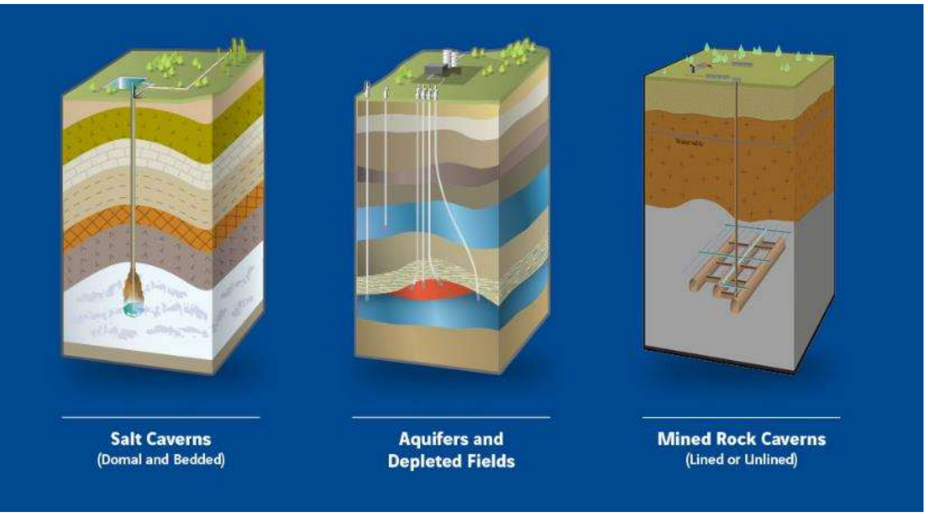
HYDROGEN FOR THE ENERGY TRANSITION : WHY ? HOW ?
PART I : INTRO AND USAGES

Dr Vivien Esnault – IFPEN (France)

GeoIndia 2022 – Continuing Education Courses October 12th 2022



YOUR « TEACHER » TODAY

“**Dr. Vivien Esnault works as a material scientist and Research & Innovation project manager at IFP Energies Nouvelles.** He has a Ph.D. from Ecoles des Ponts (France) in material sciences and processes and more than ten years of experience in managing industrial innovation projects in the fields of construction materials and energy. His current focus is on piloting IFP Energies Nouvelles efforts on a variety of topics linked to the emerging hydrogen ecosystem: **hydrogen behavior in sub-surface systems (natural hydrogen production and storage), hydrogen logistic (material interactions, safety), hydrogen industrial usages**”

ABOUT IFP ENERGIES NOUVELLES

A public sector **R&I** body

A **training** center

An industrial **group**

An international scope in the fields of energy, transport and the environment

1,635
people

1,190 engineers and technicians dedicated to research

€120.5m
budget allocation
In 2020

€146.5m
own resources
In 2020

OUR AREAS OF EXPERTISE

Climate, environment and circular economy

- Plastics recycling
- CO_2 capture, use and storage
- Air quality
- Environmental monitoring
- Climate/soil interactions and the water cycle
- Circular economy / LCA

Renewable energies

- Biofuels
- Biobased chemistry
- Biogas
- Offshore wind and ocean energies
- Geothermal energy
- Hydrogen
- Energy storage

Sustainable mobility

- Hybridization and electrification
- Electricity storage
- Connected vehicles
- Thermal engines
- Low-carbon fuels

Responsible oil and gas

- Fuels
- Petrochemicals
- Gas sweetening and conversion
- Basin modeling
- Reservoir simulation
- Enhanced oil recovery (EOR)
- Offshore production

SUBSIDIARIES AND SHAREHOLDINGS (*)
THE IFP GROUP: **€952M** TURNOVER IN 2020 - **4,500** PEOPLE

Energy transition	Geoscience consulting and software	Alternative and renewable energies, refining, petrochemicals, gas, water	Training
23.6% DriveQuant 23% Galanck 23% easyLi advanced battery systems 20% la Cie des Mobilités 14.6% K-Ryole carry on	100% BeicipFranlab 100% Tech'advantage	100% Axens Powering integrated solutions An IFP Group company Eurecat	62% IFP Training

** As of 14 April 2021*

IFP Energies nouvelles

PROGRAM OF THE COURSE (1/2)

- Part 1 : Why Hydrogen ?
  - The role of hydrogen in the energy transition
  - Hydrogen current and future usage
  - Case study : Why hydrogen in India ?
- (Tea break)
- Part 2 : The « hydrogen rainbow » : means of production for hydrogen
  - Green vs blue/black : electrolysis or hydrocarbon-sourced ?
  - Environmental impact… and economy
  - Case study : India’s assets for the production of H_2
- (Lunch break)

PROGRAM OF THE COURSE (2/2)

- Part 3 : Toward an hydrogen network
  - Technologies to transport and store hydrogen
  - Safety and quality issues
  - Case study : Your hydrogen strategy for India
- (Tea break)
- Part 4 : Hydrogen underground
  - Underground ressources for hydrogen (native hydrogen and in-situ production)
  - Storing hydrogen underground
  - Questions – open debate

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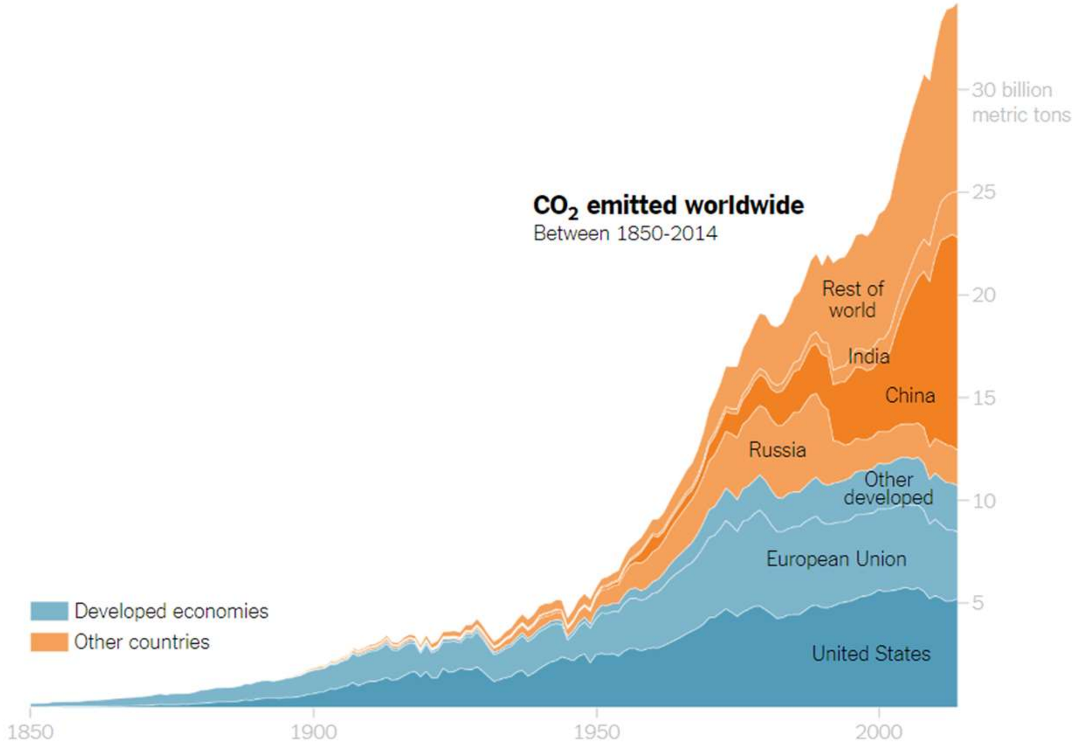
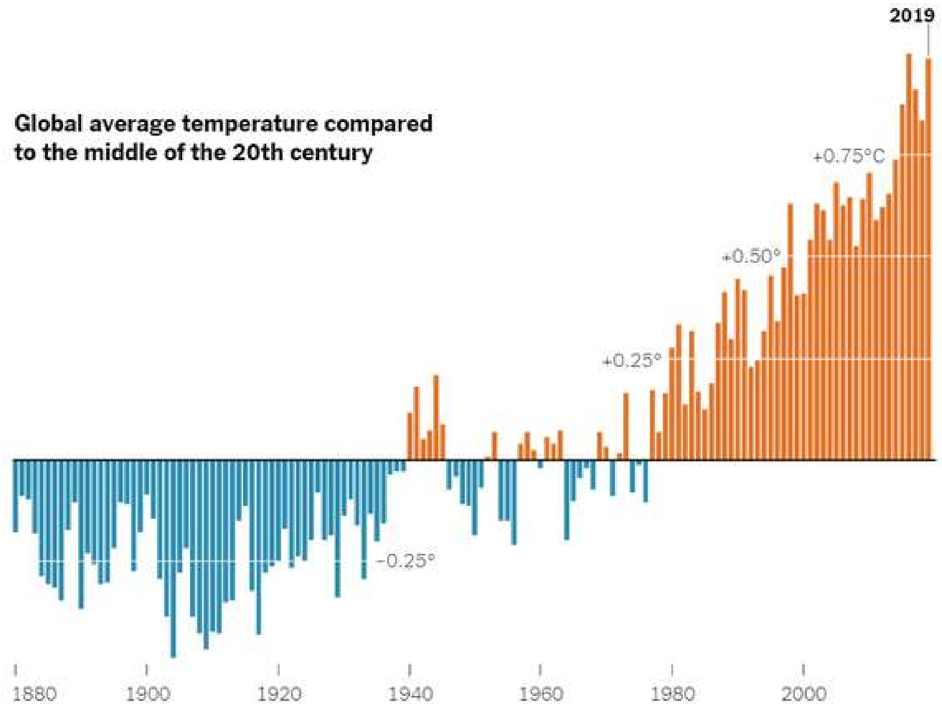
TIME TO CURB THE CO2 EMMISSIONS, NOW





New York Times

- Scientific consensus that CO2 emmisions are having a major influence on our climate

2022, CLIMATE CHANGE INTO DAYLY NEWS

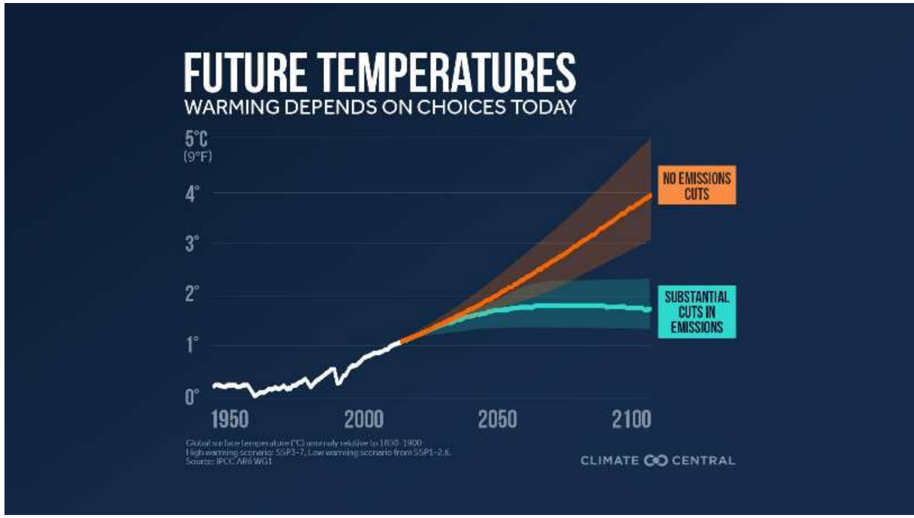
La Provence

BBC

Le Point

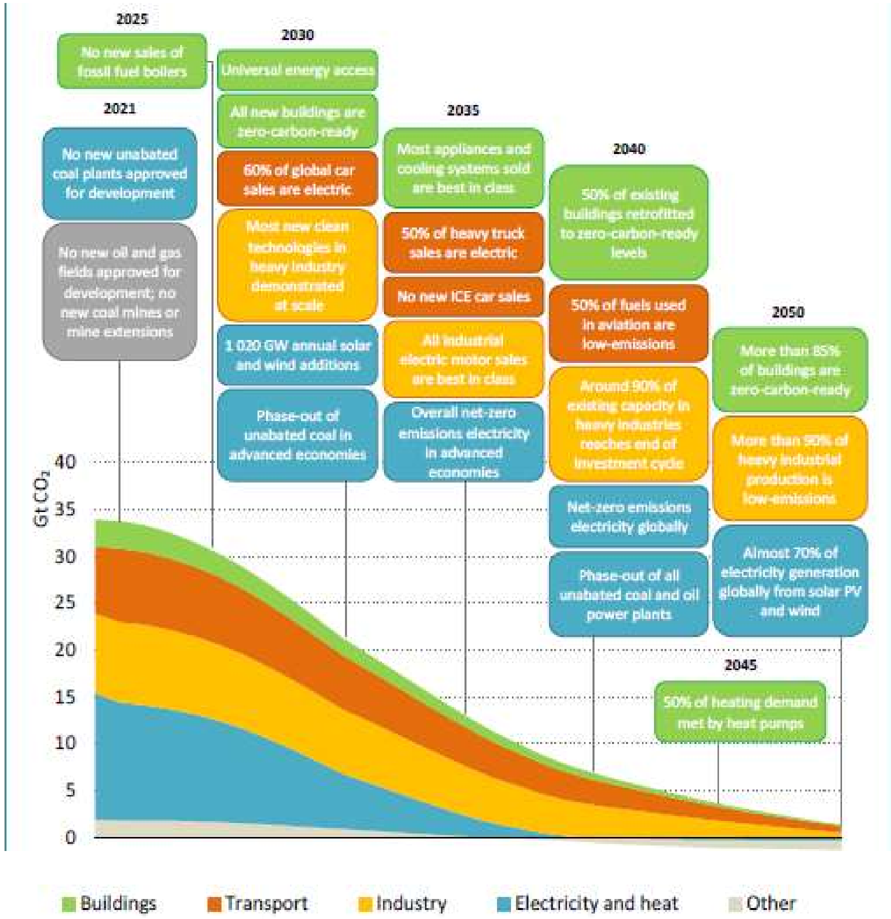
- France :
  - Massive forest fires in south-western France (and in all Southern Europe)
  - Most severe drought in Europe in 500 years
- India and Pakistan :
  - Heatwave in India and Pakistan with peaks above 49°C
  - 1/3 third of Pakistan under water following the flood of the Indus

