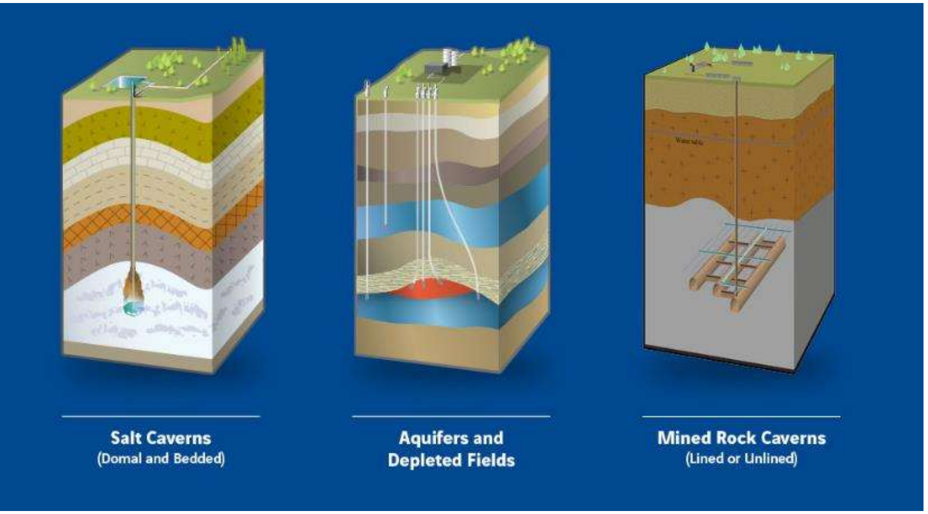
HYDROGEN FOR THE ENERGY TRANSITION : WHY ? HOW ?
PART II : PRODUCTION

Dr Vivien Esnault – IFPEN (France)

GeoIndia 2022 – Continuing Education Courses October 12th 2022



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)

PART 2 : THE HYDROGEN RAINBOW : MEANS OF PRODUCING HYDROGEN

- The hydrogen « rainbow » : how can we produce hydrogen, now and in the future ?
  - Hydrocarbon based solutions (« grey » and « blue »)
  - Electrolysis and biomass based solutions (« green »)

- Technico-economic analysis
  - Detailing environmental impacts
  - When and how do I have cheap renewable hydrogen ?

- Case study
  - Indian case analysis : India’s assets for the production of H_2

THE HYDROGEN RAINBOW : 50 SHADES OF HYDROGEN

Black hydrogen : produced from methane reforming

White hydrogen : Natural hydrogen, extracted from the ground

Green hydrogen (2) : produced from biomass (gasification or reforming of biomethane)

Grey hydrogen : produced from methane reforming

Green hydrogen : produced from renewable electricity

Turquoise hydrogen : produced with methane cracking (carbon stored)

Blue hydrogen : produced from fossils ressources, with carbon capture

Pink hydrogen : produced from nuclear based electricity

Yellow hydrogen : produced from grid electricity

Sorry, I am running out of space and colors…

HYDROGEN DOESN'T HAVE A COLOR, IT HAS A FOOTPRINT

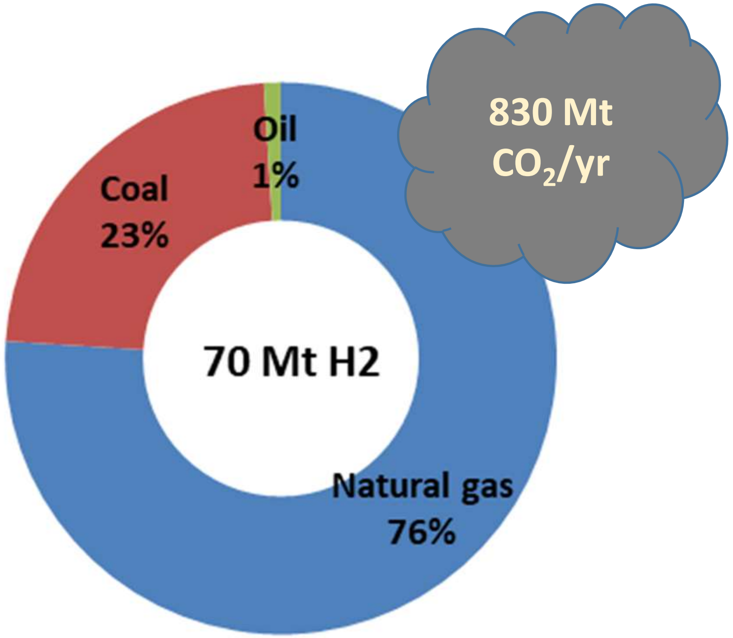
- Hydrogen can be produced from hydrocarbons
  - With different processes, and different feedstock
    - Natural gas is not the same as coal
    - Bio-based feedstock are of course a totally different story
  - Are CO2 emissions in the environment limited ?
    - Carbone capture is a %, not a yes/no answer

- Hydrogen can be produced through electrolysis
  - Hydrogen is just as green as your electricity
    - Electricity is nowhere 100% renewable, and will stay so for a while
  - How do you know which electricity went into your production ?

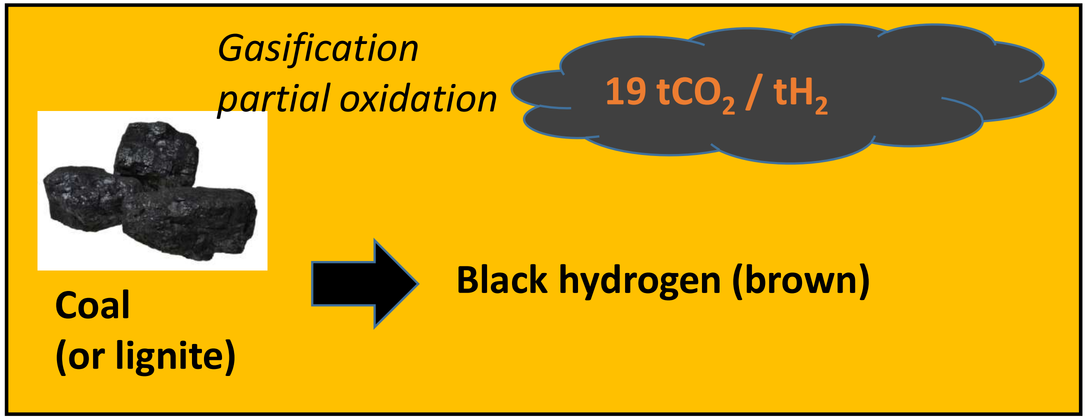
- What's your footprint ?

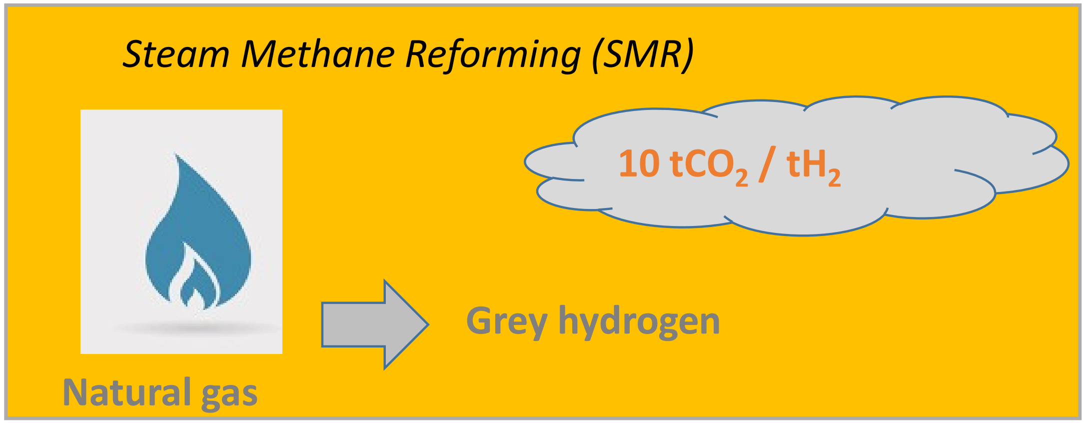
PRODUCTION OF H2 FROM HYDROCARBONS : PROCESSES

NOT ALL FEEDSTOCKS ARE THE SAME



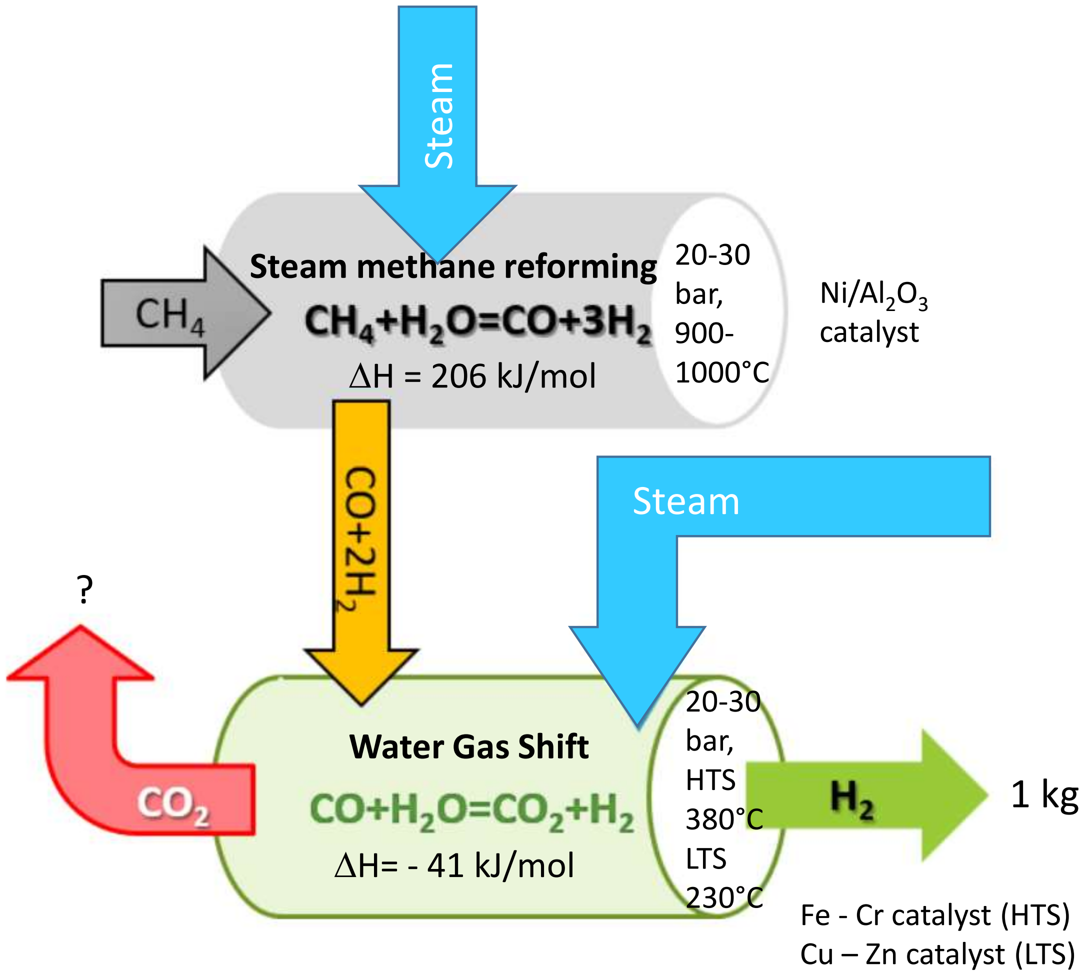
Source: International Energy Agency 2019





STEAM METHANE REFORMING (SMR)

- Feedstock
  - Methane (CH4)
  - Natural Gas: major feedstock
    - 70-90% CH4
    - Sulfur removal: eliminate H2S, COS,…
    - Elimination of C3+
  - Refinery Off Gas (ROG)
  - LPG (mainly propane and butane)
  - Naphta (light cut C5-C10)
    - Desulfurization
    - Pre-treatment to prevent coking
    - Catalyst resistant to coking

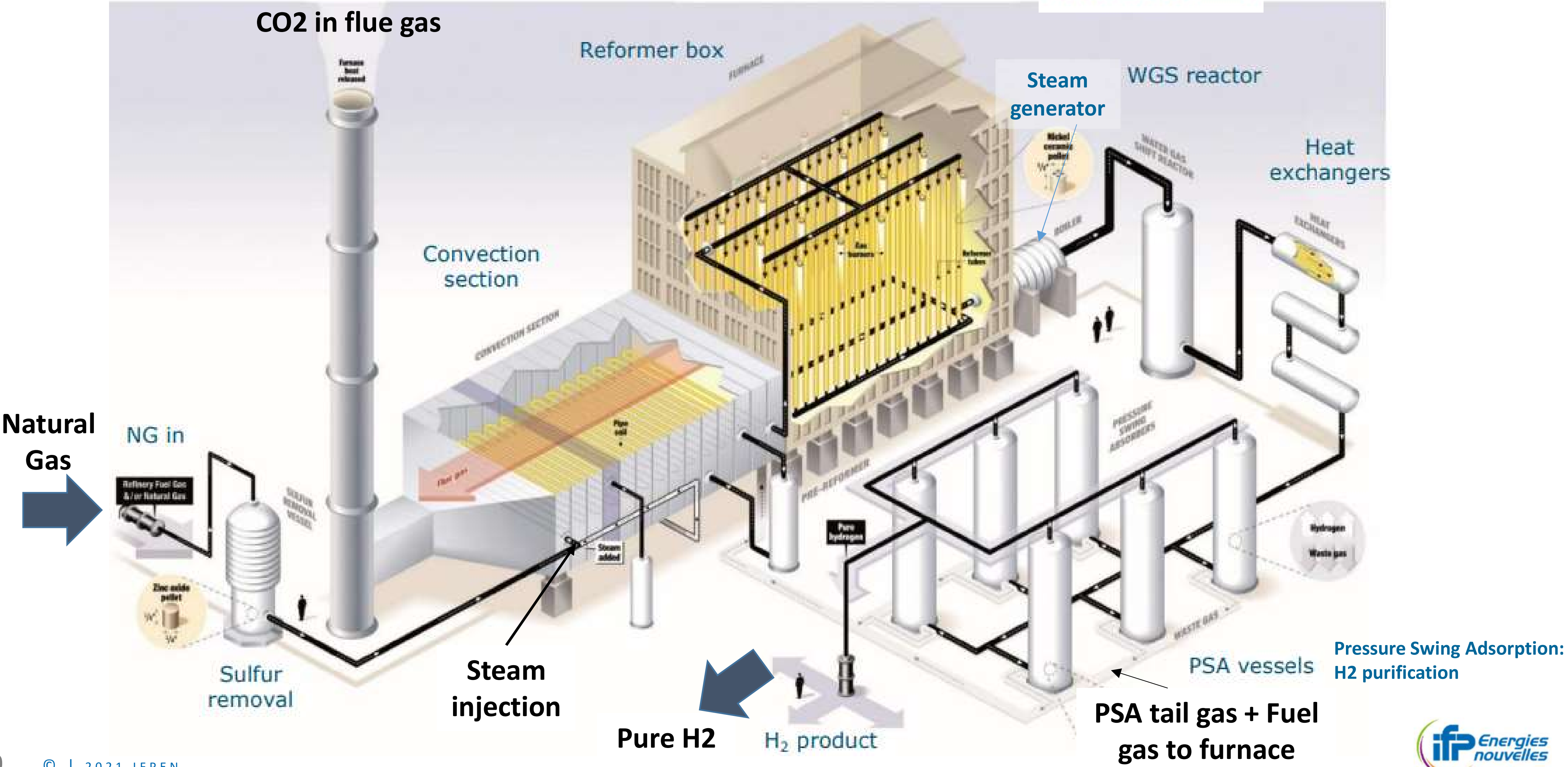


Overall balance

$$CH_4+2H_2O \rightleftarrows CO_2+4H_2$$

$$\Delta H = 165 \text{ kJ/mol}$$

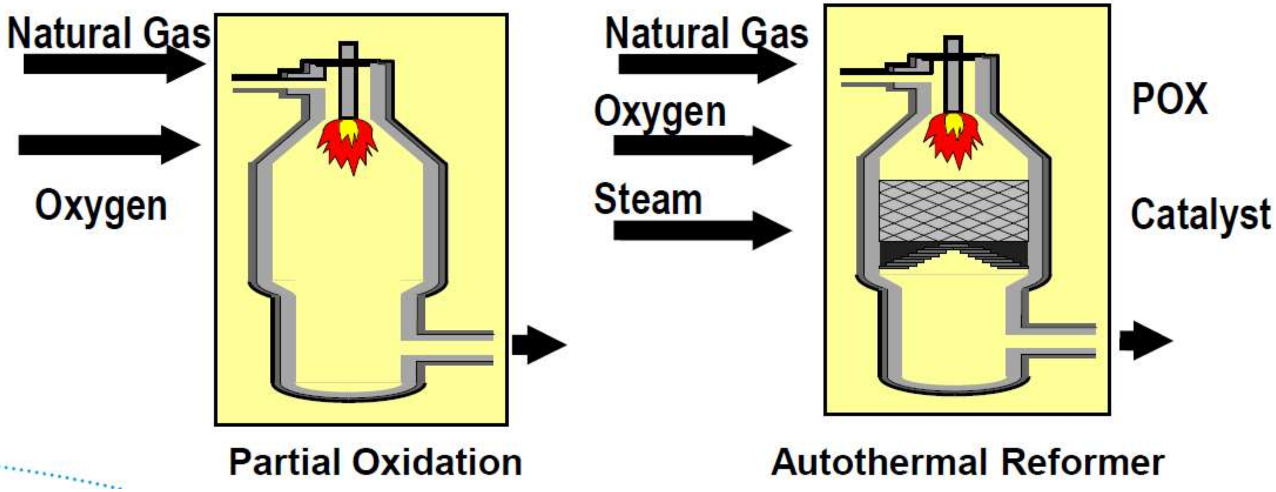
SMR LARGE SCALE UNIT



ALTERNATIVE :
AUTOTHERMAL REFORMING (ATR) OR PARTIAL OXIDATION (POX)

