Hydrogen safety considerations for the power-to-gas (P2G) conversion process

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Invited Presentation at the Hydrogen Production Workshop
Électricité de France (EDF), 78400 CHATOU, FRANCE

November 4 – 7, 2019

Presentation objectives

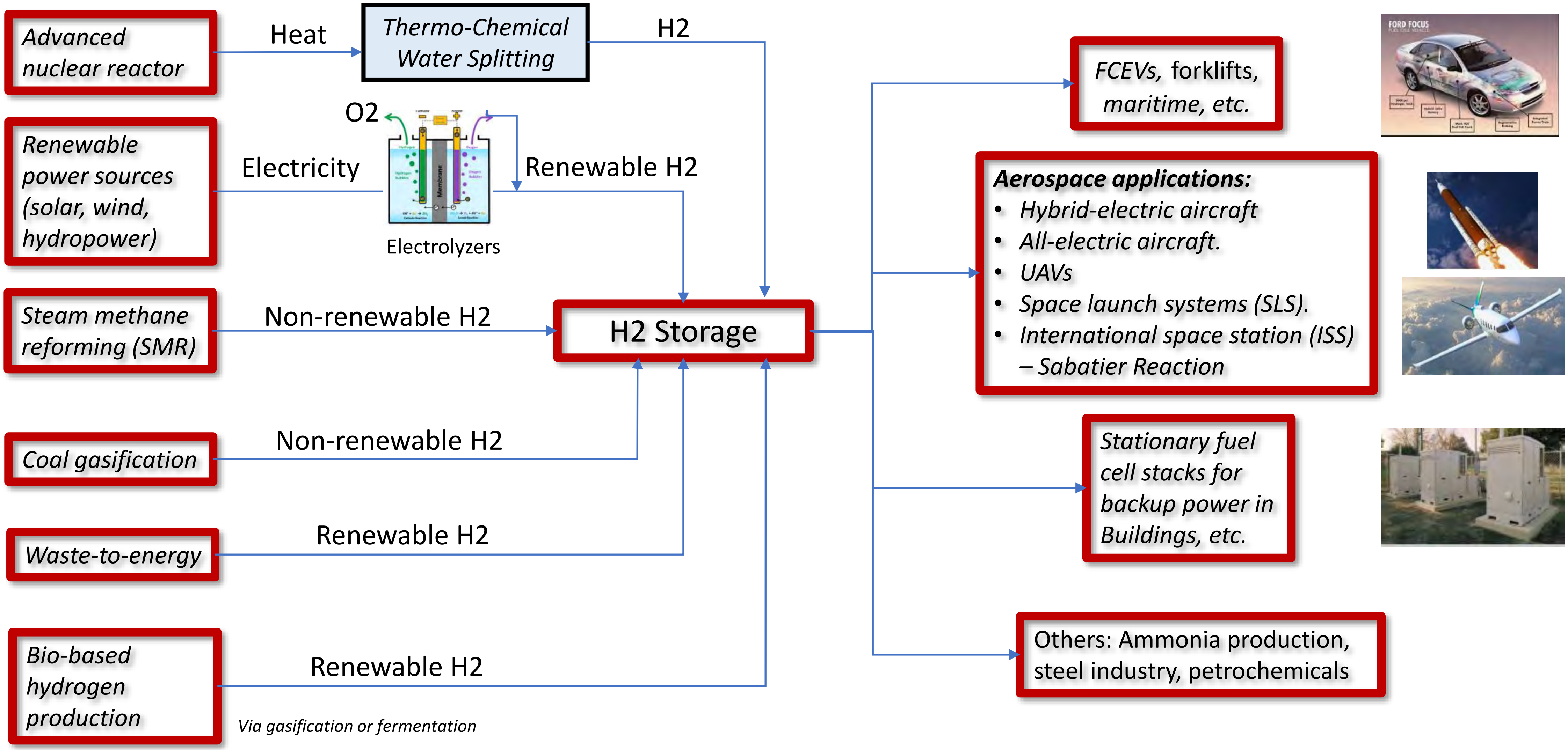
- Description of the power-to-gas (P2G) process
  - Highlight P2G benefits.
  - Discuss safety considerations associated with P2G.
- Concluding remarks / recommendations.
- References

Strategy

- Collaboration with other IEA Hydrogen Tasks
- Collaboration with other IEA TCPs

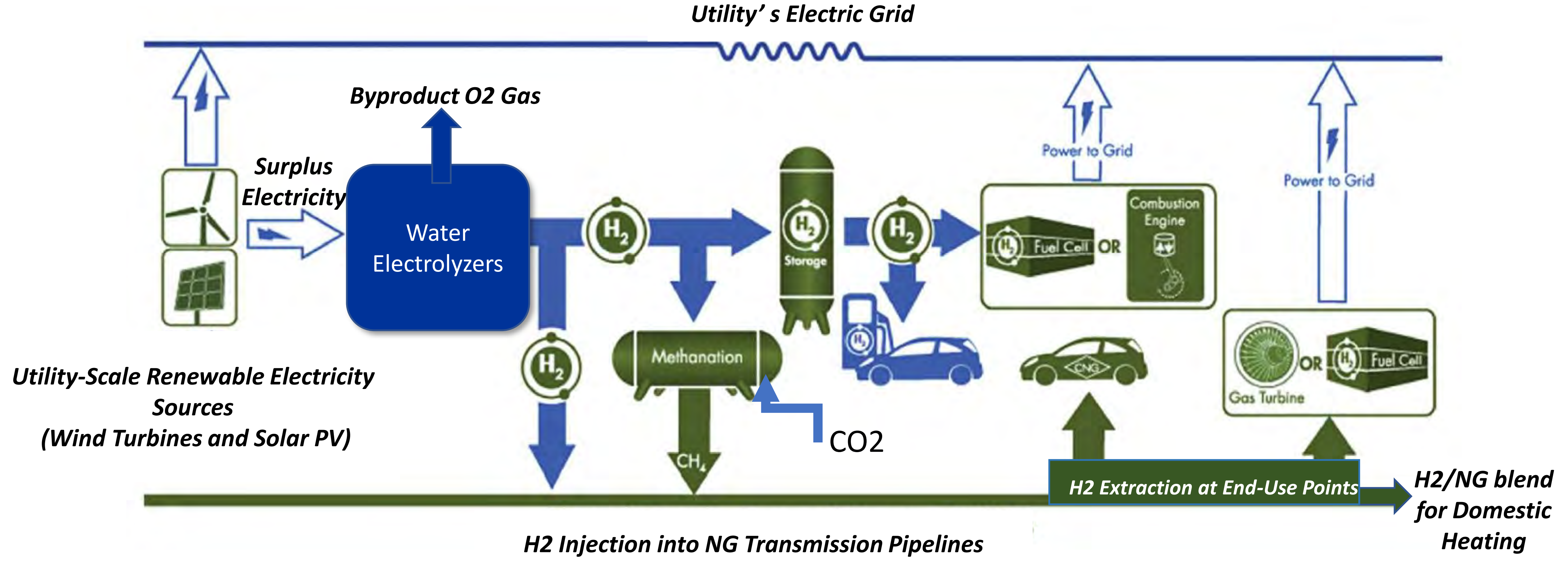
Renewable and non-renewable H2 production and key applications

Source: Khalil, Y.F. (May, 2019). Presentation at the International Energy Agency (IEA) Meeting, University of Oxford, UK.



Schematic of P2G ecosystems

- *Power-to-gas (P2G) <u>enables storage of surplus renewable electricity</u> in the form of hydrogen injected into NG pipelines.*
- ***A good case in point:** California's 2030 mandate of 50% utilization of renewable power will require considerable amounts of energy storage.*



Modified figure from: http://www.apep.uci.edu/NewsAndEvents/newsarchives/08272015-p2g.aspx

Benefits of P2G concept

- Store excess renewable electricity (from solar PV and wind turbines) in the form of hydrogen gas.
- Deliver H2 to the end-use markets (requires H2 separation and purification at points of use).
- Defray costs associated building separate pipeline infrastructures for delivery of stored H2 to points of end users.
- Support FCEVs near-term market readiness.
- Improve air quality by averting gasoline and diesel burn in internal combustion engines which leads to reduction of primary air pollutants such as SO2, NOX, and PM.
- Reduce GHS emissions for the cases where H2 production is from:
  - Renewable sources (solar PV, wind turbines, nuclear, biomass).
  - SMR integrated with CCS.

