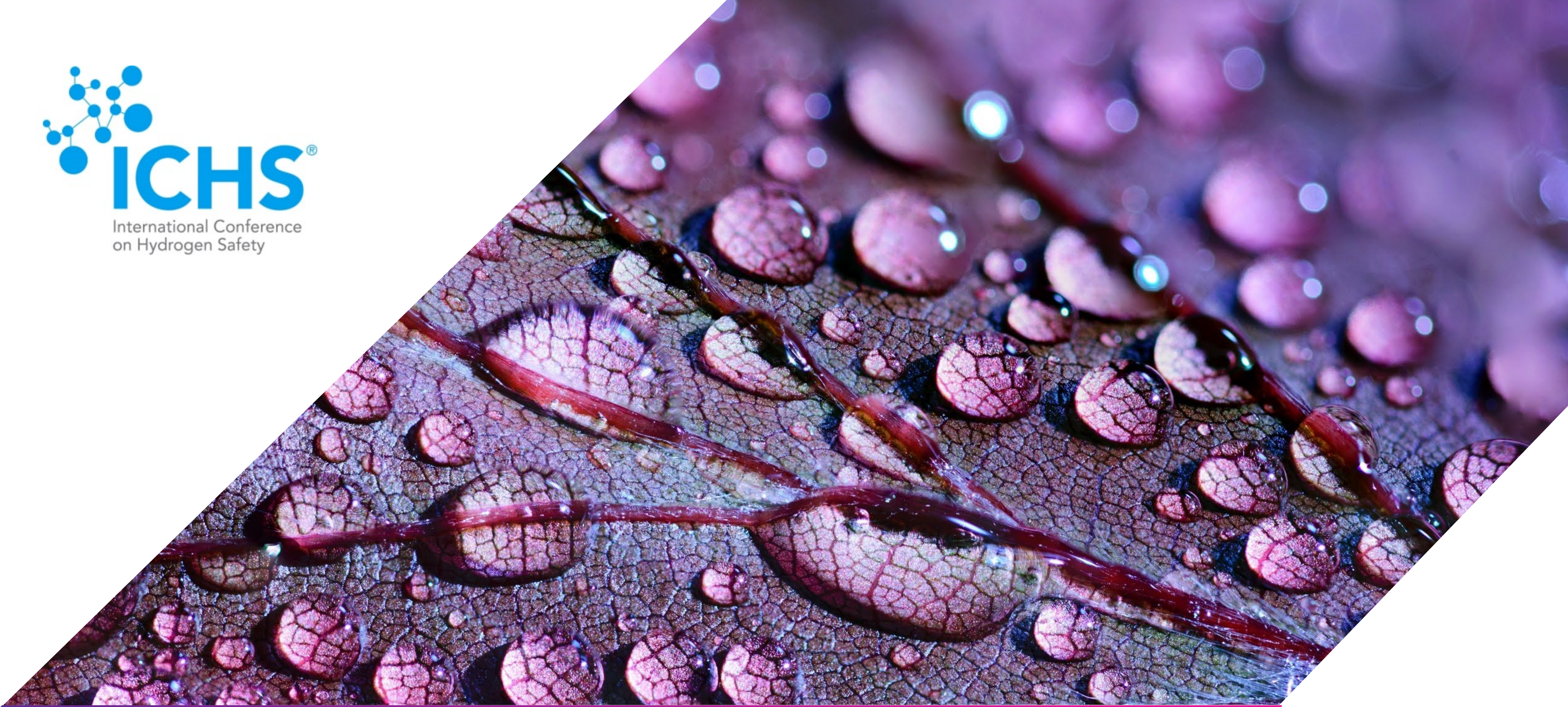


Safety Calculations for Emerging Technologies

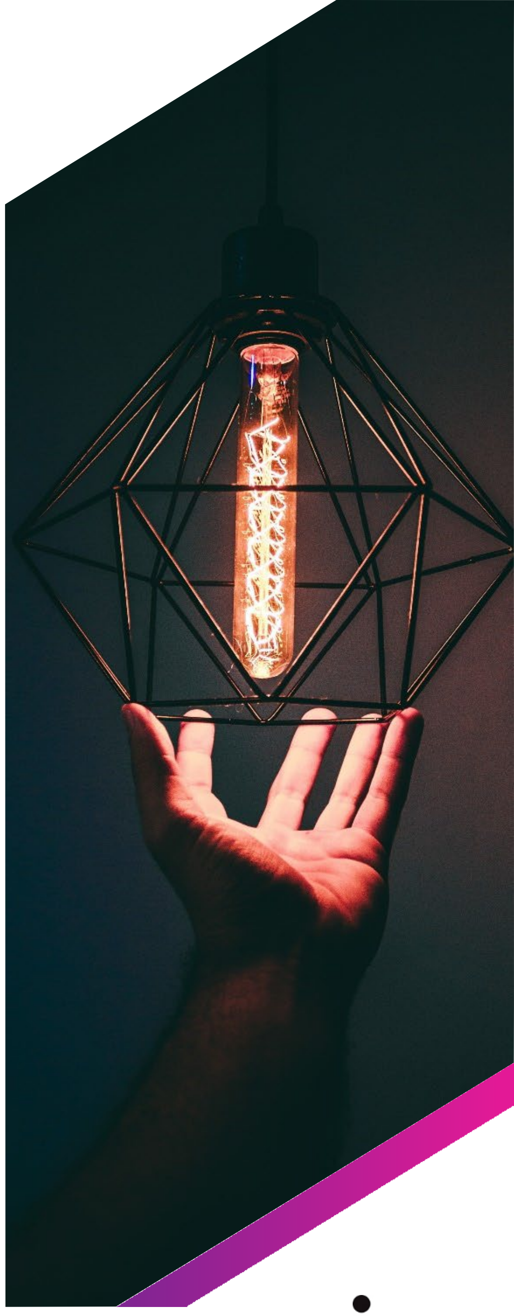
Jessica Guzzetta-King

INTERNATIONAL CONFERENCE ON HYDROGEN SAFETY 2023 – ID 272

20 September, 2023

agenda

- Who we are & what we do
- Introduction
- Leak frequency comparison
- Ignition probability comparison
- Conclusion & recommendations
- Q&A
- Thank you



