Hydrogen : promises and challenges
From past to nowadays, review of academic research directions

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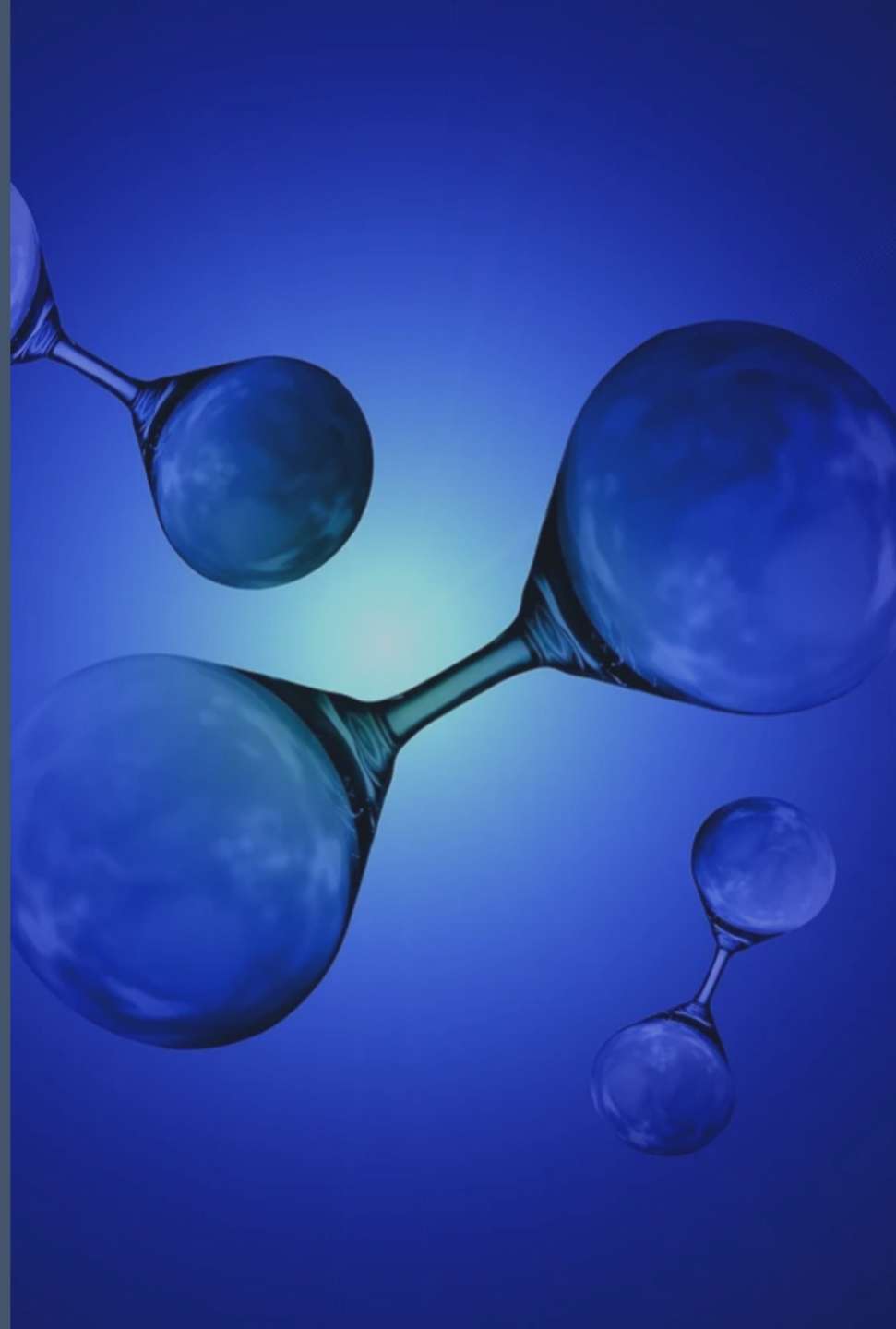
Hydrogen research

Distinct timeframes in the history of hydrogen research

- Observation and fundamental discoveries (16th - late 19th century)
- Exploration and industrial stabilization of production routes and application fields (transport, energy, chemistry) (1901-mid 70s)
- Increasing academic knowledge, most marked from the 1970s onwards



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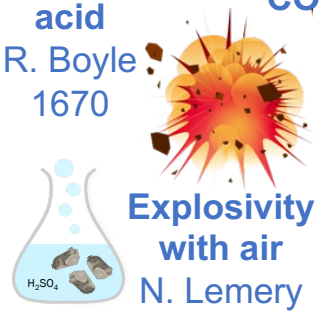
A long history of discoveries

Phase 1: discovery and exploration of key properties

Hydrogen (H2)

1st observation
Paracelse
ca 1520

Synthesis by dissolution of metals in acid
R. Boyle
1670



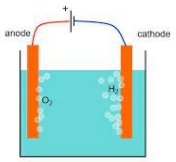
Explosivity with air
N. Lemery
1700

Water-gas shift $CO + H_2O \rightleftharpoons CO_2 + H_2$
F. Fontana
1780

Name « hydrogen » given
A. Lavoisier
1783

Heat of combustion
Lavoisier & Laplace
1783

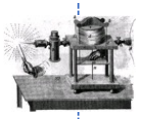
H_2-filled gas balloon
J. Charles
1783



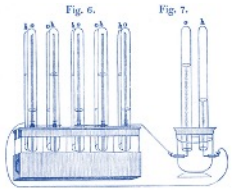
Water electrolysis
Nicholson & Carlisle
1800

