Hydrogen: challenges and opportunities

A/Prof Fatemeh Salehi
School of Engineering
Macquarie University, Australia

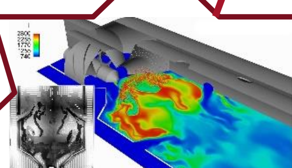
Overview

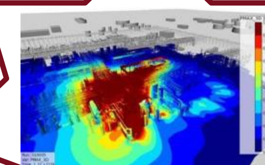
System model

Clean energy and energy efficiency

Safety and reliability

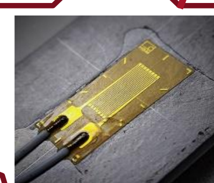
Low-carbon and efficient technologies





Failure analysis and likelihood assessment

Consequence modelling



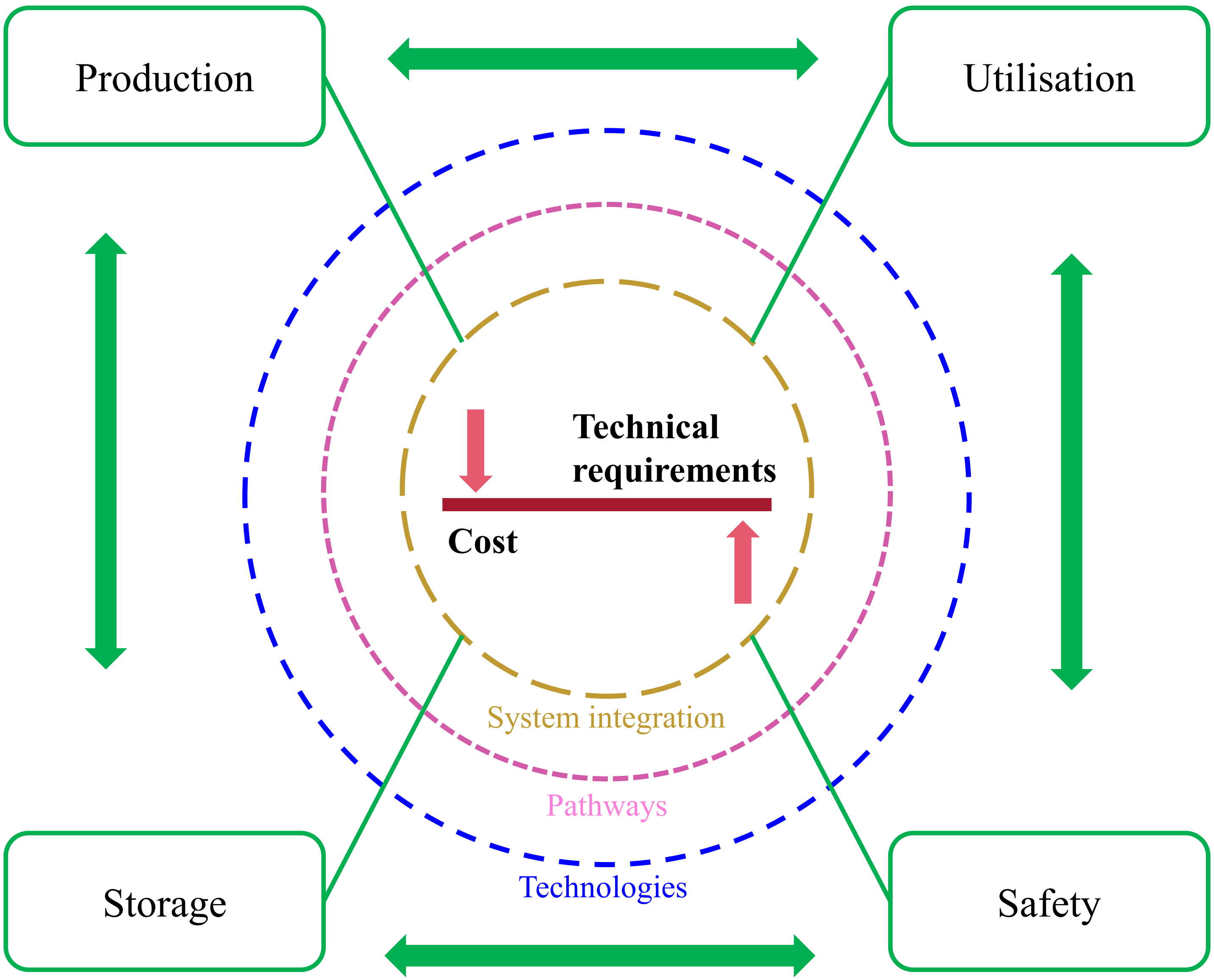
Hydrogen: challenges and opportunities

Hydrogen

"Affordable clean hydrogen for a net-zero carbon future and a sustainable, resilient, and equitable economy."

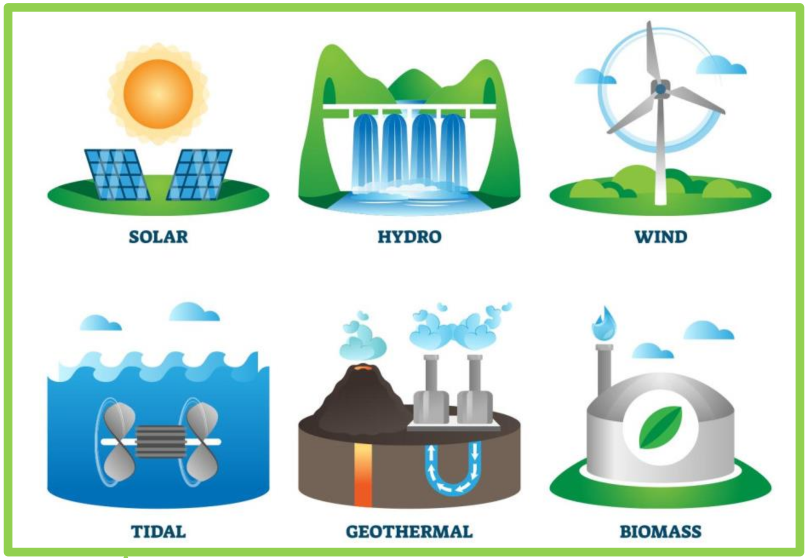
- ✓ *Hydrogen and hydrogen vectors to decarbonise energy, transport, and heavy industry sectors*

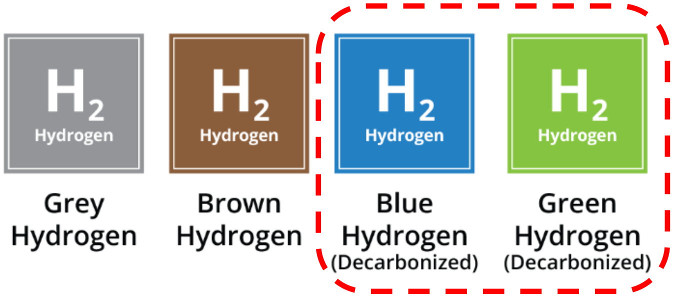
Hydrogen

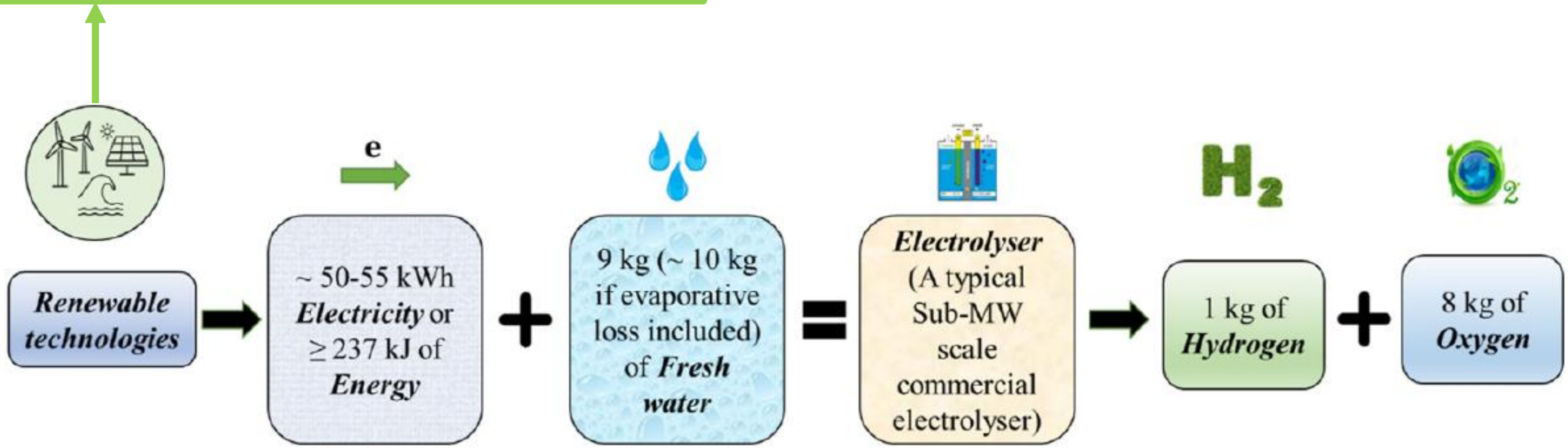


Int J Hydrogen Energy 45, 2020, 3847-3869

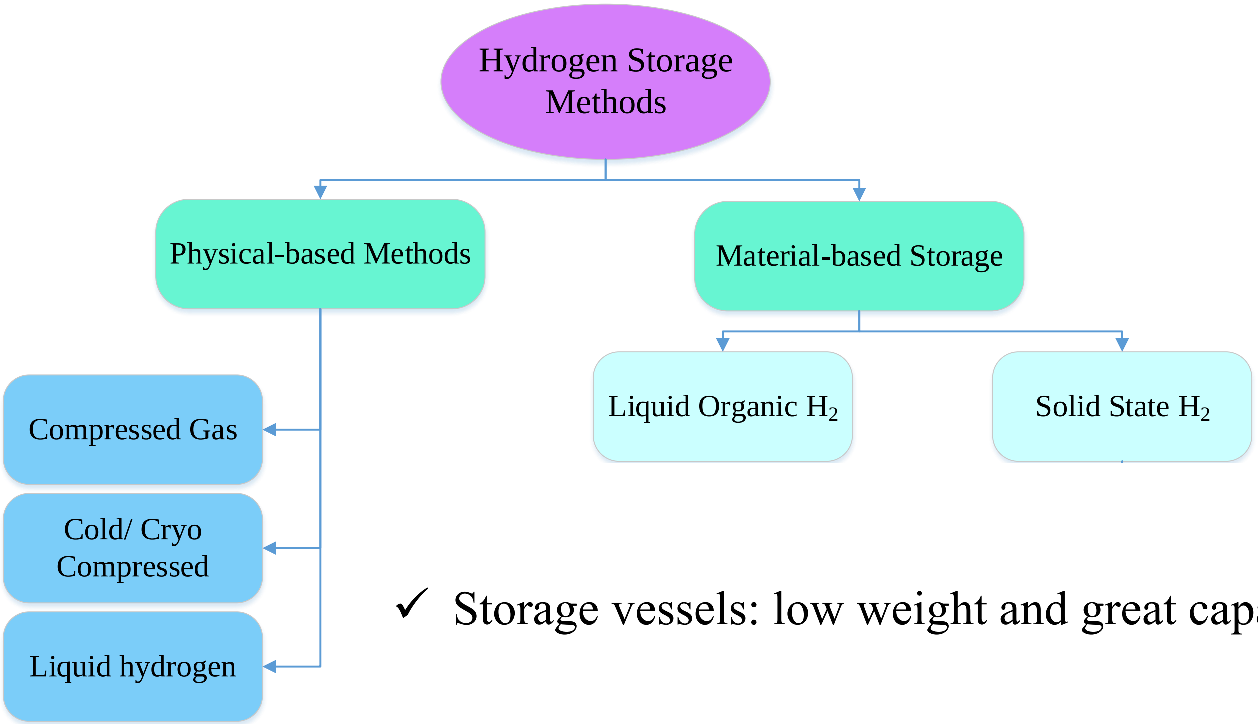
Hydrogen production







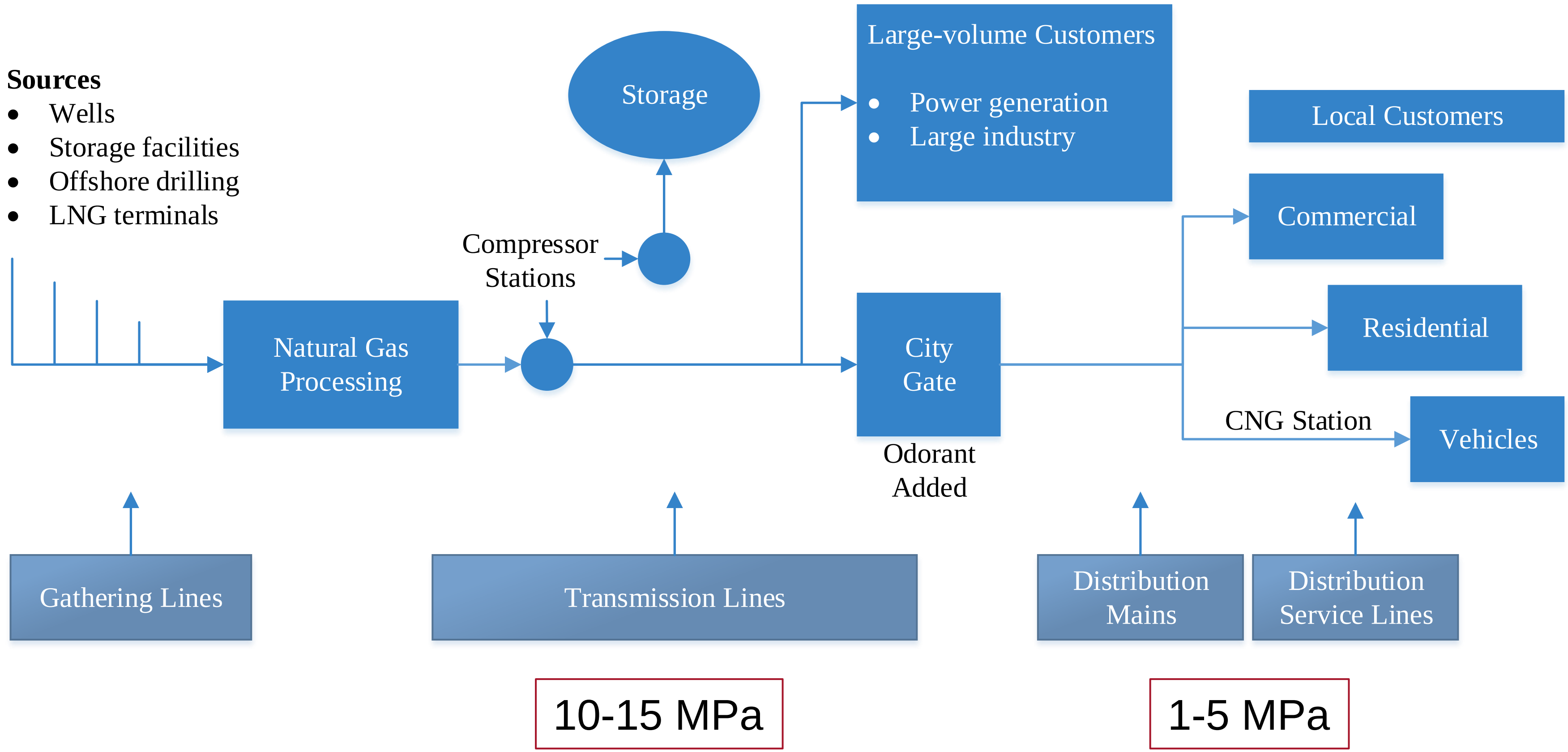
Hydrogen storage



✓ Storage vessels: low weight and great capacity

- **GH_2:** 0.03 kg per litre, 10% energy loss, brittle under low temperatures, from full metal to full composite pressure vessel: 200-1000 bars
- **LH_2:** 0.07 kg per litre, - 253°C, 40% energy loss, brittle under low temperatures, 4–10 kWh to produce 1 kg of liquid hydrogen, average to large-scale storing and supply
- **Cryo-compressed H_2:** a supercritical cryogenic gas, -233 °C, no liquefaction without evaporative losses, early stage of development