- Increasing consciouness worldwide that business as usual is not an option



TOWARD NET ZERO

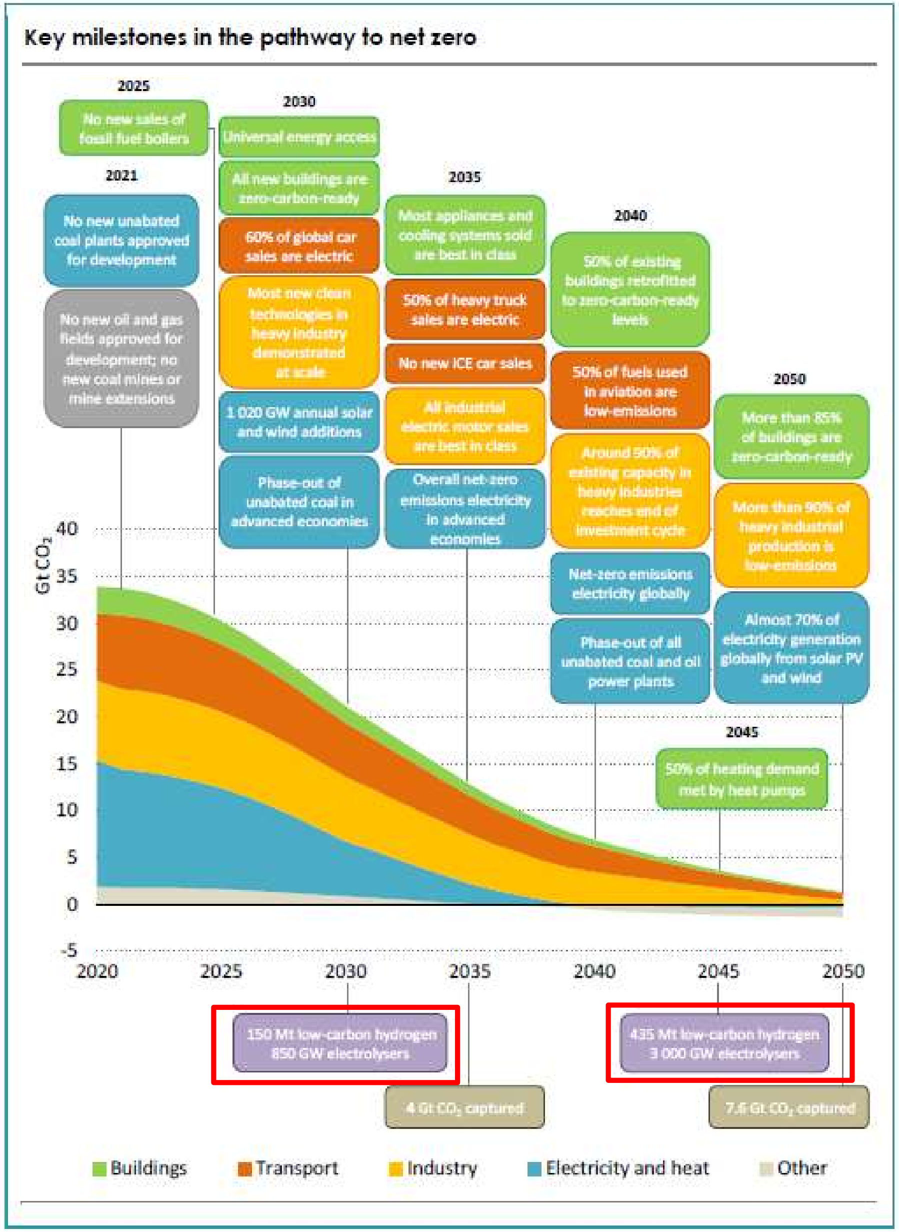
- To limit global warming within 1.5°C requires net greenhouse gas emissions to fall to zero as soon as possible
- Roadmap for Net Zero emissions by 2050 (IEA) => key milestones by energy sector



Source IEA 2021 – Net Zero by 2050 – Roadmap for the Gobal Energy Sector

TOWARD NET ZERO : RÔLE OF HYDROGEN

- To reach the net Zero goal, Hydrogen is expected to play an important role
  - 150 Mt low carbon H2 by 2030
  - 435 Mt low carbon H2 by 2050

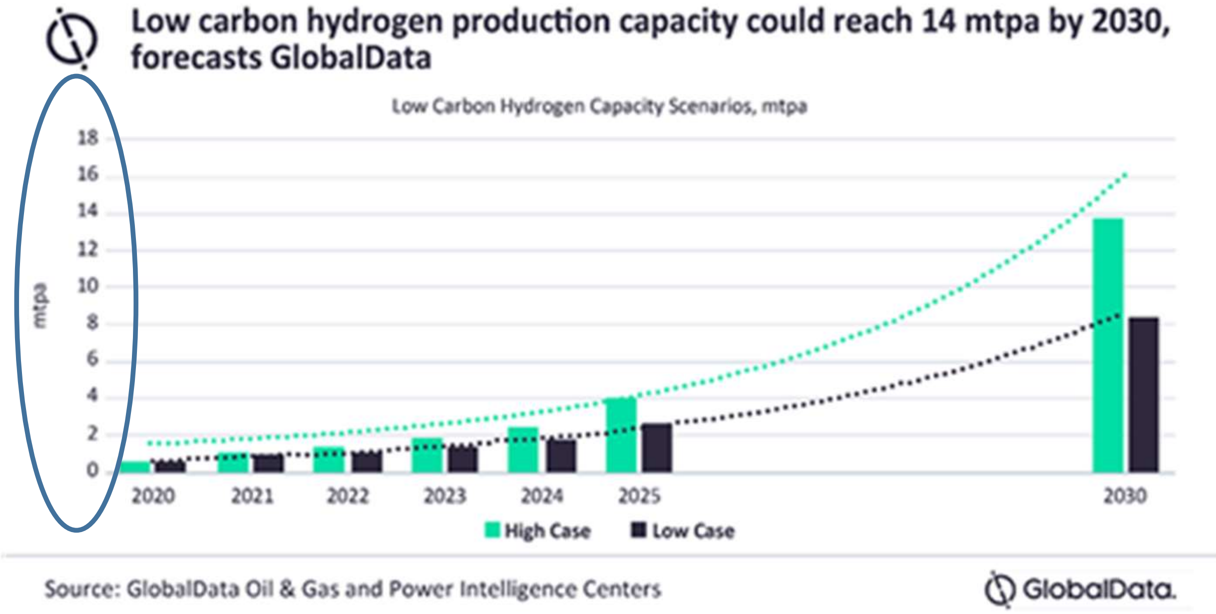


Source IEA 2021 – Net Zero by 2050 – Roadmap for the Gobal Energy Sector

HYDROGEN ON THE FAST TRACK ?

Where it should be according to IEA figures

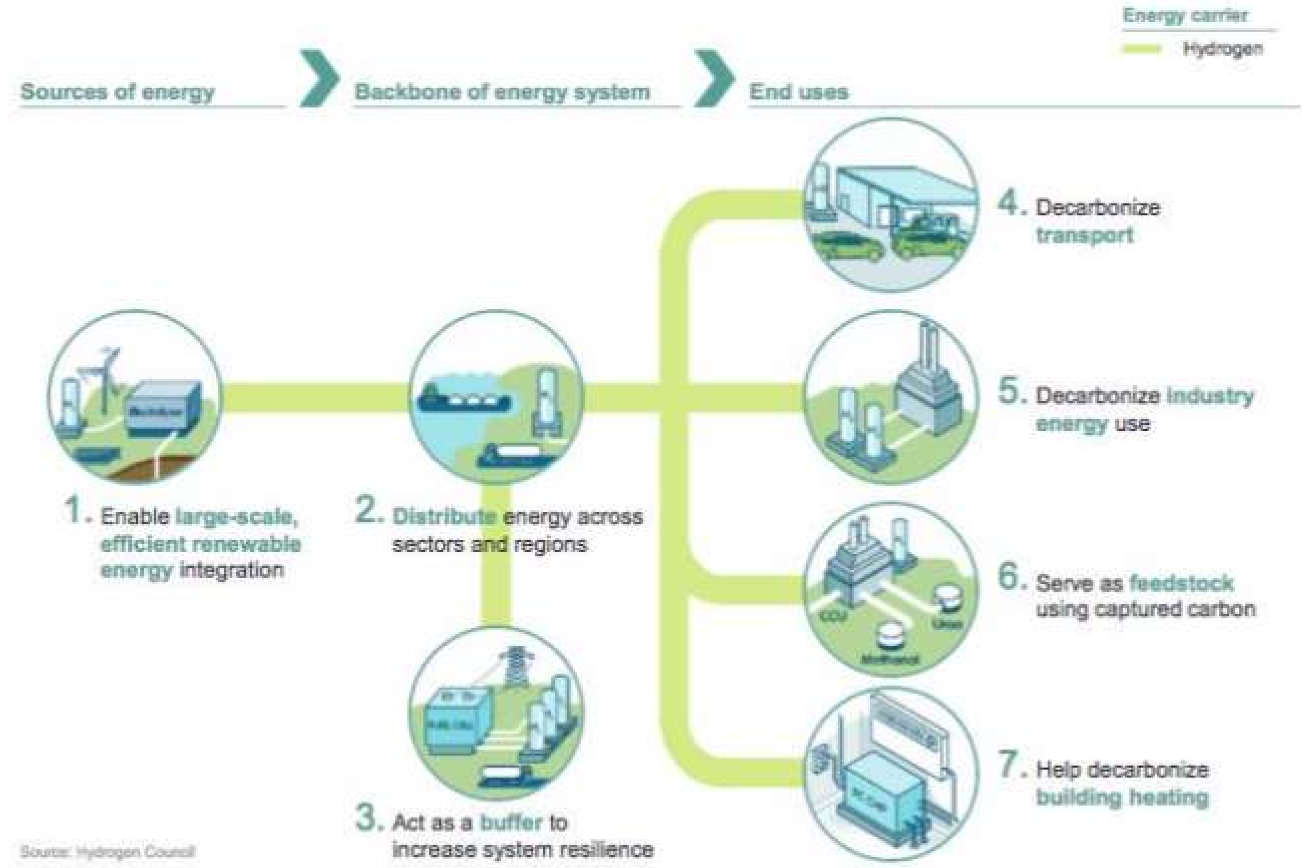
Where are my 150 Mt ?



- 2021 : 0.6 Mt of low-carbon H2, 0.06 Mt per electrolysis
- x100 towards 2030, and yet again x100 on the 2030-2050 period
- x10 offset between expectations/needs and what will actually be done in 2030

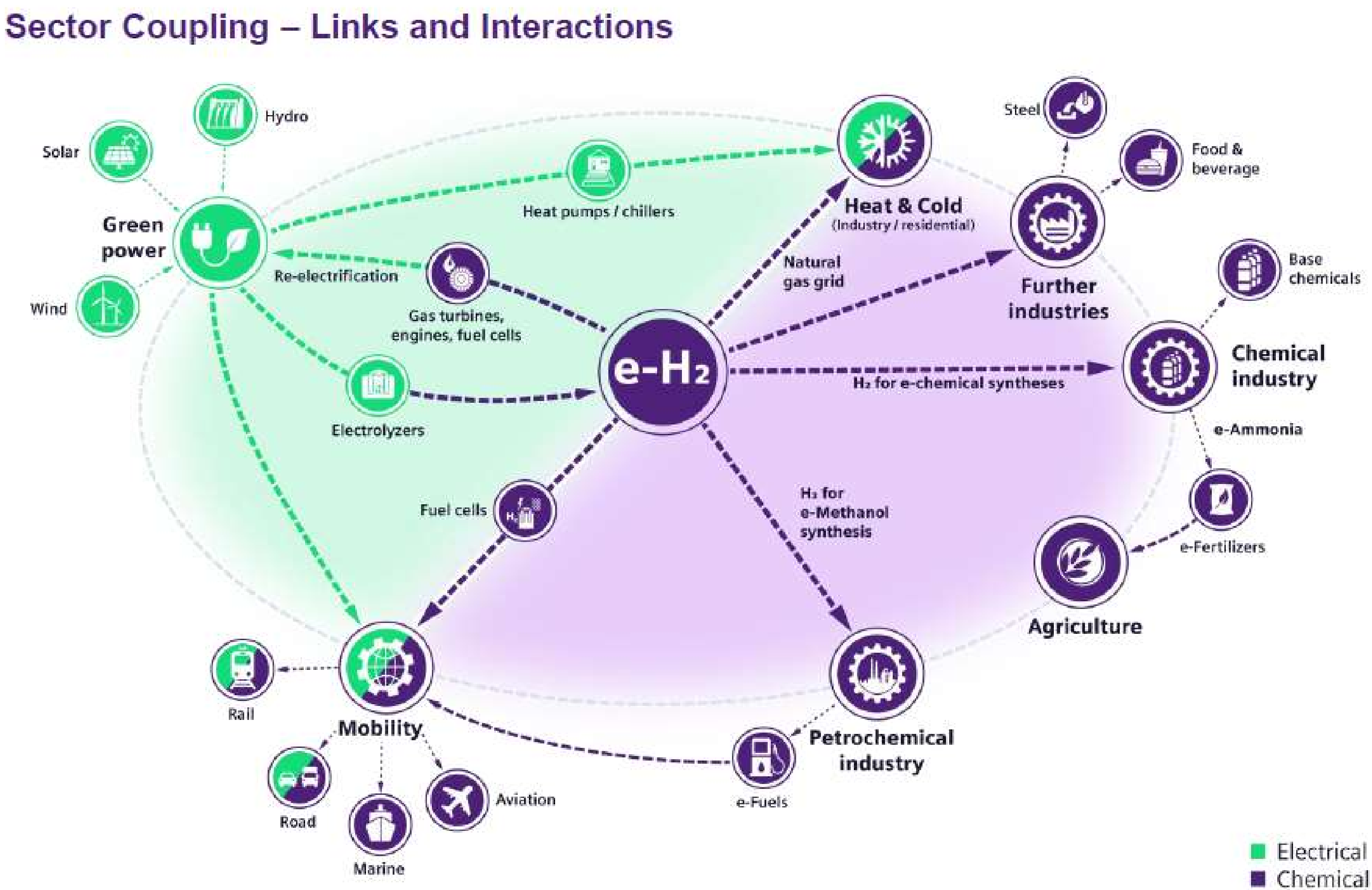
BUT WHY DO WE NEED HYDROGEN ANYWAY ?