Concept of Fuel Cell
H. Davy
1801

Oxy-H_2 blowpipe
G. Gurney
1823



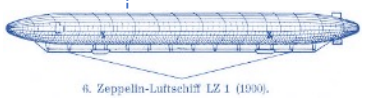
Primary cell
J. F. Daniell
1836



1st Fuel Cell
W. R. Grove
1842

Hydrogenation CO_2 into CH_4
P. Sabatier
1897

H_2 critical constants (T°, P and bp)
Z. Wroblewski
1885



H_2-filled airship
F. von Zeppelin
1900

1670 1700 1780 1783 1800 1801 1823 1836 1842 1885 1897 1900

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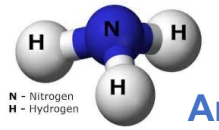
A long history of discoveries

Phase 2: mass production and commercial applications



Ammonia production
F. Haber

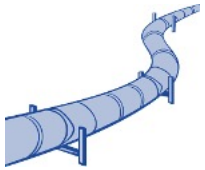
1901

Hydrogenation of lipids
W. Normann

1910

Hydrocracking coal
(Germany)

1920



Methane steam reforming
1928-1936 (UK)

1928

LZ 129 Hindenburg explosion
1937

1938

1st 240 km H_2 pipeline
Rhine-Ruhr

1943

Liquid H_2 as rocket fuel
Ohio State University

1949

Hydro-desulfurization

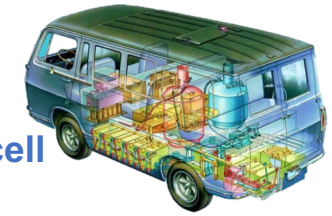
1951

Underground H_2 storage

1965

5 kW H_2-air fuel cell
F. T. Bacon
(1959)

1966



1st fuel cell automobile
General Motors

1981

Space Shuttle main engine

1990

1st hydrail locomotive
(Québec)

2002

2013

Power-to-gas 2MW
(Germany)

2022

Toyota Mirai
(2016)

Photo-catalytic water splitting

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Hydrogen economy

(Bockris, *Science*, **1972**)

« Universal energy carrier through which nuclear energy and solar energy could be produced and distributed economically» (Bockris, 1972)

« Energy storage that allows continuous base-load electricity supply in a system relying on intermittent and variable renewable energy resources such as solar and wind energy » (Clark, 2006)

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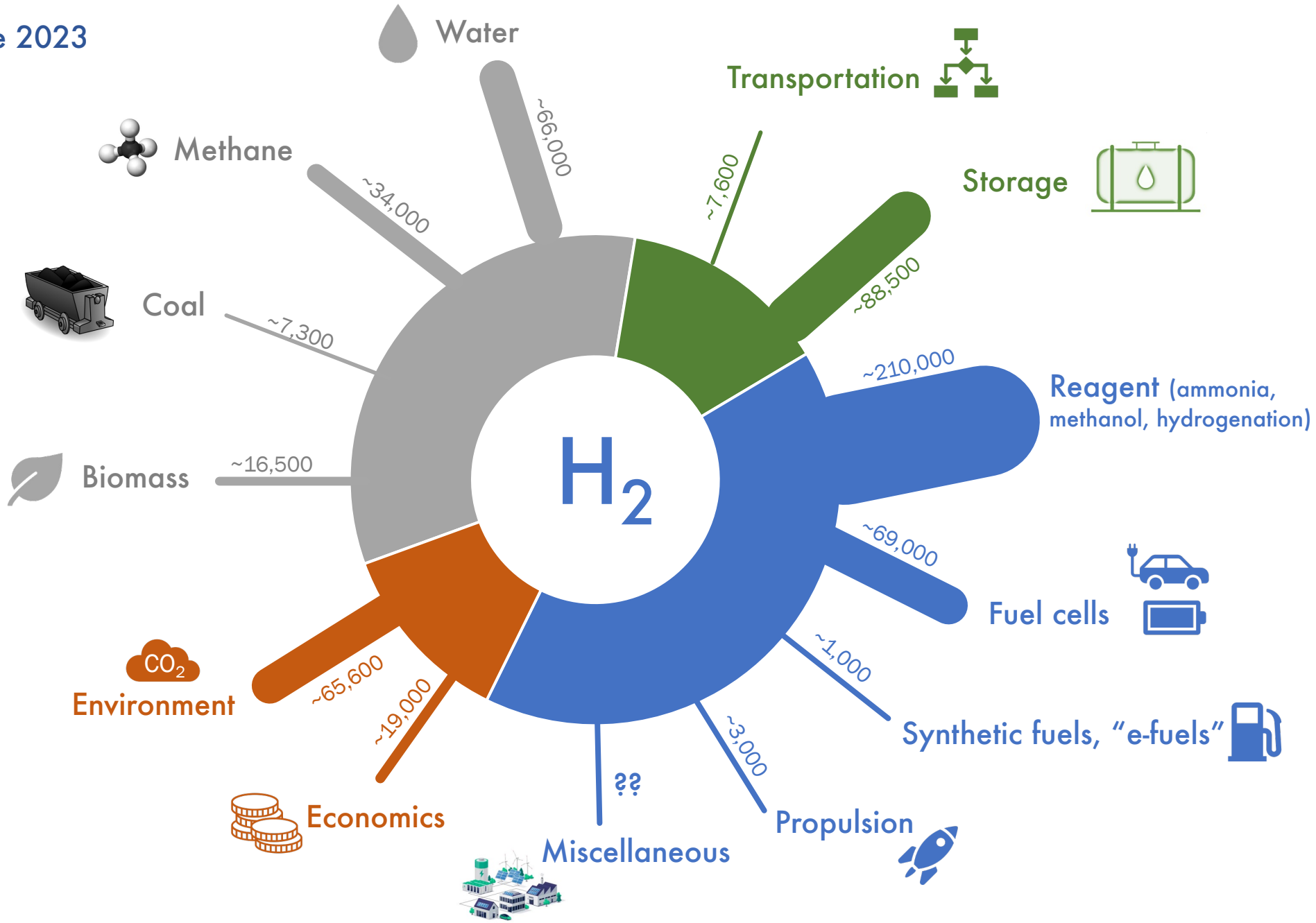
1972-2023

