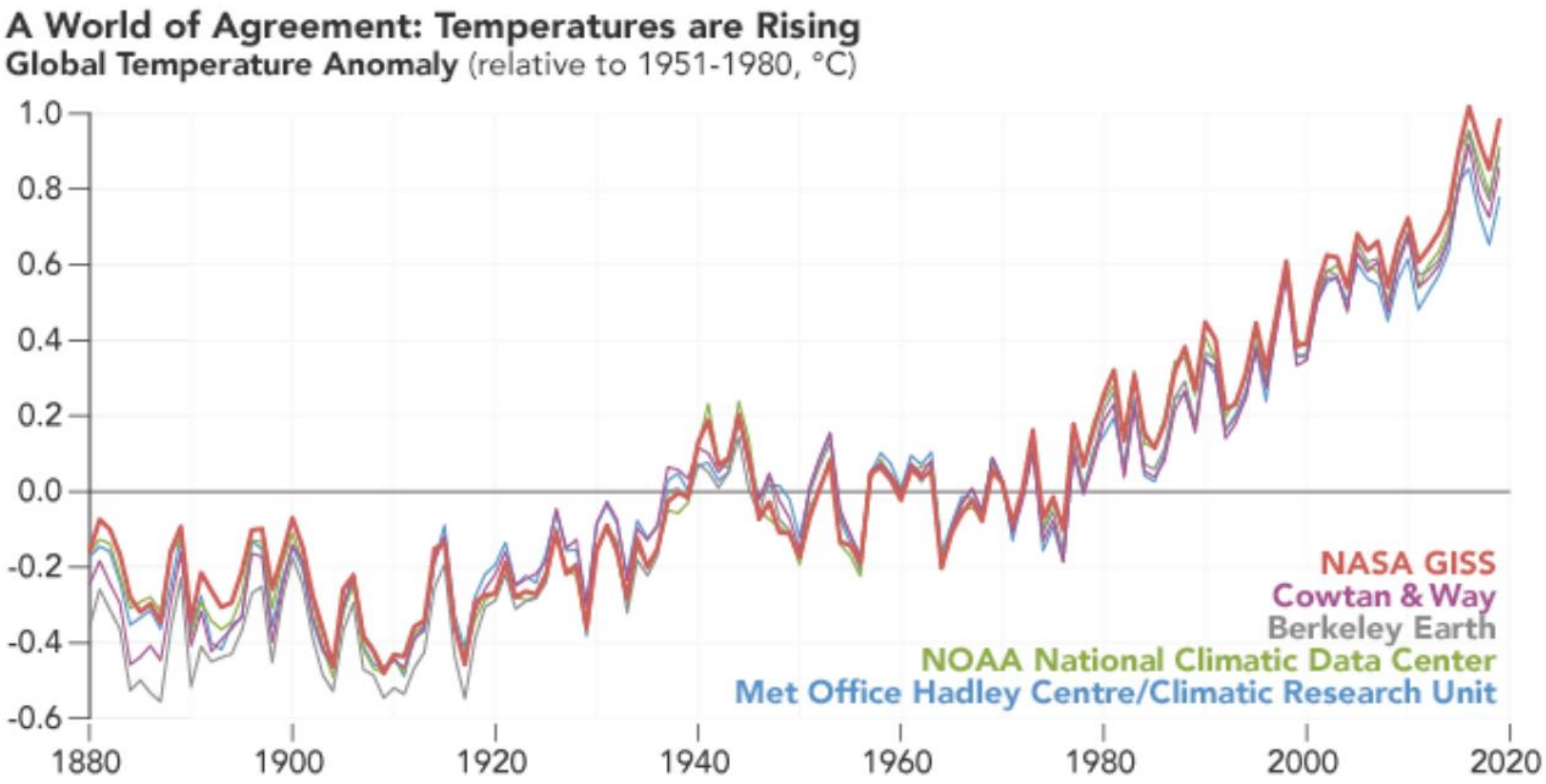
The Future Evolution of Sustainable Aviation

Hydrogen – Reality or Hype?

Dr Mark Eldridge – 22nd March 2023, Coventry

The Rapid Need to Decarbonise



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

TIME ?

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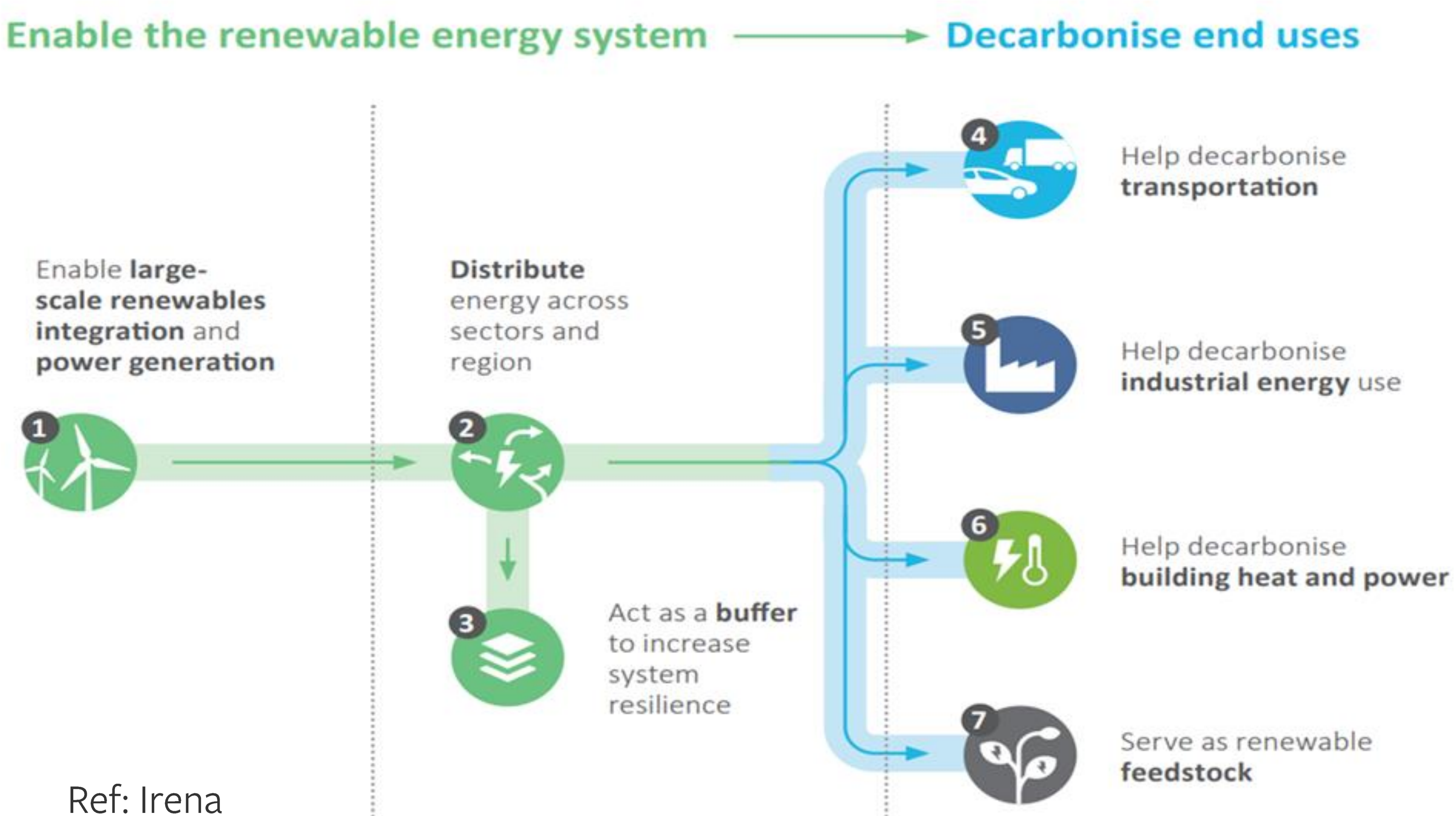
H2 is an elegant Energy Vector



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

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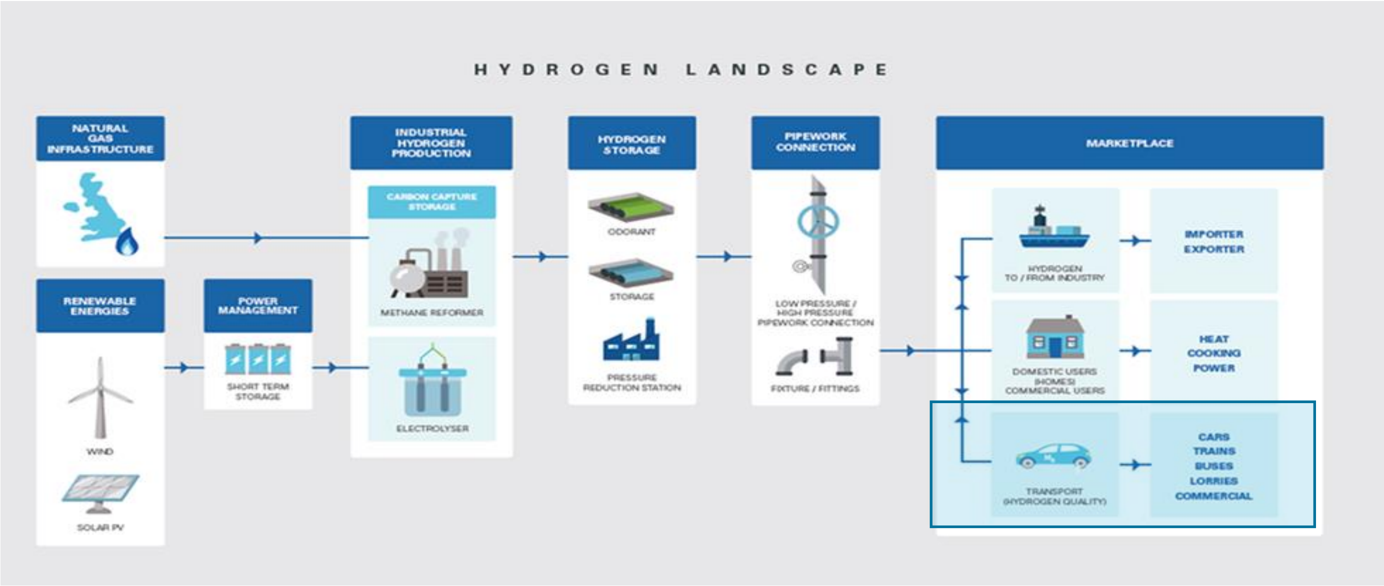
The H2 landscape

PRODUCTION

TRANSPORT AND STORAGE

UTILISATION



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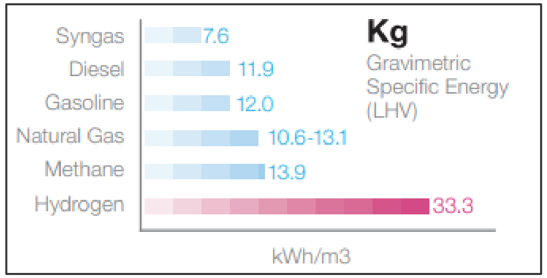
H 1 Start with something small and light..