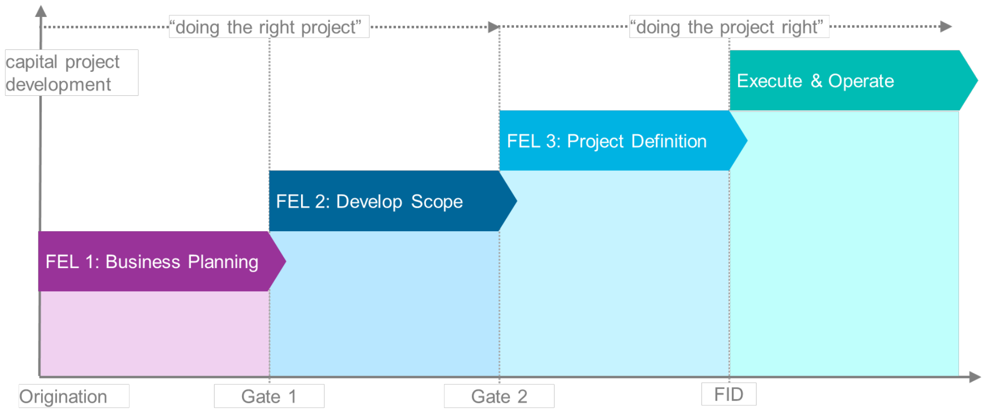
io consulting

We shape energy projects by influencing the key decisions at the earliest stages of the capital value process

Early-stage project architect, composed of engineers with a consulting mindset

JV Baker Hughes & McDermott

50 consultants & 90+ associates bring a systems thinking & phase appropriate approach, a technical, strategic & commercial frame, DQ decisions



