POLITECNICO
MILANO 1863

SCUOLA DI INGEGNERIA
INDUSTRIALE E DELL'INFORMAZIONE

Ingegneria Chimica

Open Day 2022

http://www.ccs-chimica.polimi.it/

Transizione energetica, idrogeno e… Ingegneria Chimica

Enrico Tronconi

Laboratory of Catalysis and Catalytic Processes LCCP

POLITECNICO MILANO 1863

European Research Council
Established by the European Commission

LCCP PoliMI - People

- ***Permanent staff***
- Enrico Tronconi (full professor)
- Luca Lietti (full professor)
- Gianpiero Groppi (full professor)
- Alessandra Beretta (full professor)
- Isabella Nova (full professor)
- Matteo Maestri (full professor)
- Lidia Castoldi (associate professor)
- Carlo Giorgio Visconti (associate professor)
- Alessandro Donazzi (associate professor)
- Roberto Matarrese (associate professor)
- Mauro Bracconi (assistant professor)
- Matteo Ambrosetti (assistant professor)
- Alessandro Porta (assistant professor)

Meeting of the Italian Catalysis Society, Milano 2018

PhD Students
Nicole D. Nasello
Umberto Iacobone
Maria Elena Azzoni
Francesca Zaio
……

Post-Doc Researchers
Nicola Usberti
Chiara Negri
Lei Zheng
Giulia Ferri
……….

Temporary researchers
~50 undergrads-masters/year

Visiting scientists
5-10 people/year

Technicians
Enrica Ceresoli
Roberto Losi
Daniele Marangoni

Laboratory of Catalysis and Catalytic Processes LCCP

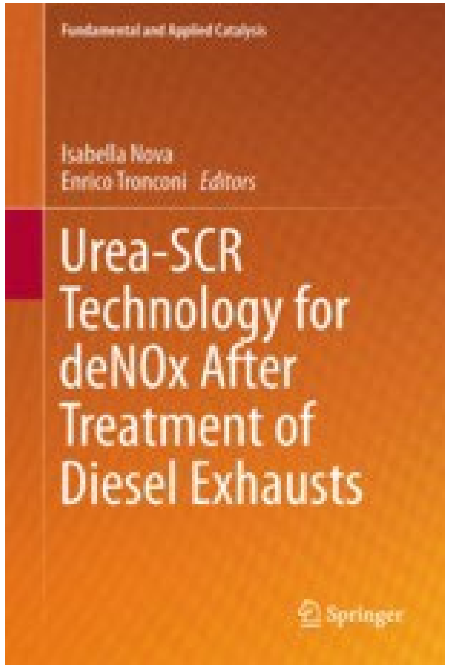
New LCCP laboratories @ Politecnico di Milano, Campus Bovisa (B18): April 2015

NH_3-SCR of NOx for automotive applications

Laboratory of Catalysis and Catalytic Processes LCCP

BLUETEC

- Since 2001 collaboration with Daimler AG: Transient 1D+1D model of monolithic SCR converters used to design Euro 4, 5 and 6 compliant Mercedes-Benz Diesel vehicles



SEVENTH FRAMEWORK PROGRAMME

CO_2RE CO2 reduction for transport

•EU FP7 project «CO_2RE» (2012-2015)

HDGAS

•EU H2020 project "HDGAS" (2015 – 2017)

Thomson

•EU H2020 project "THOMSON" (2016-2018)

DAIMLER

JM Johnson Matthey

mtu

Cummins

CORNING

浙江大學 ZHEJIANG UNIVERSITY

University of Virginia

JUST

LAT LABORATORY OF APPLIED THERMODYNAMICS

J. Heyrovský Institute of Physical Chemistry Academy of Sciences of the Czech Republic

Oak Ridge National Laboratory

KIT Karlsruher Institut für Technologie

NTNU

FPT POWERTRAIN TECHNOLOGIES

Clean synthetic fuels via Fischer-Tropsch Synthesis

- Catalytic process for the conversion of natural gas, coal or biomasses into high-quality diesel fuels and chemicals

$$CO + 2\,H_2 \longrightarrow \begin{cases} C_nH_{2n+2} \\ C_nH_{2n} + H_2O \\ C_nH_{2n+1}OH \end{cases}$$

- Main achievements in cooperation with Eni

Main achievements

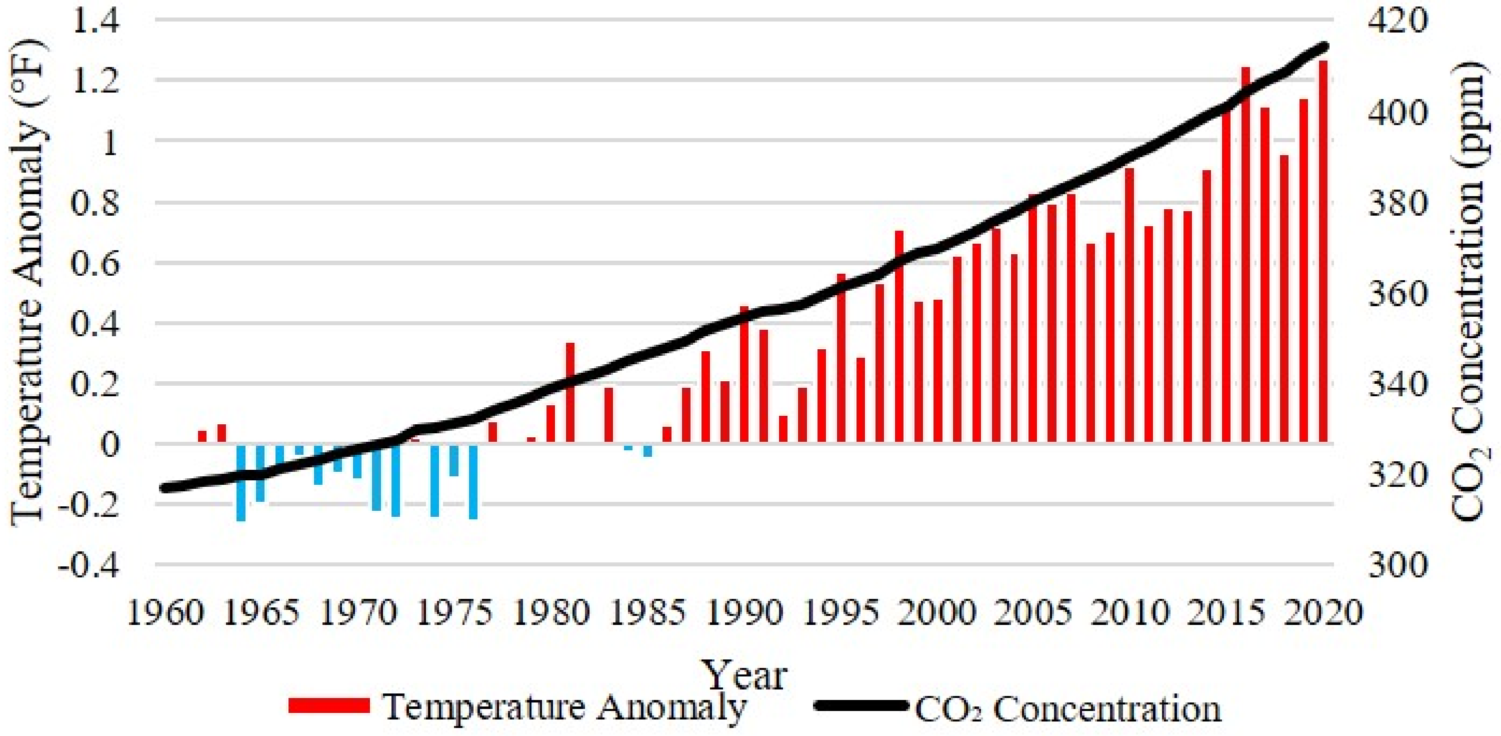
- Development of lumped and detailed kinetic models, now used for the simulation of a pilot-scale demonstrative reactor (Sannazzaro de' Burgundi Eni's refinery) and the design of industrial reactor units

- Development of an innovative compact reactor technology, based on structured catalysts (WO2010/130399 & WO2014/102350) successfully tested at the pilot scale (Eni labs in San Donato)

I gasometri della Bovisa a Milano:
il segno di una precedente transizione energetica

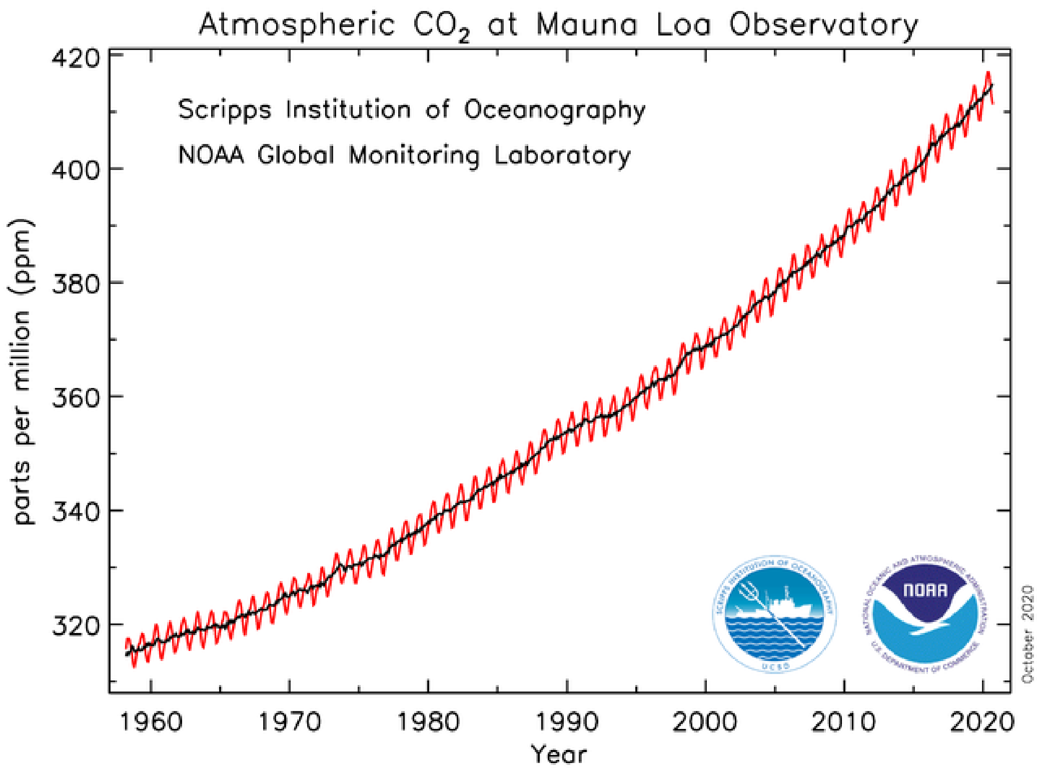
Perché una nuova transizione energetica?