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



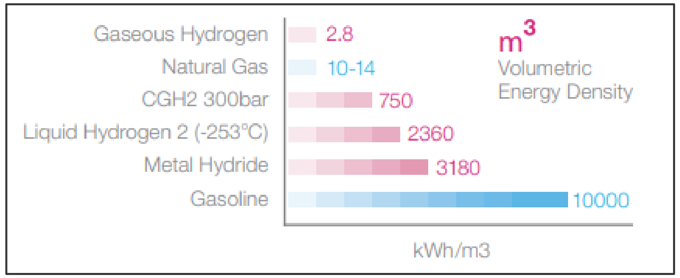


Table 1 - Characteristics of hydrogen, dry natural gas and gaseous propane

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

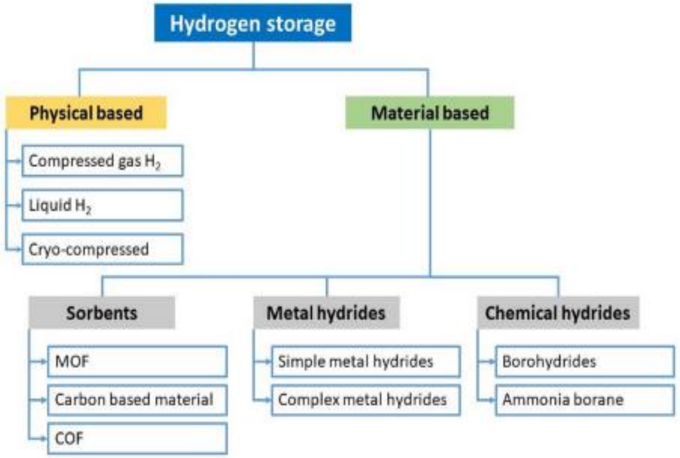
* at normal temperature and pressure – 1 atmosphere and 20°C

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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Perspectives are Key

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H2 We need to look at the whole system

Resources

Coal | Natural Gas | Biomass/Waste | Nuclear | Solar & Wind

Production

WATER

Gasification | Reforming | Pyrolysis | 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

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ITS NOT JUST HYDROGEN

Hydrogen Must Always 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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Seasonal Effect of Heating

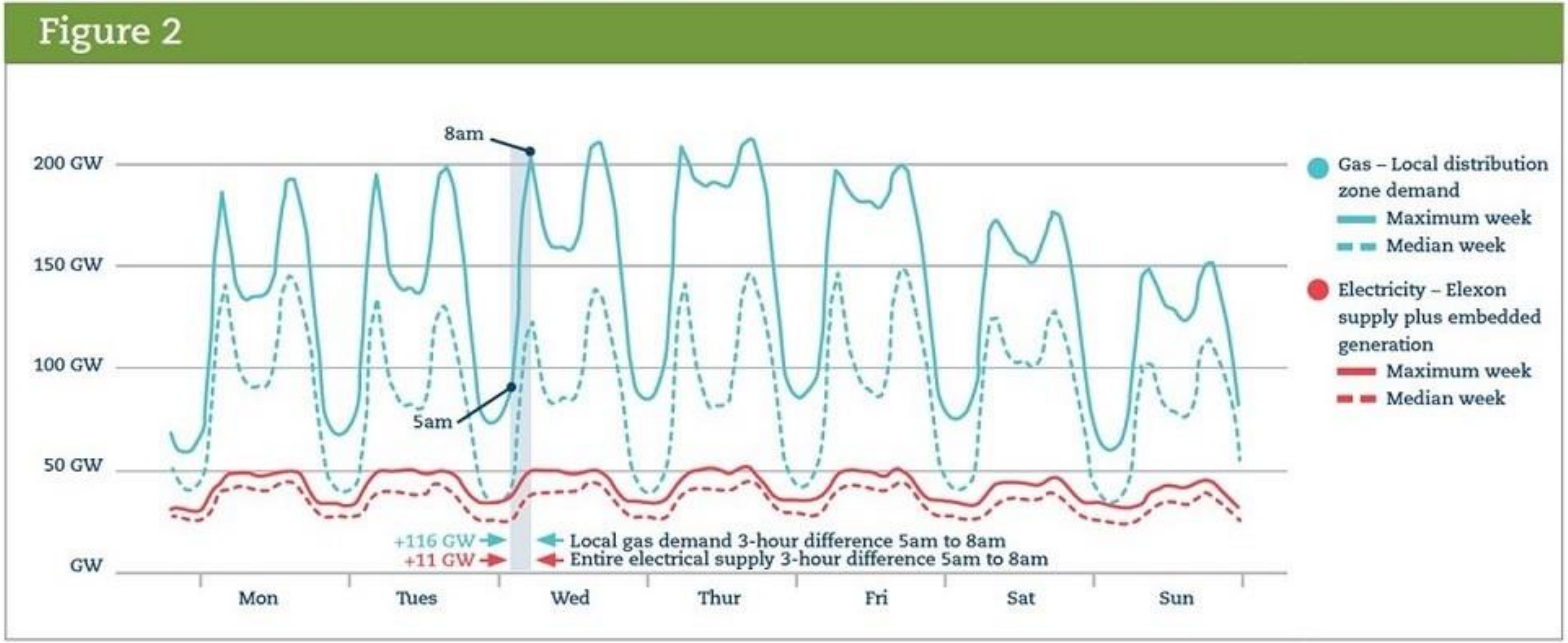
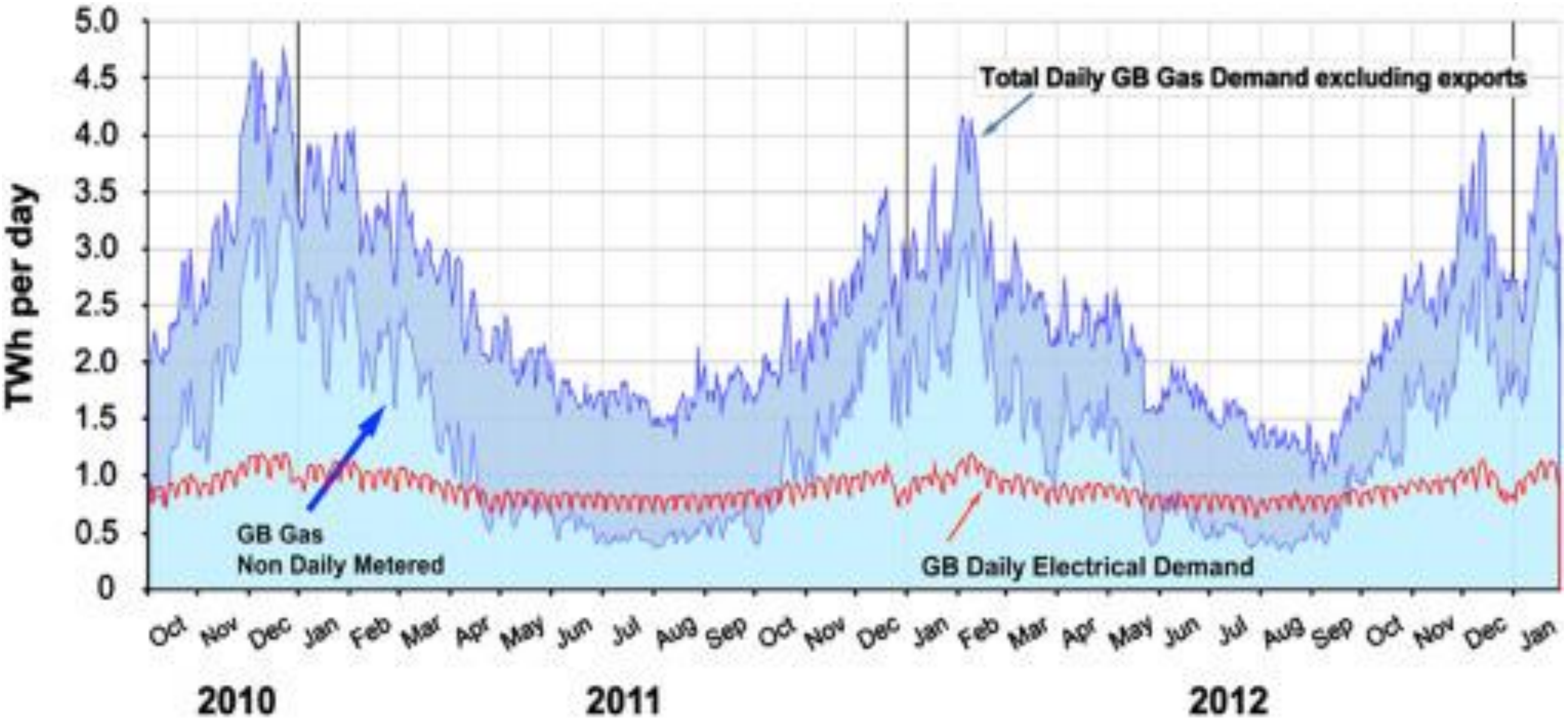


Figure 2: Britain's local gas demand and electrical system supply - median and maximum demand weeks. The week dating 22nd to 28th January is the median demand week for the 2017–2018 heating season. The week dating 26th February to 5th March represents the maximum demand week of the 2017–2018 heating season.