- Partial oxidation
  - $CH_4+1/2O_2 \rightleftarrows CO+2H_2$
  - Exothermic ΔH = - 36 kJ/mol
- Steam methane reforming
  - $CH_4+H_2O \rightleftarrows CO+3H_2$
  - Endothermic ΔH = 206 kJ/mol

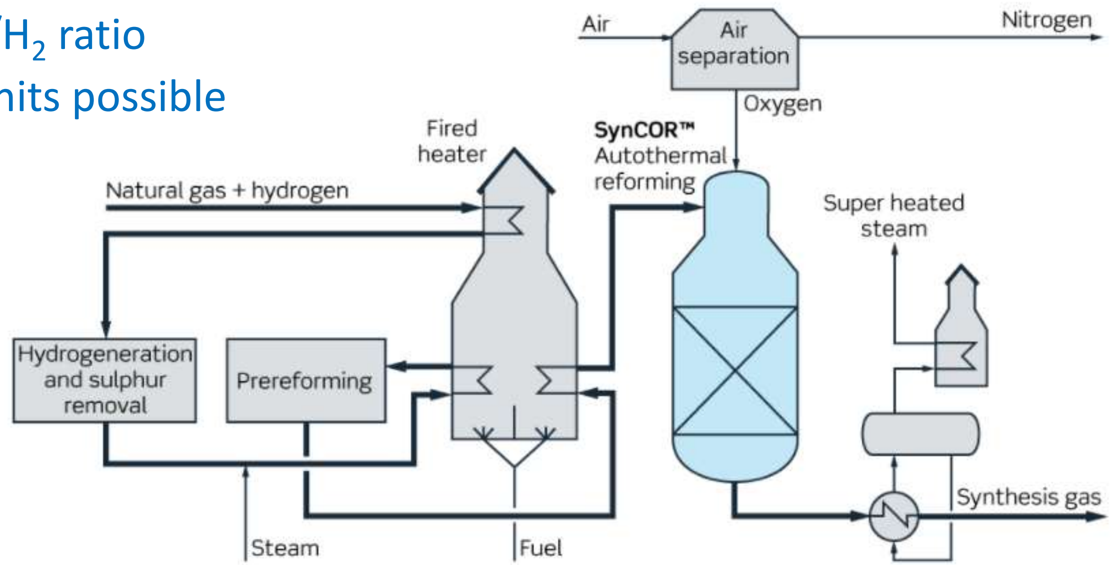
AutoThermal Reforming (ATR): combination of both reaction in the same reactor



Y. HAROUN (IFPEN)

AUTOTHERMAL REFORMING ATR

- Benefits
  - Any feedstock
  - Better thermal integration, yields
  - Less sensitive to coking vs. SMR
  - Less emissions
  - Flexibility on CO/H_2 ratio
  - Small compact units possible



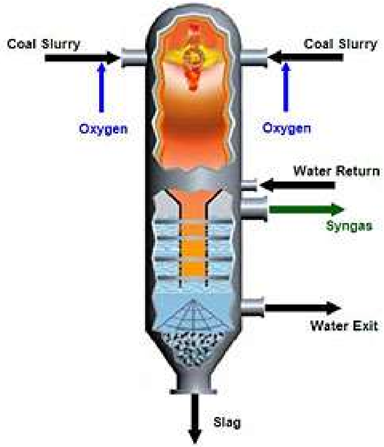
Source: Haldor Topsoe

SOLID FUEL GASIFICATION BY PARTIAL OXIDATION

- Main reactions
  - Partial oxidation: $C_nH_m + n/2\ O_2 \rightarrow n\ CO + m/2\ H_2$
  - Gasification: $C + H_2O \rightarrow CO + H_2$
  - And many side reactions
- Operating conditions
  - 1200-1500°C (controled by O2 flow)
  - 20-90 bar
  - No catalyst => thermal conversion

Coal is essentially composed of carbon
$\Rightarrow$ Syngas composition : rich in CO
$\Rightarrow$ Attractive for « power to liquid » applications

		Charbon	Coke pétrole	Lignite	RSV	Biomasse
H_2	% vol G.S	27	22	31	45	29
CO	% vol	64	65	55	48	49
CO_2	% vol	3	5	8	4	14
CH_4	% vol	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
N_2	% vol	5.5	6.5	4.3	2.9	6.3
H_2S	% vol	0.46	1.3	0.2	0.1	0.12
COS	% vol	0.04	0.16	0.02	0.01	<0.1
HCN	mg/m^3	1	0.8	1	0.2	0.3
NH_3	mg/m^3	0.4	0.3	0.24	0.4	0.4



Vs. syngas composition by SMR

Matière première	Méthane % volume	Gaz naturel % volume	GPL % volume	Naphta % volume
CH_4	3,06	2,91	2,39	2,12
CO	12,16	12,62	13,62	14,17
CO_2	9,66	10,40	12,73	14,19
H_2	75,12	73,98	71,86	69,52
N_2	-	0,09	-	-

PRODUCTION OF H2 FROM HYDROCARBONS : MITIGATING EMMISSIONS

LOW-CARBON HYDROGEN OPTIONS

Natural gas

SMR+CCS

capture

Blue hydrogen

Biogas

SMR

Biogenic CO_2

Gasification, partial oxidation

Green hydrogen

Lignocellulosic Biomass (by-products of agriculture of forestry,…)

Natural gas

pyrolysis

Turquoise hydrogen

+ Carbon black

+

Water electrolysis

Green hydrogen

CO2 CAPTURE FROM SMR (BLUE HYDROGEN)

- 3 options

Table 1: Levelised Cost of H_2 (LCOH), CO_2 Avoidance Cost and Overall CO_2 Capture Rate (IEAGHG, Techno-Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS. Technical Report 2017-02, 2017)

Capture Case	LCOH Euro Cent/Nm^3	CO_2 Avoidance Cost Euro/t	Overall CO_2 Capture Rate
No capture	11.4	-	-
Option 1	13.5	47.1	56%
Option 2	14.2	66.3	54%
Option 3	16.5	69.8	90%

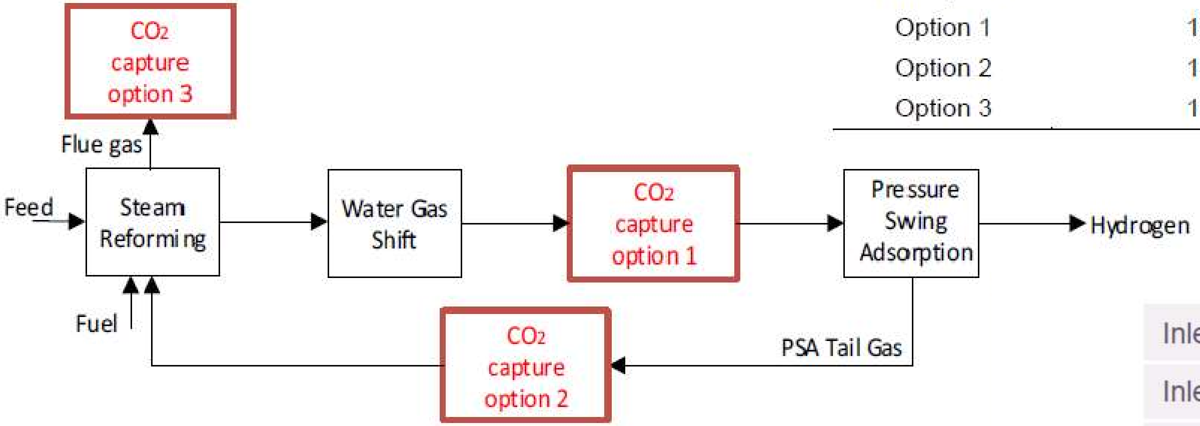
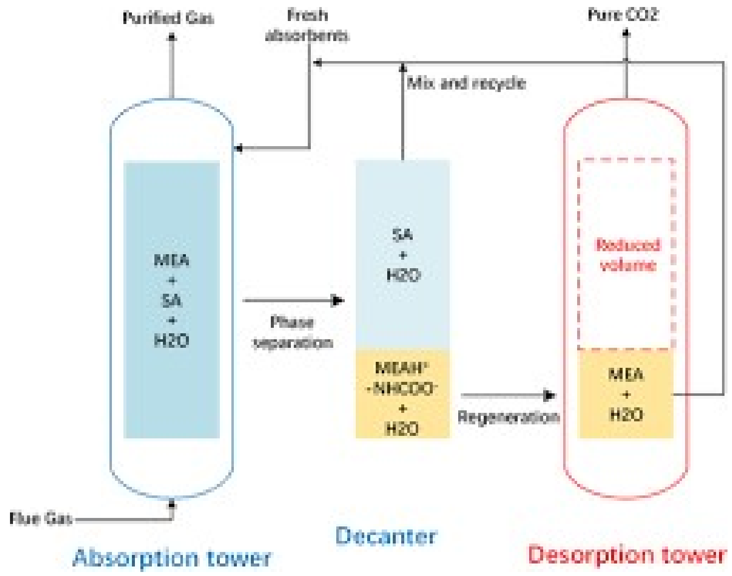


Figure 1: Steam methane reforming - CO_2 capture options

	Option 1 Syngas	Option 3 Flue Gases
Inlet Gas Pressure	30 bar	Atm
Inlet Gas CO_2 Content	17.3%	18%
Inlet Gas CO_2 partial pressure	5.2 bar	0.18 bar
O_2 in the inlet gas	No – traces	Few %
CO_2 captured on SMR	60%	90%

CARBON CAPTURE PROCESS

- Two-step for methane reforming
  - Purification : PSA (Pressure Swing Adsorption) will capture all impurities from hydrogen (CH_4, CO_2, CO…)
  - CO2 capture : Most common method use amine to specifically scrub CO_2
- Principle of amine carbon capture
  - CO2 reacts with the amine to form ions (including HCO_3^-) in the absorption section
  - The ions are soluble in water → extracted from the gas phase
  - The amine is regenerated through heating in the desorption section



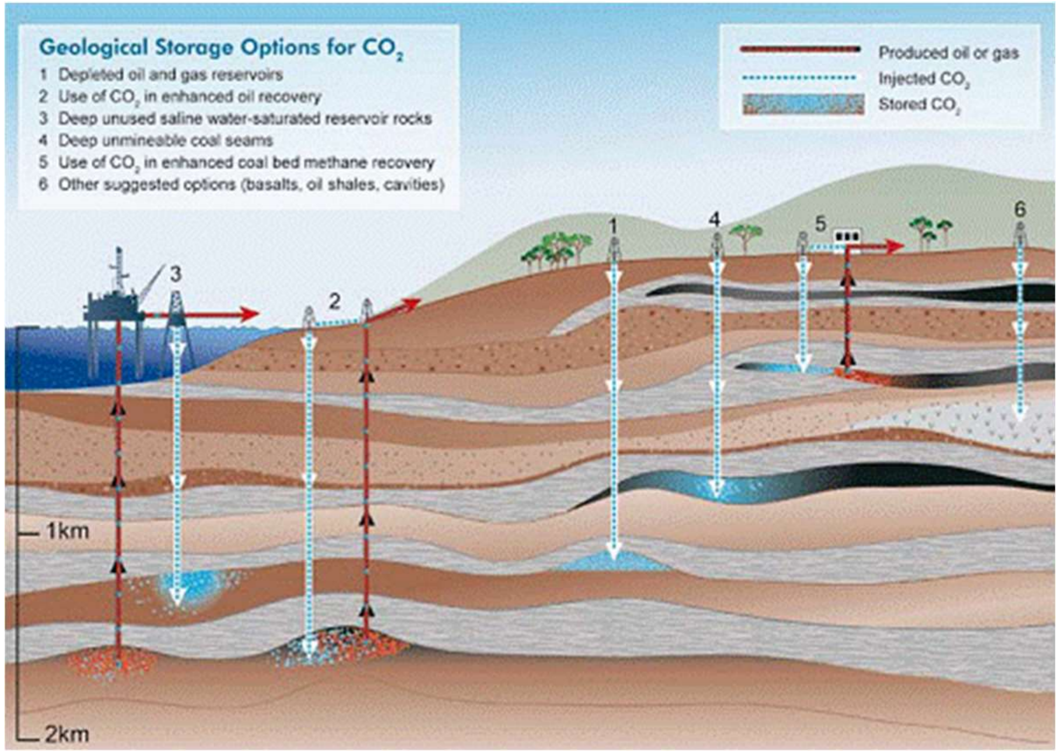
$$RNH_2 + H_2CO_3 \rightleftharpoons RNH_3^+ + HCO_3^-$$

CARBON SEQUESTRATION

- A large variety of geology can trap CO_2
  - O&G wells
  - Coals seams
  - Saline aquifers

- Still a lot of questions…
  - Durability of the trapping (cracks, degraded wells…)
  - Capacity to pump large quantities
  - Logistics

- Are we doing it or not ?
  - A lot of demos
  - No industrial scale ecosystem



HYDROGEN, AN IDEAL CANDIDATE FOR CCUS ?

- A parfect case for CCUS :
  - The process is « naturally » producing streams for almost pure CO_2
    - Not the case for many industrial flue gases
  - Large centralized units → easier logistics
  - Connection with gas producers… when gas wells are ideal candidates for capture
- Explain why the economical case sounds good :
  - CO2 could be captured and stored for between 75 to 150 $/t
  - Including CAPEX? It represents a premium around 0.5 $/kg of H_2, against a typical production cost of 2$/kg
- Only problem : there is an alternative
  - Is blue hydrogen necessary ?
  - Is blue hydrogen going to be available before green hydrogen ?