Source: SciFinder, Octobre 2023

- Production
- Distribution
- Applications
- Related researches



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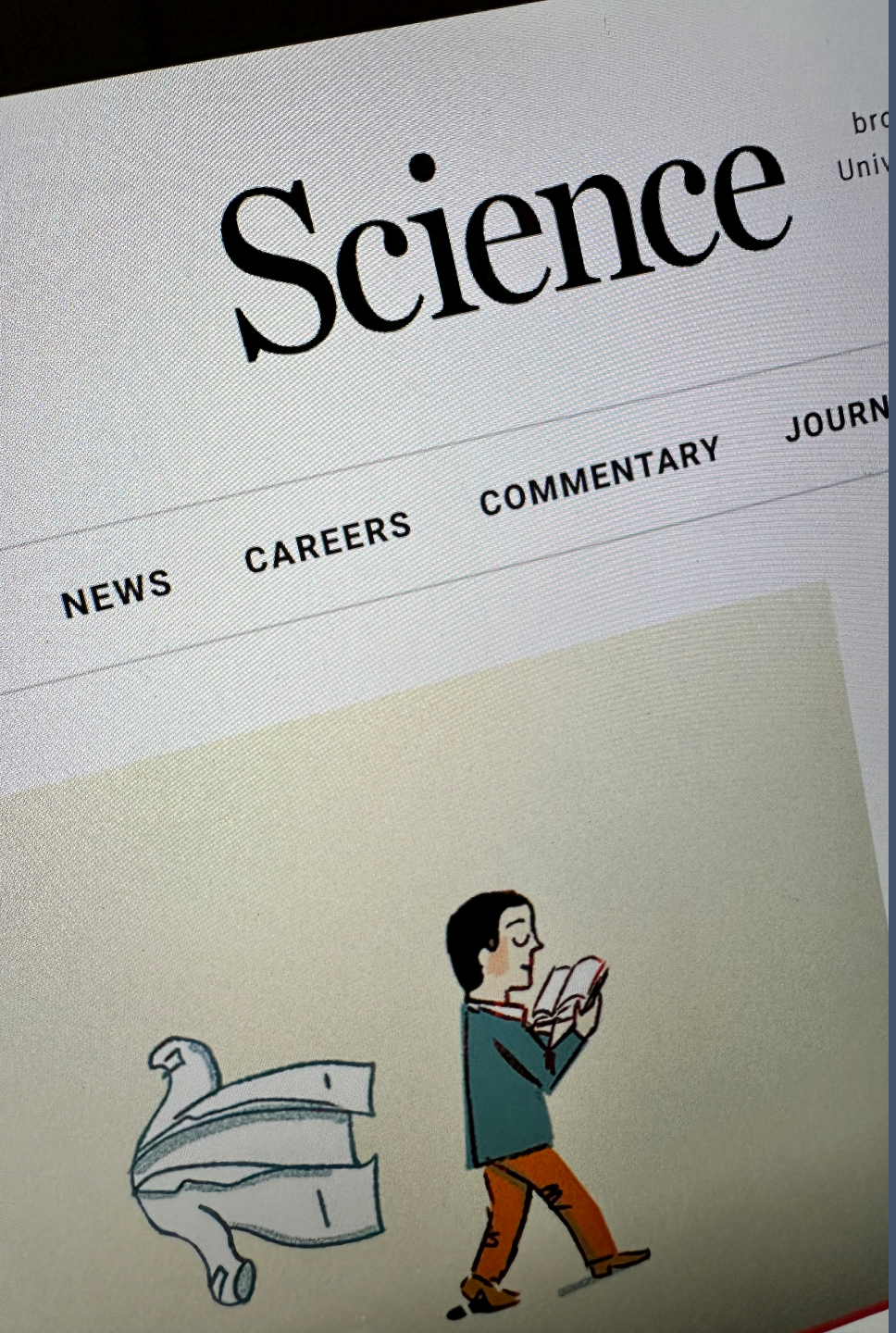
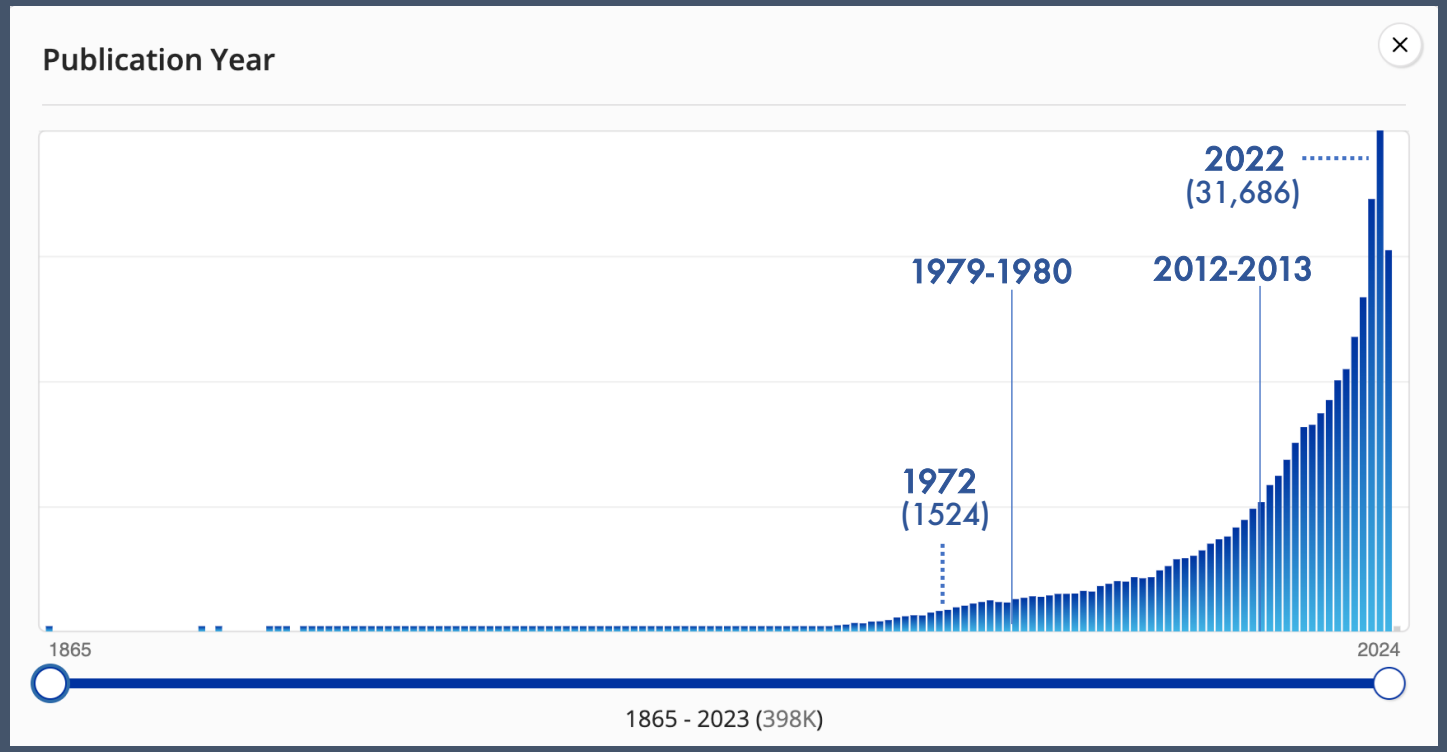
LABORATORY OF BIOMASS & GREEN TECHNOLOGIES