CCUS

power to x

industrial decarbonisation

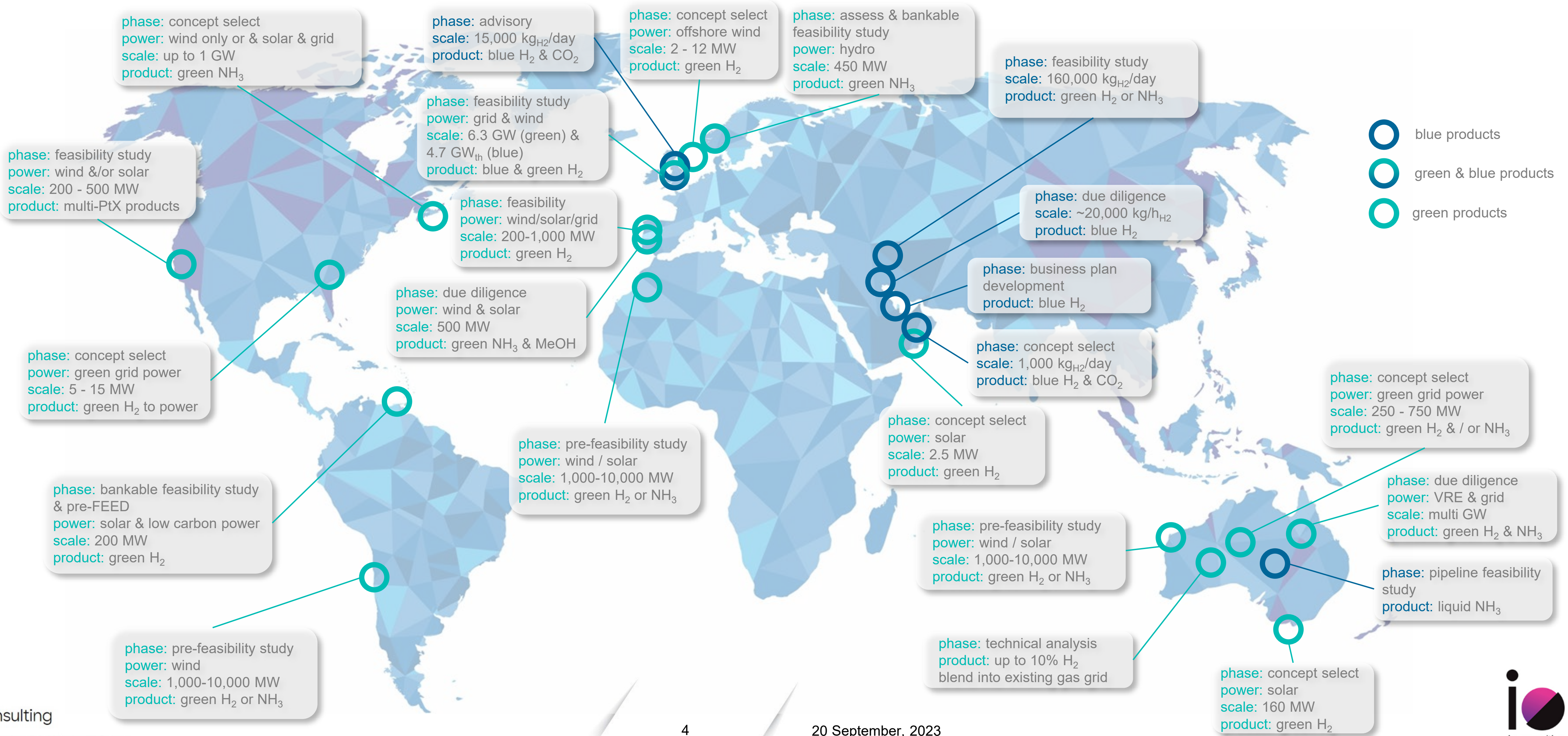
stored energy

clean energy

hydrocarbons

io consulting

Global hydrogen & PtX project experience



Introduction

Background to comparative assessment

⁄ Increase in global demand

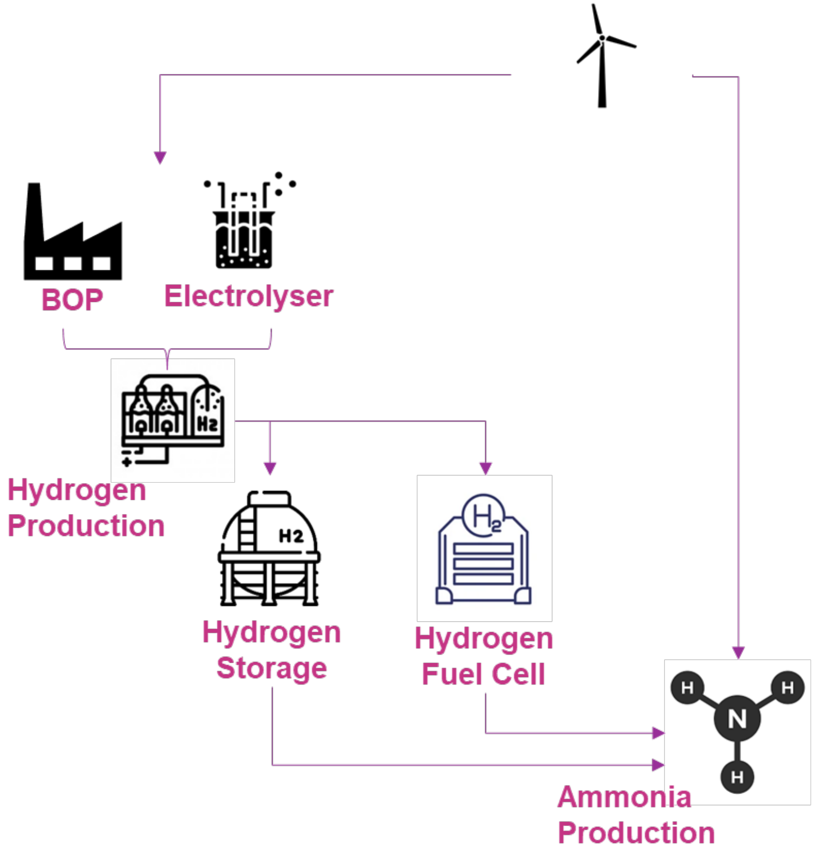
- ⁄ 28% growth in global hydrogen demand over the last decade
- ⁄ Low-carbon hydrogen demand will grow to 211Mt by 2050 (WoodMac)

⁄ Increased FEL 1, 2 & 3 projects

- ⁄ Significant increase in pre-FID hydrogen/power to X projects
- ⁄ io has seen a 40% increase in the studies through 2023ytd compared to 2022

⁄ Safety studies are critical

- ⁄ Quantitative risk assessments (QRA, FERA) are important tools to aid decisions through all project phases.
- ⁄ Industry approved data for leak frequencies and ignition probabilities are a key variable.



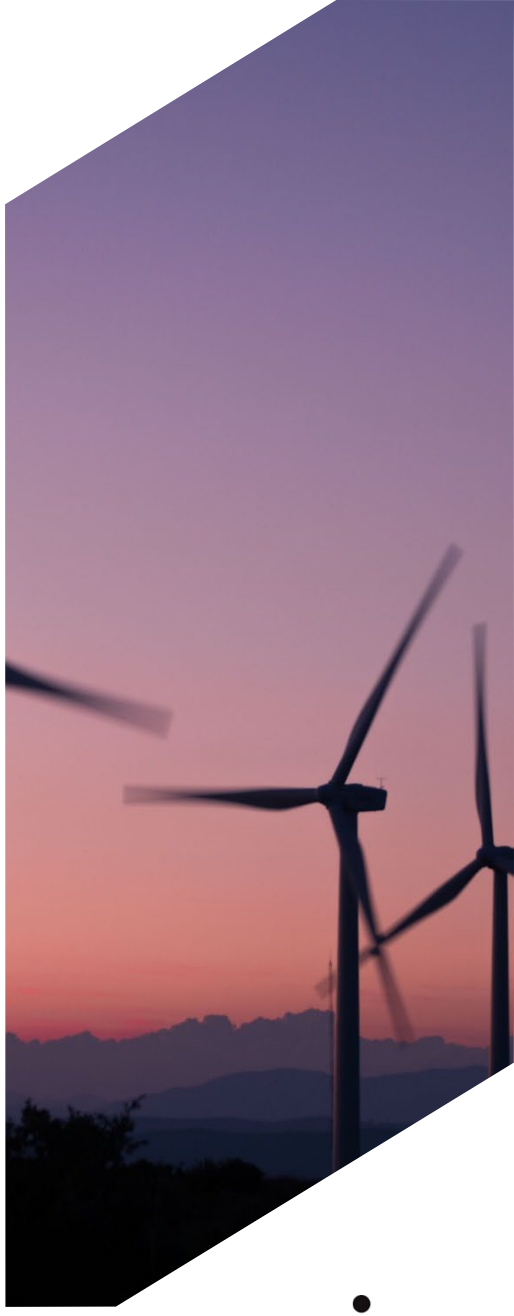
There is a growing need for consistent and reliable data to be made available to aid design decisions for Hydrogen projects.

Introduction

Scope & purpose

- Sandia National Laboratories HyRAM release frequencies and ignition probabilities are recommended for H2 projects
- Uncertainty around this data as some special fluids are likely to affect the leak frequency
- No other frequency models are validated for hydrogen leaks.
- A comparison was made between the leak frequencies for equipment in hydrogen service and the established oil and gas release frequencies from IOGP Process Release Frequencies (based on UK HSE Hydrocarbon Release Database).
- In addition, a comparison between the HyRAM recommended ignition probabilities and the correlations used for oil and gas based on the Energy Institute UKOOA correlations was conducted.

