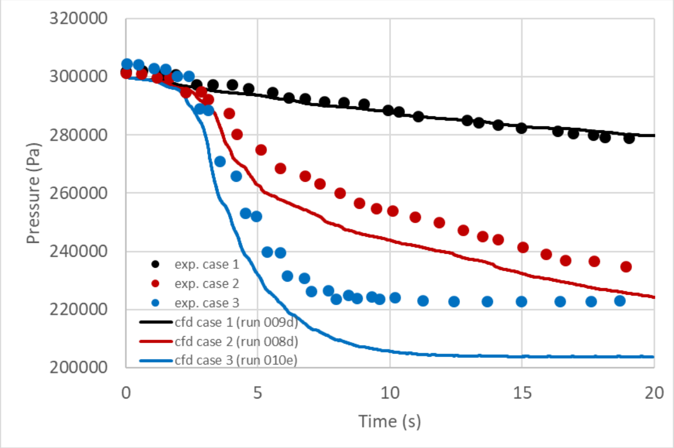
In applications where cryogenic hydrogen storage is considered, the risk of sloshing-induced hydrogen boil-off must be assessed to determine overpresurization rates

Our Capabilities

Norton Straw have implemented a calibrated boiling model in the commercial CFD tool StarCCM+. This model has then been validated against experimental data and used to produce insights regarding sloshing-induced hydrogen boil-off.

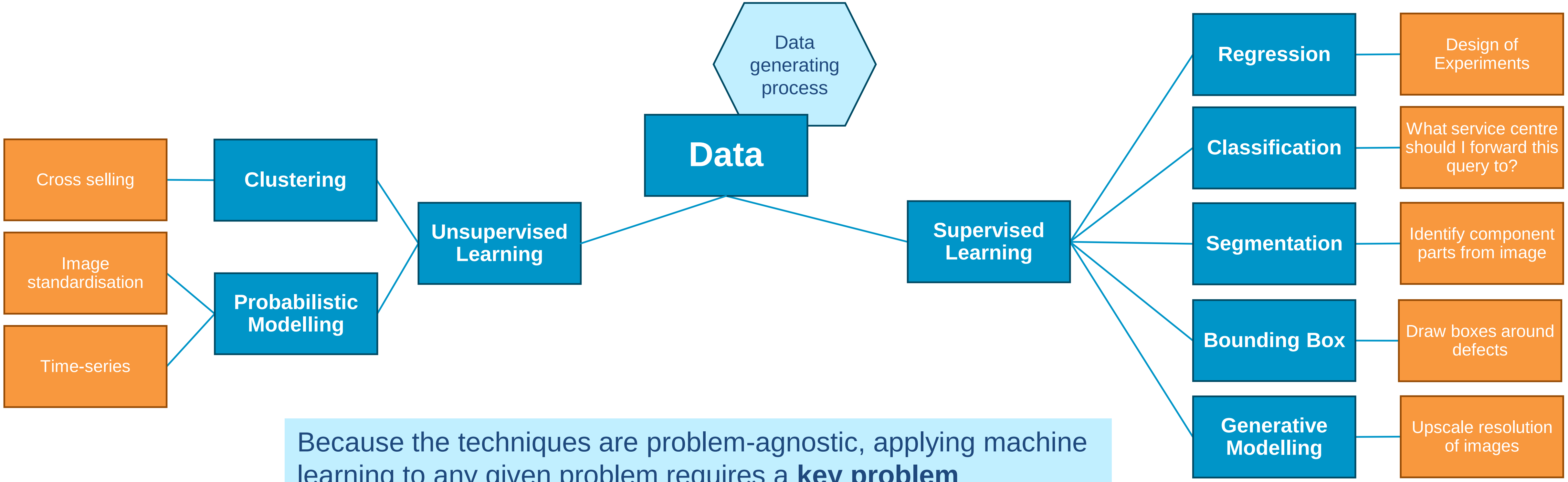
Outcome

We have assisted a UK government-funded Aerospace programme by delivering new insights regarding the behaviour of the liquid hydrogen undergoing sloshing



Further services – Analytics and Data Science

The unifying concept in **machine learning** is that algorithms are set up to perform a task whose outcome improves with experience.
Supervised and unsupervised learning algorithms can offer solutions to a wide variety of problems.



Because the techniques are problem-agnostic, applying machine learning to any given problem requires a **key problem conceptualisation** step in which includes data preparation and heavy engagement with the DE experts.

