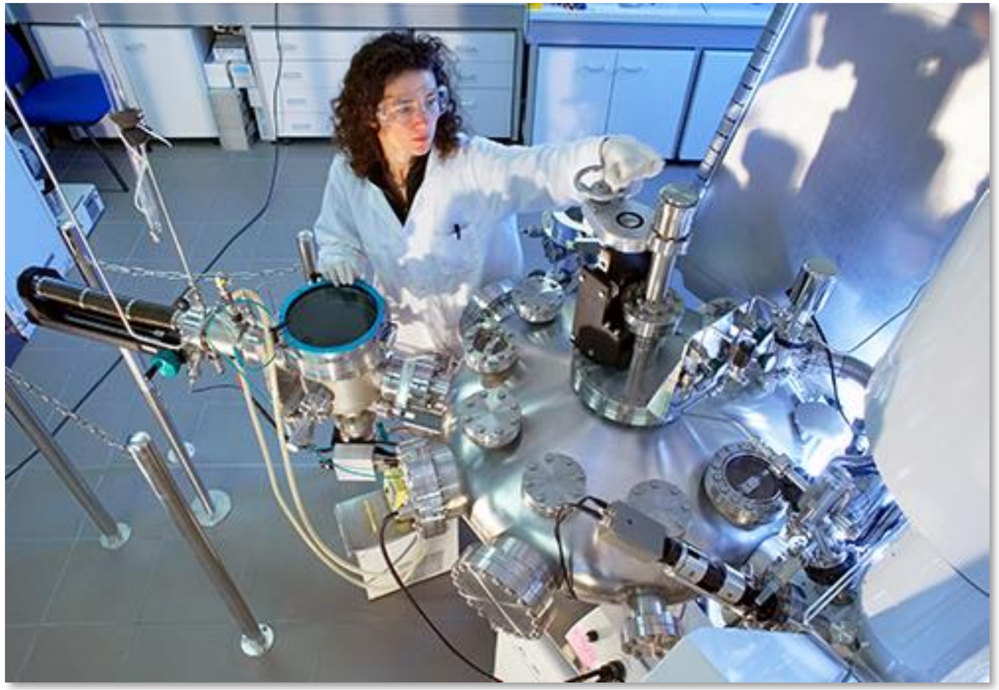

Hydrogen at the Heart of Energy Transition: Prospects and Challenges

Mickaele Le Ravalec

GDR HydroGEMM – 4 November 2024

OVERVIEW

- What role for H_2 in the energy transition?
- How to produce H_2?
- For what uses?
- How much does it cost?
- What about the environmental impact?
- Conclusion

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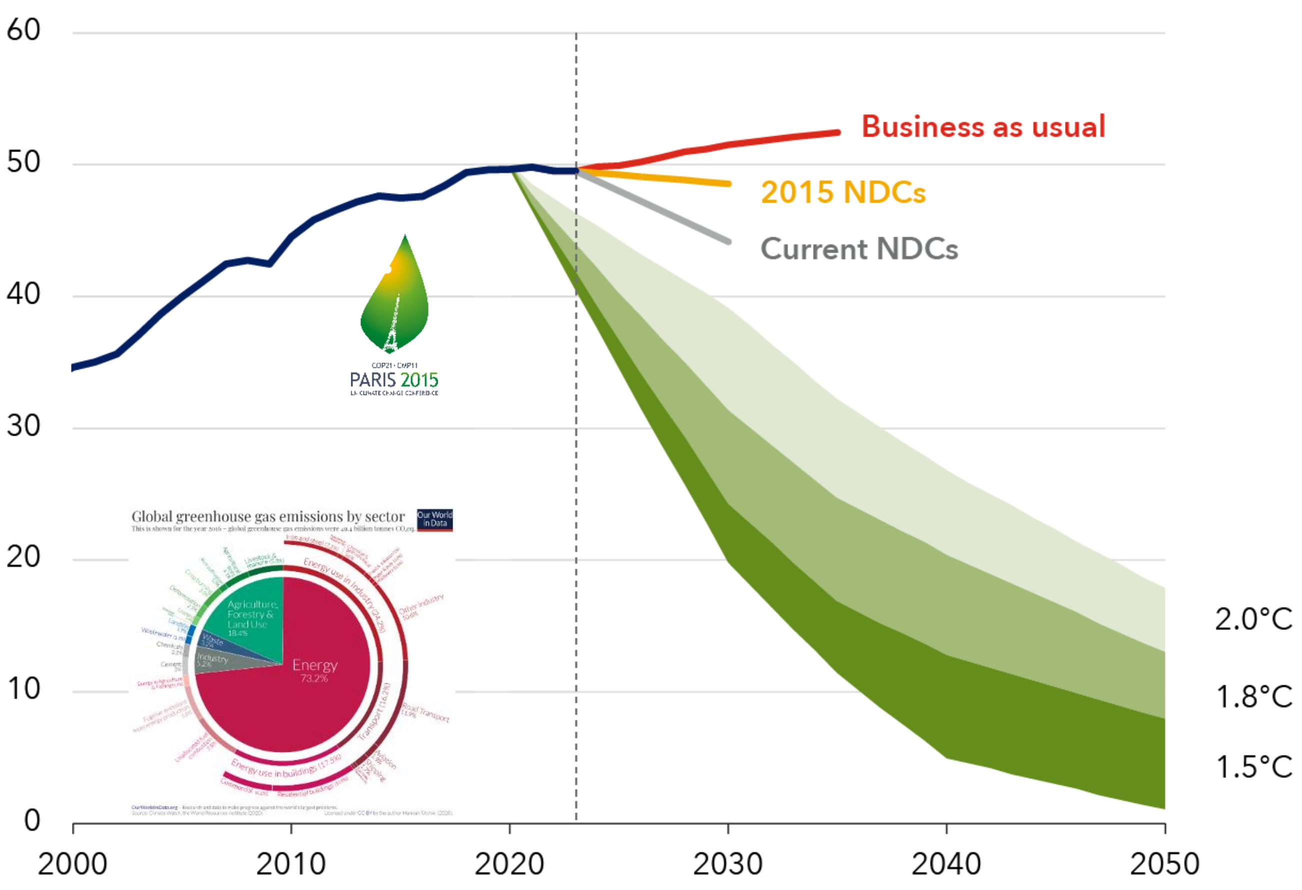
EVOLUTION OF GREENHOUSE GAS (GHG) EMISSIONS

Global GHG emissions (Gt CO_2e/year)



Right before COP28 (2023): UN Environment Program → global warming of 2.9°C in 2100

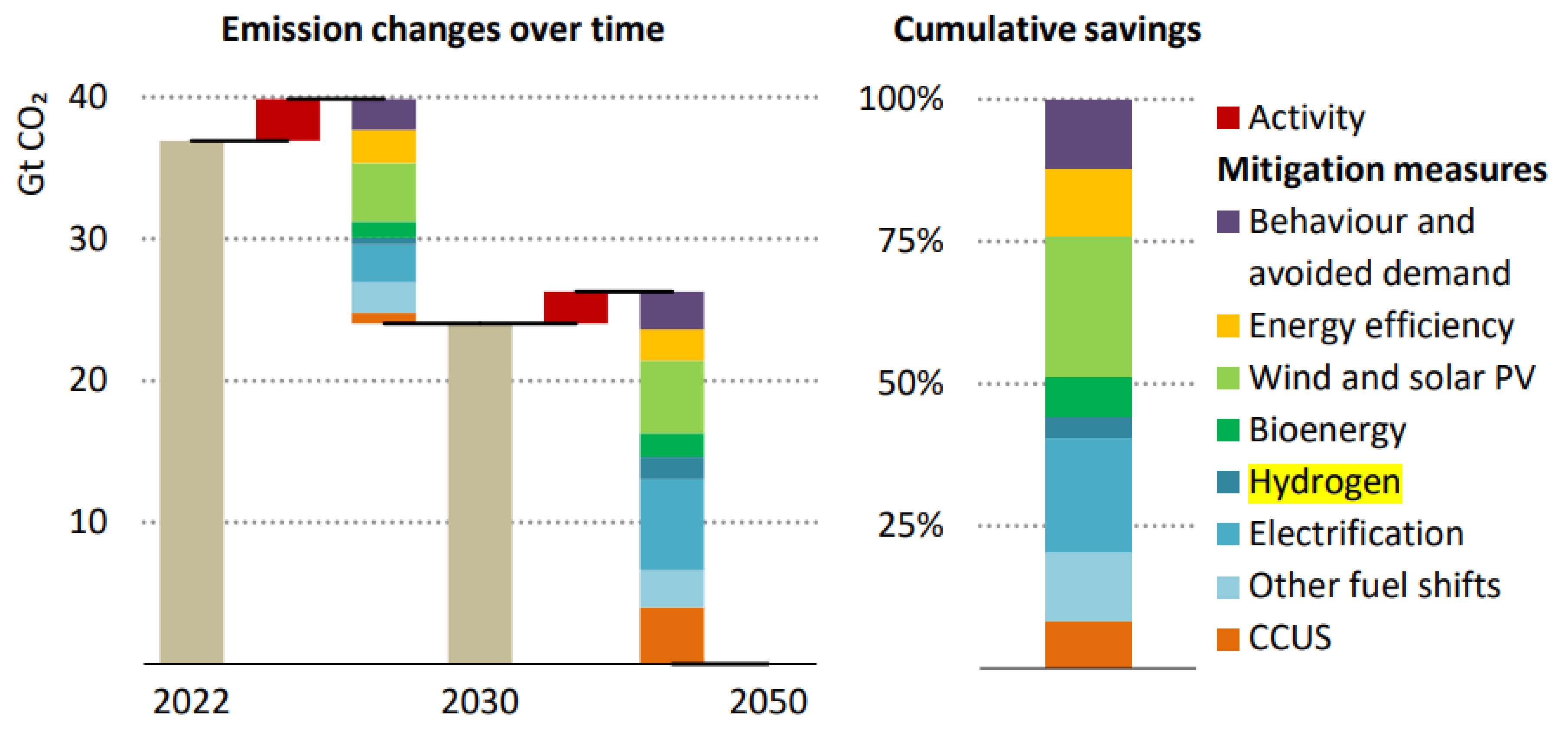
Right before COP29 (2024): UN Environment Program → global warming of 3.1°C in 2100

We need **to step up action** and set more ambitious targets

(IPCC, 2022)

WHAT ROLE FOR H_2?