Hydrogen transmission

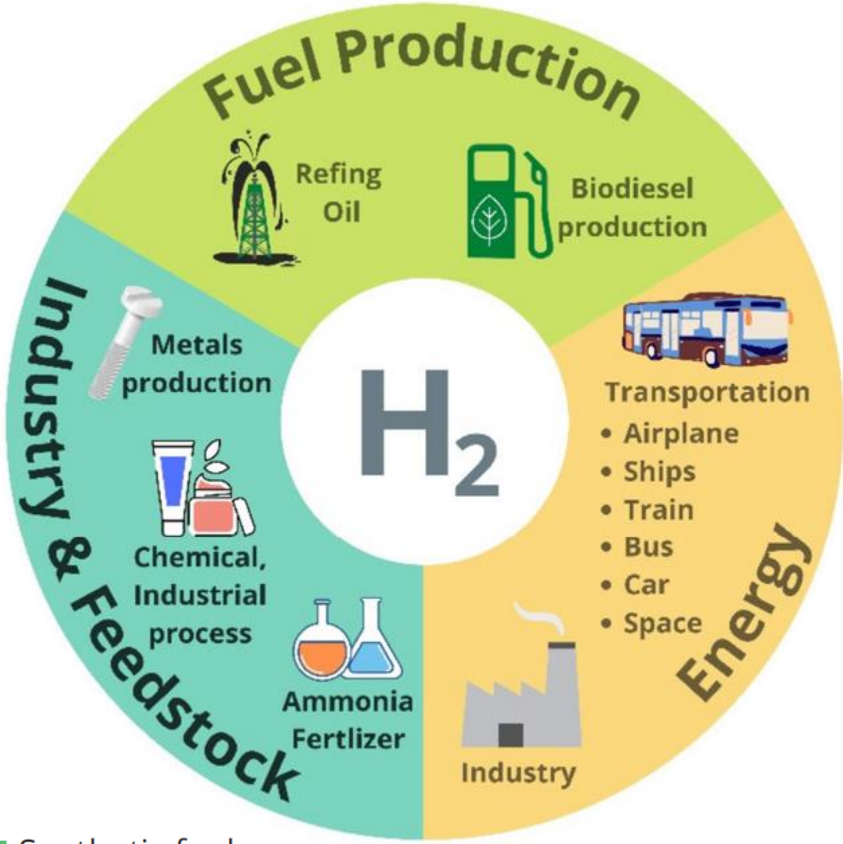


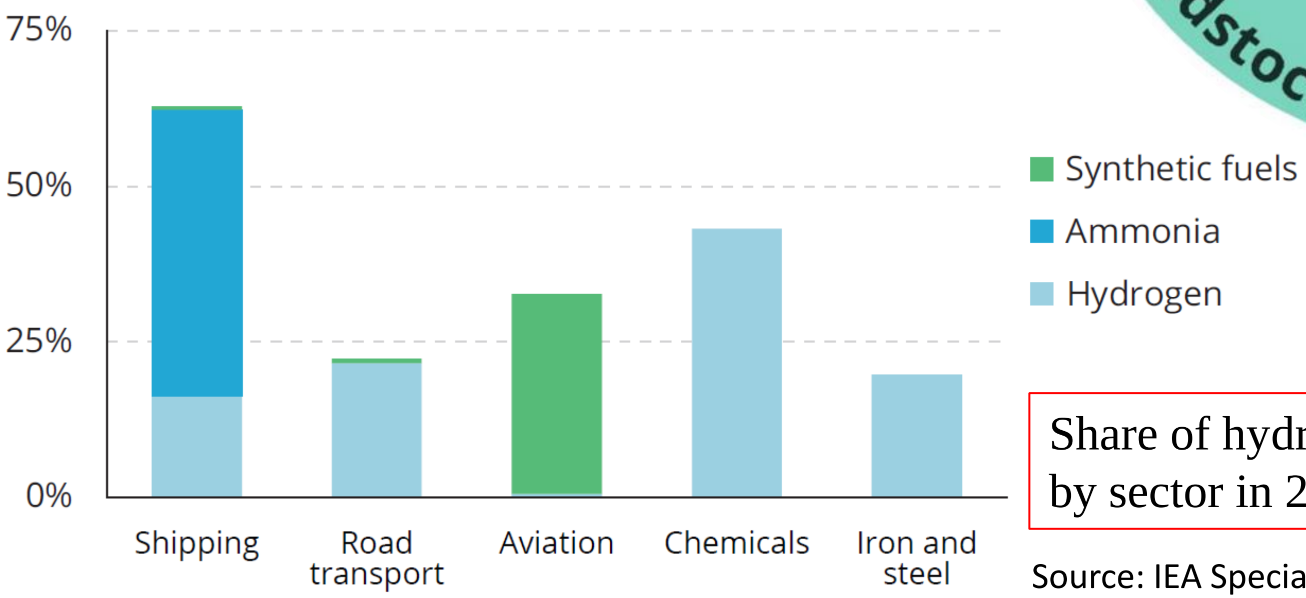
- 5%–15% hydrogen by volume
- No significantly increasing risks (overall public safety)
- Durability and integrity of the existing natural gas pipeline network.

Hydrogen utilisation

- Oil refining
- Chemical and fertiliser production
- Ammonia and steel

✓ powering vehicles
✓ generating heat
✓ trading clean energy between countries





Share of hydrogen fuels by sector in 2050

Source: IEA Special Report

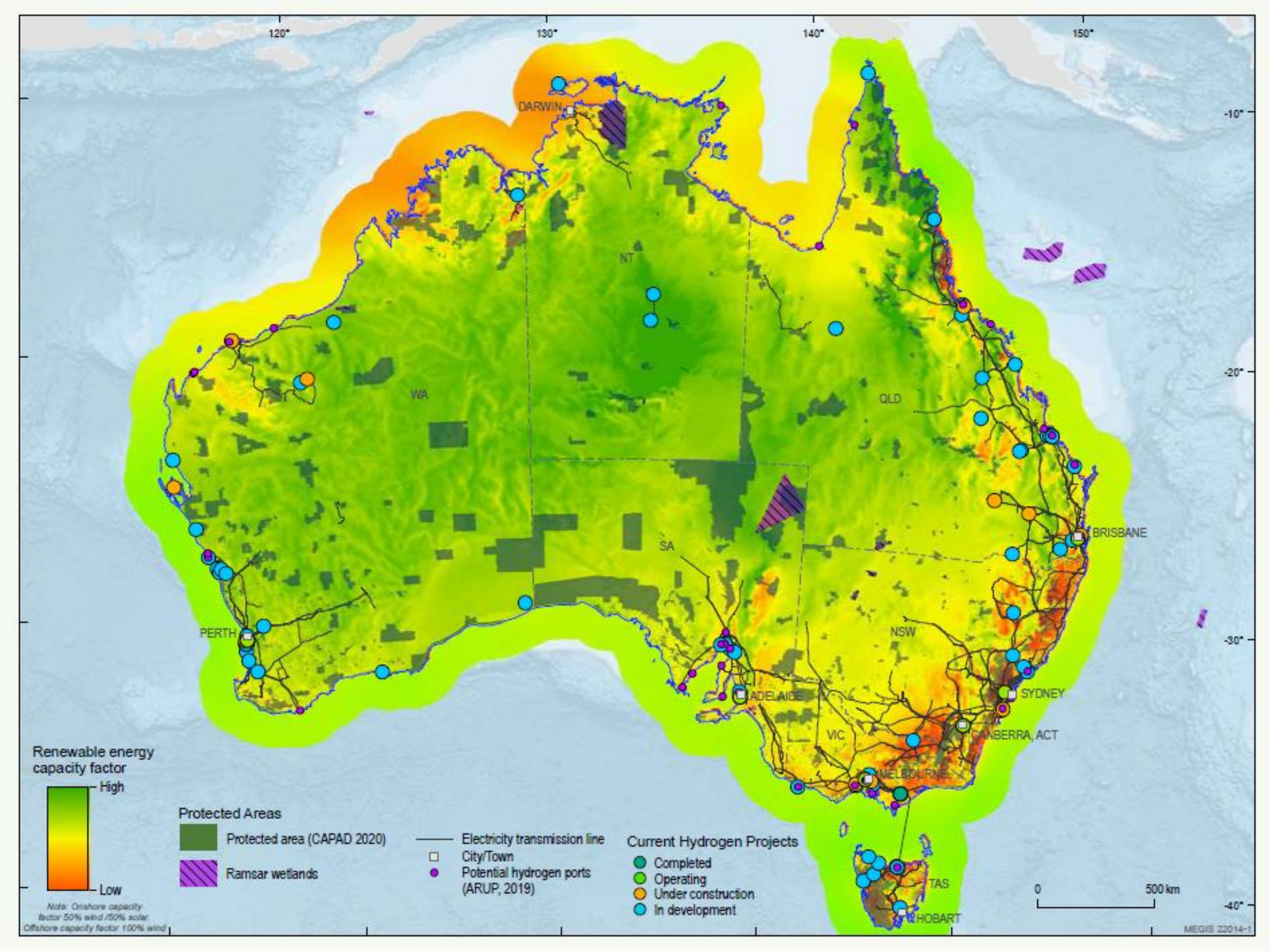
Hydrogen utilisation

	Industry (General)	Steel	Refinery	Chemical	Other Industry	Light Vehicles	Heavey Vehicles	Aviation	Other Transport	Power	Building
Australia	■	■	□	■	■	□	■			■	□
Canada	■	■	■	■	■	■	■	□	■	■	■
China	□	□	□			■	■	□	□	□	
France	■	■	■	■	■	□	■	■	■	□	□
Germany	■	■	■	■	□	□	■	■	■	□	□
India	■	■	■	■	□		■		■	□	
Japan	□	□	□	□	□	■	■	□	■	■	■
Republic of Korea	□	□				■	■		□	■	■
Singapore	■		■	■			■		■	■	
UK	■	■	■	■	■	□	■	■	■	■	■
US	■	■	■	■	■	□	■	■	■	■	■

■ Priority stated in official strategy/roadmap. or demonstrated industry deployment (in the absence of national strategies)

□ Less emphasis in official strategy/roadmap. or likely opportunity but not specified in a official strategy/roadmap

Hydrogen progress

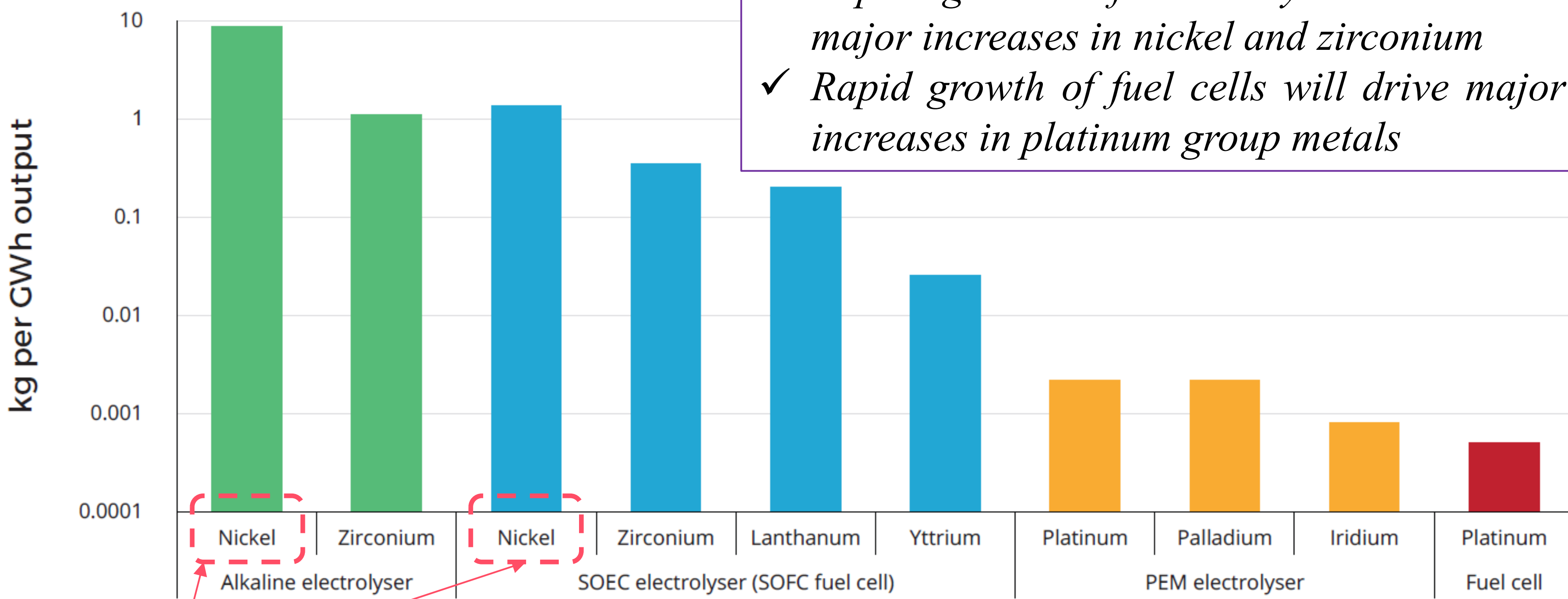


Hydrogen progress

	2021 Assessment		2022 Assessment	
Industry Development Signal	2025 Pace	2030 Pace	2025 Pace	2030 Pace
Investment	Advancing Quickly	Advancing	Advancing	Advancing
Project Scale	Advancing Quickly	Advancing Quickly	Advancing	Advancing
Cost-competitiveness	Advancing Quickly	Advancing Quickly	Advancing	Advancing
Australia's exports	Advancing	Advancing	Advancing	Advancing
Chemical feedstock	Advancing Quickly	Advancing Quickly	Advancing Quickly	Advancing
Electricity grid support	Advancing slowly	Advancing slowly	Advancing	Advancing slowly
Mining and off-grid	Advancing	Advancing slowly	Advancing	Advancing slowly
Heavy transport	Advancing slowly	Advancing slowly	Advancing slowly	Advancing slowly
Light transport	Advancing slowly	Advancing slowly	Advancing slowly	Advancing slowly
Gas networks	Advancing	Advancing	Advancing	Advancing slowly
Electricity generation	Advancing Quickly	Advancing	Advancing Quickly	Advancing Quickly
Steel and iron making	Advancing slowly	Advancing slowly	Advancing slowly	Advancing slowly
Industrial heat	Advancing	Advancing	Advancing slowly	Advancing slowly

Hydrogen – indirect impact

- ✓ *Rapid growth of electrolyser will drive major increases in nickel and zirconium*
- ✓ *Rapid growth of fuel cells will drive major increases in platinum group metals*



4th largest producer

Estimated levelised demand for selected minerals in electrolysers and fuel cells

- Normalisation by output accounts for varying efficiencies of different electrolysis technologies.
- Full load hours of electrolysers assumed to be 5,000 hours per year.