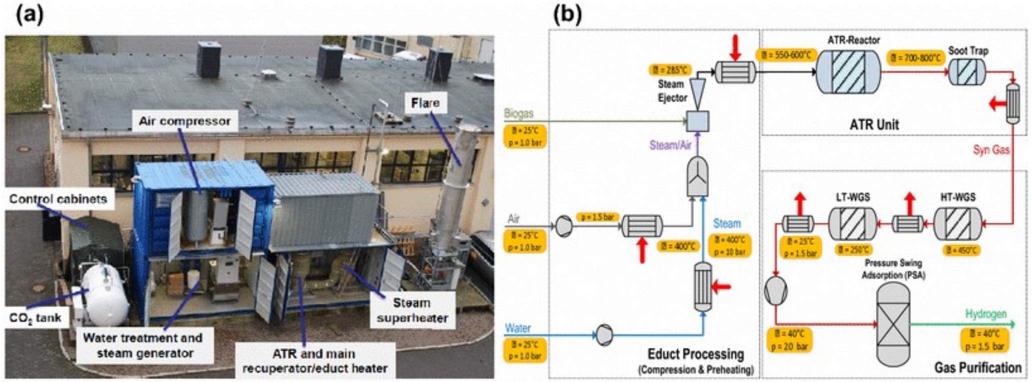
IEA

MAN Energy Solutions

REFORMING BIOMETHANE

Renewable energies

- SMR… at a small scale
  - Less economy of scale
  - Expensive feedstock
- Feedstock
  - Urban waste
  - Agricultural wastes (cereals, animal waste)



Parente et al. 2020 Renewable Energy

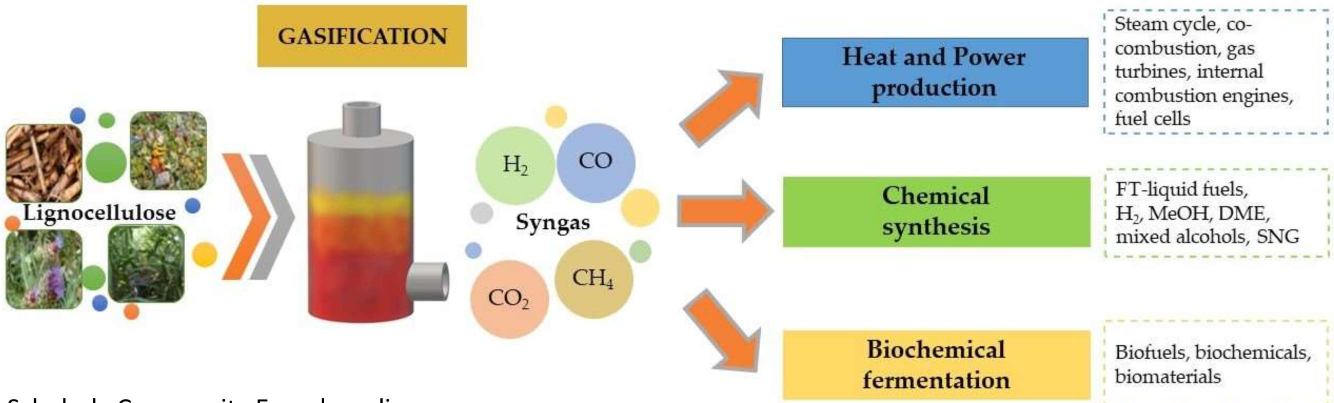
BIOROBUR project

BIOMASS GASIFICATION

Renewable energies

- High temperature gasification
  - Robust, well-known technology
  - Produce a CO-rich syngas
- Feedstock
  - Wastes rich in lignin
  - Wood chips, variety of agricultural waste

US Department of Energy



Scholarly Community Encyclopedia

Brandin et al 2011, Linnaeus University

HYDROGEN FROM BIOMASS, DISCUSSION

- Mature processes
  - « Simply » transposing processes already existing for fossil feedstock
  - Not at the same scale, though
- Economy is not favorable, at first sight…
  - Economy of scale is an important factor of what makes SMR/gasification cheap
  - The feedstock itself is expensive !
  - And limited in volume…
- More then just hydrogen production
  - Possibility to generate negative emmissions with carbon capture
  - High CO syngas →Relevant process for e-fuel/ methanol production
  - Has a role to play in the waste economy

METHANE PYROLYSIS

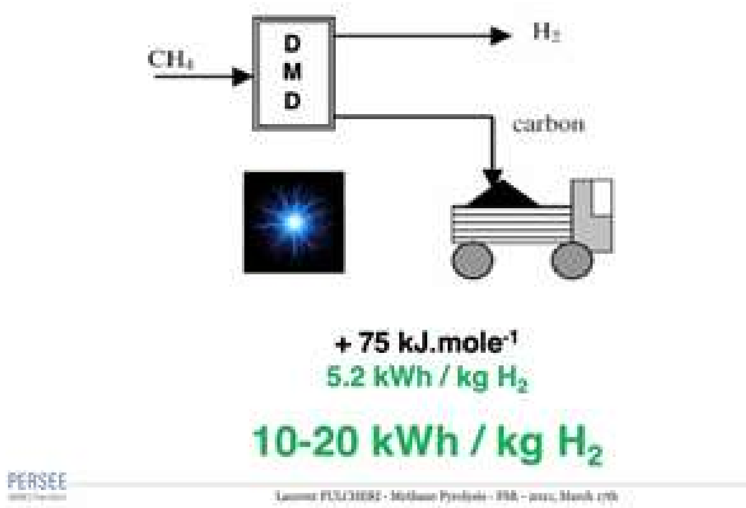
- Methane decomposition:
  $CH_4 \rightarrow 2\ H_2 + C$
- Compared to Steam Methane Reforming
  - ΔH = 75 kJ/mol vs. ΔH = 206 kJ/mol for SMR
  - Use more natural gas than SMR (2 H_2/CH_4 vs. 4 H_2/CH_4)
  - Produces C instead of CO_2 : easier to store
  - Use electricity as a source of energy
- Compared to water electrolysis
  - Use 3 to 5 times less electricity than electrolysis
- Overall energy conversion efficiency of methane and electricity combined into hydrogen is 40-45%
- Additional revenue by selling carbon black
  - For rubber, tires, printers
  - Actual demand of carbon black is 16 Mt corresponding to 5 Mt of H2

Options for turquoise H_2 production

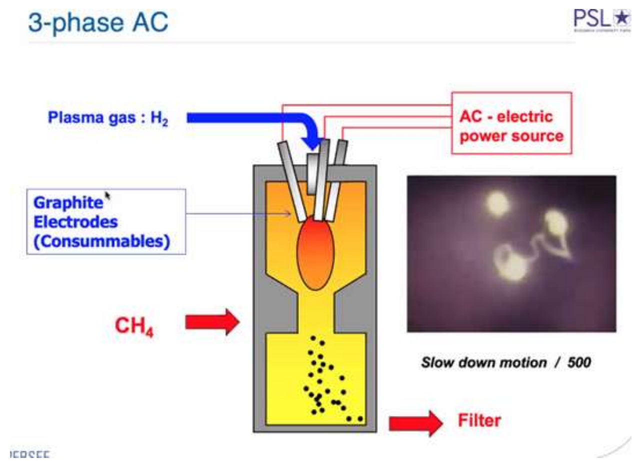
Liquid metal	Thermo Catalytic decomposition	Plasma
Liquid metal / salts Catalytic / non catalytic	Most R&D in Germany	Thermal / Non thermal
• **Hazer (Australia)** • **Czero (CA, USA)** • Ember-TNO (The Netherlands)	Fixed bed / Fluidized Bed / • **BASF** • Linde Group • ThyssenKrupp	• **MONOLITH Materials (US)** • **MPT (FR)** **LEADERSHIP POSITION TRL = 8**
• KIT (Karlsruhe) • IASS (Posdam) • TNO (The Netherlands) • BNL (USA)	• TUD (Dortmund) • TU Bergakademie (Freiberg) • RUB (Bochum)	

PERSEE

PLASMA TECHNOLOGY FOR METHANE PYROLYSIS



vs. Water electrolysis : 50-60 kWh /kg H2



Industrial development

2012-2018: Demonstration Pilot 1 MW, Mountain View USA-CA

2021:

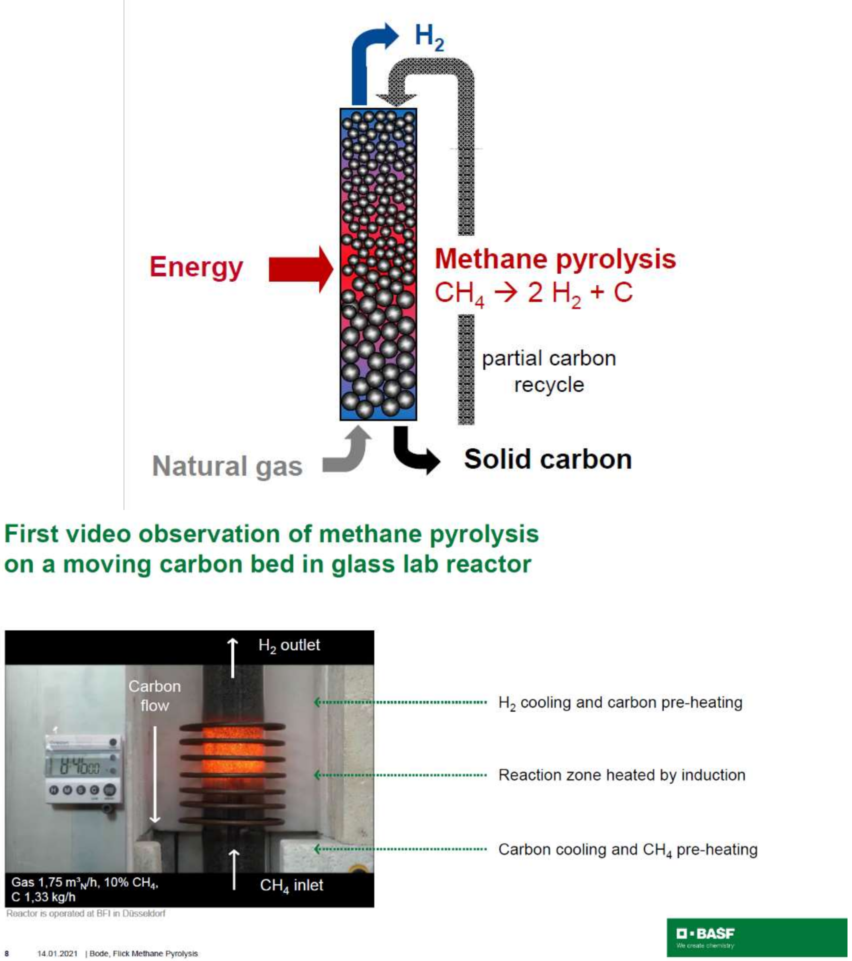
➔Comissionning 1st commercial CB&H_2 unit, *Olive Creek One (OC1)*, Nebraska

➔OC2, + NH3 production « in the pipe »

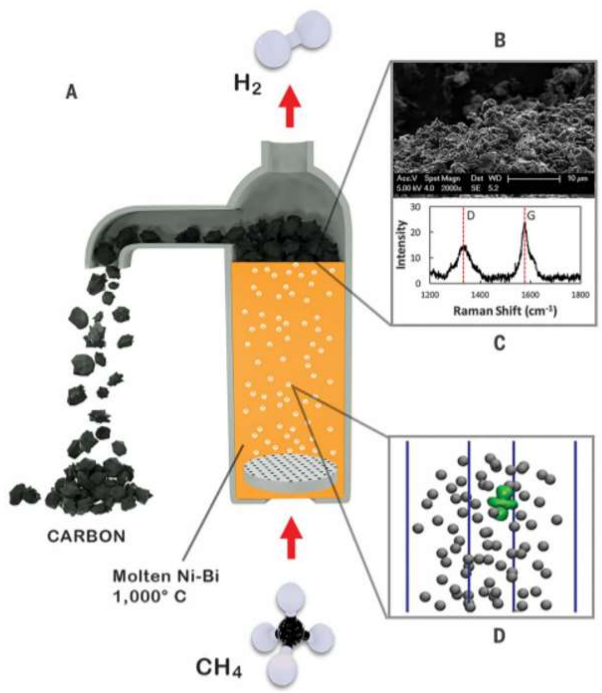
Monolith Materials
http://monolithmaterials.com/

METHANE PYROLYSIS TECHNOLOGIES AT LAB SCALE

- Moving bed (BASF)

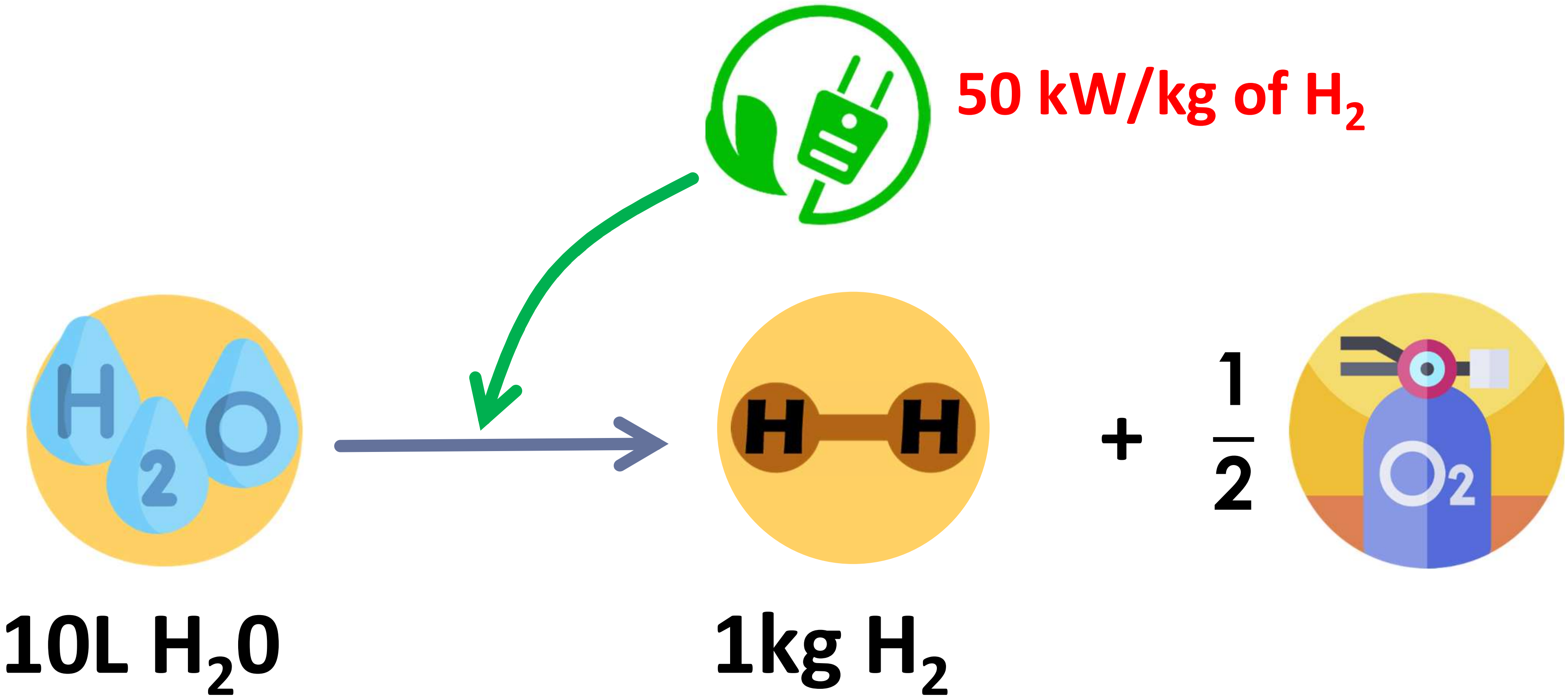


- Molten salts (KIT)



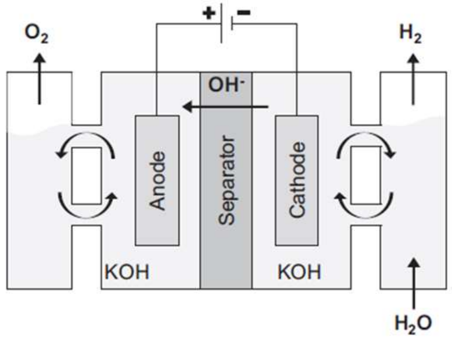
PRODUCTION OF H2 : ELECTROLYSIS

WATER ELECTROLYSIS - **POWER TO GAS**

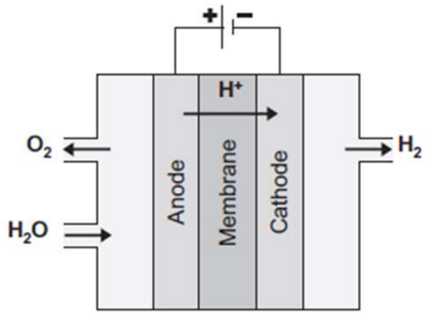


ELECTROLYZER TECHNOLOGIES

Alkaline AEC

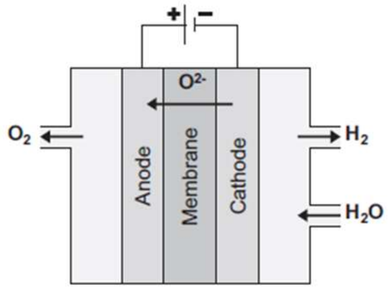


Proton Exchange Membrane PEMEC



Polymer (Nafion)

Solid Oxide SOEC

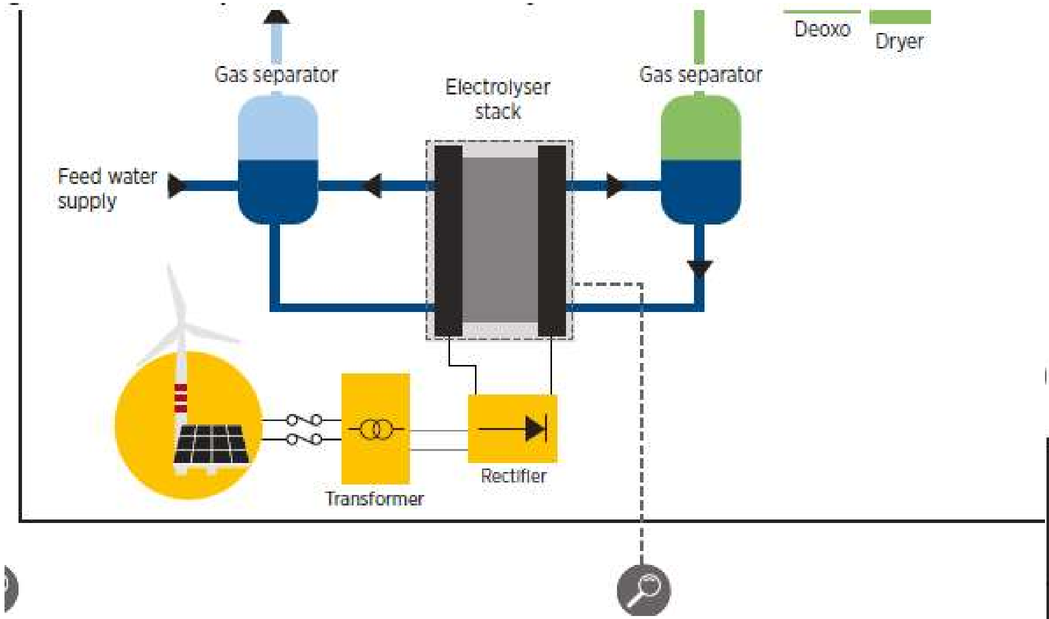


Ceramics

	Alkaline AEC	Proton Exchange Membrane PEMEC	Solid Oxide SOEC
Stack energy efficiency / LHV	60-68%	50-76%	96%
Temperature	60-90 °C	50-80 °C	700-900 °C
Technological maturity	Mature	Commercial	Demonstration