Hydrogen in scientific publications

(1865-2023, SciFindrer – « hydrogen » and « energy »
Research on Oct 3rd, 2023)

398,658 results (patents: 7%)



Hydrogen in scientific publications

(1865-2023, SciFindrer – « hydrogen » and « energy »
Research on Oct 3rd, 2023)

- 1972-1979: first phase of intensive research (4%*)
- 1980-2012: steady (but typical) increase in the number of published acts (40%*)
- 2013-2023: exponential growth in published research works (53%*)

* Distribution based on the total number of publications, including those prior to 1972

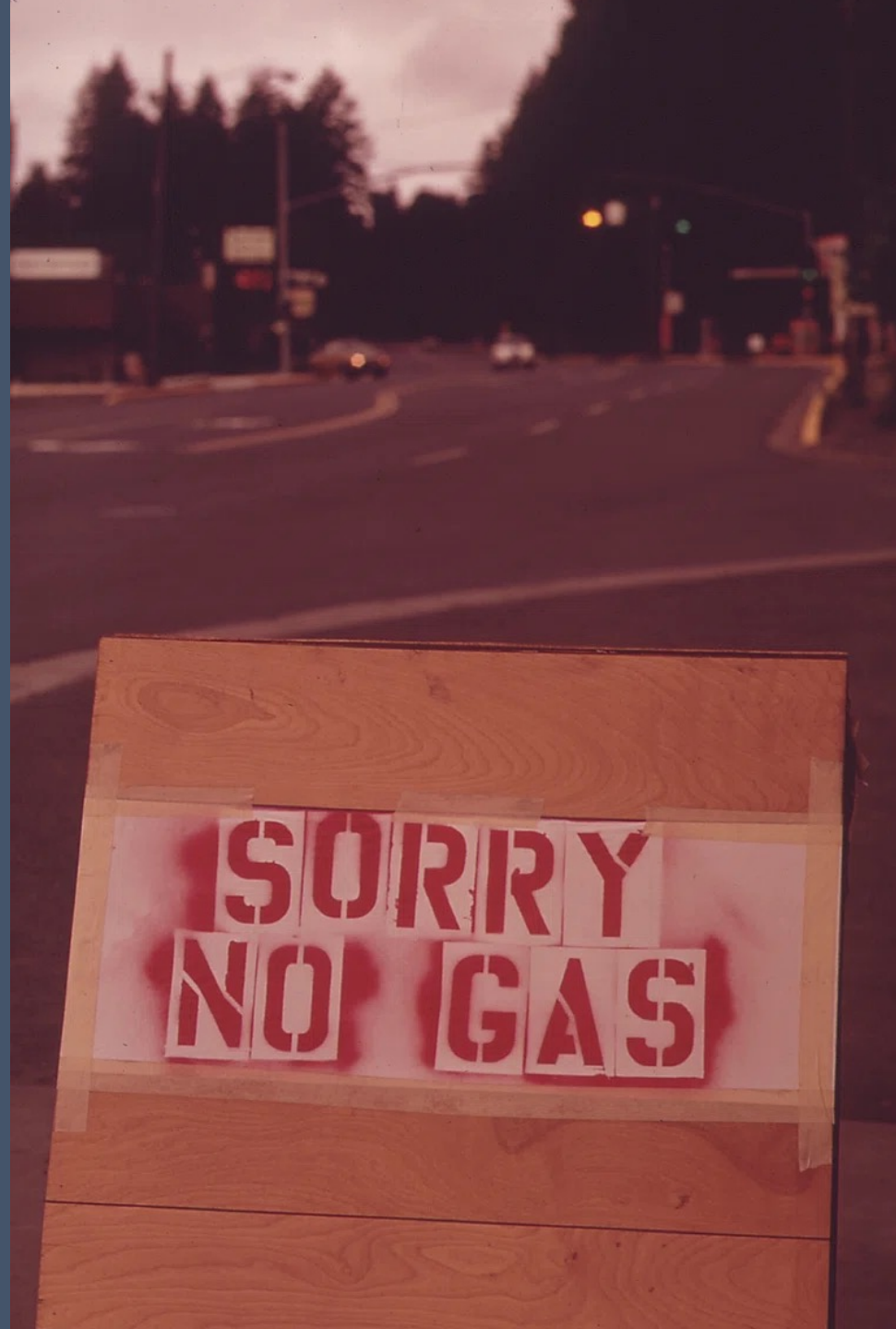
Hydrogen research: phase 1
1972-1979

Critical decade for energy (oil crises): definition of more resilient energy systems

Environmental concerns were not the main motivation

Peak after 1974 following the creation of IEA* and IAHE*

* International Energy Agency (IEA) and International Association for Hydrogen Energy



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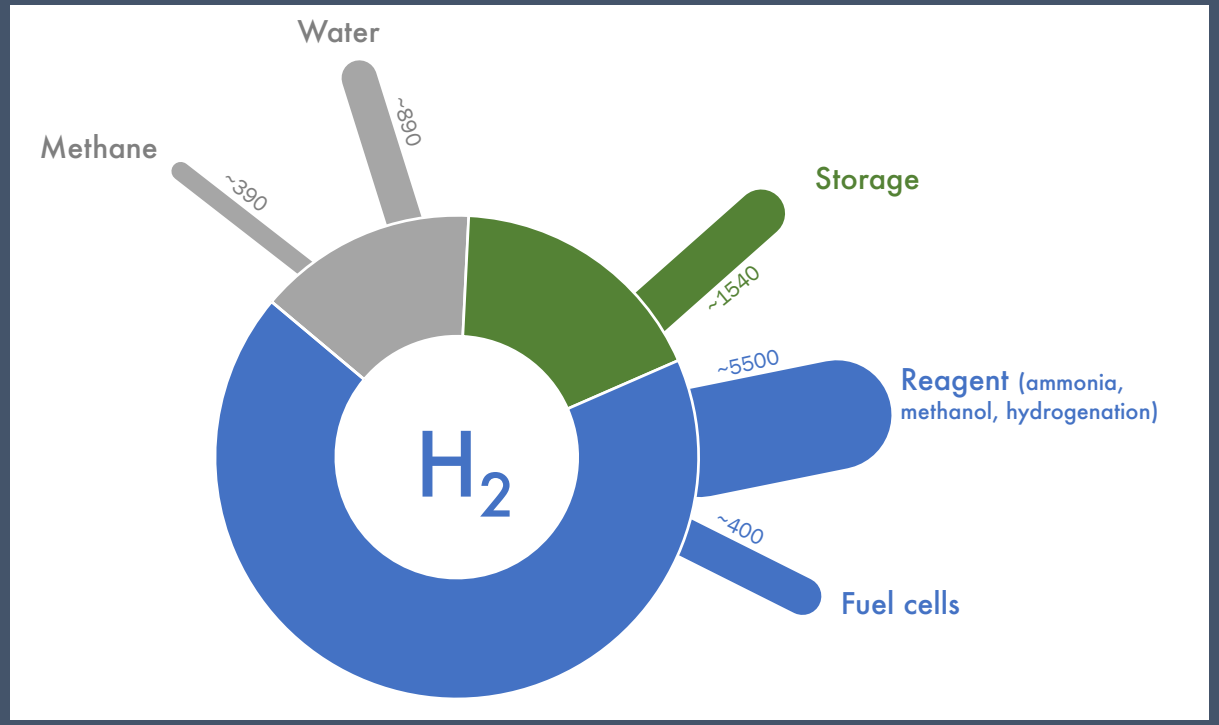
Hydrogen research: phase 1
1972-1979