- Energy vector
  - Storage
  - Transport
- Decarbonation vector
  - Mobility
  - Industry
    - Utilities
    - Raw material



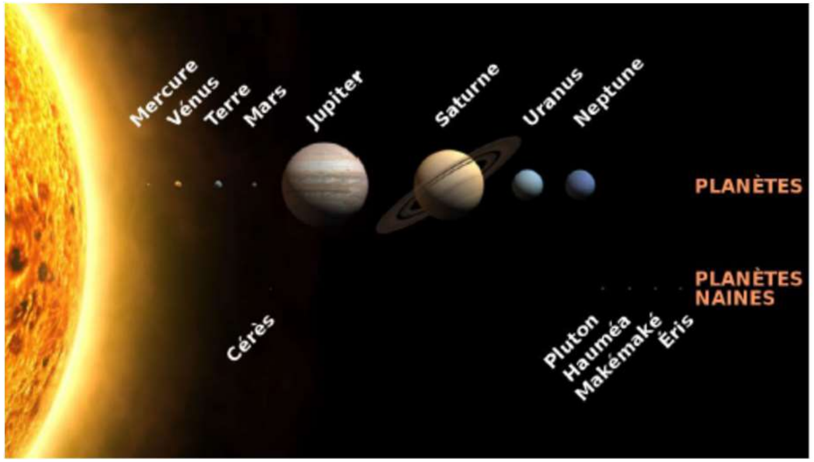
Source: Hydrogen Council, 2017.

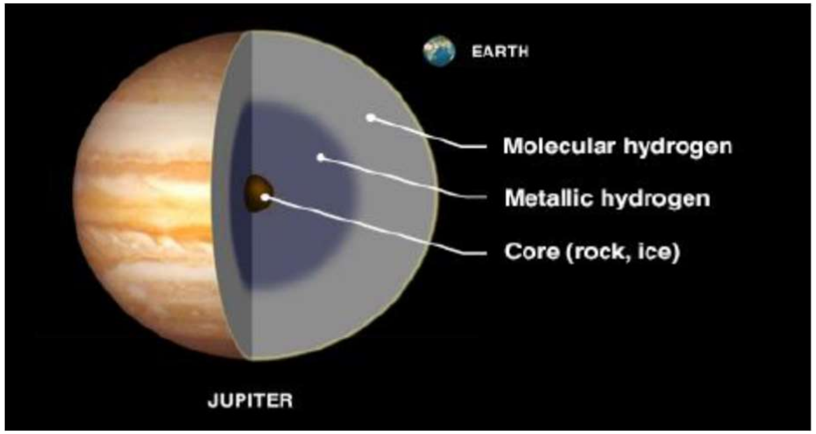
2022, CLIMATE CHANGE INTO DAYLY NEWS



HYDROGEN IS MOST COMMON MOLECULE IN THE UNIVERSE

- 75% of universe mass, 92% in atoms number
  - 73% of the Sun is hydrogen
  - Sun converts 600 millions of tons of hydrogen to helium per second
- H2 is the simplest hydrogen compound
  - Also very common : planet Jupiter is essentially a huge ball of H_2, for instance
- So why not on Earth ?
  - Because Earth is home to a rarer molecule, O_2 !
  - And in « oxydizing conditions, H_2 reacts with O_2 to form H_2O
  - Second hydrogen compounds on Earth : hydrocarbons





THE MAIN TWO CHEMICAL REACTIONS WE ARE GOING TO CARE ABOUT

$$H_2 + \frac{1}{2}\,O_2 \leftrightarrow H_2O \qquad \Delta H = -285\,kJ.mol^{-1}$$

Create energy

→ : Energetic valorization of H_2 (in a fuel cell, by combustion…)

← : Production of hydrogen by electrolysis

$$CH_4 + 2\,H_2O \leftrightarrow CO_2 + 4\,H_2 \qquad \Delta H = 165\,kJ.mol^{-1}$$

Consume energy

→ : Production of hydrogen from methane (or another hydrocarbon source)

← : « Power to fuel » applications and chemistry : making products from hydrogen and captured CO_2

HYDROGEN PHYSICAL PROPERTIES

Property	Value
Name, symbol, number	Hydrogen, H, 1
Category	Nonmetal
Atomic weight	1.008
Electrons, protons, neutrons	1, 1, 0
Color, odor	Colorless, odorless
Toxicity	None, simple asphyxiant
Phase	Gas
Density	Gas: $0.089\,g\,l^{-1}$, liquid: $0.07\,g\,cm^3$
Ionization energy	13.5989 eV
Liquid to gas expansion ratio	1:848 (atmospheric conditions)
Melting and boiling point	–259.14 °C, –252.87 °C
Lower heat value (LHV)	$118.8\,MJ\,kg^{-1}$
Adiabatic flame temperature	2107 °C
Flammability range in air	4–75%
Laminar flame velocity	$3.06\,m\,s^{-1}$
Flash point	–253 °C
Auto ignition temperature	585 °C
Research octane number (RON)	>130

Mazloomi & Gomes, Ren. And Sus. En. Reviews 2012

Air at ambient pressure : 1.225 $g.l^{-1}$
Liquid water : 1 $g.cm^{-3}$

More then 10 time less dense

Gaseous, except at extreme temperatures
0 K = -273°C

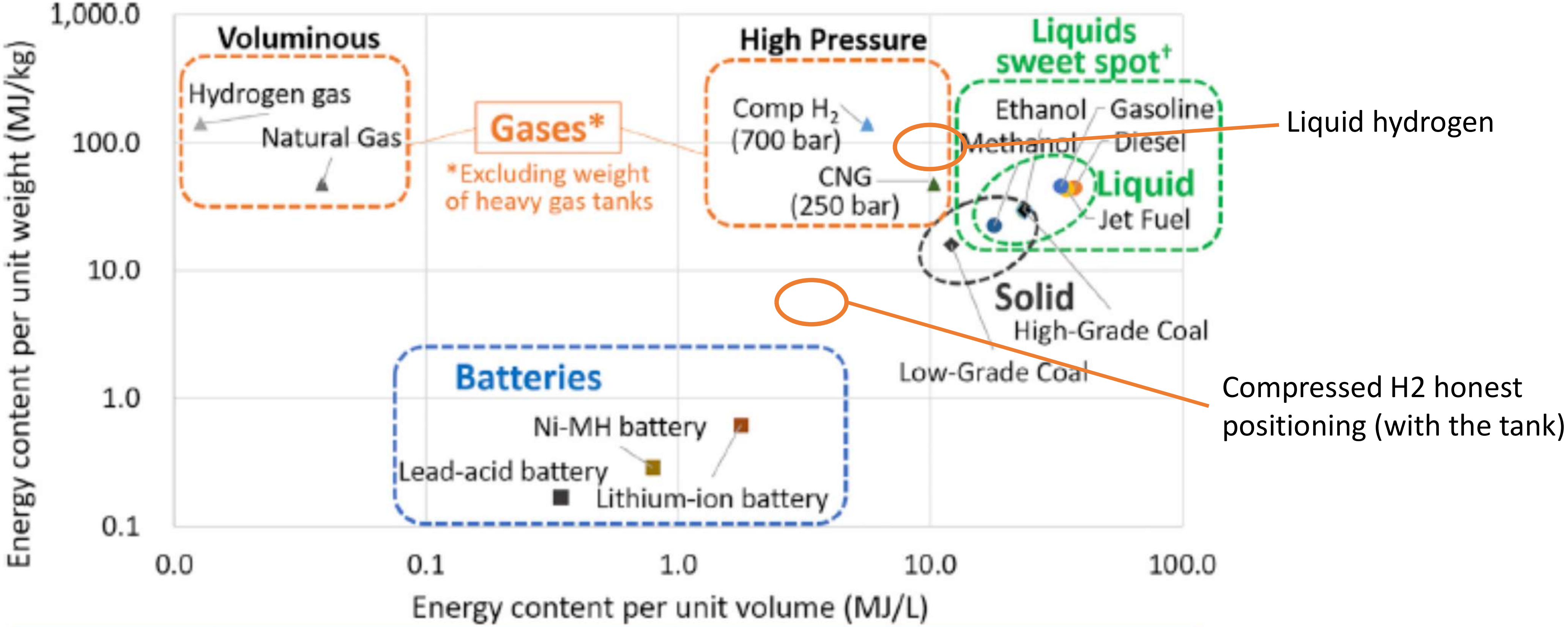
Methane : 50 $MJ.kg^{-1}$
Diesel fuel : 45 $MJ.kg^{-1}$
Wood : 17 $MJ.kg^{-1}$

Excellent energy density… per mass

Explosivity range: 18% - 59 %

Super reactive… potentially hazardous

HYDROGEN ENERGY CONTENT VS OTHER SOLUTIONS

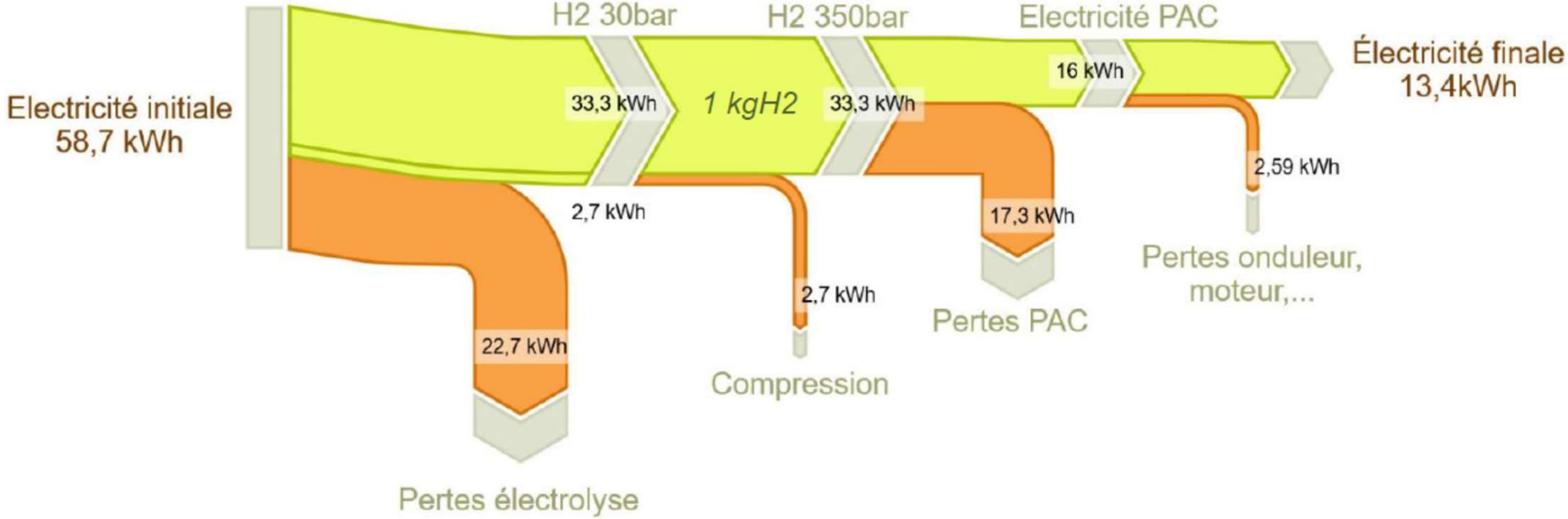


†Sweet Spot: high energy density by weight and volume; stable, easy to store, transport, distribute

Shih et al., Joule 2018

HYDROGEN TO ELECTRICITY CONVERSION

ADEME



- How much electricity for 1 kg of H2 : depends where you are looking in the value chain
    - Theoretical : 33 kWh/kg. To produce : 58.7 kWh/kg. Yield back : 16 kWh/kg
- This is <u>not</u> an efficient energy value chain

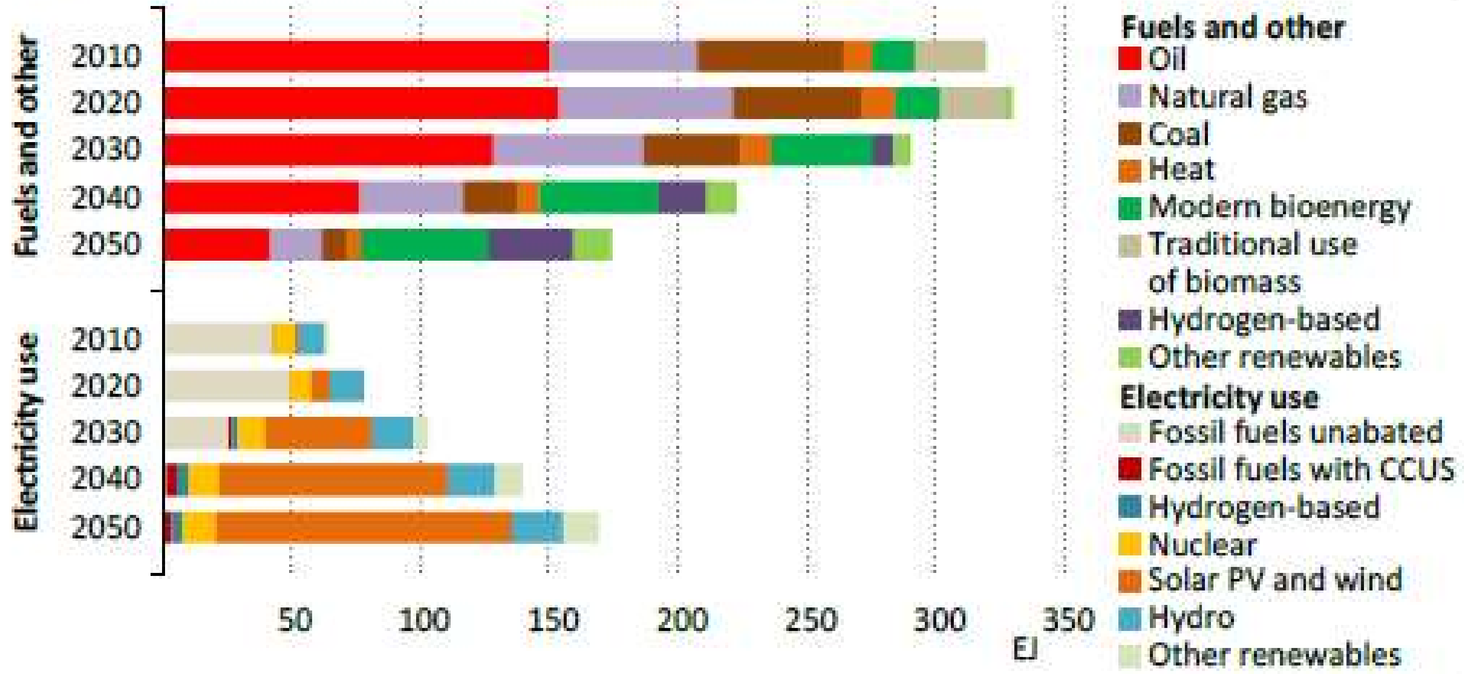
SUMMARY : HYDROGEN IS NOT A MAGIC BULLET

