Consiglio Nazionale delle Ricerche

Membrane Technologies in H_2 energy

Adolfo Iulianelli

National Research Council of Italy - Institute on Membrane Technology (CNR-ITM), via P. Bucci Cubo 17/C University of Calabria, 87036 – Rende (CS) – Italy Ph: +39 0984 492011; E-mail: a.iulianelli@itm.cnr.it, adolfo.iulianelli@cnr.it

Il CNR in numeri

Consiglio Nazionale delle Ricerche

1 **Primo** ente di ricerca per personale impegnato nella ricerca

>9.000

52% Uomini — 48% Donne

Gender balance

Il CNR conta su un patrimonio umano di oltre 9.300 dipendenti, di cui **8.713** costituiscono la **rete scientifica** dell'Ente

58%
ricercatori e ricercatrici

7 Dipartimenti

- Scienze fisiche e tecnologie della materia
- Scienze del Sistema Terra e Tecnologie per l'Ambiente
- Scienze Biomediche
- Ingegneria - ICT e Tecnologia per l'Energia e i Trasporti
- Scienze Umane e Sociali Patrimonio Culturale
- Scienze Chimiche e Tecnologie dei Materiali
- Scienze Bio-Agroalimentari

88 Istituti di ricerca	**230** Sedi e laboratori sul territorio	**141** Sedi nel sistema universitario
30 Unità di Ricerca presso terzi	**3** Basi di ricerca permanenti ai poli	**1** Nave Oceanografica «Gaia Blu»

361 Famiglie di brevetti	**64** Imprese spin off	**51** Accordi bilaterali con 37 paesi

Bilancio complessivo 2023*
1.737.556.009 €

59%
Entrate da terzi

100 — 1923 CNR 2023 — LA RICERCA VENUTA DAL FUTURO

Nel **2023**, il CNR **ha celebrato 100 anni** dalla sua istituzione: era infatti il **1923** quando, presso la sede dell'Accademia Nazionale dei Lincei, sotto la presidenza di **Vito Volterra**, il Consiglio Nazionale delle Ricerche nasceva come 'ente morale' con il compito di svolgere attività di formazione, promozione e coordinamento della ricerca in tutti i settori scientifici e tecnologici

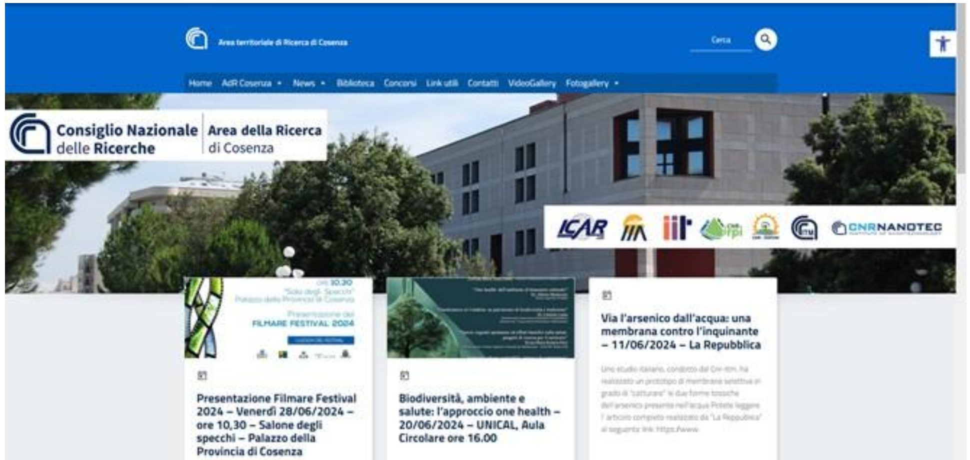
CNR Headquarter in Rome (www.cnr.it)

CNR | Dipartimento Scienze Chimiche e Tecnologie dei Materiali

Institute on Membrane Technology
National Research Council of Italy

1923 CNR 2023 LA RICERCA VENUTA DAL FUTURO

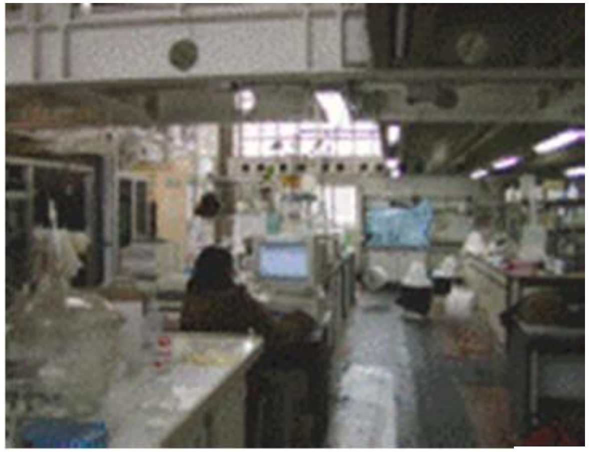
Research Area of CNR di Cosenza: https://areacs.cnr.it