Key investigators: US (Japan, UK, Europe)

Hot topics:
- Holistic approaches
- Production routes (water and methane, and coal or H_2 from oil-refining processes)
- Role of nuclear energy
- Reagent and fuel cells



Hydrogen, energy carrier of the future? By: Langenkamp, H.; Van Velzen, D. Chemie fuer Labor und Betrieb (1979), 30(12), 533-6

Nuclear methane reforming for coal gasification By: Rastoin, J.; Malherbe, J.; Pottier, J.; Lecoanet, A. Advances in Hydrogen Energy (1979), 1(Hydrogen Energy Syst.), 67-76

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Hydrogen research: phase 2
1980-2012

Steady growth in R&D initiatives

Climate considerations (UNFCC, Kyoto)

Diversification of research directions - Exploratory and/or industrial-oriented research (cost reduction in production)

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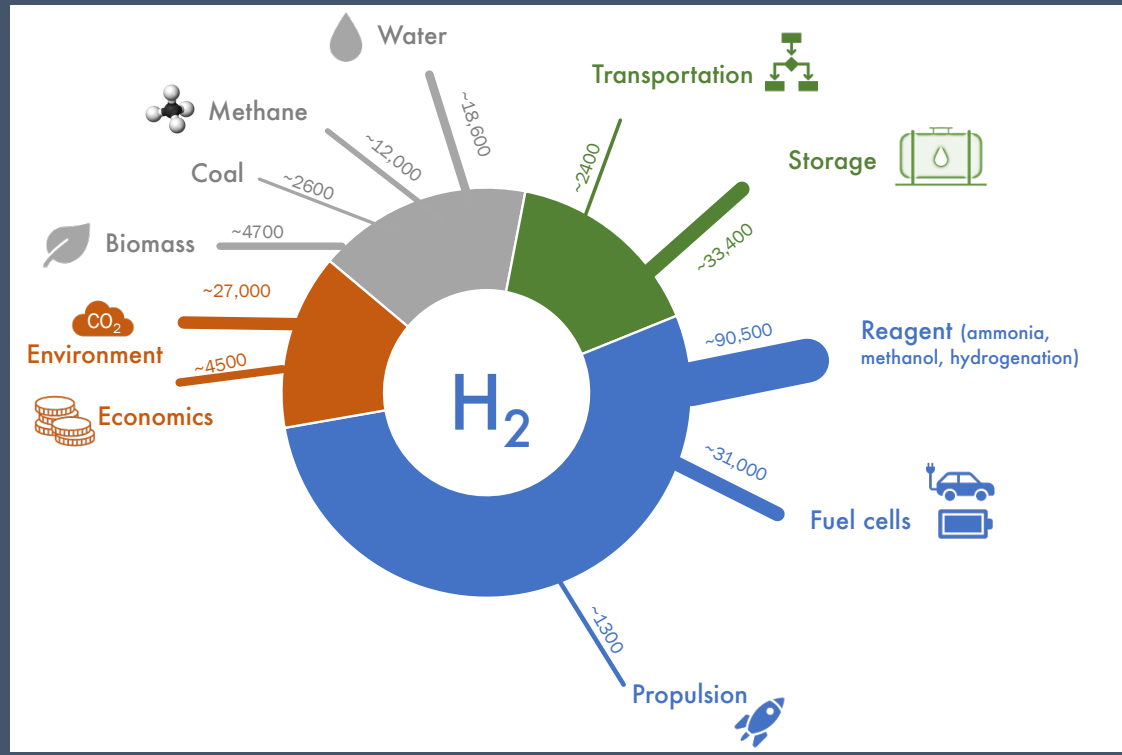
Hydrogen research: phase 2
1980-2012

Key investigators: US/China/Russia/Japan

Hot topics:

- Production from "non-polluting" sources (water, biomass)
- Solar energy and other alternative energy sources – No nuclear energy inputs
- H_2 storage and transportation (LOHC)
- Fuel cells and their integration to vehicles



Liquid Organic Hydrogen Carriers as an efficient vector for the transport and storage of renewable energy By: Teichmann, Daniel; Arlt, Wolfgang; Wasserscheid, Peter International Journal of Hydrogen Energy (2012), 37(23), 18118-18132

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Hydrogen research: phase 3
2013-2023

Change in publishing practices and digitization of journals – data-intensive research

Hydrogen Council (2017) and international cooperation

IPCC and environmental concerns

Policies, national strategies/roadmap for H_2
Investments in R&D activities related to energy transition