Hydrogen - challenges

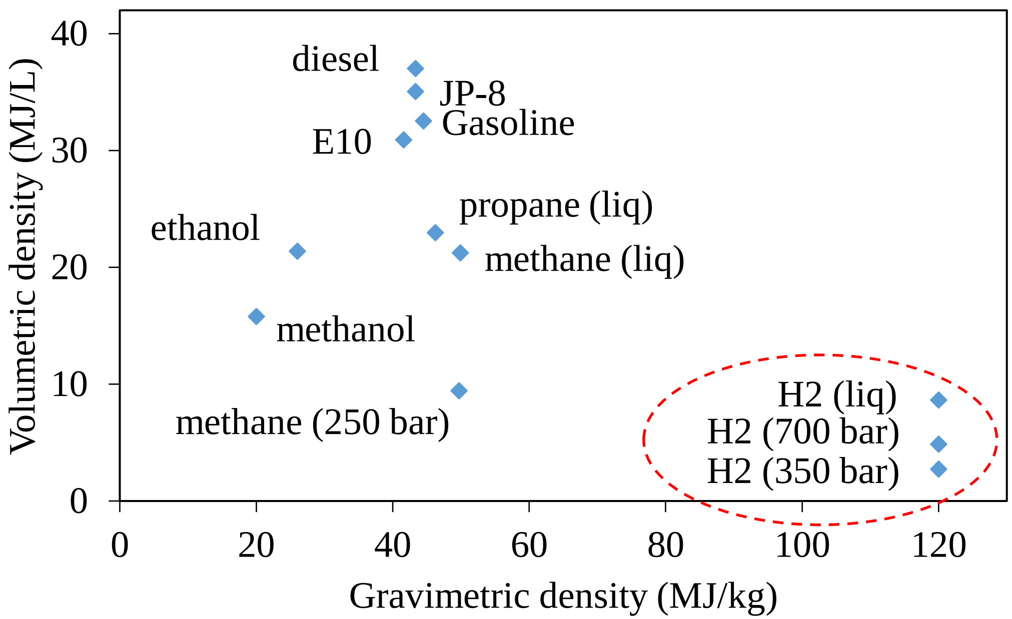
Challenges

- Cost
- Water
- Low volumetric energy density
- Storage technologies
- Infrastructure and facilities
- Policy, regulations, standards
- Social licence
- Safety and reliability

Drive 100 km using petrol ($1.43/L) ~ $13.31/kg H_2
Drive 100 km using diesel ($1.5/L) ~ $11.21/kg H_2
Deliver 1 GJ heat using natural gas ($10/GJ) ~ $1.2/kg H_2

Electrolysis 9 L
Coal gasification 9 L
Steam methane reforming 4.5 L

HFCV requires
5 kg of H_2 for a full tank
5 kg = 61 m^3 at STP
0.127 m^3 at 700 bar 25° C



Hydrogen safety

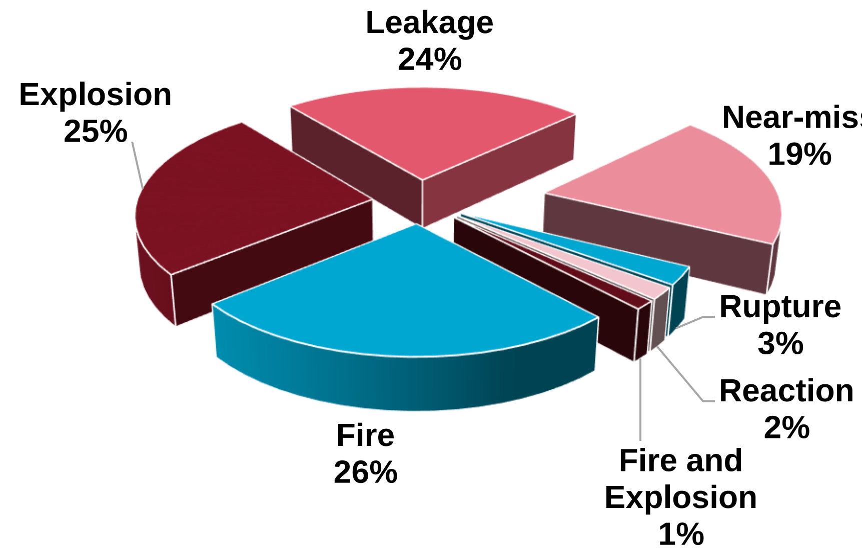
Hydrogen is not new, why is hydrogen safety important?

Hydrogen safety

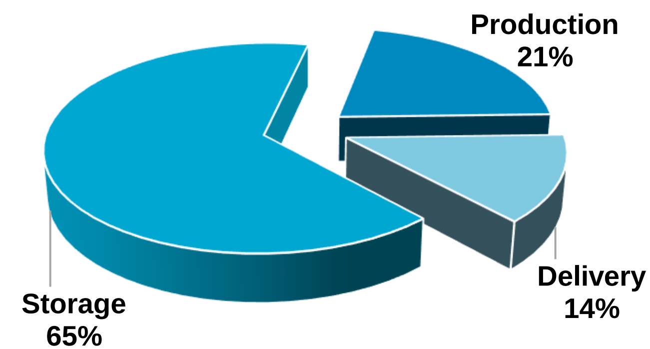
Hydrogen is not new, why is hydrogen safety important?

- Hydrogen is new as a fuel and energy carrier
- Hydrogen in scale
- Bringing hydrogen to public

Hydrogen safety



- A major release of high-pressure hydrogen occurred in Santa Clara during a gaseous hydrogen fill of a modular multi-cylinder trailer.
- 250 kg of hydrogen was released.



✓ Initial leak
✓ Miscommunication
✓ Hydrogen explosion and jet fires
✓ Subsequent fires

Learn from history
Be proactive about risks!

Risk assessment

Risk

Assessment of the presence and impact of unwanted situation at time t

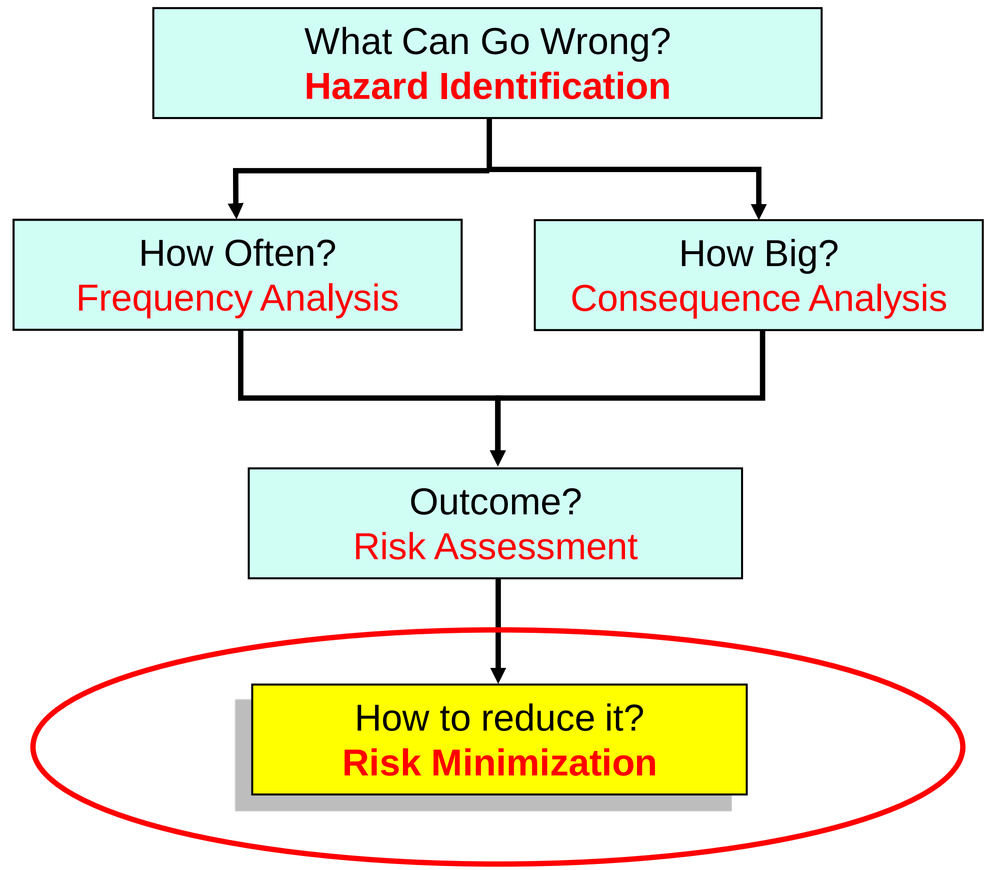
Risk (t) = occurrence of unwanted situations & its impact

$$Risk(t) = F(t).Loss\ (t)$$

Safety

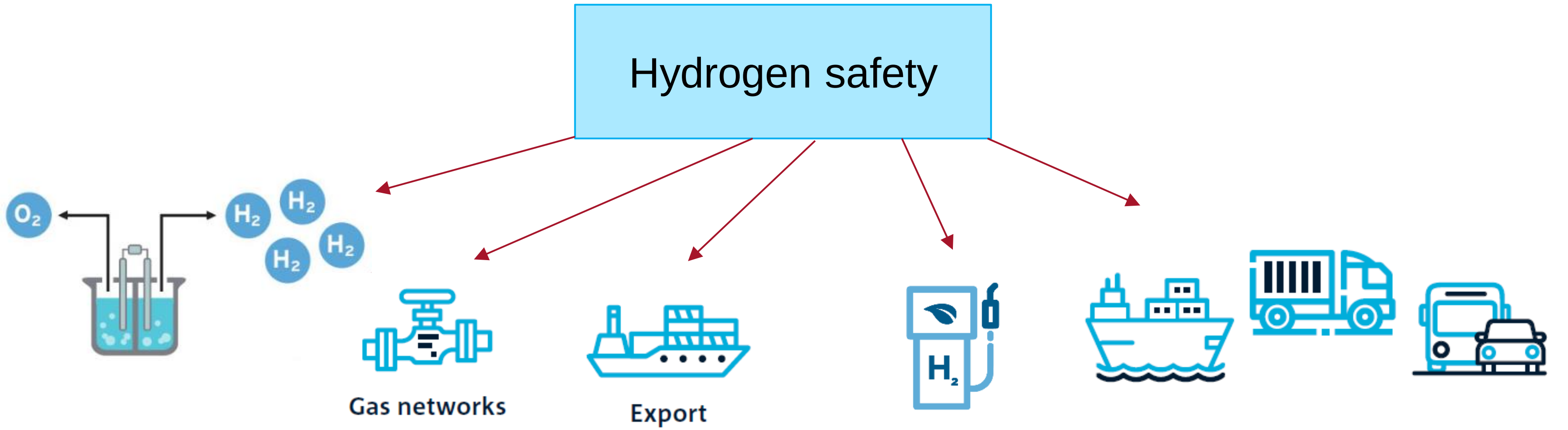
Absence of unwanted situation in system/operation at time t

