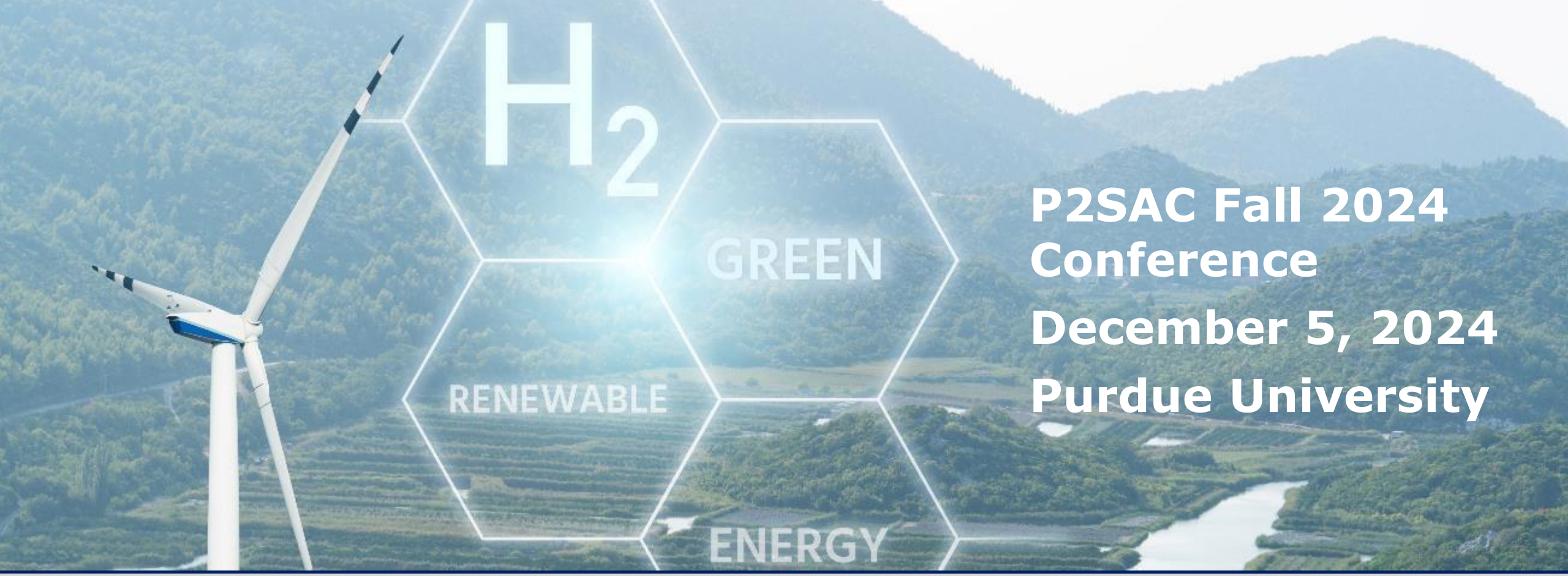

P2SAC Fall 2024 Conference

December 5, 2024

Purdue University

Process Safety for Hydrogen Use in Energy Decarbonization

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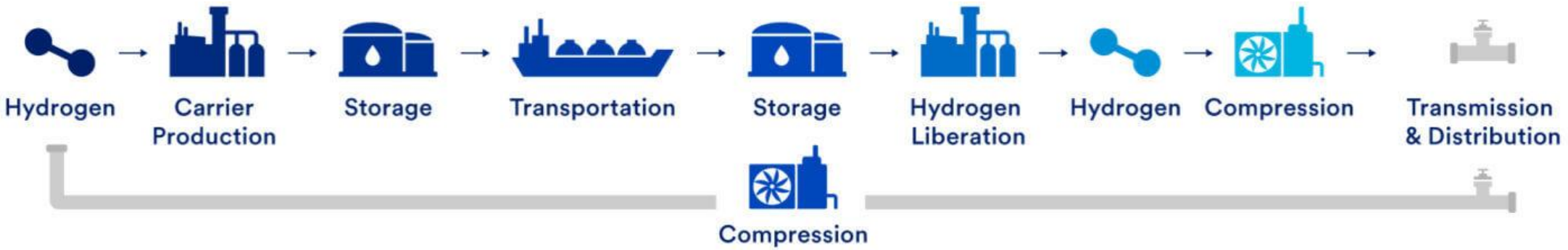
Hydrogen for Decarbonization – Opportunity and Challenges

> "Decarbonization is inevitable and is the biggest transformation of the global economy of this century.
> Which makes climate action a very, very smart thing.
> But on the other hand, what you're doing is not easy. It's not easy at all.[1]"

- While Mr. Stiell was generally referring to the business and technology issues, this is especially true for hydrogen safety – it will be a challenging endeavor that requires careful process safety management



[1] *Simon Stiell, UN Climate Change Executive Secretary, Sustainable Investment Forum, 24 Sep 2024,*

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Hydrogen Properties v Other Common Chemicals