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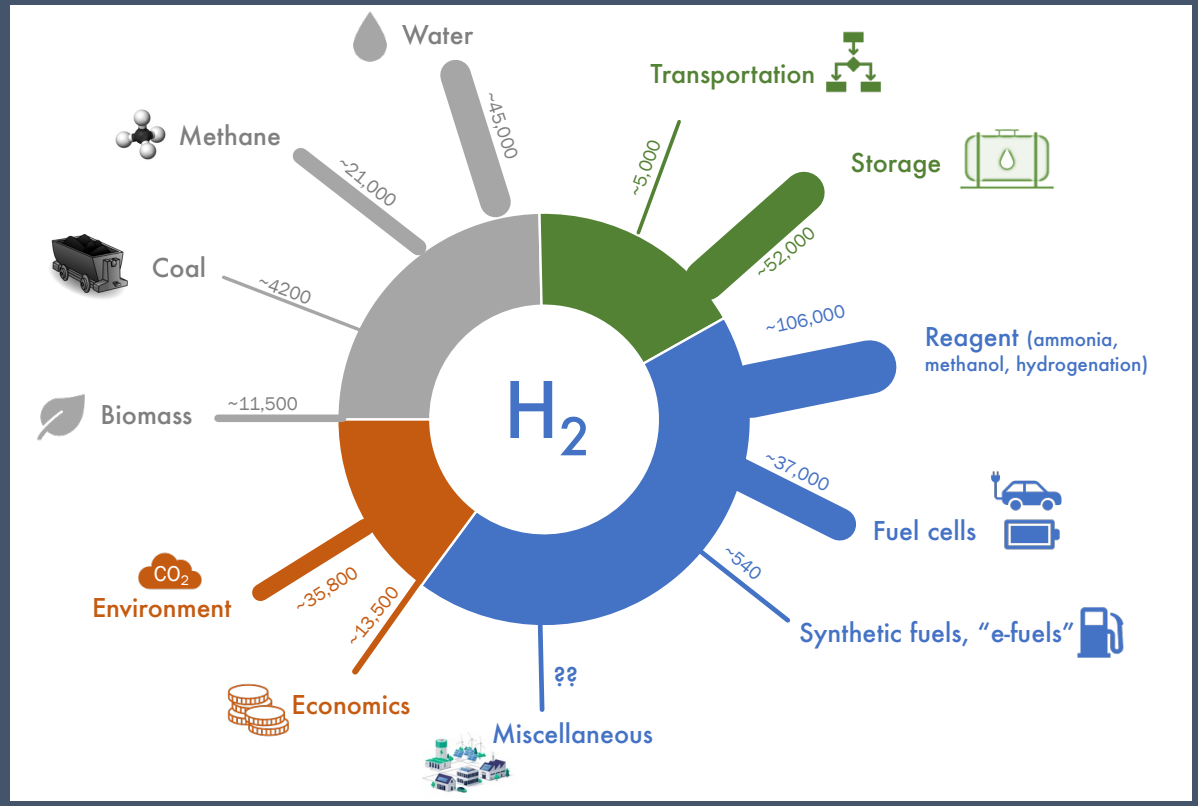
Hydrogen research: phase 3
2013-2023

Key investigators: China – US, Japan, South Korea (Europe)

Hot topics:

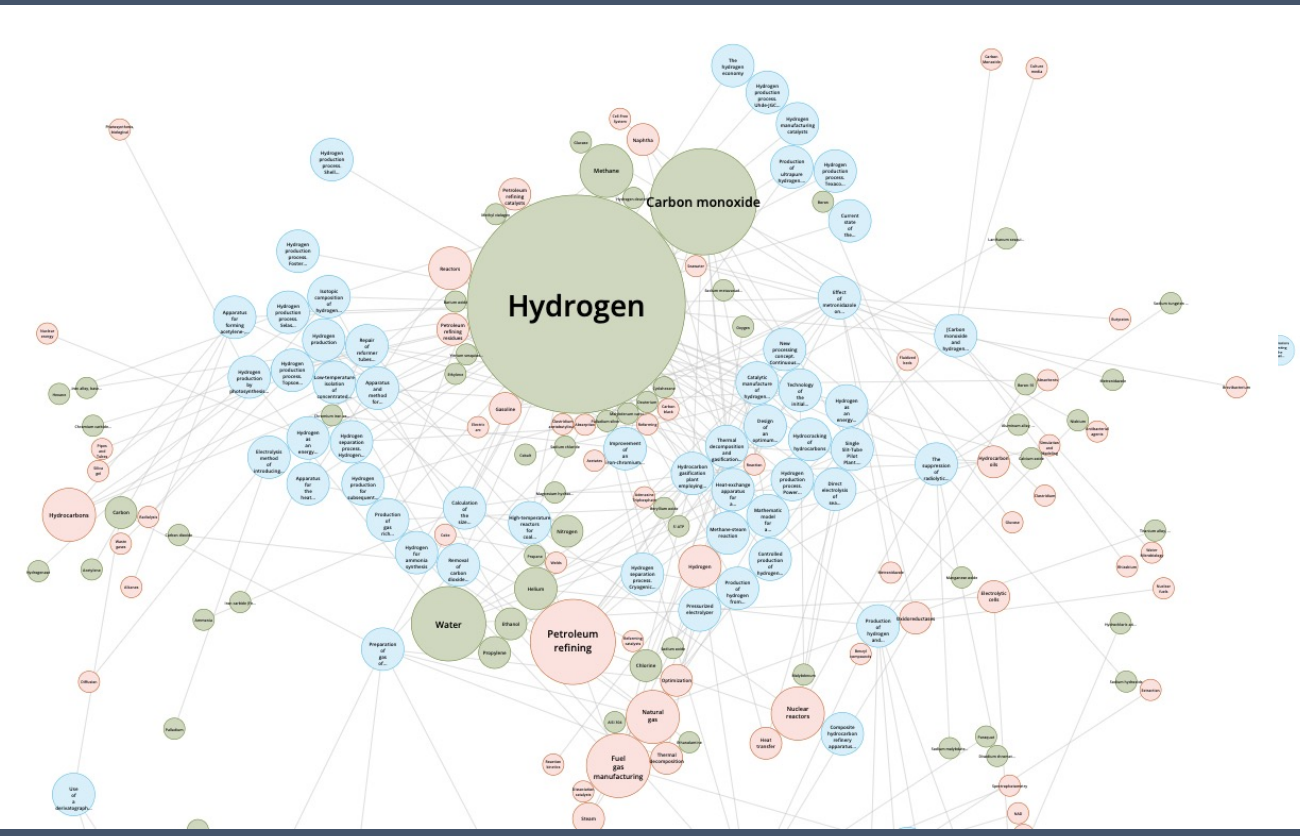
- Design of new materials for water-splitting
- Intermittent renewable energies
- Carbon capture for fossil-based productions
- H_2 storage and transportation
- Diversification of applications ("e-fuels")
- Techno-economic analyses; regulation



