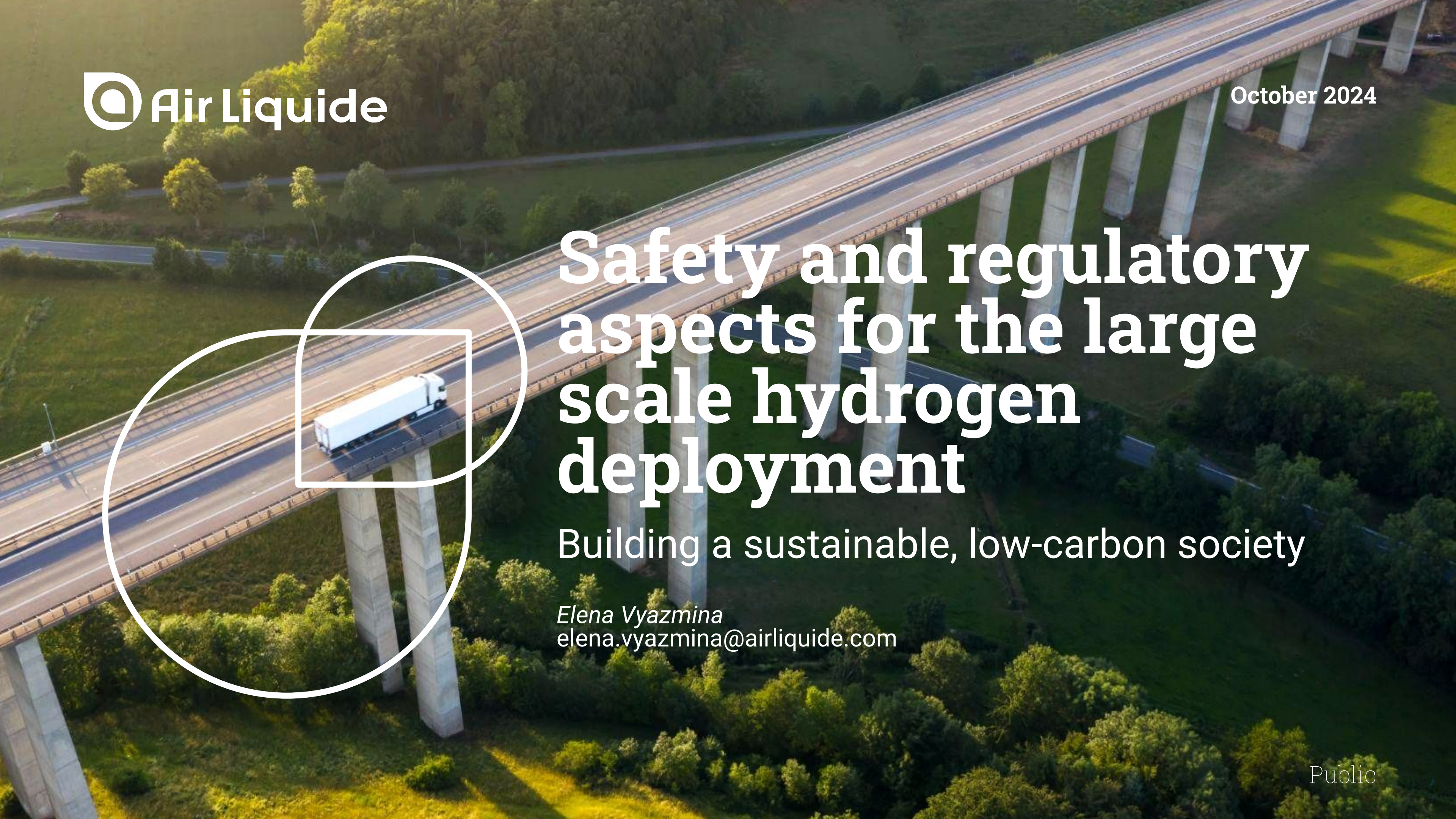

Air Liquide

October 2024

Safety and regulatory aspects for the large scale hydrogen deployment

Building a sustainable, low-carbon society

Elena Vyazmina
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Public

We think BIG for hydrogen

Before 2035

~€8bn

INVESTMENT DECISION

>3x

SALES

Hydrogen: a unique expertise and experience

60
YEARS OF EXPERTISE

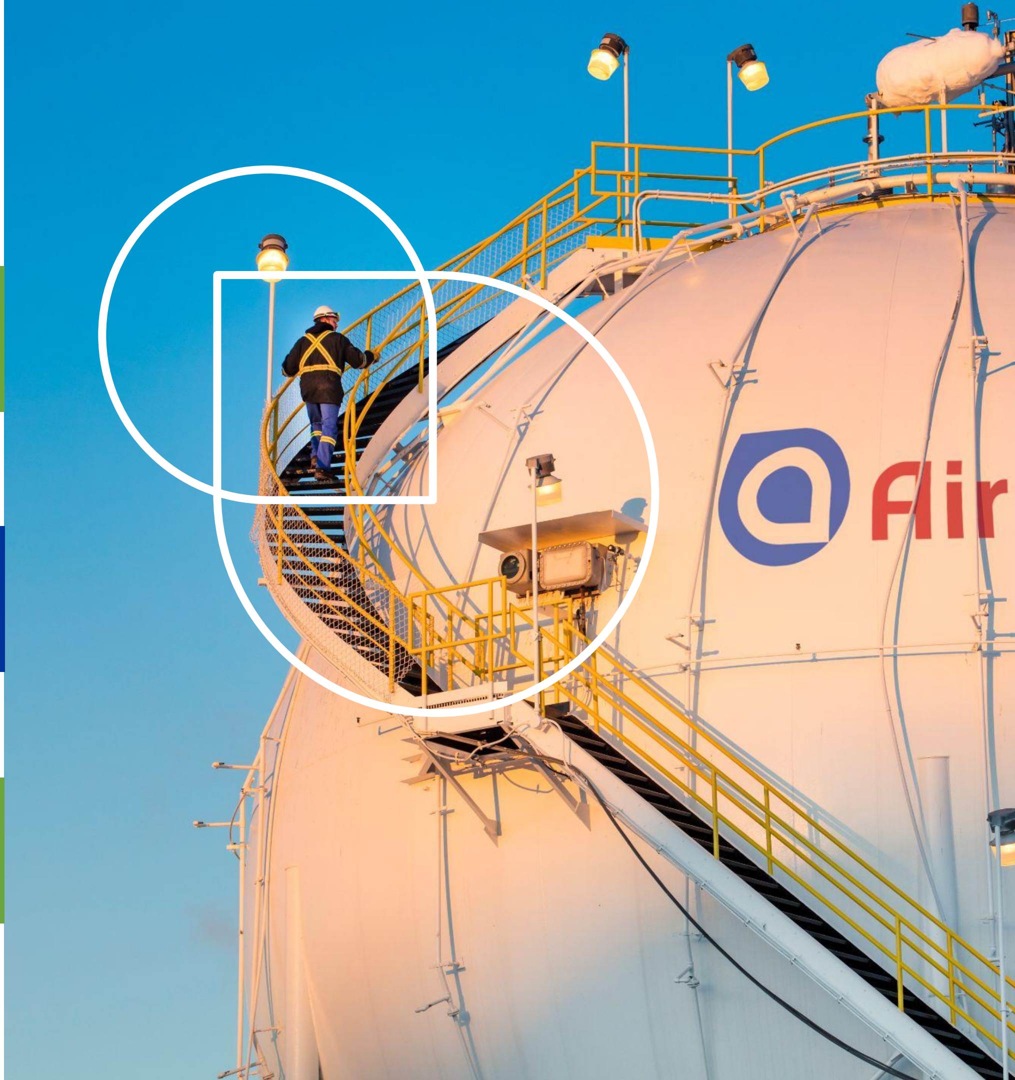
>1,000
EMPLOYEES IN HYDROGEN

€2.2bn
ANNUAL SALES

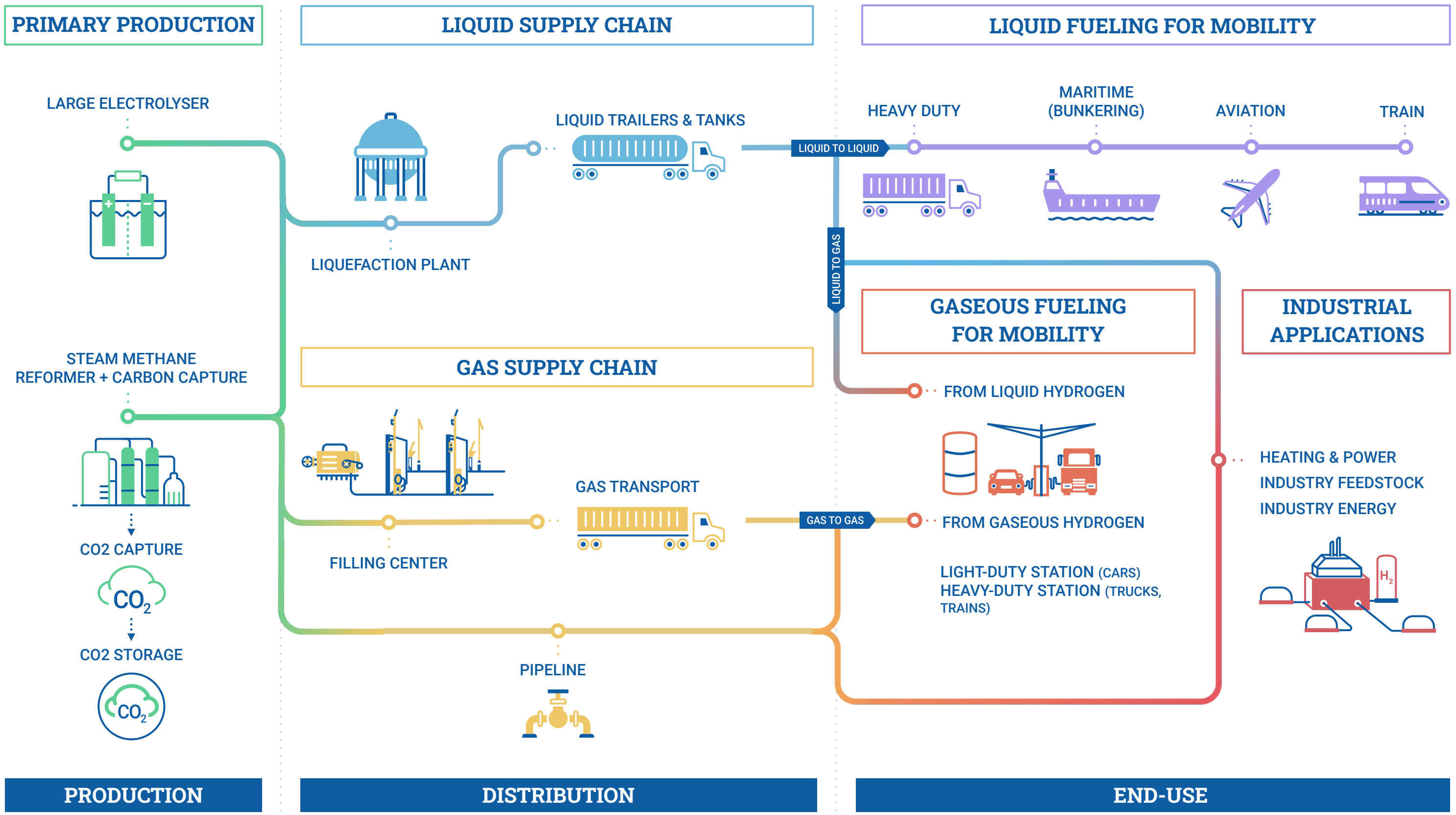
1.2 Mt
ANNUAL PRODUCTION

200+