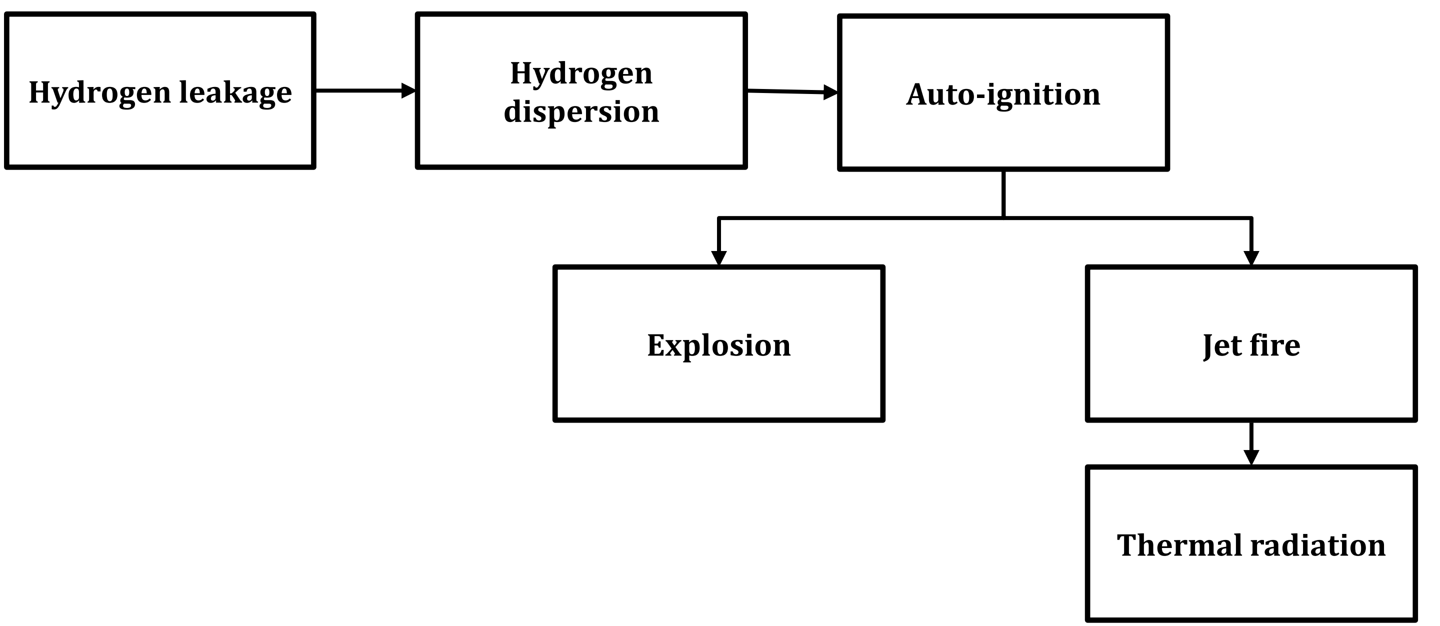
$$S(t)\ \alpha\ \frac{1}{Risk\ (t)}$$



Reduce Risk
- Reduce likelihood (probability)
- Reduce impact

Hydrogen safety

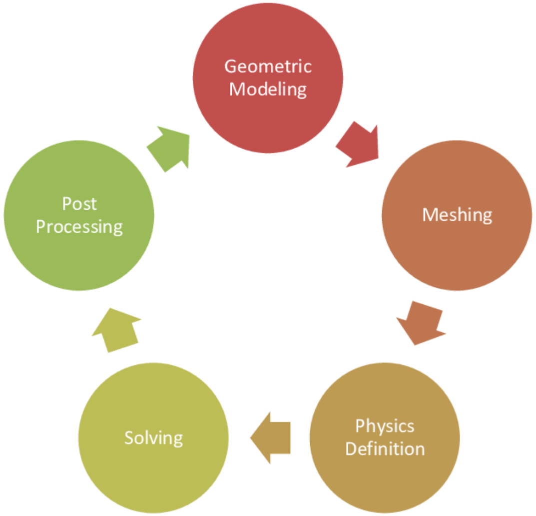




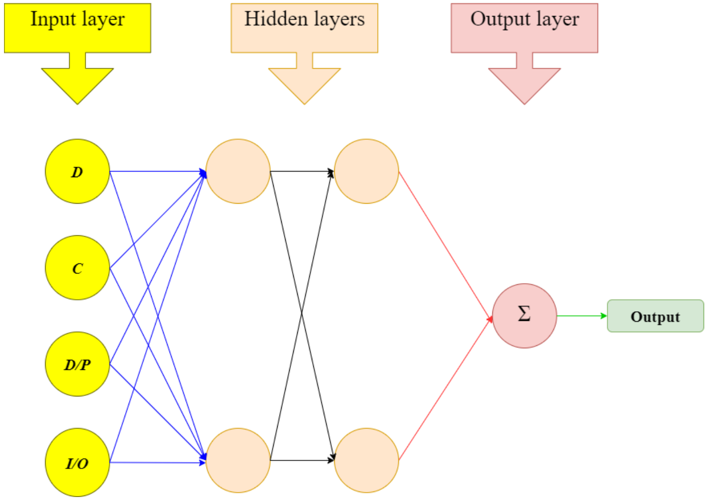
Hydrogen safety

Real-time measurements

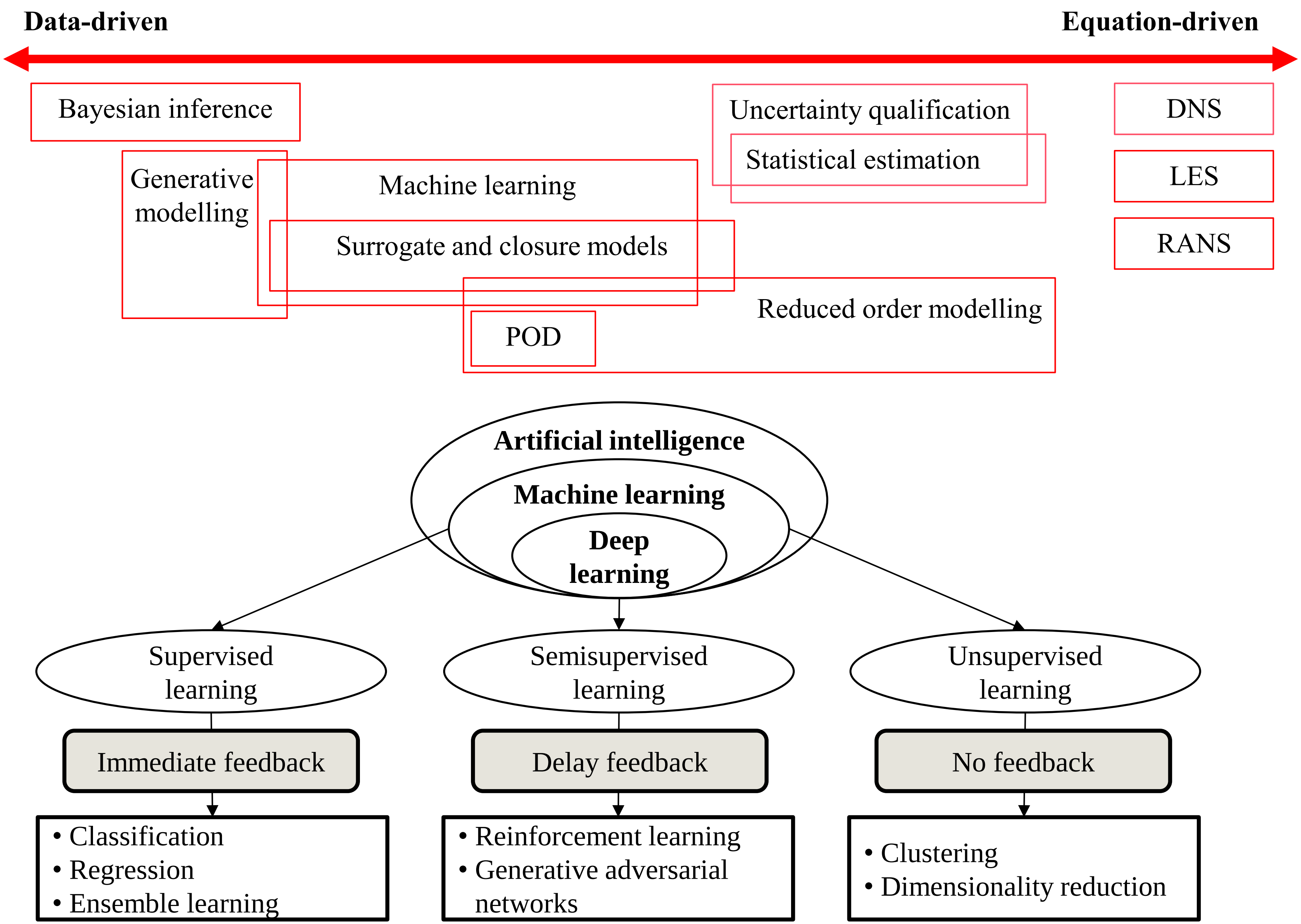
Computational fluid dynamics



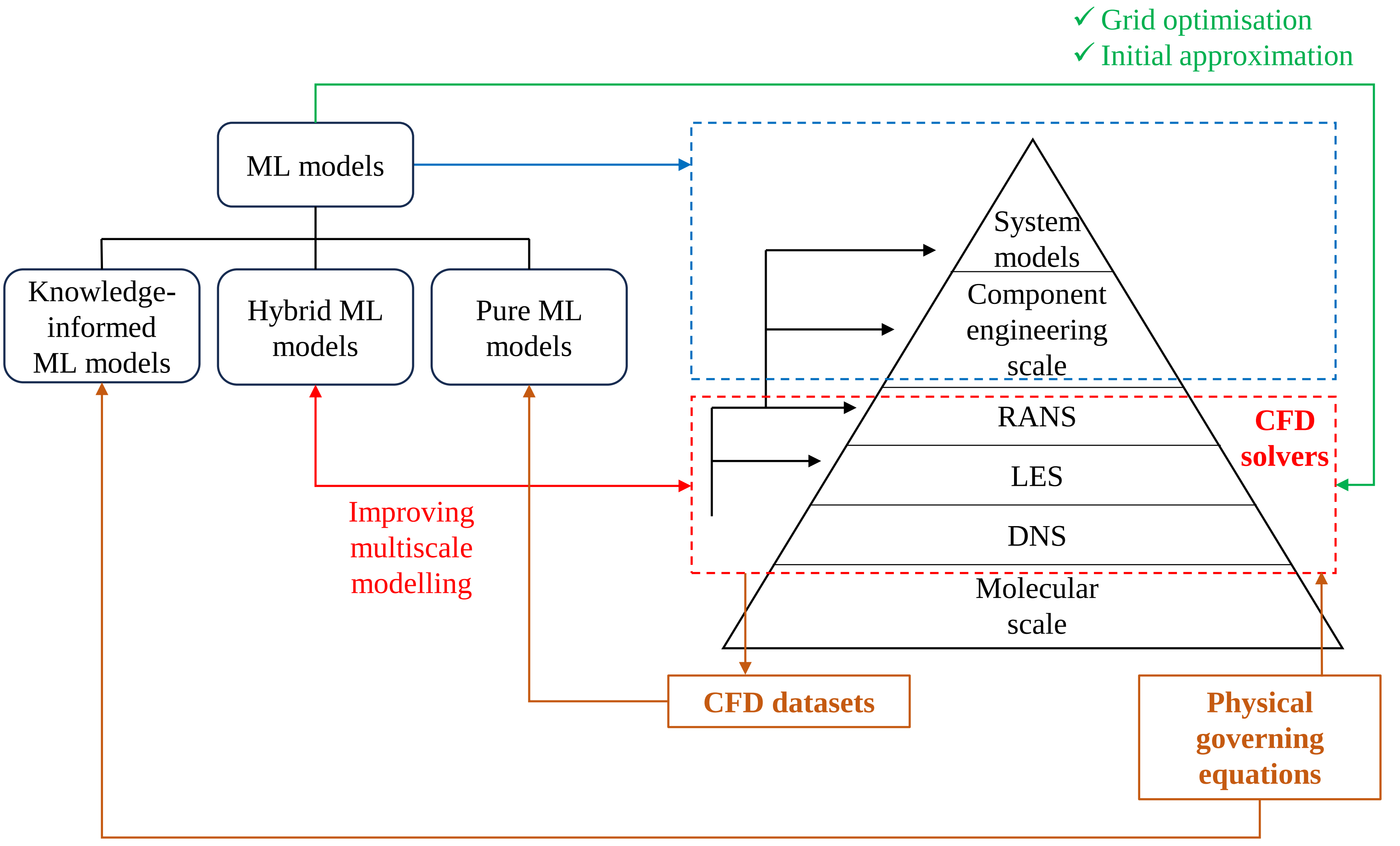
Machine learning and probabilistic modelling