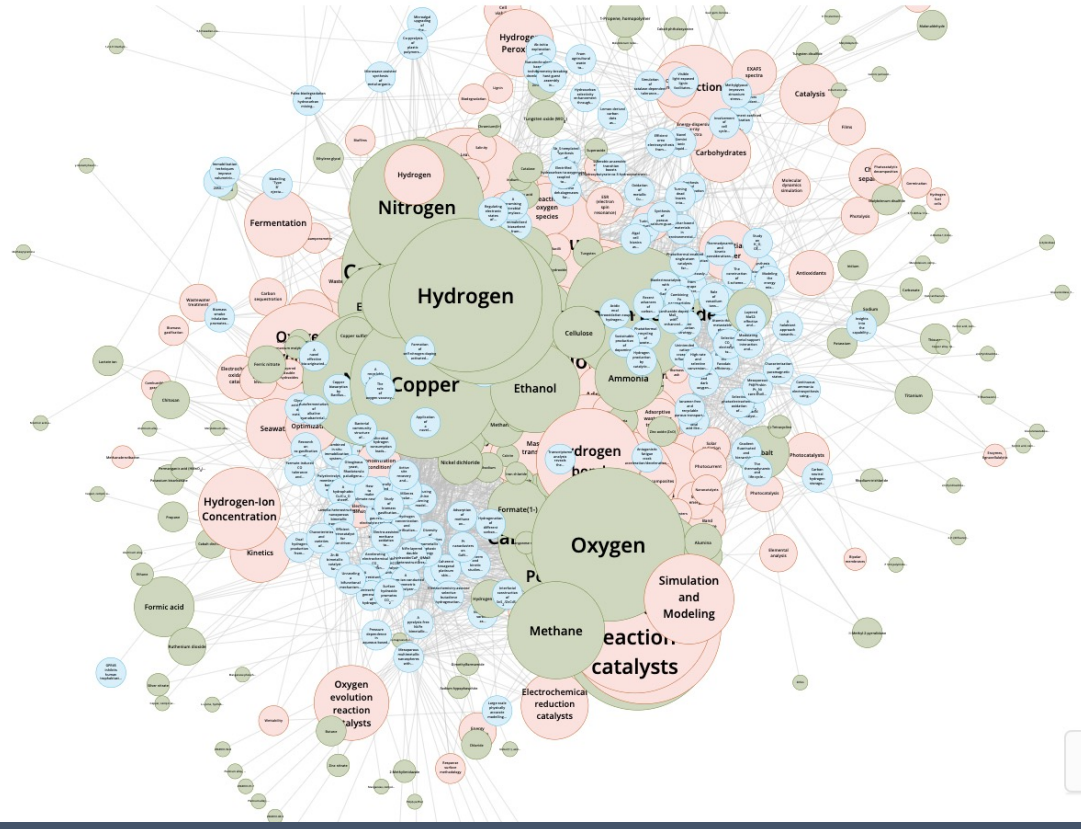
Knowledge graphs

(« hydrogen » and « energy », SciFinder, 1972 and 2022)

1972



2022



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Future research directions or recommendations

Boosting H_2 production (photocatalysts, alternative routes without rare metals or without F-containing membranes)

Evaluating innovative nuclear approaches for H_2 production

Arbitrate technological and application chains based on scientific data (multidisciplinarity)

Thoroughly study of the GWP of H_2 and reflection on controlling the entire value chain

Hydrogen research: conclusions

- 1972. Structured into 3 phases with different dynamics.
- Research objectives specific to each phase due to external (economic and environmental) factors.
- The presence of Belgian universities is only significant from phase 3 onward (due to related funding).
- The research is scattered into clusters and runs the risk of being labeled as a “hype”.
- Fields that are still relatively unexplored but crucial for achieving sustainable development goals and long-term economic viability.

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