Temperatura globale vs. concentrazione di CO_2 in atmosfera



https://storymaps.arcgis.com/stories/07b6215feddf4b499b3bd0e758dfc1c0

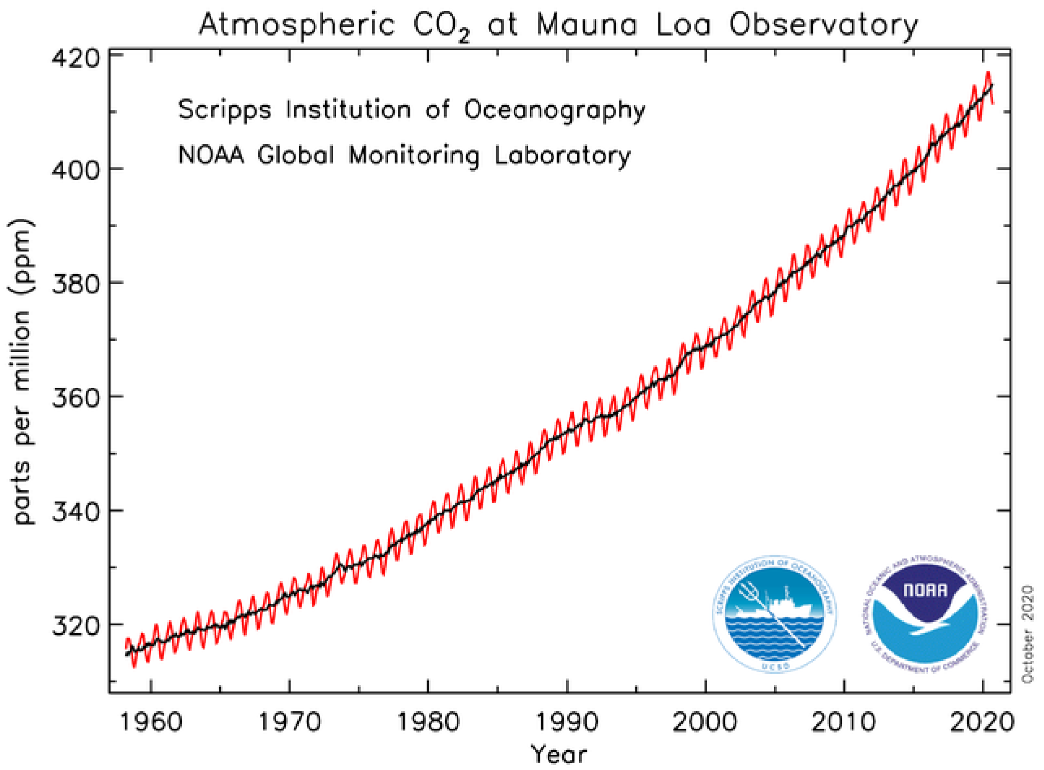
La nuova transizione energetica: decarbonizzazione



- Con gli Accordi di Parigi del 2015, gli Stati membri della Unione Europea si sono impegnati a **limitare il riscaldamento globale a + 2°C** rispetto ai livelli pre-industriali.

- Questo implica la riduzione delle emissioni di gas ad effetto serra di 80 - 95 % rispetto ai livelli 1990 **entro il 2050**.

La nuova transizione energetica: decarbonizzazione



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$CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O$ No!

- Per raggiungere tali obiettivi occorre rapidamente abbandonare i combustibili fossili a favore di **fonti energetiche rinnovabili: fotovoltaico, eolico, solare, idroelettrico, maree, biomassa ….**

La nuova transizione energetica: decarbonizzazione

1) Energia da fonti rinnovabili

IRENA
International Renewable Energy Agency

La nuova transizione energetica: decarbonizzazione

2) L'idrogeno sarà il vettore energetico chiave


IDROGENO, VETTORE DELLA DECARBONIZZAZIONE

Per raggiungere gli obiettivi di decarbonizzazione degli accordi di Parigi, occorre compiere una vera e propria transizione energetica. Questa richiederà il rapido sviluppo di fonti di energia rinnovabile e un altrettanto rapido abbandono dei combustibili fossili. Purtroppo, però, attuarla non sarà così semplice: si stima, infatti, che al 2050 più della metà dei consumi proverrà da settori non ancora elettrificati. Ma non tutto è perduto. Ci potrebbe essere una molecola ancora in grado di aiutarci a migliorare le prospettive future tracciate: l'idrogeno (H2). L'elemento più abbondante di tutto l'Universo è, infatti, un ottimo vettore energetico e, con la ricerca, ci potrebbe portare ad imitare il Sole [...]

Continua a leggere su eni.com

Dal Corriere della Sera - Domenica 19 settembre 2021

- L'**idrogeno** (H_2) è un **vettore energetico** su cui si ripone grande fiducia a livello globale per far fronte alle sfide climatiche, poiché può immagazzinare e fornire grandi quantità di energia **senza generare emissioni di CO_2** durante la combustione:

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$$

"the other leg of the energy transition"

La nuova transizione energetica: decarbonizzazione

2) L'idrogeno sarà il vettore energetico chiave

Dal Corriere della Sera - Domenica 19 settembre 2021

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$$

- L'**idrogeno** (H_2) è l'elemento più semplice e più abbondante del Pianeta, ma è **raramente disponibile allo stato libero e molecolare** (H_2), perché presente in combinazione con altri elementi chimici (come per esempio in acqua - H_20, metano – CH_4…)

- Non è una fonte energetica primaria: <u>**va prodotto (!)**</u>

Perché l'Idrogeno per la transizione energetica?

- La sua combustione **libera solo H_2O**, no CO_2
- **Alto contenuto energetico** a parità di peso (3x benzina)
- Utilizzabile per **decarbonizzare settori industriali non elettrificabili:** acciaio, cemento, petrolchimico, trasporti pesanti …
- Utilizzabile per alimentare **veicoli a Fuel Cell** (auto, treni, camion, aerei…) (no batterie, no emissioni)
- ……………….

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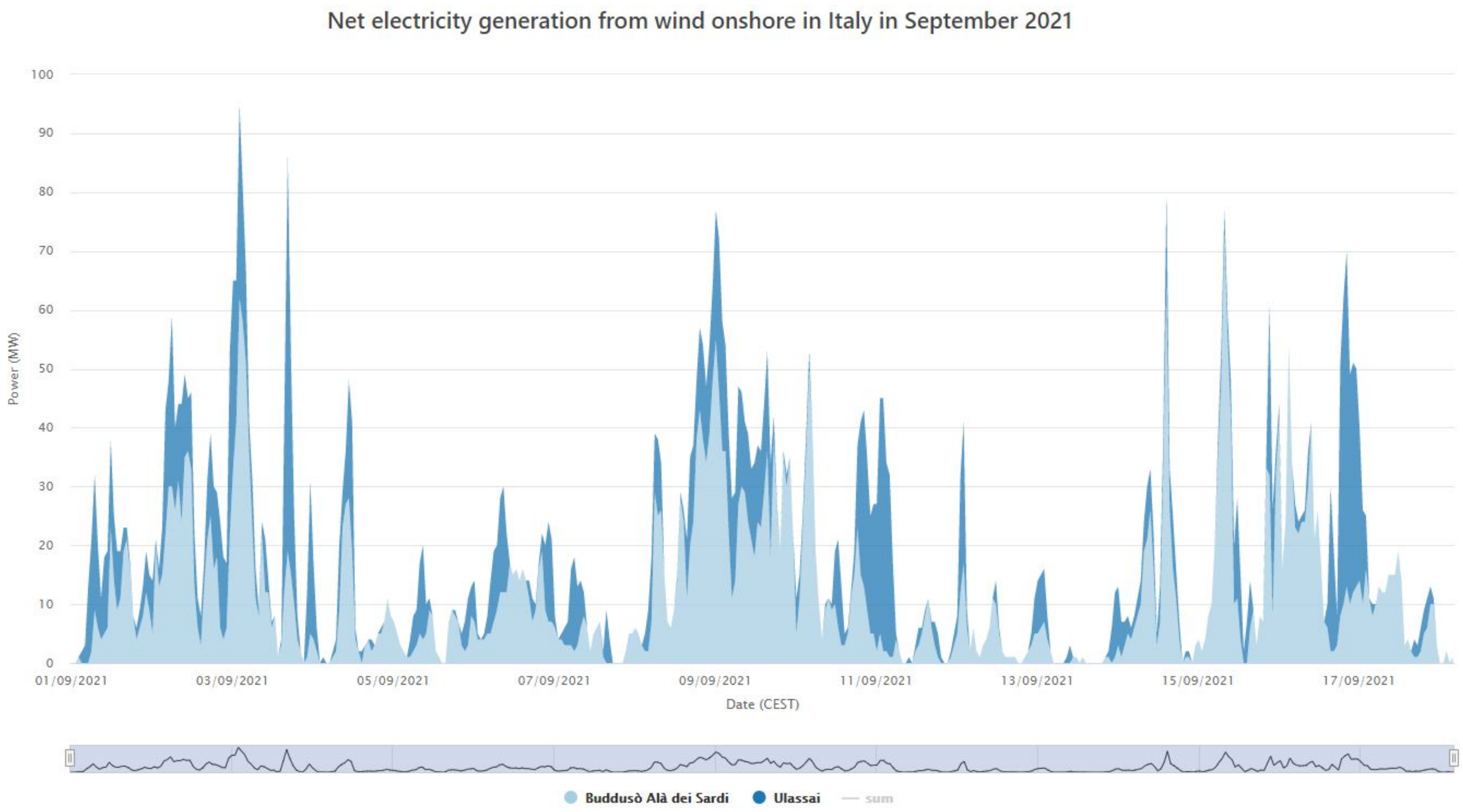
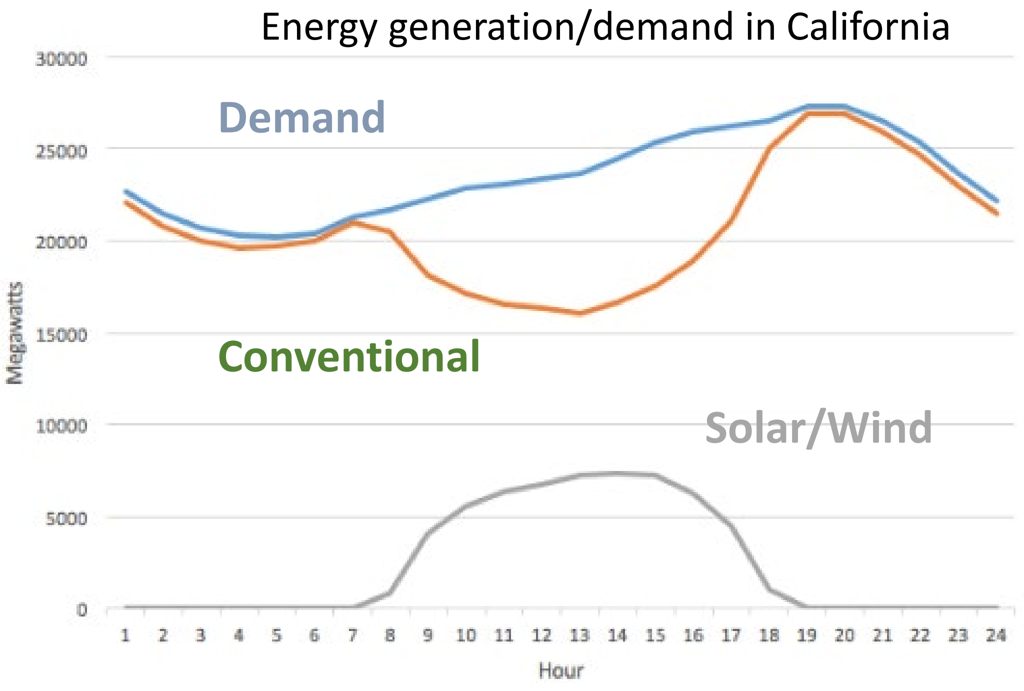
- Utilizzabile per alimentare **veicoli a Fuel Cell** (auto, treni, camion, aerei…) (no batterie, no emissioni)
- Utilizzabile per stoccaggio chimico di **energia elettrica in eccesso** prodotta da fonti rinnovabili

