EU TWG for Seveso Inspections & OECD
WP on Chemical Accidents

Hydrogen Fuel Risks Part 1

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European Commission

Consequence analysis and new scenarios – dealing with specific hydrogen fuel risks

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Speaker Profile

- Professor of Chemical Engineering at Bologna University
- Ph.D. in Chemical Engineering
- Chair of Energy Section of the European Federation of Chemical Engineering
- Member of the Working Party on Loss Prevention in the Process Industry of the European Federation of Chemical Engineering
- Chair of the Technical Committee on Chemical and Process Industry of the European Safety and Reliability Association
- Associate Editor, Safety Science (Elsevier)
- Member of Editorial Board, Journal of Hazardous Materials and Journal of Loss Prevention in the Process Industry

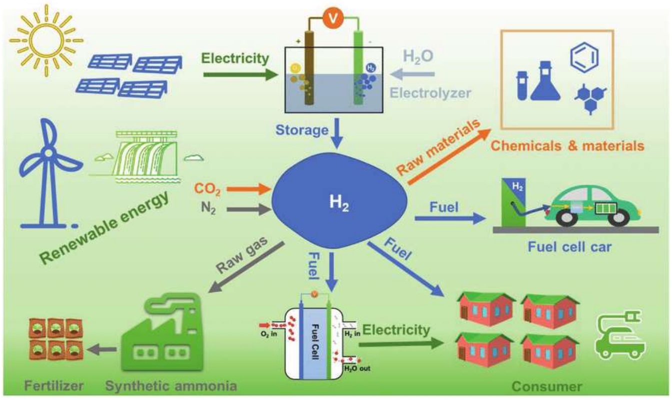
Outline of the presentation

1. Hydrogen and Energy Transition: new scenarios
2. Focus on consequence analysis
3. Conclusions and opportunities

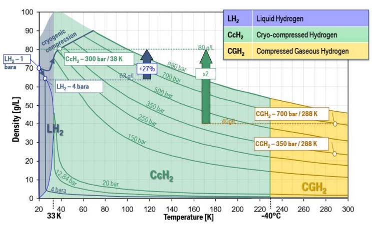
1 – Hydrogen and Energy Transition: New Scenarios

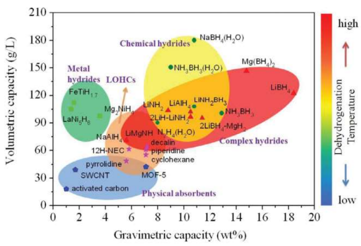
Technologies for Energy Transition:
Hydrogen

- Green hydrogen is the more important energy vector for the future energy system
- Use of hydrogen as an energy vector is proposed for both industrial and **urban / domestic** applications



Technologies for Energy Transition:
Hydrogen Storage Systems





Compressed (CGH_2) – *Mainstream*:
Single/Multi-pressure vessel 700 bar

Source: Quantum

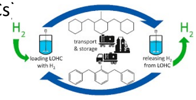
Cryogenic Liquid (LH_2) – *Demonstration level*:
Super-insulated low pressure cryotank

Source: BMW

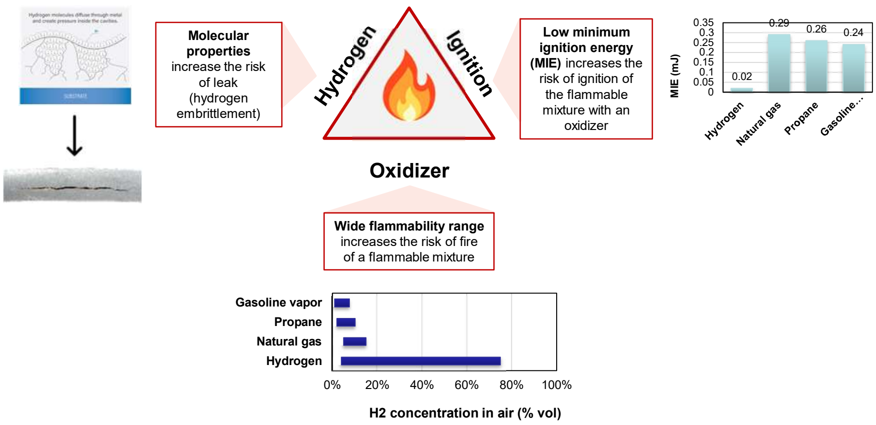
Cryo-Compressed (CcH_2) – *Prototype level*:
Super-insulated pressure cryotank (350 bar)