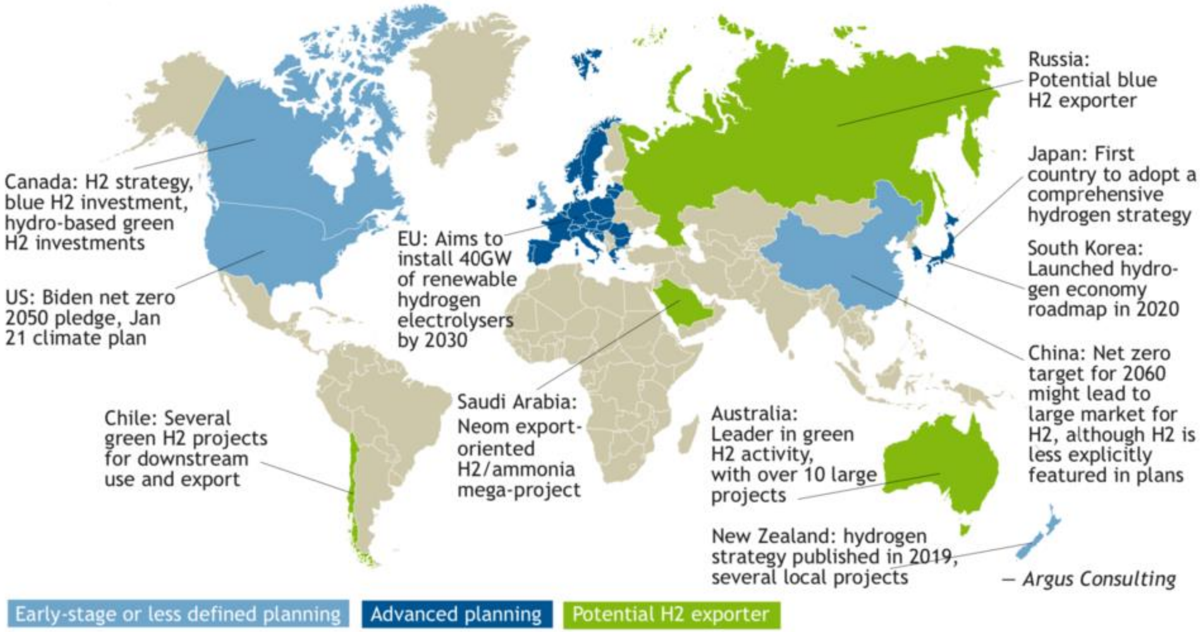
Figure 2.5 ▷ CO_2 emissions reductions by mitigation measure in the NZE Scenario, 2022-2050



- Energy-related emissions
- H_2 contribution to GHG emission reduction: 4%
- But just a trajectory…

WORLDWIDE INTEREST IN LOW-CARBON H_2

- 83 countries with national H_2 strategies to address climate issues + 30 countries developing strategic planning documents
  - Major players: European Union, United States, Australia, Japan, South Korea, China
- Within these strategies,
  - Low-carbon H_2 is intended to replace conventional fossil-based H_2 for traditional uses (production of steel, ammonia and methanol, oil refining)
  - Low-carbon H_2 is also planned for new uses.



Argus Consulting (2024)

Two types of players :

- **Importing countries with important H_2 needs**
- **Exporting countries with lots of renewable and/or gas resources**

OVERVIEW

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THE COLORS OF HYDROGEN

Brown/Black

- H_2 extracted from coal using gasification

Gray

- H_2 extracted from natural gas using steam-methane reforming

Blue

- Brown/Black/Gray H_2 with CO_2 captured, and either stored or repurposed

Turquoise

- H_2 produced by thermal splitting of methane (produced solid carbon instead of CO_2)

Green

- H_2 produced by electrolysis of water, with electricity from renewable sources like wind or solar

Pink

- H_2 produced by electrolysis using nuclear power

Yellow

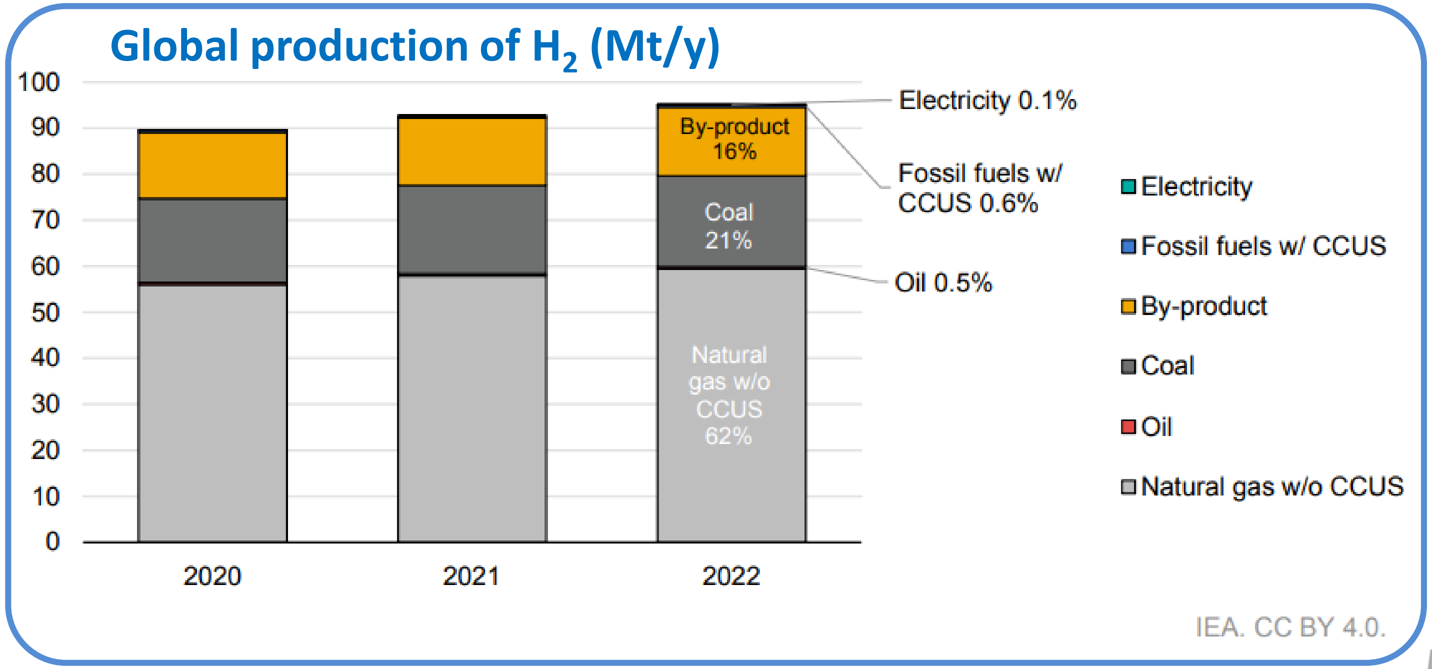
- H_2 produced from electrolysis with electricity from various sources (fossil, renewable, nuclear)