STATIONS DELIVERED

~2,000
KM OF PIPELINES



HYDROGEN VALUE CHAIN



Bottlenecks for Large Scale Hydrogen Deployment

Interoperability of existing and future assets including hardware and corresponding protocols

Harmonisation is needed

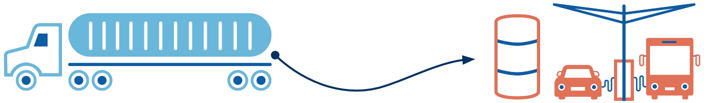
Safety Distances

Engagement of Stakeholder

Knowledge Gaps

What is Interoperability?

Process safety approach, one leverage for interfaces design & specifications



Key questions for interfaces are:

1 - Does it connect?

Physical connection for LH2, GH2, Instrument Air, process signals, data transmission etc.

+ site access and unloading place…

2 - Does it work?

Requested **functionalities for loading/unloading**

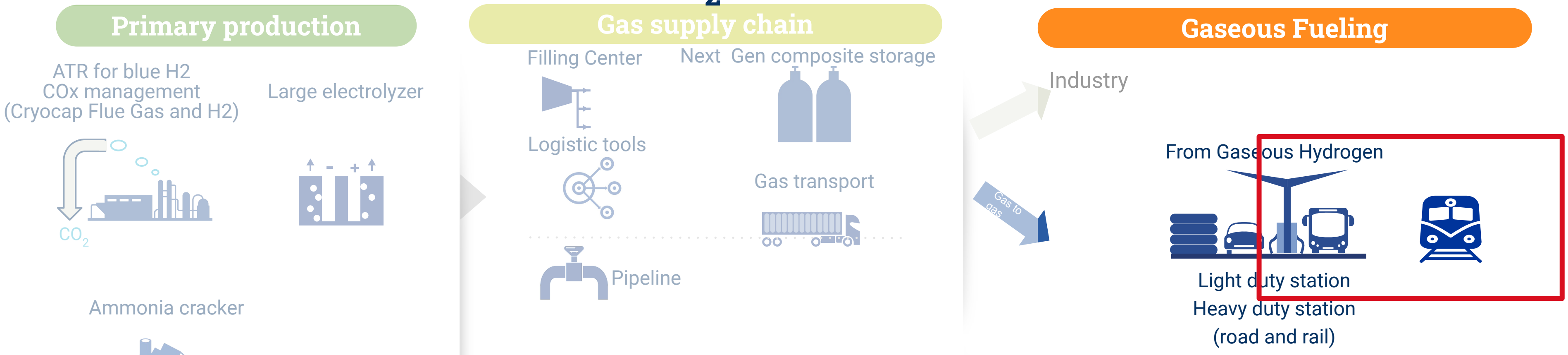
(valves, sensors, procedures, bunkering protocols…)

3 - Is it safe?

Functionalities and devices **for safe operation**

(E-stops, overpressure protection, vent system, grounding, breakaway anti tow-away…)

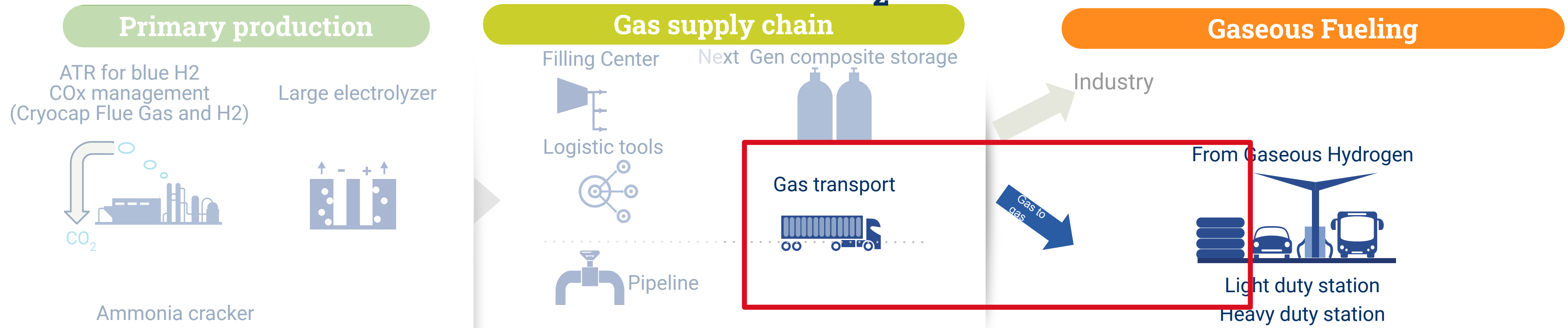
GH_2 Refueling



Heavy Duty vehicle/HRS interoperability, protocol, connections:
Hydrogen Council ITT #2 ⇒ position paper
ISO TC 197/WG 24 & 38 ⇒ std
AFIR ⇒ std