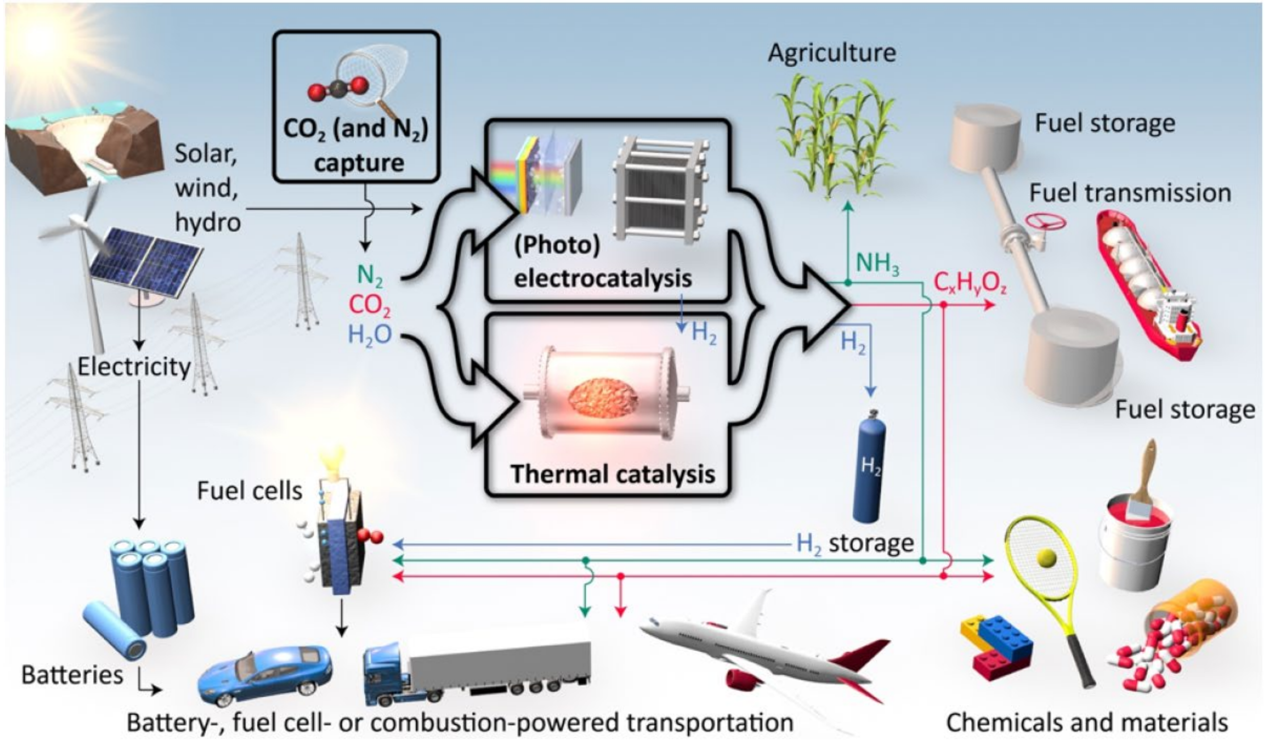
Fluctuating nature of Renewable Energy



https://energy-charts.info/charts/power/chart.htm?l=en&c=IT&stacking=stacked_absolute_area&interval=month

Excess Renewable Energy: an opportunity to decarbonize the C&PI





Energy X Group, 2020
Research needs towards sustainable production of fuels and chemicals

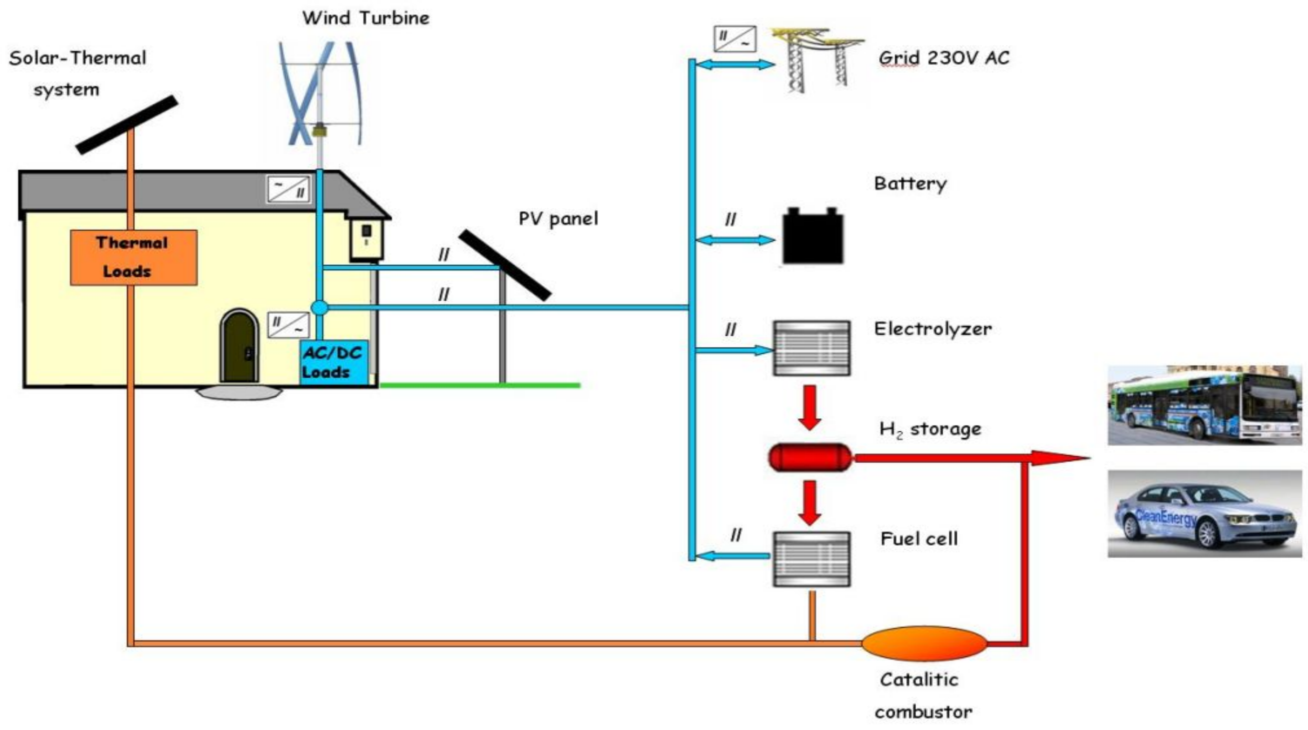
Significant excess of energy production from RES → It can be exploited in the chemical industry

Power to X

H_2 for distributed Heat & Power

H_2 can be used in several «Combined Heat & Power (CHP)» applications with a very low local impact:

- distributed electric energy production
- heat generation
- refuelling stations for vehicles (trains, trucks, cars…)