Property	Units	Hydrogen	Methane	Propane	Methanol	Ethanol	Gasoline
Chemical Formula		H2	CH4	C3H8	CH3OH	C2H5OH	CxHy (x = 4 – 12)
Molecular Weight		2.02	16.04	44.1	32.04	46.07	100 – 105
Density, NTP	kg/m³	0.0838	0.668	1.87	791	789	751
	lb/ft³	0.00523	0.0417	0.116	49.4	49.3	46.9
Viscosity, NTP	g/cm-sec	8.81 E-5	1.10 E-4	8.012 E-5	9.18 E-3	0.0119	0.0037 – 0.0044
	lb/ft-sec	5.92 E-6	7.41 E-6	5.384 E-6	6.17 E-4	7.99 E-4	2.486 E-4 – 2.957 E-4
Normal Boiling Point	°C	-253	-162	-42.1	64.5	78.5	27 – 225
	°F	-423	-259	-43.8	148	173.3	80 – 437
Vapor specific gravity, NTP	air = 1	0.0696	0.555	1.55	N/A	N/A	3.66
Flash Point	°C				11	13	-43
	°F				52	55	-45
Flammability Range in Air	vol%	4.0 – 75.0	5.0 – 15.0	2.1 – 10.1	6.7 – 36.0	4.3 -19.0	1.4 – 7.6
Auto ignition temperature	°C	585	540	490	385	423	230 – 480
	°F	1085	1003	914	723	793	450 – 900
Maximum flame velocity in air	m/s	2.83	0.45	0.46	N/A	N/A	N/A
	ft/s	9.28	1.48	1.52			

www.h2tools.com)

Hydrogen for Decarbonization – Speed of Development and Deployment Pose Safety Challenges – Caution is Necessary

- In a period of rapidly growing market driven by decarbonization goals
  - **Rapid expansion** of the use of hydrogen for a wide variety of purposes.
  - **Hydrogen industry competition landscape is diverse**, including energy companies, specialized hydrogen producers, technology developers, and new entrants
  - **Novel technologies, increased scale, or adaptations**
  - **Operating experience is very limited -** little to no prior experience for many of these applications
  - **Limited technical competency and experience** - Preparing the manpower and competency required for process safety for the new hydrogen economy will be a profound challenge.

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Public Acceptance of Hydrogen

- The hydrogen industry as it evolves will need to maintain the highest level of safety performance.
- Strive for excellence in process safety (as low as reasonably practicable).
- What level of incidents is ‘tolerable’?.
- What effect would a major incident with hydrogen fuels have on public acceptance?

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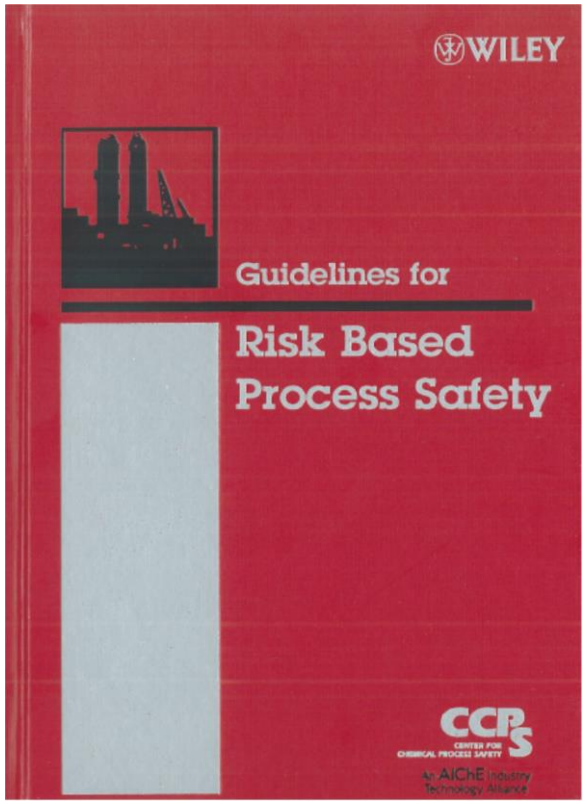
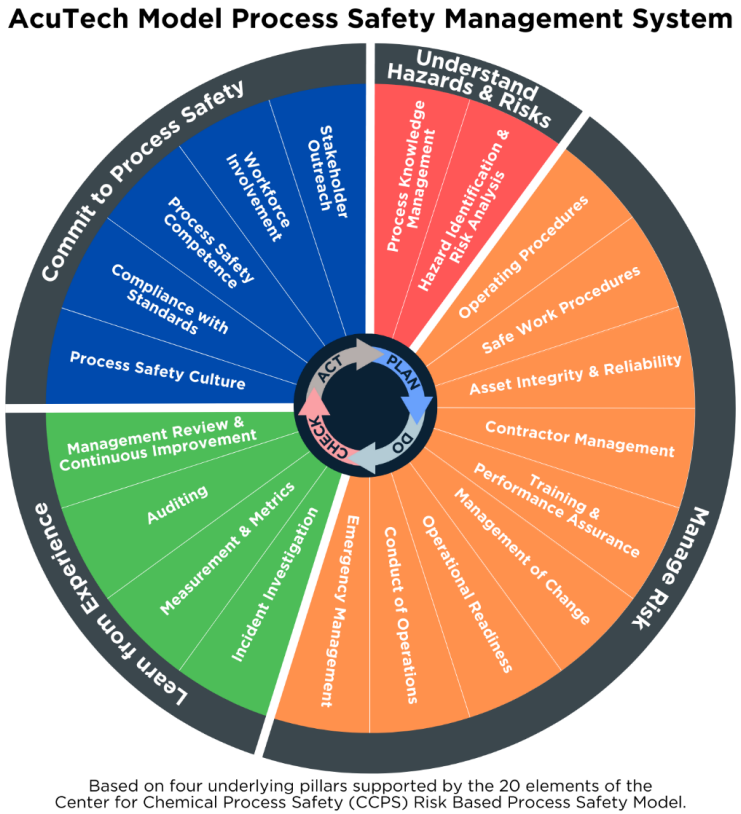
Model Risk Based Process Safety Management System