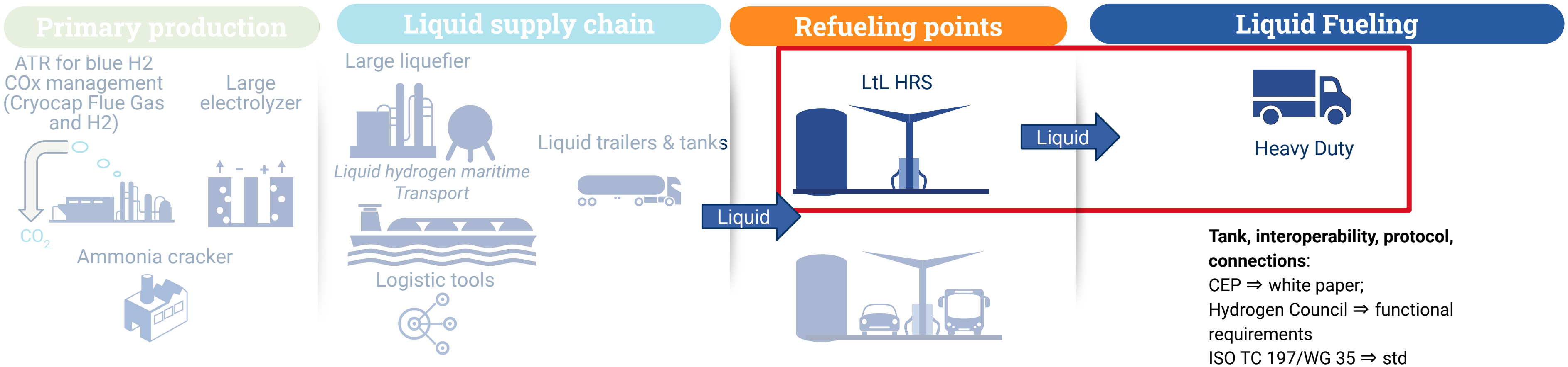
Rail (based on HD road):
HRS, protocol:
Hydrogen Council ITT#H2@rails ⇒ NP
ISO TC 197/SC 1 ⇒ std

Interoperability GH_2 trailer /HRS



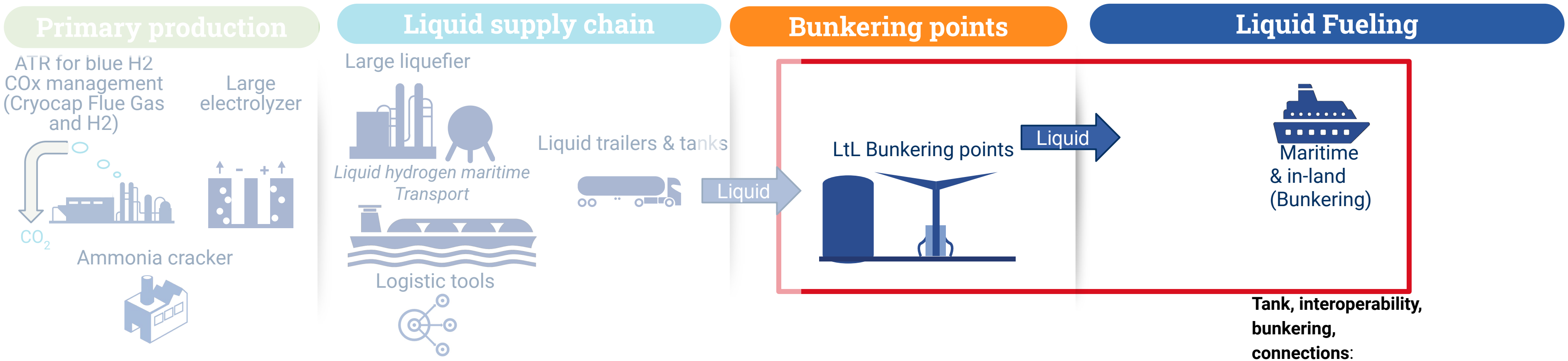
Interoperability trailer/HRS:
Hydrogen Council ITT# 3⇒ functional requirements
EIGA ⇒ risk assessment
ISO TC 197/WG 39 ⇒ std

sLH_2 Fueling



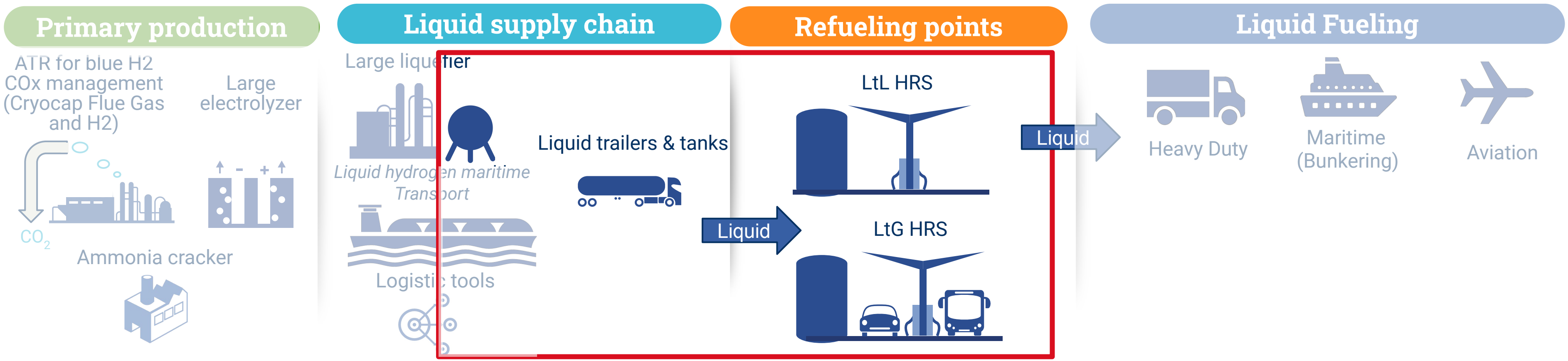
Tank, interoperability, protocol, connections:
CEP ⇒ white paper;
Hydrogen Council ⇒ functional requirements
ISO TC 197/WG 35 ⇒ std
AFIR ⇒ std