H_2 for Fuel Cell vehicles

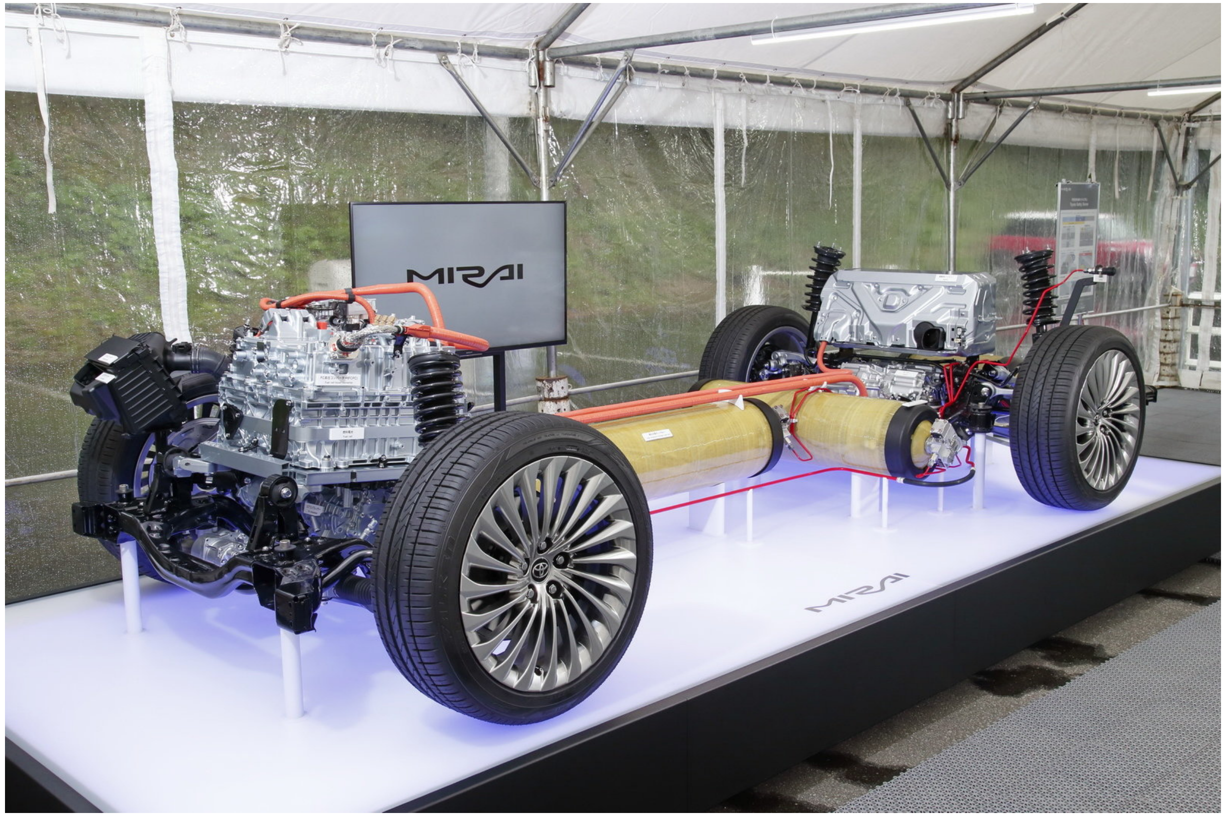
Toyota Mirai

Fuel cells (PEM) + battery + electric motor

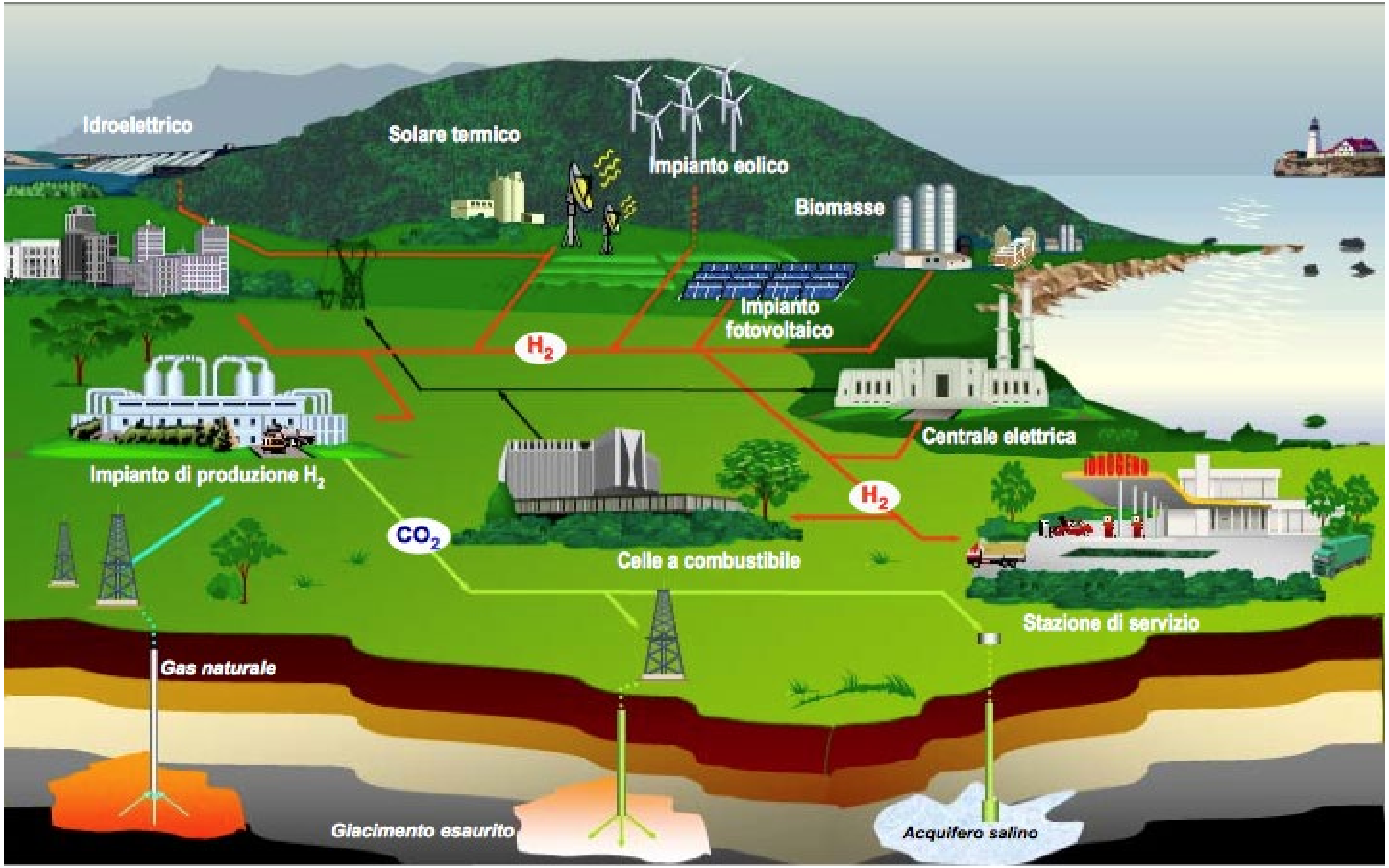
Range = 650 km, power = 128 kW, torque = 300 Nm

Tanks = 5.6 kg H_2 compressed to 700 bar

Refuelling time = 5 minutes



The H_2 dream



Idroelettrico
Solare termico
Impianto eolico
Biomasse
Impianto fotovoltaico
H2
Centrale elettrica
Impianto di produzione H2
CO2
Celle a combustibile
H2
Stazione di servizio
Gas naturale
Giacimento esaurito
Acquifero salino

Hydrogen for the Energy Transition: its Many Faces

- What is hydrogen? Relevant properties
- **Role of hydrogen in the energy transition: focus on EU**
- Hydrogen Production/Transport/Storage Technologies
- **Blue/Green hydrogen production**
- Hydrogen Storage and Delivery, Safety
- **Selected Research Projects**

EU vision: H_2 is a key priority to achieve the "EU Green Deal"

- With the recent **Fit-for-55** update of the EU Green Deal targets, with **at least -55% emission reduction in 2030** (wrt 1990), National and European policy-makers have begun to develop decarbonization frameworks.
- **Hydrogen is part of the European strategy** towards carbon-neutrality. It will be used to decarbonize industrial processes and economic sectors where carbon emissions are hard-to-abate.

2020 – 2024:
- *Decarbonize existing hydrogen production*
- *Support 6 GW H_2 by electrolysis.*

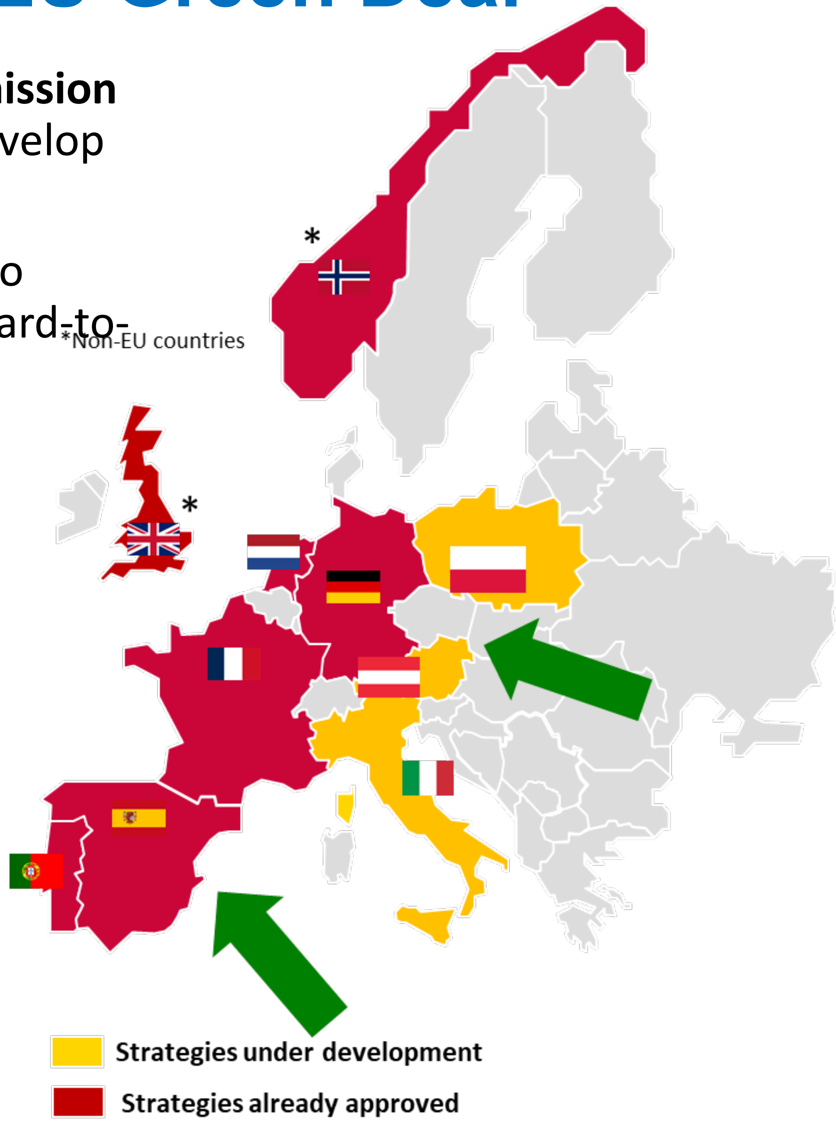
2025 – 2030:
- *Hydrogen integrated in the EU energy system.*
- *New applications in steel and transport*
- *Target 40 GW H_2 by electrolysis, and 10 Mt/y Green H_2.*

2030 - 2050:
- *Large scale Green H_2 deployment in all hard-to-abate sectors*
- *500 GW electrolyzers.*

Strategy envisaged by 2050:
- *Investment of **3–18 B€** for low-carbon fossil-derived hydrogen*
- ***180–470 B€** for Green H_2*

- *Emissions standard/threshold for low carbon hydrogen relative to the existing ETS benchmarks*
- *Quotas of renewable H2 in end-use sectors*
- *Carbon Contract for difference (CCfD)*

- *Cooperation with Eastern and Southern Neighborhoods' countries for additional 40 GW by 2030.*
- ***European Clean Hydrogen Alliance** to identify and build up viable investment projects by bringing together public and private stakeholders*



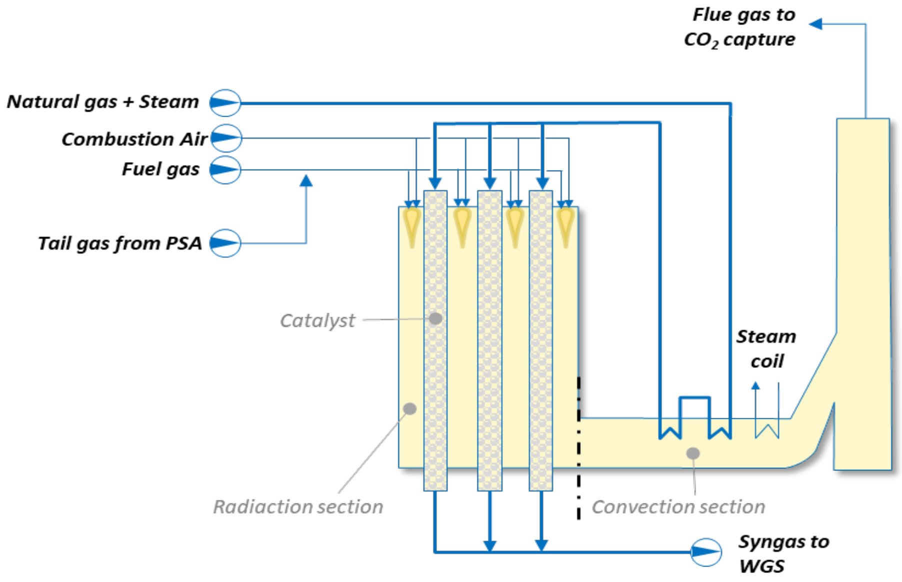
Hydrogen Europe, Hydrogen Act_Towards the creation of the European Hydrogen Economy, www.hydrogeneurope.eu

Hydrogen production via Natural Gas reforming

50 MMscfd Steam Methane Reformer Hydrogen Plant at Lagoven, Amuay in Venezuela

Hydrogen Production via Natural Gas reforming

- **MSR** is widely used to produce **high-purity H_2** in Refineries.
- **Feedstocks** range from Natural gas, off-gas from refining processes and LPG to liquid fuels (i.e. Naphtha, Kerosene).
- **Fire tubular reformer** is based on a Radiation section with specific catalytic tube and burner arrangement, and a Convective section for heat recovery. CH_4 steam reforming reaction is endothermic (ΔH°= -206 kJ/mol), catalysed by Ni supported catalyst at high Temp. (730 - 850 °C) and low pressure (25 - 30 bar).
- A typical feedstock-flexible hydrogen plant includes a pre-reformer unit, a downstream WGS unit and a PSA package for pure H2 production.



It is nowadays the most common and most economically convenient process to produce hydrogen: > 50% of global H_2 production.

Highly endothermic process: additional fuel combustion, CO_2 emissions.

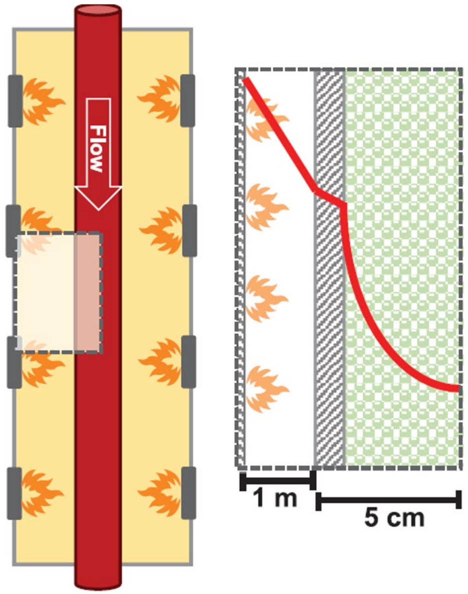
$$CH_4 + H_2O = CO + 3H_2$$
$$(\Delta H_r^0 = +206\ kJ/mol)$$

$$CO + H_2O = CO_2 + H_2$$
$$(\Delta H_r^0 = -41\ kJ/mol)$$

- ☐ Half of CO_2 emissions from fuel combustion;
- ☐ Industrial MSR: 3% global CO_2 emission;
- ☐ Decarbonization required for green H_2 production.

☐ Heat transfer issue

Industrial MSR process



Multi-tubular reactors:
10-14 m long, more than 100 tubes;
Ni-based catalysts.