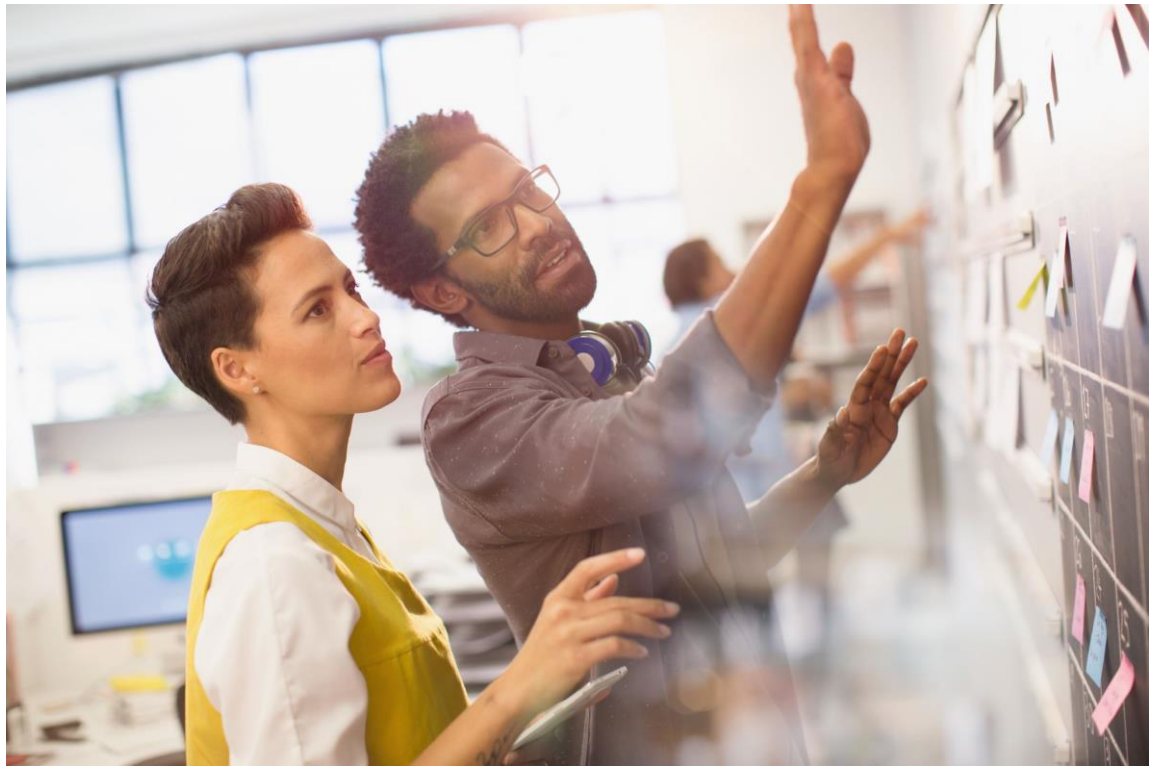
- Based on AIChE CCPS Risk Based Process Safety Model
- 4 Pillars
  - Commit to Process Safety
  - Understand Hazards & Risks
  - Learn from Experience
  - Manage Risk
- 20 elements
- Plan Do Check Act (Deming Cycle)





Importance of a Process Safety Framework for Hydrogen

- There is a need for the hydrogen sector to center on a process safety management (PSM) system to manage safety risks.
- It may seem obvious to experienced PSM engineers, especially at legacy hydrogen producers, who have well-established PSM systems
- But not all users of hydrogen are familiar or even plan to use PSM as a management system
- Companies with mature PSM cultures may adapt to hydrogen but those without this culture are not applying best practice.