LH_2 Bunkering



Tank, interoperability, bunkering, connections:
IMO, ISO/TC 8 ⇒ functional requirements
PNR projects ⇒risk assessment
ISO/TC197 ⇒ std
AFIR ⇒ std

Liquid Hydrogen storage and interoperability & safety



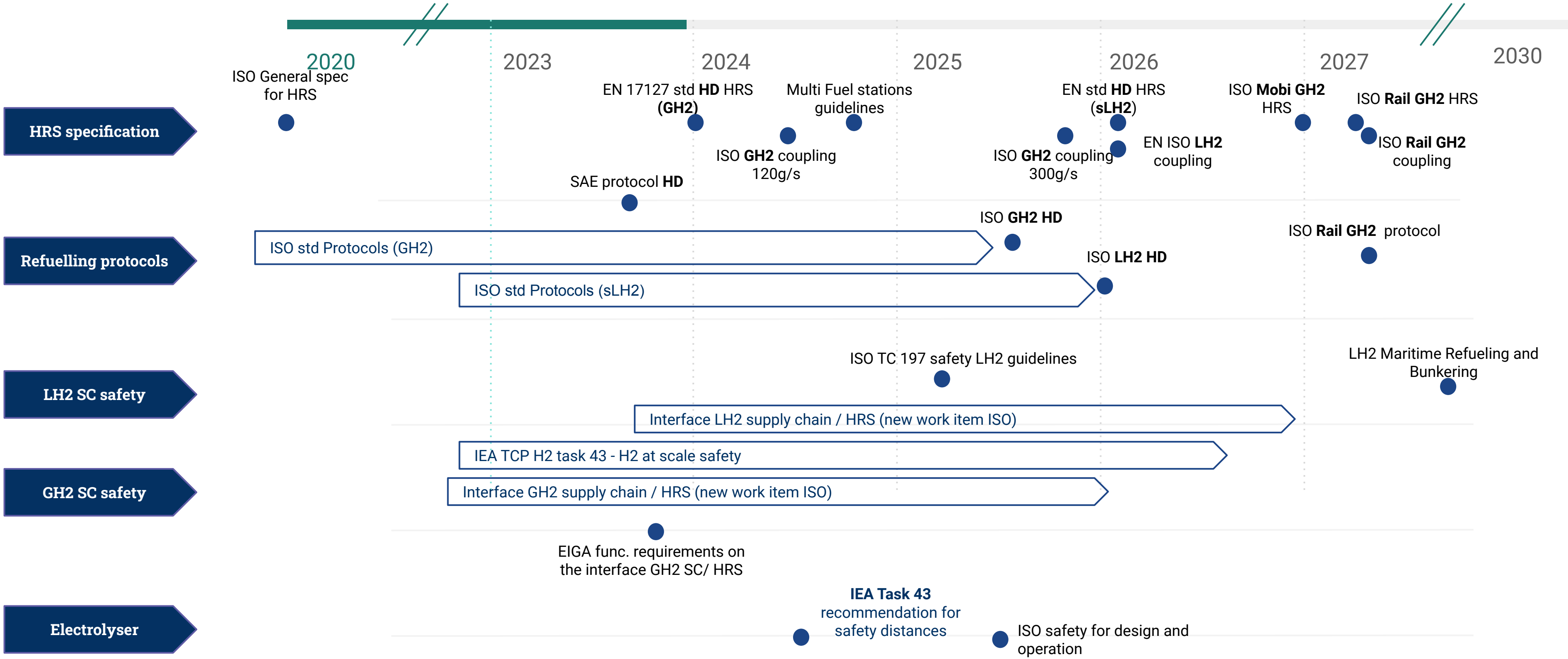
Interoperability trailer/LH2 storage:

Hydrogen Council ⇒ functional requirements

CGA ⇒ couplings

Safety & RCS

Milestones



Harmonisation of Safety Distances

Objectives:

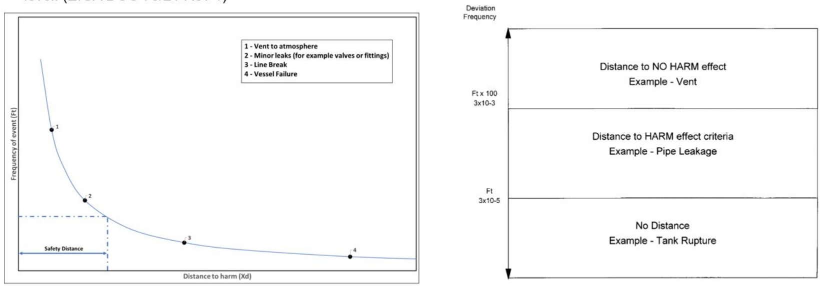
1. Review available methodologies and develop recommendations for a methodology for safety distances for large scale GH2 and LH2 systems and applications also considering the different vulnerability of potential targets
2. Show common basis and develop recommendations for harmonization of such methodologies
3. Define reference document for minimal requirements for safe hydrogen deployment

Purpose : to give an insight on different *methodologies and recommendations* developed *for hydrogen (mainly) risk management and consequences assessment* of accidental scenarios.