Computational and data-driven models

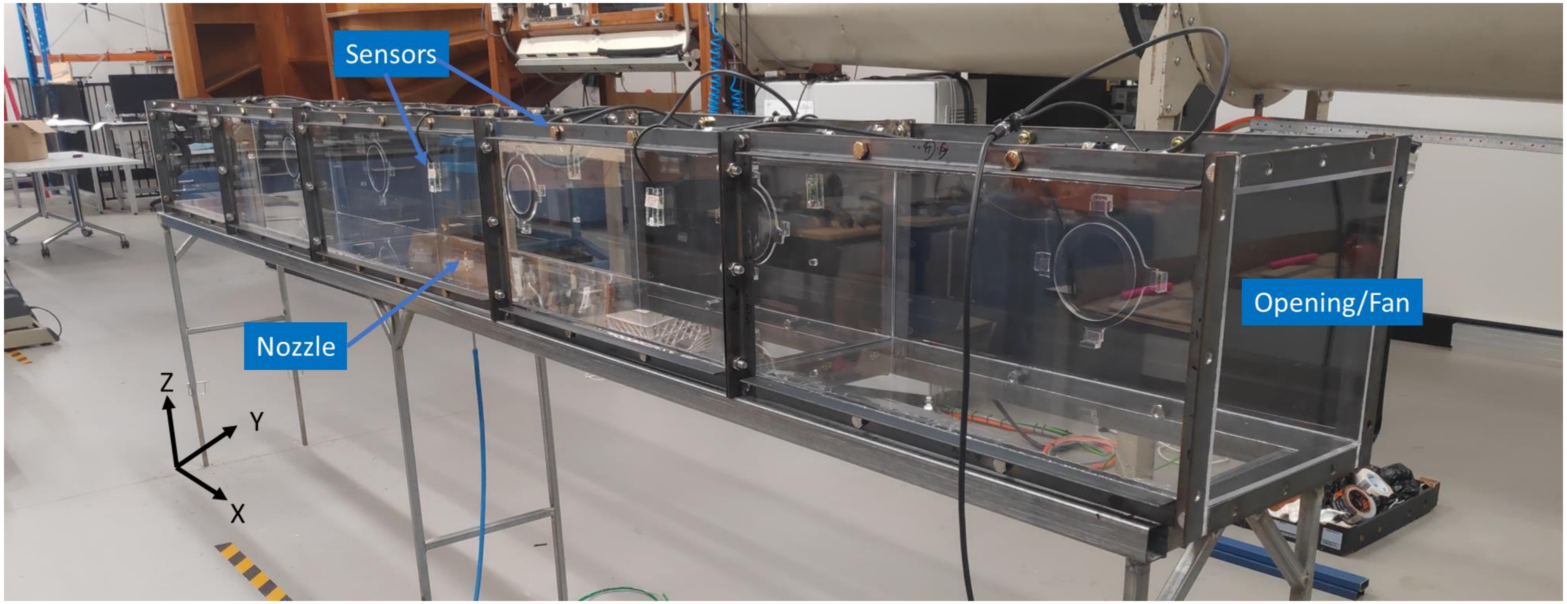


Computational and data-driven models



Fuel, under review

Hydrogen dispersion

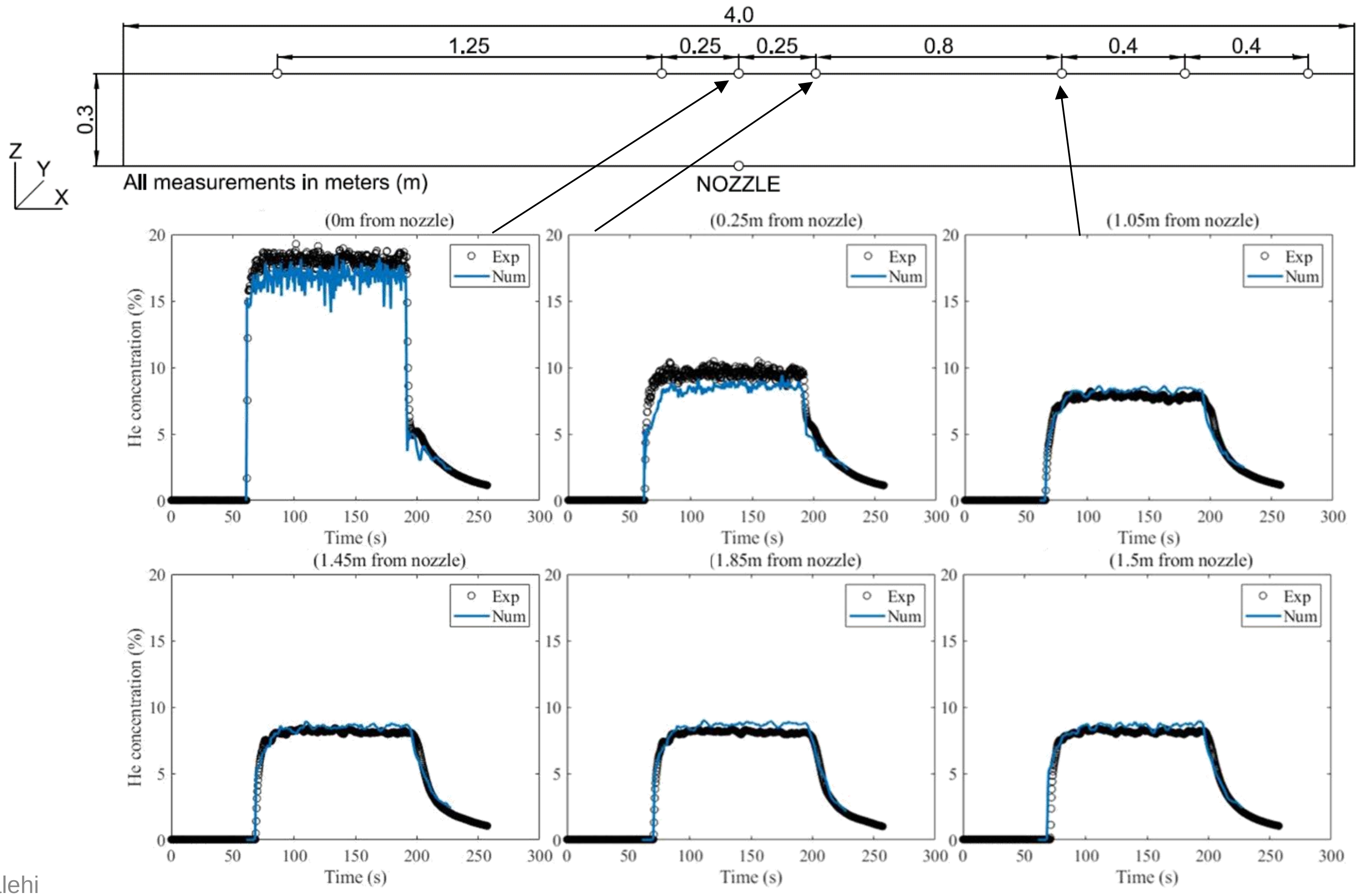


- 4m×0.3m×0.3m chamber
- 12 sensors, 20 sensor locations, allowing us to move them as required
- XEN-5320 gas sensors
- Using Helium as a surrogate for hydrogen
- Standard 20MPa gas cylinder
- Flow rate controlled by an air flow meter (L/min)
- Fan dismounted for natural dispersion study

✓ leakage rate
✓ wind velocity
✓ slope
✓ obstacles and barrier

Hydrogen dispersion

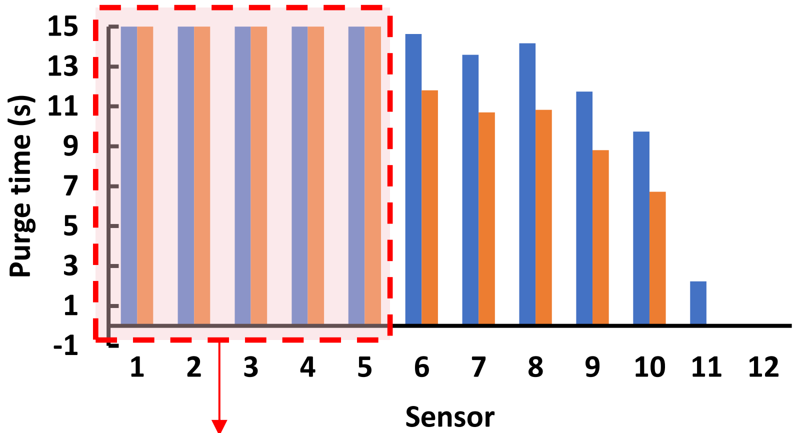
- Validation benchmark (Fan dismounted, wind velocity= 0 m/s)
- Helium gas flow rate: 67.29 litre/min (Corresponding to 25 litre/min reading as air)



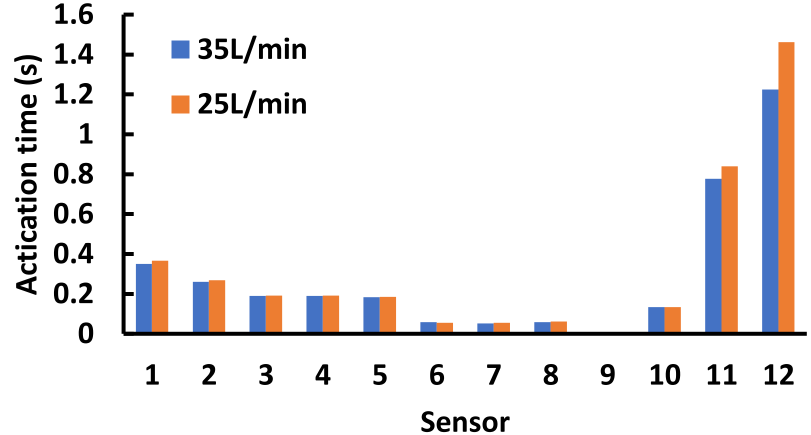
Hydrogen dispersion

Fan velocity 5 Hz

Purge Time (Stop to clear)



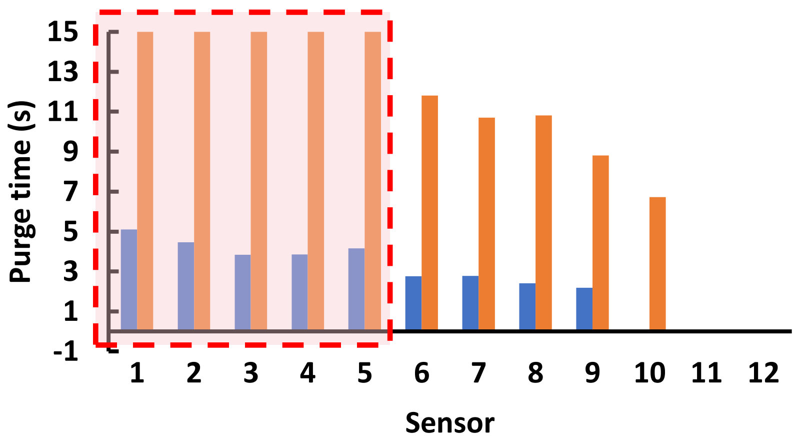
Activation Time (Release to record)



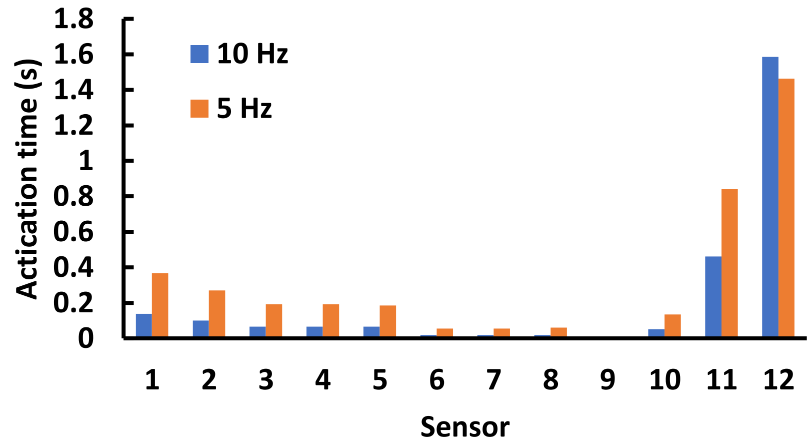
Purge time is larger than 15 s for 5 Hz

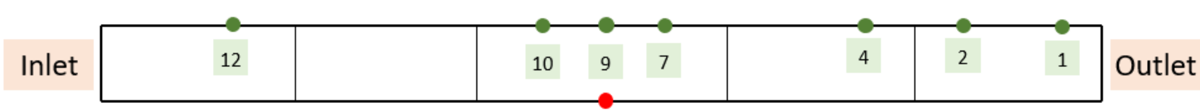
25 L/min @air gauge

Purge Time (Stop to clear)

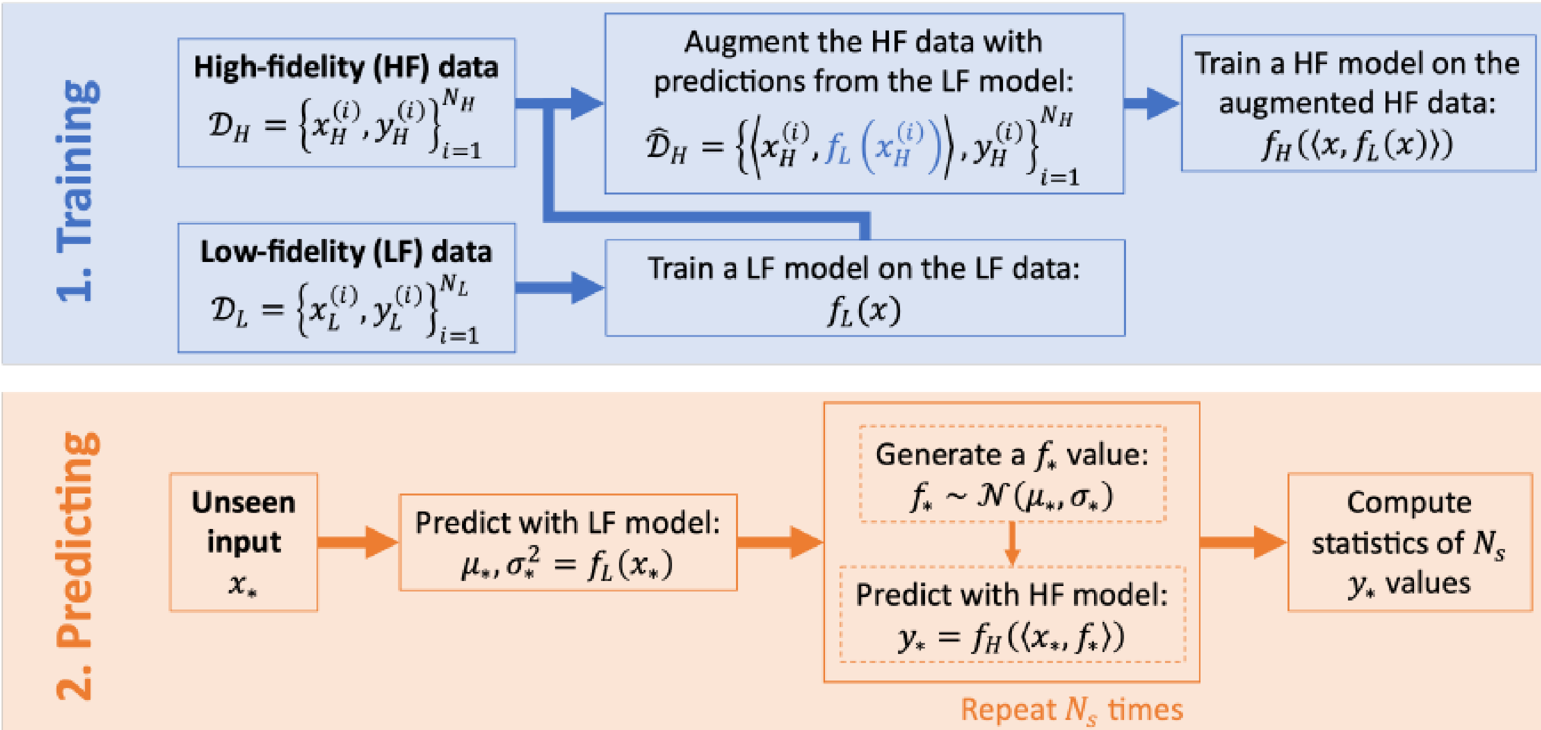


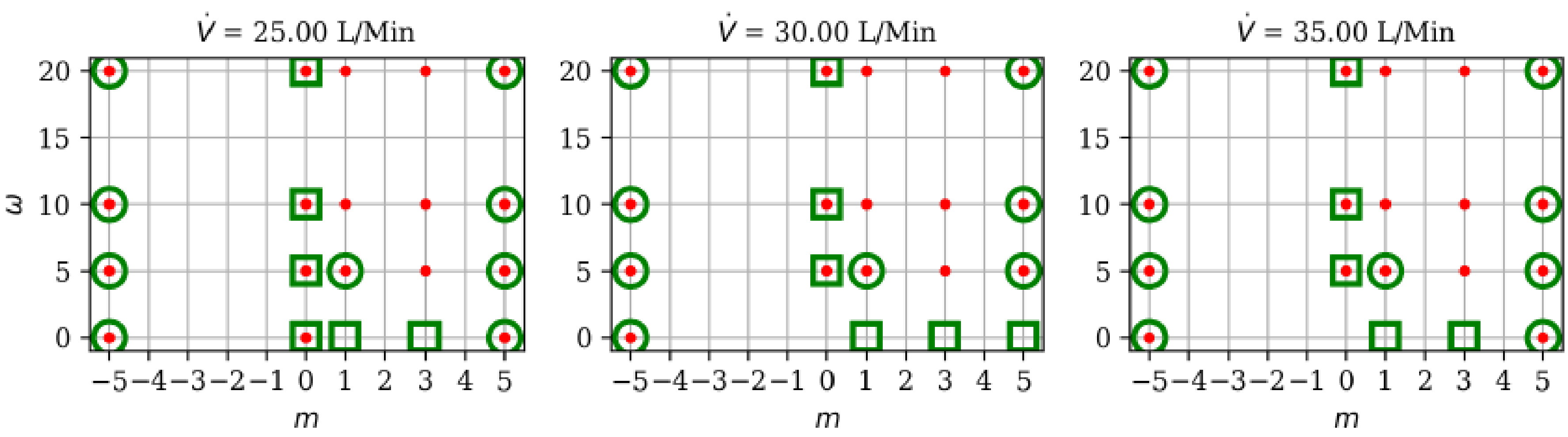
Activation Time (Release to record)