White

- H_2 occuring in its natural form

Color indicates production method, not carbon content

SOME OF THE MOST COMMON ANTHROPIC PRODUCTION METHODS

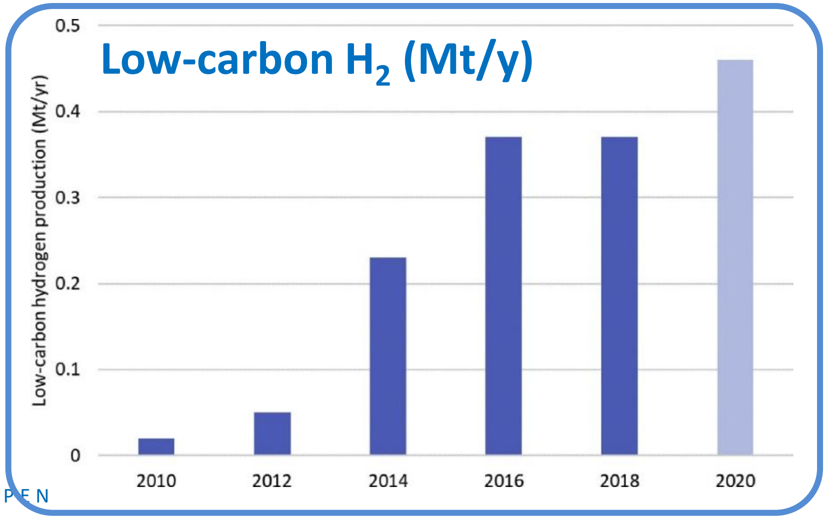


Current production of H_2

World ≈ 100 Mt / y

Europe ≈ 10 Mt / y

France ≈ 1 Mt / y



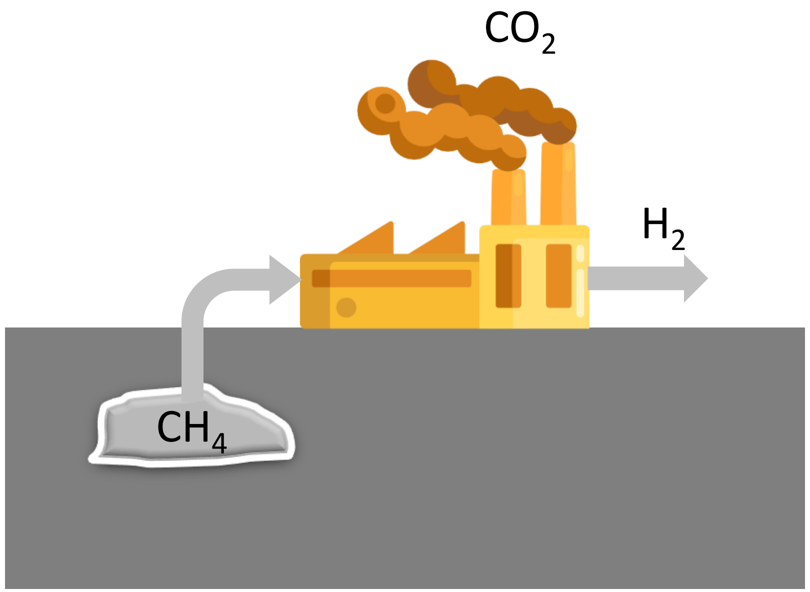
Gray H_2 (62 %)

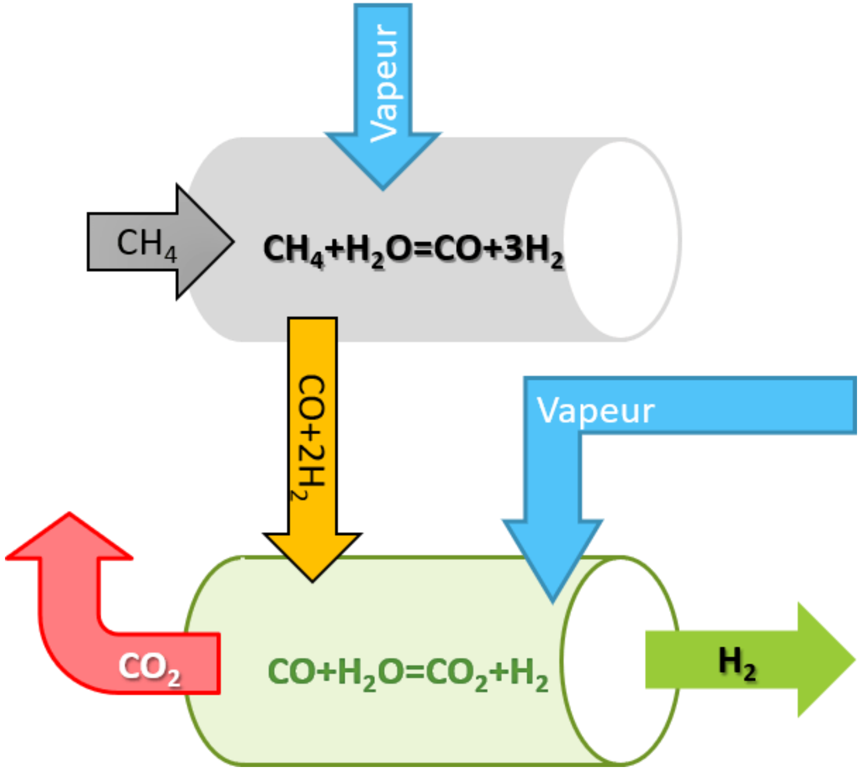
Green H_2 (0,1 %)

Blue H_2 (0,6 %)

STEAM-METHANE REFORMING

Gray H_2



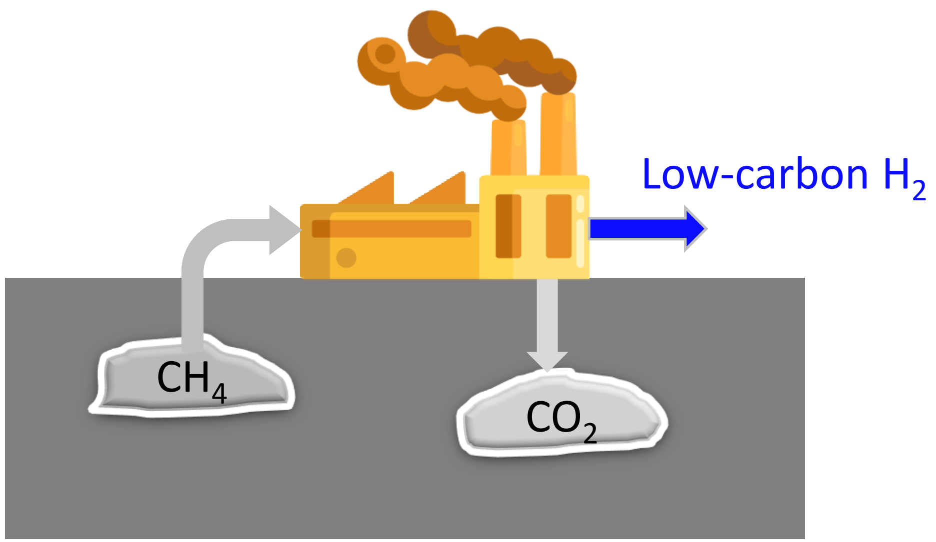


≈10 kg CO_2e / kg H_2 produced

(55 % for the process / 45 % for energy)

STEAM-METHANE REFORMING + CCUS

Blue H_2



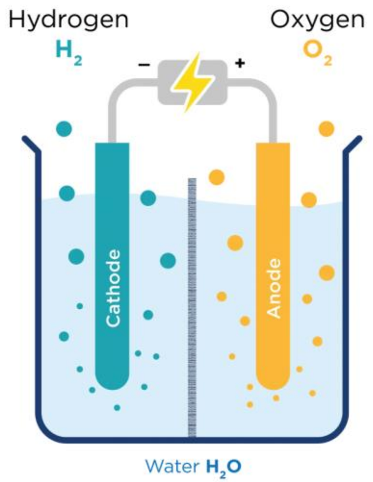
CCUS: Carbon Capture, Utilization and Storage

CO_2 captured for the process or both the process and energy

- Dunkirk hub: the whole chain with CO_2 post-capture, transport, liquefaction, intermediate storage and ship loading for export to the North Sea or possible reuse
- Location of the demonstration pilot for the DMX™ process, which aims to capture the CO_2 in the gases emitted during steel production at the ArceloMittal
- DMX™ process developed by IFPEN

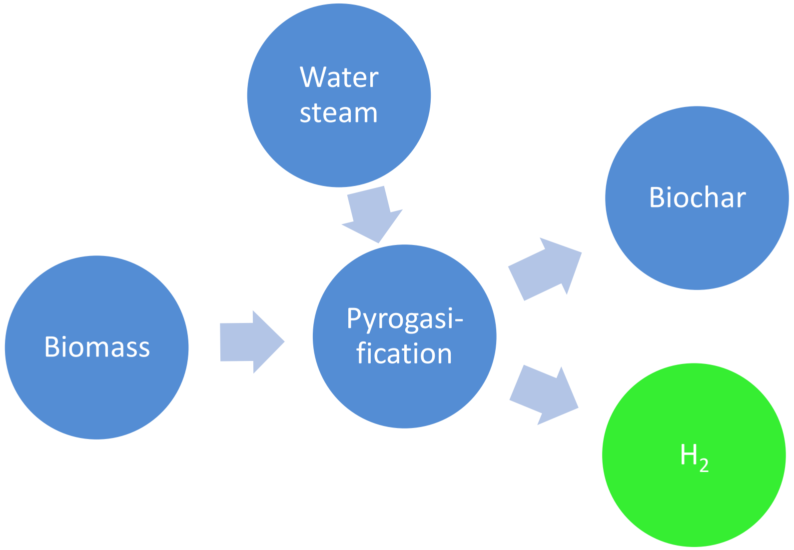
Green H2

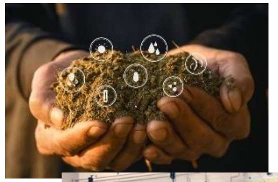
ELECTROLYSIS OF WATER

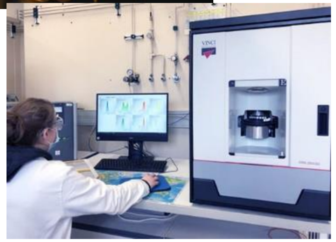


- For H_2 to be green, electricity must be generated from renewable sources
- To produce 1 Mt H_2
  - 55 TWh
  - 9 Mt of desalinated water (10-13 due to losses) or 20-30 Mt of sea water
- Energy content of 1 Mt H_2: 33 TWh → 60 % efficiency
- Electrolyzers
  - Alkaline: mature, cheapest technology, V1 not suitable for intermittent energy
  - PEM: more recent technology, more expensive (requires rare metals), can handle intermittent loads
  - SOEC: at demonstration level, even more expensive but more efficient, not suited for intermittent loads
  - AEM: most recent technology, the best of alkaline and PEM

PYROGASIFICATION OF BIOMASS







- For H_2 to be green, biomass ← wastes
- 30 t of biomass → ≈ 1 t of H_2 + 5,5 t of biochar
- Biochar: used to amend soils, acts as a stable carbon sink

(Derbilova et al., 2024)

WHAT ABOUT NATURAL H_2?