This comparison was performed to support FERA and QRA studies carried out for an onshore large-scale Green Hydrogen Project during the pre-FEED phase.



Leak Frequencies Comparison

HyRAM vs IOGP

Leak Frequencies HyRAM

- Established model for hydrogen leaks based on the work at Sandia National Laboratories.
- Annual frequency of a hydrogen release is calculated for release sizes of 0.01%, 0.1%, 1%, 10%, or 100% relative to the pipe flow area.
- The default values are generic hydrogen-system leak frequencies developed on statistical analysis where data from different sources was collected and combined using a Bayesian statistical method [6].
- Frequency calculations based on the geometric mean (median) as a more consistent metric of central tendency for the distribution.

Leak Frequencies IOGP

- Typically use IOGP database which is based on UK HSE's Hydrocarbon Release Database (HCRD).
- HCRD based on the number of incidents recorded p/yr from offshore facilities in the UK (1992 -2015).
- Data given as a function of both hole size and equipment dimension in the form of different classes.
- Representative hole (or release) sizes range from 1mm to > 150mm.
- Hole sizes are used to represent different damage scenarios

Leak Frequencies Comparison

HyRAM vs IOGP

Leak Frequencies HyRAM [3]

Table 2-2 Parameters for frequency of random leaks for individual components

Component	Release Size	μ	σ	Mean	5th	Median	95th
Compressors	0.01%	−1.73	0.22	1.8×10^{-1}	1.2×10^{-1}	1.8×10^{-1}	2.6×10^{-1}
	0.10%	−3.95	0.50	2.2×10^{-2}	8.5×10^{-3}	1.9×10^{-2}	4.4×10^{-2}
	1%	−5.16	0.80	7.9×10^{-3}	1.5×10^{-3}	5.8×10^{-3}	2.2×10^{-2}
	10%	−8.84	0.84	2.1×10^{-4}	3.6×10^{-5}	1.4×10^{-4}	5.7×10^{-4}
	100%	−11.34	1.37	3.0×10^{-5}	1.3×10^{-6}	1.2×10^{-5}	1.1×10^{-4}
Cylinders	0.01%	−13.92	0.67	1.1×10^{-6}	3.0×10^{-7}	9.0×10^{-7}	2.7×10^{-6}
	0.10%	−14.06	0.65	9.6×10^{-7}	2.7×10^{-7}	7.8×10^{-7}	2.3×10^{-6}
	1%	−14.44	0.65	6.6×10^{-7}	1.8×10^{-7}	5.4×10^{-7}	1.6×10^{-6}
	10%	−14.99	0.65	3.8×10^{-7}	1.1×10^{-7}	3.1×10^{-7}	9.0×10^{-7}
	100%	−15.62	0.68	2.1×10^{-7}	5.3×10^{-8}	1.6×10^{-7}	5.0×10^{-7}
Filters	0.01%	−5.25	1.99	3.8×10^{-2}	2.0×10^{-4}	5.3×10^{-3}	1.4×10^{-1}
	0.10%	−5.29	1.52	1.6×10^{-2}	4.2×10^{-4}	5.0×10^{-3}	6.1×10^{-2}
	1%	−5.34	1.48	1.4×10^{-2}	4.2×10^{-4}	4.8×10^{-3}	5.5×10^{-2}
	10%	−5.38	0.89	6.9×10^{-3}	1.1×10^{-3}	4.6×10^{-3}	2.0×10^{-2}
	100%	−5.43	0.95	6.9×10^{-3}	9.1×10^{-4}	4.4×10^{-3}	2.1×10^{-2}
Flanges	0.01%	−3.92	1.66	7.9×10^{-2}	1.3×10^{-3}	2.0×10^{-2}	3.0×10^{-1}
	0.10%	−6.12	1.25	4.8×10^{-3}	2.8×10^{-4}	2.2×10^{-3}	1.7×10^{-2}
	1%	−8.33	2.20	2.7×10^{-3}	6.4×10^{-6}	2.4×10^{-4}	9.0×10^{-3}
	10%	−10.54	0.83	3.7×10^{-5}	6.7×10^{-6}	2.6×10^{-5}	1.0×10^{-4}
	100%	−12.75	1.83	1.5×10^{-5}	1.4×10^{-7}	2.9×10^{-6}	5.9×10^{-5}
Hoses	0.01%	−6.83	0.28	1.1×10^{-3}	6.8×10^{-4}	1.1×10^{-3}	1.7×10^{-3}
	0.10%	−8.73	0.61	1.9×10^{-4}	5.9×10^{-5}	1.6×10^{-4}	4.4×10^{-4}
	1%	−8.85	0.59	1.7×10^{-4}	5.4×10^{-5}	1.4×10^{-4}	3.8×10^{-4}

Leak Frequencies IOGP

Equipment Type: (2) Flanged Joints

Definition:

The following frequencies refer to a flanged joint[3], comprising two flange faces, a gasket (where fitted), and two welds to the pipe[4]. Flange types include ring type joint, spiral wound, clamp (Grayloc) and hammer union (Chicksan).

Spectacle blinds and orifice plates would be the equivalent of 1.5 flanged joints

Flanges per year by diameter (based on 2006-2015 data)

General equation $F(d) = Cd^m + B, \quad 1\ mm < d \leq D$

$F(d) = 0, \quad d > D$

Where the parameters C, m and B are dependent on the equipment size (D) as given in by interpolation from the following table

	Equipment Diameter (mm)		
Parameter	0	174	508
C	5.37×10^{-6}	1.31×10^{-5}	3.10×10^{-5}
m	-0.775	-0.790	-1.071
B	-1.40×10^{-7}	4.00×10^{-7}	2.05×10^{-6}