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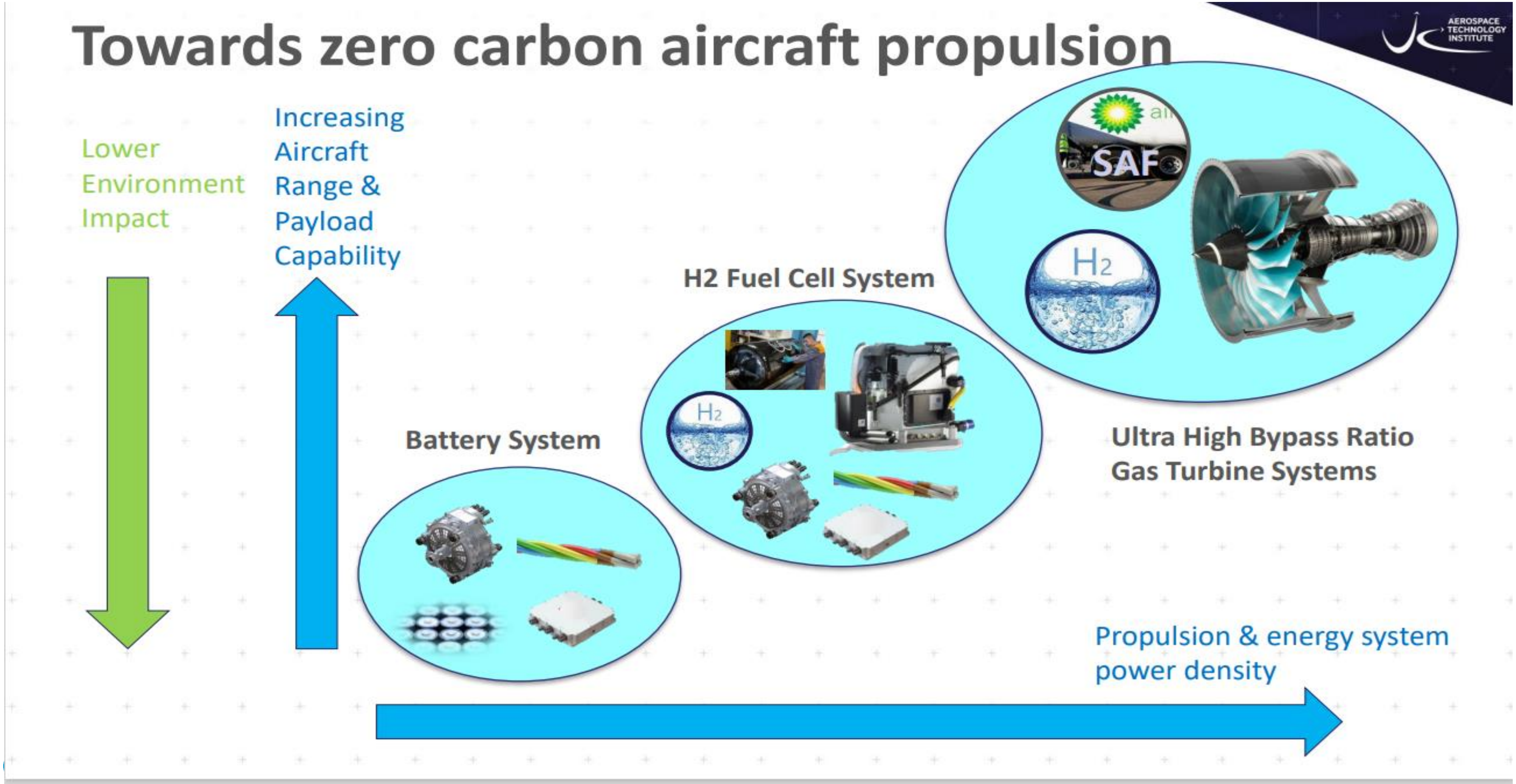
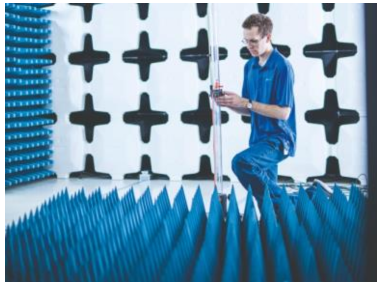
Cross over to other Technologies



Connected Technologies

Internet of Things



Radio Frequency Identification (RFID)

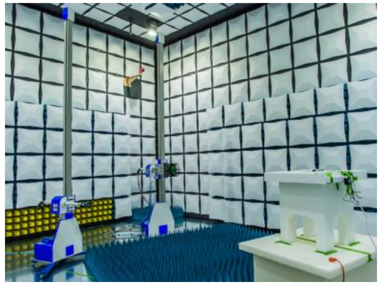
International Certifications, CE Marking and Approvals

Lithium Battery Testing and Certification

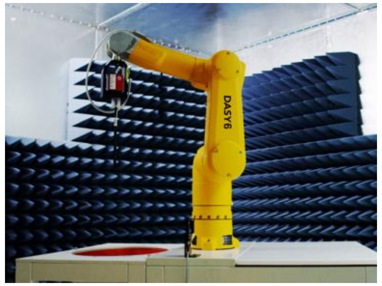
5G Test and Certification

Field Interoperability Testing (FIT)

Long Term Evolution LTE Conformance Testing

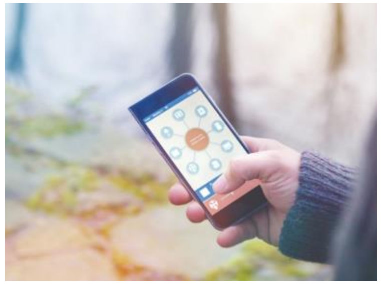


RF Parametric & Protocol Testing

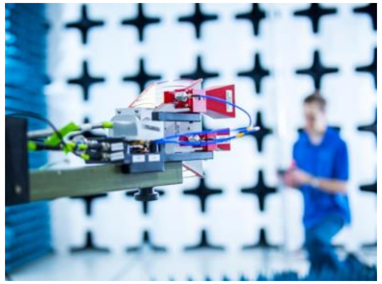


Specific Absorption Rate (SAR)