Brown/Black
- H_2 extracted from coal using gasification

Gray
- H_2 extracted from natural gas using steam-methane reforming

Blue
- Brown/Black/Gray H_2 with CO_2 captured, and either stored or repurposed

Turquoise
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Green
- H_2 produced by electrolysis of water, with electricity from renewable sources like wind or solar

Pink
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Yellow
- H_2 produced from electrolysis with electricity from various sources (fossil, renewable, nuclear)

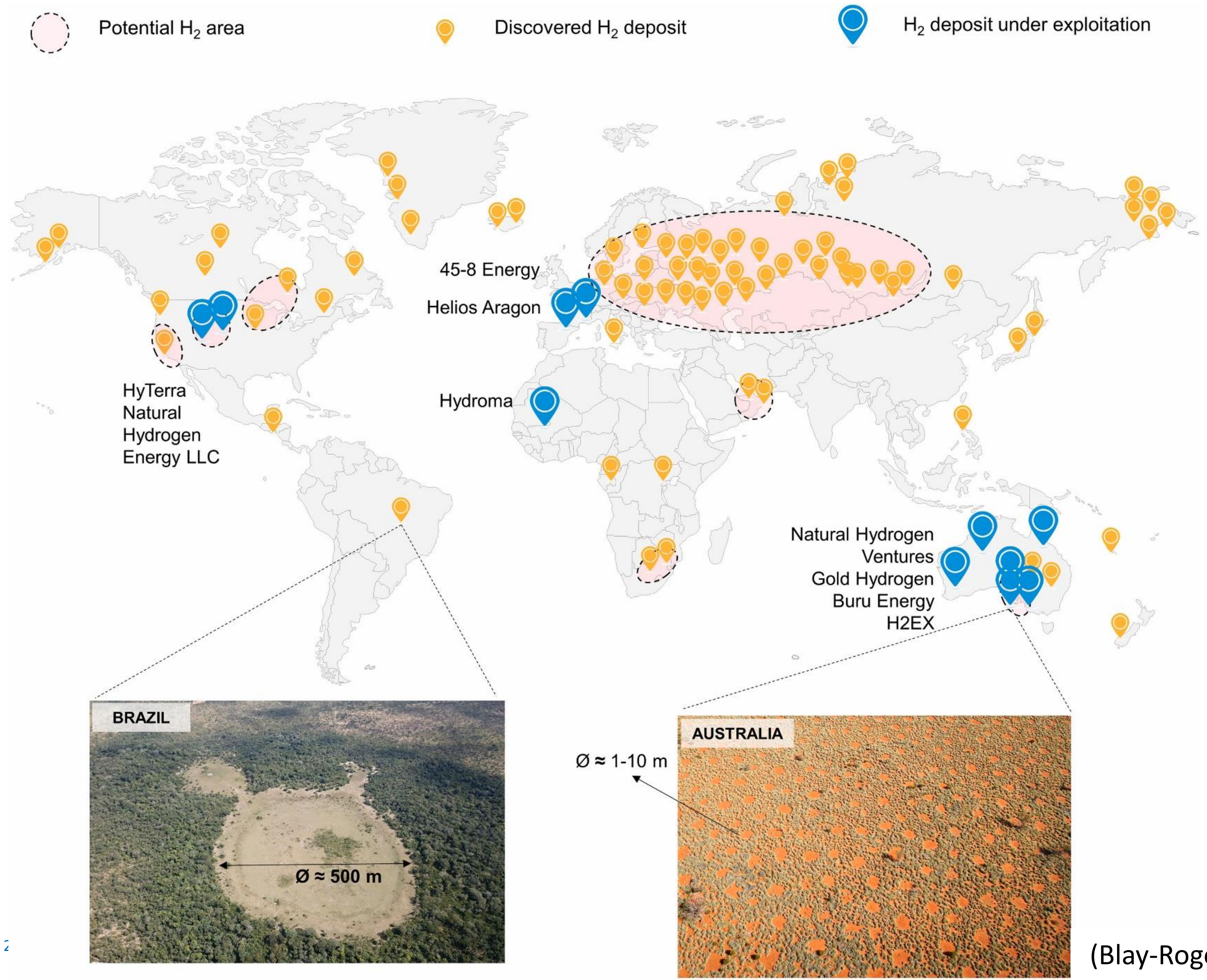
White
- H_2 occuring in its natural form

Energy vector

H_2 as a resource: what potential?

AN EXPLOITATION IN ITS INFANCY

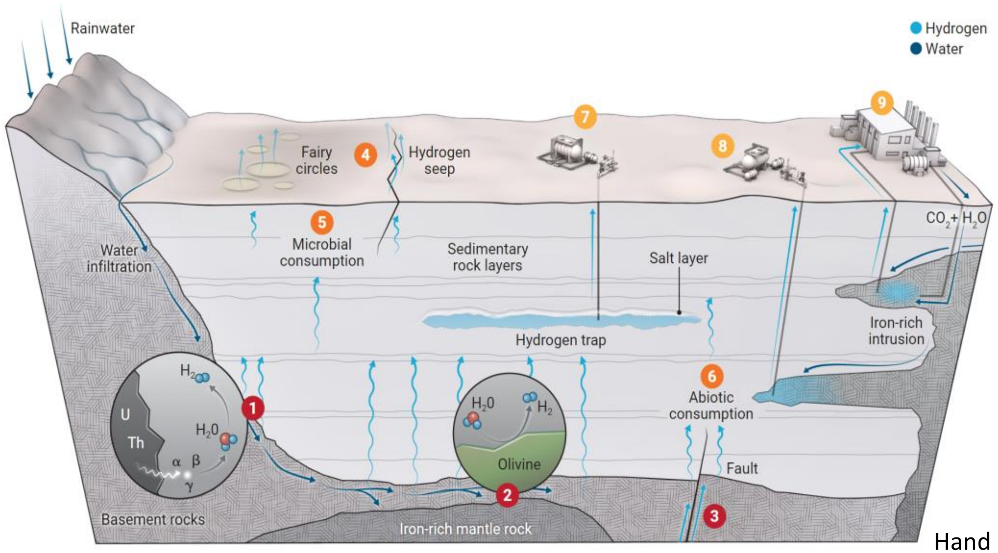
White H_2



(Blay-Roger et al., 2024)

- Known natural hydrogen deposits and fairy circles. Fairy circles can be found all over the world.
- Diverse diameters, locations, and densities

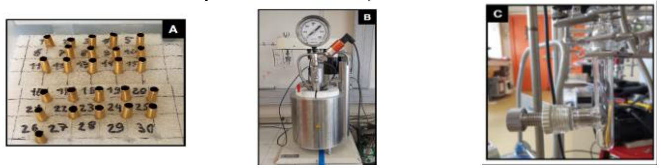
NATURAL H_2: SOME IFPEN WORKS (IN A VERY FEW WORDS)



Hand (2023)

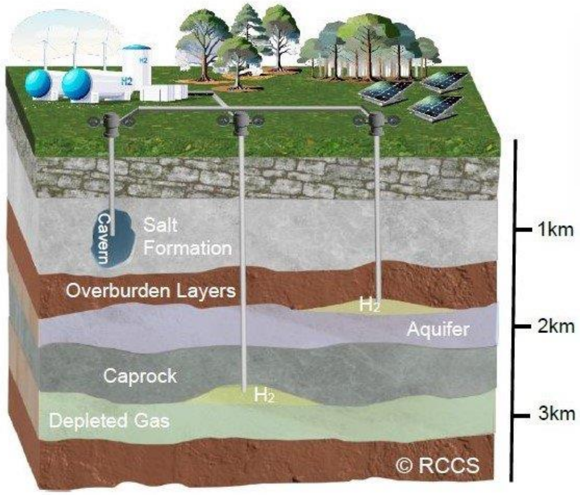
Formation de fer rubanée

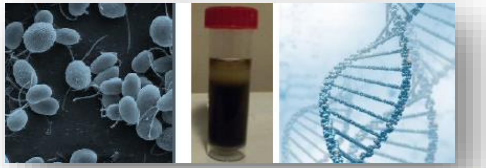
Réaction mise en évidence
par étude expérimentale