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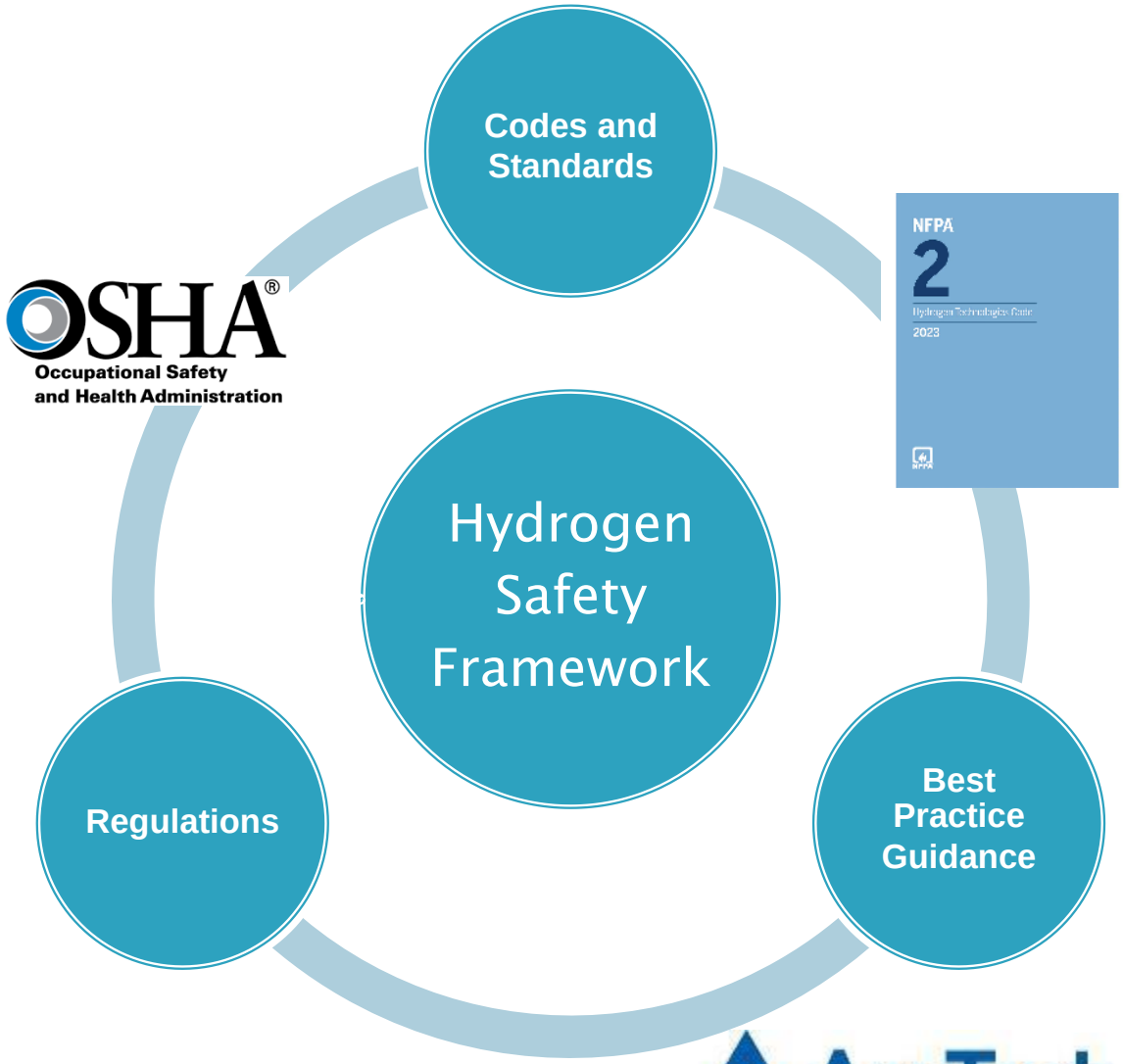
Hydrogen Industry Safety Approach

- Network of global regulations, engineering standards, codes, and guidance for best practices for hydrogen safety.
- Need a management system to tie together the elements into a working system continuously improving
- **Gaps?** –
  - Others may operate in countries that do not have a PSM regulation or regulations vary
  - They may be excepted by threshold quantities
  - Management may not be committed to voluntary mgmt systems



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Hydrogen Industry Safety Approach

- **Recommendations:**

1. Producers, suppliers, facility operators, users, and their contractors and employees would all benefit from an industry approach to voluntary PSM even if not required by regulation.
2. The CCPS RBPS is one such model management system that is very applicable to hydrogen activities.

A Process Safety Management Framework for the Compressed Gas Industry – CGA P-86

- The process safety management framework provided in CGA P-86 may be applied to all processes within the industrial gases industry.
- The intent of this publication is to make process safety management understandable beyond the requirements found in (OSHA) PSM regulations.
- CGA P-86 is designed to address process safety hazards and to be equally suitable for processes found across the industry

21 Essential Process Safety Management Elements

- Element 1 – Leadership commitment and responsibility
- Element 2 – Compliance with legislation and industry standards
- Element 3 – Employee selection, training, and competency
- Element 4 – Workforce involvement
- Element 5 – Communication with stakeholders
- Element 6 – Hazard identification and risk assessment
- Element 7 – Documentation, records, and knowledge management
- Element 8 – Process and operational status monitoring and handover
- Element 9 – Operating procedures
- Element 10 – Management of operational interfaces
- Element 11 – Standards and practices
- Element 12 – Management of change
- Element 13 – Operational readiness and process startup
- Element 14 – Emergency and crisis management
- Element 15 – Inspection and maintenance
- Element 16 – Management of safety critical devices
- Element 17 – Work control, permit to work, and task risk management
- Element 18 – Contractors and suppliers – selection and management
- Element 19 – Incident investigation
- Element 20 – Audit, management review, and intervention
- Element 21 – Measures and metrics

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Limitations of Codes and Standards

- Current codes and standards may not adequately address all hazards and current learnings especially with an emerging industry
- For example – Detonation following loss of primary containment
  - The overpressure hazards from the delayed ignition of a H2 vapor cloud or of releases in confined and congested areas are not considered in NFPA 2 Hydrogen Technologies Code for siting of facilities
  - Several incidents have occurred in which a significant amount of hydrogen was released and ignited under a delayed ignition scenario resulting in explosions with fatalities, injury, and damage.
  - Interaction of multiple atmospheric vents simultaneously releasing may not be fully considered
  - Not all hazards are fully understood and codes are generally incomplete or in development

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Hydrogen Incidents of Note

- Augsburg Germany
- Commissioned 17 June 2024
- Explosion and fire 26 June 2024

- Reported to be an explosion within a compressor enclosure
- Illustrates the issue of confined space explosion potential with H2

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Importance of a Process Safety Framework for Hydrogen

- The hydrogen value chain will bring more public exposures
- Transportation and mobility sectors have experienced many incidents, and represent a leading indicator.
- For example, A pickup truck towing a trailer carrying full hydrogen tanks on US-23 in Delaware County Ohio explodes after crash.
  - Three people were transported to a hospital with minor injuries.
  - Contributing factors were found related to the trailer design that codes do not address at this time.