Blending and the Seasonal Effect of Heating



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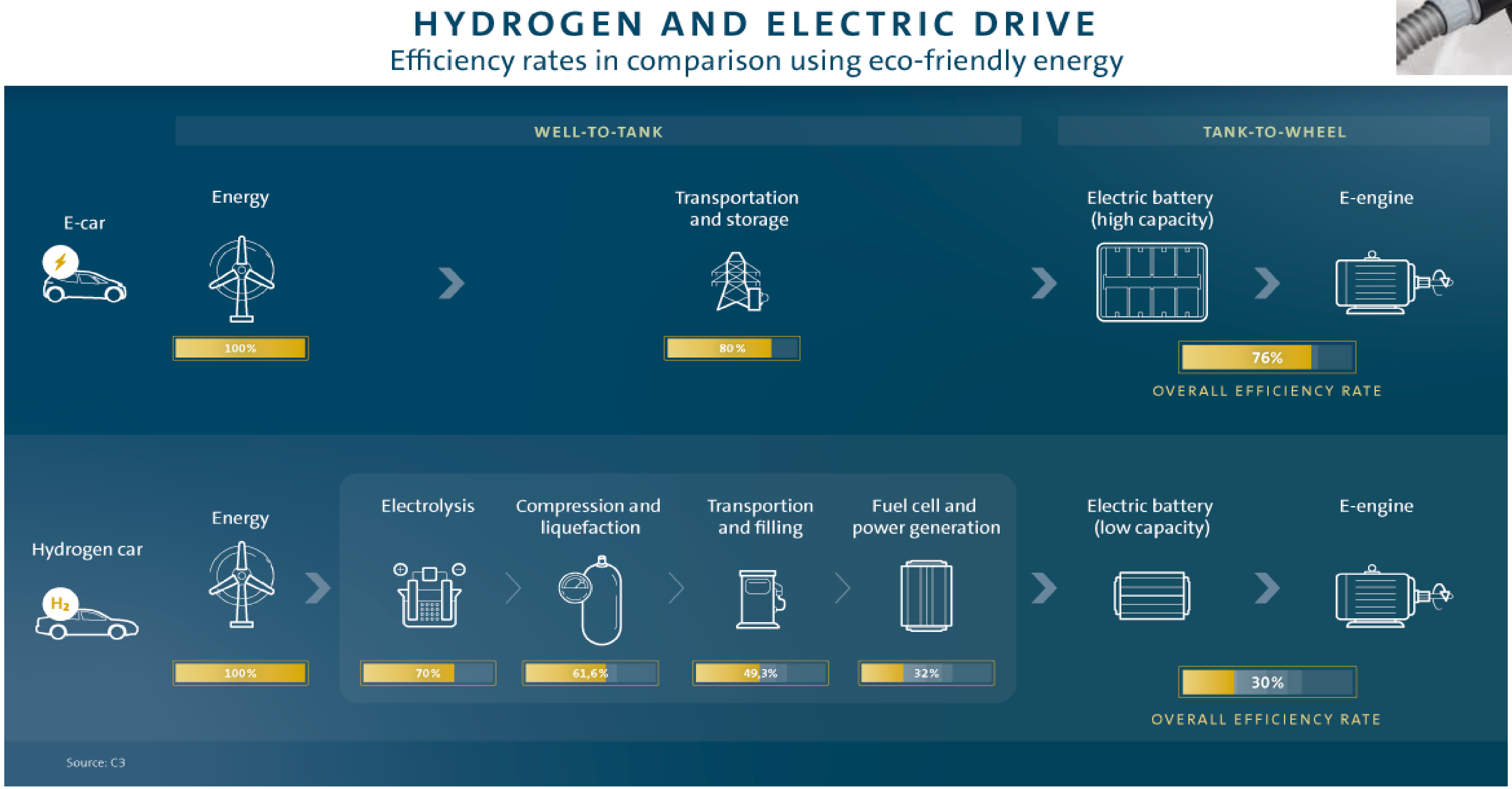
Efficiency Losses



20 - 30% of energy is lost in the process of creating hydrogen. The hydrogen must then be compressed and stored, losing another 10%. Finally, another 30% is lost when converting the hydrogen into electricity. This leaves you with 30 – 40% of the original energy used.

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

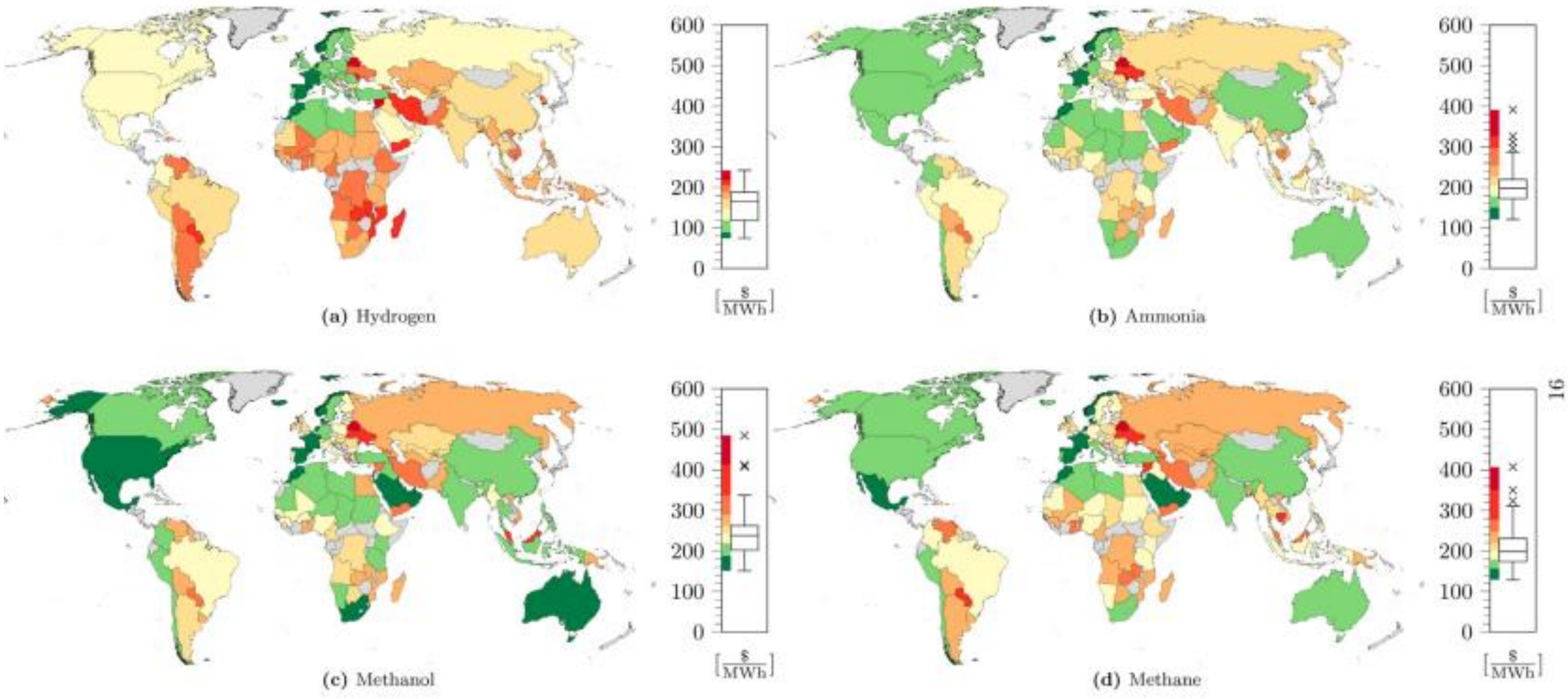
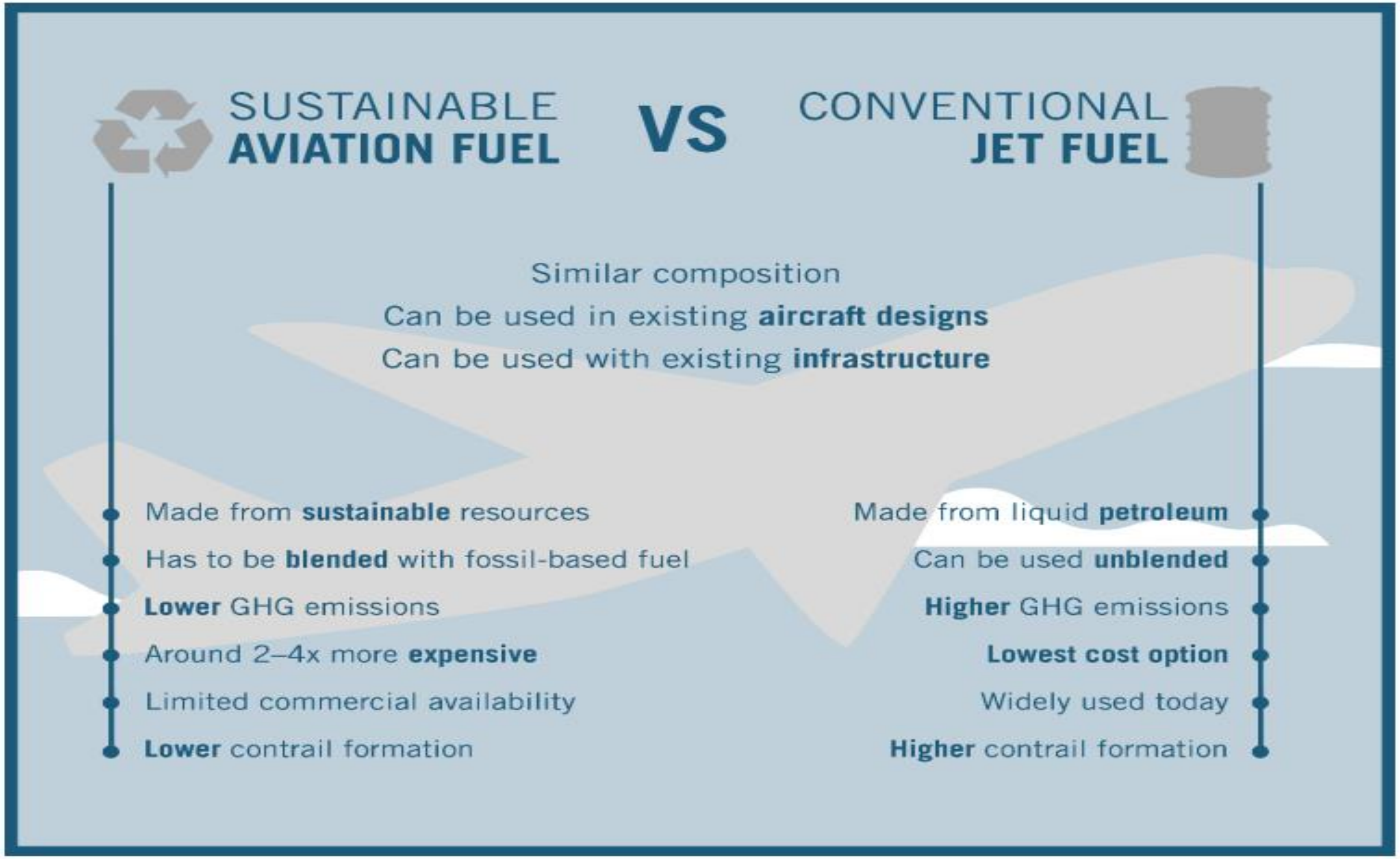


Fig. 6 – Supply cost to Germany for an import volume of 100 TWh/a in the baseline scenario and the year 2030.