And some (less mature) others : Anion exchange membranes, photoelectrolysis, electrolysis of biomass

BASIC COMPONENTS OF WATER ELECTROLYZER AT DIFFERENT LEVELS

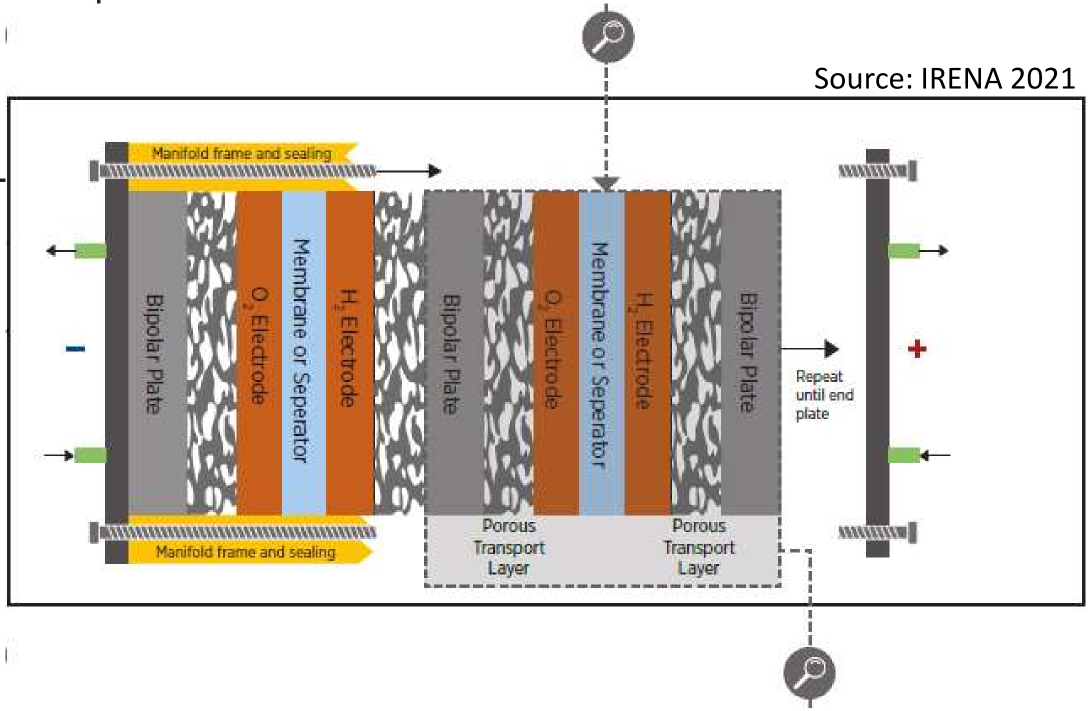


H_2 99.5- 99.9% (after drying)

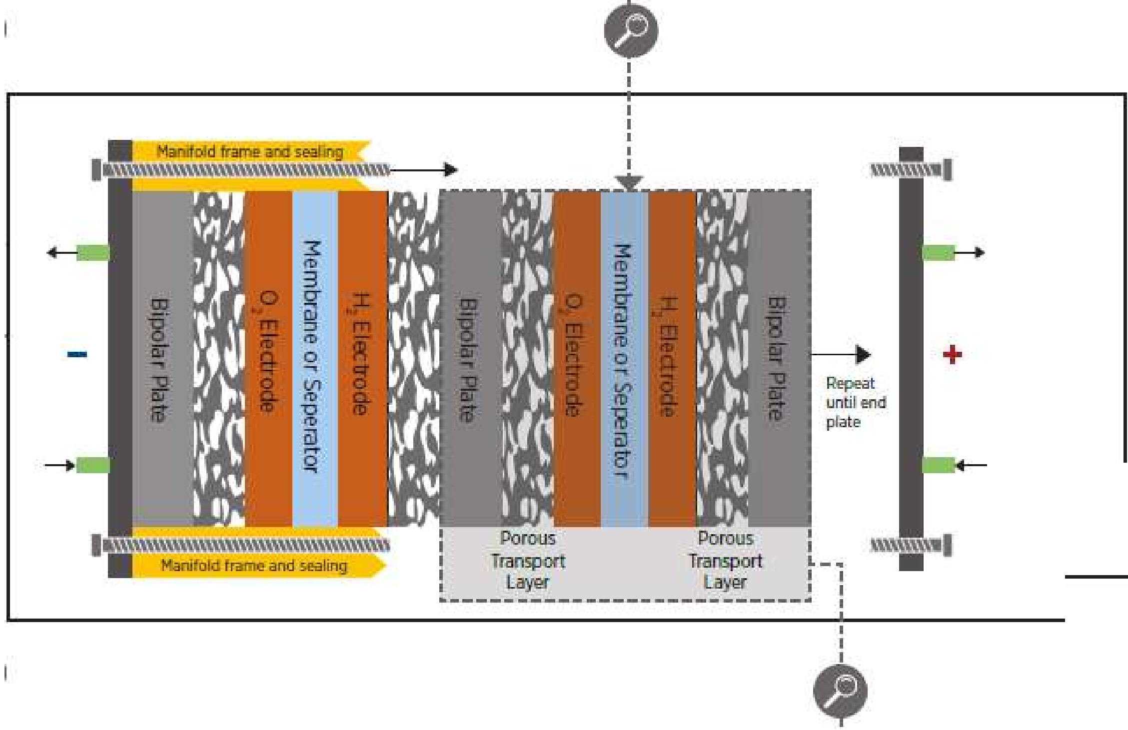
O_2 99- 99.8% (after deoxo & drying)

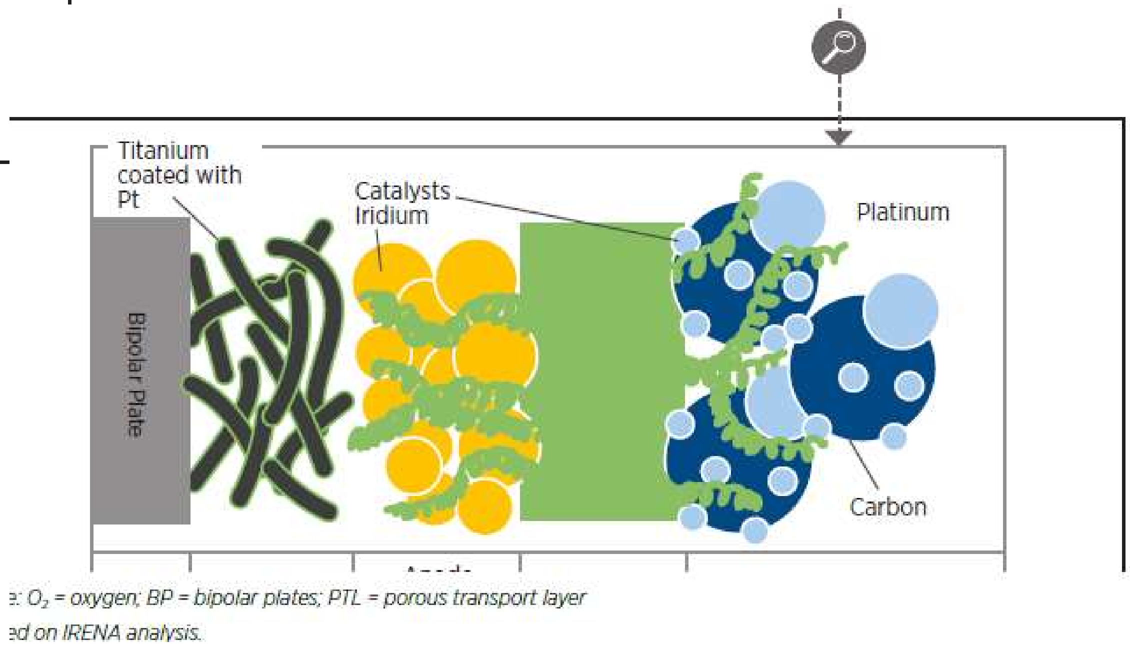
	AE	PEM	SOE
η stack	60-68%	50-76%	96%
η plant (utilities, rectification, compression)	40-60%	40-60%	76-81%

Source: IRENA 2021



BASIC COMPONENTS OF WATER ELECTROLYZER AT DIFFERENT LEVELS





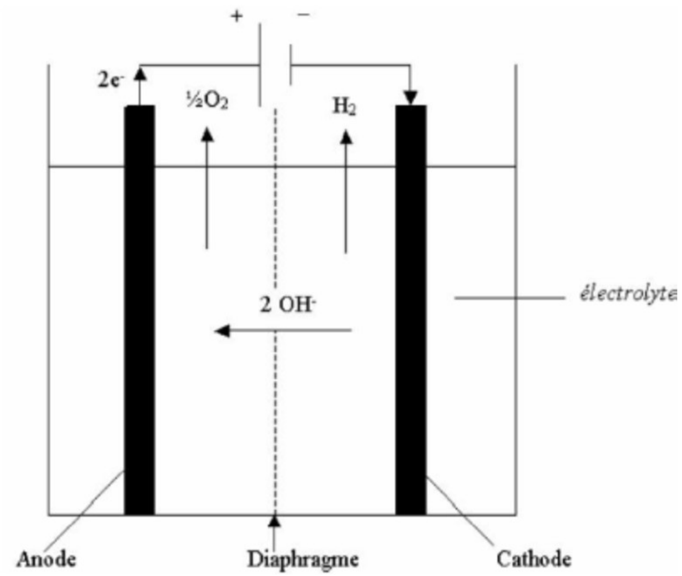
Source: IRENA 2021

ALKALYNE ELECTROLYSIS

- Transport of OH^- ions in water solution

- An « old » technology
  - Used for decades for Cl_2 and NaOH production
  - Not very compact, not very high pressure…

- Don’t dismiss too fast old technologies…
  - Efficiency vastly improved and now close to PEM
  - No expensive catalysts !



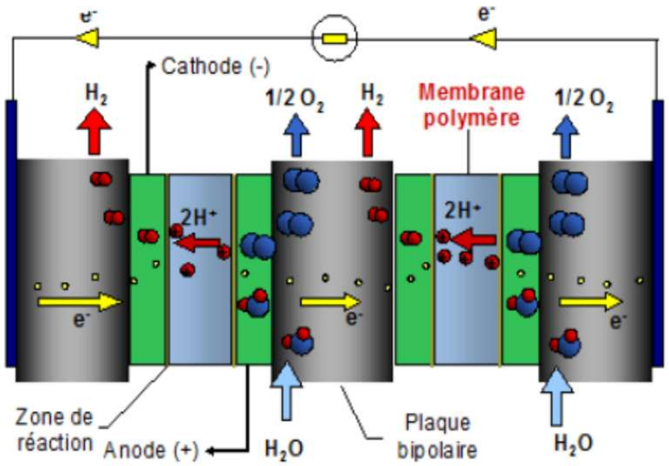
France Hydrogène

PEM ELECTROLYSIS

- Transport of H^+ ions in polymer membranes

- Scaling-up the technology
  - Known for a long time for small units (submarines)
  - Now scaling up to mass production
  - Compact and efficient, high pressure (70 bar)

- Too reliant on strategic components ?
  - Platine and iridium catalysts needed (for now)
  - In competition for the ressource with PEM fuel cells



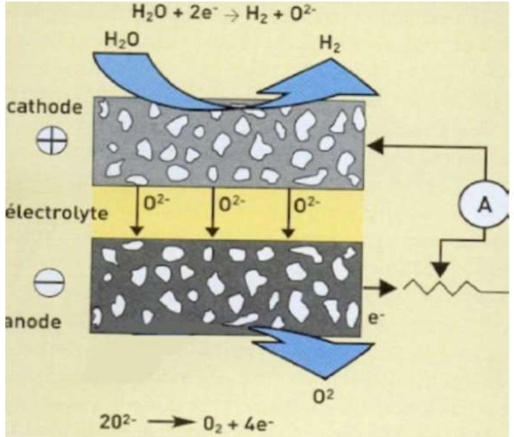
France Hydrogène

NEL

Air Liquide

SOEC/SOFC ELECTROLYSIS

- Transport of O^{2-} ions in a ceramic membrane
  - Still in development
- The « hot » electrolyzer
  - Operations at 400°C to 1000°C, depending of tech
  - Super efficient… if you have access to waste heat
  - Low pressure of hydrogen → not space efficient
- Nuclear reactor’s best friend
  - Adapted to large units, need for waste heat…



France Hydrogène

Encyclopedia Brittanica

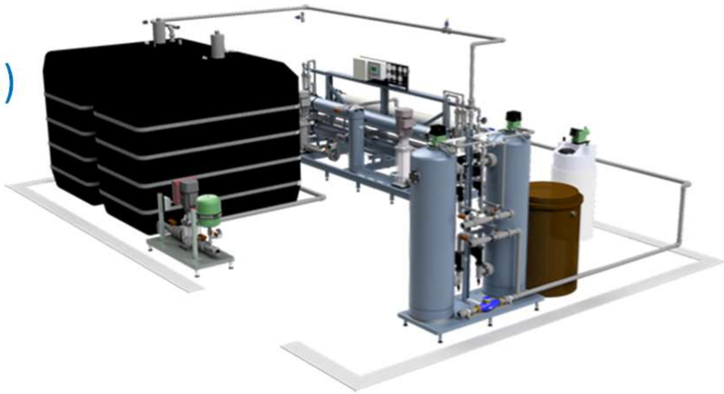
CEA/LITEN

ELECTROLYZER SIDE EQUIPMENTS

- Water purification
  - Electrolysis needs water… but not so much
  - Requirements are hard but technologies exists
  - If needed, water desanilization not a big deal in the global balance

CSIC

- Gas purification
  - Very strict requirements
  - Less pollution then with reforming, but different (H_20, 0_2…)
- Compression
  - Efficient transport and usage of hydrogen needs pressure
  - Low pressure → larger installations and CAPEX
  - Pressure of operation of the electrolyzer is key



Eurowater

THERMOCHEMICAL SPLITTING : ANOTHER WAY TO PRODUCE H_2 FROM H_2O

- At high temperature, water will decompose in H_2 and O_2
  - 3000°C : not very practical
  - The same result can be obtained using reactional intermediate, at lower temperatures : 400°C for Iode/sulphur cycle

$$I_2 + SO_2 + 2H_2O \Rightarrow 2HI + H_2SO_4$$

$$2HI \Rightarrow H_2 + I_2$$

EDF

- You still need large amounts of heat
  - Initially developped by the nuclear industry
  - Potentially attractive for thermal solar
    - Direct use of heat, no electricity
- Is this too late to the party ?
  - Electrolysis is industrializing, reducing costs…
  - Same apply to other innovative ways of producing hydrogen

CARBON FOOTPRINT AND ECONOMIC CONSIDERATIONS

WHAT IS GREEN ?