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Example Hydrogen Mobility Sector Incident: Golden Empire Transit, Bakersfield, California – 2023

- During refueling of a bus, a fire occurred consuming the bus ($1.1 million loss)
- No injuries
- The cause is still under investigation
- One of ten hydrogen buses as part of its transition to zero emissions fuels.
- 100% percent of new California public transport will be required to be zero-emission by 2040

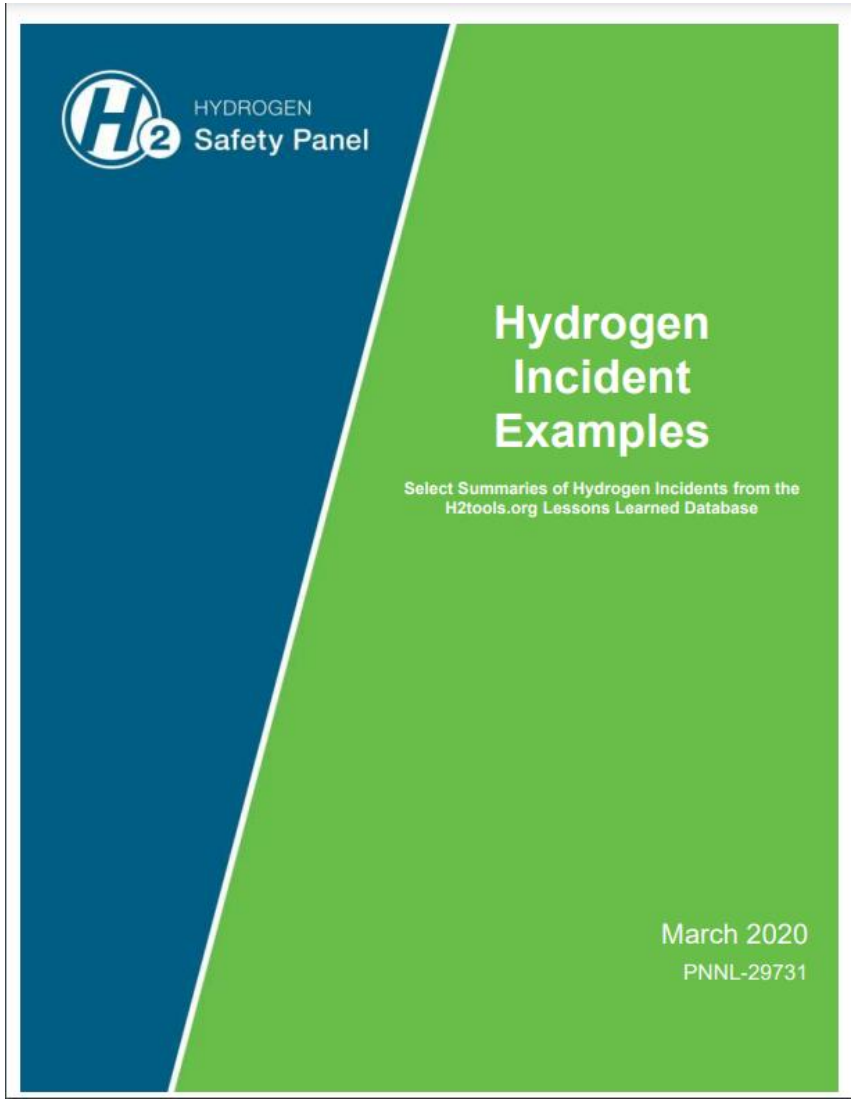
KGET News https://www.youtube.com/watch?v=tx8aj-SnHu8

Kjorbo, Norway, Hydrogen Fueling Station - 2019

- Refueling stations and electrolyzers also have had incidents illustrating this point:
  - An improperly assembled cylinder boss/valve assembly caused loss of containment of hydrogen from a 950bar storage cylinder in a paneled enclosure which contained multiple storage cylinders.
  - A flammable gas cloud formed and ignited and an explosion resulted after about 3 seconds..
- Panels around the storage cylinders may have limited dispersion
- The surrounding wall was not designed for a delayed ignition
- $3M penalty give to the company by regulators

Damage included destruction of the storage cylinder enclosures and several equipment modules in close proximity, significant failure of the surrounding wall/fence, the activation of air bags in several passing cars with 2 people taken to the hospital (damage to office building windows 200ft away suggested a detonation, likely due to a 2nd confined explosion event likely from an enclosed module).

US DOE Hydrogen Safety Panel – Hydrogen Incident Examples



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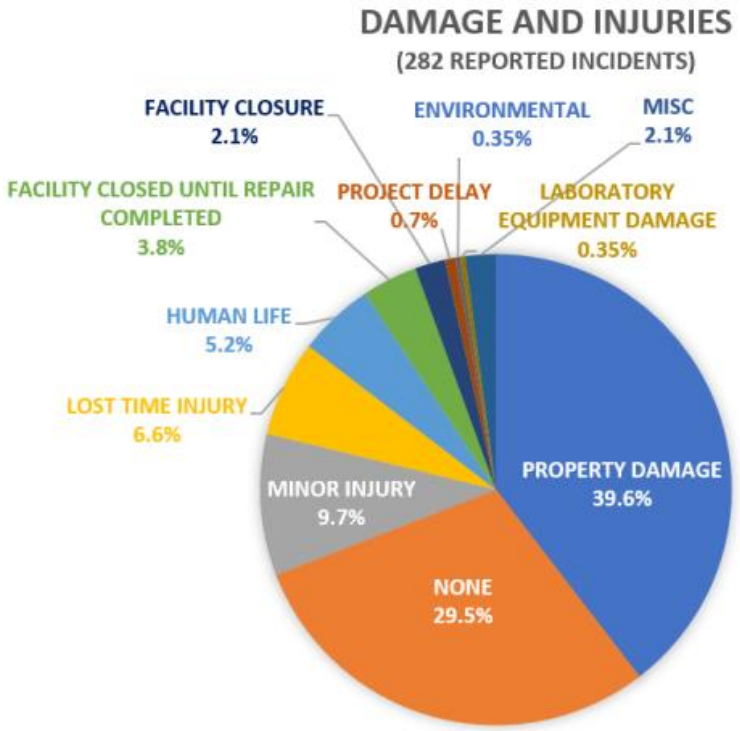

Figure 3: Reported damage and injury categories resulting from hydrogen related incidents reported to h2tools.org.