Green Hydrogen - H_2O electrolysis

Alcaline

$$2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$$

$$2H_2O \rightarrow H_2 + 2OH^- + 2e^-$$

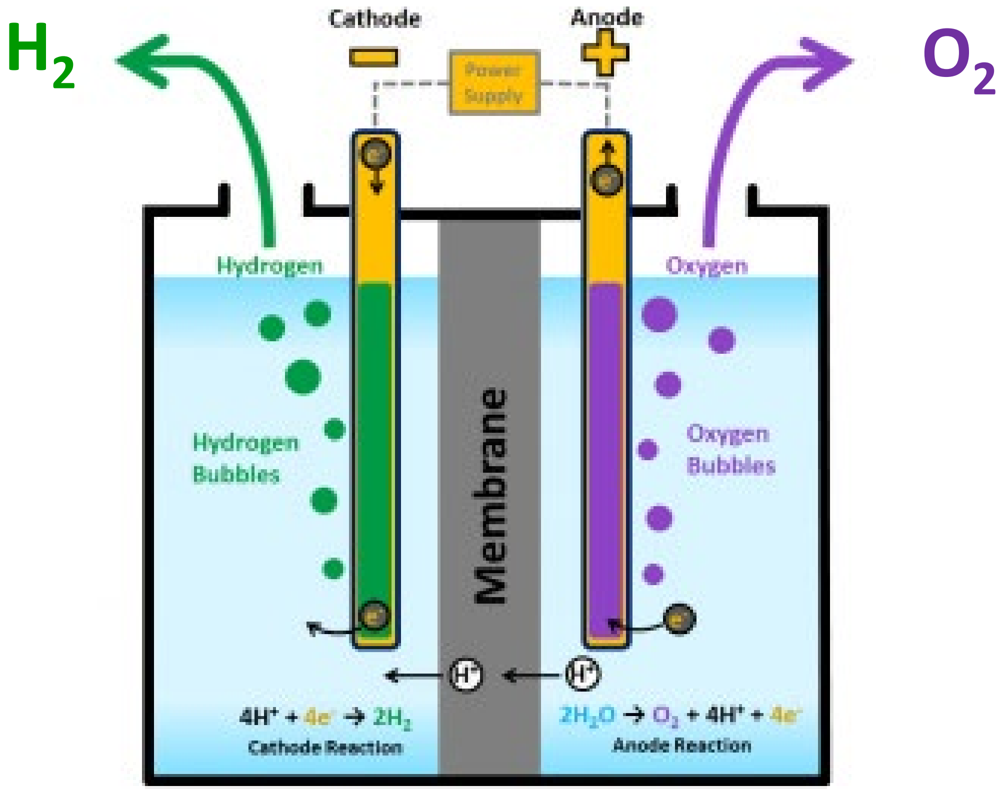
PEM

$$H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^-$$

$$2H^+ + 2e^- \rightarrow H_2 +$$

TD Energy demand : 241 kJ/mol H_2

	kWh/Nm^3 H_2	Efficiency
Alkaline	**4.5**	**63 – 70%**
PEM	**3.5**	**60 – 66%**



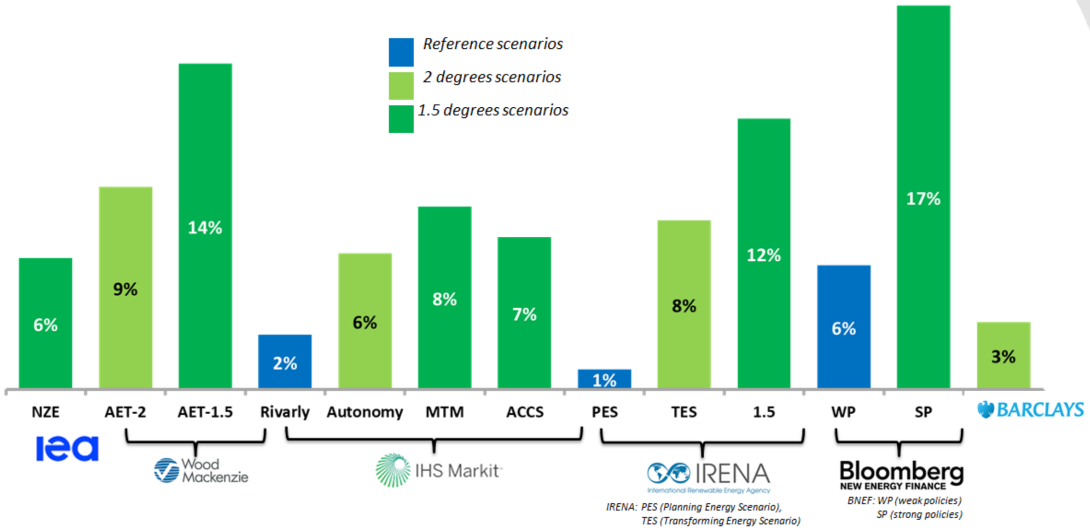
Hydrogen «colours»

- Hydrogen is a colourless gas, nevertheless in the present days the energy industry has assigned a different «colour code» to differentiate the types of hydrogen production

		Hydrogen Colours code	Technology	Feedstock	GHG footprint
Low Carbon Hydrogen	Production via Electricity	*Green H_2*	Electrolysis	Wind, Solar, Hydro, Geothermal, Tidal	Minimal
		Purple/Pink H_2		Nuclear	
		Yellow H_2		Mixed origin grid energy	Low/Medium/High
	Production via Fossil Fuels	*Blue H_2*	Gas reforming + CCUS Gasification + CCUS	Natural gas, Virgin Naphtha, Coal	Low
		Turquoise H_2	Pyrolysis	Natural gas/Virgin Naphtha	Solid Carbon by-product
High Carbon Hydrogen		*Grey H_2*	Gas reforming		Medium/High
		Brown H_2	Gasification	Brown coal (lignite)	
		Black H_2		Black coal	

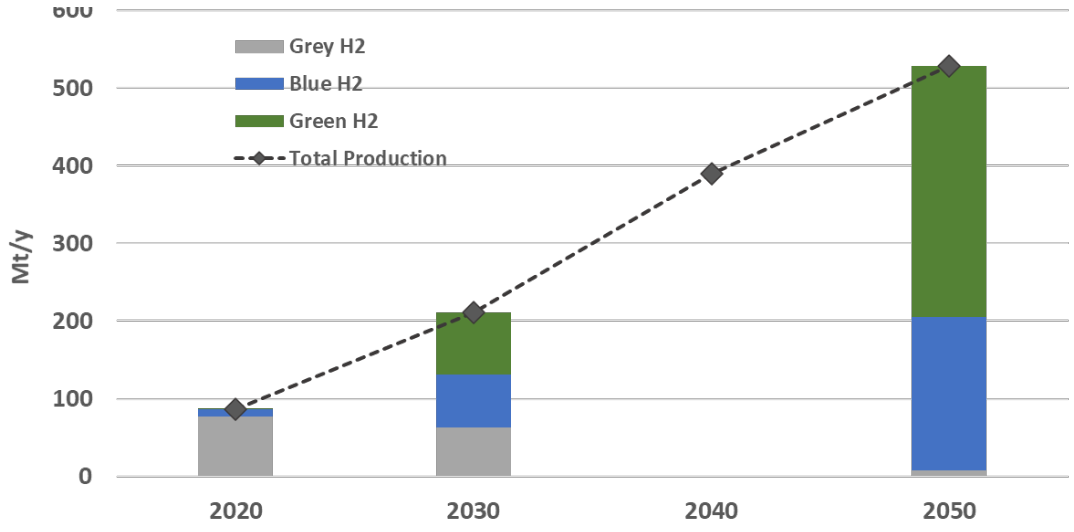
Global hydrogen use expansion forecasts

- *In the last year the analysts produced **dozens scenarios** of "low carbon hydrogen" expansion. The share of hydrogen in the future energy consumption (2050) is different **global warming degree limit** is:*
  - *in between 1% and 6% in **reference scenarios**,*
  - *6%-9% in **2°C scenarios**,*
  - *6%-17% in **1.5°C scenarios***



- According to **IEA Net Zero Emission scenario** the **global hydrogen use**:

- Will expand from less than 80 Mt in 2020 to more than 200 Mt in 2030;
- **The proportion of Green and Blue hydrogen rises from 10% in 2020, 70% in 2030, to about 98% in 2050.**
- Around half of low-carbon hydrogen produced globally in 2030 comes from electrolysis and the remainder from coal and natural gas with CCS,
- In 2050 the share of Green hydrogen from water electrolysis will account for 60% of total production.