- « Hydrogen can produced from and converted in electricity »
  - With a loss of 60-70 % along the way
- « Hydrogen can be stored and transported easily compared to electricity»
  - But not in a jerrycan…
- « Hydrogen allows for more efficient energy storage then batteries for mobility systems »
  - But is still far from the levels of performance from hydrocarbons

EXPECTED EVOLUTION OF FINAL ENERGY CONSUMPTION BY FUEL

- Electrification
- Emergence of H2

Figure 2.9 ▷ Global total final consumption by fuel in the NZE

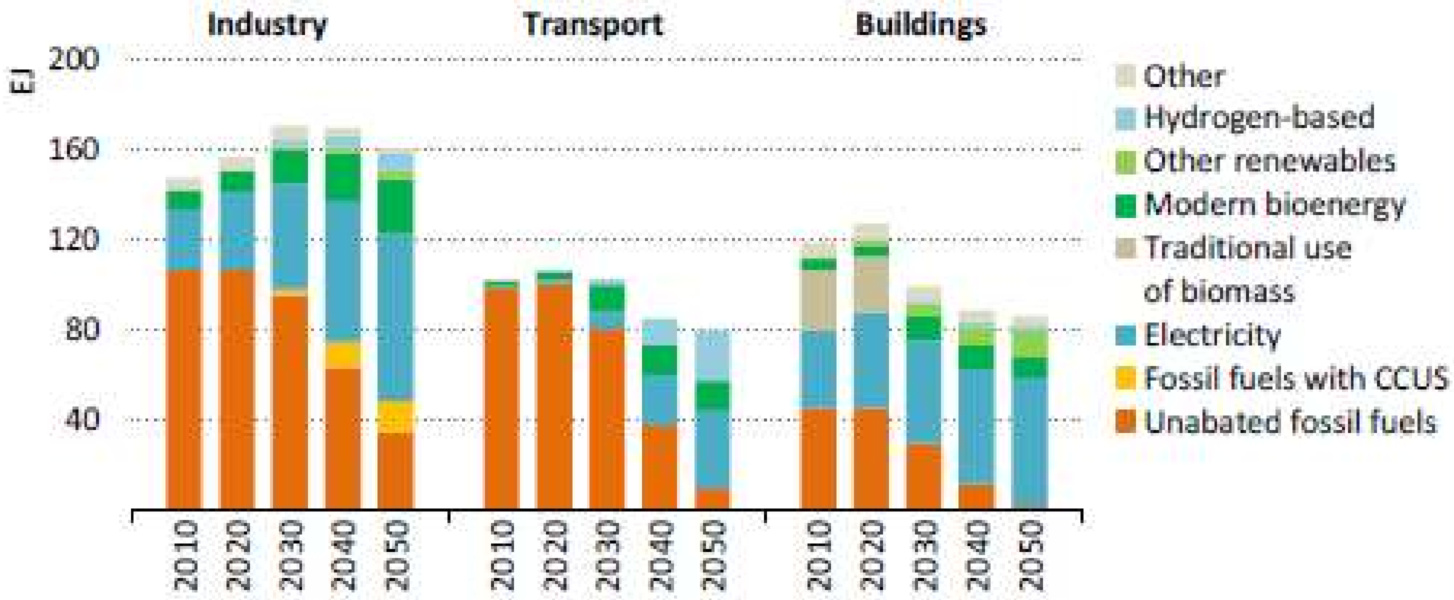


The share of electricity in final energy use jumps from 20% in 2020 to 50% in 2050

EXPECTED EVOLUTION OF FINAL ENERGY CONSUMPTION BY SECTOR

- New H2 demand driven by the transport sector

Figure 2.10 ▷ Global final energy consumption by sector and fuel in the NZE



There is a wholesale shift away from unabated fossil fuel use to electricity, renewables, hydrogen and hydrogen-based fuels, modern bioenergy and CCUS in end-use sectors

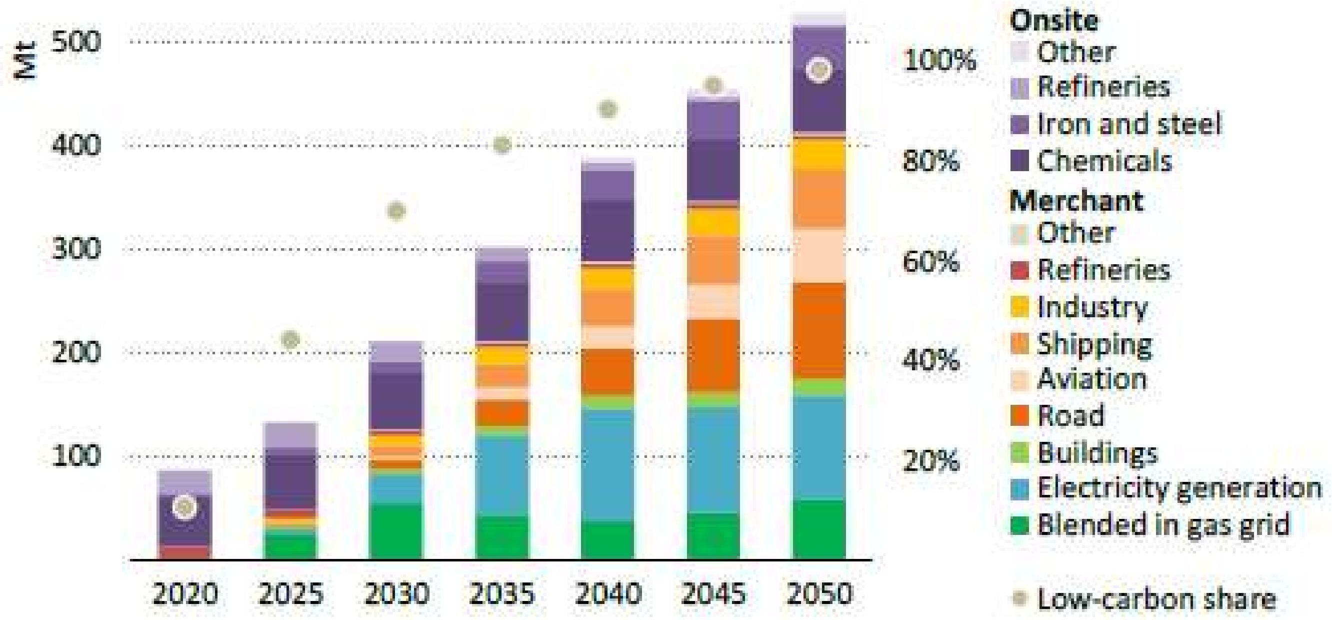
Note: Hydrogen-based includes hydrogen, ammonia and synthetic fuels.

Source IEA 2021 – Net Zero by 2050

HYDROGEN USE: TODAY AND TOMORROW

From 90 Mt fossile based H2 today to 500 Mt low carbon H2 by 2050

Figure 2.19 ▷ Global hydrogen and hydrogen-based fuel use in the NZE



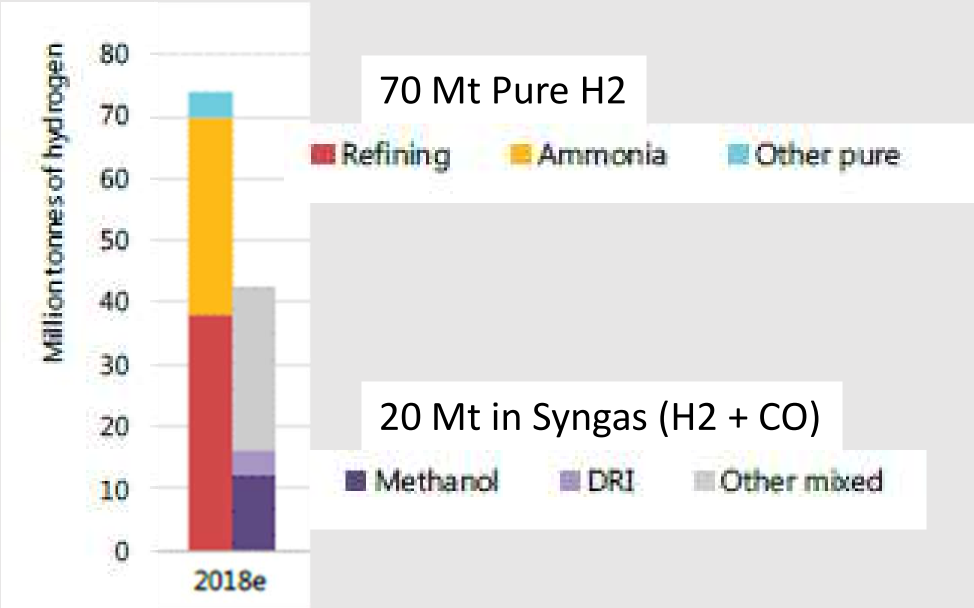
The initial focus for hydrogen is to convert existing uses to low-carbon hydrogen; hydrogen and hydrogen-based fuels then expand across all end-uses

Note: Includes hydrogen and hydrogen contained in ammonia and synthetic fuels.

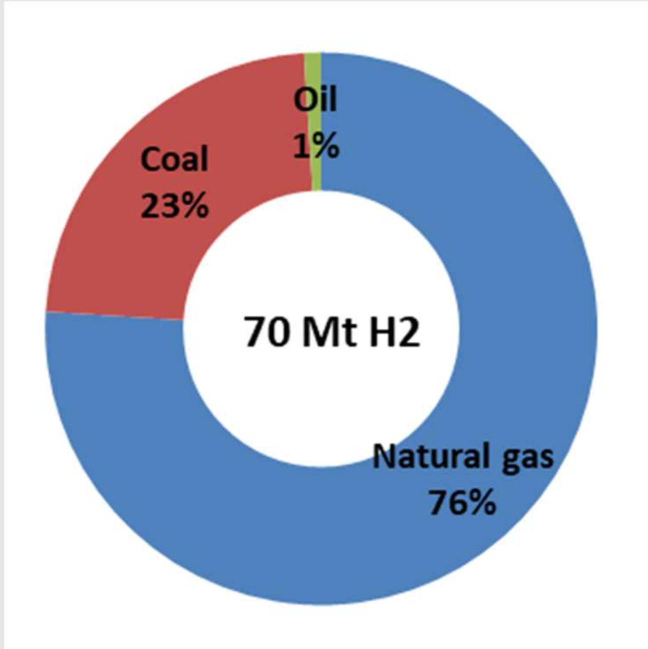
INDUSTRIAL USAGES : EXISTING

STARTING WITH TODAY'S USAGE

Today (world) : 70 Mt = 10 EJ

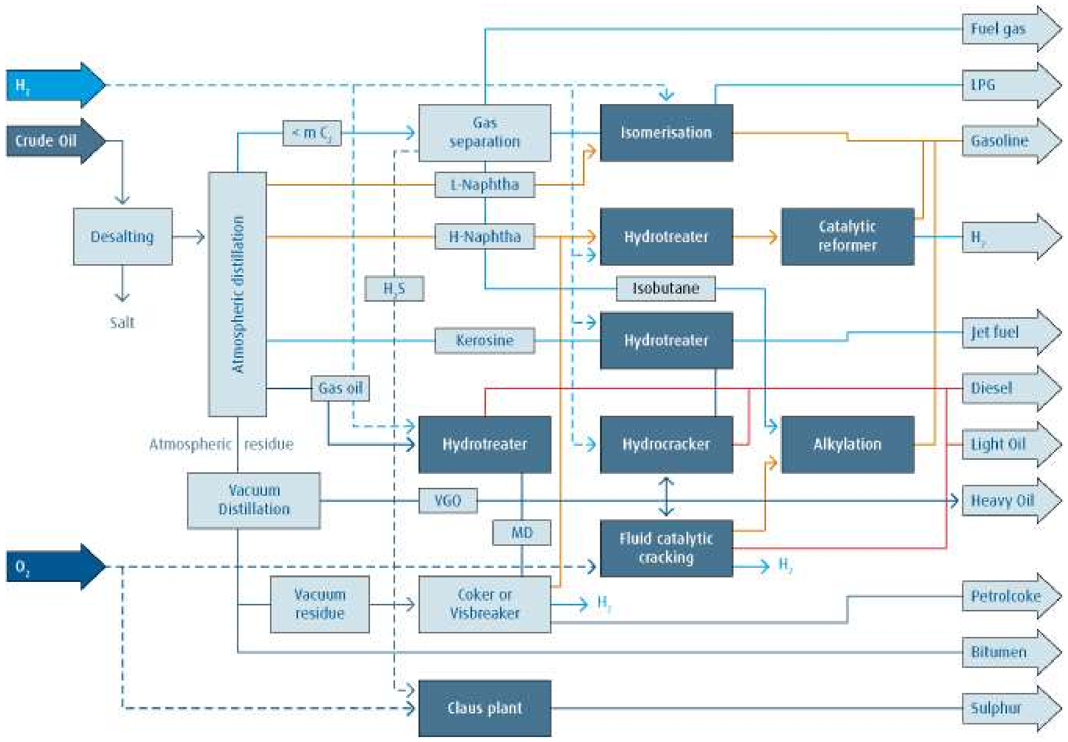


Source: International Energy Agency 2019



Source: International Energy Agency 2019

HYDROGEN USAGE IN REFINING



Linde Engineering

- The refinery produce and consume hydrogen, at different steps
    - But is most of the time, globally, deficient in hydrogen
- The refinery needs hydrogen for a variety of usages :
    - Hydro-desulphurization : removing sulphur from load to form H_2S
    - Hydrocracking : form lighter products from heay oil compounds
    - Dearomatization