Values greater than 508 mm use the same value as for 508 mm

Tabulation

HOLE DIA RANGE (mm)	2" DIA (50 mm)	6" DIA (150 mm)	12" DIA (300 mm)	18" DIA (450 mm)	24" DIA (600 mm)	36" DIA (900 mm)
1 to 3	4.4E-06	7.0E-06	1.3E-05	1.9E-05	2.1E-05	2.1E-05
3 to 10	2.0E-06	3.1E-06	5.0E-06	6.5E-06	6.9E-06	6.9E-06
10 to 50	9.1E-07	1.4E-06	1.9E-06	2.1E-06	2.2E-06	2.2E-06
50 to 150	3.8E-07	3.2E-07	3.7E-07	3.4E-07	3.3E-07	3.3E-07
>150	---	5.7E-07	1.3E-06	2.0E-06	2.2E-06	2.2E-06
TOTAL	7.7E-06	1.2E-05	2.1E-05	3.0E-05	3.3E-05	3.3E-05

Leak Frequencies Comparison

HyRAM vs IOGP comparing data

- Both data sets to be in the same format.
- Assessment hole sizes were extrapolated against percentage leak size (HyRAM) to find representative leak size percentage.
- HyRAM release frequencies were extrapolated using leak size percentages calculated for the assessment hole sizes

Approximate Hole Sizes Based on Piping Sizes (mm) for HyRAM frequencies

Leak size	0.75	1	2	8	20
0.01%	0.002	0.003	0.005	0.02	0.05
0.1%	0.02	0.03	0.05	0.20	0.51
1%	0.2	0.3	0.5	2.0	5.1
10%	1.9	2.5	5.1	20.3	50.8
100%	19	25	51	203	508

Cumulative leak sizes % for assessment hole sizes (mm)

	0.75	1	2	8	20
5	26.2%	19.7%	9.8%	2.5%	1.0%
25	100.0%	100.0%	49.2%	12.3%	4.9%
100	-	-	100.0%	49.2%	19.7%
FB	-	-	-	100.0%	100.0%

HyRAM release frequencies (p/yr) per Assessment hole size (mm)

Component	Hole Size (mm)	Equipment / Piping Diameter (in)				
		0.75	1	2	8	20
Compressors	5	2.10E-01	2.10E-01	2.10E-01	2.10E-01	2.10E-01
	25	3.00E-05	3.00E-05	1.32E-04	2.05E-04	2.20E-04
	100	0.00E+00	0.00E+00	3.00E-05	1.32E-04	1.91E-04
	FB	0.00E+00	0.00E+00	0.00E+00	3.00E-05	3.00E-05
	Total	2.10E-01	2.10E-01	2.10E-01	2.10E-01	2.10E-01
Cylinders (Pressure Vessel)	5	3.10E-06	3.10E-06	2.79E-06	2.42E-06	2.35E-06
	25	2.10E-07	2.10E-07	3.06E-07	3.76E-07	3.90E-07
	100	0.00E+00	0.00E+00	2.10E-07	3.06E-07	3.62E-07
	FB	0.00E+00	0.00E+00	0.00E+00	2.10E-07	2.10E-07
	Total	3.31E-06	3.31E-06	3.31E-06	3.31E-06	3.31E-06
Filters	5	7.49E-02	7.49E-02	6.80E-02	6.11E-02	6.11E-02
	25	6.90E-03	6.90E-03	6.90E-03	6.90E-03	6.90E-03
	100	0.00E+00	0.00E+00	6.90E-03	6.90E-03	6.90E-03
	FB	0.00E+00	0.00E+00	0.00E+00	6.90E-03	6.90E-03
	Total	8.18E-02	8.18E-02	8.18E-02	8.18E-02	8.18E-02
Flanges	5	8.65E-02	8.65E-02	8.65E-02	8.65E-02	8.65E-02
	25	1.50E-05	1.50E-05	2.74E-05	3.64E-05	3.82E-05
	100	0.00E+00	0.00E+00	1.50E-05	2.74E-05	3.46E-05

Leak Frequencies Comparison

HyRAM vs IOGP comparing data

Leak Frequency comparison results

- Comparison of Leak frequency totals per component for HyRAM and IOGP release data for the equivalent equipment size / diameter

HyRAM vs IOGP Total Release Frequencies (p/year) per Components and Equipment Diameters

Component	Equipment Diameter	0.75	1	2	8	20
Compressors	IOGP	0.00E+00	0.00E+00	5.82E-03	5.83E-03	5.83E-03
Compressors	HyRAM	0.00E+00	2.10E-01	2.10E-01	2.10E-01	2.10E-01
Cylinders (Pressure Vessel)	IOGP	0.00E+00	0.00E+00	6.42E-04	6.42E-04	6.42E-04
Cylinders (Pressure Vessel)	HyRAM	3.31E-06	3.31E-06	3.31E-06	3.31E-06	3.31E-06
Filters	IOGP	0.00E+00	0.00E+00	1.83E-03	1.83E-03	1.83E-03
Filters	HyRAM	8.18E-02	8.18E-02	8.18E-02	8.18E-02	8.18E-02
Flanges	IOGP	0.00E+00	0.00E+00	7.69E-06	2.16E-05	3.26E-05
Flanges	HyRAM	8.66E-02	8.66E-02	8.66E-02	8.66E-02	8.66E-02
Hoses	IOGP	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hoses	HyRAM	1.68E-03	1.68E-03	1.68E-03	1.68E-03	1.68E-03
Joints	IOGP	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Joints	HyRAM	9.36E-05	9.36E-05	9.36E-05	9.36E-05	9.36E-05
Pipes	IOGP	0.00E+00	0.00E+00	2.52E-05	1.59E-05	1.88E-05
Pipes	HyRAM	1.64E-05	1.64E-05	1.64E-05	1.64E-05	1.64E-05
Valves	IOGP	0.00E+00	0.00E+00	2.59E-04	1.85E-04	2.30E-04
Valves	HyRAM	6.58E-03	6.58E-03	6.58E-03	6.58E-03	6.58E-03
Instruments	IOGP	0.00E+00	1.97E-04	1.97E-04	0.00E+00	0.00E+00
Instruments	HyRAM	1.53E-03	1.53E-03	1.53E-03	1.53E-03	1.53E-03

1. No IOGP data for anything less than <2".
2. IOGP data for 1" is only for instruments.
3. HyRAM data - based on release size as a % of the total equipment size.
4. IOGP Valves Frequency in comparative table = Manual + Automatic valve frequencies.
5. No IOGP data for hoses and joints (included as other equipment).
6. Pressure Vessels included within cylinders component category

Comparison conclusions

- HyRAM release frequency data > IOGP.
- HyRAM release frequencies are considered to provide a more conservative approach.
- Release frequencies were combined with system parts counts to obtain the initiating frequency.
- Total release frequency for the facility based on the HyRAM dataset was 200% > IOGP equivalent.
- Higher initiating frequency could increase the fire and explosion event frequency and drive the requirement for additional safety considerations.