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 vs Where we are Today



BACK TO HYDROGEN PROPERTIES

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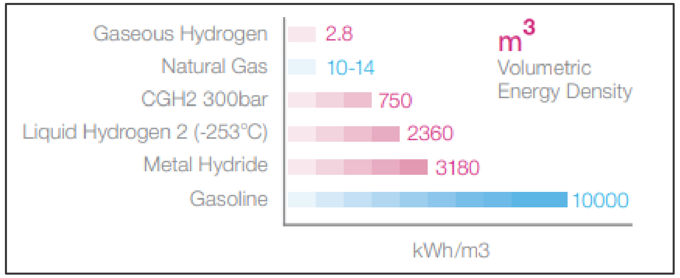
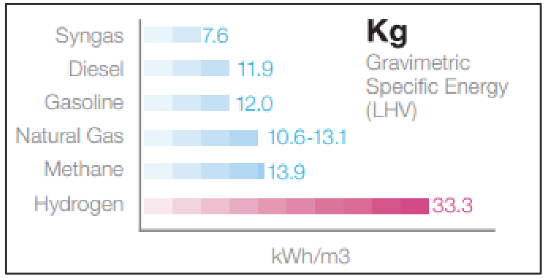
10% of our Body
Commonly found in water
Only element that can exist without neutrons





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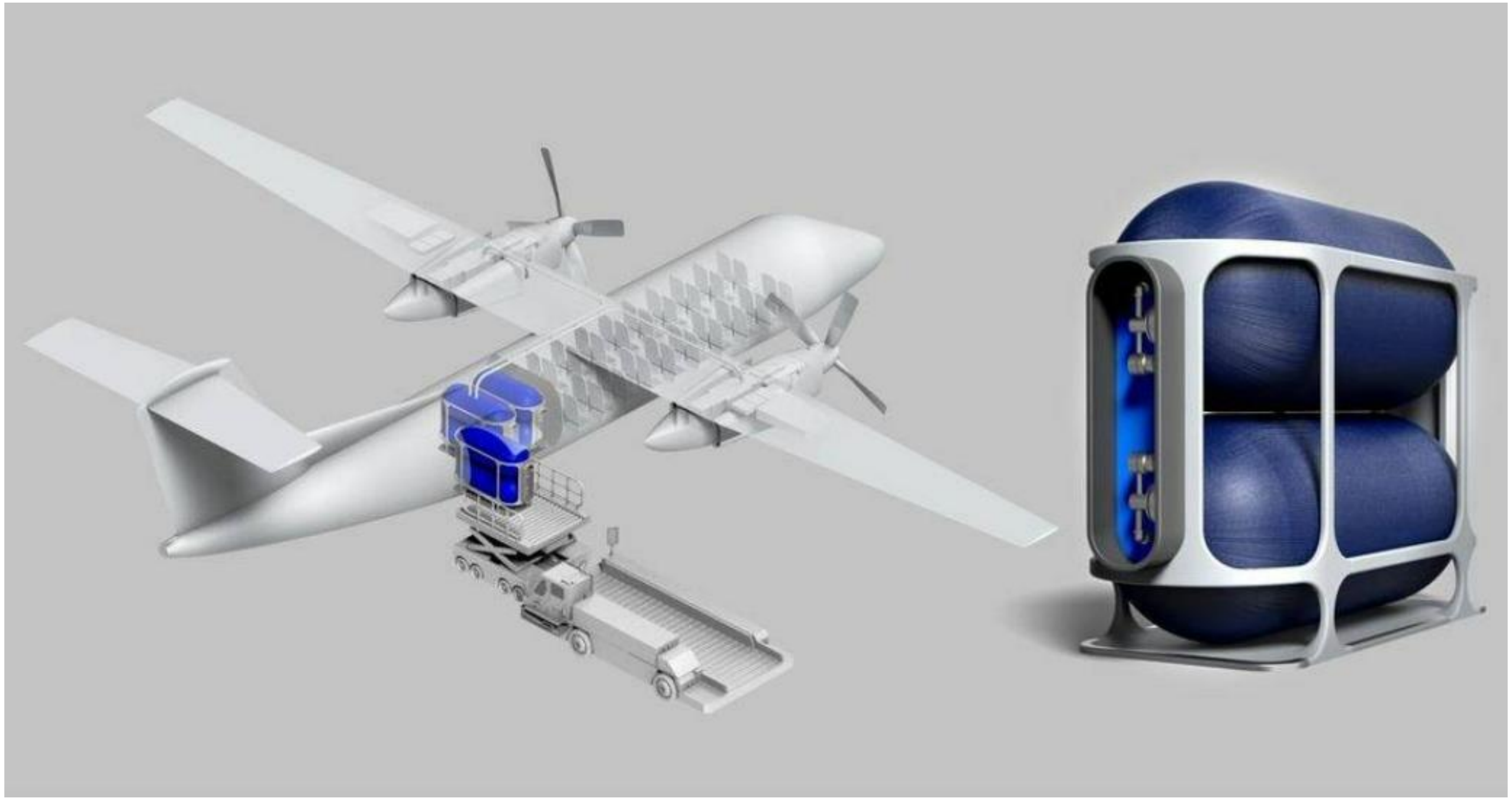
Wings to Central Body



Options for Range Flight

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Possible Roll-Out Scenarios?

	2020	2025	2030	2035	2040	2045	2050
Commuter ▪ 9–19 seats ▪ < 60 minute flights ▪ < 1% of industry CO_2	SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF
Regional ▪ 50–100 seats ▪ 30–90 minute flights ▪ ~3% of industry CO_2	SAF	SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF
Short haul ▪ 100–150 seats ▪ 45–120 minute flights ▪ ~24% of industry CO_2	SAF	SAF	SAF	SAF and possibly some hydrogen	Hydrogen and/or SAF	Hydrogen and/or SAF	Hydrogen and/or SAF
Medium haul ▪ 100–250 seats ▪ 60–150 minute flights ▪ ~43% of industry CO_2	SAF	SAF	SAF	SAF	SAF and possibly some hydrogen	SAF and possibly some hydrogen	SAF and possibly some hydrogen
Long haul ▪ 250+ seats ▪ 150 minute + flights ▪ ~30% of industry CO_2	SAF	SAF	SAF	SAF	SAF	SAF	SAF

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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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Airport Challenges (aside from the Aircraft)

1

Supply of Hydrogen:

- Scale of competitive H2
- Distributors outside Airport and Transportation
- Infrastructure on site – Energy/Production/Liquefaction

2

Implementation:

- Storage at Airport
- Double infrastructures
- Logistics to supply (trucks or pipe)
- Reconfigured infrastructures

3

The nature of the business plan:

- Management of ticket price increase
- Adaption of the air traffic of rotations

4

Regulations and Safety

Ecosystems to build

Energy Suppliers

OEMs

Airports / Companies

Element – Assuring Your Energy Transition

PRODUCTION TRANSPORT AND STORAGE UTILISATION

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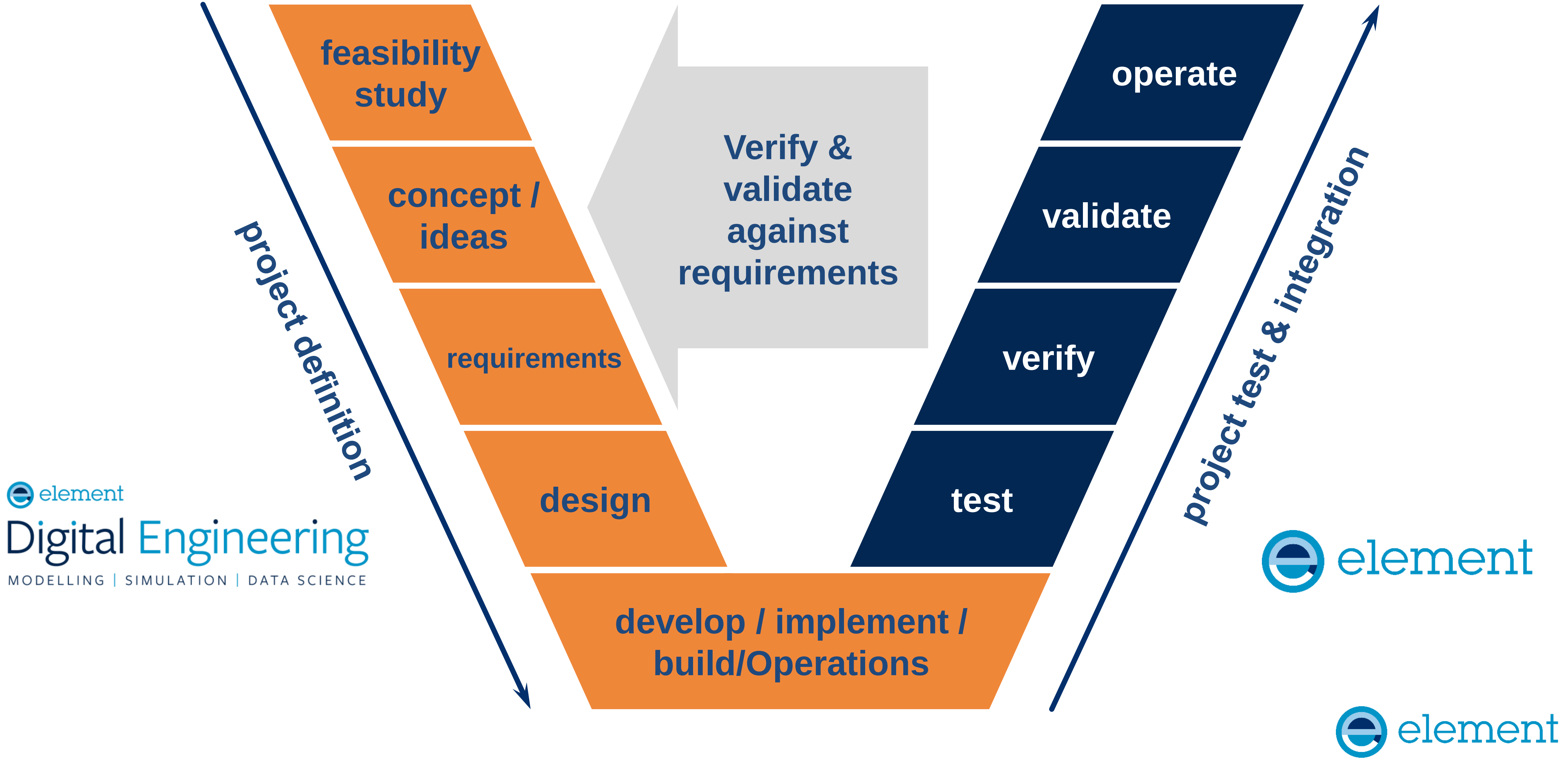
Combination of Testing and Digital Engineering : Full Product Development Life Cycle