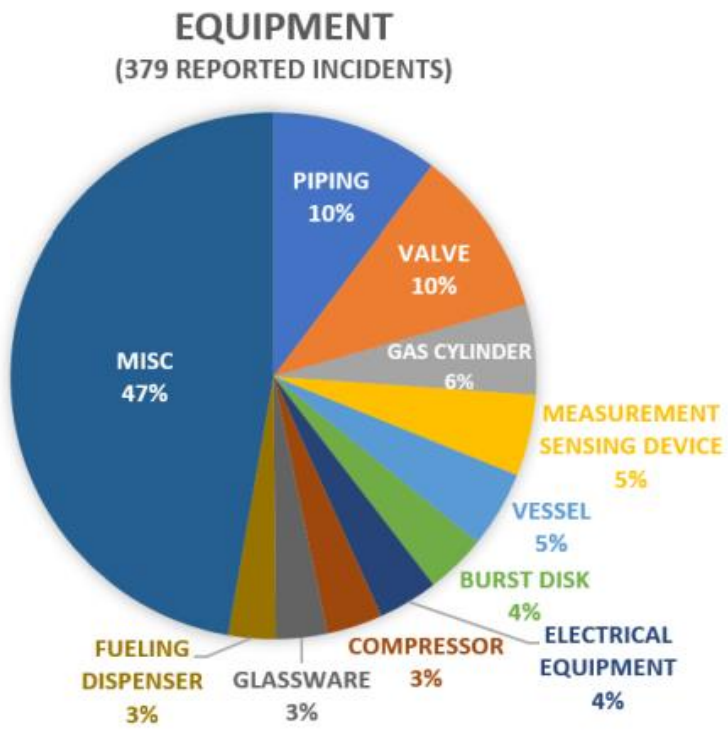

Figure 4: Reported categories for equipment involved in hydrogen incidents reported to h2tools.org. (The primary causes for the equipment-related incidents include component failure, operation error, installation/maintenance, etc.).

Weiner and Fassbender (2012) – Reference: Hydrogen Safety Review for Gas Turbines, SOFC, and High Temperature Hydrogen Production 30 March 2023 Office of Fossil Energy and Carbon Management DOE/NETL-2022/3329

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Hydrogen Incidents – www.h2tools.com

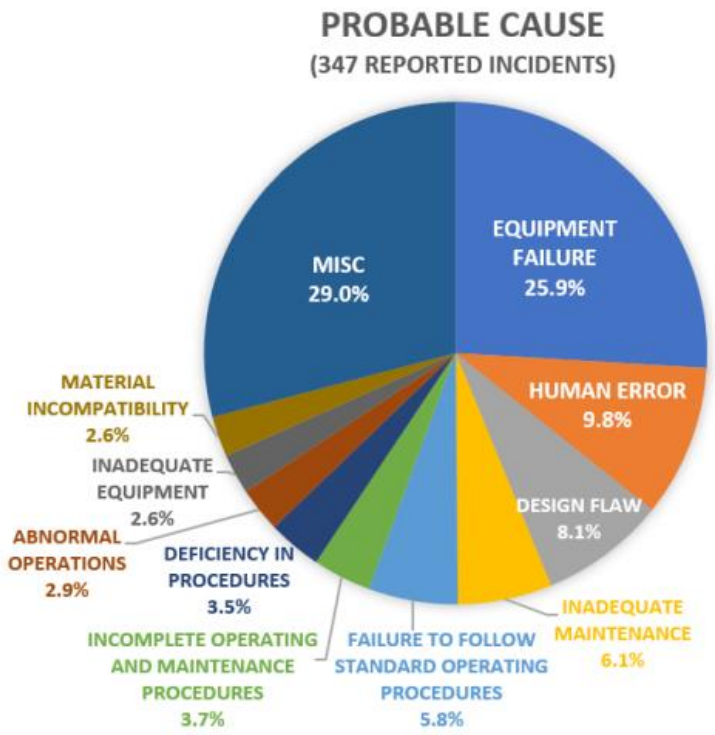

Figure 5: Probable cause categories for hydrogen incidents reported to h2tools.org.