Ignition Probabilities Comparison

HyRAM H2 Ignition probabilities and derivation calculations

- HyRAM ignition probabilities based on historical ignition probability data for methane from Cox, Lees, & Ang ignition probabilities modified for H2.
- H2 ignition probabilities based on release rate values.
- Approach to modify the ignition probabilities for H2:
  - Reduce leak flow ranges by factor of 8, allows for differential molecular weights of CH4 vs H2, which directly affects the size of flammable cloud.
  - Increase ignition probabilities by 16%, allow for the ratio of the flammable range of H2 vs CH4.
  - Immediate to delayed ignition probabilities assumed to have ratio of 2:1.
  - Total ignition probability = immediate and+ delayed probabilities.

Hydrocarbon Ignition Probabilities (Cox, Lees, Ang)

Leak Size	Pign Gas
<= 1 kg/s	0.01
1 - 50 kg/s	0.07
> 50 kg/s	0.3

Estimated ignition probabilities in HyRAM

H2 Release Rate (kg/s)	Immediate Ignition Probability	Delayed Ignition Probability	Total Ign Prob
< 0.125	0.008	0.004	0.012
0.125 - 6.26	0.053	0.027	0.08
> 6.25	0.23	0.12	0.35

Ignition Probabilities Comparison

IOGP / UKOOA ignition probability data

Cox, Lees & Ang “Classification of Hazardous Locations” (1990)

- Data dates back to 90’s
- While widely used, Cox, Lees and Ang state that it was speculative only.

UKOOA, EI, UK HSE Review of Existing Ignition Probabilities and Data Models (2002)

- Very generic mass release rate-based correlations were overly simplistic, may lead to unrealistic/ very conservative estimates of risk
- Didn’t reflect up to date historical ignition probability data and knowledge, or
- Consideration of types of plant, substances, process conditions, ignition source characteristics, dispersion of flammable vapours in ventilated areas, overland ignition modelling.

UKOOA Ignition Probability Correlation models

- Provides means of estimation of overall ignition probability and approximate time/location distribution for a specific release scenario.
- 17 generic types of correlations cover plant, onsite and offsite land use types, including hazardous area classification areas and the use of Ex rated equipment.

Ignition Probabilities Comparison

Modifying UKOOA/IOGP data for H2

- Analysis was for an onshore ignition scenario based on the IOGP Ignition Probabilities definition for large gas plant:
  - UKOOA 'Large Plant Gas LPG' Scenario 8 – Releases of flammable gases, vapour or liquids significantly above their normal boiling point from large onshore outdoor plants (plant area above 1200 m2, site area above 35,000 m2).
- Correlation was selected due to the nature and applicability to the Green H2 Project facilities (large onshore facility).
- UKOOA ignition probabilities were modified for H2 based on HyRAM methodology.
- Immediate to delayed ignition probability taken as 2:1.

Immediate and delayed ignition probabilities UKOOA Scenario 8 – modified for H2

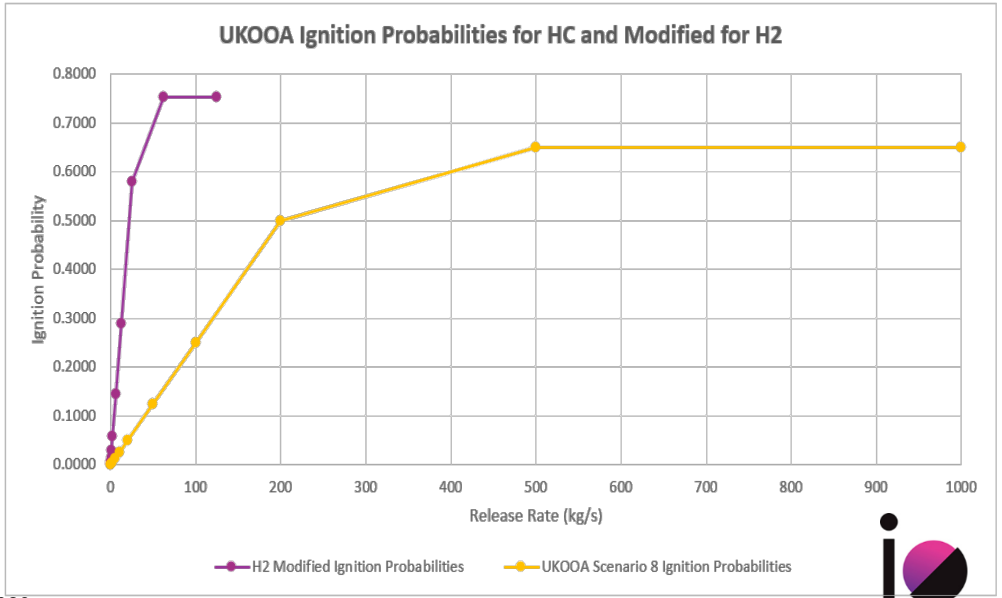
H_2 Release Rate (kg/s)	Probability Immediate Ignition	Probability Delayed Ignition
< 0.125	0.0019	0.0010
0.125 - 6.25	0.097	0.048
> 6.25	0.40	0.20