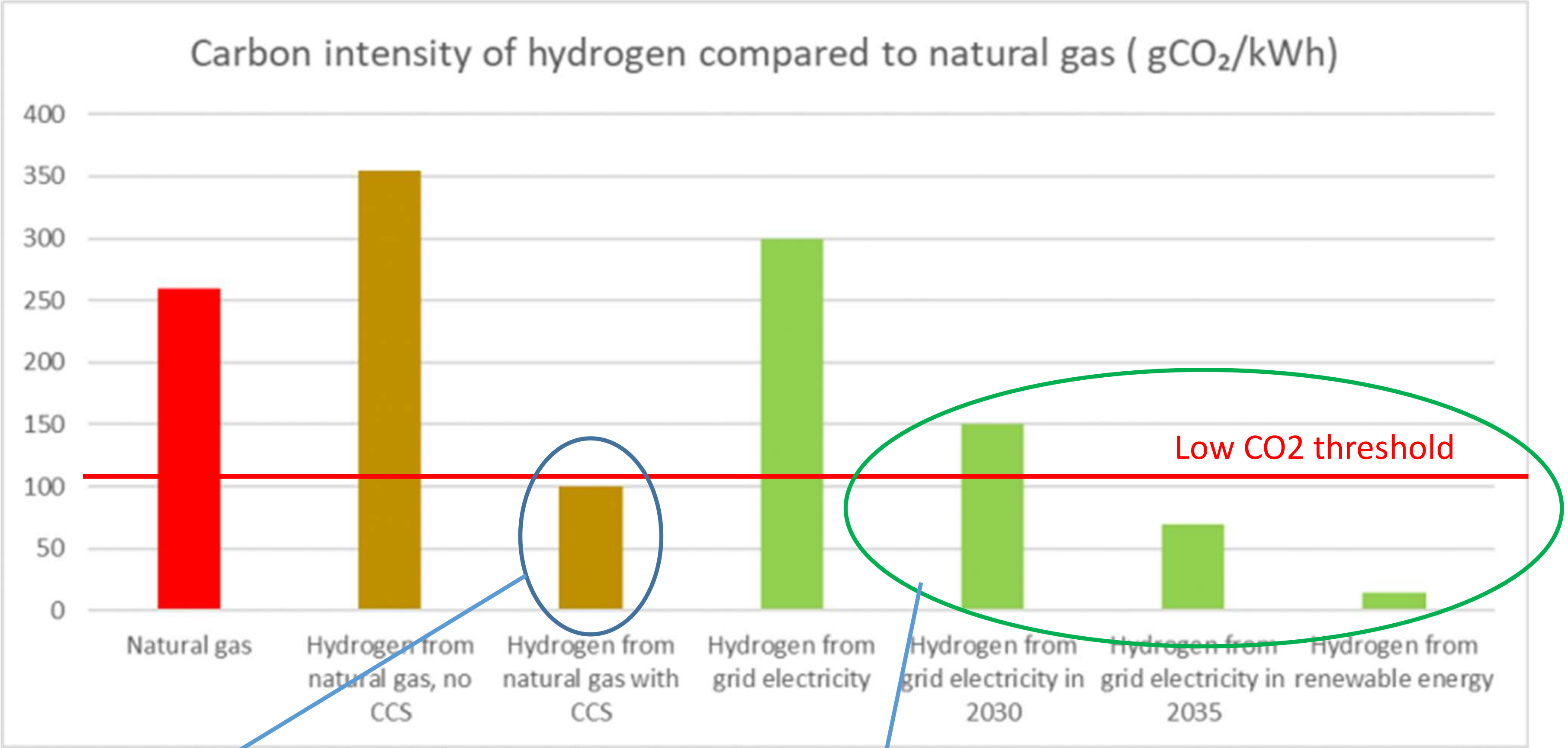
- Every process has a carbon footprint
  - CAPEX : amortized consumption to produce the system
  - OPEX : cabon footprints of intrants : electricity, methane

- Different approaches to define « acceptable » hydrogen
  - By type of process : complicated, and not satisfying
  - By carbon footprint :
    - International standard for a threshold
    - International standard for a methodology to measure the footprint

- EU most likely definition : low-carbon hydrogen is less then 3 t_{CO2}/t_{H2}
  - Arbitrary, but a balance between sufficiently low and reachable by both blue and green

WHAT IS GREEN ?

Indian grid



Friends of the Earth Institute

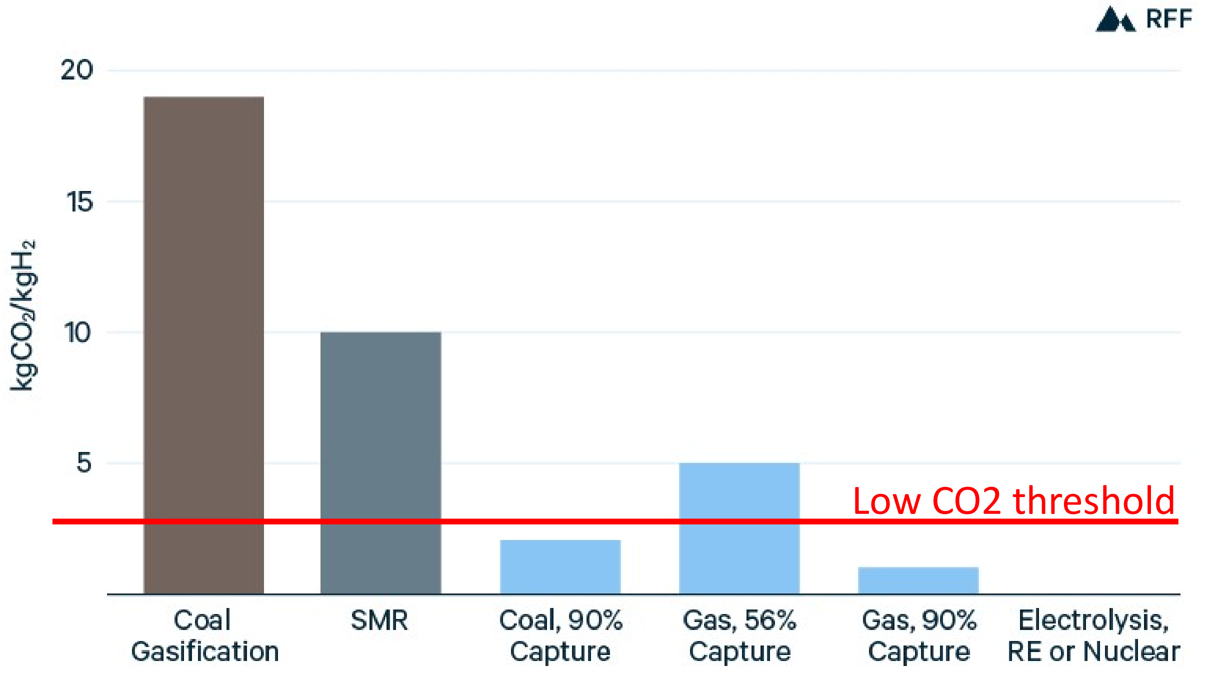
How good is your capture ?

How good is your electricity ?

HYDROGEN FROM HYDROCARBON : CCUS NEEDS

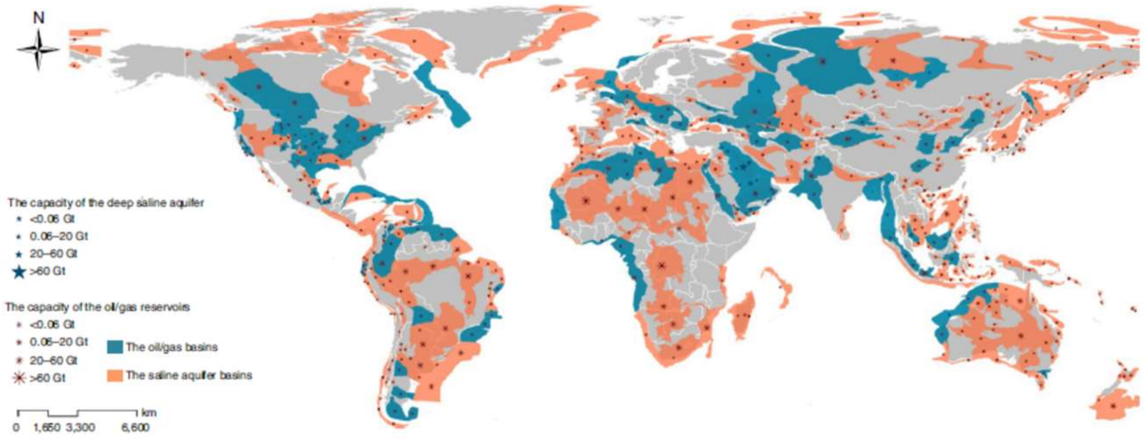
- It can be reached…
  - But you need « perfect » CCUS
  - The process is favorable, but still

- A « good enough » hydrogen ?
  - Aggressive discourse toward ever greener products
  - When electrolysis has the reputation of being , « 0 emission »
  - What place for hydrogen at reduced footprint, but above 3 t/t ?

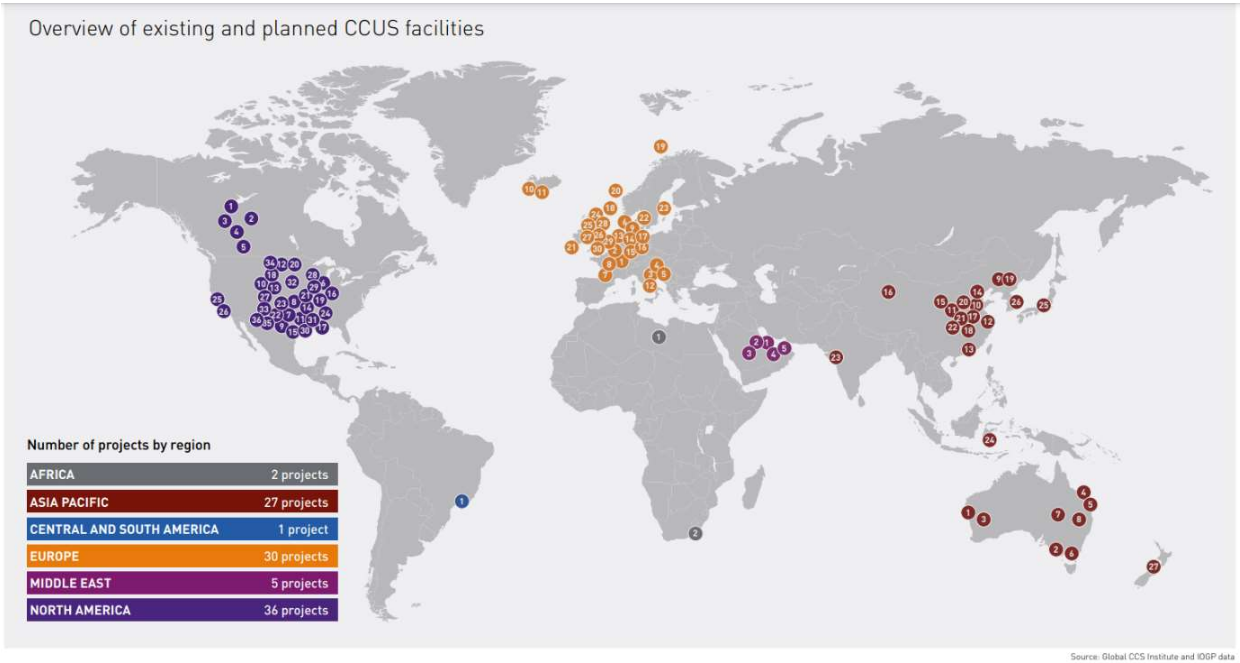


CCUS POTENTIAL

- Widely available around the world
- Still , logistics to reack the fields is key



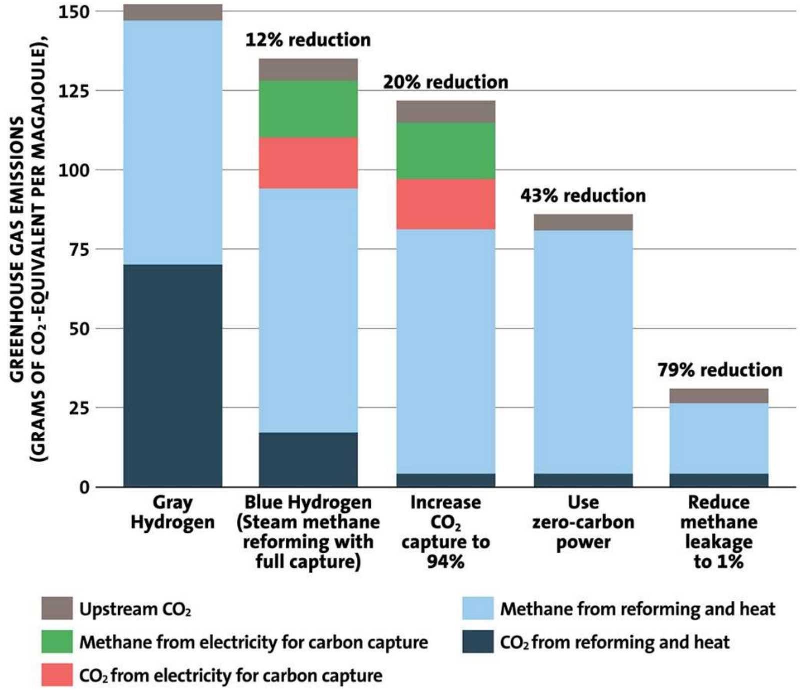
- Actual projects are much rarer…
  - And largely dependant of O&G industry (enhanced oil recovery)



HYDROGEN FROM HYDROCARBON : METHANE RELATED EMMISSIONS

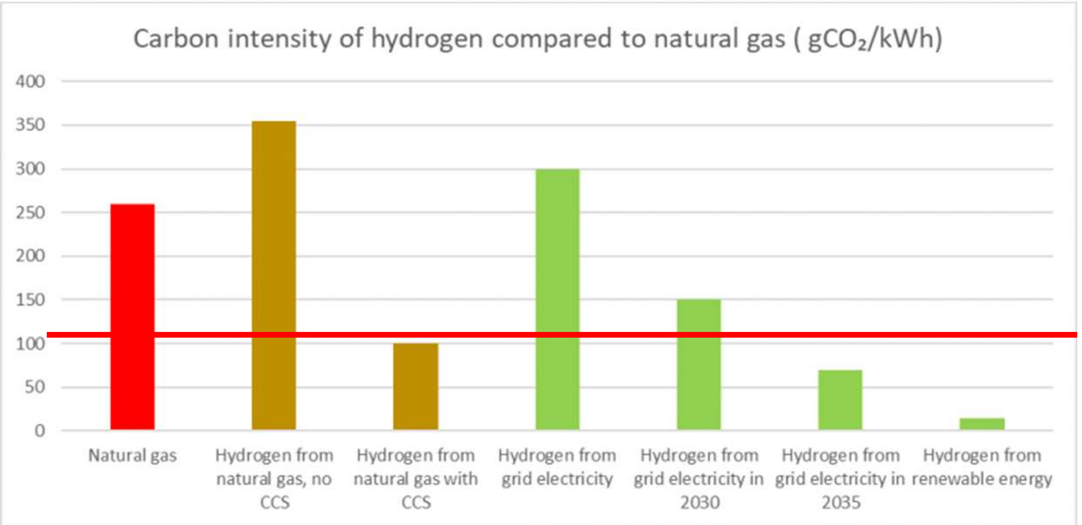
- Methane is an extremely powerful greenhouse gas
  - Especially short term : 80x at 20 years
- Recent debates around methane leakage on extraction sites
  - Estimations varying by a factor of 100…
  - In truth, very site and process dependant
  - US shale gas has a poor footprint, North Sea gas much better
- Important consequences for hydrogen
  - Methane footprint can kill all by itself the hydrogen footprint if poor
  - Difficult to take footprints at face value…

FIGURE 1A: LIFE-CYCLE HYDROGEN PRODUCTION EMISSIONS, 20-YEAR TIME FRAME

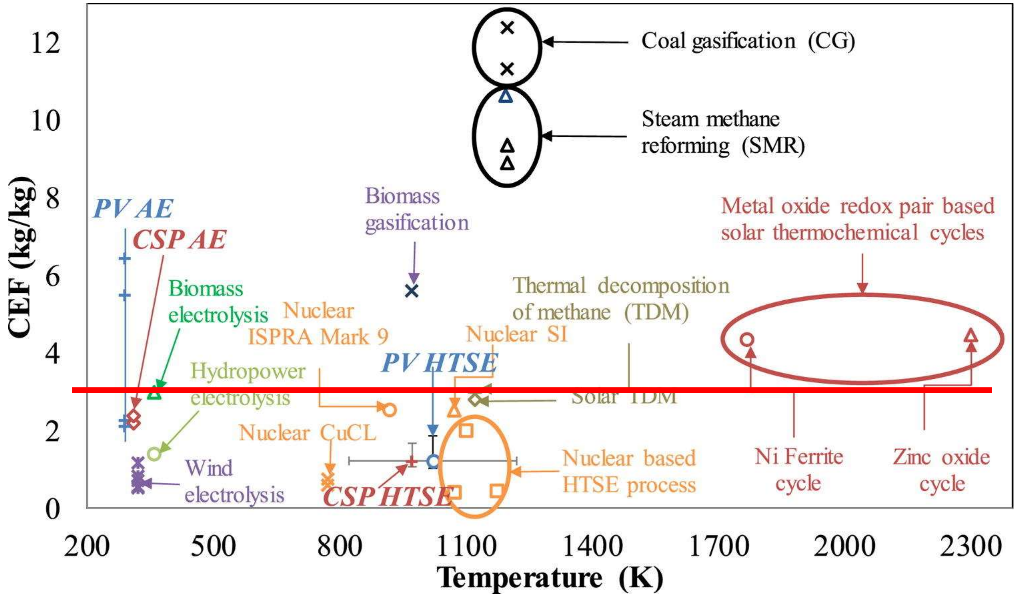


SOURCE: Howarth and Jacobson (2021)