Source: BMW

Liquid Organic Hydrogen Carriers (LOHCs)



Hydrogen Safety

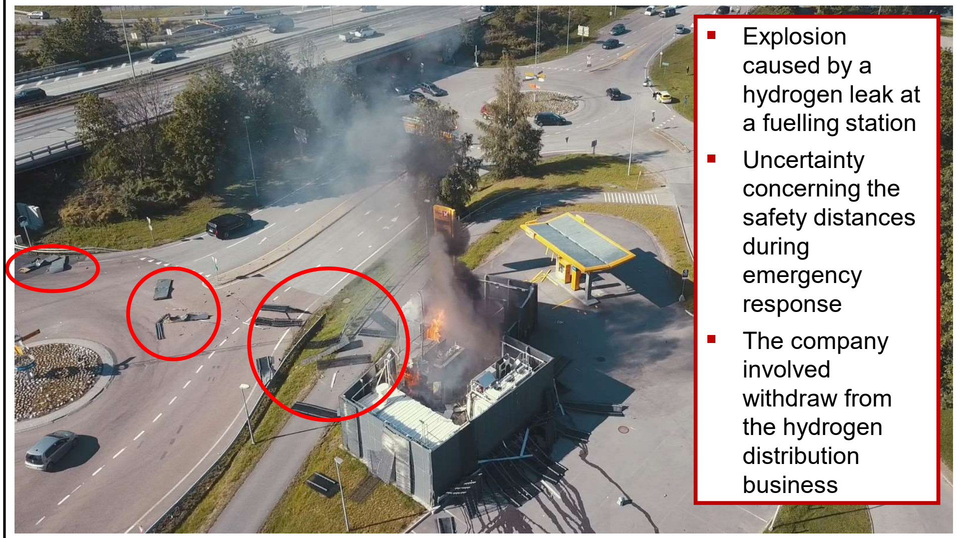


Hydrogen Safety:
No more only a problem of "big players"

- Meeting the Paris agreement objectives requires the decarbonization of domestic applications and of private transportation
- Renewable energy technologies and energy vectors are expected to be applied outside industrial areas: in ports, airports, fuel stations, residential areas, schools…
- Operating experience with hydrogen is wide, **but limited to industrial use**:
  - ✓ Trained operators
  - ✓ Clearance areas
  - ✓ Limits to simultaneous operations
  - ✓ ATEX standards (no/limited ignition sources)

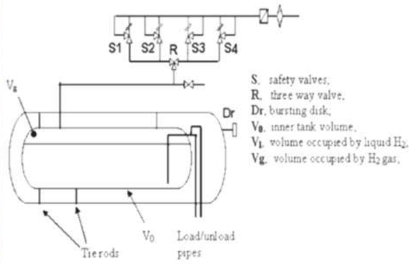
A completely different scenario is expected when the application addressed urban / residential areas

Kjørbo, Sandvika, Norway, 2019



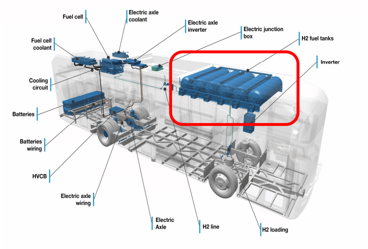
- Explosion caused by a hydrogen leak at a fuelling station
- Uncertainty concerning the safety distances during emergency response
- The company involved withdraw from the hydrogen distribution business

Porta Susa Marshalling Yard, Turin, Italy, 1991



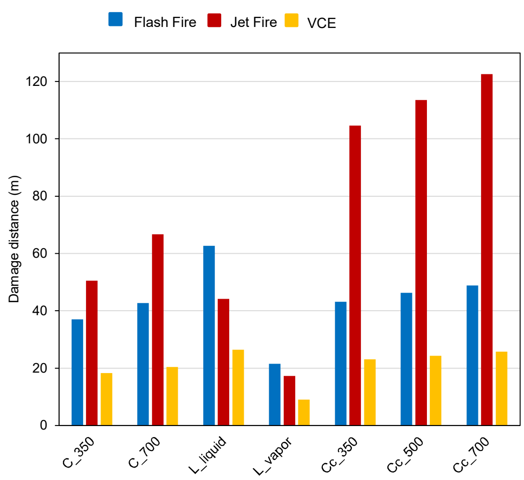
- Loss of vacuum in the thermal insulation layer of a cryogenic tank (42m^3) for hydrogen transportation by railway
- Unignited gaseous hydrogen release from PRV
- No further consequence, tank emptied in 7 hours