Blending H2 with NG: Impact on NG gas properties and safety considerations

Gas Property / Safety Issue	Impact of H2 Addition on NG Properties
Gas density	Decrease **(Fig. 1)**
Gas viscosity	Decrease
Gas leak rate	Increase
Lower flammability limit (LFL)	Minor change **(Fig. 3)**
Higher flammability limit (HFL)	Increase **(Fig. 3)**
Flammability range	Wider **(Fig. 3)**
Detonability range	Winder

Gas Property / Safety Issue	Impact of Blending H2 with NG
Explosive energy per unit volume	Decrease
Explosive energy per unit mass	Increase
Minimum ignition energy (MIE)	Decrease **(Fig. 4)**
Auto ignition temperature	Higher **(Fig. 2)**
Uncontrolled ignition	Easier to occur **(Fig. 4)**
Severity of explosive damage	Lower
Risk of explosion in confined spaces	Higher
Risk of explosion in open spaces	Lower

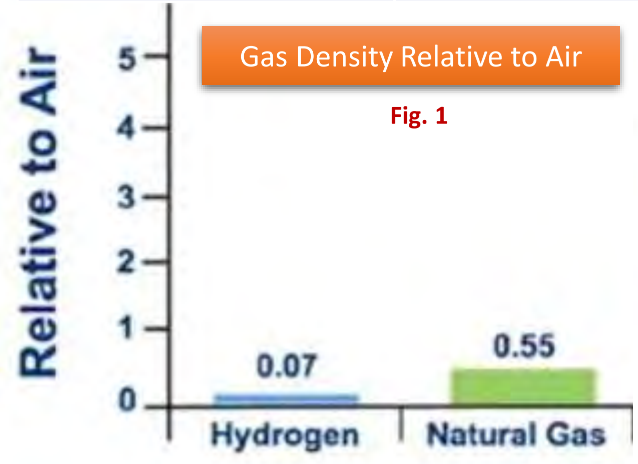


Fig. 1

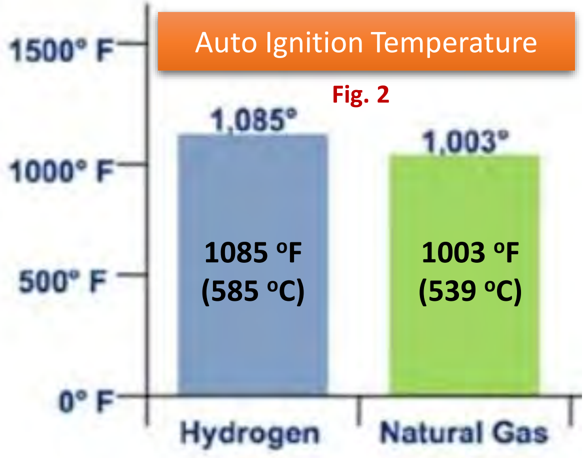


Fig. 2

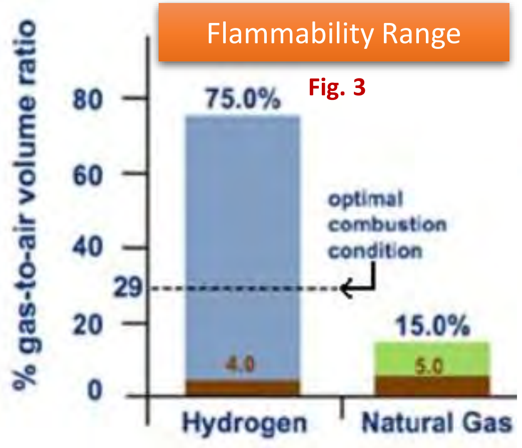


Fig. 3

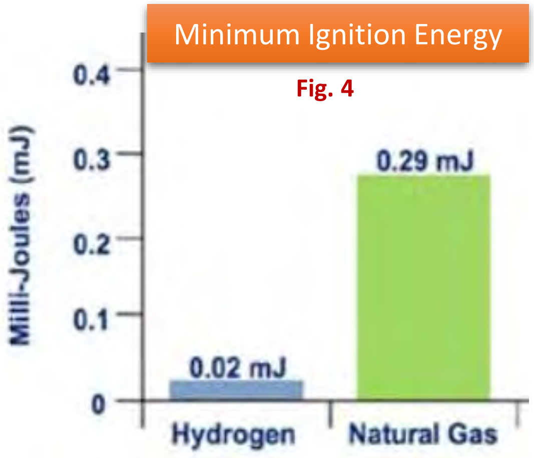
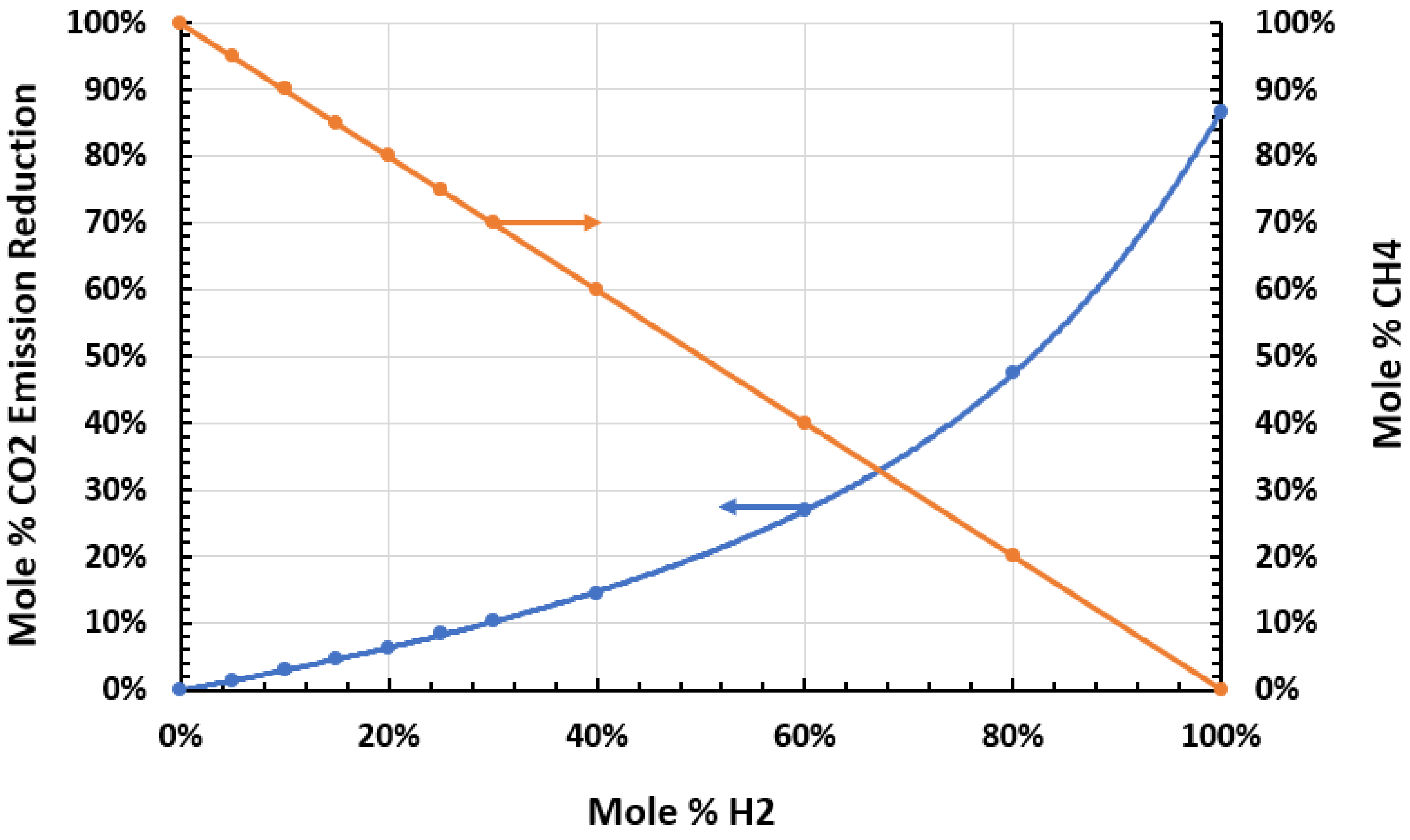


Fig. 4

CO2 emission reduction due to blending H2 with NG

- The calculation shown assumes that H2 in the blend is produced by SMR with carbon capture and recovery efficiency of ≈ 87 mole% (hence, CO2 emission would be 13 mole%).

- For gases, mole% is the same as volume%.



- A 5% blend of H2 could reduce CO2 emissions by ≈ 2%.
- A 30% blend of H2 could reduce CO2 emissions by ≈ 10%.
- A 80% blend of H2 could reduce CO2 emissions by ≈ 50%.

Khalil, Y.F. (2019).

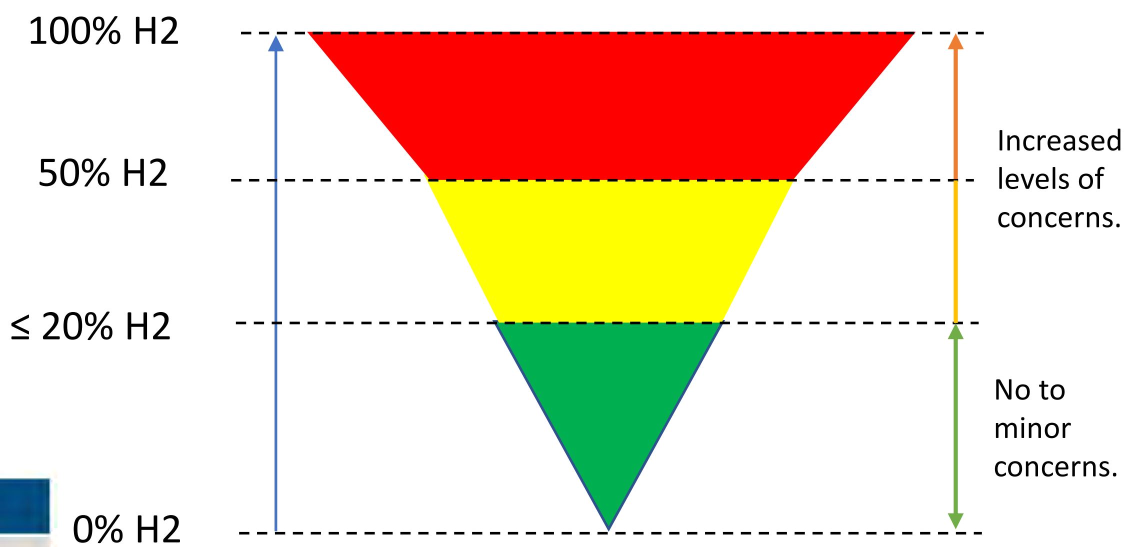
Potential safety issues associated with P2G process

- Hydrogen leaks in confined spaces ➔ fire and explosion hazards.