Need for unified/harmonized approach

Safety Distance Philosophy of Approach

- The safety and separation distances **are not intended to provide protection against catastrophic events** or major releases, these should be addressed by other means to reduce the frequency and / or consequences to an acceptable level. (EIGA DOC 75/21 Rev 1)



Safety distance is NOT intended to protect from catastrophic events

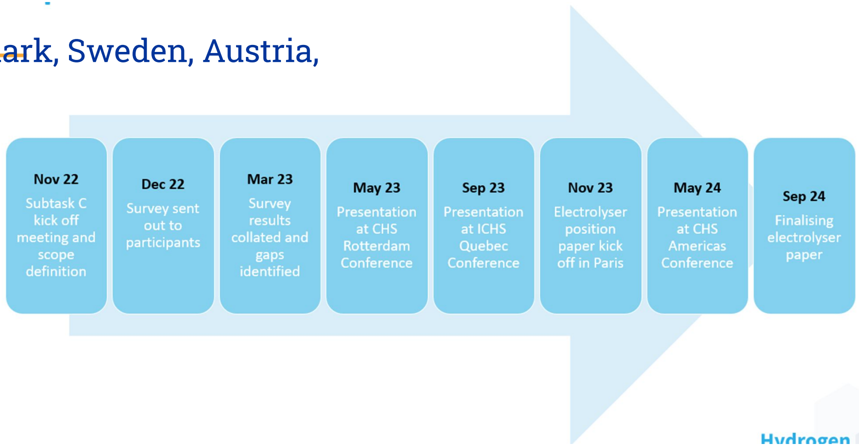
Harmonisation of Safety Distances - Task 43 approach

Target areas

- Review of safety distance methodologies for the following industry use cases:
- Electrolysers (Gaseous hydrogen) - large scale and on-site production
- Hydrogen refuelling stations (Gaseous hydrogen) (GtG and LtG HRS, LtL)
- Marine bunkering (Liquid hydrogen)
- Liquid storage of capacity >10t (airport, ports, hydrogen liquefiers, HRS etc applications)

Review of safety distance methodologies for the following regions :

- Japan
- USA, Canada
- Europe – France, Belgium, Netherlands, Germany, UK, Denmark, Sweden, Austria,
- Australia



Harmonisation of Safety Distances

IDENTIFIED GAPS

Harm criteria

- Thermal radiation vs. temperature
- People: Overpressure criteria varies from 50 mbar – 140 mbar to "not considered"
- Equipment: Thermal radiation criteria varies from 10 kW/m2 – 40 kW/m2. Some consider overpressure

Leak scenarios

- Range of hole sizes for consequence & risk based approaches
- Explosion severity limits to be considered (LFL vs 8% vs 10% in air)

Participant	Participant A	Participant B	Participant C	Participant D	Participant E	Participant F	Participant G	Participant H
Use Case	HRS, Electrolysers, Storage	Electrolysers	Electrolyser	HRS, Electrolysers, Storage	Electrolysers	HRS	HRS	Any H2 installations
Country	France	Global	EU, Australia, Japan	Sweden	Global	Netherlands, Germany, UK	France	USA
Regulation	ICPE 4715/1416	No legal mandatory standards found for electrolysers	BCGA GN 41 'Separation Distances in the Gas Industry'	MSBFS 2020	No legal mandatory standards found for electrolysers	PGS 35 TRBS-3151 APEA/BCGA/EI Guidance – UK 'Blue Book'	national regulation, standards are used to evaluate the failure probability	NFPA-2
Company Methodology For Safety Distances	Consequence based at feasibility stage Risk based at detailed design stage	Consequence based at feasibility stage Risk based at detailed design stage	Follow BCGA separation distances	Follow MSBFS 2020 approach which is consequence based	Consequence and risk based approach	Follow safety distances in relevant standards	Safety distance objective is to prevent any consequences on target (human beings). The evaluation is risked based, consequences and probabilities are taken into account.	Consequence-based distances using a risk-informed leak size
Leak Scenarios	Feasibility: Full bore (external safety distance) 10% diameter leak (internal safety distance) Detailed design: Same approach but further refinements	50mm leak for consequence analysis Small/Medium/Large/ FBR leak for risk based	Prescribed safety distances from BCGA 41 followed	3% leak - asset damage 10% leak - single fatality 100% leak - multiple fatalities	Small leak (% of pipe diameter depending on country specific RCS)/medium/large leaks for risk based analysis	Safety distances based on 10% leaks of typical pipe diameters at HRS for PGS 35 Unknown for Germany & UK	Full bore rupture and 10% of the diameter leak, thermal aggression on storage	Multiple leak sizes (from 0.01%-100% of flow area) for the risk-informed analysis, but then setback distances themselves use a constant 3% (now 1%) fractional leak size for gaseous hydrogen and 5% for liquid hydrogen
Harm Criteria	French Regulations used in France only Company specific harm criteria based on NFPA 2020 used in other regions **People**: 4.7kW/m2 & 50mbar **Buildings**: 25kW/m2 & 140mbar **Equipment**: 25-40kW/m2 & 200mbar	**People**: 5kW/m2 & 140mbar **Buildings**: 70-140mbar **Equipment**: 37.5kW/m2 & 200mbar **Risk Based:** 10-4/yr or 10-5/yr LSIR contour inside fence **Societal Risk:** PLL, FN-curve at specific location	**People**: 70mbar & Thermal Effects from Table 3 from EIGA Doc 211/17 **Equipment**: 35kW/m2	**People**: 309degC for individuals, 115degC for areas with groups of people **Buildings**: Flame impingement Equipment: 10 - 30kW/m2 depending on equipment size and pressure	French regulations: **Thermal radiation**: 3kW/m2, 5kW/m2, 8kW/m2 **Overpressure**:20mbarg, 50mbarg, 140mbarg, 200mbarg:	Dutch standards (PGS 35) **People**: 3kW/m2 (public), 10kW/m2 (1% lethality) **Buildings**: 10-35kW/m2 **Equipment**: 10-35kW/m2	French regulation (29/09/2005) **Thermal radiation** : 3 kW/m², 5 and 8 kW/m² **Overpressure** : 50 mbar for non-reversible effect, 140 and 200mbar for 1 to 5% of lethality	**Thermal Radiation**: 4.732 kW/m2 exposure of employee for 3 minutes 9 kW/2 for LH2, 4.732 kW/m2 for GH2 for cars and exposed persons not servicing the system and combustible buildings 20 kW/m2 for non-combustible buildings and other hazardous materials **Overpressure** (only considered for LH2): 70mbar, 137mbar, 170mbar