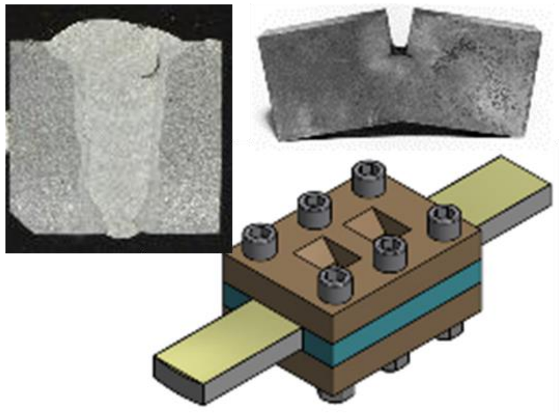


Physical Experience

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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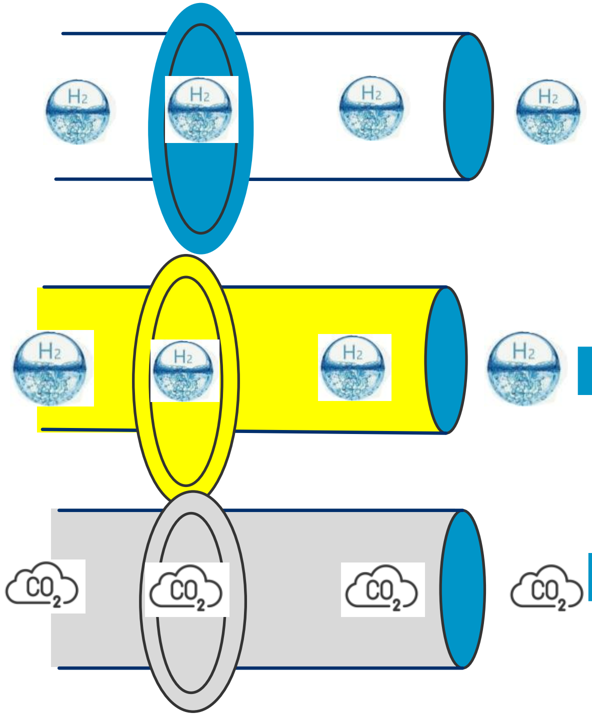
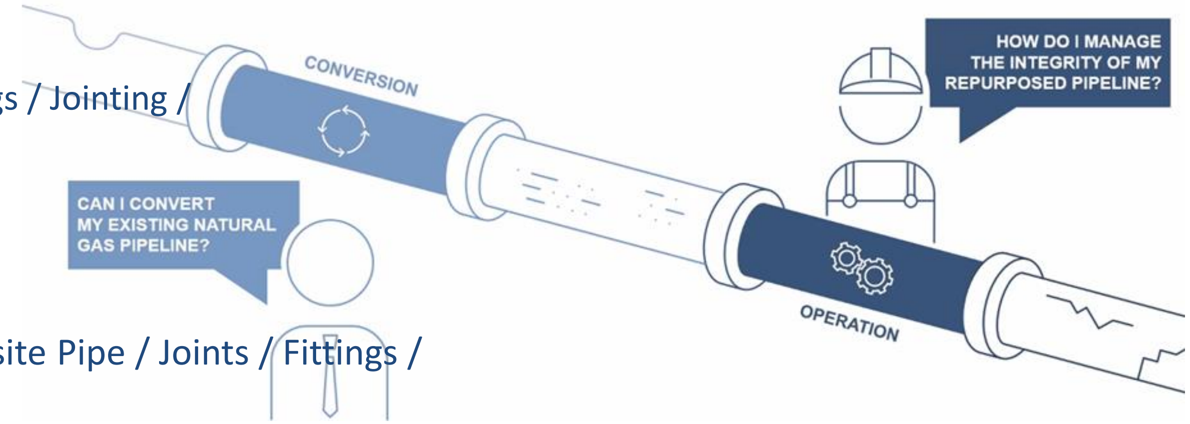
H2 Piping – Evolving Infrastructures



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

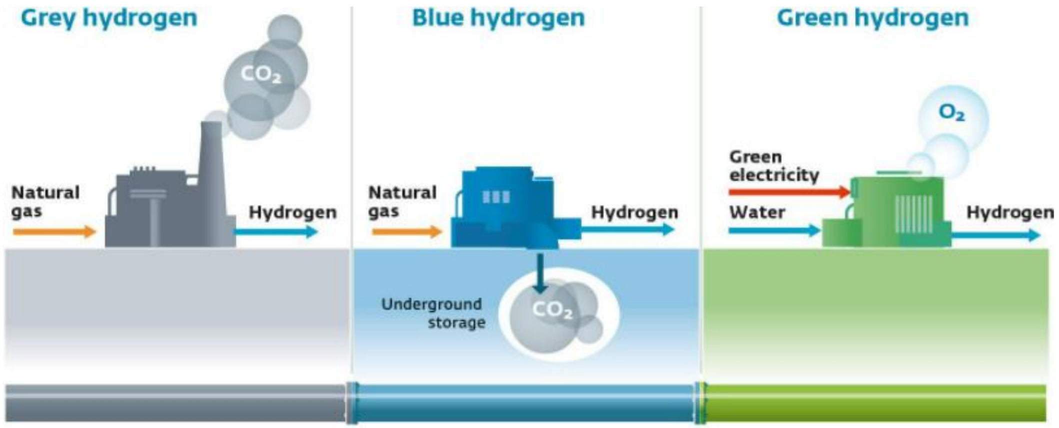


Non Metallic Polymer/composite Pipe / Joints / Fittings / Coatings / Seals / Permeation

Ref:Rosen

CO2 Pipelines

- H2 Blends
- Impurities
- 100% Hydrogen
- Cryogenics



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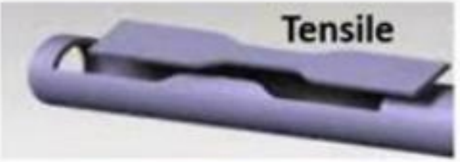
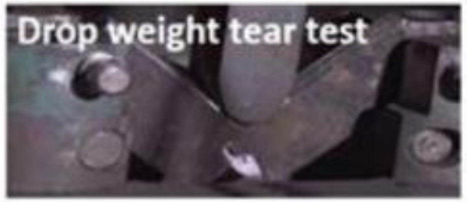
Examples for Metallics

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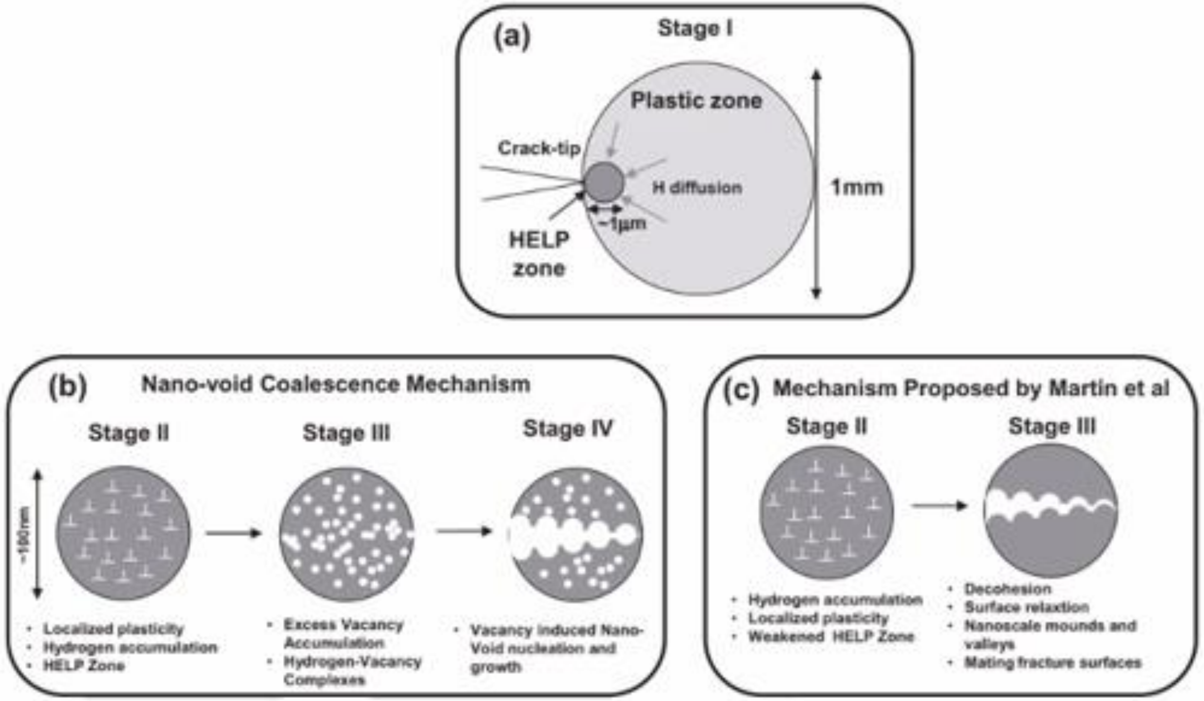
Like sand on the beach – it gets everywhere!!
HE Cracking Mechanisms



Schematic NVC mechanism – from Neeraj et al., Hydrogen embrittlement of ferritic steels: Observations on deformation microstructure, nanoscale dimples and failure by microvoiding, Act. Mat. 60(2012, 5160-5171