- Materials compatibility issue (H2 embrittlement) and impacts on durability and integrity of:

  - ✓ NG pipeline networks.
  - ✓ Household appliances (*viz.*, stoves, boilers).
  - ✓ Industrial boilers for steam and hot water generation.

vol% H2 in NG/H2 blend



P2G safety implications.

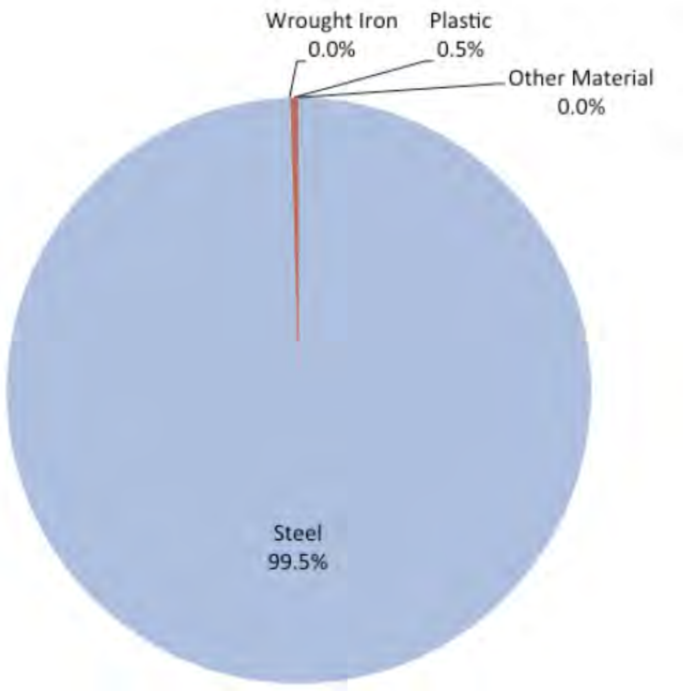
Property	Hydrogen	Comparison
Density (gaseous)	0.089 kg/m^3 (0°C, 1 bar)	1/10 of natural gas
Density (liquid)	70.79 kg/m^3 (-253°C, 1 bar)	1/6 of natural gas
Boiling point	-252.76°C (1 bar)	90°C below LNG
Energy per unit of mass (LHV)	120.1 MJ/kg	3x that of gasoline
Energy density (ambient cond., LHV)	0.01 MJ/L	1/3 of natural gas
Specific energy (liquefied, LHV)	8.5 MJ/L	1/3 of LNG
Flame velocity	346 cm/s	8x methane
Ignition range	4–77% in air by volume	6x wider than methane
Autoignition temperature	585°C	220°C for gasoline
Ignition energy	0.02 MJ	1/10 of methane

➔ LFL_{CH4} = 4.9 vol% & UFL_{CH4} = 15 vol%

NG transmission and distribution service pipelines (PHMSA 2012).

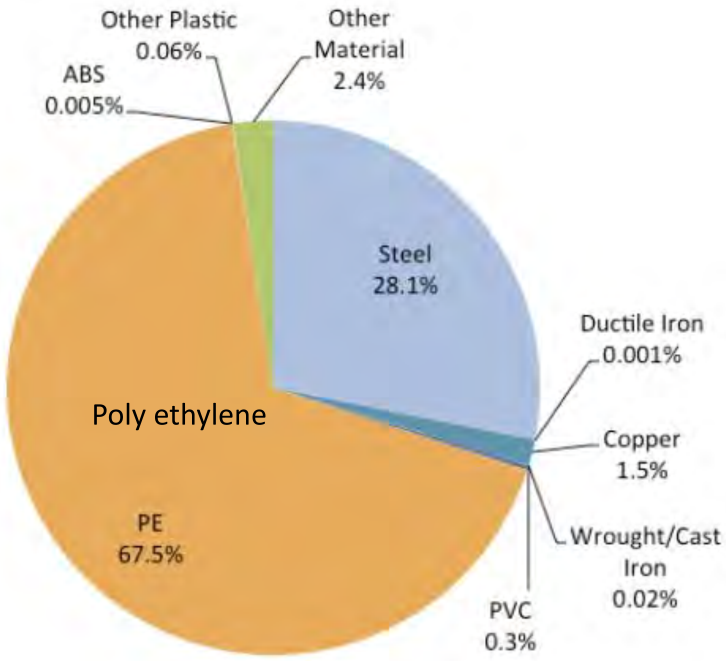
- *For the case of blending H2 with NG, the probability of a gaseous leak (P_{leak}) is dependent on several factors including: H2 concentration in the blend, internal gas pressure and* ***type of pipeline material****.*

- *H2 permeation rates are* ***≈4 to 5 times faster than CH4*** *in typical polymer pipes used in the U.S. natural gas distribution system.*



Pipelines durability and integrity are potential long-term concerns with increased H2% in the blend

Leak Risk = P_{leak} x C_{leak}



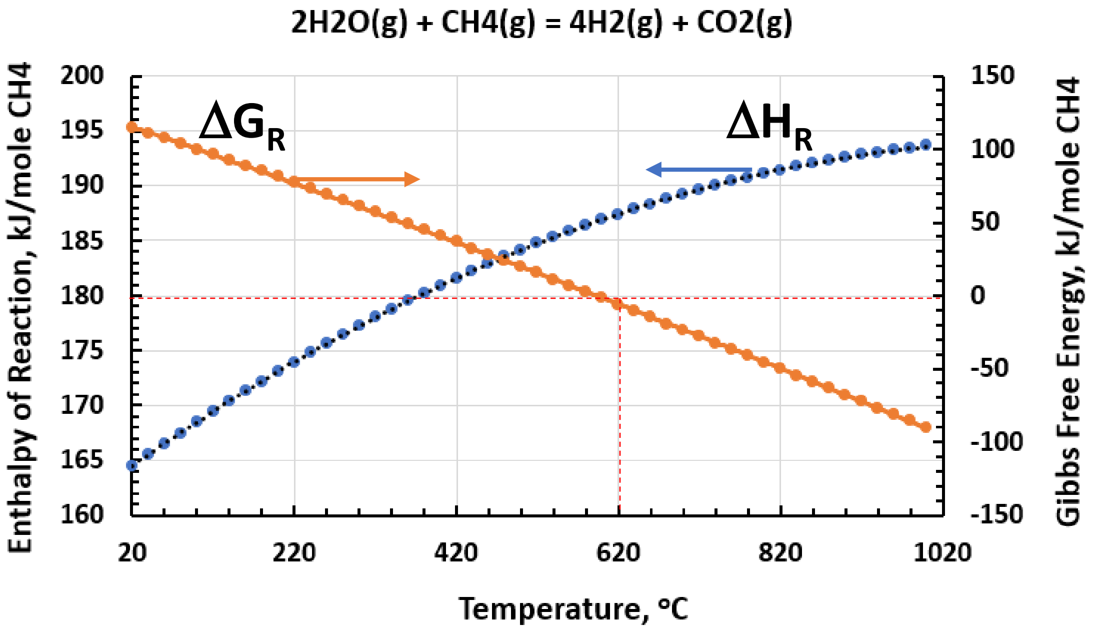
Materials used for NG transmission pipelines [tend to be large in diameter (*e.g.*, 48”) and at higher pressures (*e.g.*, 85 bar)].

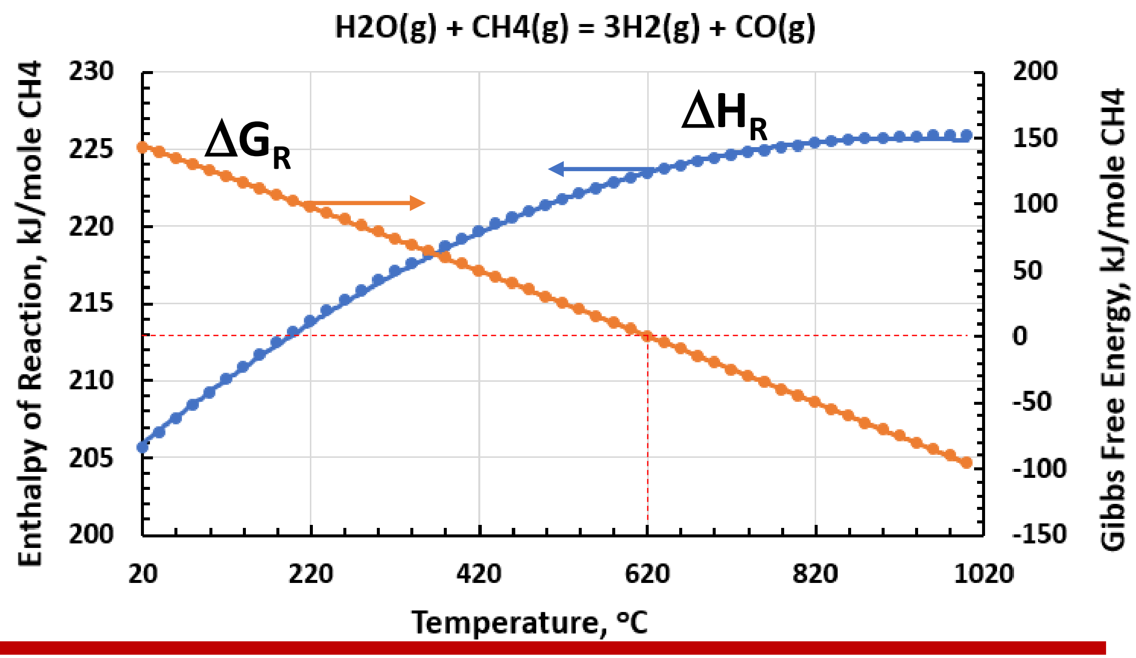
Materials used for NG distribution service pipelines [tend to be smaller in diameter (*e.g.*, 4”) and at lower pressure (*e.g.*, 6 bar)].