E. Vyazmina, G. de Reals, R. Chang, L. Phillips, S. Quesnel, B. Truchot, J. Hocquet, D. Torrado Beltran, M. Runefors, B. D. Ehrhart, "IEA TCP Task 43- subtask Safety Distances: state on the art", Center for Hydrogen Safety Europe Conference 2023, Rotterdam, Netherlands, 9-11 May, 2023.

E.Vyazmina, G. de Reals, R. Chang, L. Phillips, S. Quesnel, B. Truchot, J. Hocquet, D. Torrado Beltran, M. Runefors, B. D. Ehrhart, "IEA TCP Task 43- subtask Safety Distances: state on the art", ICHS, Québec City, Canada, September 19-21, 2023.

Harmonisation of Safety Distances - Task 43 approach

On-going activities:

Position paper on the electrolyser safety

Position paper on the explosion severity limits

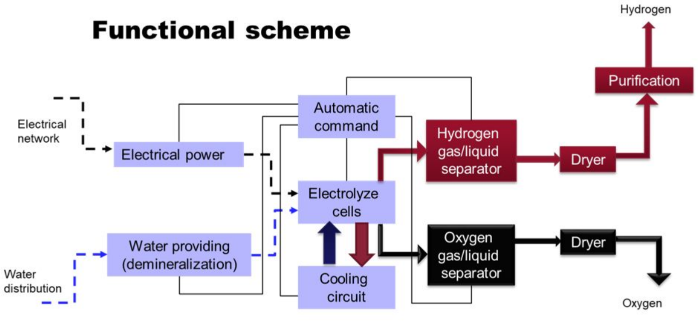
Position paper on Liquid storage

Position paper on safety distances for Multi Fuel refueling points : outcome of MultHYfuel project

Harmonisation of Safety Distances - electrolyser (1/2)

Electrolyser System

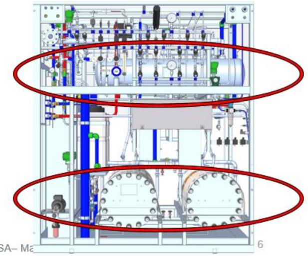
Functional scheme



Electrolyser can be installed in a building or in a container

- Only those installations are considered here (most common operation mode)

Downstream equipment such as dryers, purification, compression, etc. are outside the scope of this study



Technical safety requirements ISO/TC 197/WG 34

E. Vyazmina, R. Chang, S. Quesnel, B. Truchot, J. Hocquet, D. Torrado Beltran, N. Hart, M. Runefors, Th. Jordan, K. Ramsey-Idem, M. Halinen, L. Bouchet, R. Ariel Perez, G. de Reals, L. Phillips, D. Houssin, S. Jallais, A. Tchouvelev, “IEA TCP TASK 43 - SUBTASK SAFETY DISTANCES: ELECTROLYSER”, Center for Hydrogen Safety Europe Conference 2024, Las Vegas, USA, 21-23 May, 2024.

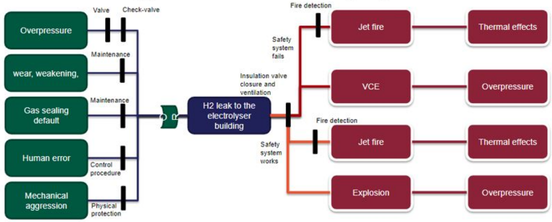
Hazard Identification

- Pressure – failure of vessels, components etc.
- Flammable gas (hydrogen) – release to air to form flammable / potentially explosive atmosphere
- Oxygen – increased propensity for combustion or otherwise non-combustibles
- Hydrogen/oxygen mixtures – explosion internal to pressure system
- Electricity – electrocution
- High voltage, electrical short circuits or discharges
- Degradation of membrane
- Pressure difference between hydrogen and oxygen compartment (break of membrane)
- Freezing of the cooling water in the stack
- Fracture of a pressurized pipe, compartment
- Hydrogen leakage from the stack
- Cross-over of oxygen into hydrogen and vice versa
- Leakage of electrolyte
- Accumulation of explosive hydrogen/oxygen mixtures in the gas liquid separator
- Lower power level low power production → increased gas impurities
- Low power level standby → Safety level depends on standby strategy, standby without gas production
- Long term overload operation: overheating, hotspots
- Down the line hydrogen utilization and pressure control can have impact on pressure control in electrolyser system

Harmonisation of Safety Distances - electrolyser (2/2)

Potential Explosion of a Container or Building

Bow-tie approach and safety systems



Prevention and mitigation

Pressure – pressure control (sensors) and pressure relief valves

Flammable gas – dependent upon location / part of system:

Stacks – external leak: forced ventilation

Zone 2 NE

Stacks – internal leak: water flow, no ignition sources (outside of stack), vessel open to atmosphere, over-pressure calculations

Natural ventilation – electronics, controlled access

Vents – High level, Zone 1 / 2, natural ventilation, no ignition sources, no impact in case of ignited jet

Oxygen – vented

Hydrogen/oxygen mixtures – differential pressure, and de-oxo catalyst with temperature monitoring

Pressure – pressure control (sensors) and pressure relief valves

Electricity – Ingress protection (touch and water), procedures (inc. Lock out tag out or LOTO)

Enclosures increase explosion risk and lead to larger safety distances (pressure relief panel can be used)

Only small or very limited hydrogen amounts can be released from cell

➔ A suitable scenario for safety distances?