New Hydrogen Buses in Urban Areas



Storage technology	H_2 physical state	Pressure (bar)	Temperature (K)	Type of tank
Compression (**CH_2**)	Gas	350-700	T_{amb}	High-pressure vessels, Type III and Type IV
Liquefaction (**LH_2**)	Liquid	< 10	~ 20 K	Super insulated cryogenic tanks
Cryo-compression (**CcH_2**)	Gas/Liquid	350-700	66-78	High-pressure super insulated cryogenic tanks

Damage Distances – Full bore rupture



- Simulation of the consequences of full bore rupture of main connection line
- Commercial or highest TRL solution considered for storage tank
- Simulations using Phast DNV 8.4, Pasquill class F, wind speed 1.5 m/s
- **Jet fire** is critical for high-pressure hydrogen; distances for CcH_2 (>100 m) are twice the ones for CH_2 with the same pressure level;

2 –
Focus on Consequence Analysis

Consequence analysis of hydrogen releases:
Pre-normative European Research

FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

PRESLHY

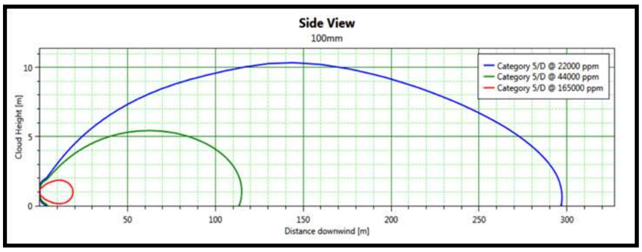
ELVHYS

PRENORMATIVE RESEARCH FOR SAFE USE OF LIQUID HYDROGEN
https://preslhy.eu/home/

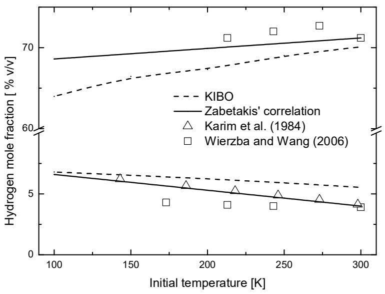
SH_2IFT project

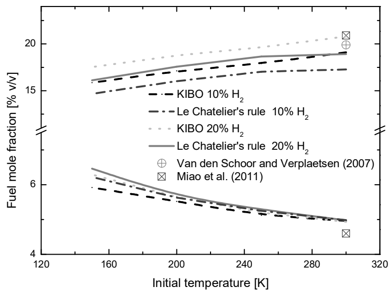
In the following, focus limited to:
- ❑ Dispersion and reactivity
- ❑ Jet Fires
- ❑ Cryogenic vessels

Hydrogen vs. Methane dispersion



Hydrogen vs. Methane reactivity





Pio and Salzano. 2019, J Hazard Mater, 362, 224-229

Detailed modelling: CFD

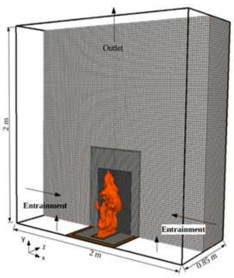
Several CFD models can be used for the modelling of hydrogen scenarios:
- ❑ ANSYS Fluent (multi-purposes, commercial)
- ❑ NIST FDS – Fire Dynamics Simulator (low-Mach simulator, open-source)
- ❑ OpenFOAM (multi-purposes, open-source)
- ❑ Gexcon FLACS – FLame ACceleration Simulator (commercial)
- ❑ …

ANSYS FLUENT®

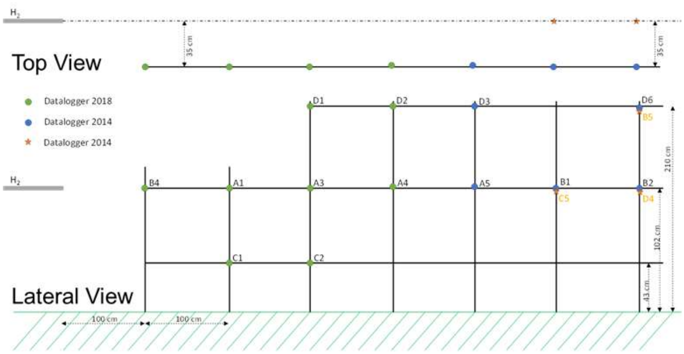
NIST Fire Research Division Engineering Laboratory