HEDE – Hydrogen Enhanced Decohesion

AIDE – Adsorption Induced Dislocation Emission

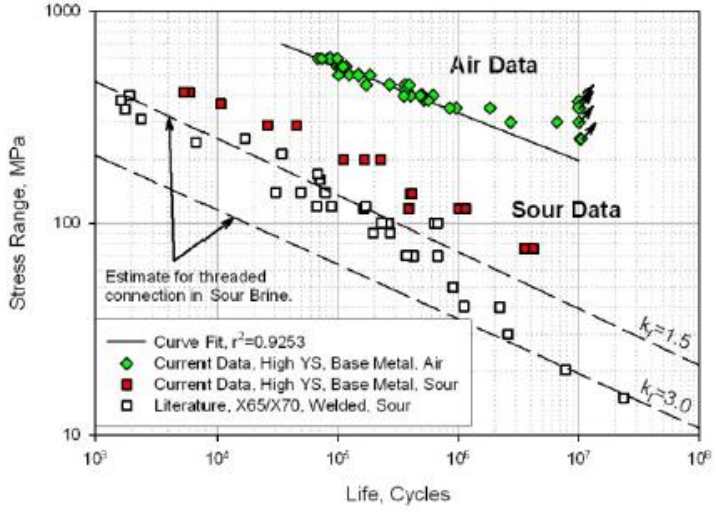
IHAC – Internal Hydrogen Assisted Cracking

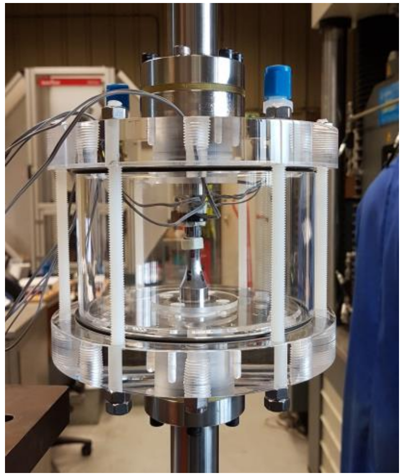
HEAC – Hydrogen Environment Assisted Cracking

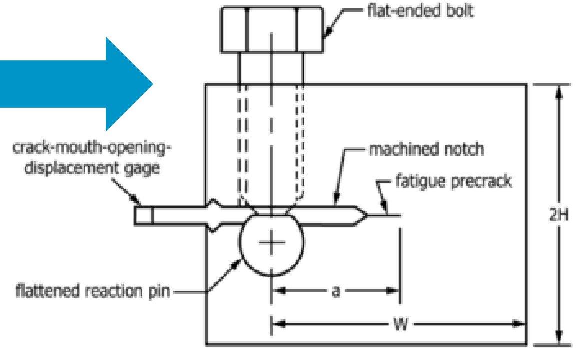
NVC – Nano Void Coalescence

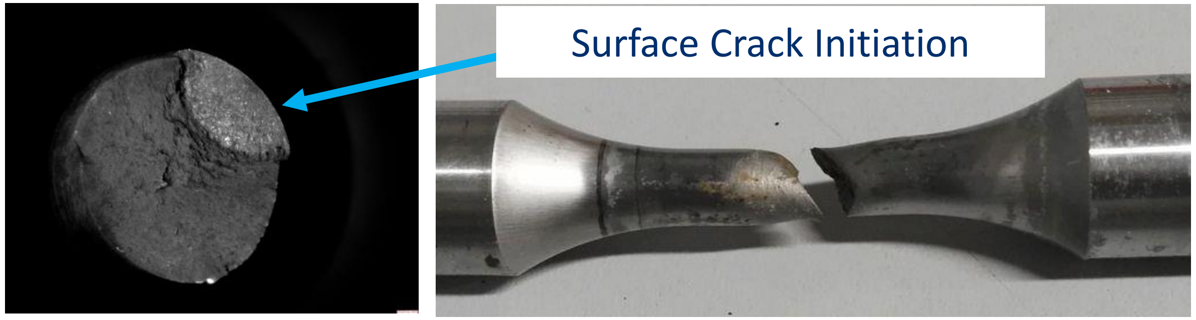
HELP – Hydrogen Enhanced Local Plasticity

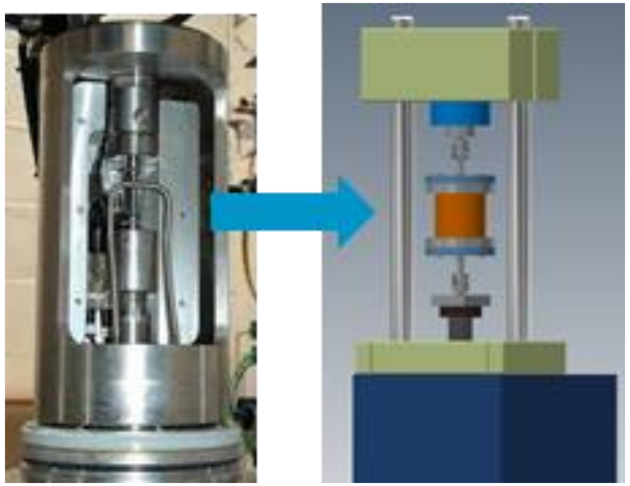
Fatigue Endurance - in-situ









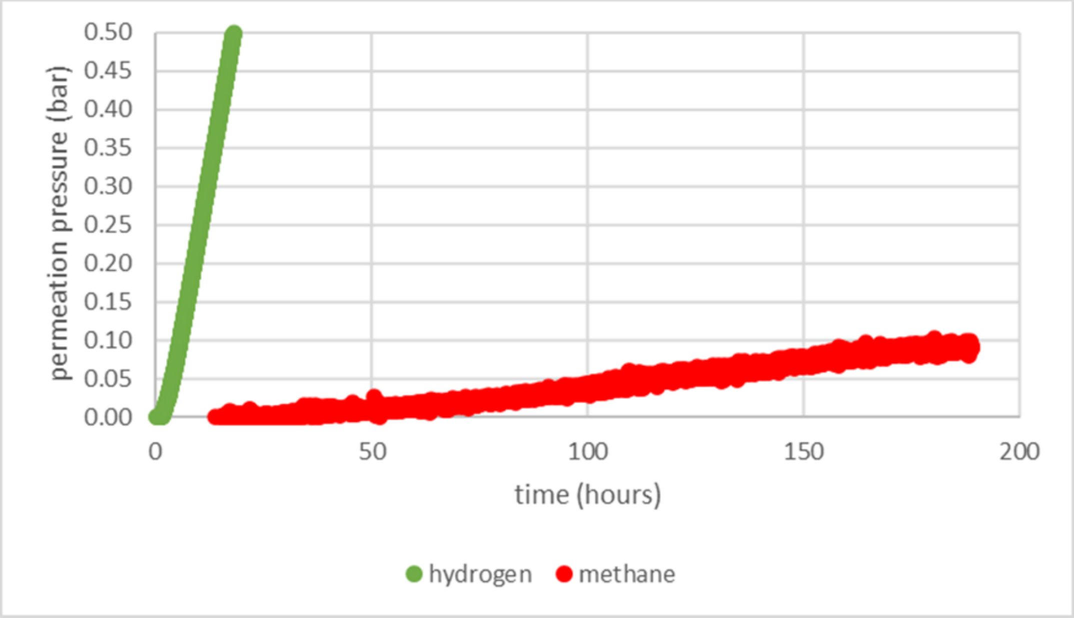


ASME B31.12 Standard on Hydrogen Piping and Pipelines contains requirements for piping in gaseous and liquid hydrogen service and pipelines in gaseous hydrogen service.

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:

Digital Experience

PRODUCTION

TRANSPORT AND STORAGE

UTILISATION

PRODUCTION

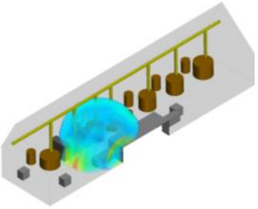
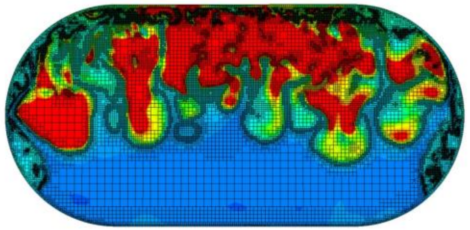
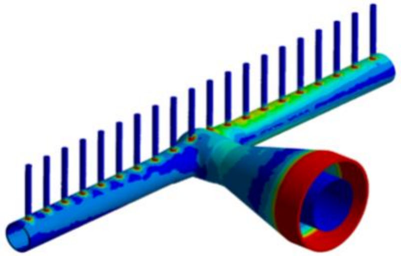
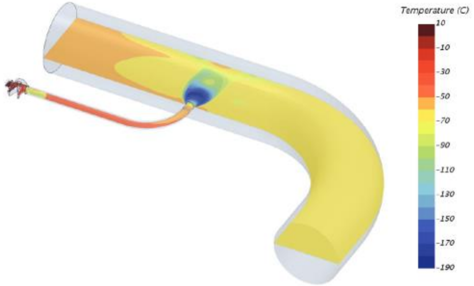
- EXPLOSION RISK AND CONSEQUENCE MODELLING OF ELECTROLYSERS
- ELECTROCHEMICAL MODELLING OF ELECTROLISER STACKS
- PLUME DISPERSION AND IGNITION RISK MODELLING

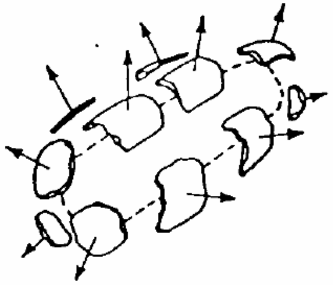
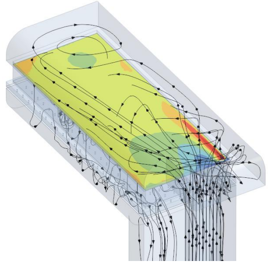
TRANSPORT AND STORAGE

- SYSTEM-LEVEL MODELLING OF STORAGE CONTAINER RE-FUELLING OR DISCHARGE OPERATIONS
- THERMO- AND FLUID DYNAMICS OF CRYOGENIC HYDROGEN STORAGE AND TRANSPORT
- LEAKS AND EXPLOSION MODELLING OF TRANSPORT INFRASTRUCTURE
- PLUME DISPERSION AND IGNITION RISK MODELLING