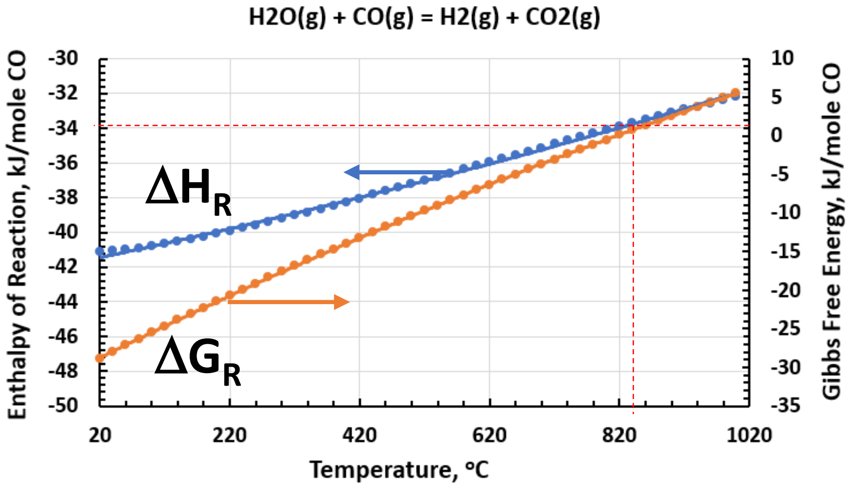
PHMSA = The U.S. Pipeline and Hazardous Materials Safety Administration.

Thermodynamic calculations of SMR reaction for non-renewable H2 production

Source: Khalil, Y.F. (2019). Thermodynamic calculations of SMR reaction for non-renewable H2 production.







Water-gas shift (WGS) reaction.

Thermodynamic calculations of combustion reactions: CH4, H2, and CH4/H2 blend

iea hydrogen

Source: Khalil, Y.F. (2019). Thermodynamic calculations of SMR reaction for non-renewable H2 production.

- All three combustion reactions are thermodynamically feasible (*i.e.*, negative ΔG) at room temperature.

- Exothermic heat per mole of CH4 > exothermic heat per mole H2/NG blend (50:50 mole%) > exothermic heat per mole H2

CH4(g) + 2O2(g) = CO2(g) + 2H2O(g)			
T	deltaH	deltaS	deltaG
C	kJ	J/K	kJ
20.0	-802.606	-5.403	-801.023
25.0	-802.556	-5.233	-800.996

H2(g) + 0.5O2(g) = H2O(g)		
T	deltaH	deltaS
C	kJ	J/K
20.0	-241.776	-44.252
25.0	-241.826	-44.421

0.5H2(g) + 0.5CH4(g) + 1.25O2(g) = 1.5H2O(g) + 0.5CO2(g)			
T	deltaH	deltaS	deltaG
C	kJ	J/K	kJ
20.0	-522.191	-24.828	-514.913
25.0	-522.191	-24.827	-514.789

- On a volumetric basis, H2 requires less air than CH4 for a stoichiometric combustion.
- H2 has higher energy content per kg compared to CH4 (120.9 MJ/kg H2 vs. 50.2 MJ/kg CH4).

Risk quantification

Annual Risk = Initiating event frequency (IEF) x Consequence should the event occurs

- The event could be NG/H2 blend fire (or explosion) given presence of an ignition source
  - Note that explosion requires semi-confined or confined spaces.
- The consequence could be human injury (or fatality) and may also include property damage (if can be easily quantified).
  - See Khalil, Y.F. (2017)* for estimated statistical values of human injuries and fatalities.

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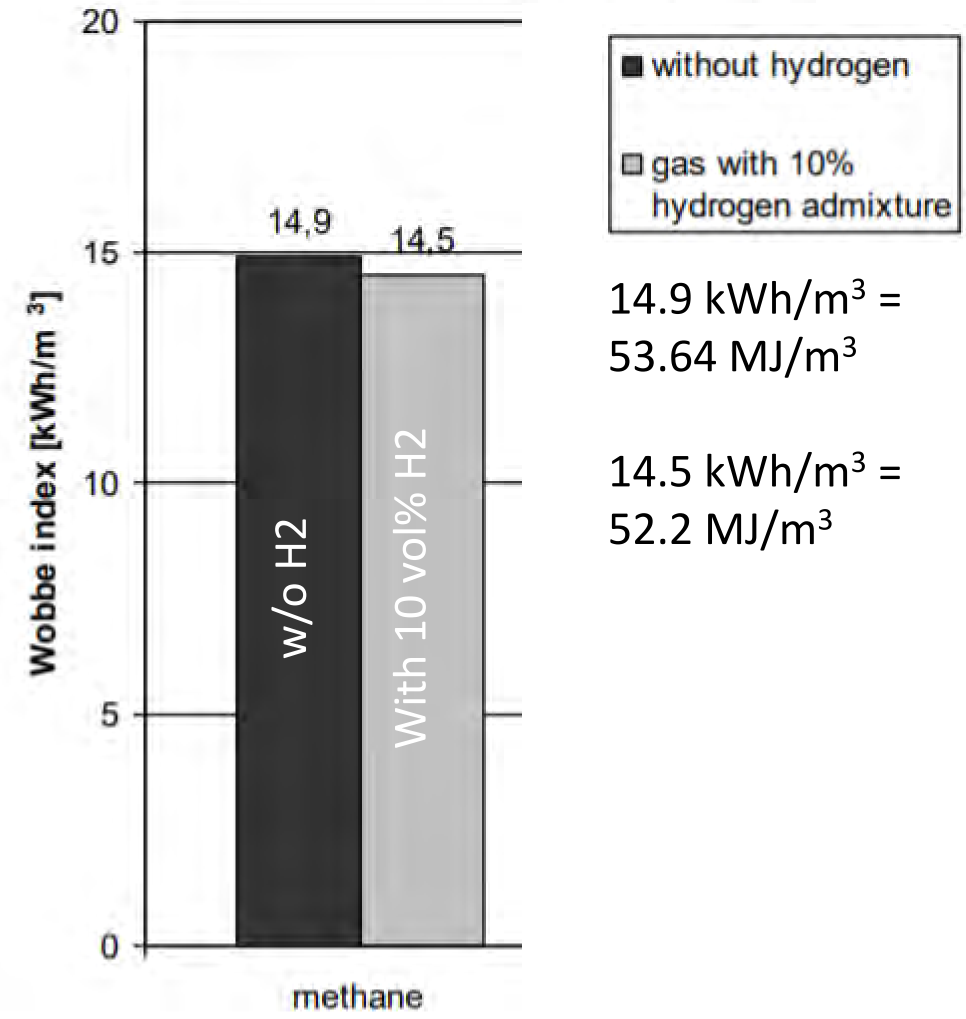
* *Khalil, Y.F. (2017). A probabilistic visual-flowcharting-based model for consequence assessment of fire and explosion events involving leaks of flammable gases. Journal of Loss Prevention in the Process Industries, 50, 190–204.*