HYDROGEN USAGE IN REFINING : CONFLICTING TRENDS

- If fossil fuels are phasing out, shoudn't we have less refining ?
  - Yes but how fast ?
  - Residual needs for the plastic industry, hard to abate usage…
  - Bio-fuels also needs refining

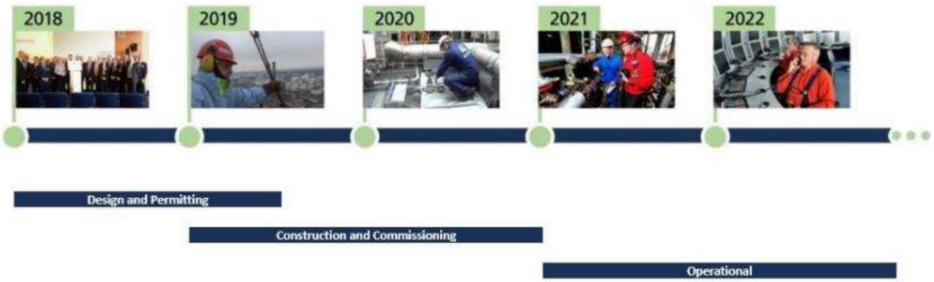
Linde Engineering

- Modern refining is more and more demanding in hydrogen !
  - Appetite for light products (diesel, gasoline...)…
  - … While oils fraction processed are heavier and heavier !
  - Ever decreasing tolerance to sulphur in fuels.
- Wood Mackenzie estimates refining demand at 50 Mt/year in 2050
  - Higher then current demand at 37 Mt/year !

GREEN HYDROGEN IN THE REFINERY

REFHYNE
CLEAN REFINERY HYDROGEN FOR EUROPE

- Why not ?
  - No technical difficulties in using
  - Large centralized user : potential as early adopter
- Refhyne 1 & 2: early EU-funded projects
  - 100 MW capacity
  - Desulphurization process in Germany
- Not a favorable economic context…
  - Current refining process rely on very cheap, locally produced, carbon-based hydrogen
  - Very little price elasticity on the product and little « green » marketing

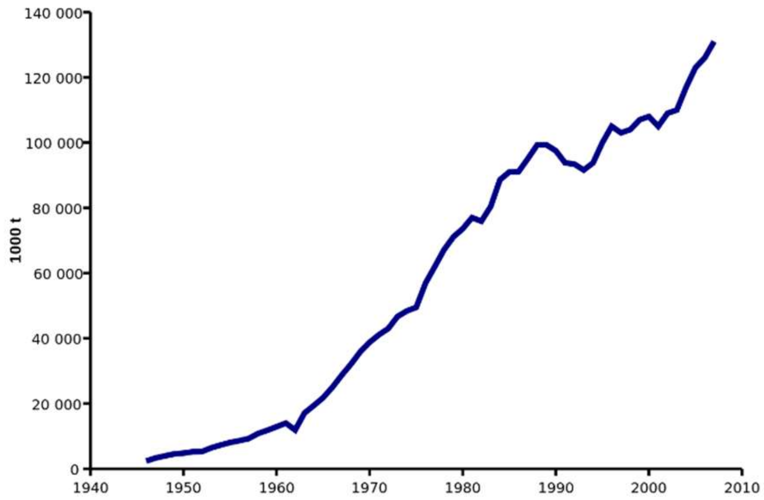


IFP Energies nouvelles

AMMONIA : A DISCRETE BUT UBIQUITOUS COMMODITY PRODUCT

- Historically, one of the molecules behind the green revolution
  - Industrial processes invented in early XXth century
  - Allowed for the worldwide democratization of nitrogen fertilizers
- Worldwide production at 175 Mt in 2018
  - 6th most produced chemical commodity in mass !
- Usages :
  - Fertilizers (80-90%)
  - Chemical commodity (dyes, explosives, plastics, refrigerant…)
  - An a promising energy vector (see that later)

Wikipedia



CTCN

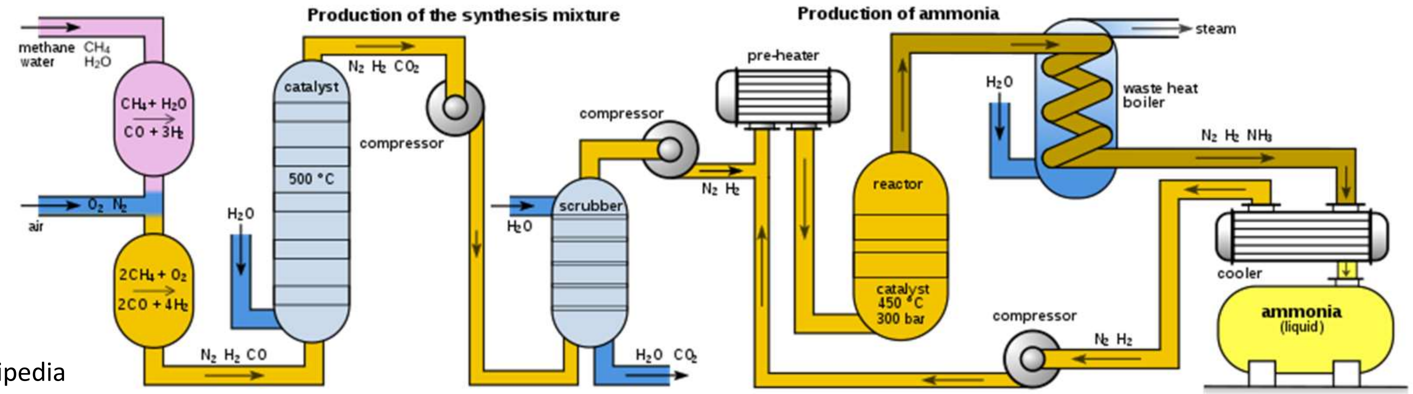
AMMONIA : A HEAVY (AND DIRTY) INDUSTRIAL PROCESS

- Haber-Bosh process
  - Old (1913) but efficient and well known
  - Combine N_2 from the ambient air with H_2 at high temperature

$$N_2 + 3H_2 \longrightarrow 2NH_3 \quad \Delta H^0_{298} = -92,2\,\mathrm{kJ/mol}$$

Technip FMC

- Today, a carbon intensive process, because of its hydrogen needs
  - Very centralized process
  - Produces energy
  - Huge methane consumption (5% of today's production !)



Wikipedia

GREEN AMMONIA ?

- Interesting crossling between energy and industry
  - Large, centralized industrial user (early adopter ?)
    - Possible marketing for « green » fertilizer
  - But also an energy vector for long range transportation !

- 2021 : Iberdrola and Fertiberia launch the largest green ammonia demonstrator in Spain
  - 100 MW
  - 150 millions euros investment

- Saudi Arabia announces huge investment in green ammonia
  - $6.5 billion for 4000 MW of capacity…
  - And more ambitions then just fertilizers (energy vector)

Arab News

METHANOL : ANOTHER HYBRID COMMODITY

$$CH_4 + H_2O \rightarrow CO + 3\,H_2$$

$$CO + 2\,H_2 \rightarrow CH_3OH$$

$$CO_2 + 3\,H_2 \rightarrow CH_3OH + H_2O$$

- Worldwide production : 110 Mt/year
  - Precursor for a very wide range of chemicals through formaldehyde
  - Applications : plastics, paints, resins, explosives, textiles…
- Same dual usage potential as ammonia
  - Massive industrials needs are not going away
  - Potential as an energy vector if produced from captured CO_2 or biomass

Bestcurrentaffairs.com

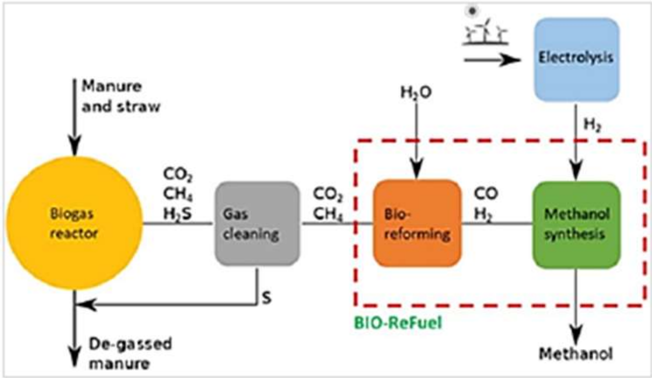
Topsoe

GREEN METHANOL

- But green hydrogen is not the only issue here !
  - Make sense only if the carbon in the molecule does not come from fossile fuel
  - Carbon monoxyde CO is very desirable for the synthesis

- Production from biomass or biomethane makes more sense
  - CO is readily available through the process
  - No ambiguity on carbon footprint

- Still, the methanol could be integrated in a carbon and capture usage logic

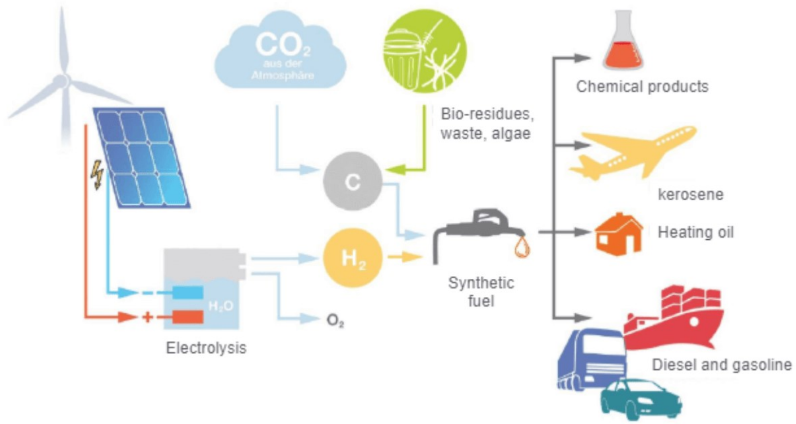


IEA bioenergy

Methanol institute

FROM CO2 AND H2 TO CHEMICALS… INCLUDING FUELS ?

- You can push for longer carbon chains, and make fuel !
  - Chemical processes relatively well known
    - Fischer-Tropsch processes industrialized by Germany during WWII
  - Very costly, very innefficient



- Does it make sense environmentally ?
  - Definitive yes, if your carbon source is from biomass
  - If you are using captured CO2, it is more ambiguous
    - I am capturing CO2 and using it : nice
    - I am using a fuel based on waste so I compensate my emmissions : nice
    - But you can’t claim both at the same time

INDUSTRIAL USAGES : NEW USAGES

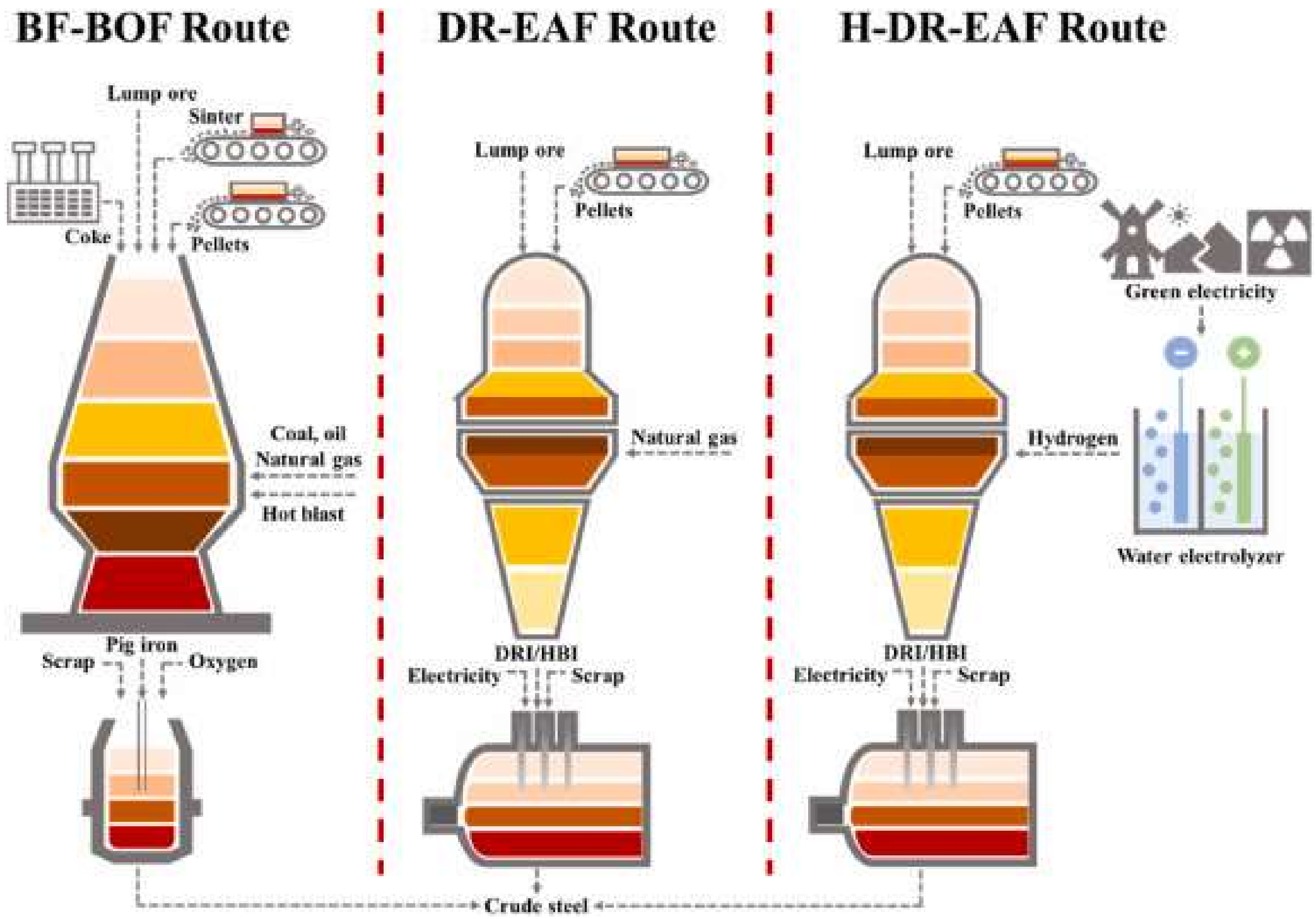
HYDROGEN FOR THE STEEL INDUSTRY : DIRECT REDUCTION PROCESS

- Iron ore needs to be reduced

$$3\,Fe_2O_3 + CO/H_2 \longrightarrow 2\,Fe_3O_4 + CO_2/H_2O$$
$$Fe_3O_4 + CO/H_2 \longrightarrow 3\,FeO + CO_2/H_2O$$
$$FeO + CO/H_2 \longrightarrow Fe + CO_2/H_2O$$