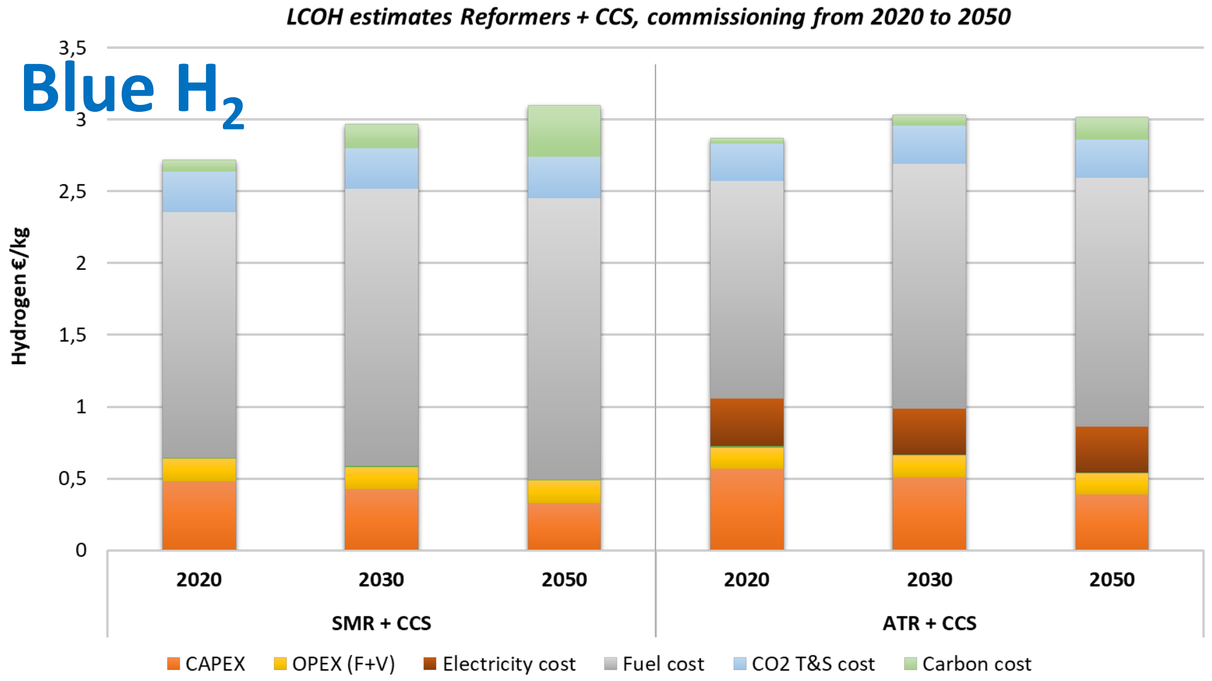


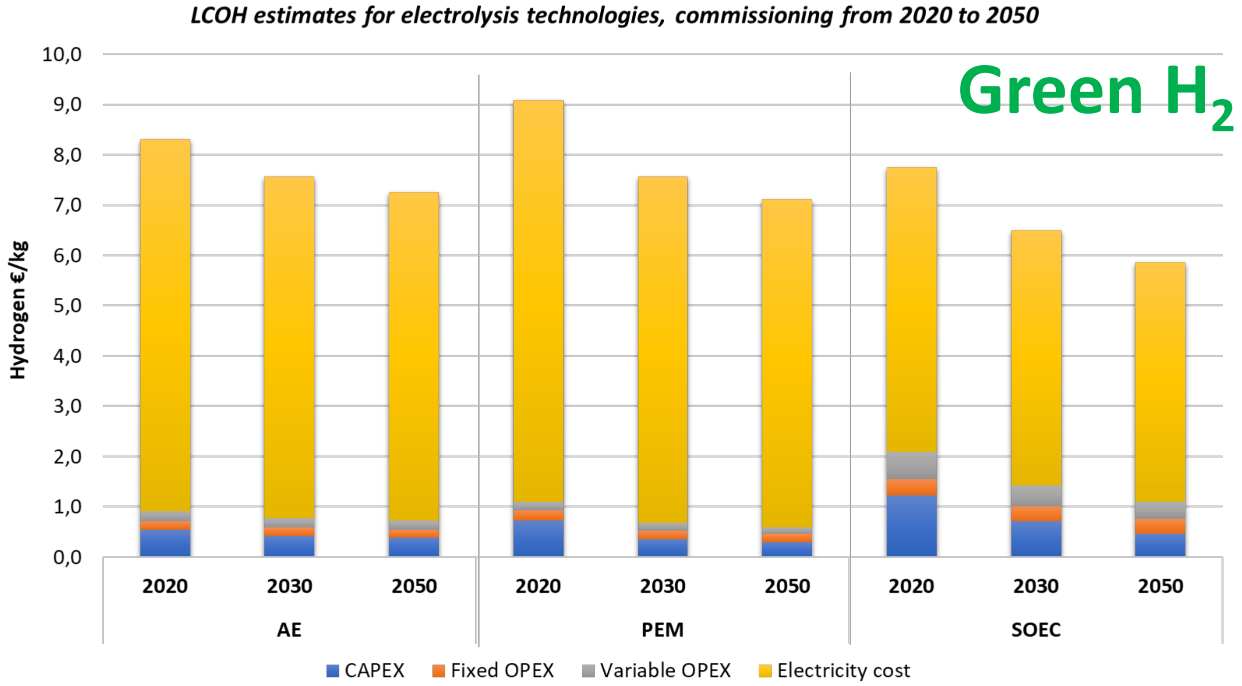
Based on data from International Energy Agency (2021) *Net Zero by 2050*: Net Zero by 2050 Scenario - Data product - IEA; as modified by Eni

Levelised Cost of Hydrogen Production

- LCOHs of SMR and ATR, with CCS, are fairly constant over time based on two effects:
  - CAPEX decrease due to a learning-by-doing process;
  - the fuel and carbon costs increase.

- *LCOH for Electrolyzers is dominated by grid-electricity prices.*
- *Variable Operating costs, due to the periodic replacement of stacks, have a significant costs' impact, especially for SOEC.*
- *LCOH shows a general CAPEX decrease due to the learning-by-doing process, especially for the less mature SOEC technology.*





Eni elaboration from BEIS – Hydrogen Production Costs (August 2021)

Hydrogen for the Energy Transition: its Many Faces

- What is hydrogen? Relevant properties
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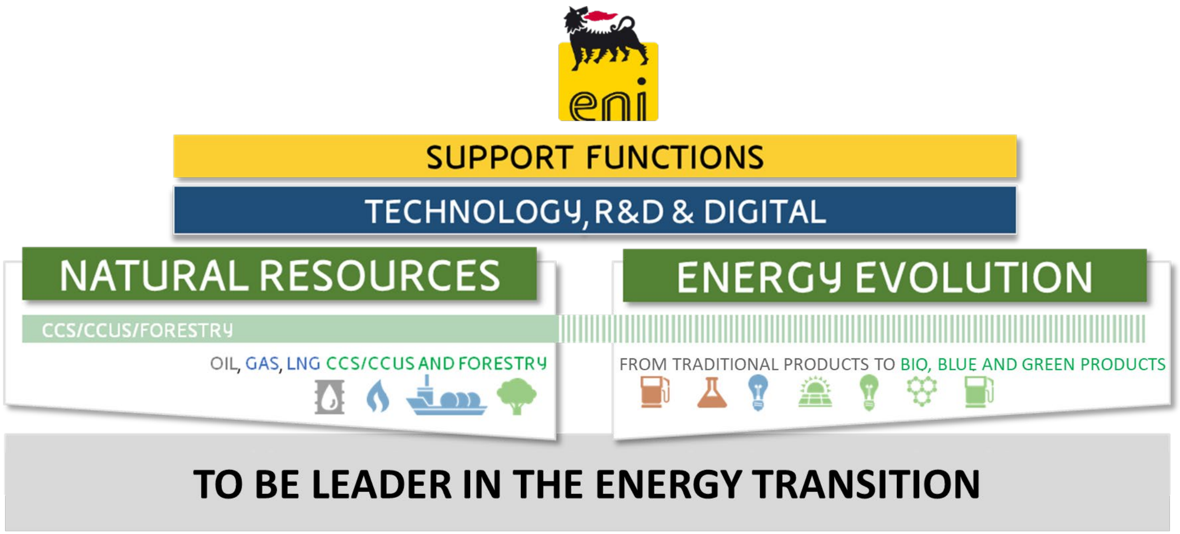
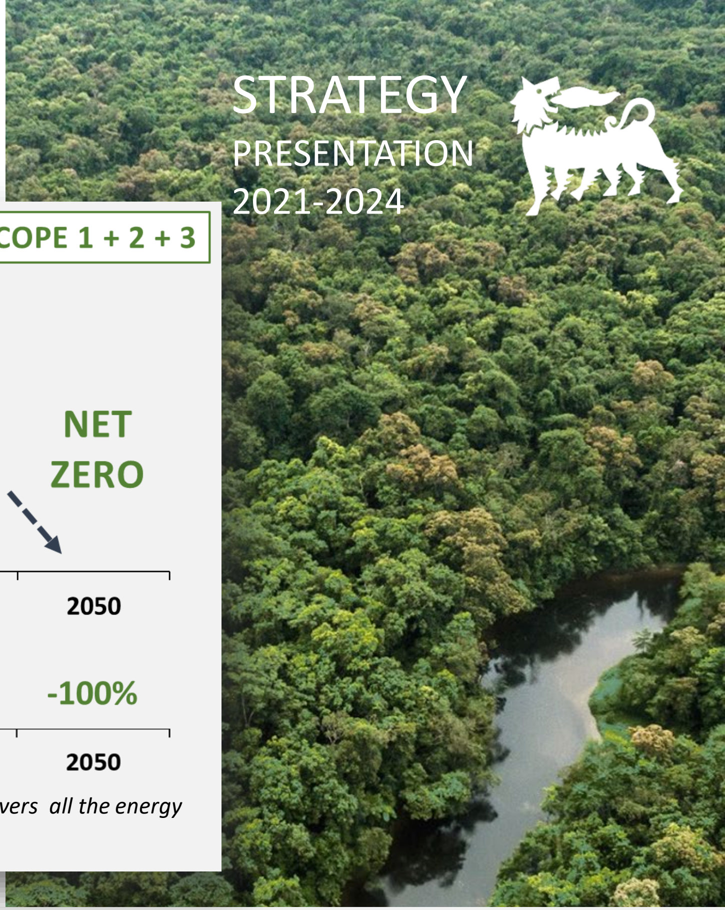
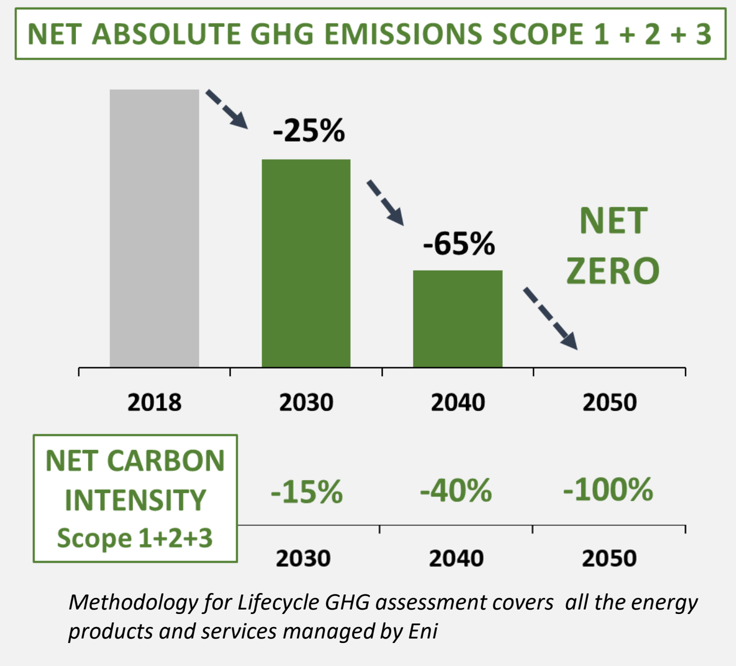
Eni – NET ZERO EMISSION BY 2050

- *ENI - THE NEW 2020 ORGANIZATION*





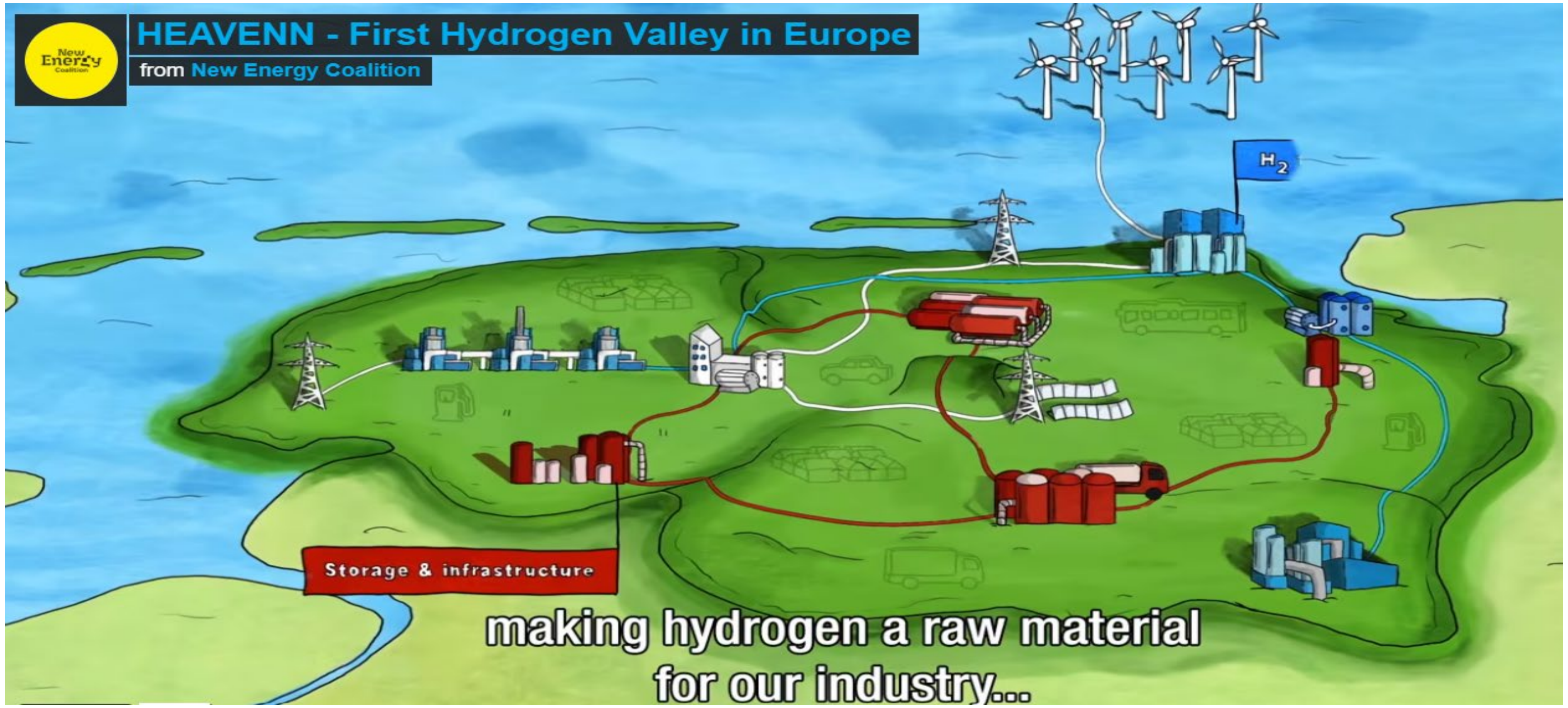


- ***LEVERS***
  - *CARBON FREE PRODUCTS AND SERVICES*
  - *INCREASED GAS SHARE ON TOTAL PRODUCTION*
  - *BIOMETHANE FOR DOMESTIC USE AND MOBILITY*
  - *BIO-REFINERIES AND CIRCULAR ECONOMY*
  - ***BLUE AND GREEN HYDROGEN***
  - ***CCS AND REDD+ PROJECTS***