Ignition Probabilities UKOOA Scenario 8

HC Release Rate (kg/s)	Ignition Probability
0.1	0.0011
0.2	0.0014
0.5	0.002
1	0.0025
2	0.005
5	0.0125
10	0.025
20	0.05
50	0.125
100	0.25
200	0.5
500	0.65
1000	0.65

Ignition Probabilities UKOOA Scenario 8 – modified for H2

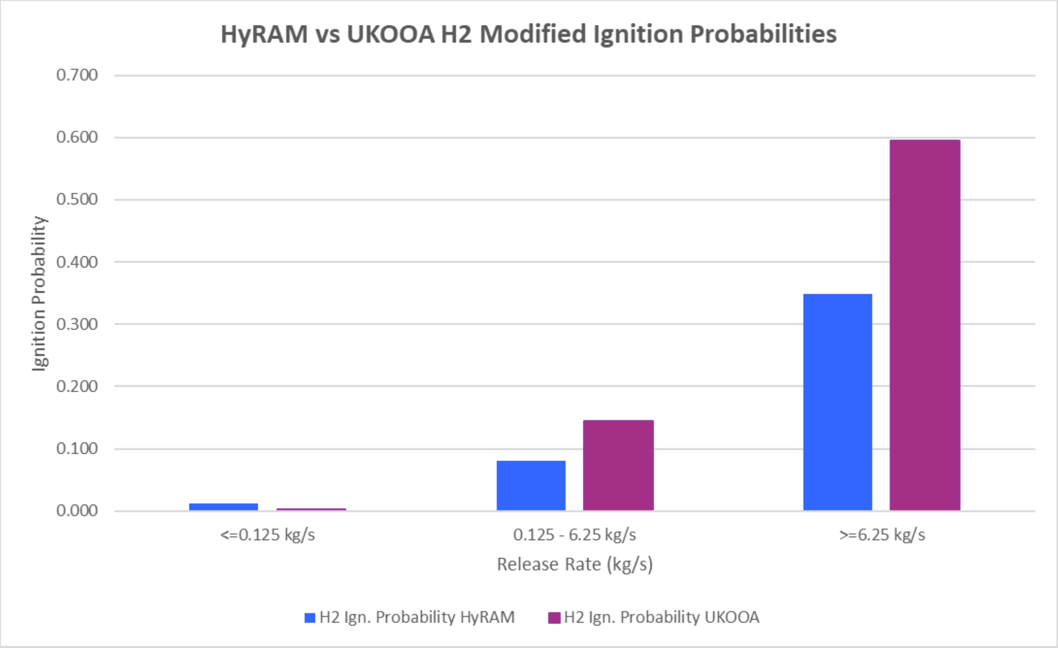
H2 Release Rate (kg/s) (HC / 8)	H2 Ignition Probability (HCign + 16%)
0.0125	0.0013
0.025	0.0016
0.063	0.0023
0.125	0.0029
0.25	0.0058
0.63	0.015
1.25	0.029
2.5	0.058
6.25	0.145
12.5	0.29
25	0.58
62.5	0.75
125	0.75



Ignition Probabilities Comparison

HyRAM vs IOGP / UKOOA ignition probability data (modified for H2)

Results comparison



UKOOA Ignition probabilities correlations

- Comparing both models, with the same modification for H2 applied to the release rate and ignition probabilities given for gas in the UKOOA ignition probability model, shows a significant difference
- H2 modified UKOOA ignition probabilities are higher than those for HyRAM modelling for any releases larger than 0.125kg/s.
- This has potential to affect risk modelling outcomes.

Conclusions

Key outcomes from comparative assessment

Release frequency

- HyRAM release frequency data are higher than that suggested by the IOGP for similar equipment items and components
- HyRAM release frequencies are considered to provide a more conservative approach.
- When release frequencies were combined with the system parts counts to obtain the initiating frequency, the total release frequency for the facility based on the HyRAM dataset was 200% higher than the IOGP equivalent.
- This higher initiating frequency could increase the fire and explosion event frequency, driving the requirement for additional safety considerations

Ignition probabilities

- Comparing both models, with the same modification for hydrogen applied to the release rate and ignition probabilities given for gas in the UKOOA ignition probability model, shows a significant difference
- H2 modified UKOOA ignition probabilities are higher than those for HyRAM modelling for any releases larger than 0.125kg/s
- This has potential to affect risk modelling outcomes.

Recommendations

Robust data for future design

Standardise

- Given the growth in global H2 demand & the increase in H2 related projects, it is important that H2 data for assessments become standardized
- Standardization will facilitate more reliable and consistent design decisions; bringing greater certainty to bankability assessments & enabling more projects to achieve FID.

Comparison & sensitivities

- For early-stage H2 projects, it is worth using the most conservative data to support QRA & FERA.
- However, comparative assessments on available datasets should be encouraged
- Sensitivities should be applied to the comparative results to ensure the conclusions drawn for such assessment remain robust and continue to support the goal to reducing risks to As Low As Reasonably Practicable (ALARP).