Potential Explosion in Gas-Liquid Separator

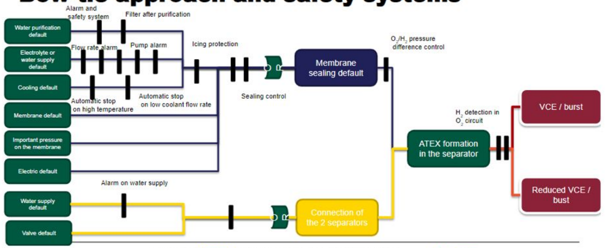
Bow-tie approach and safety systems

Formation of a flammable mixture of O2 and H2 in a gas-liquid separator

- Design parameters
  - Separator volume
  - Operating pressure
  - Operating temperature

2 steps modelling

- Evaluation of the explosion pressure
- Evaluation of the burst consequences



Example of hazard distances for different H2/O2 mixture

Separator volume	Operating pressure	$[H_2]$	Operating temperature	Explosion max. pressure	Dist. to 200 mbar	Dist. to 140 mbar	Dist. to 50 mbar
25 L	15 bar	Stoechiometric	65°C	139 bar	4 m	5 m	12 m
25 L	15 bar	10%	65°C	75 bar	3 m	4 m	9 m
100 L	35 bar	Stoechiometric	65°C	335 bar	9 m	11 m	25 m
100 L	35 bar	10%	65°C	175 bar	7 m	9 m	20 m

Largest amount of hydrogen in gas-liquid separator among all electolyser systems

Worst Case Scenarios

Based on the identification of possible events, two main scenarios are considered as worst-case:

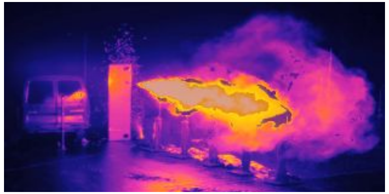
1. Explosion inside the container / building following a hydrogen release (loss of containment of separators, kg)
2. Explosion inside one of the two separators
   - H_2/O_2 mixture formed in the electrolyser cells
   - Mixture is pushed downstream to the different installations

⇒Considering only electrolysers, **gas-liquid separators correspond to the worst-case (largest hydrogen volume and highest risk)**

HOWEVER, is this a suitable scenario for safety distances?

Harmonisation Safety Distances - Multi Fuel refueling points

Explosion without venting panel



Flame from dispensing hose

- **Experimental investigations performed by HSE (UK) in order to assess consequences on the forecourt of different accidental scenarios**
  - Have been simulated
    Internal release with delayed ignition // **Jet fire from the dispensing hose** // **Whipping hose** // **Pool fire** from conventional fuel…

- **Results**

(1) **Simple model gives conservative results compared to experiments (in the Safety direction +++)**

(2) **Effects: Dispenser internal explosion < Flame from a hose release**
Dispenser scenario can be excluded for separation distances definition if equipped with explosion venting panels and smartly located

⇒ **Thus, it seems relevant to define Separation Distances based on the flame induced by a release from the hose, according to maximum flow rate**

A maximum of 6 m could be satisfying, even conservative because detection and ignition probability were not considered
(today 8 m for French regulation for 120 $g.s^{-1}$)

(3) **A pool fire from a conventional fuel at 2 m from the H_2 dispenser has no impact**

(4) **Comparison of equivalent jet fire scenarios between CNG and H_2 → CNG gives higher hazardous distances**

⇒ **No reason to have more drastic separation distances for H_2 than those existing for CNG**
(quid of separation distances for NG stations)

MultHyFuel

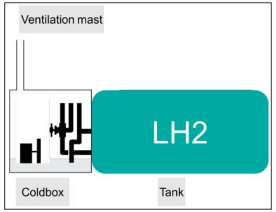
Stakeholders engagement

- Associations (EIGA, CGA, Hydrogen Council, IEA TCP H2, etc.)
- Research institutes
- First responders via funded projects/ trainings
- Regulatory & Standardisation bodies

HyResponder

CENTER FOR Hydrogen SAFETY

Knowledge gaps - on-going research activities



ESKHYMO

Large scale

- Experimental setup for pool spreading studies
- First experiments and validation using LN2
- Experiments with LH2 at INERIS summer 2025

Lab and medium scale :

- Determination at low T for H2/Air mixtures
    - flammability limits
    - ignition energies
    - Flame speeds
    - Flame acceleration in balloon

ELVHYS

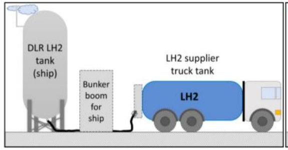
Start : 2023

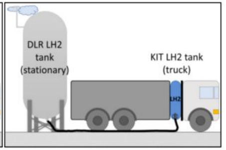
1st workshop on the SoA of cryogenic transfer technologies and related safety issues

2nd workshop on Experimental research and case studies of cryogenic hydrogen incidents at HSE, Buxton UK

Experimental program

- LH_2 refuelling procedure
- O_2 enrichment and condensed phase explosion
- Material testing against unignited / ignited jets
- LH_2 releases in confined spaces
- Rupture of transferring line






Air Liquide
Thank you!
Public