Impact of adding 10 vol% H2 in NG: Wobbe Index (W)

$$\text{Wobbe Index} = \frac{\text{Heating Value}}{\sqrt{\text{Specific gravity}}}$$

$$\text{Specific gravity} = \frac{\text{Density fuel gas}}{\text{Density air}}$$



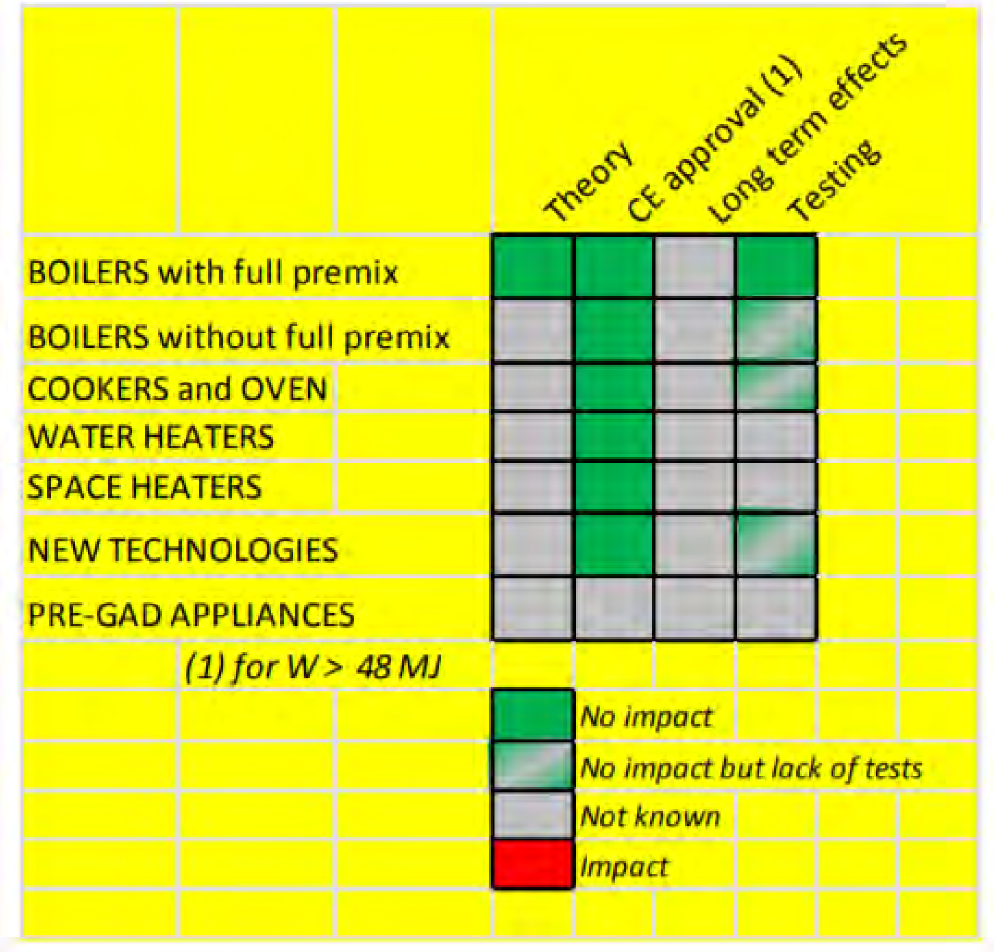
14.9 kWh/m³ = 53.64 MJ/m³

14.5 kWh/m³ = 52.2 MJ/m³

- The Wobbe index (W) is an indicator of the interchangeability of different gaseous fuels.
- Gaseous fuels with the same W-index produce the <u>same heat load in a gas burner</u>.
- W-index is the most important combustion parameter for gas appliances and is typically specified in all countries.
- Addition of 10% H2 in NG slightly reduces W-index by ≈ 2.8 %.

http://gerg.eu/public/uploads/files/publications/GERGpapers/HIPS_-_the_paper_-_FINAL.pdf

Impact of adding 10% H2 in NG for different appliances

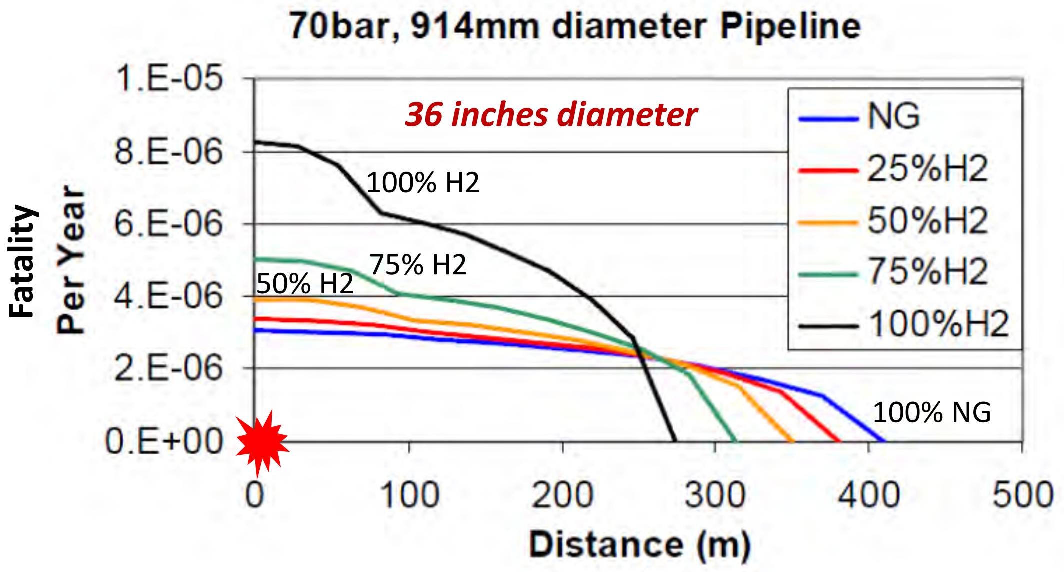


- Addition of 10 vol% H2 in NG seems to have a reasonable near-term future prospect for the shown domestic and commercial appliances considered.
- The “Gray” areas indicate uncertainties associated with long-term effects.
- Such uncertainties need to be addressed using science-based methods.

W is the Wobbe index of the fuel.

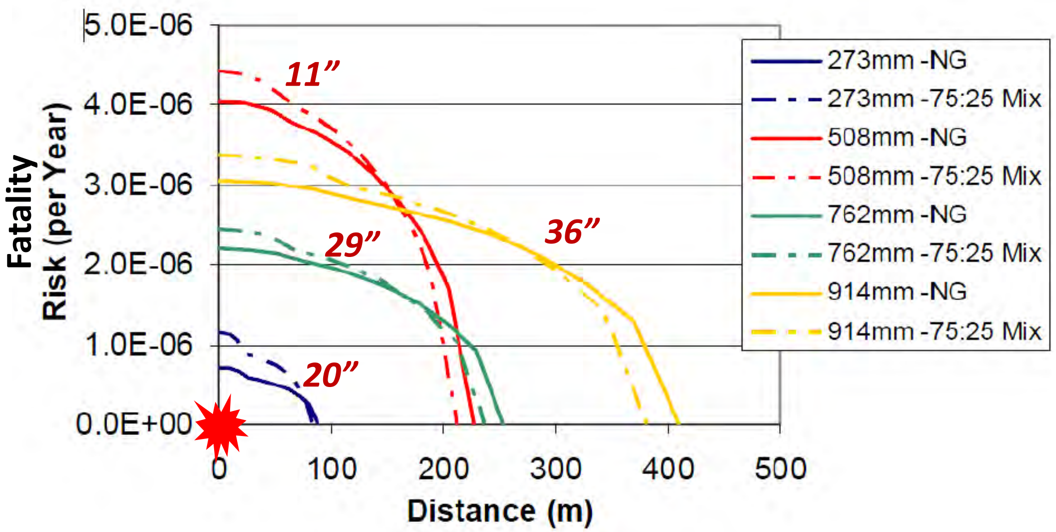
http://gerg.eu/public/uploads/files/publications/GERGpapers/HIPS_-_the_paper_-_FINAL.pdf

Fatality risk as a function of distance from the explosion point (*Lowesmith, 2009, NaturalHy project*).



Annual individual fatality risk as a function of distance from pipeline.

- Fatality risk declines for H2 blends at a distance of 265–400 m and increases closer to the pipeline.
- The risk associated with explosion of a NG pipeline drops to zero at just over 400 m from the pipeline. However, adding 25% H2 decreases this distance by about 25 m while slightly increasing risk closer to the pipeline.
- The rapid dispersion of H2 mixtures, which results in lower concentrations at shorter distances and therefore reduced risk at the far edge of the hazard distance.
- For 50% and 75% H2, the hazardous distance is reduced by ≈ 75 m and 100 m, respectively, and the increase in risk closer to the pipeline is more significant.



Annual individual fatality risk by adding H2 to NG pipeline

- The 508-mm (11-inch) pipeline is apparently at a lower pressure than the other pipelines and therefore follows a different trend.
- The smaller-diameter pipelines have shorter hazardous distances and addition of 25% H2 reduces the hazardous distance while slightly increasing risk near the pipeline. This shift is quite small for a 25 vol% H2 in the H2/NG blend.

Operational hazard during hydrogen burning

- As mole% H2 increases in the H2/NG blend, domestic operational hazard (e.g., during cooking) increases due to reduced visibility of hydrogen flame during burning.