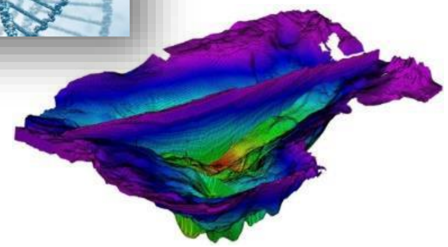


Geymond et al. (2023)

Generation	1. Radiolysis, 2. Serpentinization, 3. Mantle core, …
Losses	4. Emanations, 5. Microbial activity, 6. Geochemical reactions, …
Extraction	7. Traps, 8. Source rocks, 9. Stimulated production







H_2 storage in salt caverns and aquifers, microbial interactions, modeling
Compatibility with materials (steels, polymers)

OVERVIEW

- What role for H_2 in the energy transition?
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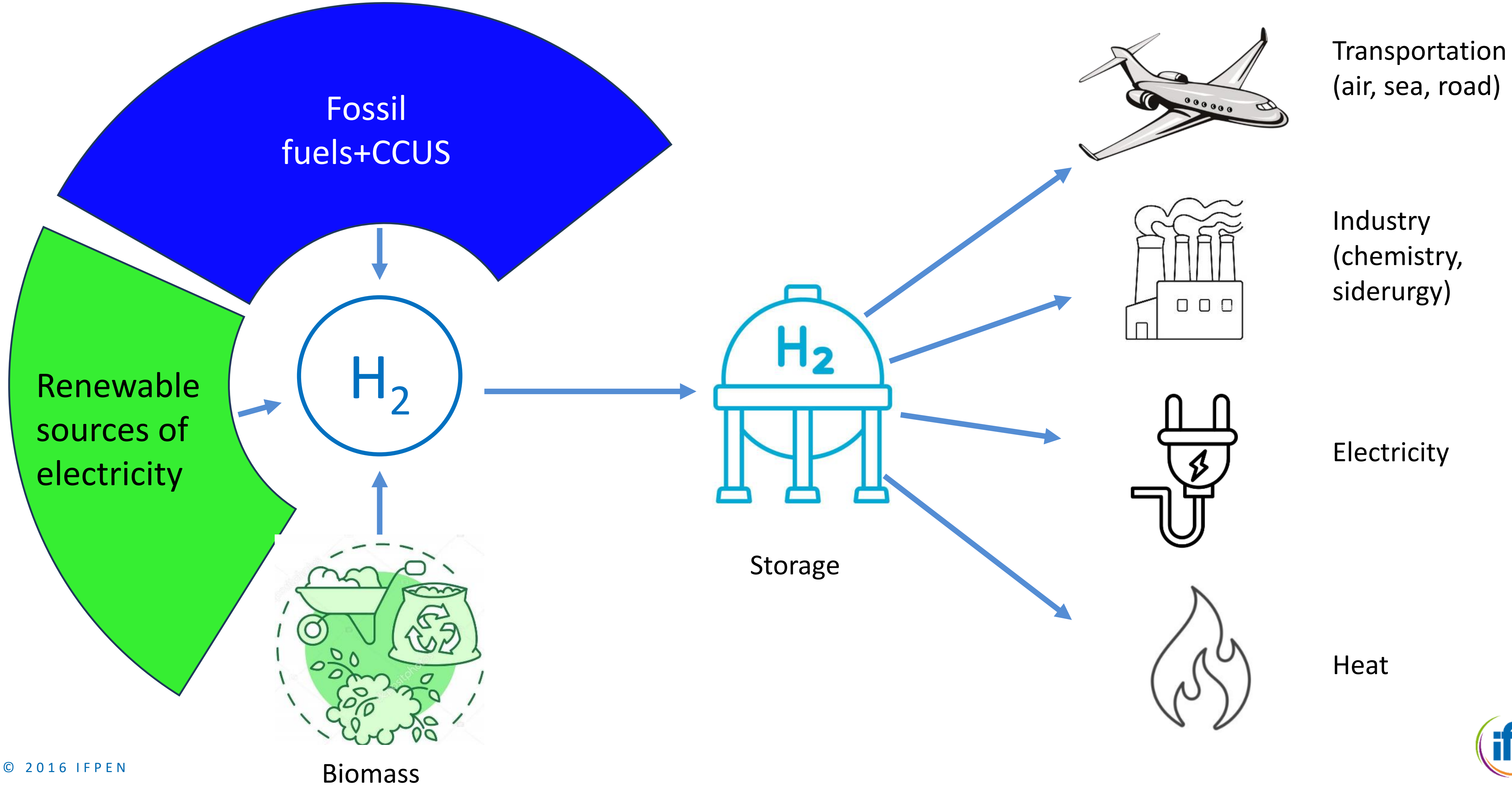
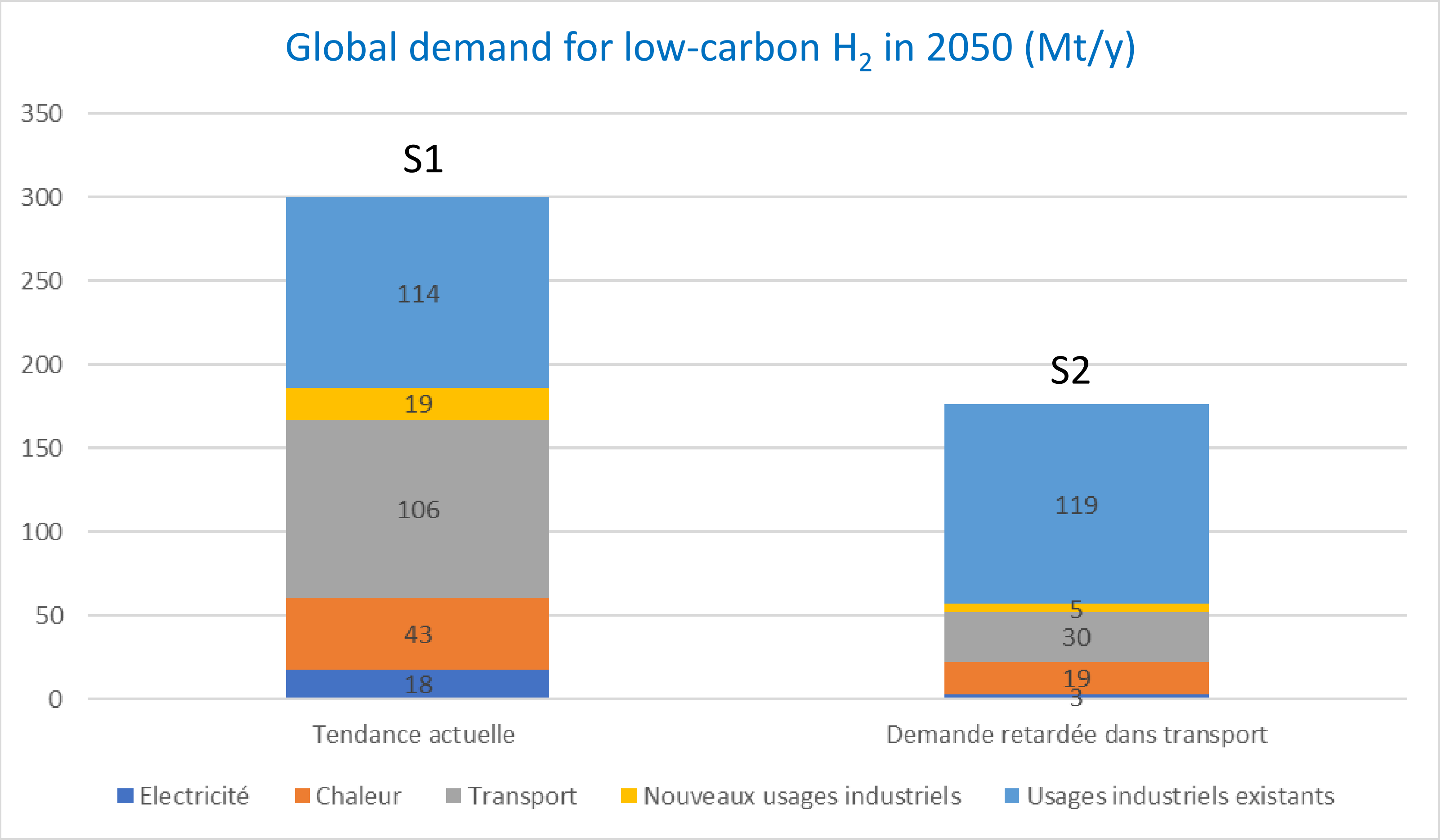
FEEDSTOCK AND ENERGY CARRIER



H2 NEEDED TO MEET CARBON NEUTRAL OBJECTIVES



Share of low-carbon H_2	89 %	73 %

- Industry is expected to be the main driver of low-carbon H_2 demand until 2030
- Transportation could then take over, reaching the same level as industry
- But there are major uncertainties, mainly concerning transportation

McKinsey (2023)

H_2 FOR TRANSPORTATION: SOME IFPEN WORKS (IN A VERY FEW WORDS)

H2

- Direct use
  - Combustion in heat engine
  - Fuel cell
- Indirect use
  - Biofuels
    - Hydrotreatment of vegetable oils
    - Gasification and Fischer-Tropsch
  - E-fuels
    - Fischer-Tropsch

Renault Trucks with H_2 engine

Optimization of costs and energy management system

Hydrotreatment of vegetable oils: Biofuel that can be incorporated directly into conventional diesel and kerosene bases→ Vegan process developed by IFPEN and marketed by Axens

Gasification and Fischer-Tropsch: H_2 addition increases efficiency → BioTfuel® process developed by IFPEN + partners
Construction of an industrial unit to produce sustainable aviation fuels (SAF) by 2028 (Elyse Energy, Axens, Avril, Bionext, IFP Instissements - ADEME)

Fischer-Tropsch: Agreement between IFPEN, Holcim, EDF and Axens to develop an industrial pilot plant producing e-kerosene in the Pays-de-Loire region. This fuel will be bought by Air France.