HYDROGEN FROM ELECTROLYSIS : ELECTRICITY FOOTPRINT



Friends of the Earth Institute



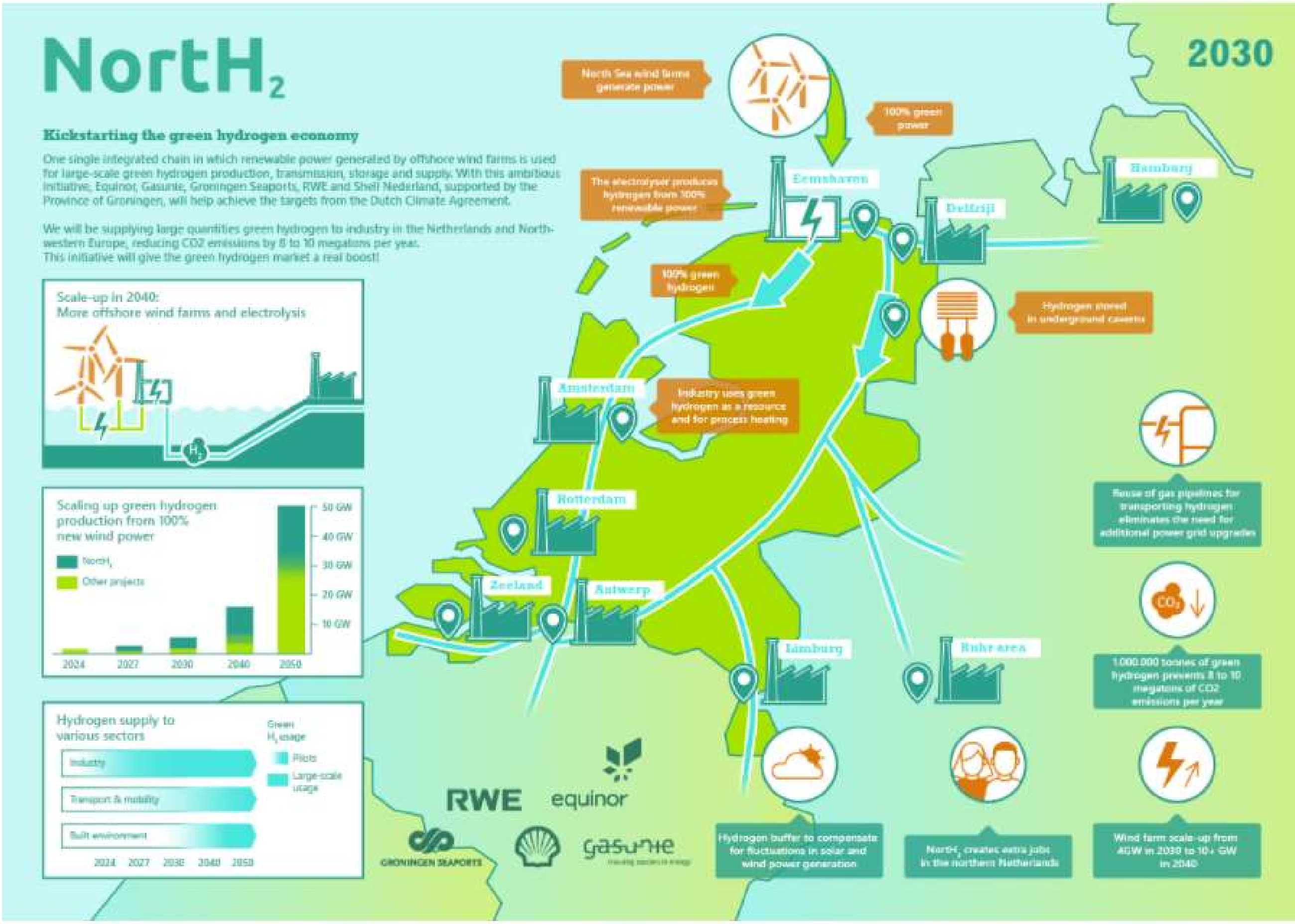
Yadav and Banerjee 2020 Applied energy

- Any « green » electricity will do
  - Wind and hydropower is better then solar, though
- The grid is not there…
  - And won't be there any time soon

HOW DO YOU GUARANTEE GREEN ELECTRICITY ? DEDICATED CAPACITY

- Local hub, with dedicated power source

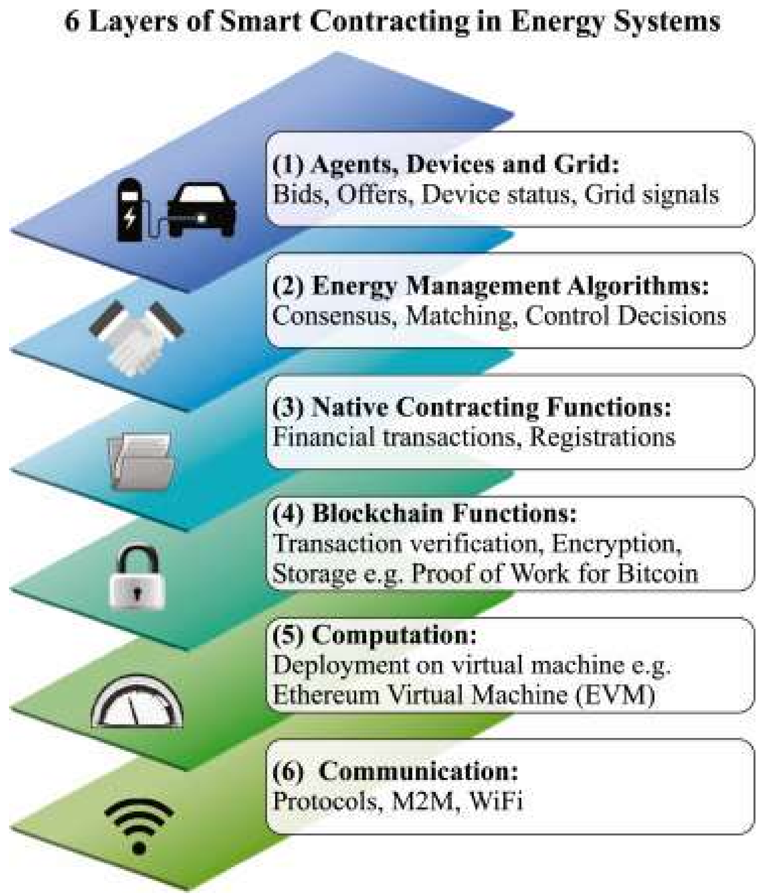
- No balance of intermittence, so you better still be plugged to a grid



Source: RWE

LAST BUT NOT LEAST : HYDROGEN DIRECT FOOTPRINT

- Plug on the grid, get the electricity you want
  - The producer divide its production in lots
  - Lots are sold separately
  - Legit if the same green lot is not sold two times
- Technology helps if you want to make it flexible
  - Communication, blockchains…
- Does not make anything greener…
  - Won’t be cheap to get the best lots
  - Who get to consume the junk electricity ?



Kirli et al. 2022 Renewable and Sustainable Energy Reviews

LAST BUT NOT LEAST : HYDROGEN DIRECT FOOTPRINT

- Recent polemic around H_2 greenhouse potential
  - Complex mechanism involving the stabilisation of methane in the atmosphere
  - Studies made a huge polemic stating H_2 greenhouse potential was 200x of CO_2 !
    - Yes, but « immediate potential », which does not make sense
  - Latest studies : 10x time the potential of CO2 at 100 years, the current benchmark

- Current leak practices are not up to the task
  - On average, electrolyzer leaks 9.4%, logisitics up to 20 %...
  - 30% leakage = equivalent footprint 3 tCO2/tH2 = you are not green

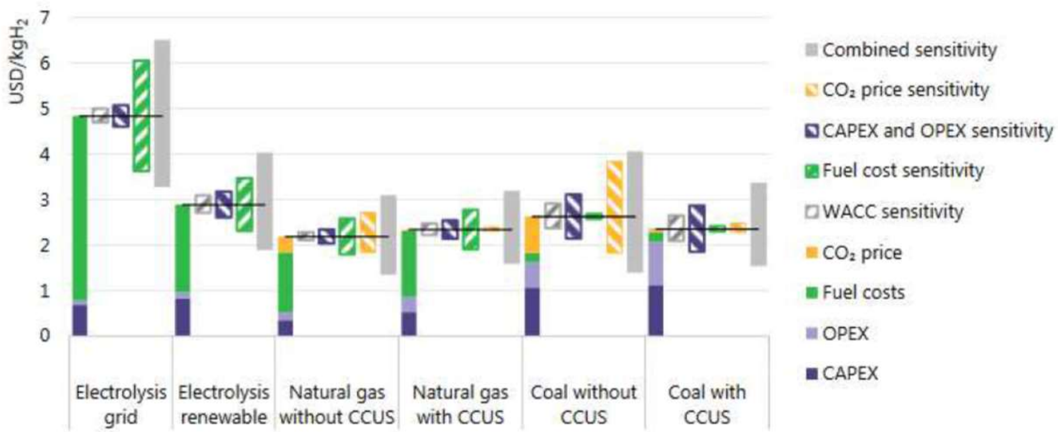
- In reality : a more mature industry will (and have to) leak less
  - Larger, more continuous electrolysis could leak as little as 0.5%
  - Logisitics needs to benchmark methane wich leaks < 1%

NTS

SSE

2 $/KG : « AFFORDABLE HYDROGEN »

- Considered the current baseline price
  - Centralized large SMR unit
  - Methane at 7 $/MBTU or 20 $/MWh
- Main argument for blue hydrogen : it is not much more expensive
  - 50/150 $/t of CO_2 treated
  - 0.5 to 1.5 $/kg price premium
- No logisitics in those calculations !
- When is electrolysis going to deliver at 3 or even 2 $/kg ?



Notes: WACC = weighted average cost of capital. Assumptions refer to Europe in 2030. Renewable electricity price = USD 40/MWh at 4 000 full load hours at best locations; sensitivity analysis based on +/-30% variation in CAPEX, OPEX and fuel costs; +/-3% change in default WACC of 8% and a variation in default CO_2 price of USD 40/tCO_2 to USD 0/tCO_2 and USD 100/tCO_2. More information on the underlying assumptions is available at www.iea.org/hydrogen2019.

Source: IEA 2019. All rights reserved.

STABLE METHANE PRICES, REALLY ?

Tradingeconomics.com 04/10/2022

« SOVEREIGN HYDROGEN »

- But there is a crisis right now !
  - But are you sure we are not running into the next one ?
- A matter of national sovereignty
  - States don’t like to be dependant for something as crucial as energy
  - At least in Europe : very severe clampdown on any technology which is natural gas dependant
- Electrolysis is much more reassuring on this point
  - Locally produced (possibly)
  - Stable price defined at commissioning (for offgrid systems)

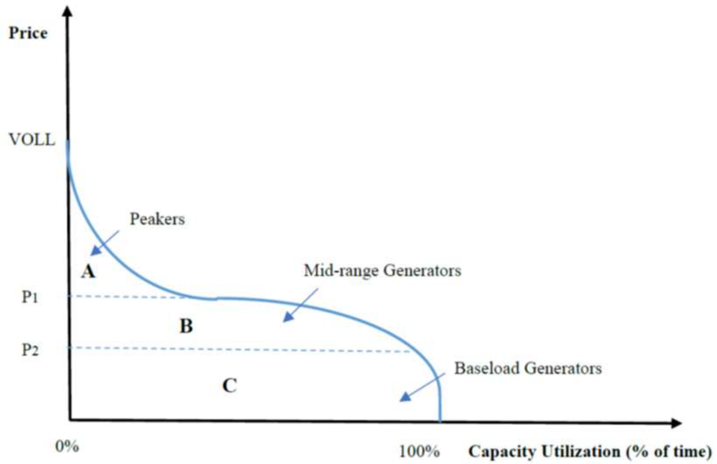
Wall Street Journal

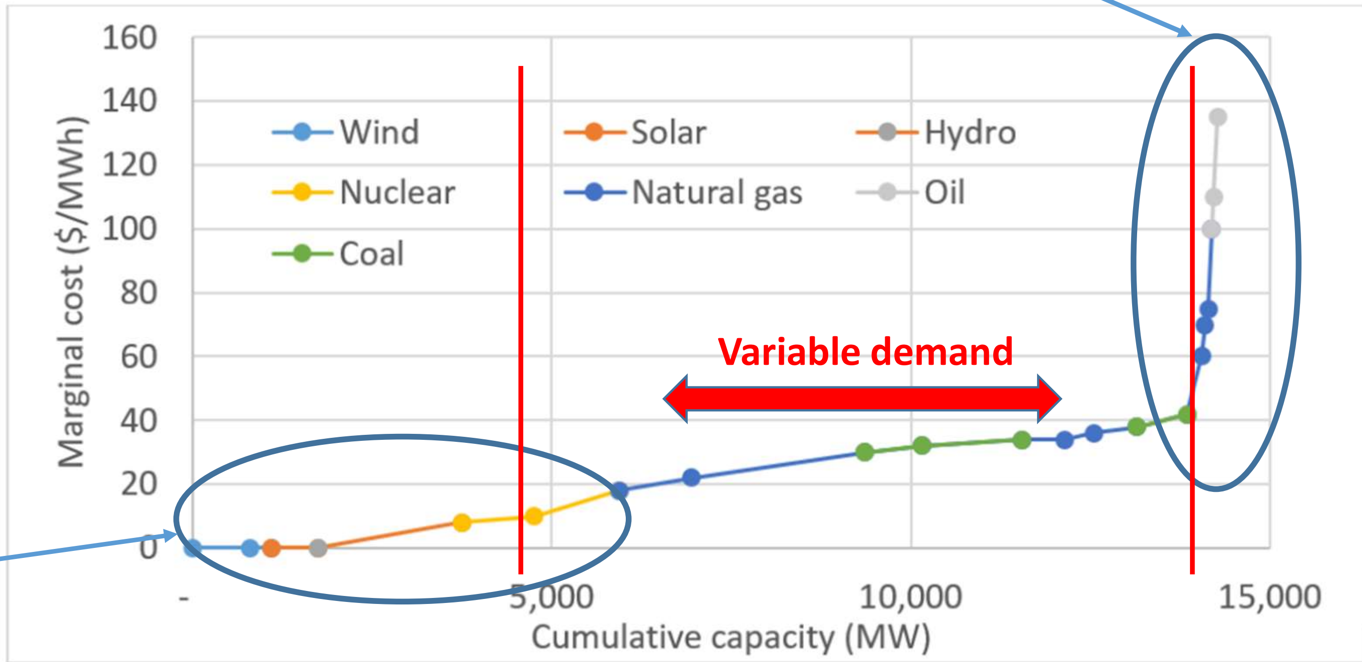
Euronews

CHEAP ELECTRICITY FOR HYDROGEN

- The plan : produce during peak production
  - You are solving the intermittence problem
  - And the electricity is cheap

Peak prices : key to the price you pay if you want a regular supply





Low marginal cost : the place you want to operate producing hydrogen

CURRENT PICTURE : KILLED BY BOTH ELECTRICITY PRICES AND CAPEX

- CAPEX are curently too high to allow for that…
  - It is actually cheaper to run full-time with expensive electricity !
- Baseline electricity prices are far from allowing a 2$/kg hydrogen
- And current cost struggle to go below 10 $/kg

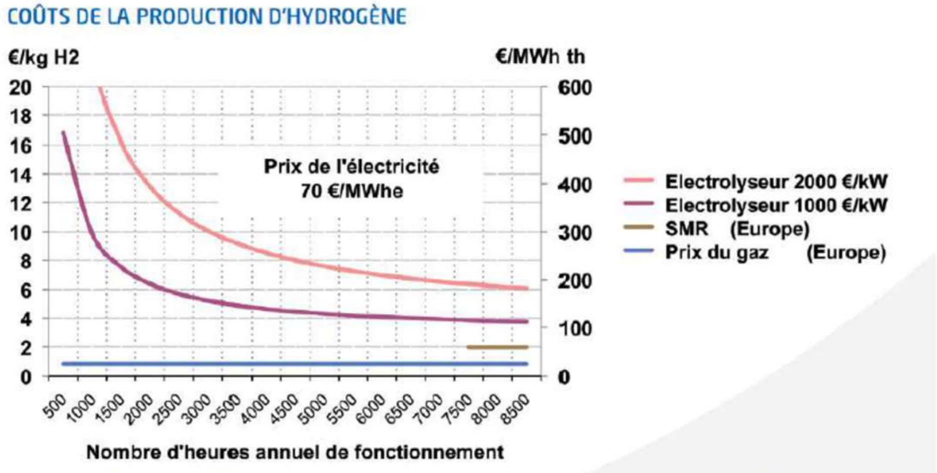


Figure 10 - Coût de l'hydrogène en fonction du mode de production
(Document France Stratégie - Août 2014)