- CCTV visual flame detectors cannot detect flames that are invisible to the naked eye such as hydrogen flames.*

https://h2tools.org/bestpractices/hydrogen-flames

* *Hydrogen burns with a pale blue flame that is almost invisible during daylight hours thus fires are almost impossible to see with the naked eye.*

https://ieaghg.org/docs/General_Docs/Reports/Ph4-24%20Hydrogen%20in%20nat%20gas.pdf

http://s7d9.scene7.com/is/content/minesafetyappliances/Flame%20Detector%20Technologies%20White%20Paper

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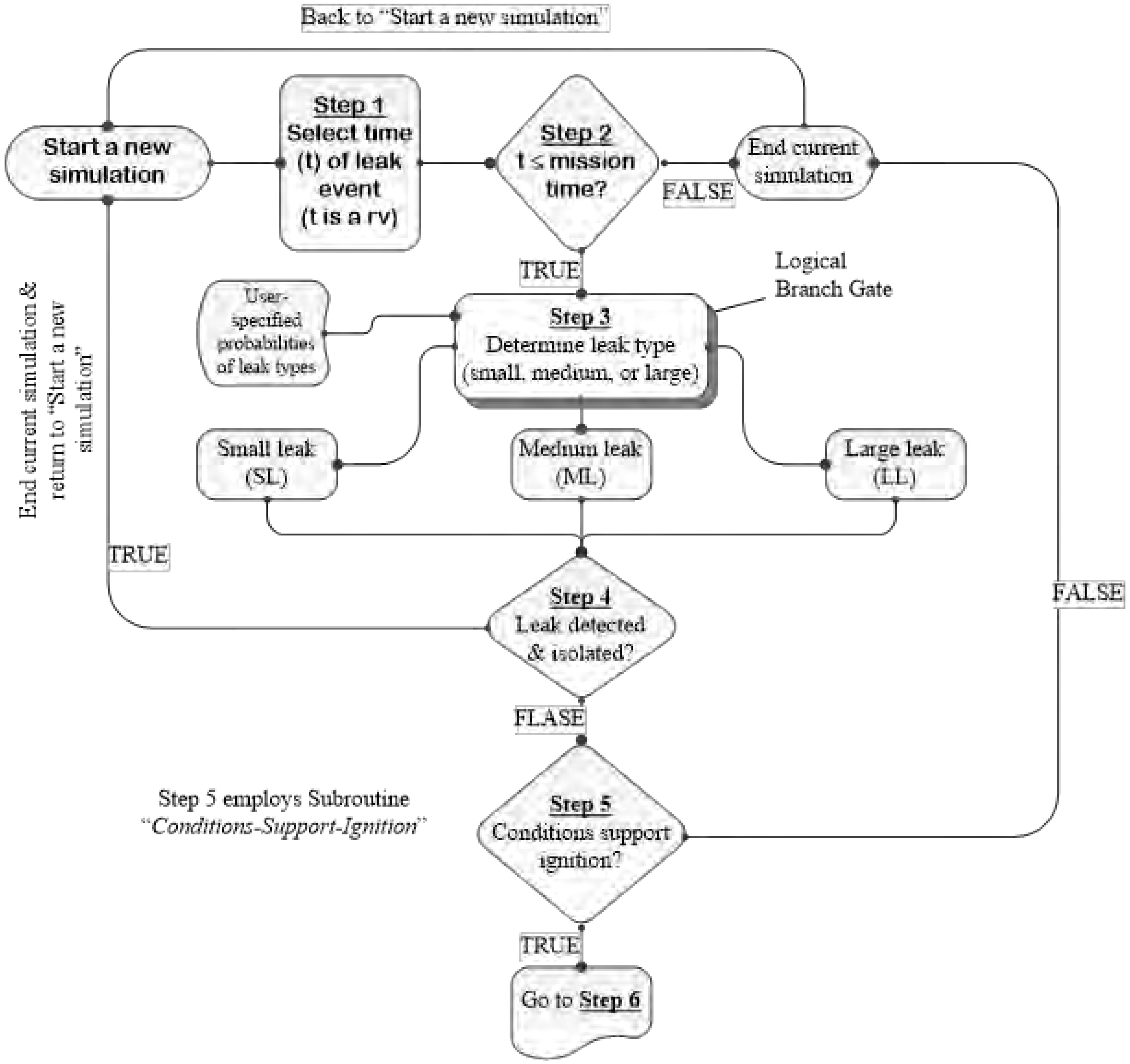