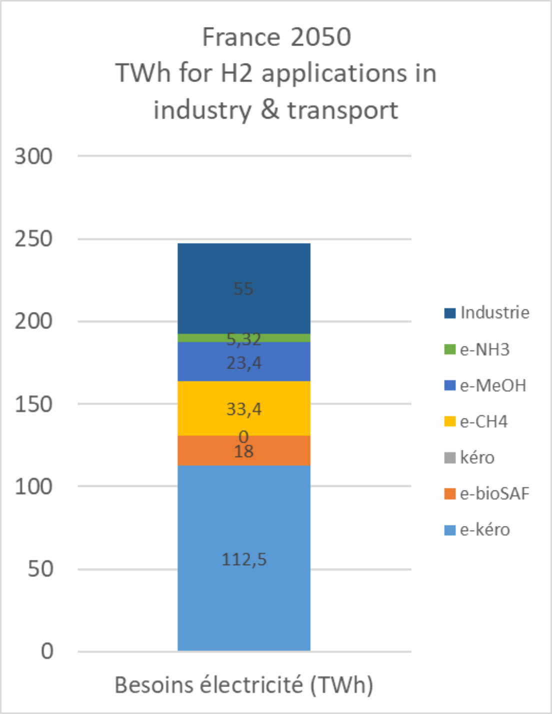
ANNUAL FUEL DEMAND IN FRANCE IN 2050

- ReFuelEU Aviation: European regulation requiring the use of low-carbon fuel in the aviation sector

	2025	2030	2035	2040	2045	2050
Taux d'incorporation de SAF[7] (e-kérosène et biokérosène)	**2 %**	**6 %**	**20 %**	**34 %**	**42 %**	**70 %**
Part minimale de e-carburants (e-kérosène uniquement)	-	*1,2 % (sur 2030-2031) 2 % (sur 2032-2034)*	*5 %*	*10 %*	*15 %*	*35 %*

- FuelEU Maritime: European regulation setting GHG emission reduction targets for the maritime sector

	2025	2030	2035	2040	2045	2050
Cible de réduction de l'intensité GES des carburants	- 2 %	- 6 %	- 14,5 %	- 31 %	- 62 %	- 80 %



Electricity is needed mainly for electrolysis

Hyp: the current 1 Mt gray H_2 becomes 1 Mt low-carbon H_2

Sea

Air

1 EPR ≈ 11 TWh

250 TWh ≈ 22 EPR

OVERVIEW

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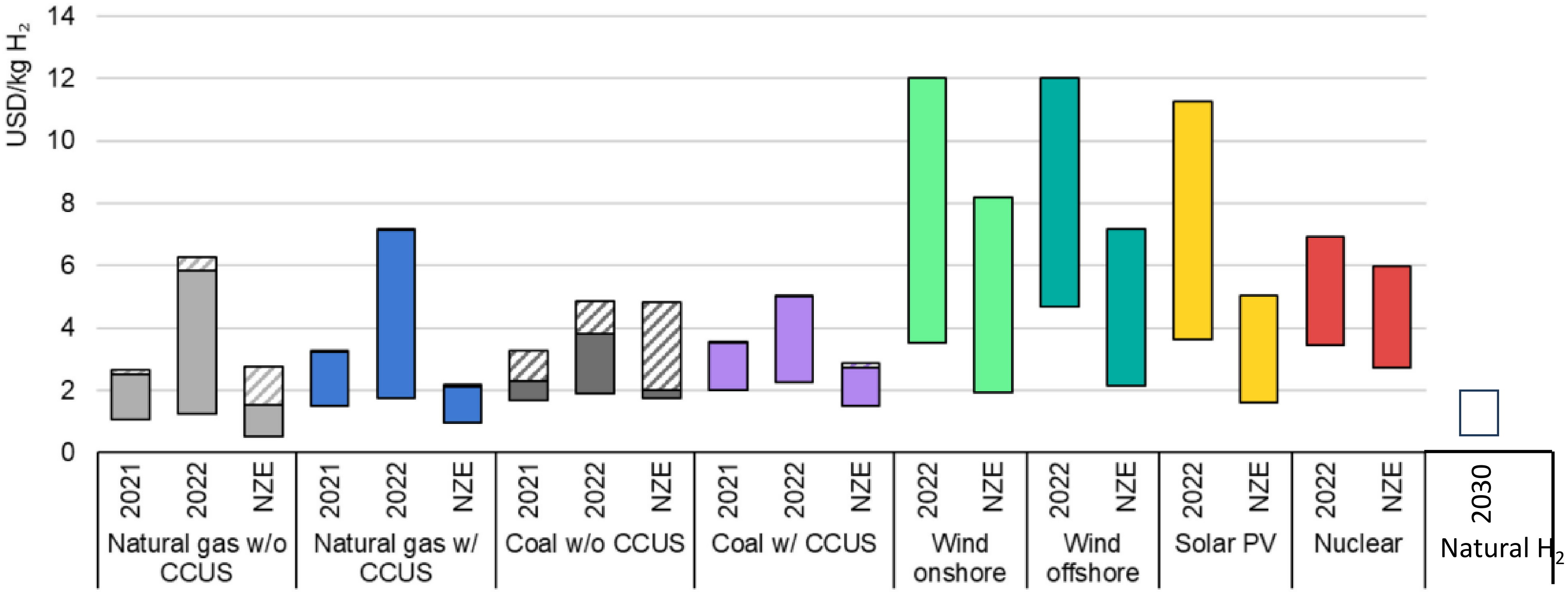
HOW MUCH TO PRODUCE 1 kg OF H_2?

Levelized costs for 2021, 2022 and estimated costs for 2030 in the NZE scenario



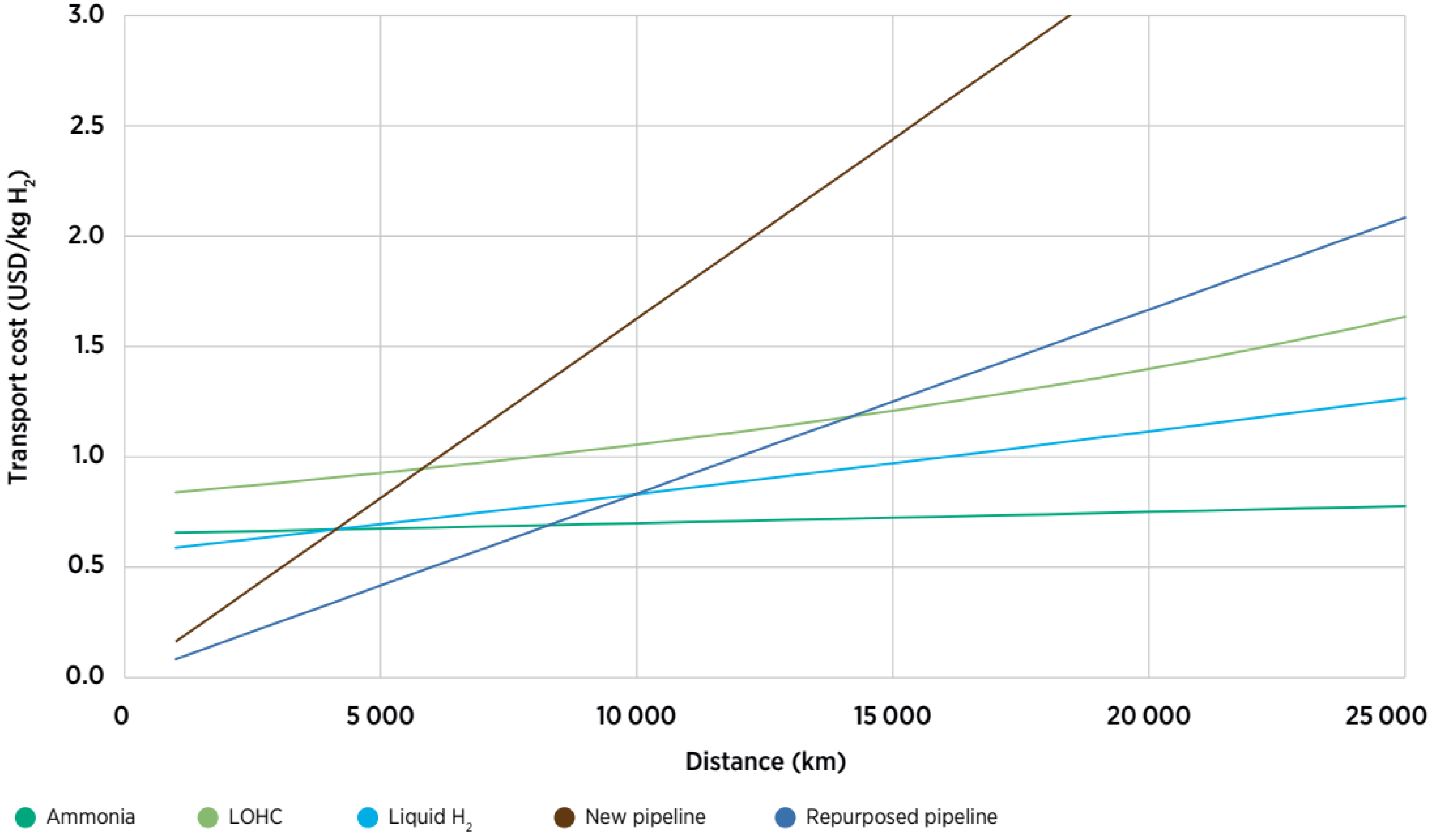
- The cheapest one
  - Today: gray H_2
  - In 2030: blue H_2 becomes cost-competitive