REDD+ = Reducing emissions from eforestation and forest degradation

EU: Hydrogen Valleys

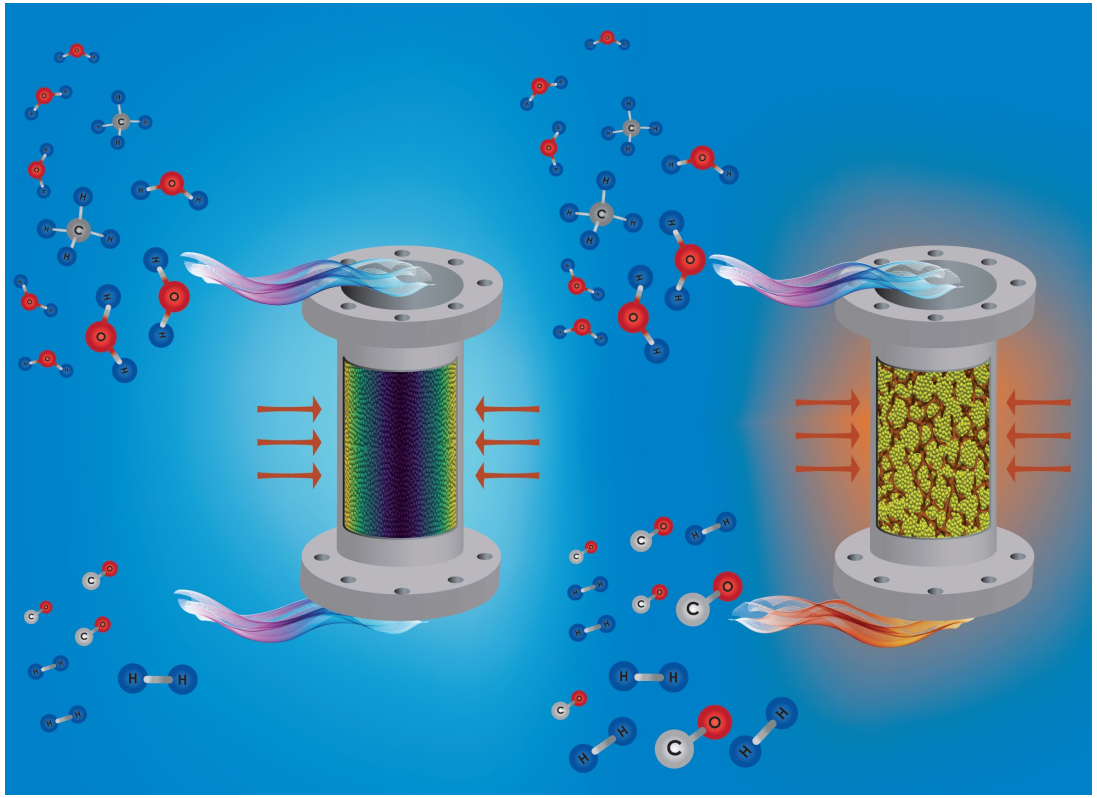
The Netherlands has become the first region in Europe to receive a subsidy for its so-called Hydrogen Valley. The North Netherlands grant application for a Hydrogen Valley has been approved by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) of the European Commission. It concerns a subsidy of 20 million euro with a public-private co-financing of 70 million euro. This grant is for the development of **a fully functioning green hydrogen chain** in the northern Netherlands. This six-year project HEAVENN started in January 2020.



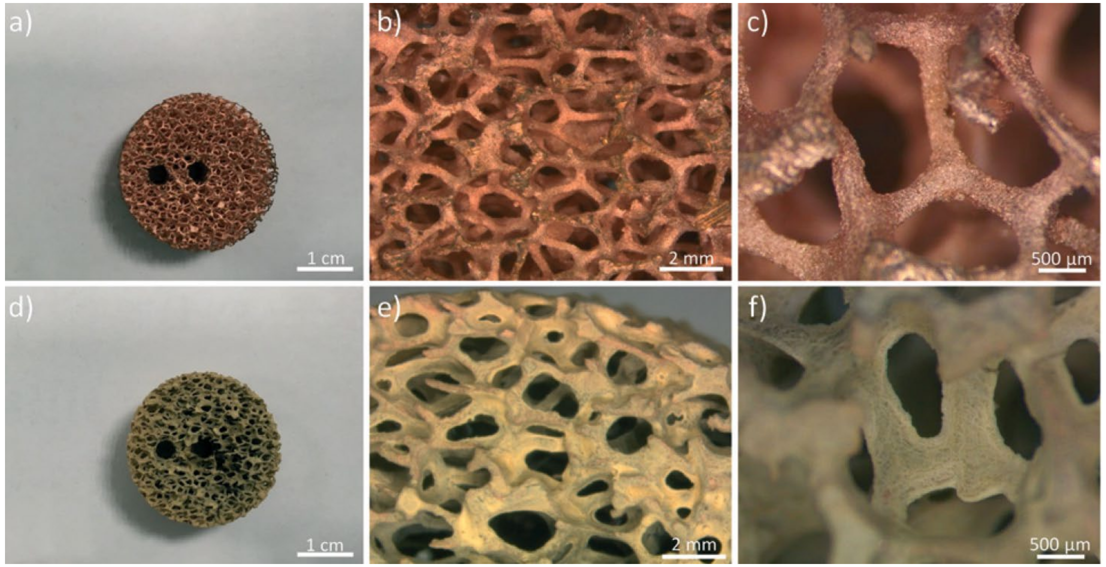
Intensifying Methane Steam Reformers for distributed H_2 production

Laboratory of Catalysis and Catalytic Processes LCCP

erc European Research Council Executive Agency



Overcoming the heat transfer issue in Methane Steam Reformers: highly conductive cellular internals (open-cell Cu foams)



R. Balzarotti et al., Reaction Chemistry & Engineering, 4 (2019) 1387 – 1392

R. Balzarotti et al., Chem. Engng. Journal 391 (2020) 123494

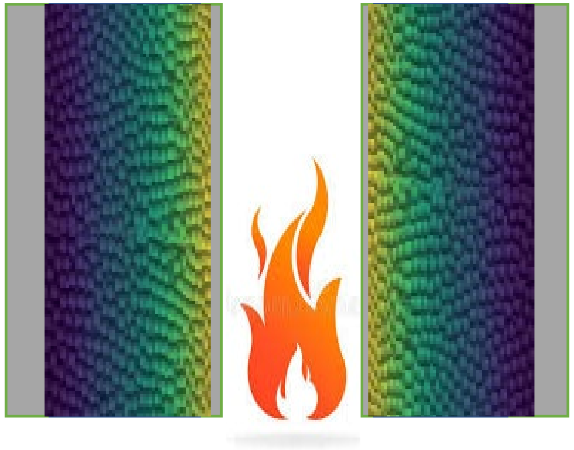
ERC PoC 2020 – Action 694910: INSTANT

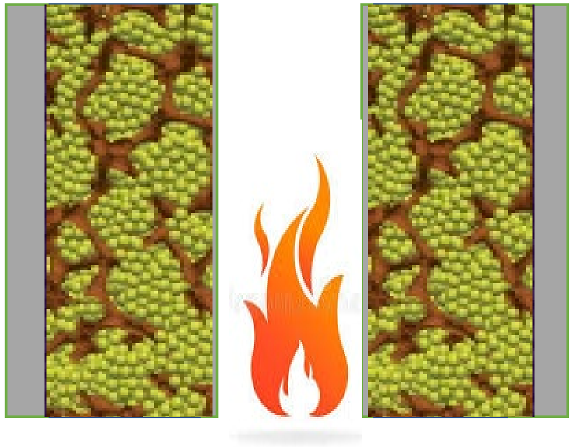
«EffIcieNt Small scale uniT for distributed heAt and hydrogeN generaTion »

Laboratory of Catalysis and Catalytic Processes LCCP

Application of the conductive packed foams concept to the design of an intensified reformer for distributed small scale H_2 generation

Packed bed www.intent.polimi.it/instant **Packed foam**





Conductive packed foams: the improved heat transfer is expected to greatly increase the **H_2 productivity**

➔ **compact reformers for micro-CHP systems**

H_2 production from electric energy

H_2O Electrolysis

Alcaline

$$2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$$

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PEM

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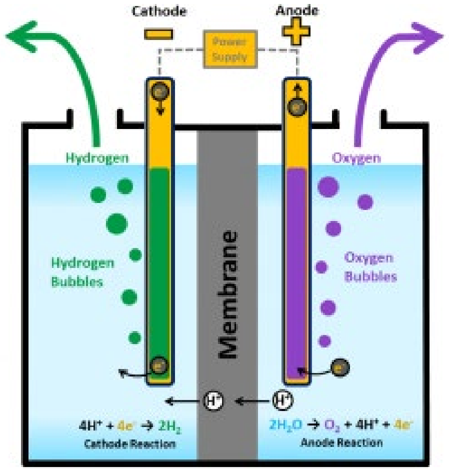
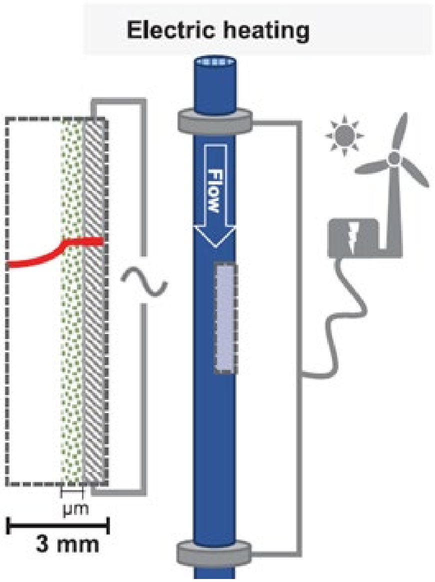
TD Energy demand : 241 kJ/mol H_2



	kWh/Nm³ H_2
Alkaline	4.5
PEM	3.5

Is there an alternative?