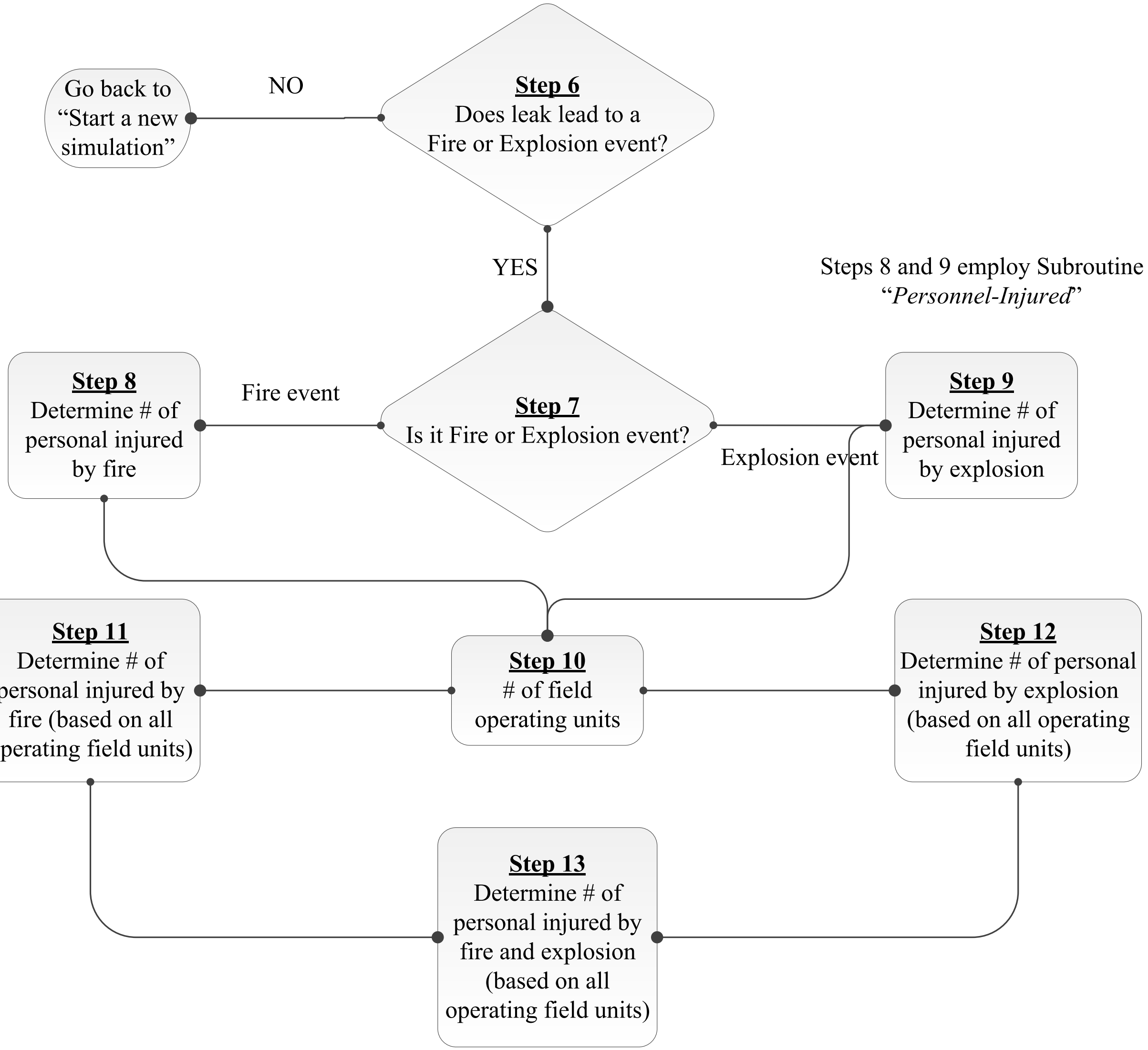

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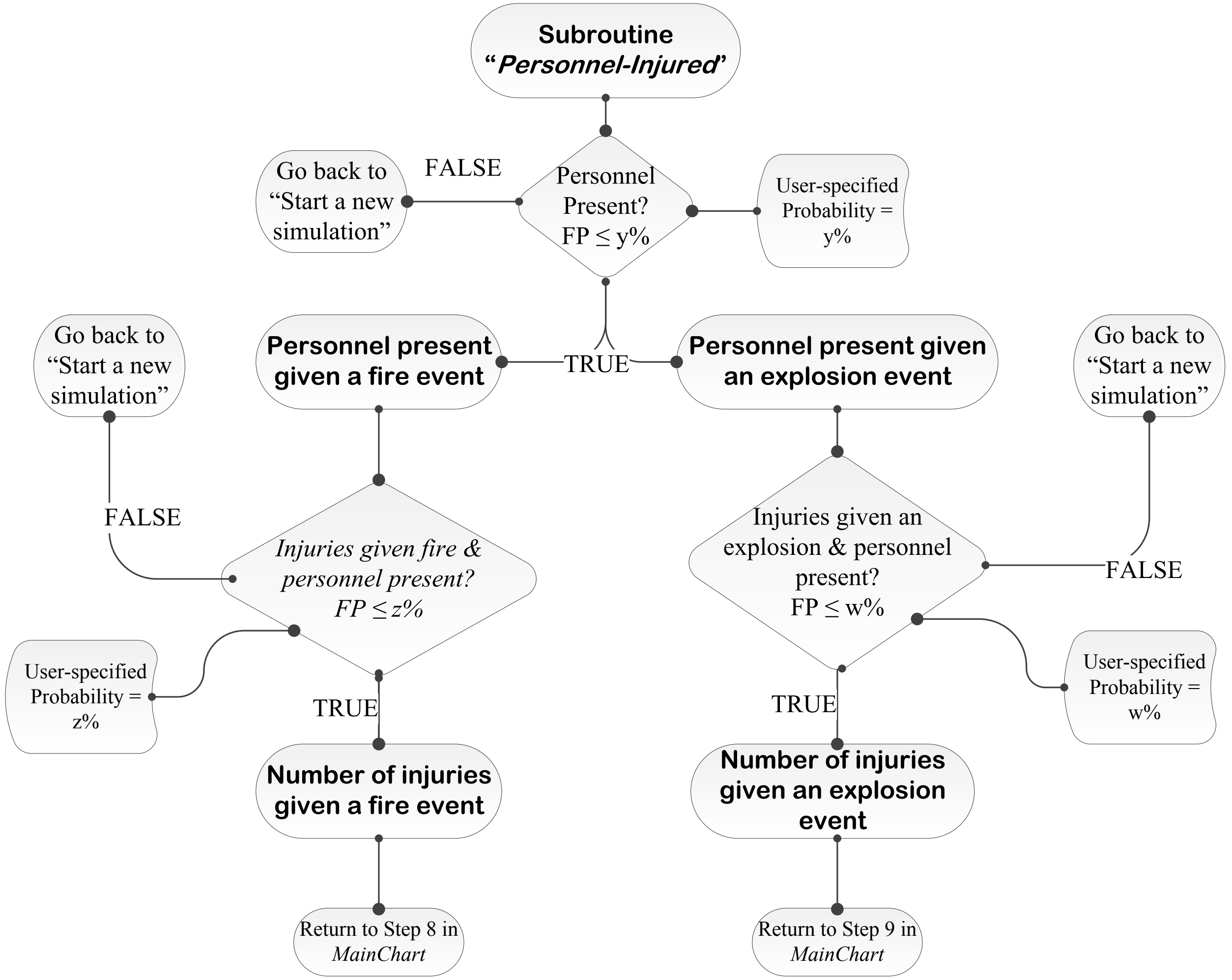
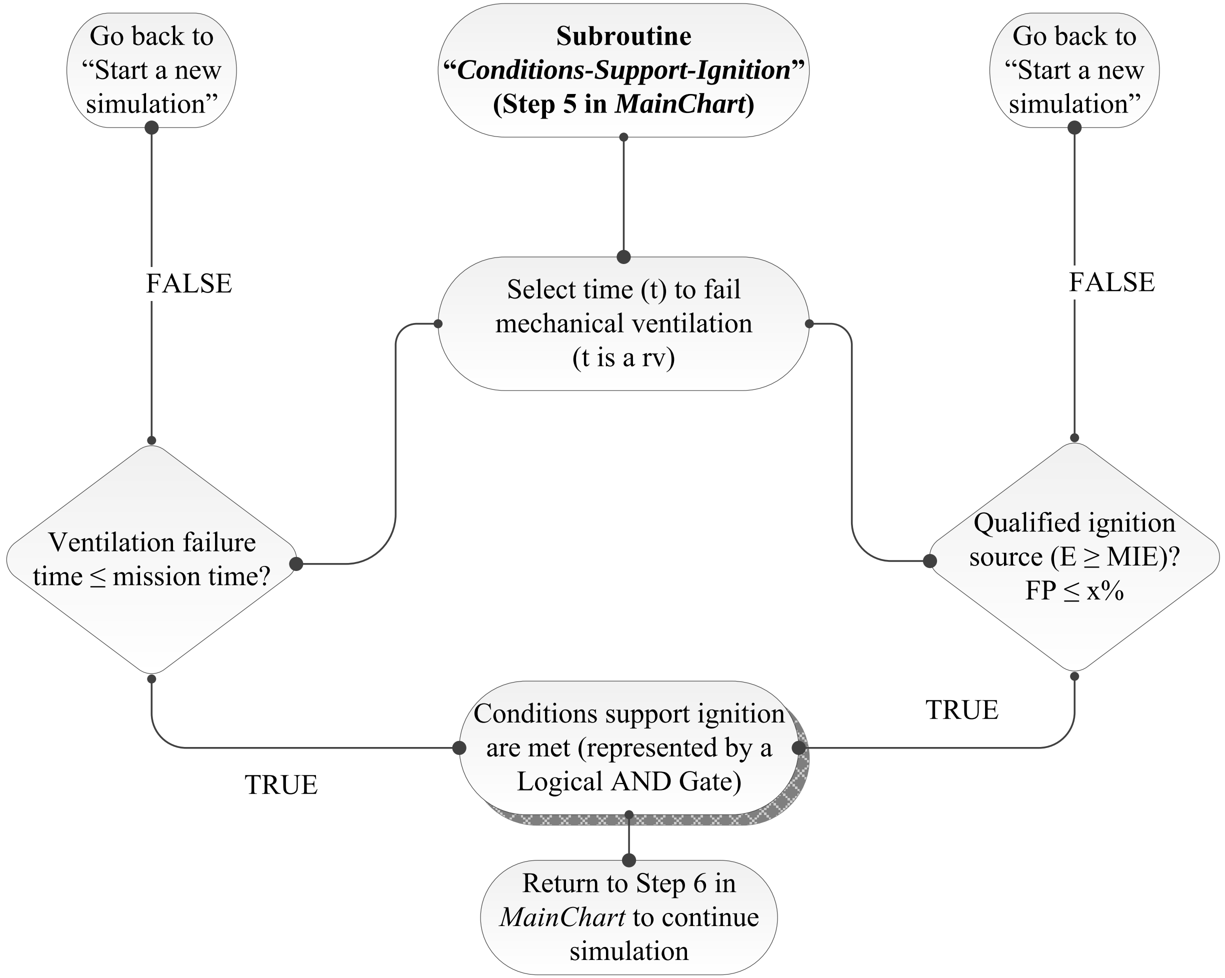




Calculated annual risks of fire and explosion injuries.

Khalil, Y.F. (2017). Journal of Loss Prevention in the Process Industries, 50, 190–204