- Coke is the traditional feedstock, with terrible emmissions impact

- Using hydrogen as the reducing agent



Wang et al. 2021 Journal of Cleaner Production

GREEN STEEL PROJECTS

- A lot of direct reduction pilots on the way, at least in Europe

- Not including projects downstream in the steel production process (annealing…)

Steel producer	Location	Current status
ArcelorMittal	Hamburg, Germany	Demonstration plant by 2023. Target for commercial operation 2025.
ArcelorMittal	Dunkirk, France	Feasibility study
ArcelorMittal	Taranto, Italy	Planning stage
ArcelorMittal	Eisenhuttenstadt, Germany	Online in 2026 (pilot plant)
ArcelorMittal	Bremen, Germany	Online in 2026 (large-scale)
Voestalpine	Leoben (Donawitz), Austria	Commissioning in Q2 of 2021
Salzgitter AG	Salzgitter, Germany	Demonstration plant ordered 12/2020. Scheduled to go online 1st half of 2022.
Salzgitter AG	Wilhelmshaven, Germany	Feasibility study
SSAB	Gällivare-Oxelösund, Sweden	Pilot plant, market production 2026
LKAB	Kiruna-Malmberget-Svappavaara, Sweden	First DRI plant in Malmberget in 2029 [3]
Thyssenkrupp	Duisburg, Germany	First production in DRI plant 2025
Liberty	Galati, Romania	DRI plant installed between 2023-2025
Liberty	Dunkirk, France	Feasibility study ongoing
H2 Green Steel	Boden-Luleå, Sweden	Large scale production by 2024

Bellona

Tata Steel 65 millions euros investment in the Netherlands

WHAT'S THE COST OF GREEN STEEL ?

- A few estimates :
  - At « current » prices (3.6 to 5.2 $/kg), excess cost is 30-40%
  - With the same projection, CO2 tax should be 300-400 $/t to make price balance
  - With a projected 2030 price of 1.8 $/kg, excess cost is 10%
  - Even with very optimistic price prospects, profitability is not there…

- Thinking differently :
  - What's the cost of the steel in a car ?
    - A few thousands euros
  - What's the excess cost of having green steel in a car ?
    - A few hundred euros
  - What's the worth for your customer of having a truly green car ?
    - The car on the right is priced at 85 000 $...

AZO Cleantech

BMW

HYDROGEN COMBUSTION FOR HEAT GENERATION

- Industry uses considerable quantities of methane for heating
  - 1/3 of current natural gas consumption in the USA

- H_2 can replace CH_4, provided technical difficulties are taken care of :
  - Differences in flame properties
    - flame size, temperature, backflow…
  - NOx generation
    - Due to high T° in the flame, but solved with oxycombustion
  - Fuel flexibility
    - No guarantee of 100% H_2 feed at least to begin with
  - Issues with materials and products
    - H_2 impact on steel at high T°, Water vapor at high T°

Indianmart

Glassonweb.com

HEAT GENERATION FOR THE INDUSTRY : ELECTRICITY VS HYDROGEN

https://americanhistory.si.edu/

- Why burn hydrogen when you have electricity ?
  - Electricity has, hand-down, much better energy efficiency
  - Can make sense when you use fossil CH_4, but not e-produced H_2
- Processes have other requirements then energy efficiency
  - High temperature resistance are not cheap/durable (> 900°C)
  - Combustion might be more adapted in terms of heat distribution
- Who could be interested then ?
  - Ceramics, glass, metallurgy, cement…
  - Probably not you for your individual home

https://www.steelsupplylp.com/

EXAMPLE OF PROJECTS

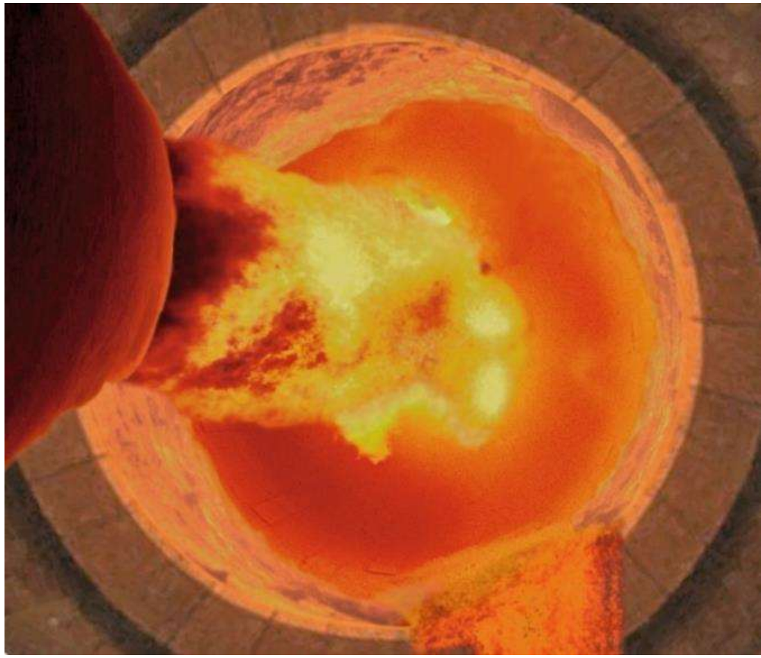
- HYREADY :
  - Consortium of gas suppliers and industrials to demonstrate combustion applications
  - Demonstrator in Germany for salt processing : 2 MW
- Italian consortium around SNAM on glass making
  - Consortium between labs, gas supplier and glass industrial
- Common points
  - Consortium between users and producers to take into account process specificity
  - Preoccupations around fuel flexibility and using existing assets
  - Very limited volumes : the economy is not there yet !

DNV

SNAM

THE PARTICULAR CASE OF CEMENT PRODUCTION

- An important candidate
  - Needs heat up to 1450°C
  - Massive amount of carbon emmisions (8% worldwide!)
  - No complete substitution in sight
- But a very difficult one
  - Burns cheaper fuels then methane
  - Only 50% of the emmisions comes from combustion
    - The rest is from the calcium carbonate
- Might be a better candidate for carbon capture
  - Still some interest from the industry



ZKG

Wikipedia

CONCLUSION ON INDUSTRIAL APPLICATIONS

- Current usage are not going anywhere any time soon
  - Petro-chemistry, ammonia, methanol… we still need them
  - Even replacing current use is a huge challenge for green hydrogen

- Emerging industrial usage are massive in scale, but not for tomorrow
  - Could amount to adding the current quantity being used to the demand
  - Steel producting expected to be prominent, but not only
  - But currently classified as « hard to abate » and mostly planned in the 2050 plans…

- Take into account industrial realities
  - Cost : today you can only sell it if you market it as « green » and the customer is willing to pay
  - Fuel flexibility vs securing the supply : industrials wants to be sure they have access to energy !
  - Use existing assets as far as possible

https://www.steelsupplylp.com/

MOBILITY USAGES

WHY USE HYDROGEN ON A VEHICLE ?

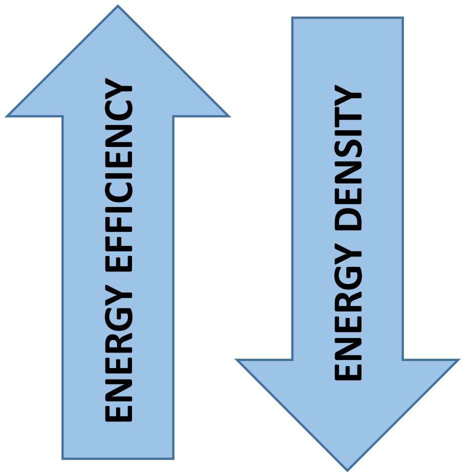
- Efficiency is far better with direct electrification
  - With the same energy, you can drive 2-3 km with a battery vehicle against 1 km with a Fuel Cell Electric Vehicle (FCEV)
- But energy density needs to be taken into account
  - How much energy can you take with you ?

Batteries

300-600 bar gaseous hydrogen

Liquid hydrogen

Hydrogen-derived fuel



Motorcycle

Individual car

Small delivery truck

Long range truck

River navigation

Regional airplanes

Oceanic navigation

Intercontinental aircrafts

WHAT ARE THE OPTIONS FOR USING HYDROGEN FOR MOBILITY ?

- Fuel Cell Electric Vehicle
  - Electric propulsion
  - Hydrogen (main) source of energy, transformed into electricity by a fuel cell
- Hydrogen Combustion Vehicle (Internal Combustion Engine, turbine…)
  - Regular combustion engine (heavily adapted)
  - Hydrogen burnt as a fuel
- Vehicle using an hydrogen-based fuel in a combustion engine
  - Regular combustion engine (slightly adapted)
  - No hydrogen onboard. Hydrogen is used upstream to produce NH3, methanol, e-kerosene

ROAD VEHICLES

BATTERY VS HYDROGEN COMPARISON

Figures based on a 500 km autonomy assumption

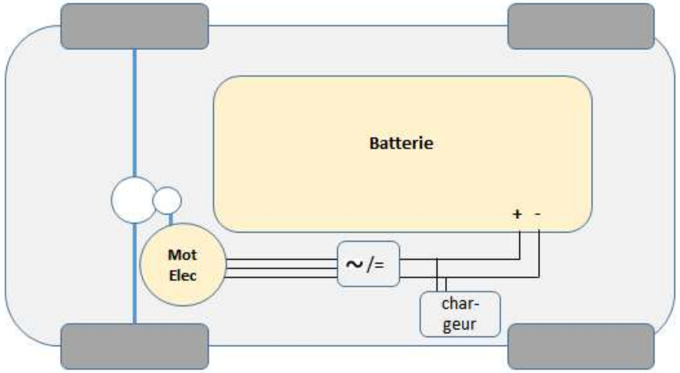
	Energy need (Wh/km)	Energy for 500 km (kWh)	Battery equivalent mass	Equivalent mass of H2 (including reservoir)	Exemples de FCEV (masse H_2 / énergie batterie)
Individual car	120 – 200	60 – 100	400 à 700 kg	env. 5 kg (100 kg)	Toyota *Mirai 2* : 5,6 kg / 1,2 kWh
Urban bus	900 – 1400	450 – 700	3 à 5 tonnes	env. 35 kg	Safra *Businova* : 30 kg / 132 kWh
Long-haul truck	1400 – 2000	700 – 1000	4 à 7 tonnes	env. 50 kg (1 tonne)	Hyundai *xCient**: 32 kg / 73 kWh Mercedes GenH2**: 80 kg/ 70 kWh
Regional train	3000 – 5000	1500 – 2500	> 10 tonnes	env. 150 kg	Alstom *Coradia iLint* : 180 kg / - -

https://www.steelsupplylp.com/

BATTERY VEHICLE ARCHITECTURE?

- General architecture of a Battery Electric Vehicle (BEV)

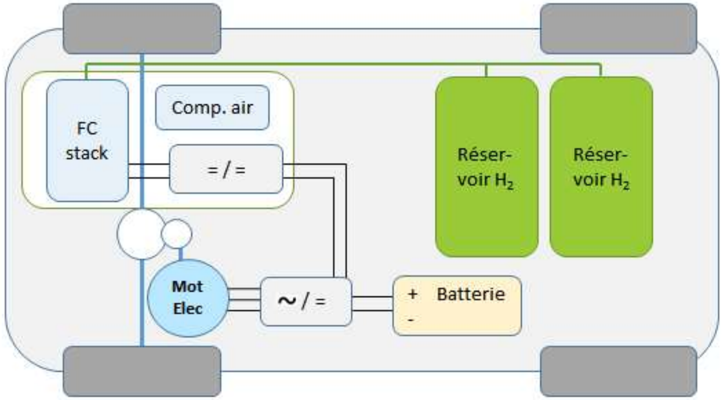
- The battery vehicle include :
  - **At least one electric motor**
    - Use alternative current ("AC")
  - **A battery for energy storage**
    - Deliver electric current ("DC")
  - **Power electronics systems, at a minimum :**
    - An AC/DC converter between battery and motor
    - Charging device (AC/DC)



- Fast charge on DC are increasingly required
  - 50 kW and more

FUEL CELL VEHICLE ARCHITECTURE

- General architecture of Fuel Cell Electric Vehicle FCEV
  - 2 sources of electric energy :
    - **A fuel cell** ("DC")
    - **A battery** ("DC")
      - Used as an energy buffer to absorb power peaks
  - The FCEV additionally needs :
    - **An hydrogen storage system**
    - Power electronics system :
      - AC/DC converters between the motor and the energy sources
      - DC/DC tension converters to equalize between the sources



Actually very similar : possible for industrial to work in a « platform »logic

RANGE AND REFUEL COMPARISON

- BEV

- Limited range
  - Handicap for heavy or intensive usage vehicles
- Most likely solution : charge by night and compelement if needed through fast charge
- Today fast charge up to 350 kW
- However, fast charge is potentially dangerous for batteris

FCEV

- Range comparable to current vehicles
- Reservoirs :
  - Gaseous storage : 5 à 7% of useful mass
    - 5 kg d'H2 <=> 100 kg of reservoir system
    - Cylindrical reservoir, not easy to integrate (especially on small vehicle)
- Reload in a few minutes