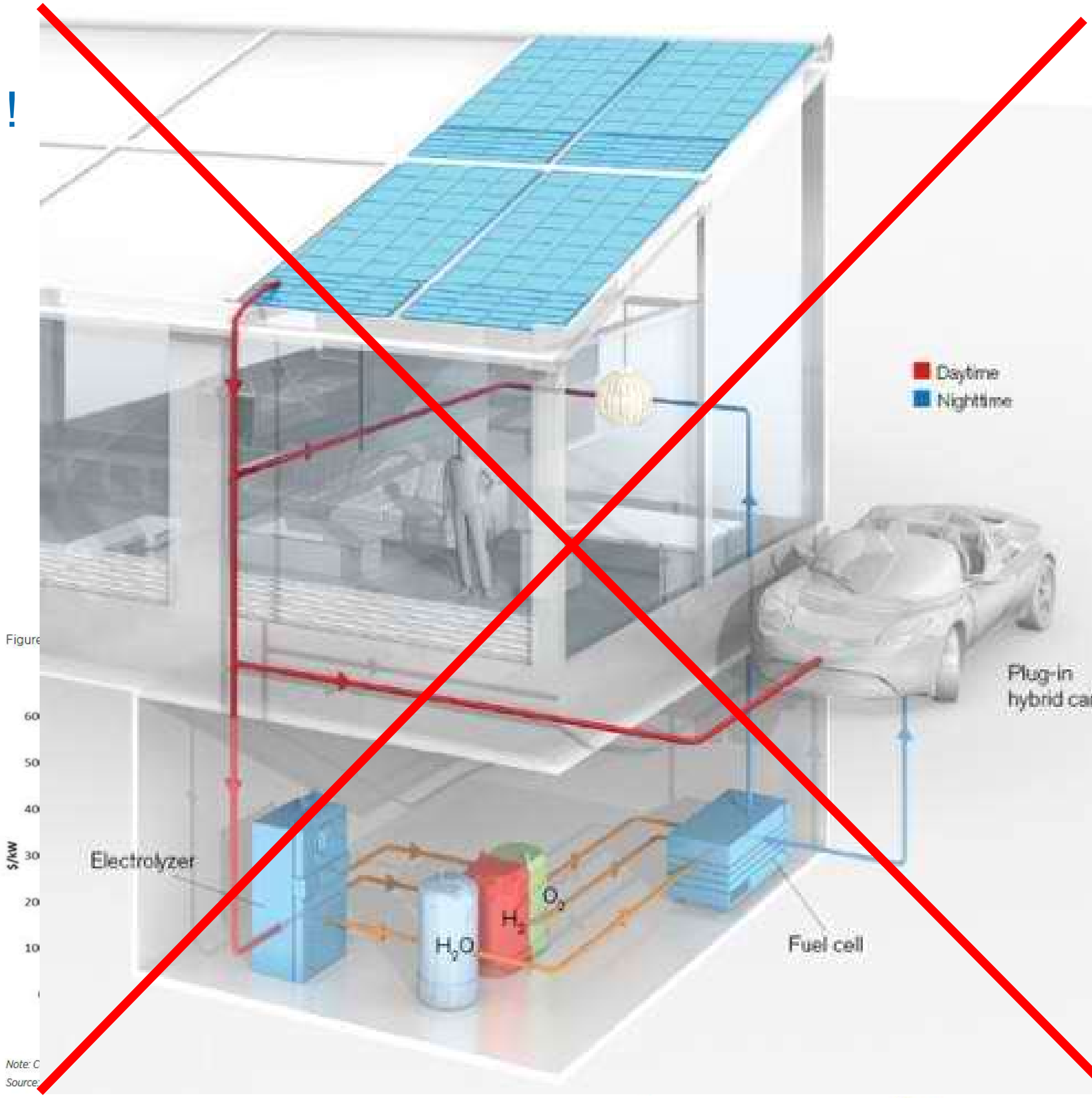
COÛTS DE PRODUCTION DE L'HYDROGÈNE PAR ÉLECTROLYSE SUIVANT DIVERS SCÉNARIOS

Scénario			1	2	3	4	5	6
Coût de l'électrolyseur		€/kW	2 000	2 500	800	800	800	800
Rendement électrolyse			60 %	50 %	80 %	80 %	80 %	80 %
Production annuelle		kWh	7 000	2 000	2 000	1 000	500	7 000
Coût de l'électricité stockée		€/MWh	70	70	70	140	0	60
Coût de l'H2 produit		€/kg	7,0	18,3	6,1	12,2	10,5	3,7
	soit	$/MBtu	68	177	59	118	102	36
	soit	€/MWh	178	463	154	309	267	94

Source : CGSP

WE NEED CHEAPER ELECTROLYZER !

- And they are coming !
  - Price could go as low as 200 $/kW
- But the main driver is economy of scale
  - Massive mega-farms
- Important conclusions regarding processes :
  - Intermittent production become relevant !
  - But you won't get it in your backyard



https://www.making-hydrogen.com

THE LONG TERM PICTURE ?

	2020				2050			
	Alkaline	PEM	AEM	SOEC	Alkaline	PEM	AEM	SOEC
Cell pressure [bar]	< 30	< 70	< 35	< 10	> 70	> 70	> 70	> 20
Efficiency (system) [kWh/kgH$_2$]	50-78	50-83	57-69	45-55	< 45	< 45	< 45	< 40
Lifetime [thousand hours]	60	50-80	> 5	< 20	100	100-120	100	80
Capital costs estimate for large stacks (stack-only, > 1 MW) [USD/kW$_{el}$]	270	400	-	> 2 000	< 100	< 100	< 100	< 200
Capital cost range estimate for the entire system, >10 MW [USD/kW$_{el}$]	500-1000	700-1400	-	-	< 200	< 200	< 200	< 300

Note: PEM = polymer electrolyte membrane (commercial technology); AEM = anion exchange membrane (lab-scale today); SOEC = solid oxide electrolysers (lab-scale today).

Based on IRENA analysis.

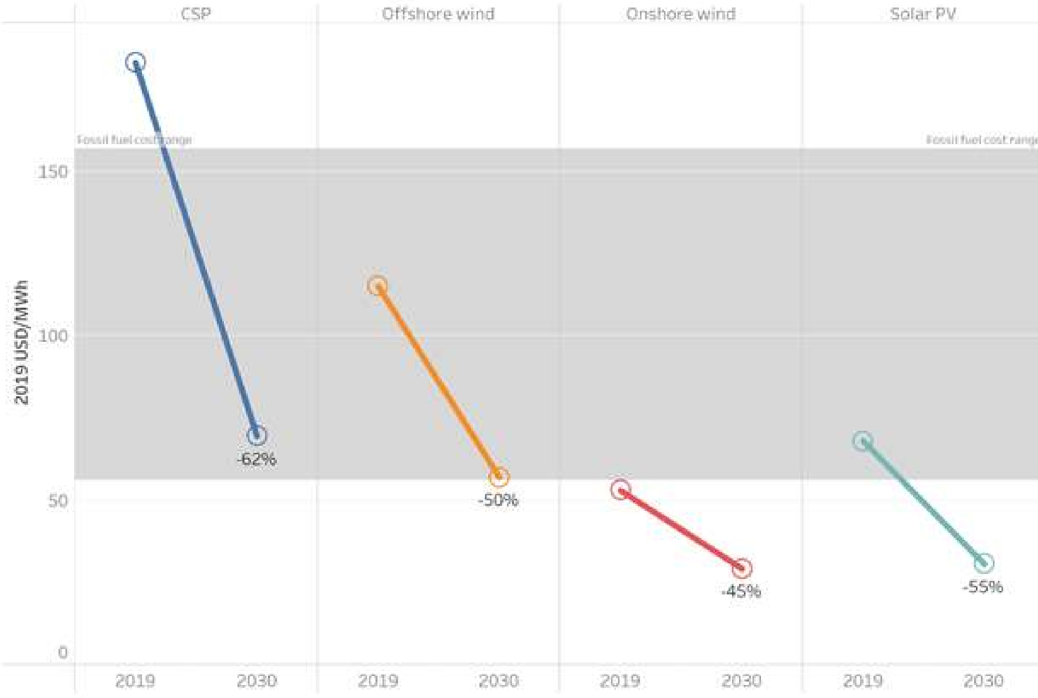
RENEWABLE ELECTRICITY PRICE

- Intermittent production : direct plug to a renewable source realistic

- Very exciting perspectives in terms of electricity price !
  - But strong debates on the realism of those estimates

Conditions for a 2$/kg H_2 :
- Electrolyzer at 200 $/kW, running 2000 hours a year (1/4 of the time) : 0.5 $/kg
- Electricity at 20 $/MWh : 1 $/kg

Logistic costs 0.5 $/kg ?



NUCLEAR-BASED ELECTRICITY FOR HYDROGEN ?

- How cheap/expensive is nuclear electricity ?
  - Countries with an existing, amortized park pay relatively low marginal prices : 40-50 $/MWh
  - Hinkley Point (UK) new reactor : 120 $/MWh
  - More controlled new generation : 60-70 $/MWh

Financial Times

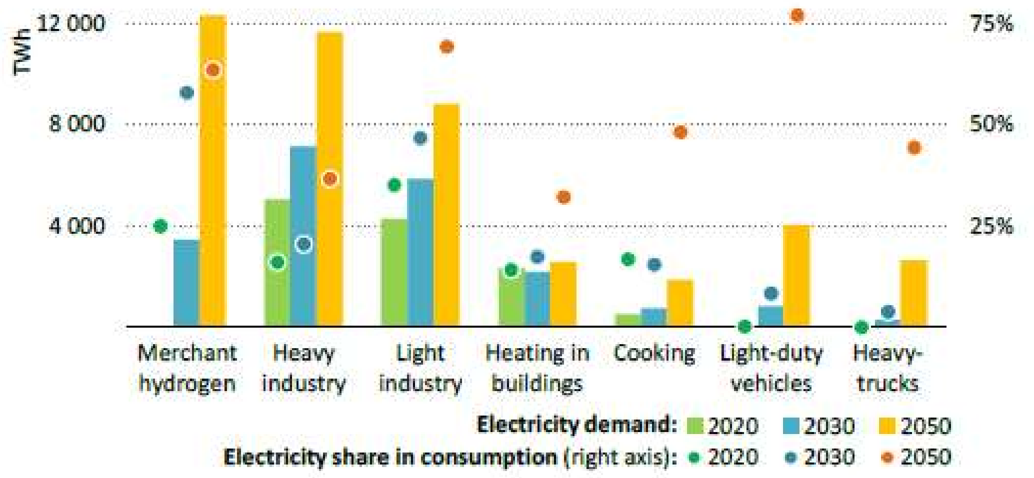
- Not cheap, but its a baseline, steady supply
  - Very nice for a grid which relies heavily on renewables

- Good for hydrogen today, not so much tomorrow
  - Countries with a large nuclear park are the only one today producing low-carbon hydrogen from the grid
  - Too expensive in the future to be of interest for gneralized H_2 production

EVERYBODY WANTS GREEN ELECTRICITY…

- Electricity needs are up, everywhere
  - Mobility is there, but only a small share
  - Massive industrial swift to electricity
- Hydrogen comes on top of that…
  - To become the first consumer in 2050 ?
- Cheap green electricity, really ?
  - Production costs are going down, sure…
  - But we are in for a massive offer crisis

Figure 2.16 ▷ Global electricity demand and share of electricity in energy consumption in selected applications in the NZE

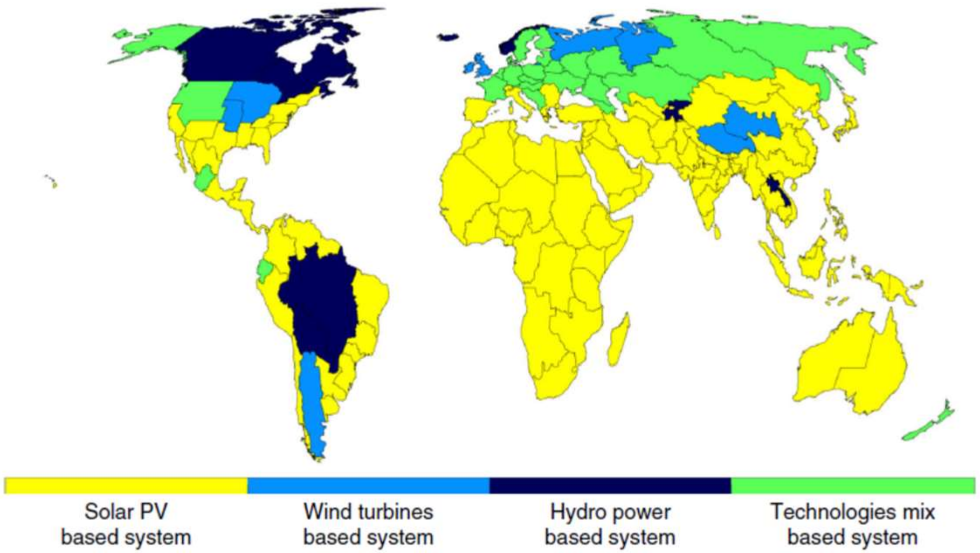


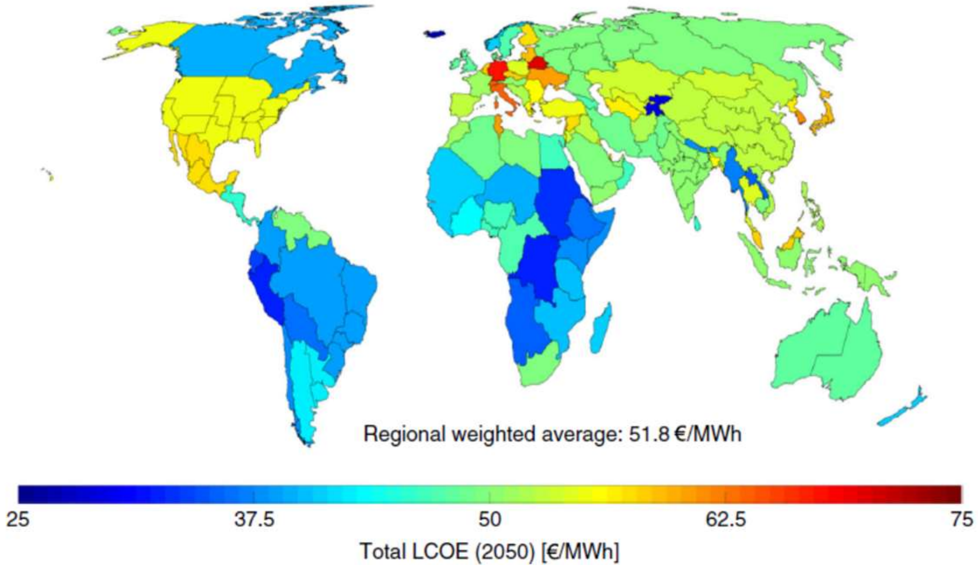
Global electricity demand more than doubles in the period to 2050, with the largest rises to produce hydrogen and in industry

Notes: Merchant hydrogen = hydrogen produced by one company to sell to others. Light-duty vehicles = passenger cars and vans. Heavy trucks = medium-freight trucks and heavy-freight trucks.