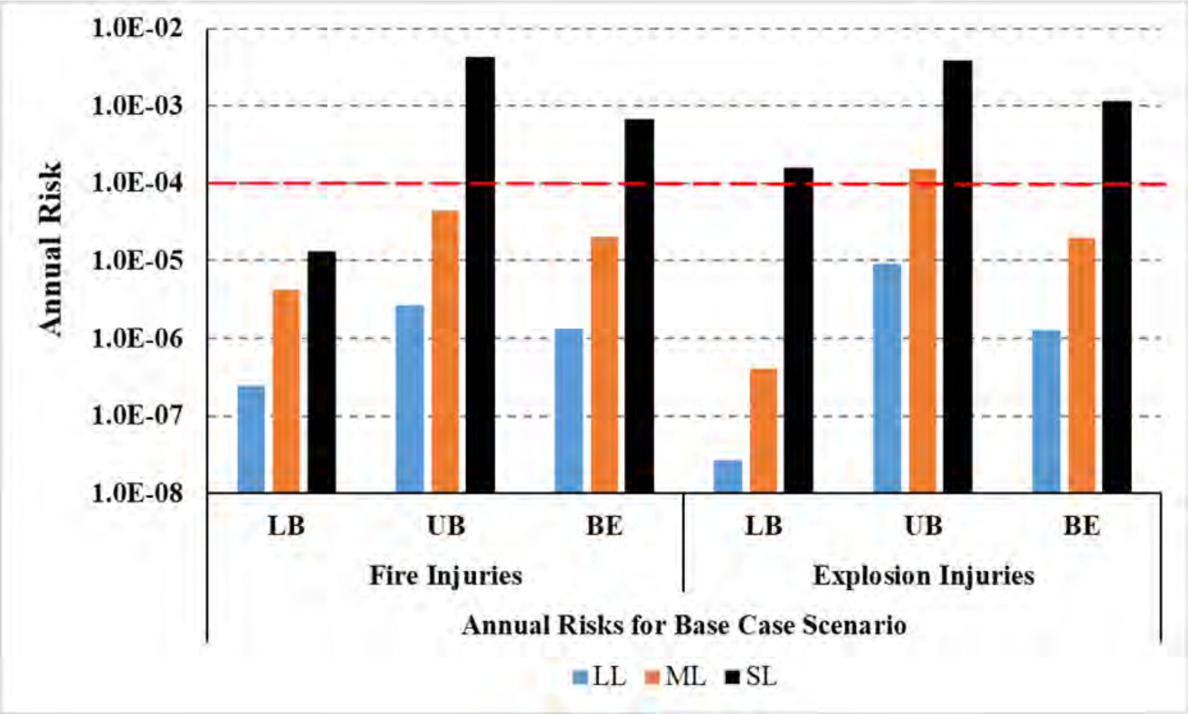


Fig. x. Base case scenario

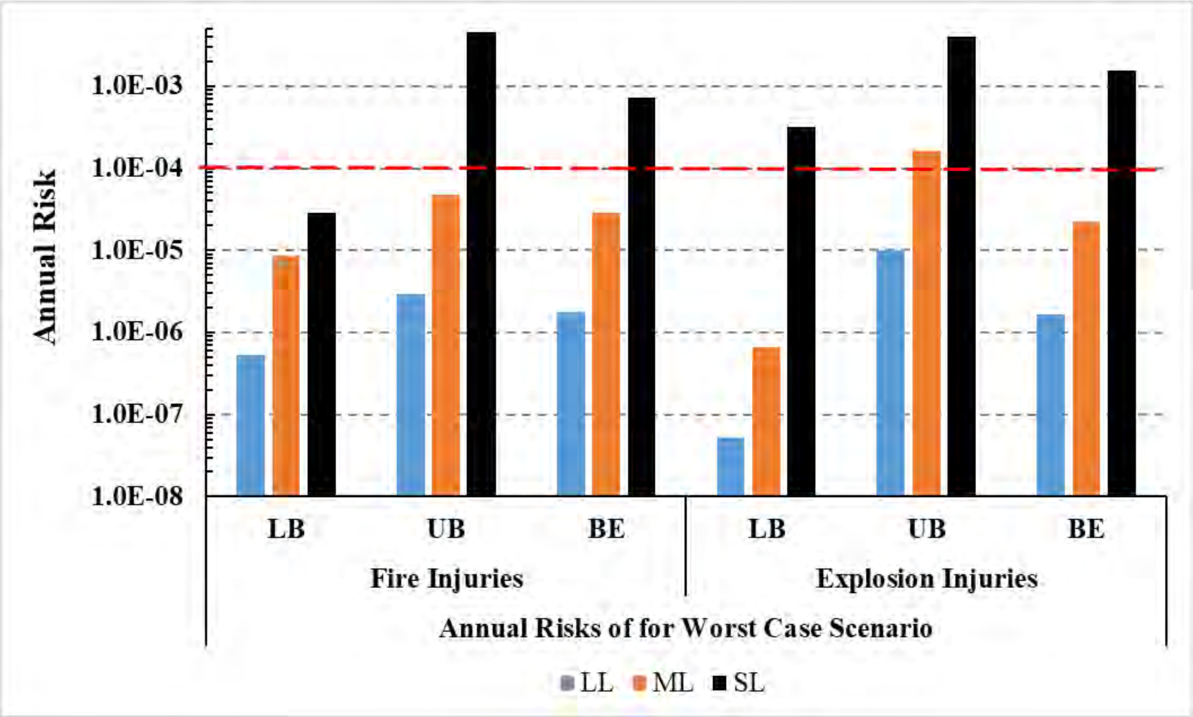
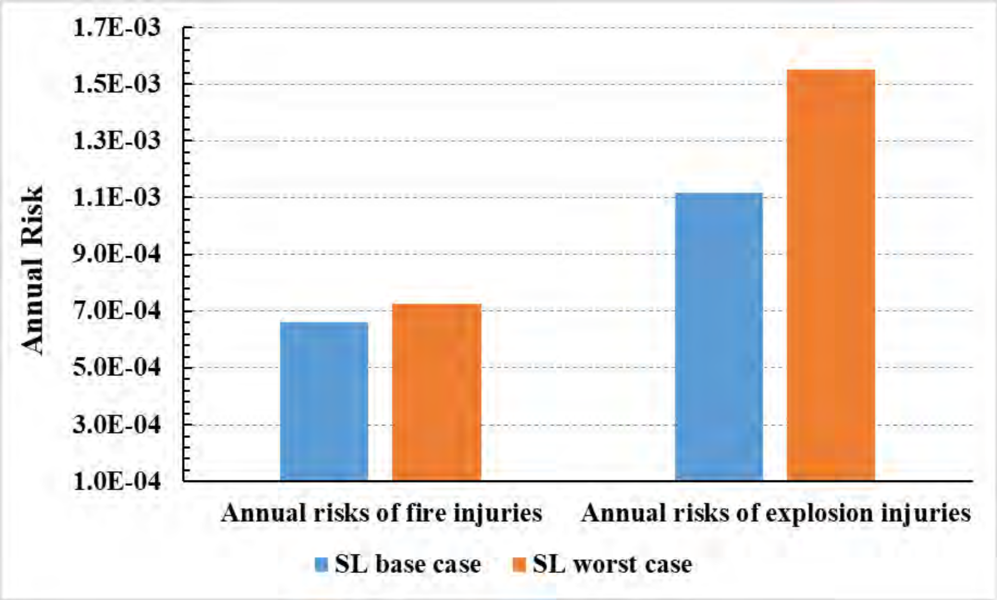
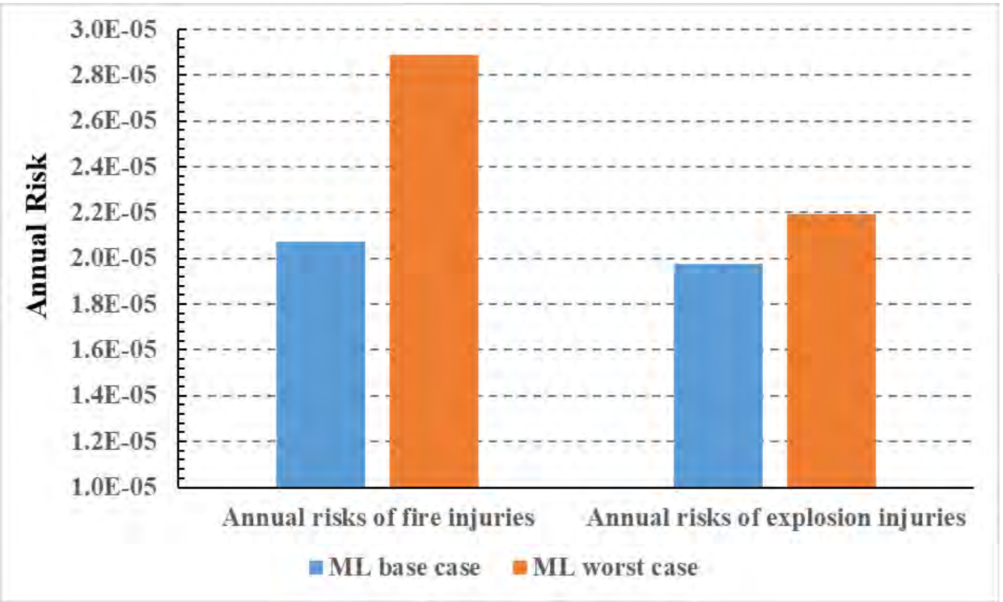


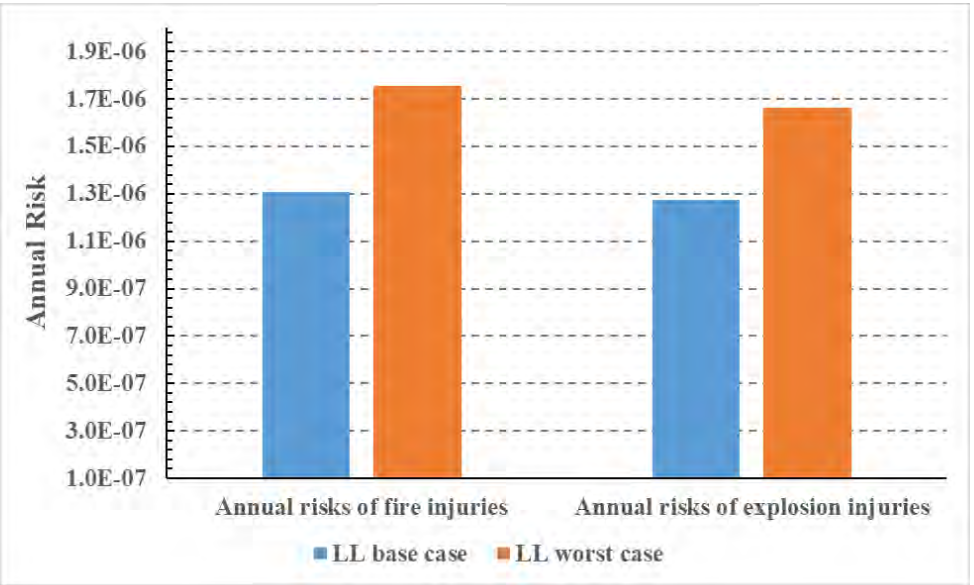
Fig. x. Worst case scenario

Note: the horizontal dashed line represents the occupation risk acceptance threshold of 1.0E-4/year.

Calculated annual risk of fire and explosion injuries for base case and worst-case scenarios







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Concluding remarks

- Install H2 detection devices to uncover early leaks from H2/NG transmission and distribution service pipelines.

- Harmonize H2 safety standards related to blending H2 with NG (ISO, NFPA, etc.)
  - Risk acceptance criteria ($\Delta R_{Acceptable}$) and safety margins for H2 levels in NG pipelines.
  - Certifying use of H2/NG blends in new appliances, boilers, etc..
  - Define acceptable risk management practices for domestic use of H2/NG blends.

- Consider a credit trading mechanism for mixing renewable H2 with NG in a manner similar to the allowance credit associated with mixing renewable electricity with conventional utility grids.

- Determine the maximum percentage of H2 to be added to NG pipelines without compromising safety, reliability of domestic appliances, and the structural integrity of transmission and distribution service pipelines.

- Address (viz., quantify and resolve) uncertainties associated with the log-term use of H2/NG blends in domestic appliances.

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Backup Slides

NaturalHy project

NaturalHy project:

- Co-funded by the European Commission.

- Led by:
  - Loughborough University (UK);
  - Leeds University (UK);
  - Commissriat a' l'Energie Atomique (France);
  - Shell Hydrogen;
  - Health and Safety Executive (UK);
  - National Grid (UK).

- Investigated potential risks of H2 transport using the existing NG pipeline networks.

- Assessed the following three risks of blending H2 with NG:
  - H2/NG (up to 50% H2) blend buildup in confined spaces ➔ no gas separation was observed.
  - Potential explosions in confined spaces w/ & w/o ventilation ➔ explosion similar to NG for ≤ 20 vol% H2
  - Risk associated with the transmission pipelines ➔ fatality risk is dominated by catastrophic pipe rupture.