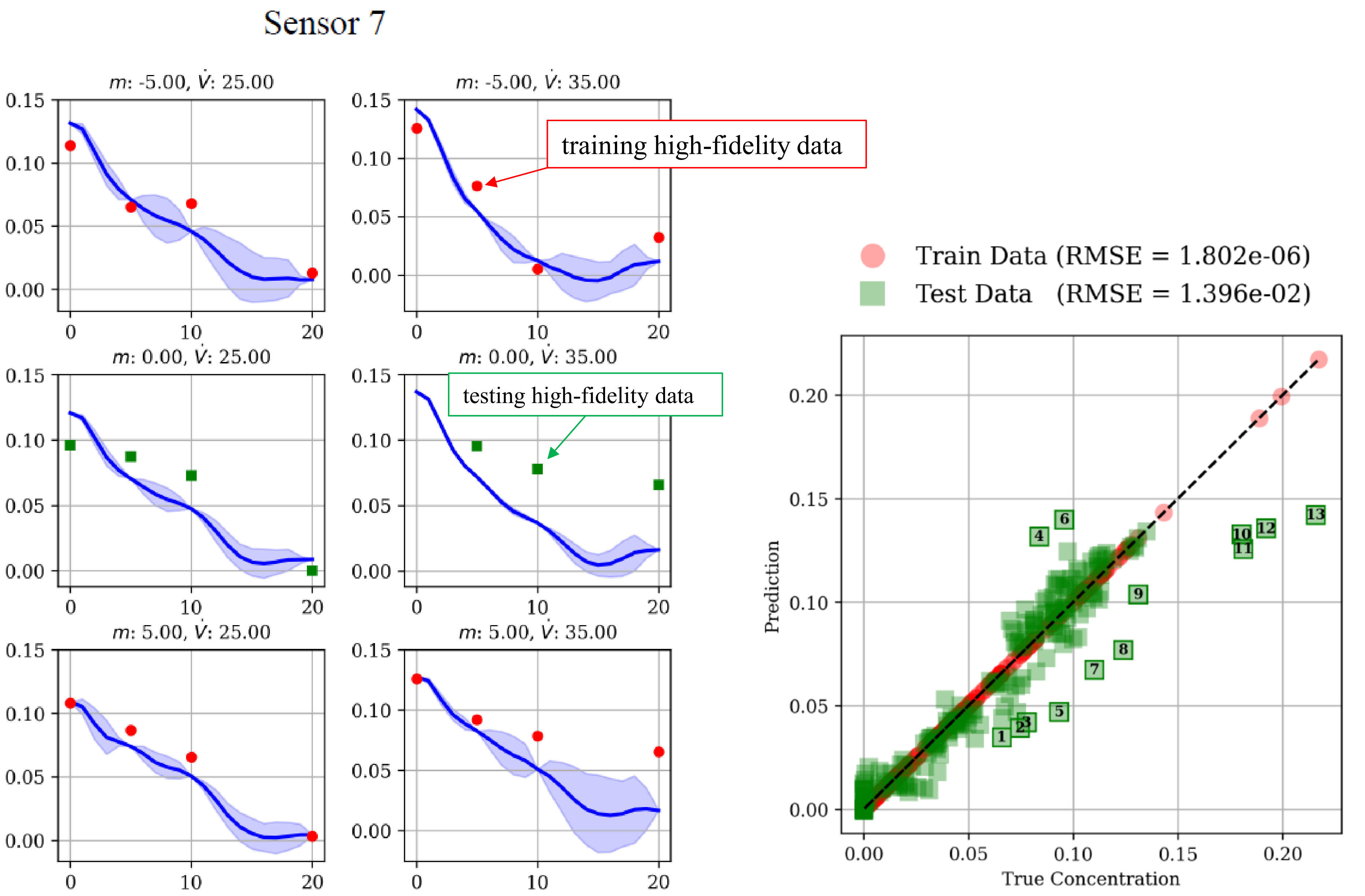


Bayesian inference of gas dispersion





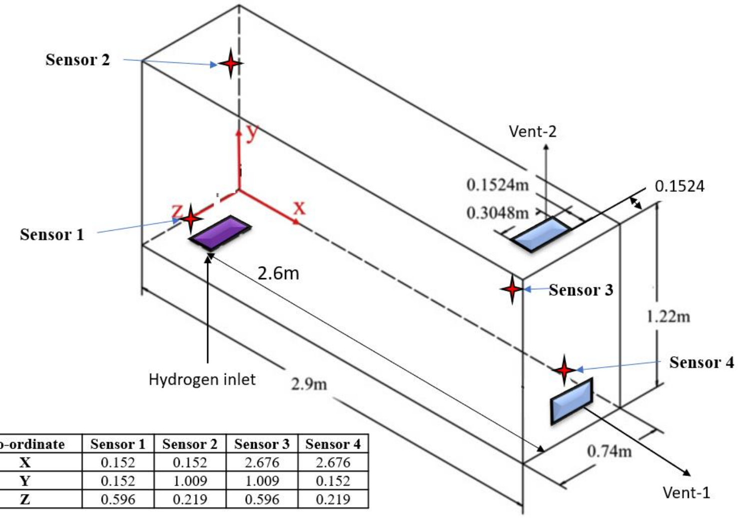
Bayesian inference of gas dispersion



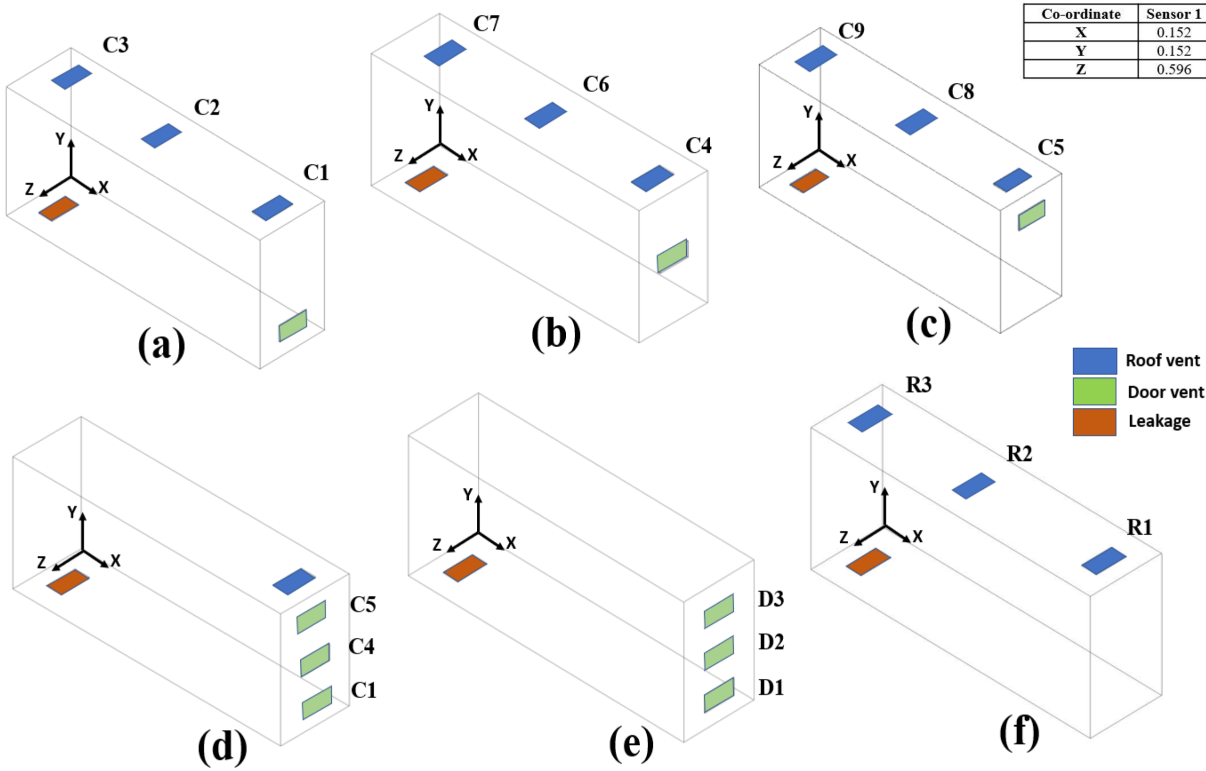
Hydrogen dispersion

Impact of ventilation

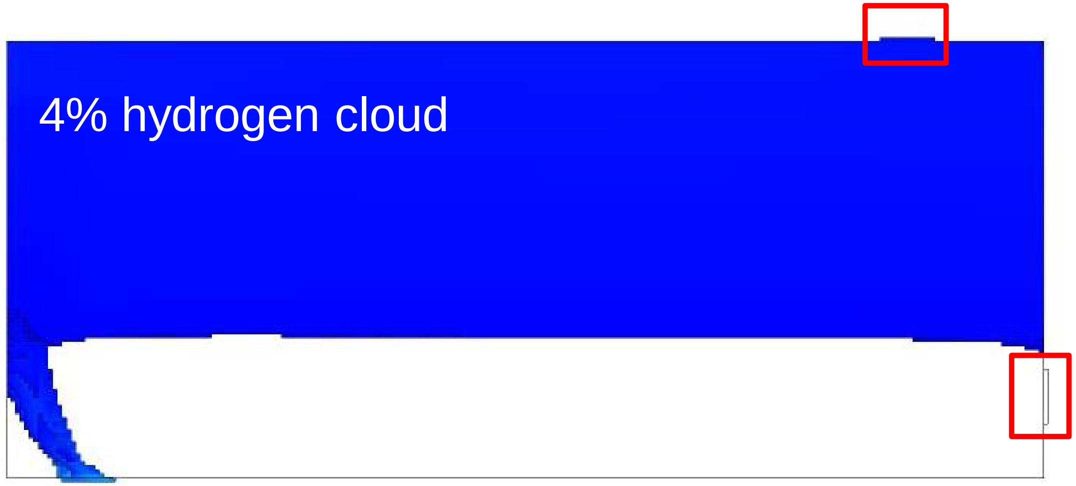
- 2 SCFM (laminar flow)
- 6.94% of hydrogen mass fraction at the inlet
- Simulations were conducted using Ansys/Fluent



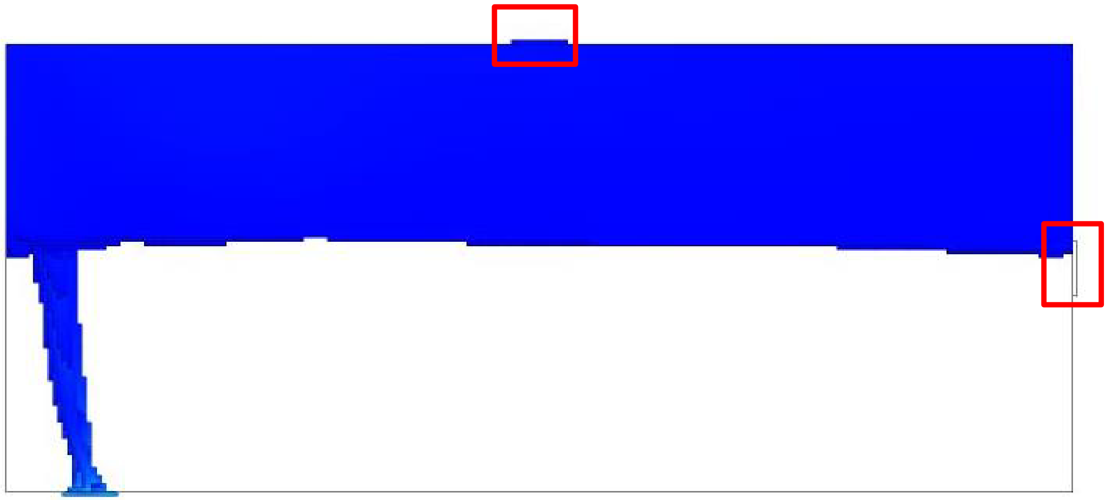
Co-ordinate	Sensor 1	Sensor 2	Sensor 3	Sensor 4
X	0.152	0.152	2.676	2.676
Y	0.152	1.009	1.009	0.152
Z	0.596	0.219	0.596	0.219