OpenFOAM

GEXCON



Consequence analysis of hydrogen releases:
Jet-Fire Testing



- Large-scale testing, VVF Trentino experimental field, Rovereto, Italy, release of compressed hydrogen, 240 – 450 bar

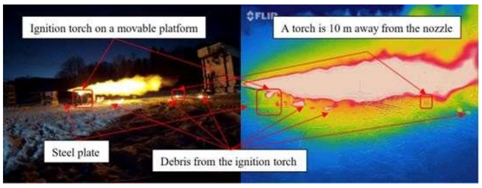
Vianello et al., Chemical Engineering Transactions, 82, 247-252, 2020
http//doi.org/10.3303/CET2082042

Consequence analysis of hydrogen releases:

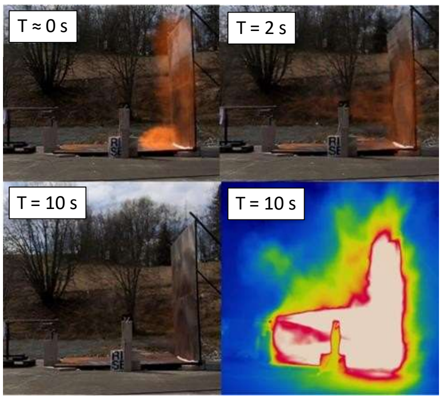
Jet-Fire Testing - SH_2IFT project

Results
Flame characteristics

Visibility decreases with daylight and when relative humidity in air is low



T = 2.5 s; RH= 95%

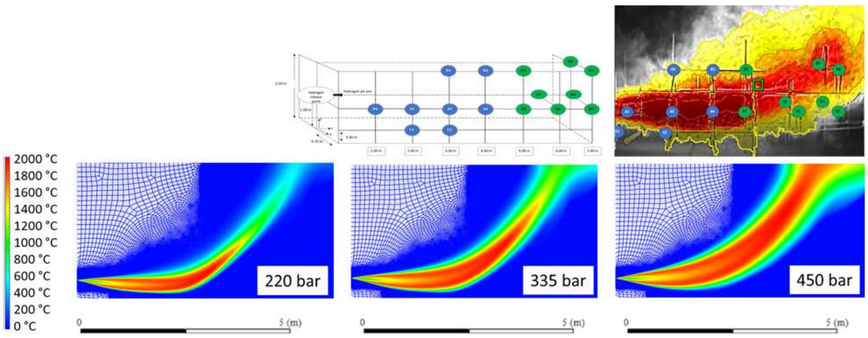


RH= 60%

21

A roadmap towards risk governance in energy transition:

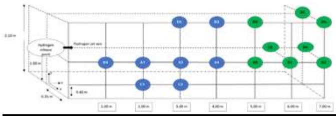
Jet-Fire Testing

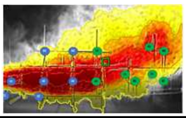


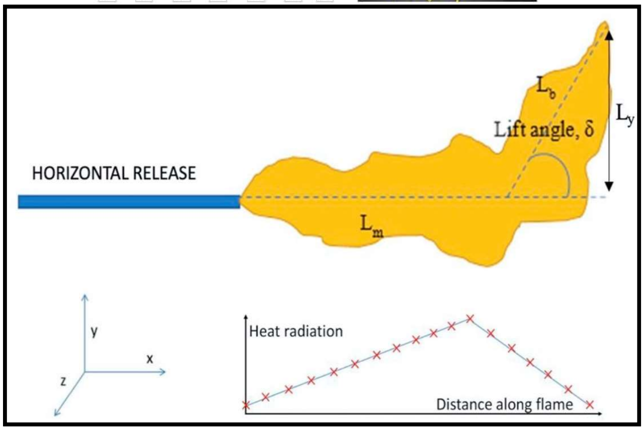
- CFD validation for jet-fire simulation obtained using full-scale experimental testing allows a more reliable assessment of safety distances