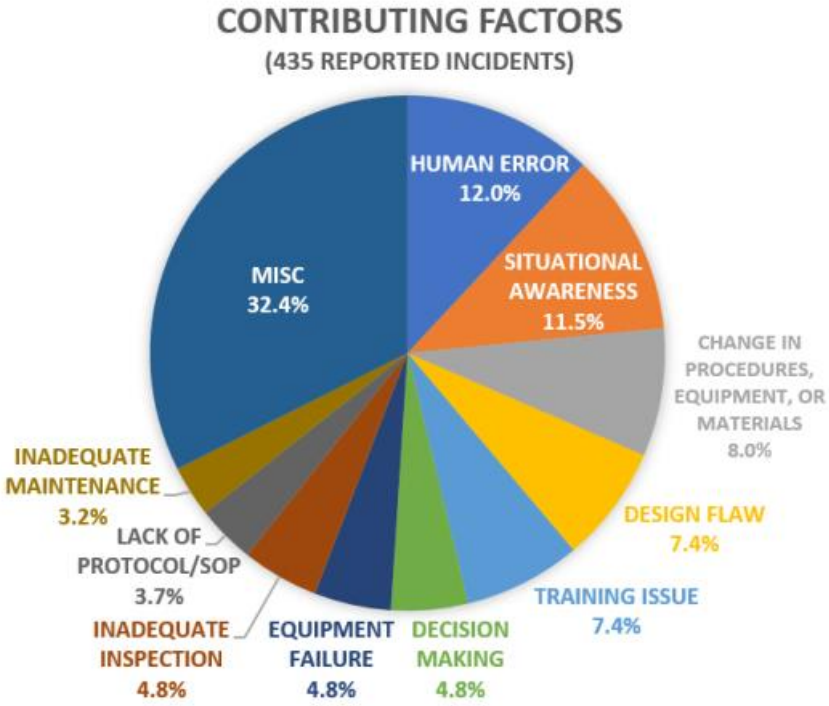

Figure 6: Contributing factors categories for hydrogen incidents reported to h2tools.org.

Weiner and Fassbender (2012) – Reference: Hydrogen Safety Review for Gas Turbines, SOFC, and High Temperature Hydrogen Production 30 March 2023 Office of Fossil Energy and Carbon Management DOE/NETL-2022/3329

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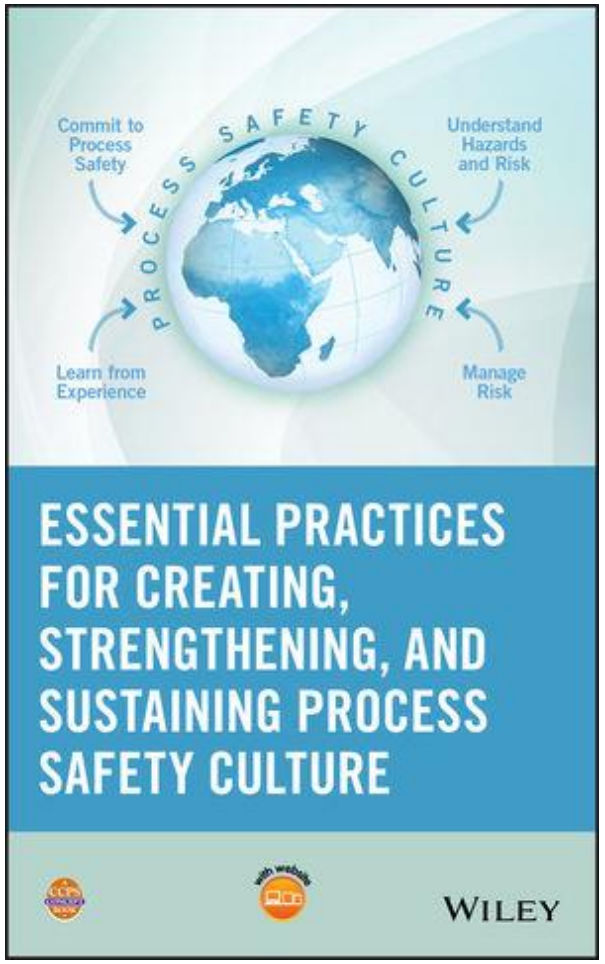
CCPS RBPS v PSM Culture Principles

Example of CCPS PSM RBPS Model v Implementation in the Hydrogen Industry
(AcuTech's Observations of the Application of Hydrogen as a Fuel for Decarbonization at Less Sophisticated Sites

RBPS Elements	Issues Observed
Applicability	- Planning to have just under the threshold quantity required by a regulation - Lack of a formal documented approach for applicabilty of the PSM system
Process Safety Culture	- Policy statement does not exist for process safety management - Contractors are not directly engaged in PSM system or culture - Employees are less aware of PSM policies and programs.
Conduct of Operations	- Policy statement does not exist for conduct of operations. - Lack of operating discipline. - Iconsistentcy across sites -Employees and/or contractors don't consistently follow procedures.
Compliance with Standards	- No requirement to ensure the design is compliant with codes and standards. - RAGAGEP not defined for hydrogen systems. - Known inconsistencies to codes and standards are tolerated
Process Knowledge Management	-Policy statement does not exist for process knowledge management. Expectation for minimum engineering deliverables not consistent with industry practice.
Process Safety Competency	-Policy does not exist for process safety competancy - Inadequate expertise in hydrogen engineering and PSM for hydrogen
Training and Performance	-Refresher training is not practiced at sites surveyed. Lack of refresher training emphasis may be due to short employee tenure.

Importance of Process Safety Culture



CCPS Guidelines Definition of PSM Culture (2017)

"The pattern of shared written and unwritten attitudes and behavioral norms that positively influence how a facility or company collectively supports the development of and successful execution of the management systems that comprise its process safety management program, resulting in the prevention of process safety incidents."