- The cheapest low-carbon H_2 in 2030 according to IEA projections
  - Solar green H_2: min is 1,7 $/kg H_2
  - Wind H_2: min is 2 $/kg H_2
  - Nuclear H_2: min is 2,8 $/kg H_2

Stripped zone: impact of CO_2 price (15 to 140 $/t)

COSTS FOR TRANSPORTATION

FIGURE 6.7. Transport cost by pathway as a function of distance for a fixed project size of 1.5 MtH_2/yr in 2050



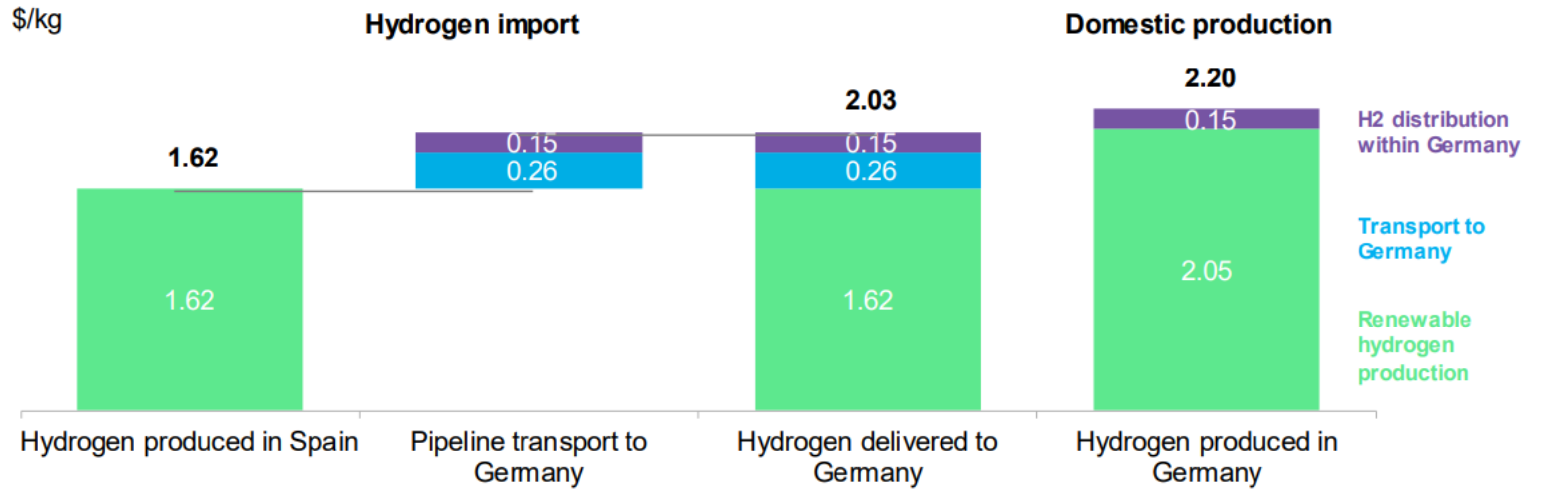
Note: Optimistic scenario for costs.

For short distances: pipelines are more attractive than ships, with costs < USD 1/kg H_2

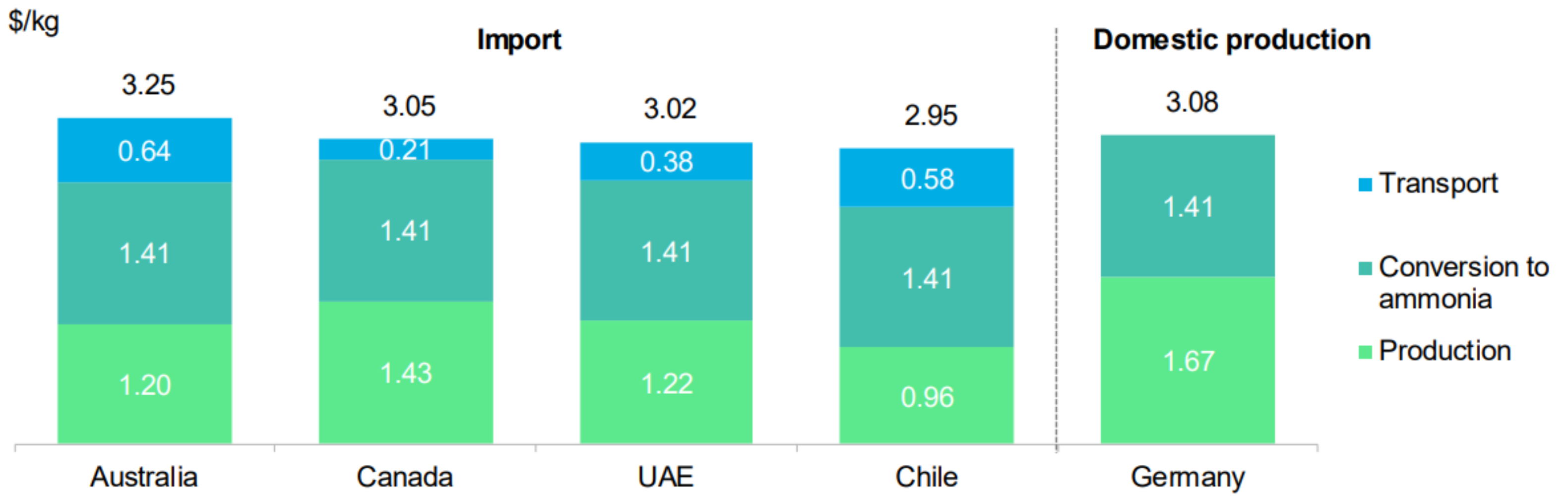
For larger distances: ammonia is the most attractive carrier for shipping H2.

IRENA (2022)

GERMANY EXAMPLE: PRODUCTION AND TRANSPORTATION



Source: BloombergNEF. Note: Assumes 2,000km pipeline transport form Valencia, Spain to Duisburg, Germany using a repurposed 48-inch pipeline operated between 80-60bar. Compressor stations every 500km along the pipeline. Local distribution distance is 50km using a repurposed 8-inch pipe operated at 7-3bar. Hydrogen is produced using western alkaline electrolyzers in both countries. Electricity from tracking solar PV is used in Spain, onshore wind in Germany.



Source: BloombergNEF. Note: Assumes ship transport to Germany over 20,000km from Australia, 6,500km from Canada, 12,000km from UAE and 18,000km from Chile.

Green H_2 imported by pipeline from Spain to Germany

H_2 imported from Spain would be cost-competitive in other European coutries (e.g., Germany).

Import of H_2 in the form of ammonia

Imported derivative products would be less costly when there is no reconversion stage.

WHERE ARE WE IN 2024?

- The number of FID projects has doubled
- Expected production in 2030 (based on FID projects): 3.4 Mt/y = 1.9 Mt/y (Electrolysis) + 1.5 Mt/y (Blue H_2)
- Many projects were delayed or even suspensed due to unclear demand signals, funding barriers, delays in rolling out incentives, regulatory uncertainties, licencing and permitting issues and operation challenges.
- China
  - Accounts for 40% of growth, has 60% of the world's electrolyzer production capacity.
  - Lower production costs