UTILISATION

- FUEL CELL THERMAL AND FLUID DYNAMIC MODELLING AND OPTIMISATION
- FUEL CELL EXPLOSION AND CONSEQUENCE ANALYSIS

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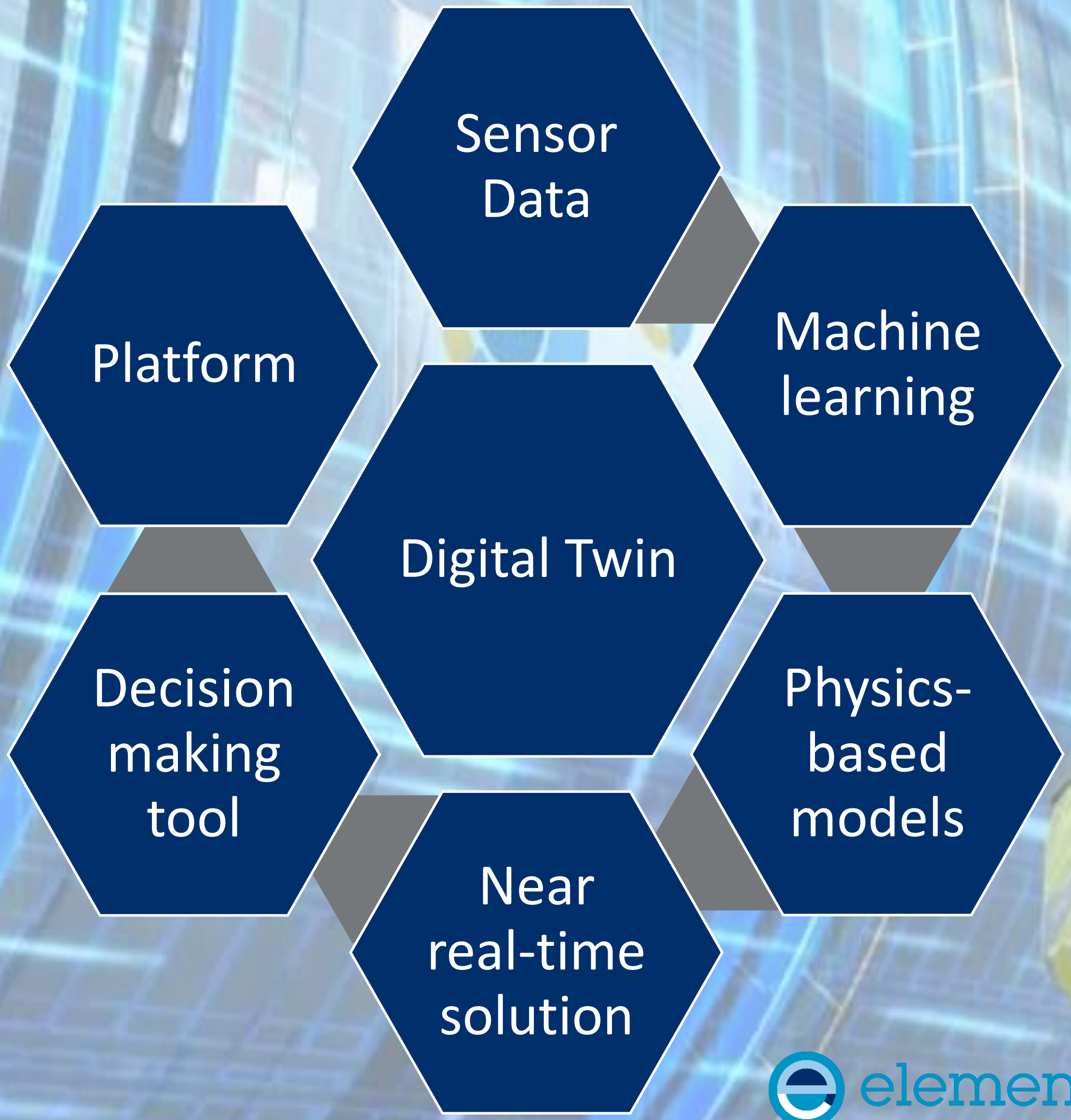
Digital Asset Management

- Digital twin technology for real time condition assessment
- Life extension / extended time between overhaul
- Maintenance based on actual use not conservative design assessment



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Safety: Explosion modelling and structural response

Challenge

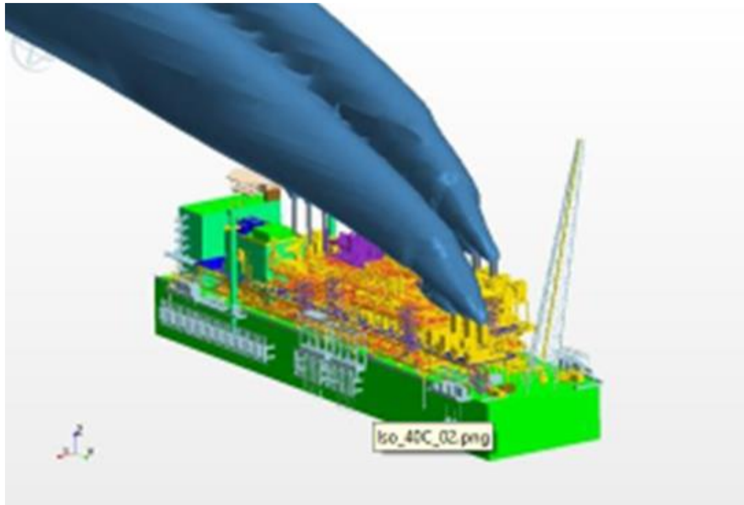
- Safety studies for FPSO
- Dispersion, helideck safety & blast response
- Simulation used to support FPSO design

Outcome

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

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



Sloshing of cryogenic hydrogen tanks

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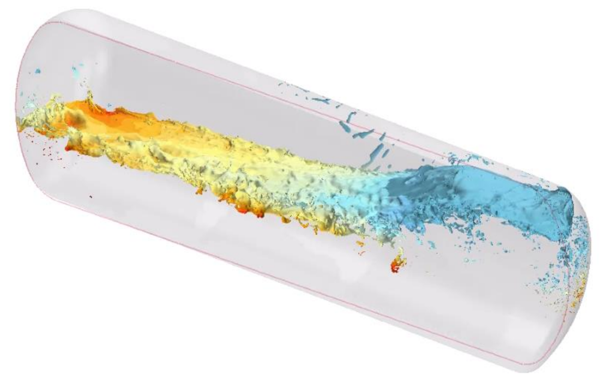
Digital Engineering



Challenge

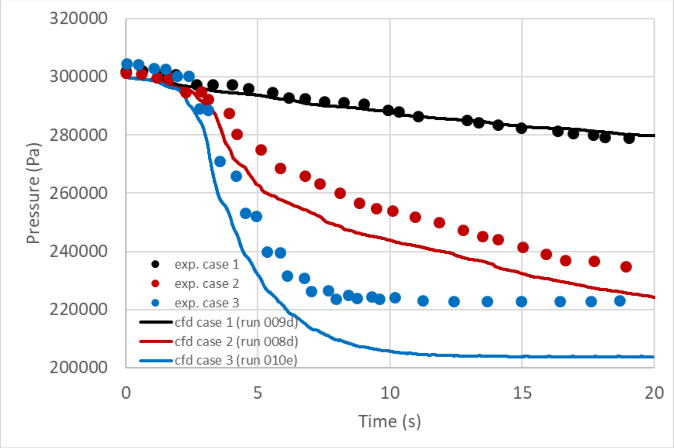
In applications where cryogenic hydrogen storage is considered, the risk of sloshing-induced hydrogen boil-off must be assessed to determine overpresurization rates

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



Cryogenic cooling using liquid Nitrogen

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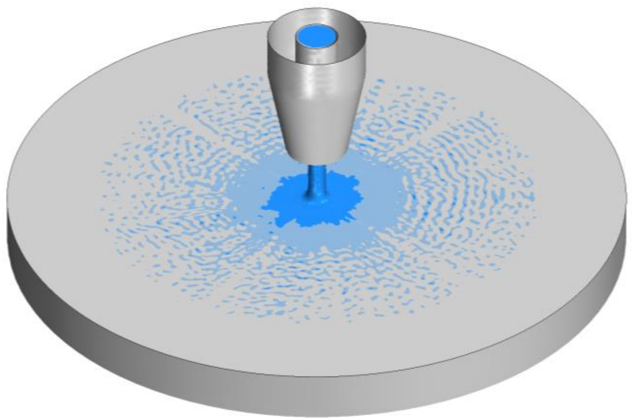


Challenge

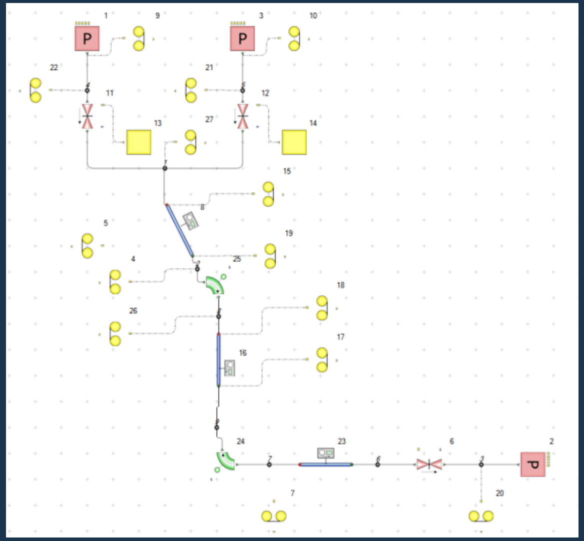
A client have approached Element asking for support in development of a tool that operated cryogenic N_2 to cool metal structures

Our Capabilities

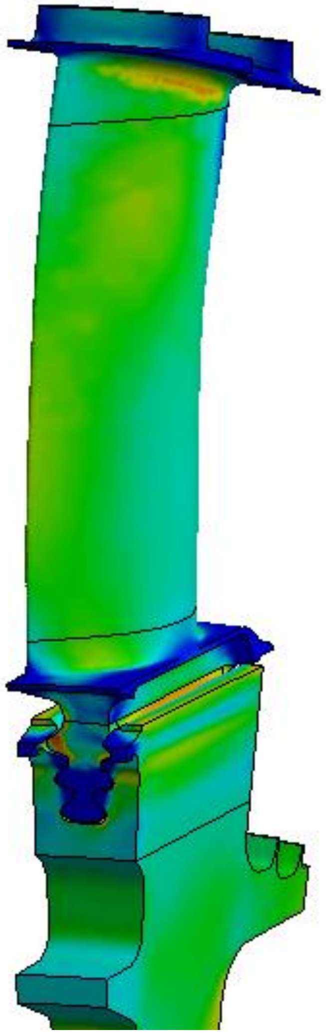
We have produced two analyses. A system-level analysis was conducted using FlowMaster to determine pressure-drop in the system and the level of heating of the Nitrogen. A CFD multi-phase analysis was then conducted to determine the efficiency of the deployed Nitrogen jet to cool metal structures