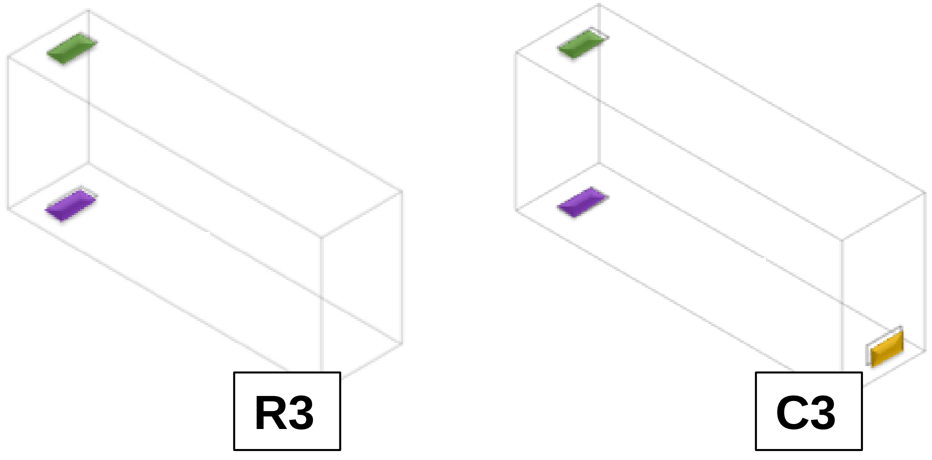
Hydrogen dispersion – ventilation

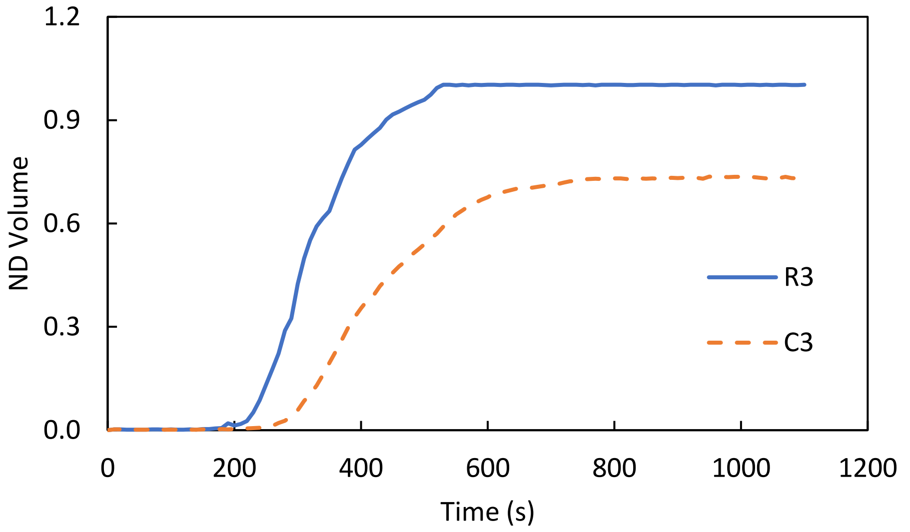


volume containing more than 4% H_2 concentration



Hydrogen dispersion and ventilation



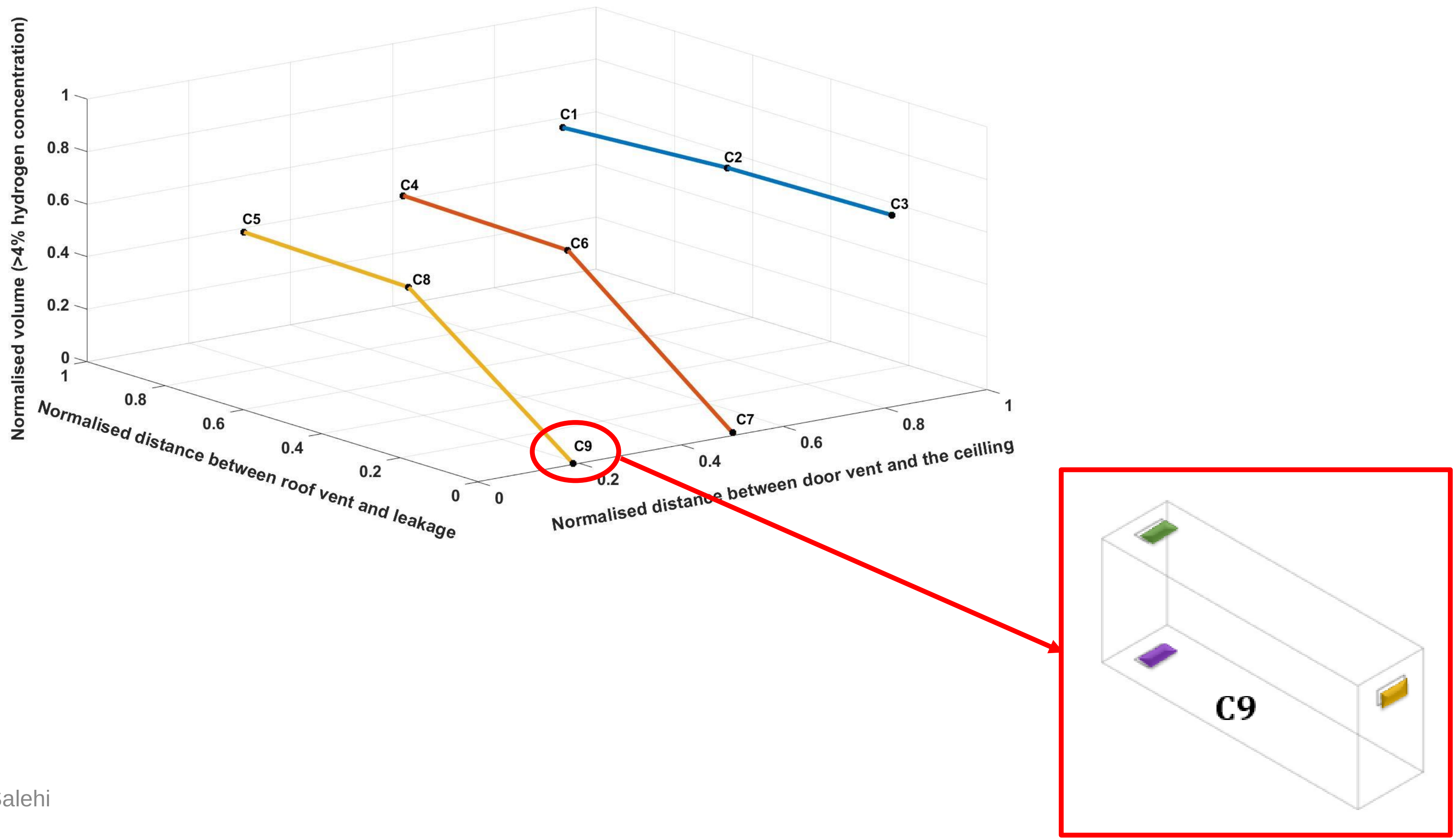


Average extracted hydrogen from roof vent

- R3: 2.42E-5 (kg/s)
- C3: 1.96E-3 (kg/s)

Hydrogen dispersion and ventilation

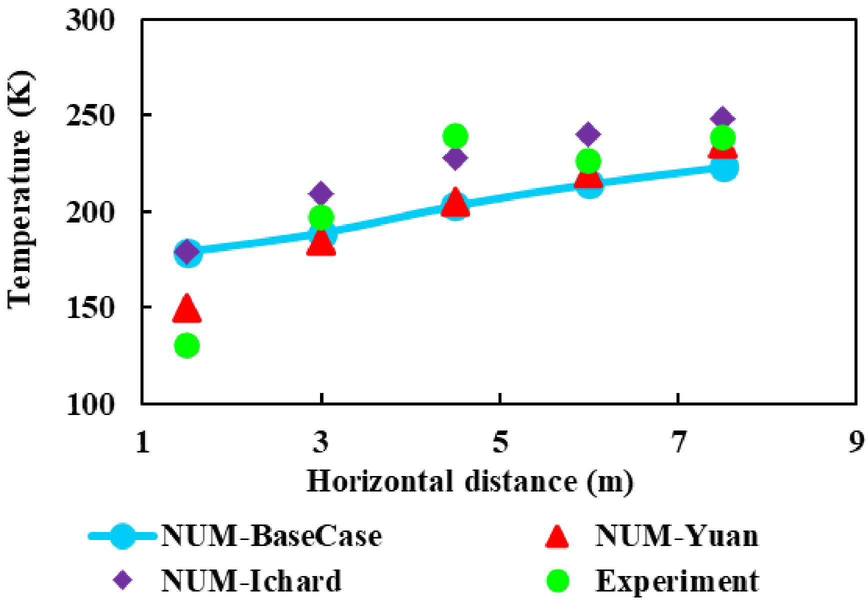
✓ C_9 has the best performance to extract hydrogen speedily and not allow to build up the of flammable gas cloud



Cryogenic hydrogen – dispersion

Health and Safety Laboratory Test 5

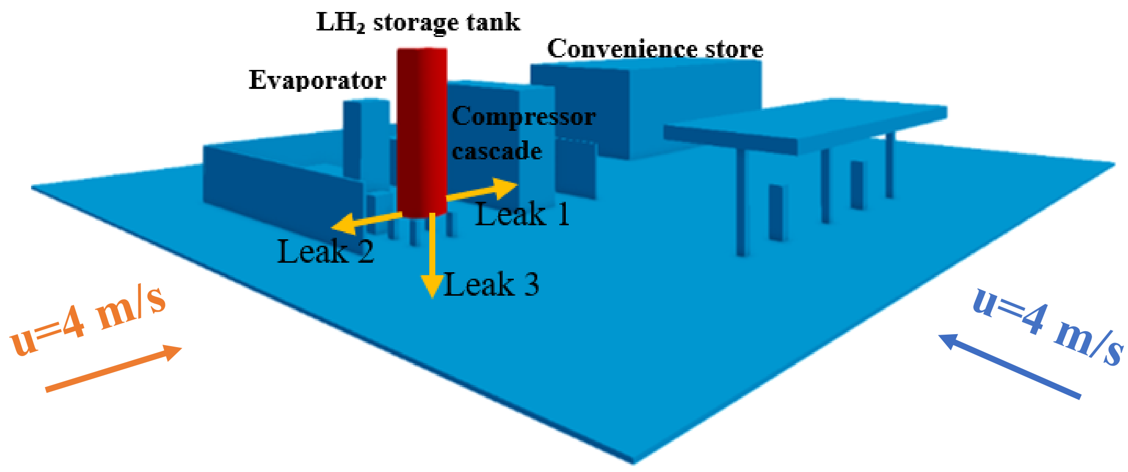
Spill diameter (mm)	26.6
Source height (mm)	860
Release rate (kg/s)	0.07
Release duration (s)	305
Wind speed @ 2.5 m (m/s)	3.07
Ambient temperature (K)	284
Ambient humidity (%)	68

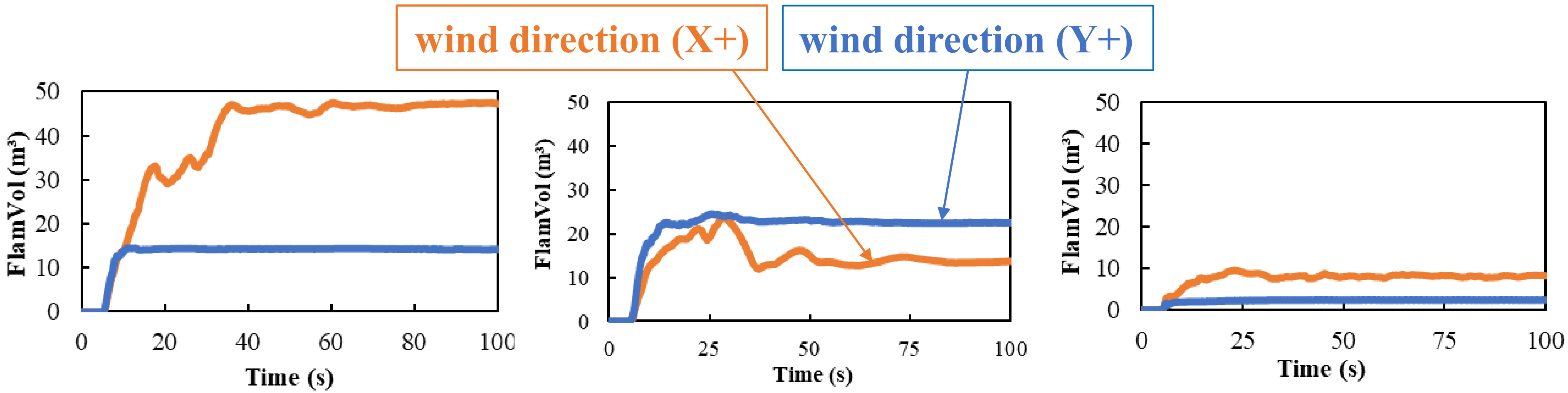


- Simulations were conducted using FLACS
- Porosity/distributed resistance concept
- RANS ($k-\varepsilon$ model)
- A pseudo-source model for leakage