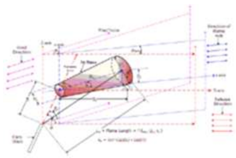
Vianello et al., Chemical Engineering Transactions, 82, 247-252, 2020
http//doi.org/10.3303/CET2082042

Consequence analysis of hydrogen releases:
Integral models: Miller model for jet fires

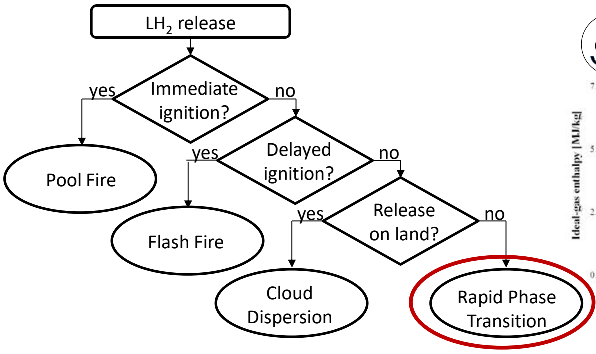


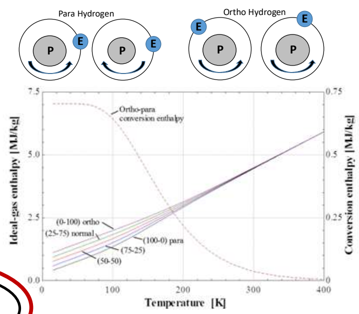






Consequence analysis of hydrogen releases:
Specific scenarios for cryogenic releases



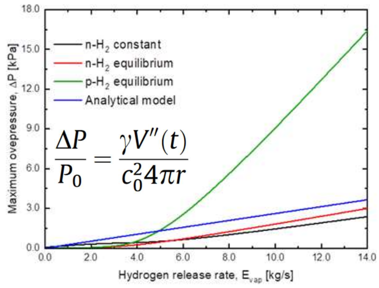


Ortho-para transformation (involves ~1.5 latent heat of vaporization)

Consequence analysis of hydrogen releases:

Rapid Phase Transition Explosion

RPT test: https://www.youtube.com/watch?v=h-EY82cVKuA

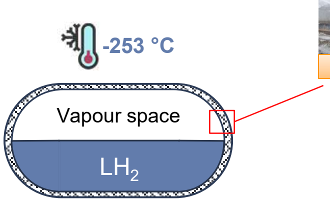


Prevalent theory for RPT explosion is Superheat Limit Temperature

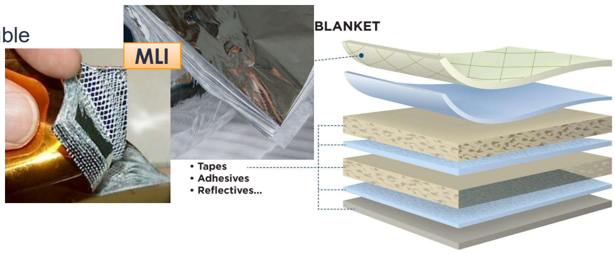
Salzano et al., 2020, Int J Hydrogen Energ, 45, 32676-32685

Consequence analysis of hydrogen releases:

BLEVE of cryogenic vessels



Cryogenic vessels are double walled and equipped with super-insulation materials



Consequence analysis of hydrogen releases:
BLEVE of cryogenic vessels

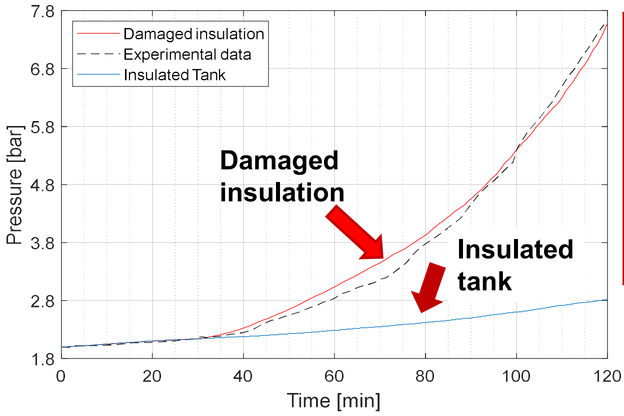
Fire Exposure

A roadmap towards risk governance in energy transition:
Full Scale Testing

BAM
Bundesanstalt für Materialforschung und -prüfung

A roadmap towards risk governance in energy transition:

CFD Modelling of Full-Scale Tests



CFD modelling is able to capture the dramatic modification in tank pressurization following loss of vacuum

Iannaccone et al., Process Safety Env. Protection, 149:735-749 (2021)
https://doi.org/10.1016/j.psep.2021.03.027

A roadmap towards risk governance in energy transition:

CFD Modelling of Full-Scale Tests

CFD analysis of cryogenic tanks involved in external fires:

A. Horizontal tanks for fuel storage on ships
B. Horizontal tanks for fuel storage on trucks

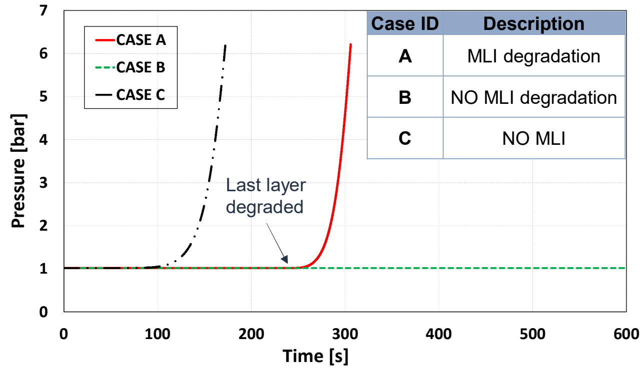
Thermal insulation: granular perlithe under vacuum

Case ID	Filling degree	Substance	Inner diameter [m]	Insulation thickness [m]	Insulation k_{tot} [mW/ (m K)]	Length [m]	Init. pressure [bar]	Init. temperature [°C]	MAWP; MDT [bar;°C]	Nominal capacity [m³]
Case A - Open-deck ship-fuel tank										
A85	85%									
A50	50%	CH_4	4.3	0.25	300	16.5	6.0	-134.42	11.0; 50	240
A15	15%									
Case B - Road tanker										
B85	85%									
B50	50%	CH_4	2.3	0.12	300	13.8	1.0	-161.49	3.0; 50	58.0
B15	15%									

MDT: maximum design temperature, as indicated by Annex B of EN 13458-2:2002

Iannaccone et al., Process Safety Env. Protection, 149:735-749 (2021)
https://doi.org/10.1016/j.psep.2021.03.027

Consequence analysis of hydrogen releases:
BLEVE of cryogenic vessels

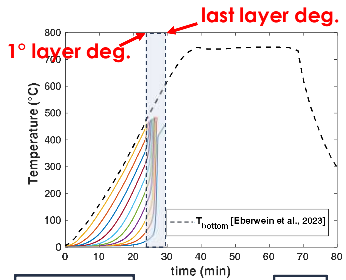


Case ID	Description
A	MLI degradation
B	NO MLI degradation
C	NO MLI

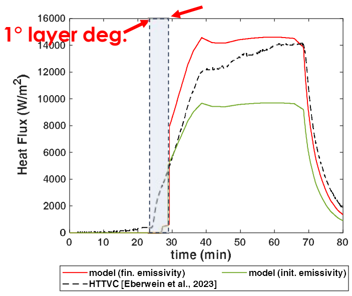
- Tank response with MLI degradation (A) is similar to the one of an unprotected tank (C) rather than one with an intact insulation (B)
- CASE B pressurization is negligible

Consequence analysis of hydrogen releases:
BLEVE of cryogenic vessels

Temperature of MLI layers



Heat flux measured vs simulated



EBERWEIN et al., 2023

Moment at which the heat flux measured by HTTVC strong increases is simulated pretty well by the model(a voce)

6 –
Conclusions and opportunities

Conclusions and future perspectives

- The energy transition and the diffusion of hydrogen as an energy vector for urban and residential application is expected to strongly influence the safety of workers and population
- Specific accident scenarios are expected to become relevant due to: **new technologies, specific hydrogen properties, cryogenic applications**
- New knowledge and a rapid evolution of consequence analysis tools to support the regulatory framework is required to assure a safe use of hydrogen
- Energy transition is also an opportunity to develop and implement safer and more resilient digitalized sustainable energy technologies

Acknowledgments

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