Source IEA 2021 – Net Zero by 2050

YOU WON'T FIND 20 $/MWH ELECTRICITY EVERYWHERE





Bogdanov et al. 2019 Nature Communications

- But that will be for next chapter…

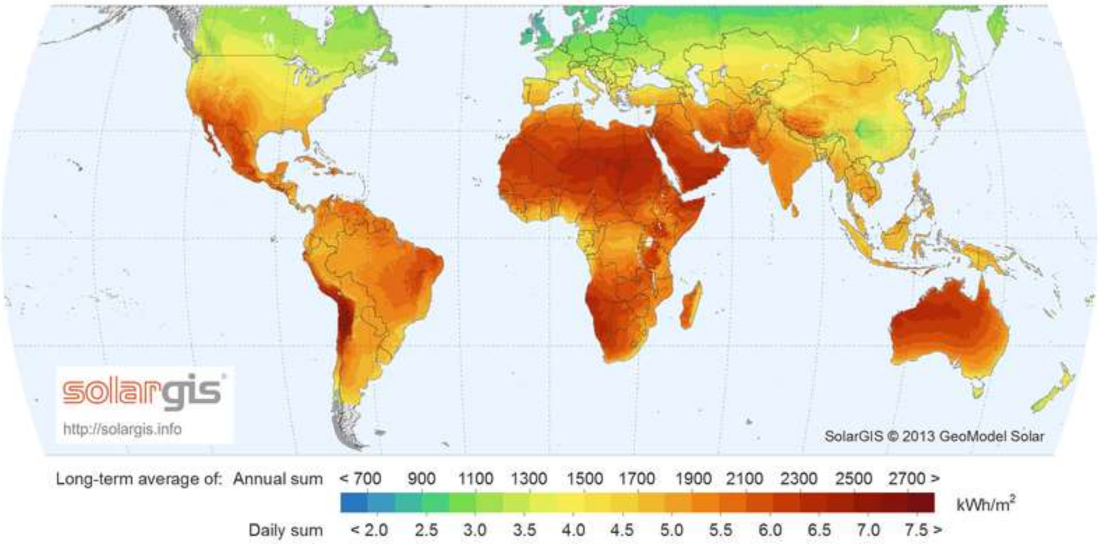
CASE STUDY

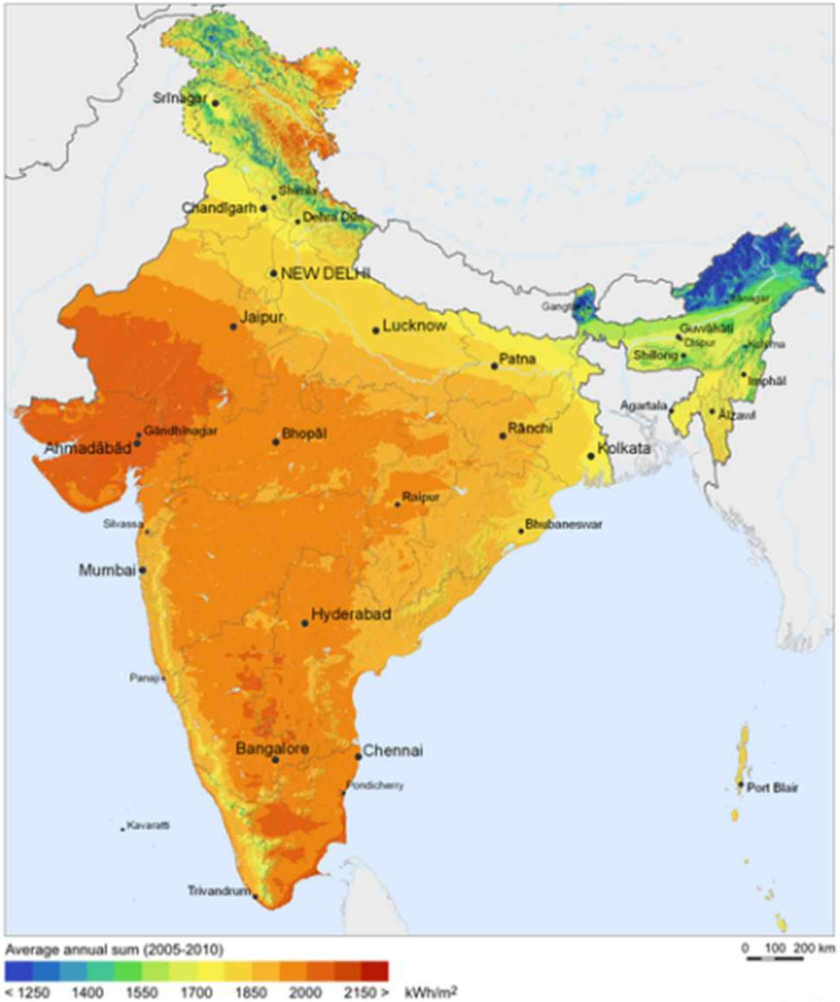
YOUR TIME TO WORK !

- India’s hydrogen strategy : offer
  - Identify the opportunities in India to produce low-carbon hydrogen
    - Type of production ?
    - Geography ?

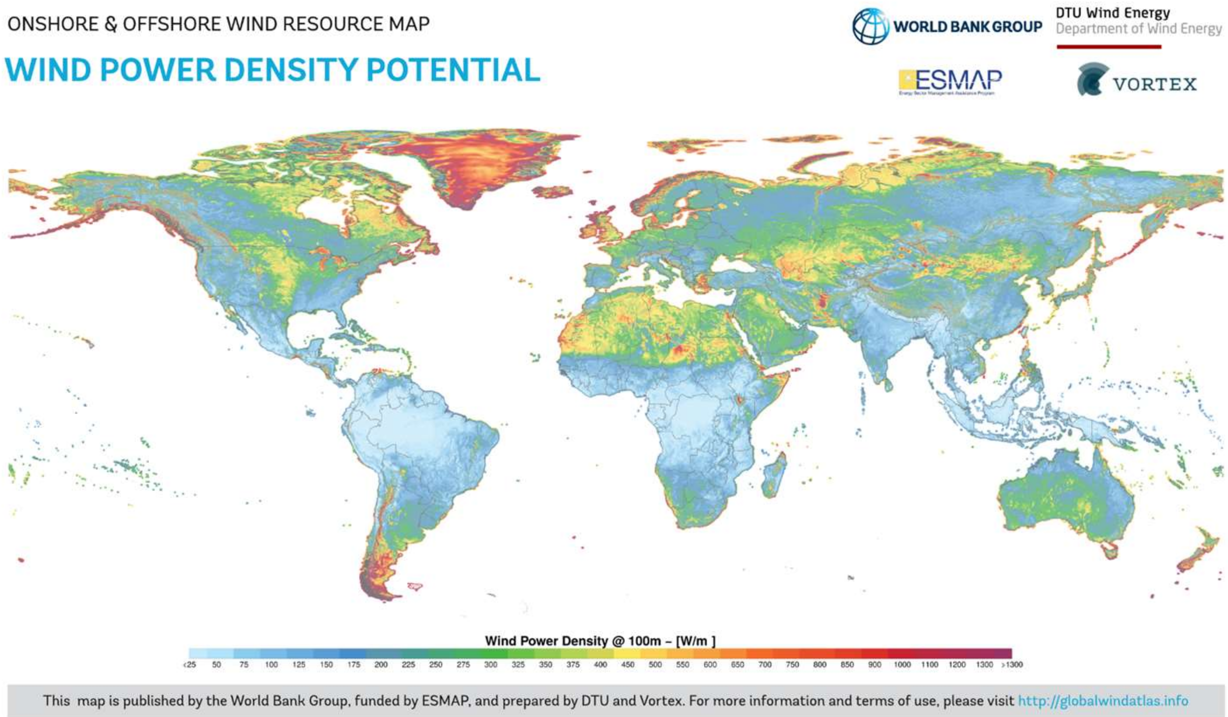
- I don’t have a correction !
  - You are the experts concerning India, not me…
  - But I have a few éléments and we can debate

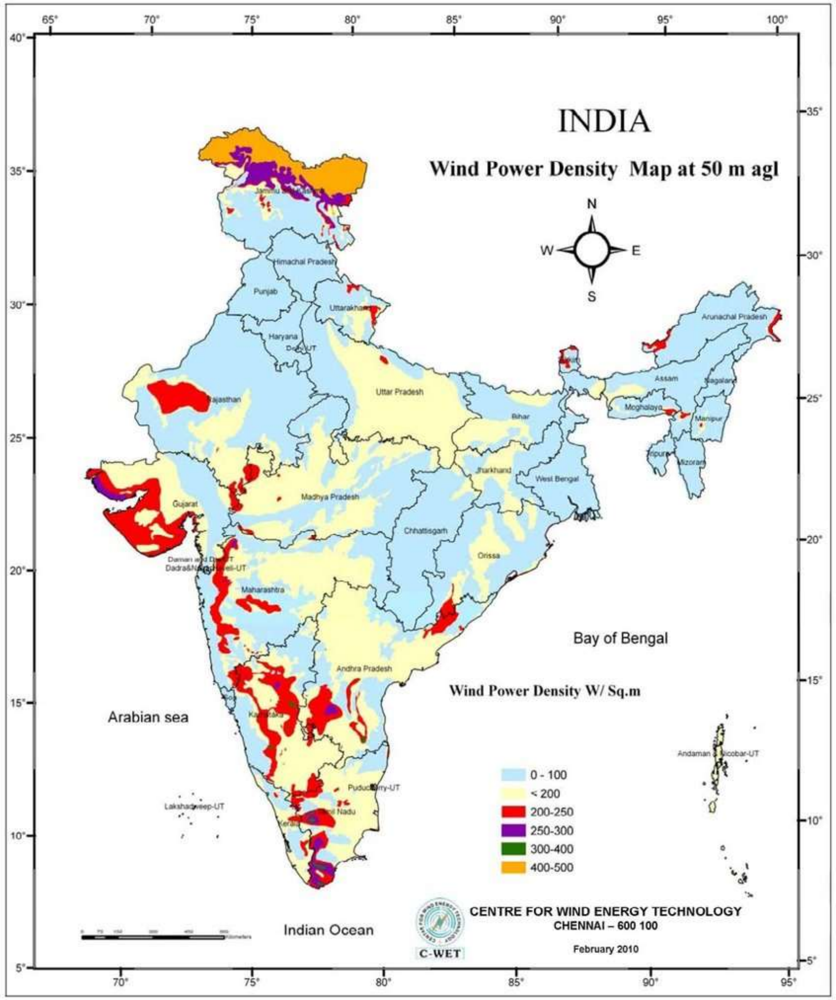
RENEWABLE POTENTIAL OF INDIA : SOLAR





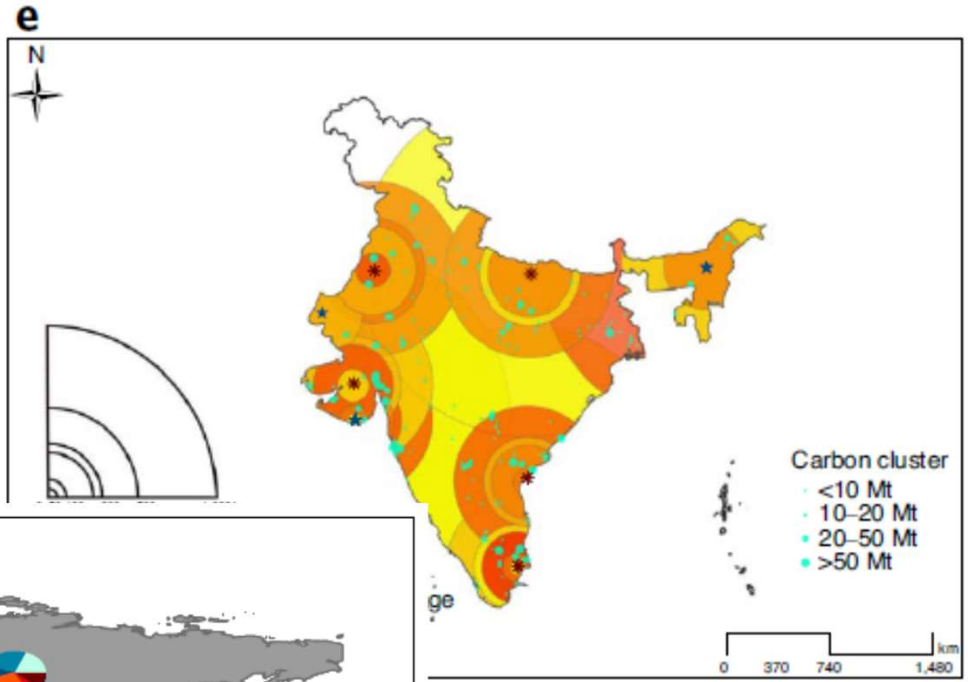
RENEWABLE POTENTIAL OF INDIA : WIND

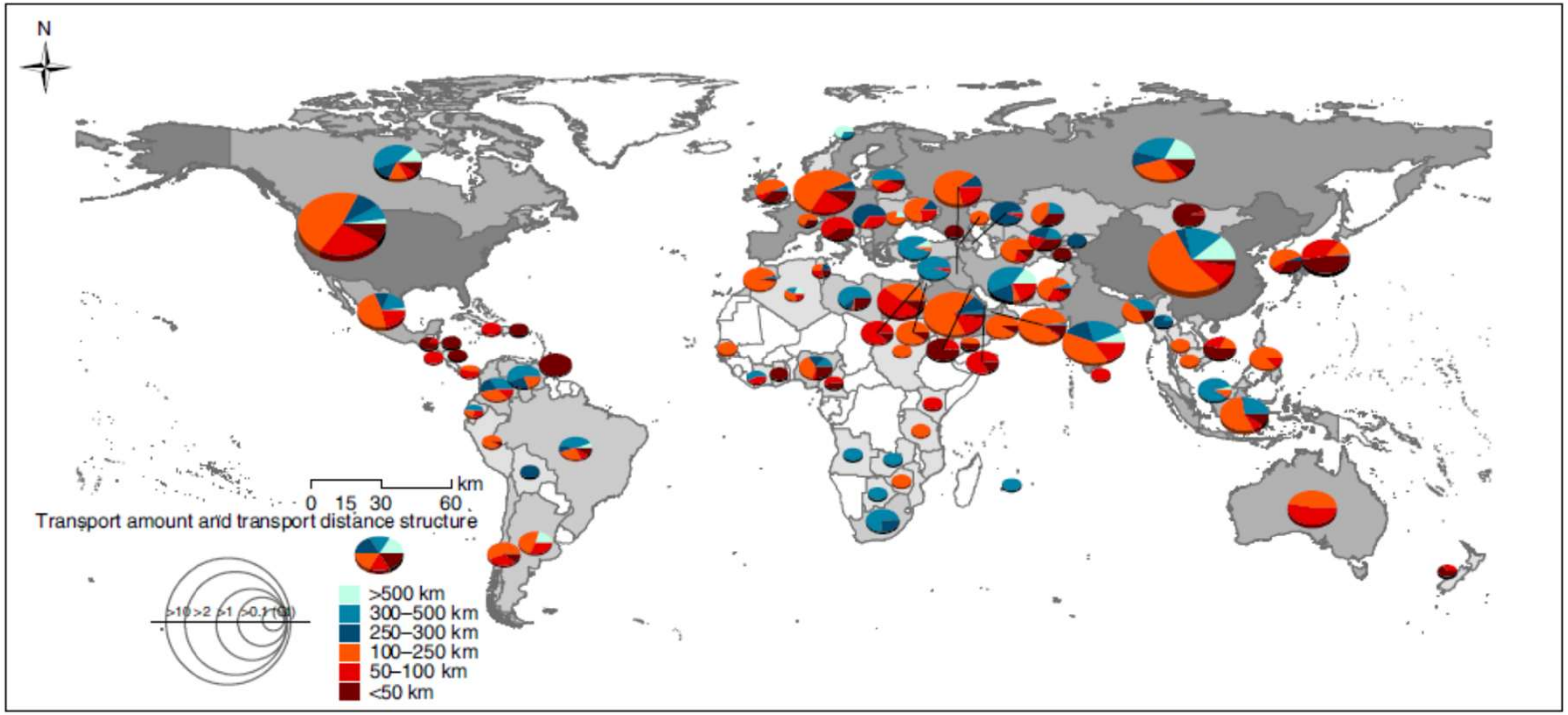




IFP Energies nouvelles

CCUS POTENTIAL OF INDIA

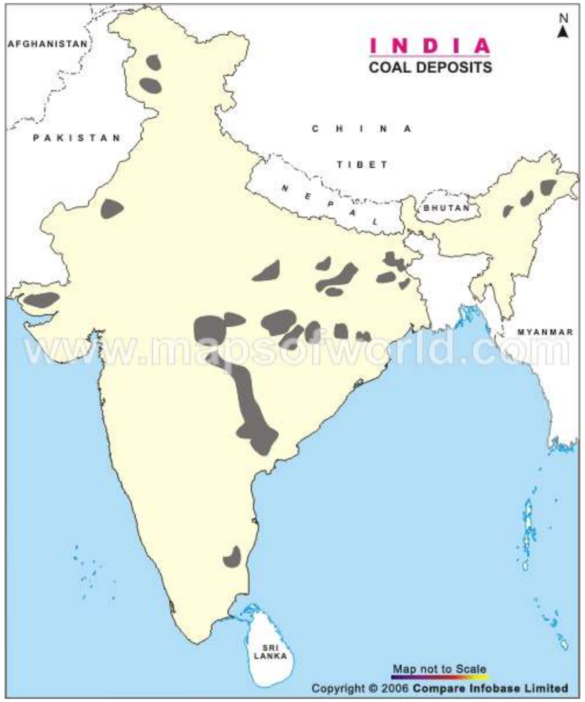




WRAP-UP

- India is a sun country (and a good one)
  - Solar likely dominant in the renewable mix
  - Solar thermal on the table due to local conditions
    - With SOFC electrolysis or thermochemical splitting ?
  - Doesn't mean hydro or wind can't be locally deployed

- India's CCUS potential is decent but…
  - India has no domestic methane production
  - No project started yet
  - Coal gasification ?



- India is a big country
  - We will talk about logistics in the next chapter…

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