Over-the-Air (OTA) Testing



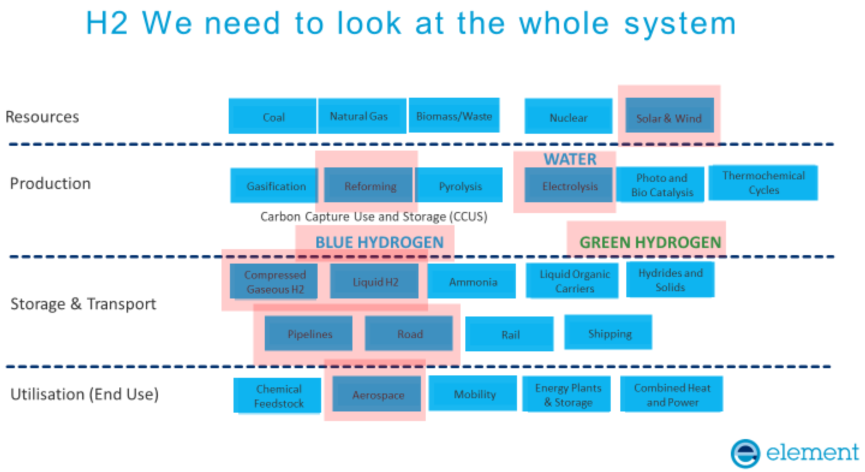
Zigbee Certification Testing

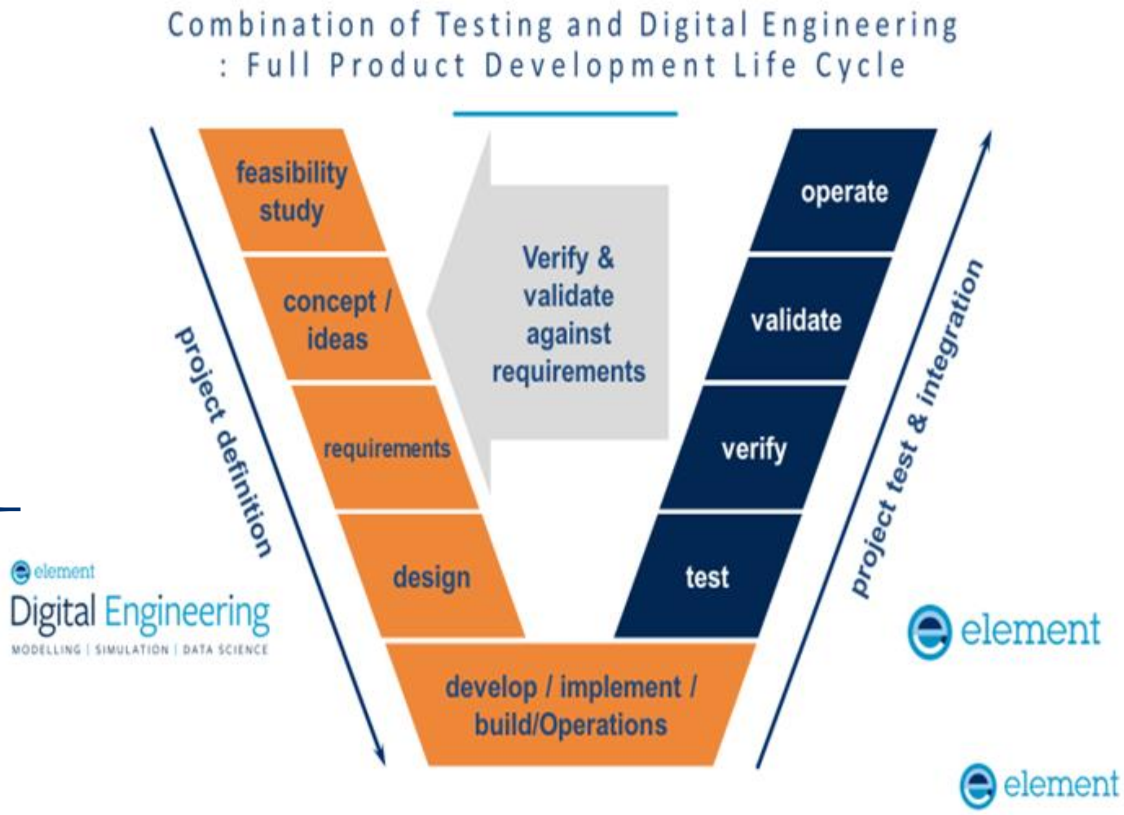


Radio Certifications and Testing

element

Redefining Testing: Systems and Component Level





Redefining Testing with the Needs of the H2 Value Chain

Come and talk to us to accelerate your Energy transition

Making tomorrow safer than today

Thank you for Listening ☺

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