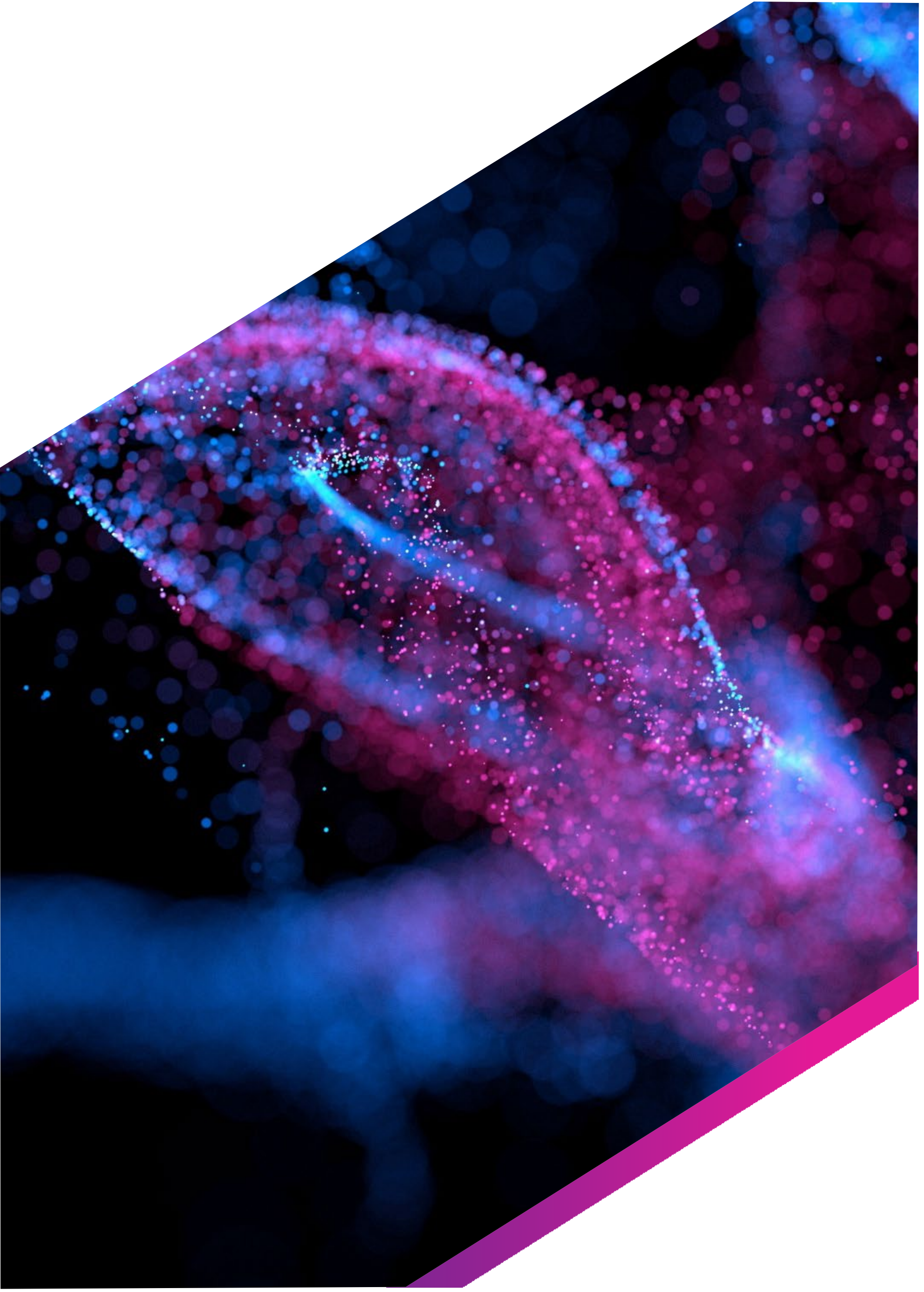
Q&A

ioconsulting.com

Thank you

Jessica Guzzetta-King
Principal Consultant, Safety & Risk
+44 (0) 20 3878 4235
jessica.guzzetta-king@ioconsulting.com

Follow us on LinkedIn



References

1. https://www.woodmac.com/our-expertise1/focus/transition/2050---the-hydrogen-possibility/#:~:text=By%202050%2C%20low%2Dcarbon%20hydrogen,2050%2C%20from%20practically%20zero%20today.
2. https://www.woodmac.com/market-insights/topics/hydrogen-guide/
3. Risan, A., Pappas, J., Dalheim, J., “Guidelines for Quantitative Risk Analysis of Facilities Handling Hazardous Substances”, November 2021, Vysus Group, Report No. PRJ11100262033/R1.
4. Ehrhart, B. D., Hecht, E. S., Growth, K. M. (University of Maryland), “Hydrogen Risk Assessment Models (HyRAM) Version 3.0 Technical Reference Manual”, September 2020, Sandia National Laboratories, Report No. SAND2020-10600.
5. IOGP, Risk Assessment Data Directory, “Process Release Frequencies”, 2019, Report No. 434-01.
6. Energy Institute, “IP Research Report – Ignition Probability Review, Model Development and Look-Up Correlations”, EI, January 2006
7. LaChance, J., Houf, W., Middleton, B., and Fluer, L., “Analyses to support development of risk-informed separation distances for hydrogen codes and standards,” Sandia National Laboratories, Albuquerque, NM, SAND2009-0874, March 2009.
8. Cox, A. W., Less, F. P., Ang, M. L., “Classification of Hazardous Locations”, IChem e, 1990.
9. Ehrhart, B. D., Brooks, D., Hecht, E. S., “Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) for LNG Facilities”, Project: PHMSA Support for Safety, Regulation, Production, Distribution and Use of Liquified Natural Gas, Contract No. 693JK320N0000030001, Sandia National Laboratories, March 2022.
10. https://www.hse.gov.uk/offshore/strategy/ignition.htm
11. “Plant Specific Ignition Probability Model and Correlations for Use in Onshore and Offshore QRA", Symposium Series No. 151.
12. IOGP, Risk Assessment Data Directory, “Ignition Probabilities”, 2019, Report No. 434-06.

Nomenclature

CH4	Methane
EI	Energy Institute
FB	Full Bore
FEED	Front End Engineering Design
FERA	Fire and Explosion Risk Assessment
H2	Hydrogen
HC	Hydrocarbon
HSE	Health and Safety Executive
HyRAM	Hydrogen Risk Assessment Models
in	inch
IOGP	International Association of Oil and Gas Producers
LPG	Liquified Petroleum Gas
m2	Square Metre
mm	millimetre
OEUK	Offshore Energies UK
Ping	Probability of Ignition
PtX	Power to X
QRA	Quantitative Risk Assessment
UK	United Kingdom
UKOOA	United Kingdom Offshore Operators Association