CCPS RBPS v PSM Culture Principles

Core Principle → / RBPS Element ↓	Establish an Imperative for Safety	Provide Strong Leadership	Maintain a Sense of Vulnerability	Understand and Act Upon Hazards/Risks	Empower Individuals to Successfully Fulfill their Safety Responsibilities	Defer to Expertise	Ensure Open and Frank Communications	Foster Mutual Trust	Combat the Normalization of Deviance
PSM Program Applicability	X	X	X	X		X			
Process Safety Culture	X	X	X	X	X		X	X	X
Process Safety Competency					X	X			
Compliance with Standards						X			X
Process Knowledge Management				X	X				X
Workforce Involvement					X		X	X	
Hazard Identification and Risk Analysis			X	X			X		X
Operating Procedures							X		X
Safe Work Practices	X	X	X	X	X		X		
Asset Integrity and Reliability	X	X				X	X		X
Contractor Management				X	X		X	X	X
Training and Performance Assurance					X	X	X		
Operational Readiness				X			X		X
Conduct of Operations	X	X			X		X	X	
Management of Change	X	X	X	X			X		X
Emergency Management			X	X	X				X
Incident Investigation	X	X		X	X			X	X
Measurement and Metrics		X		X			X		X
Auditing				X			X		X
Management Review and Continuous Improvement				X			X		X

Process Safety Management Systems – License to Operate

- There is a strong business case for implementing process safety management systems – the value is in preventing the loss of lives, preserving the integrity of operations and protecting the environment.
- Safety management systems are well developed over the past 50+ years
- It takes years of development to make a PSM system effective and diligence to sustain that level

Presentation Summary

- Hydrogen incidents are occurring due to preventable causes and contributing factors that speak to the need for process safety frameworks
- Industry experience of over 50 years of PSM has shown that it has positively changed the way safety is managed
- The application of a PSM framework to hydrogen operations can apply throughout the lifecycle and ecosystem
  - Manufacturing of hydrogen.
  - Transportation.
  - Use of hydrogen as a fuel
- It is recommended that we influence the industry to ensure hydrogen safety through a modern process safety framework

Thank You and Questions

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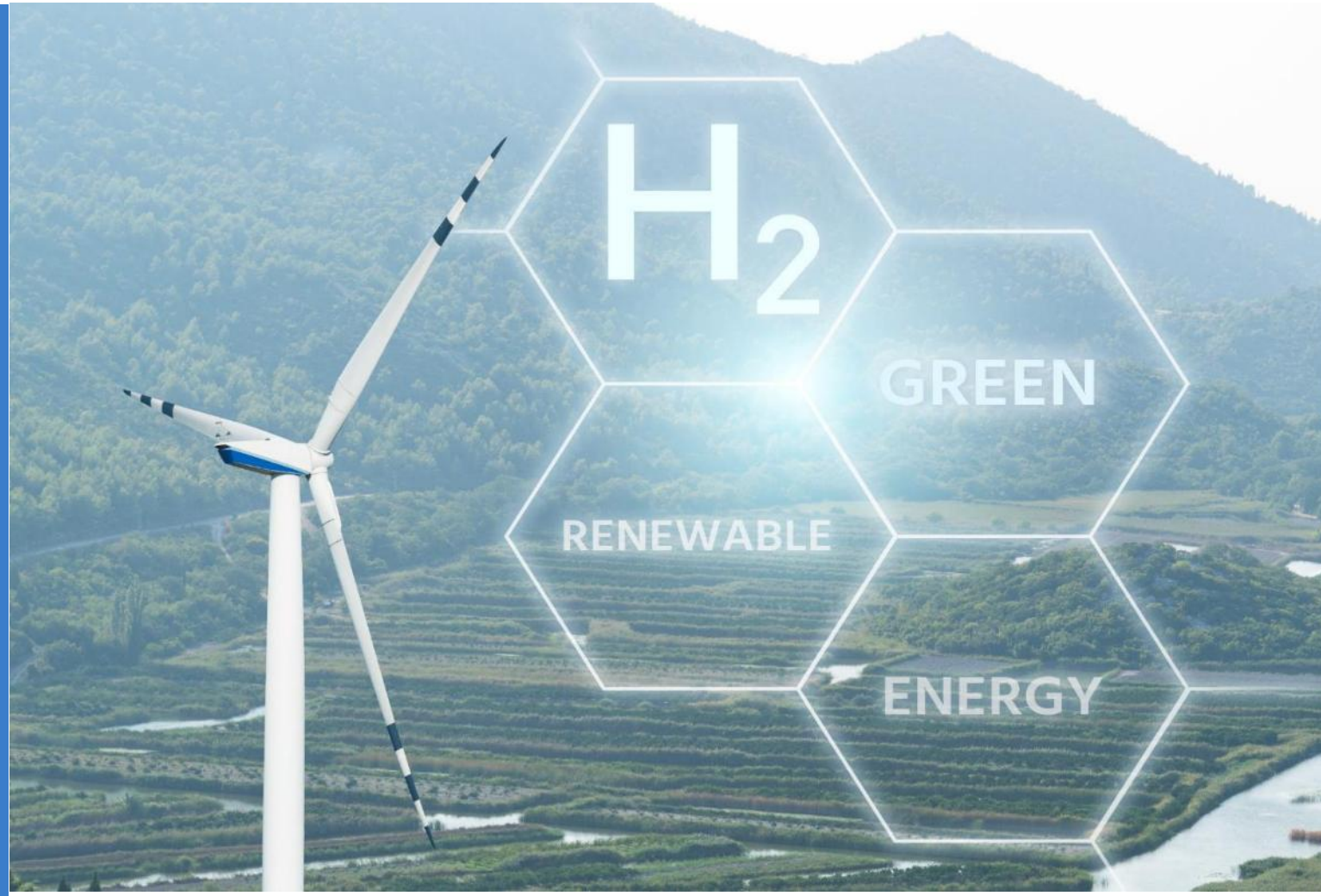

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