MASSIVE INFRASTRUCTURE NEEDS… FOR EACH TECHNOLOGY

BEV

More advanced deployment (compared to H2)

Equipements needs at different levels:

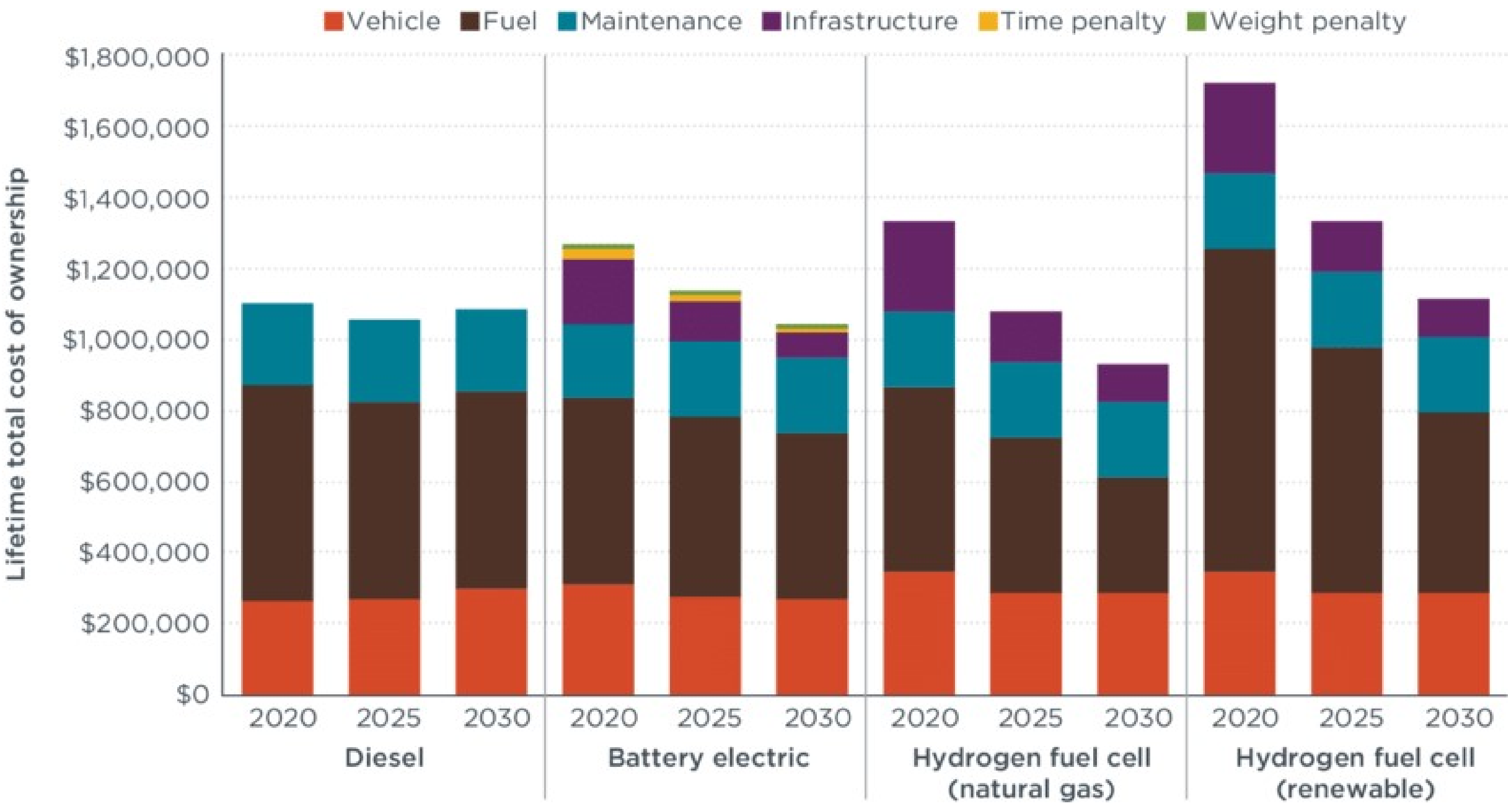
- « Plug access", équipements at home or in companies
- Public domain plug access
- Fast charge stations on key roads

FCEV

- Stations : 350 / 700 bar
  - Adequate safety requirement
  - Currently no self-service, for instance
- In parralel, deployment of an hydrogen distribution system
  - Centralized through pipes
  - Decentralized with independant electrolyzers

Air Liquide

TOTAL COST OF OWNERSHIP FOR VARIOUS LONG-HAUL TRUCK OPTIONS



ICCT

CONCLUSION ON RANGE/REFUELING

- Clear pattern on which vehicles are interesting to convert to hydrogen
  - Heavy, long range, powerful
    - Trucks, buses, construction machinery
  - Intensive usage with no time for refueling
    - Taxis, industrial equipments (forklifts)

- « Winner takes it all » logic for the infrastructure deployment
  - No one is going to be willing to invest in two separate widespread distribution systems
  - And the winner is likely going to be battery vehicles

- Hydrogen applications compatible with a « captive fleet » logic
  - Vehicles operates from or between « hubs » where hydrogen is available
  - Hydrogen only handled by professionals, in a few centralized locations (safety)

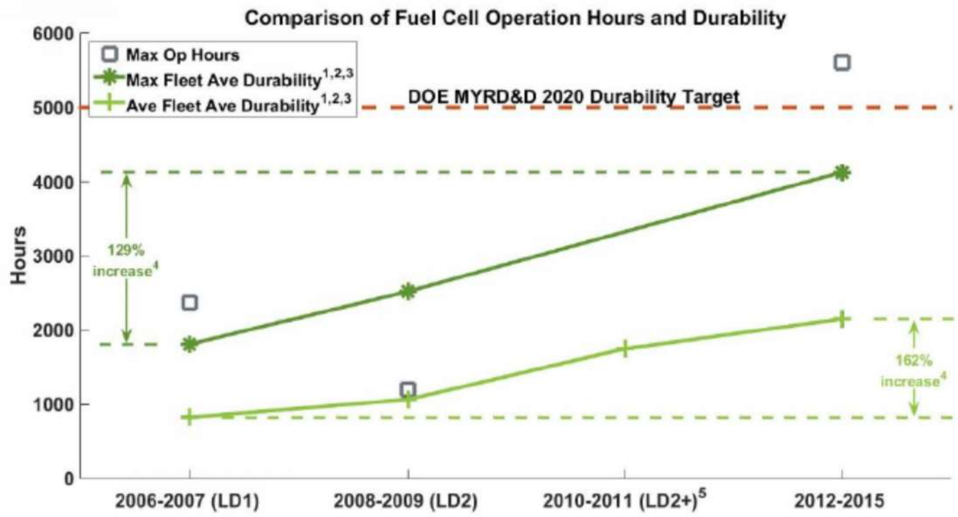
TECHNICAL ISSUES AROUND THE FUEL CELL VEHICLE

- Complicated vehicle architecture
  - An electric vehicle, with more stuff inside then a battery vehicle

- Fuel cells are expensive and potentially use strategic materials
  - Platinoids used in catalysts

- Durability of the systems is still questionable
  - Making progress but still
  - Problematic given vehicle prices and applications

- Very demanding on hydrogen purity
  - Otherwise you sacrifice durability…



NREL

HYDROGEN INTERNAL COMBUSTION ENGINE : AN ALTERNATIVE TO FCEV

- A combustion engine… using hydrogen as a fuel

- CONS:
  - Less efficient energetically
    - 60% of a FCEV, and no breakage energy recuperation
  - NOx emmissions
    - Solvable, but not « zero-émission » strictly speaking

- PROS :
  - Way less groundbreaking technology
  - Far easier to deal with power peaks
  - No requirements on hydrogen purity

- Two way it could prosper along FCEV :
  - A « transition technology » waiting for FCEV to mature
  - Niche markets : construction and industrial engines, retro-fitting, luxury vehicles

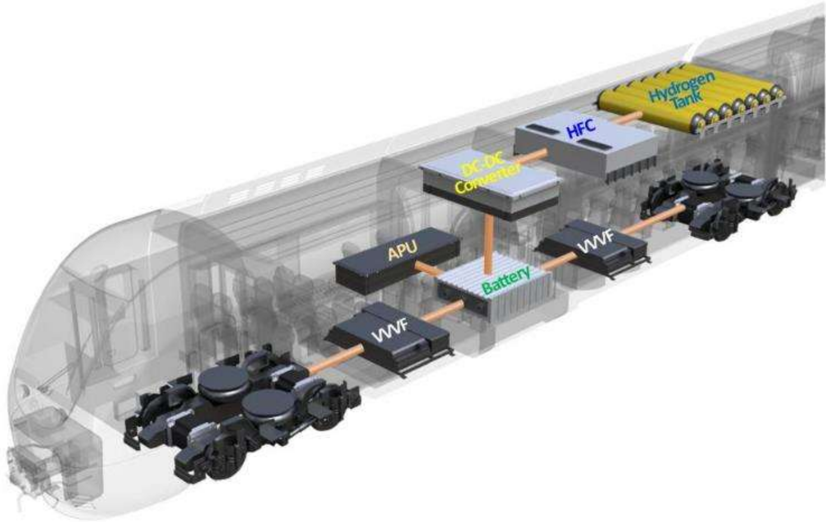
Wikipedia

OTHER VEHICLES

TRAINS

- Of course, direct electrification is way more efficient
  - Electrification of networks a priority wherever possible
- But some segments resists electrification
  - Difficult terrain, incompatible infrastructure (tunnels)
  - Currently being operated by diesel
- Various demonstration projects underway
  - Relatively « easy » application despite the scale
    - Steady power, fixed itinerary between stations, large space
  - First functional train claimed by ALSTOM
  - First line functional in Germany in 2022
  - Developments in Asia (Malaysia, China, Korea)

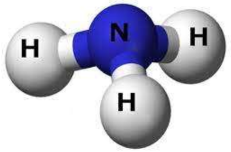
Alstom



Korea Railroad Research Institute

HYDROGEN BASED FUEL COMPARISON

For anything heavier then that… gaseous hydrogen is not going to do the job

- Liquid hydrogen 
- Ammonia 

- E-fuels 

- **Pros : it's hydrogen !**
  - More direct, less energy waste
  - Same tech as other hydrogen applications
  - No toxicity
- **Cons : it's cold (-250°C !!!)**
  - Energy density
  - Cryogenic réservoirs and maintenance
  - Boil-off : 5% loss per day
  - Impact on materials to assess, explosive

- **Pros : liquid and carbon free**
  - Liquid at reasonable temperature (-20°C or a few bars of pressure)
  - No carbon
  - Twice the energy density of liquid H_2
- **Cons : it kills people**
  - Distinctive odor of rotten fish
  - Toxic vapor when leaking
  - Environmentally hazardous
  - Does not burn well and forms NOx

- **Pros : it's fuel !**
  - No need for end-users to adapt their technologies
  - Best possible energy density
- **Cons : it's fuel !**
  - Terrible energy efficiency to produce
  - Very costly
  - Ambiguous carbon footprint if not based on biomass

NAVAL TRANSPORTATION

- Fluvial transport can be dealt with hydrogen
  - Existing small scale demonstrators
  - River transport of goods seems accessible

- Sea transport is another story…
  - Power requirements are massive
  - Ranges are huge (several weeks of autonomy)
  - Ships are used for decades
  - Ports infrastructure

Actu-economie.com

Wikipedia

NAVAL TRANSPORTATION : NO CONSENSUS ON BEST SOLUTION

- LNG already sold out as a solution for greener maritime transport
  - Technically accessible by the end of the decade
  - Excellent solution in terms of air quality
  - But little to negative impact on carbon emmissions…
  - Specific issue with methane slipping in the atmosphere

Marcogaz

- Ammonia technically the best carbon-free option
  - Best in class energy density
  - But more technical constraints
  - Legitimate fears about its toxicity, on board and in ports

NYK Line

NAVAL TRANSPORTATION : CONFLICTING STRATEGIES

- Methane based
  - Invest now on a technology which is near-ready, and rip the benefits in terms of air quality
  - Count on future availability of e-methane (from hydrogen) or bio-methane (from biomass) for reducing the carbon footprint
- Ammonia based
  - Invest in a technology you are sure can curb the carbon emmissions
  - But risk the techology uncertainties
  - And continue to run fuel-propelled ship in the meantime
- You can't play both cards
  - Considering a large ship is at least a 60 years investments…
  - And ports will want to know which infrastructure they build

CMA CGM

Hyundai

GREEN AIRCRAFT : A TRICKY PROBLEM

- A question of mass
  - On current planes, fuel represents :
    - 26% of MTOW for medium-haulers (Maximum Take-Off Weight)
    - 45% of MTOW for long haulers
- Aircrafts have very little tolerance to additional mass
  - And hydrogen is denser in mass only if you ignore the tanks…
- And not all propulsions can be electrified…
  - Propellers can be used with an electric motor, no issue
  - But jet engines requires something to burn
    - Specific design necessary for using different fuels
    - Decreased energy efficiency

Boeing

Airbus

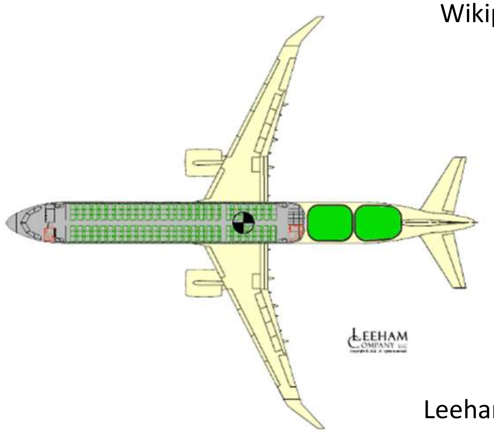
AIRCRAFT : LIQUID HYDROGEN

- Hydrogen has to be liquid to go on a plane
    - Gaseous tanks are not energy dense enough
    - Airport will have the technical skills to manipulate it

- Far from an ideal solution, though
    - Energy density still cannot be compared to current fuels
    - Reservoir integration is a nightmare