F. Salehi

Cryogenic hydrogen – dispersion



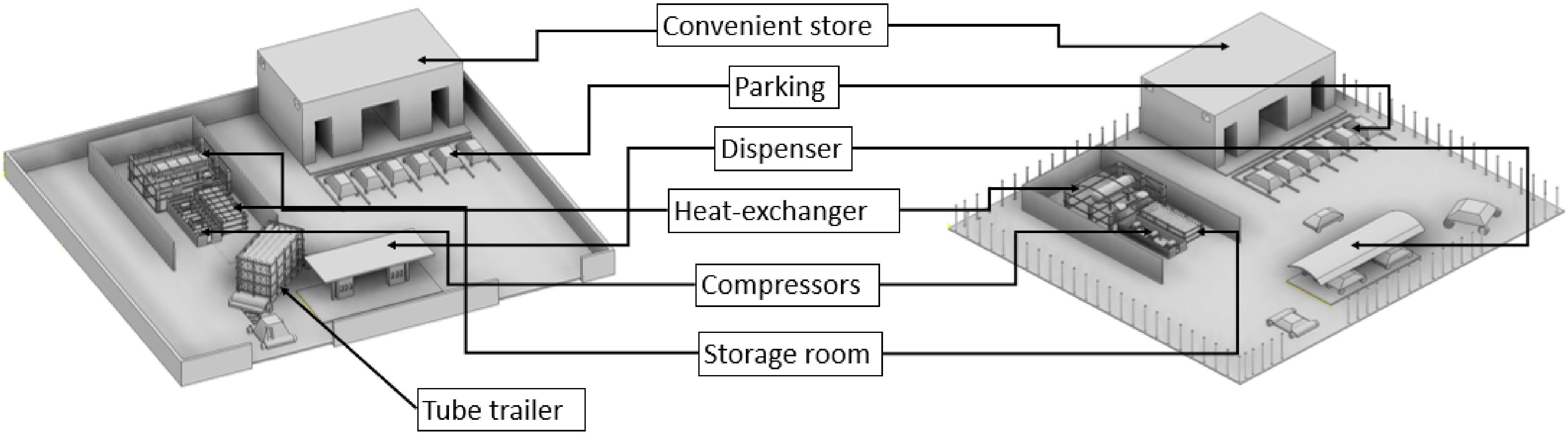


Leak 1

Leak 2

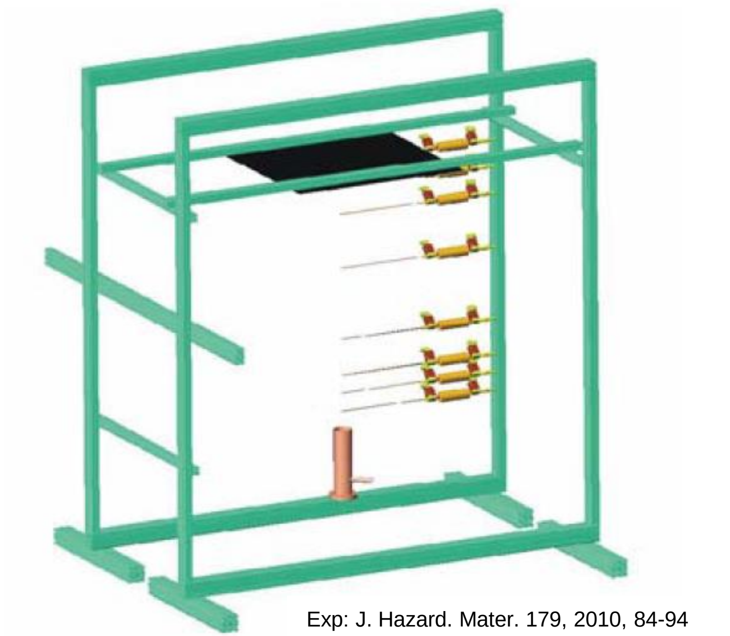
Leak 3

Hydrogen fire and explosion

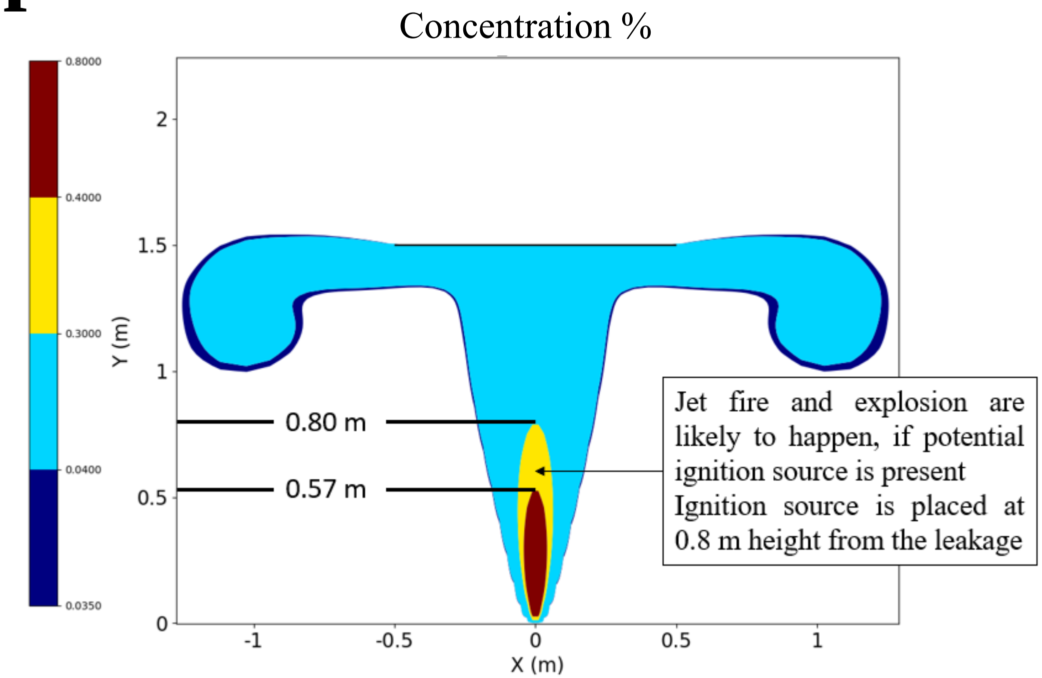


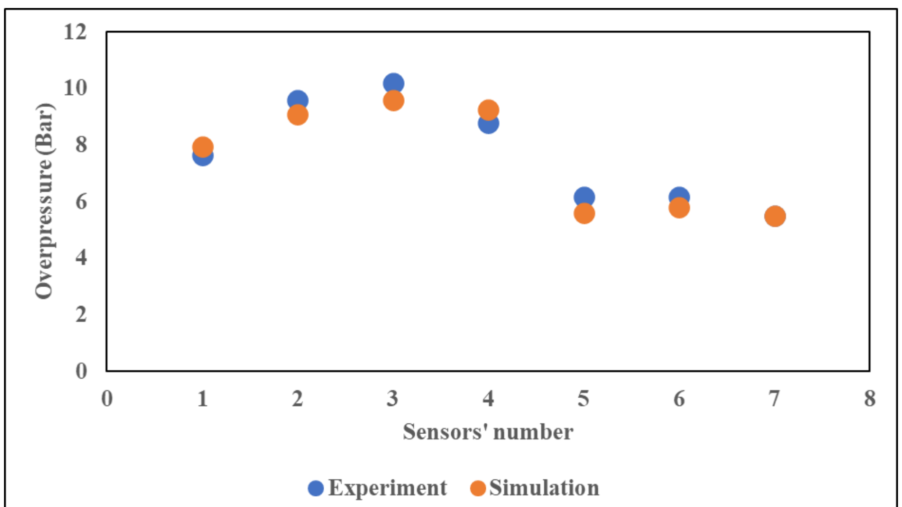
- Providing recommendations regarding the separation distance
- Simulations were conducted using FLACS-CFD
- $k-\varepsilon$ model turbulence and an eddy dissipation concept combustion models
- Abel-Noble equations
- Hydrogen dispersion, fire, and explosion are modelled

Hydrogen fire and explosion



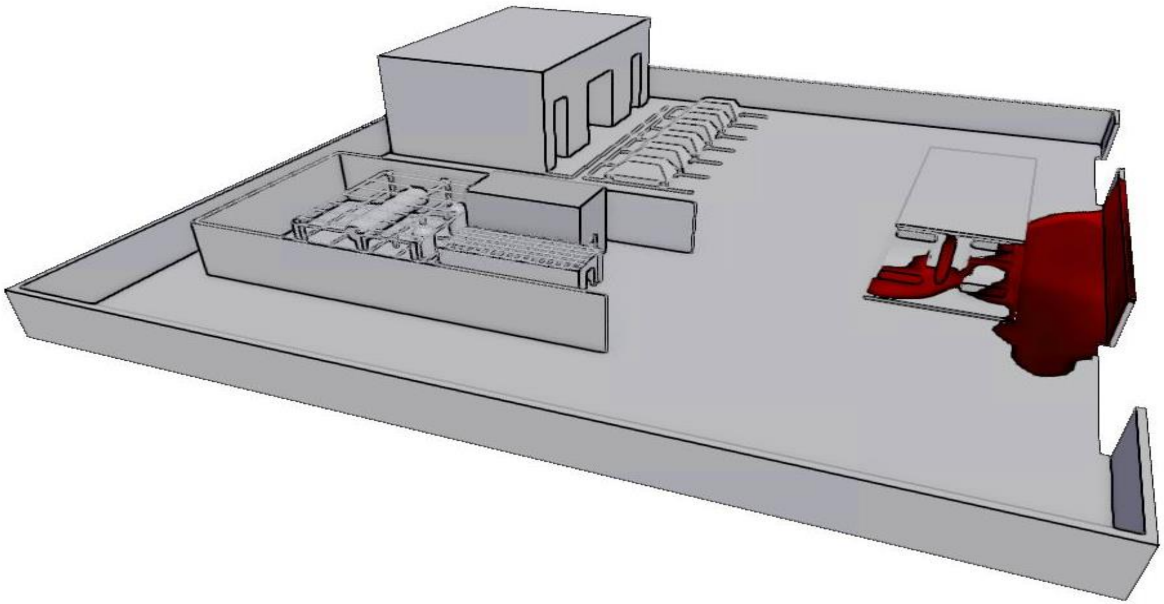
Exp: J. Hazard. Mater. 179, 2010, 84-94





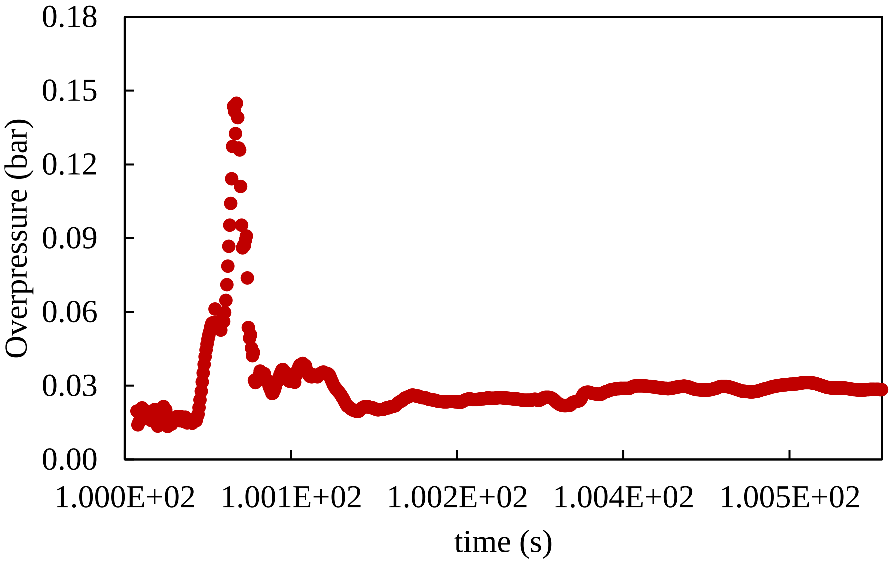
Leakage area	0.000346 m^2
Leakage diameter	21 mm
Leakage mass flow rate	6 g/s
Leakage velocity	200 m/s

Hydrogen fire and explosion

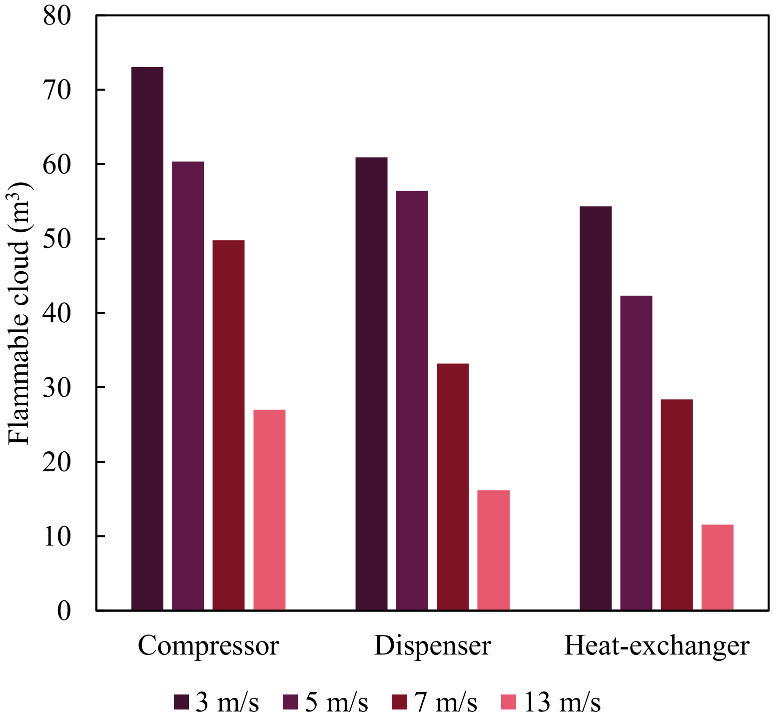


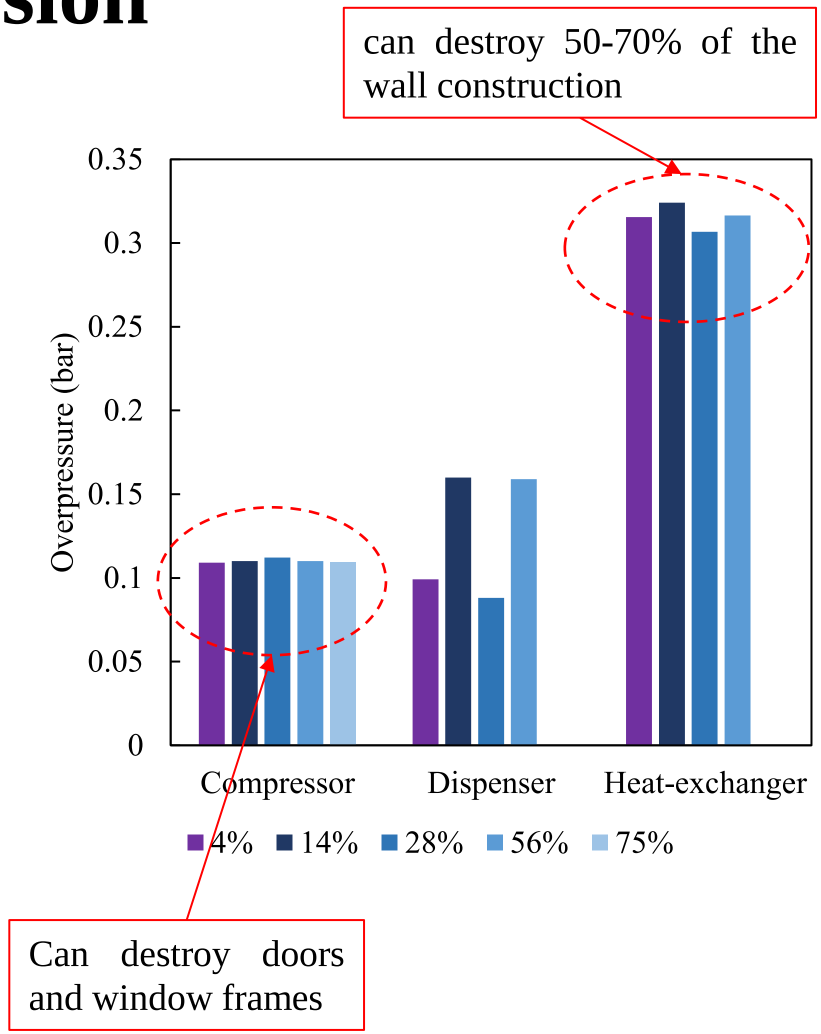
Release from dispenser

- Domain: 43 m × 38 m
- Leakage size 10 mm
- Impact of leak location on over-pressure
- 70 MPa for compressor, heat-exchanger, storage room, and dispenser,
- 20 MPa for tube-trailer leakage



Hydrogen fire and explosion





Remarks and future directions

- Safety recommendations for maintenance and recommissioning
- Intelligence sensing and monitoring systems – affordable sensors with high sensitivity in different environments (e.g. high humidity levels)
- Integration of real-time data for safety and reliability assessment
- Safety recommendations for high-risk environments/industries
- Risk analysis and social licence

✓ Better understanding of auto ignition

✓ Data-driven models

✓ Efficient models for integrated accidents

Thank you for your attention.

Fatemeh Salehi

fatemeh.salehi@mq.edu.au

Acknowledgement

- Blue Economy Cooperative Research Centre
- CSIRO Innovation Connections
- Macquarie Sustainable Energy Research Centre
- National Computational Infrastructure Australia
- Australian-American Fulbright Commission
- Department of Climate Change, Energy, the Environment and Water