Outcome

As a result of our work, our client could make an informed decision with respect to the viability and cost-savings associated with the tool they were deploying



Turbine Component Lifing



Our Experience

- Development of novel materials test programs to support
  - Constitutive model development
  - Creep-fatigue lifing models
  - Corrosion / coating models

- Lifing model development
  - Classical N/Nf and t/tr approaches
  - Development of ductility exhaustion methods, e/ef
  - Combined Creep-Fatigue

- Implementation to Finite Element Analysis
  - Development of User Elements / UMATs for industry standard solvers
  - Development of bespoke FEA solutions

- Methods development to support life extension of UK Nuclear AGRs

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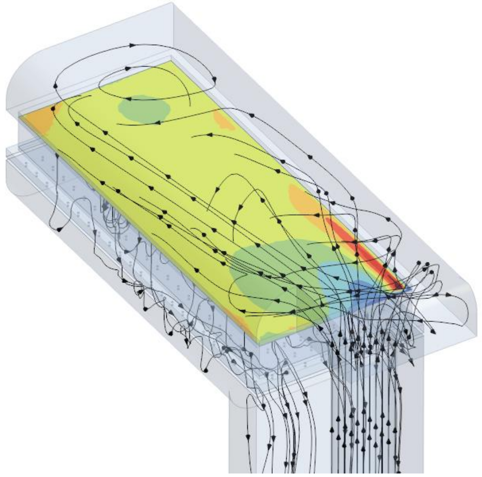
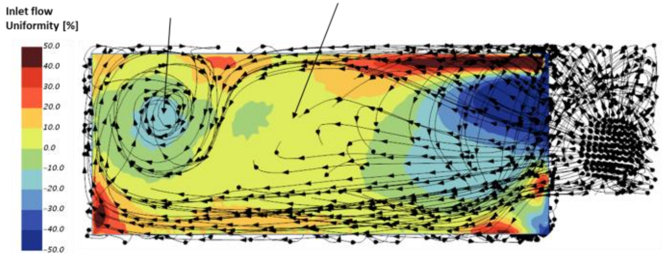
Hydrogen fuel cell performance optimisation

Digital Engineering



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.

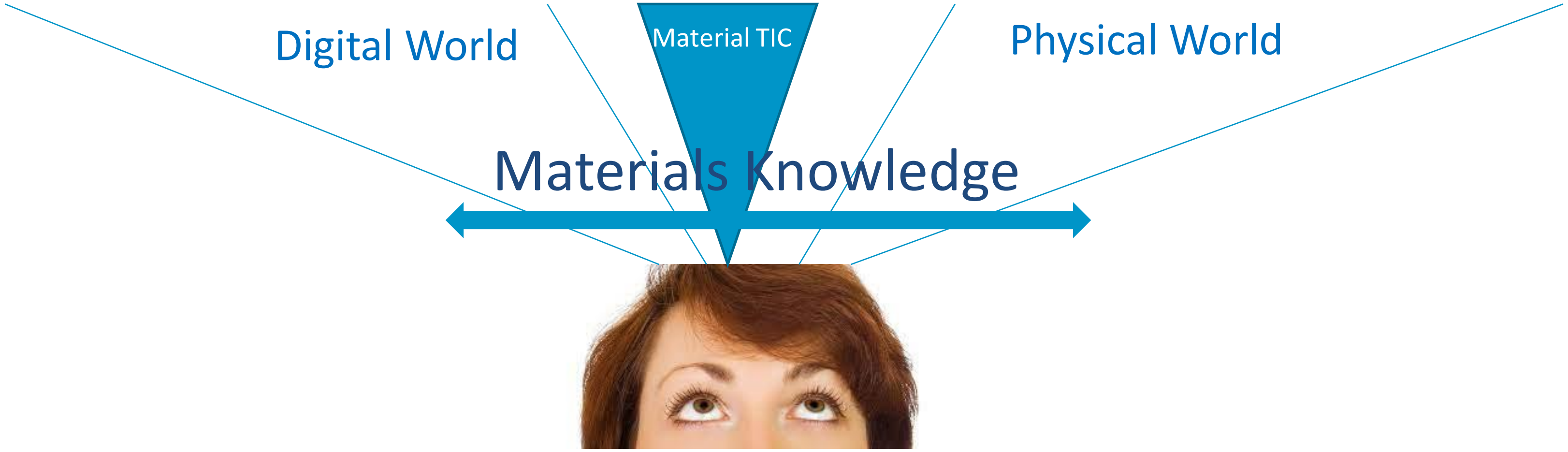
The team proposed a design modification consisting of porous strips used to improve flow uniformity within the fuel cell.

Outcome

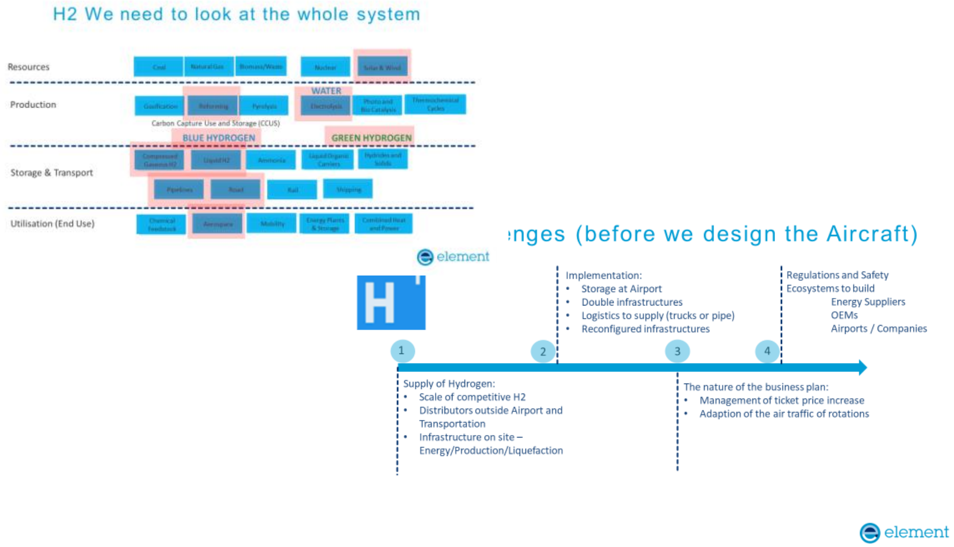
The client received a solution which helped reduce wear of fuel cell whilst in operation saving costs of maintenance over time.

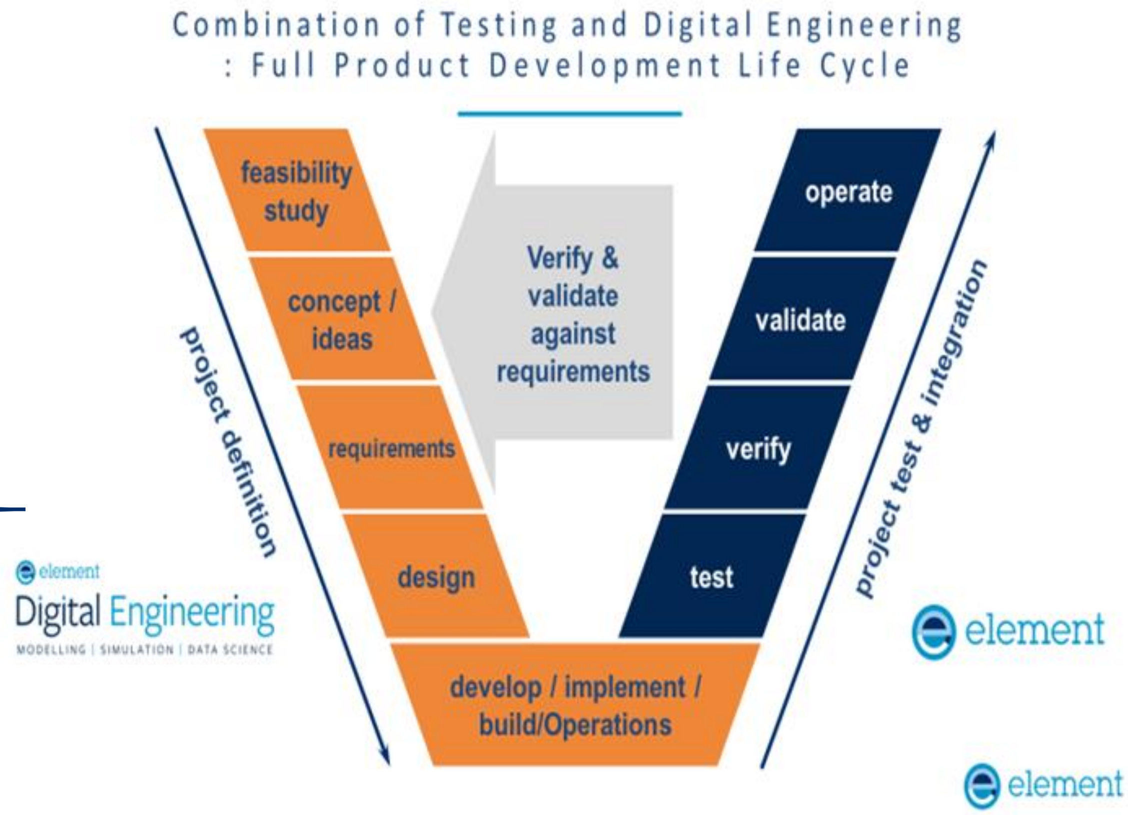
Element – Assuring Your Energy Transition

PRODUCTION | TRANSPORT AND STORAGE | UTILISATION



Where can we fit: Systems and Component Level





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Hydrogen Must Always be Considered as Complimentary in the Energy System based on Sound:

Economic – Supply/Demand/Cost
Thermodynamic and Metallurgy
Environmental
Alternatives
Specific Contexts
AND/OR – to Both?
Where is the system boundary
Resistance to HE
In a timely fashion….

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H 1
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CALM
&
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Thank you for listening…..

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