- Not every plane needs to cross an ocean
    - Max range claimed for Airbus demo planes : 3700 km
    - A little above ¼ the range of a Boeing 777
    - But enough for a lot of domestic or regional flights

Wikipedia

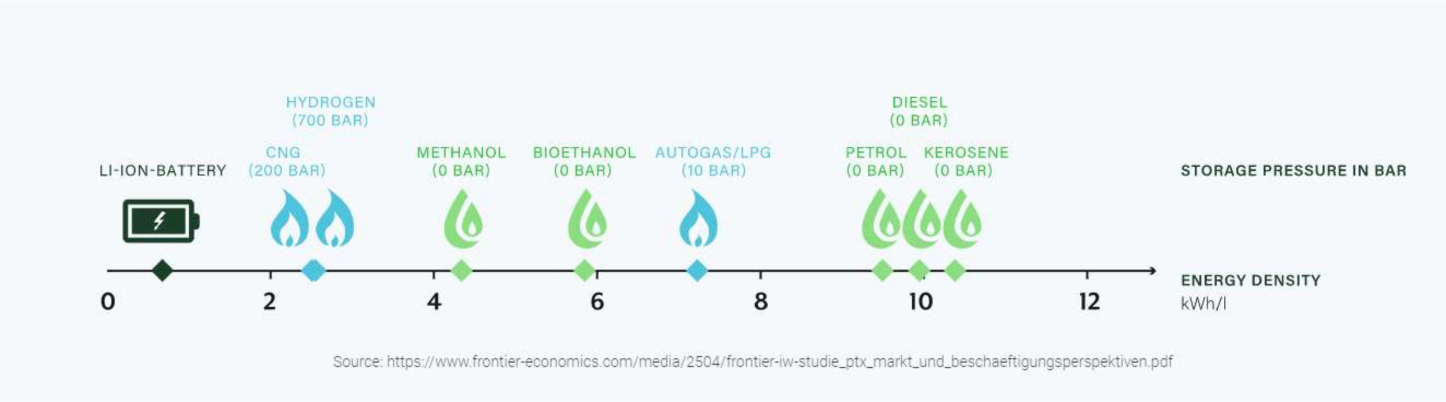


Leeham

AIRCRAFT : E-FUEL

- For an aircraft designer, e-fuel are very tempting
  - Best energy density available
  - No technology adaptation necessary
  - Smooth transition possible

- A reasonable solution ?
  - Many problems with e-fuel, as discussed above
  - Probably not enough for everyone
  - But if one application needs it, it is aviation



CONCLUSION ON MOBILITY APPLICATIONS

- Time for diversity
  - The time where one fuel type would be good for everything form rickshaw to airplane is over
  - Hydrogen fits « in-between » other solutions
    - Not as efficient as batteries for light applications
    - Not dense enough for very heavy or long range transportations (oceanic transports, long-haul planes)

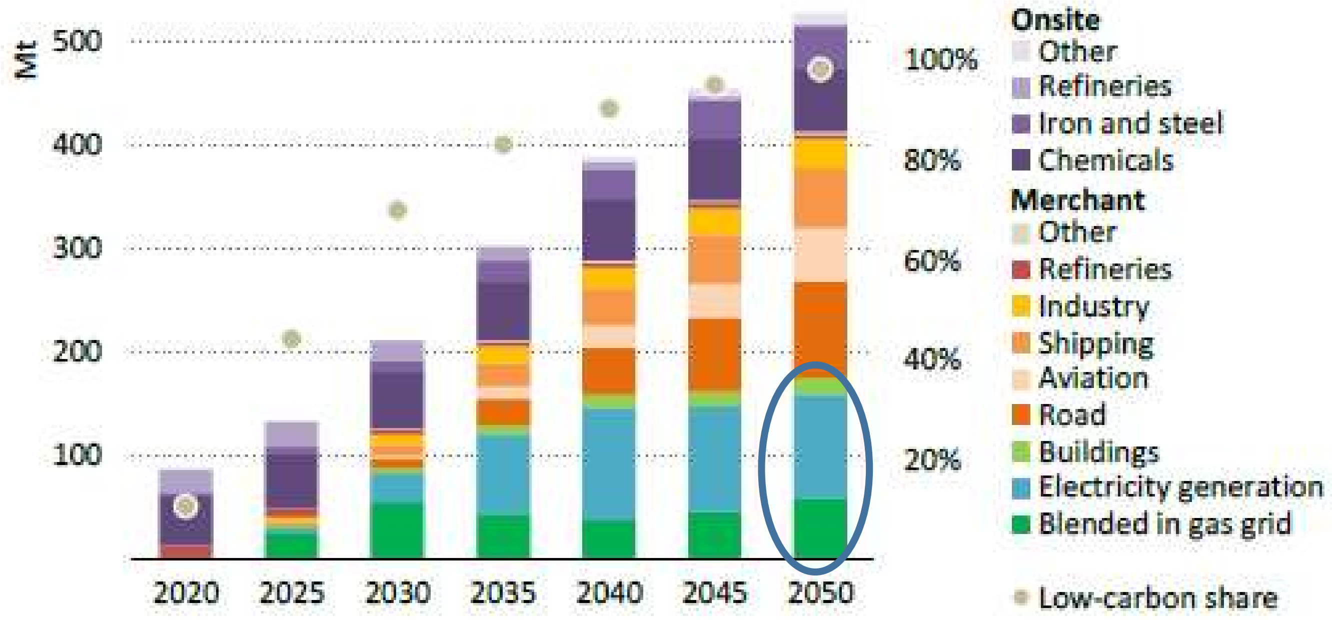
- There is more then one type of vehicle
  - Even within common categories such as « cars » or « trucks », a large diversity of usage and needs

- A mobility technology deployment needs to be supported by adequate infrastructure
  - And efficient deployment need choices to be made

LAST FAMILY OF USAGE : « ENERGY USAGE »

From 90 Mt fossile based H2 today to 500 Mt low carbon H2 by 2050

Figure 2.19 ▷ Global hydrogen and hydrogen-based fuel use in the NZE



The initial focus for hydrogen is to convert existing uses to low-carbon hydrogen; hydrogen and hydrogen-based fuels then expand across all end-uses

Note: Includes hydrogen and hydrogen contained in ammonia and synthetic fuels.

Electricity generation
Blend in the gas network…

We'll talk about that in the logistic part of the course

CASE STUDY

YOUR TIME TO WORK !

- India’s hydrogen strategy : Demand
  - Identify the opportunities in India in terms of hydrogen demand :
    - which sectors ?
    - Tomorrow ? 2030 ? 2050 ?

- I don’t have a correction !
  - You are the experts concerning India, not me…
  - But I have a few elements and we can debate

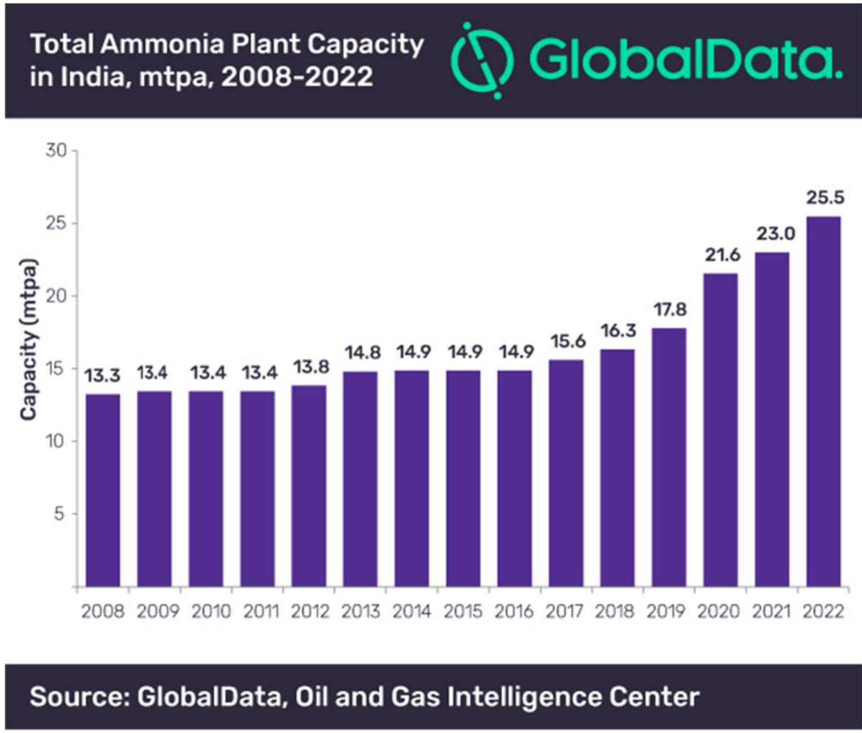
STEEL INDUSTRY

Tata Steel

- India’s steel industry is very strong… and responsible of 30% of India’s industrial emmisions
- Strong actors, with large investment capacity
  - Can touch the export market with « green » products as early adopters ?
- Interesting specificities of Indian steel industry : 56 % of direct iron reduction already !
  - Using gasified coal… too bad
  - Because metallurgy grade coke is hard to come by in India

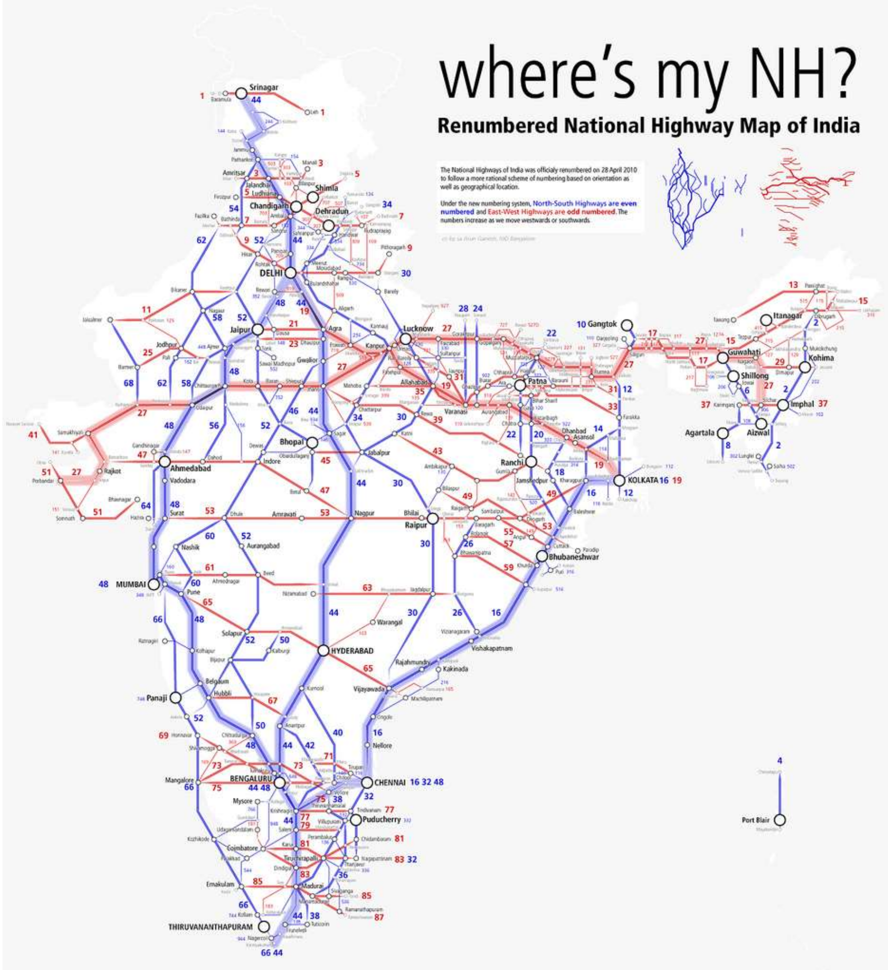
AMMONIA

- India is a big ammonia player :
  - Third producer in the world (behind China and Russia)
  - First importer in the world !
  - 10% growth in recent years
- Due to the country huge agriculture, of course…
- A strategic need for India ?
  - Current industry 100% dependant of gas imports
  - Food security, and support to export for the agricultural sector ?
  - Beyond national demand, an export commodity



TRANSPORTS

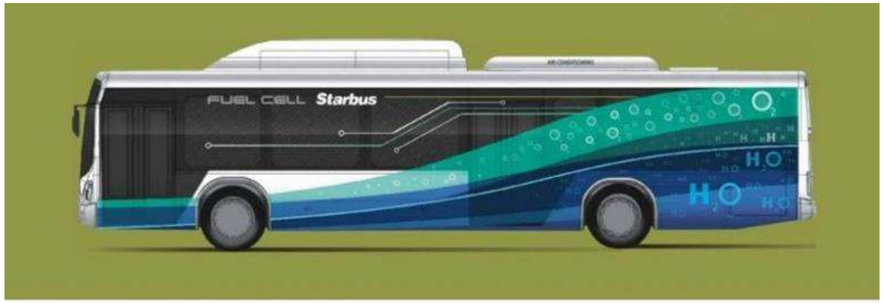
- Trains are ongoing electrification, and it’s a better idea then hydrogen
- Trucks typology in India ?
  - Long-haulers or captive local fleets ?
  - Large transportation companies or small private entrepreneurs ?

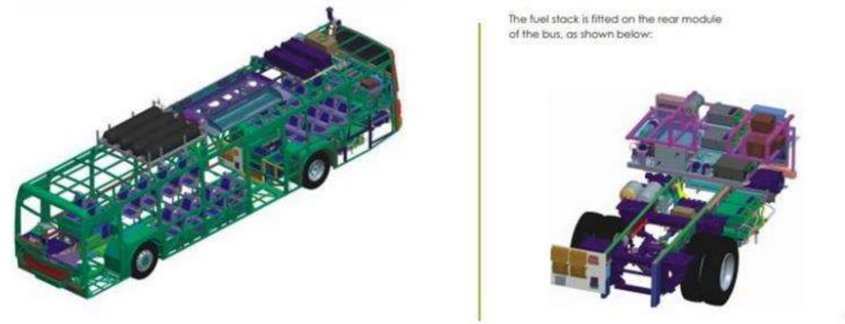


Wikipedia

TRANSPORTS

- Public transportation !
  - Huge needs in Indian cities
  - Cities are strong early adopters all around the world





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