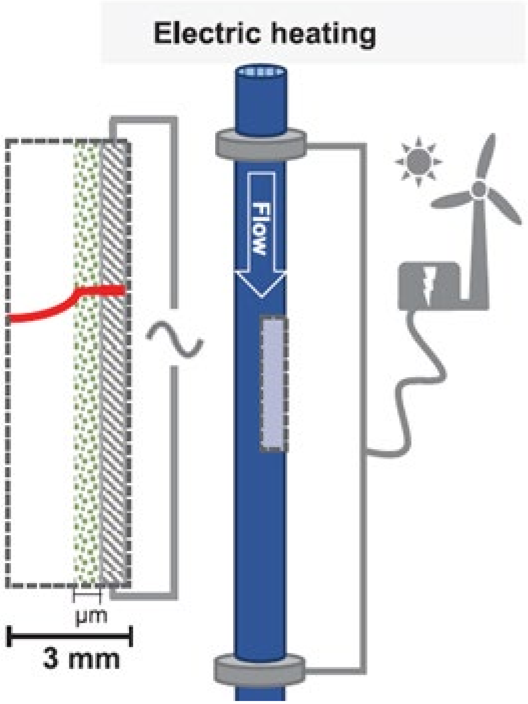
Use electric energy as direct heat input for MSR



Wismann et al., Science 364, 756–759 (2019)

Electrified methane steam reforming (eMSR)

Same feed of conventional reforming
Reaction heat supplied by Joule effect [1]



[1] Wismann et al., Science 364, 756–759 (2019)
[2] Wismann et al., I&EC Res. 51, 23380-23388 (2019)

$$CH_4 + H_2O \rightarrow CO + 3H_2$$
$$CO + H_2O \rightarrow CO_2 + H_2$$
$$\overline{}$$
$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$

TD Energy demand: 41 kJ/mol H_2

CO_2 per mol H_2: 0.25 (vs. 0.3-0.5 in fired MSR)

kWh_{el}/Nm_3 H_2: 0.6 (vs. 3.5 in PEM electrolyser)

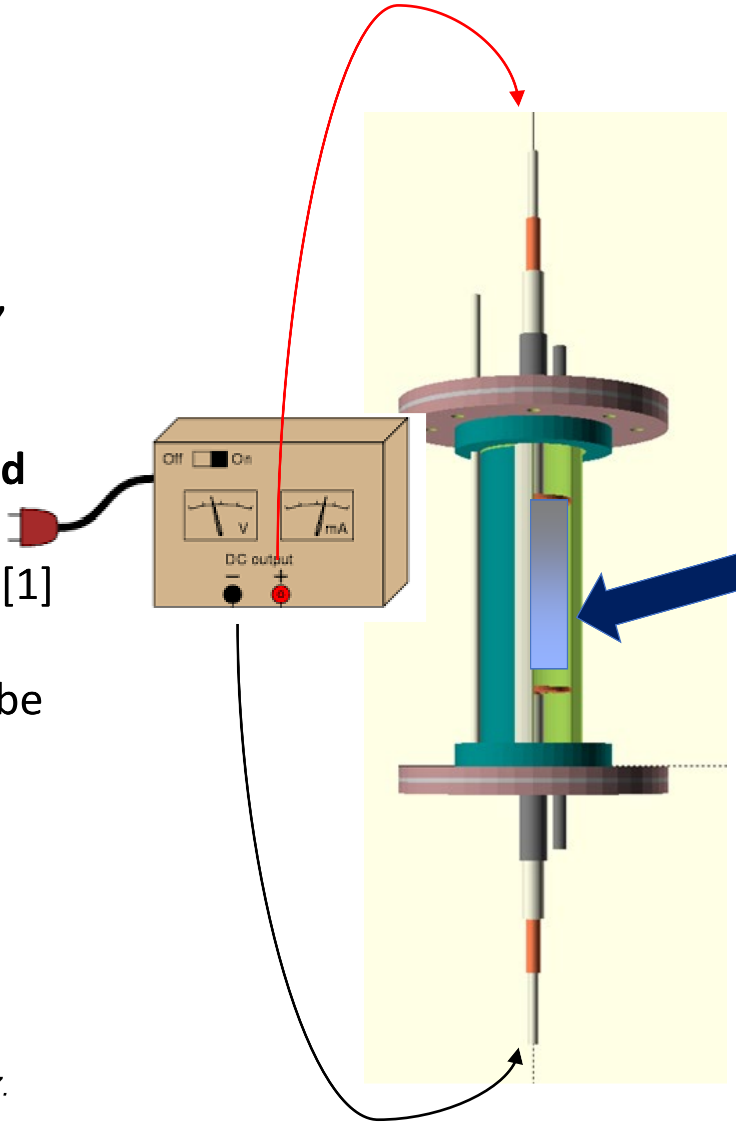
Reduction of CO_2 emissions:
20-50 % with respect to conventional MSR

Reduction of specific power consumption:
600-900 % with respect to H_2O electrolysis

Key technology for transition to decarbonization and exploitation of renewable energy sources

eMSR Reactor configuration – PoliMI

- **Direct electrification by Joule heating** is the best tradeoff between complexity, efficiency, power density
- Open-cell foams offer **enhanced trasport properties** for Methane Steam Reforming [1]
- The 3D network of foams may be used for **uniform power distribution** when applied as heating resistance



Washcoated resistive foams:
Direct Joule heating of the washcoated foam

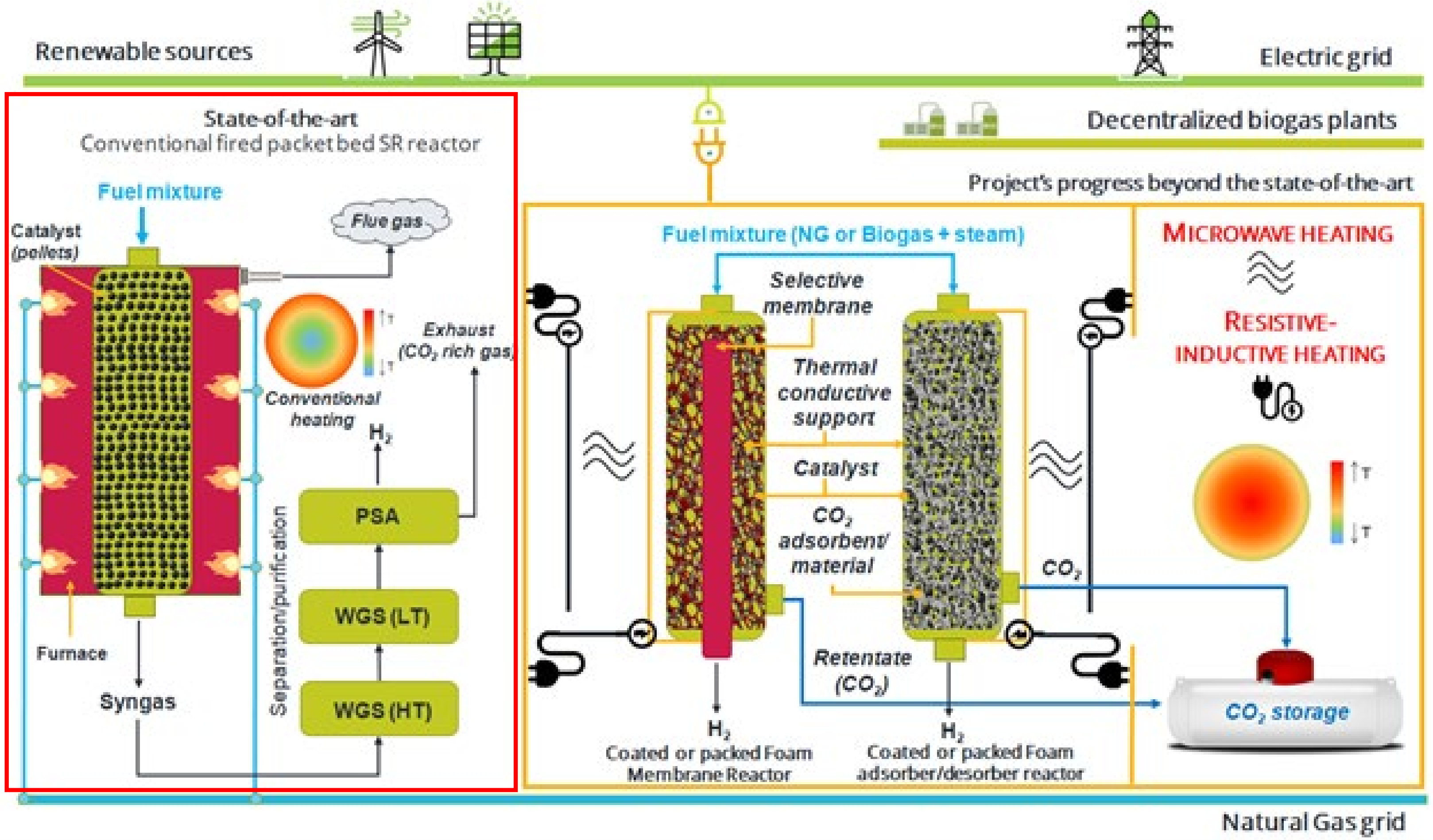
Goal:

✓ **Direct electrification of structured catalysts (open-cell foams) for eMSR**

✓ **Design of small-scale reformers to enable domestic H_2 usage**

[1] R. Balzarotti et al., React. Chem. Eng., 4 (2019) 1387.

PLUG-IN project: compact reformer integrating electric heating with membrane reactor for CO_2 capture and pure Blue/Green H_2 production from NG/Biogas



Project of Relevant National Interest (PRIN) funded by the Italian Ministry of University & Research: 2022 – 2025

Grant ≈ 800 kEuro

Laboratory of Catalysis and Catalytic Processes LCCP

Prospettive

- **Mario Draghi**: «*le conseguenze dei cambiamenti climatici sono devastanti. La transizione ecologica ed energetica non è rimandabile, ma avrà dei costi*»

- **L'idrogeno** svolgerà un ruolo chiave nei prossimi anni in vari settori industriali: energetico, chimico, siderurgico, trasporti …

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    - ✓ Riduzione dei **costi di produzione di green H_2**: da 5-12 €/kg ➔ 3 – 5 €/kg
    - ✓ Downscaling per fare **H_2 distribuito**

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E' un buon momento per essere Ingegneri Chimici!!

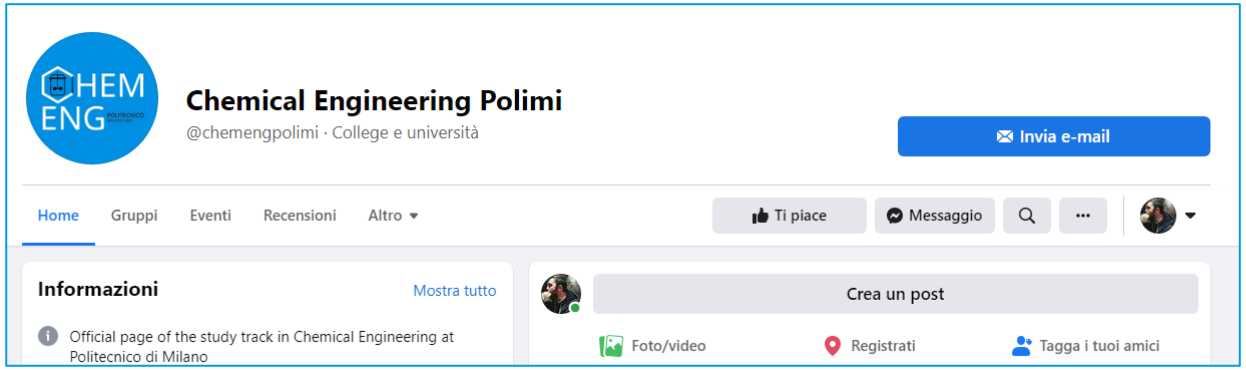
Chi siamo

POLITECNICO MILANO 1863

Isabella Nova
(Coordinatrice CS Ing. Chimica)

chemeng_polimi

chemengpolimi



Acknowledgments

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Established by the European Commission

European Research Council (ERC)
the European Union's Horizon 2020 research and innovation programme (GA No. 694910 -'INTENT')

Grazie per la gentile attenzione!

Meeting della Società Italiana di Catalisi: Milano, Settembre 2018