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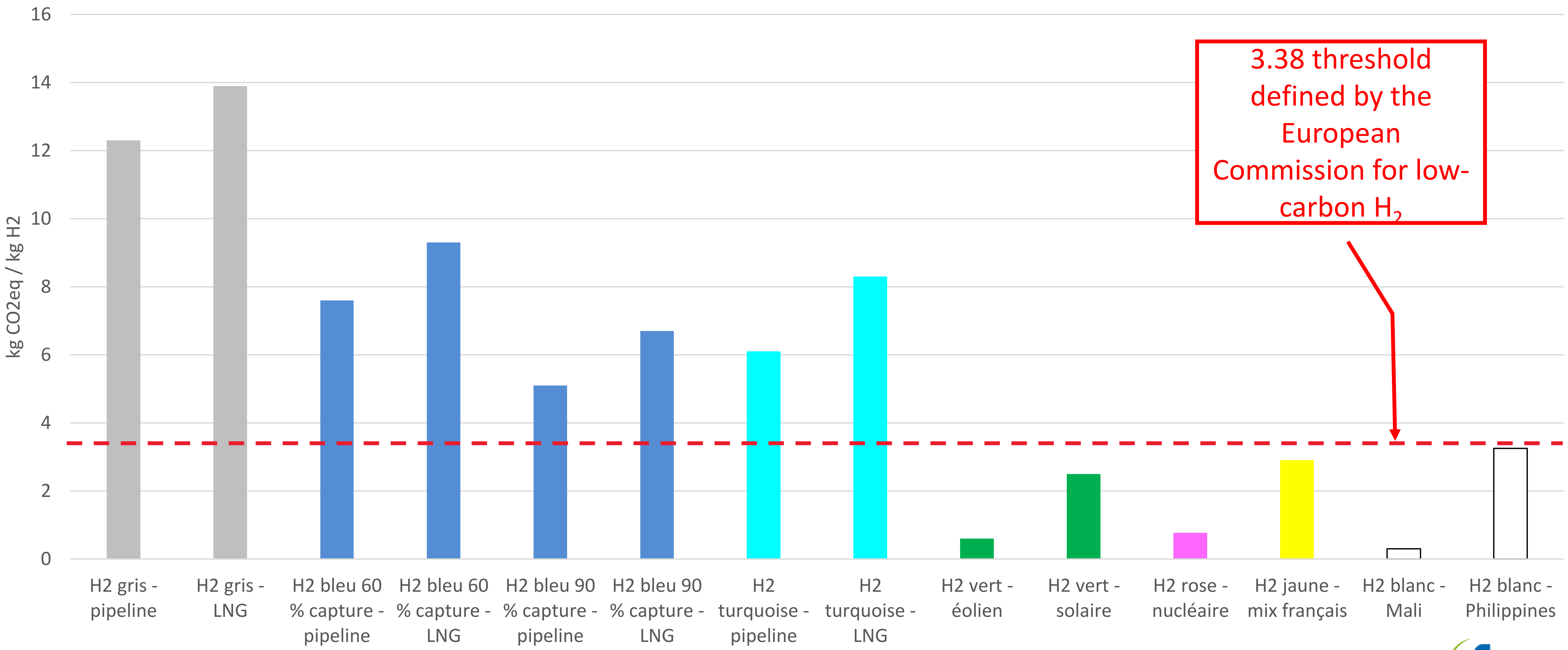
LIFE CYCLE ANALYSES - CO_2 EMISSION INTENSITY FOR DIFFERENT PRODUCTION METHODS



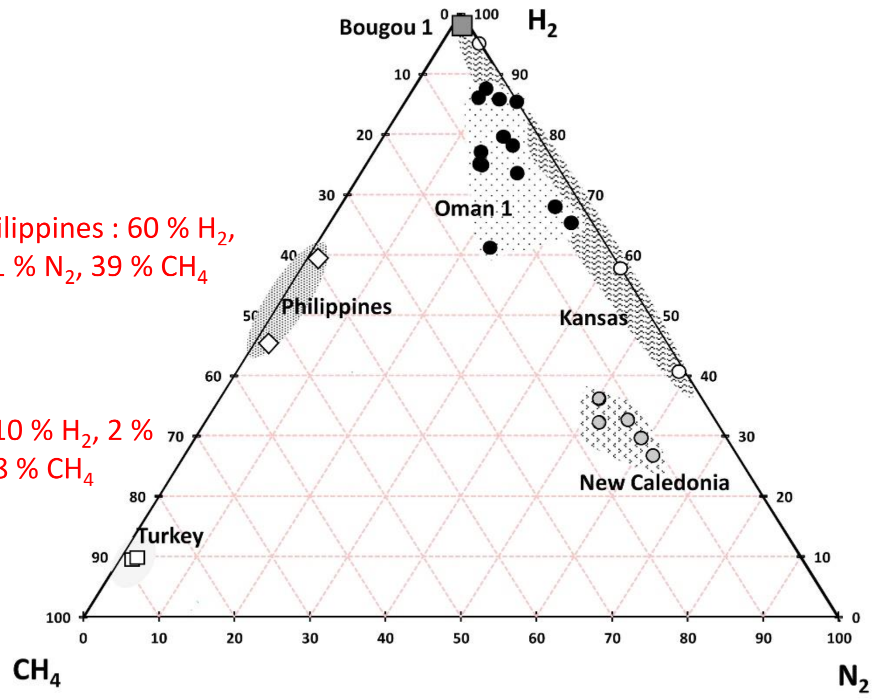
LIFE CYCLE ANALYSES - CO_2 EMISSION INTENSITY FOR DIFFERENT PRODUCTION METHODS

- Natural H_2 is associated to other gas, with varying concentrations
- CO_2 emission intensity depends on the concentration of these gases

Mali : 97,4 % H_2, 1,2 % N_2

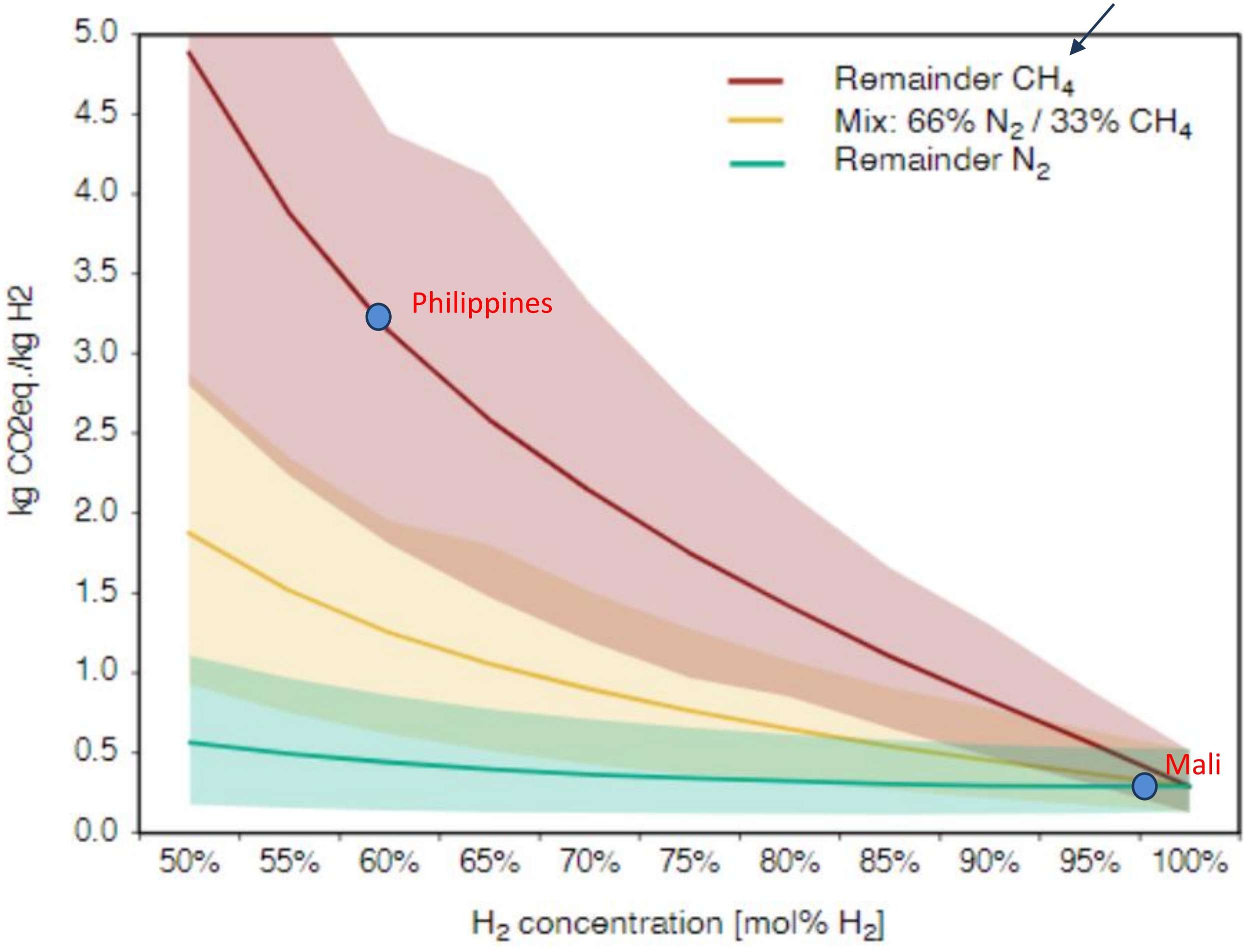
Philippines : 60 % H_2, 1 % N_2, 39 % CH_4

Turquie : 10 % H_2, 2 % N_2, 88 % CH_4



Vacquand et al. (2018)

What the non H_2 part contains



Brandt (2023)

CONCLUSION

- More and varied uses → very high demand projections
  - Green H_2 / Blue H_2 for transitional low-carbon H_2?
  - Importing / exporting countries → new geopolitical challenges?
  - Exports in what forms?

H_2	Decreases GHG emission intensity	Low cost	Low electricity requirements	Maturity
Blue	+	++	++	+++
Green	+++	-	--	++
White	++ ?	++	++	-

Natural H_2 = possible game changer

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