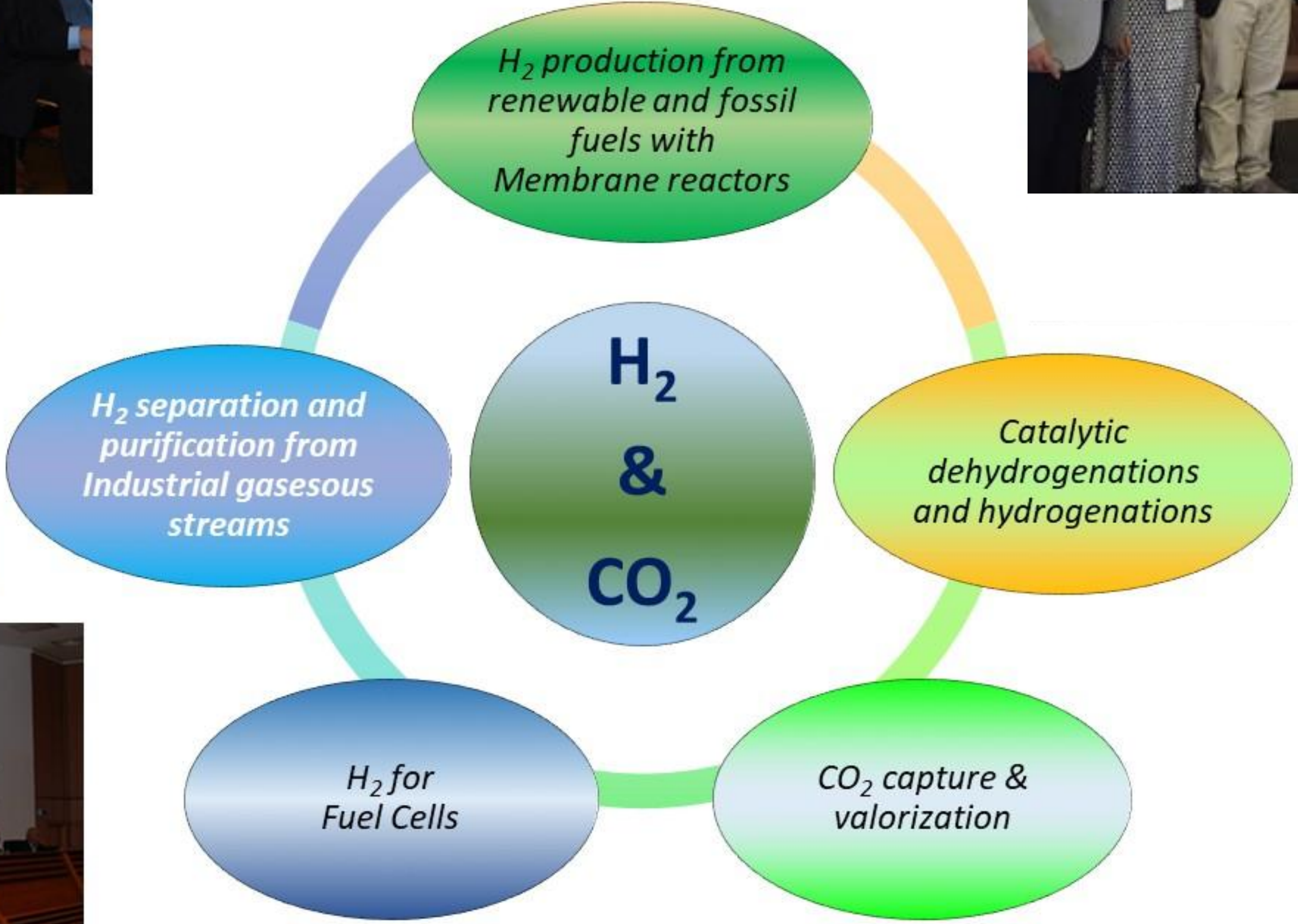
www.itm.cnr.it

- 7 (+1) CNR institutes
- 300+ Researchers/Technicians/Technologists/TD researchers

- Over 100 Personel units
- 50 Associated Professors/PhD Students/Visiting scientists

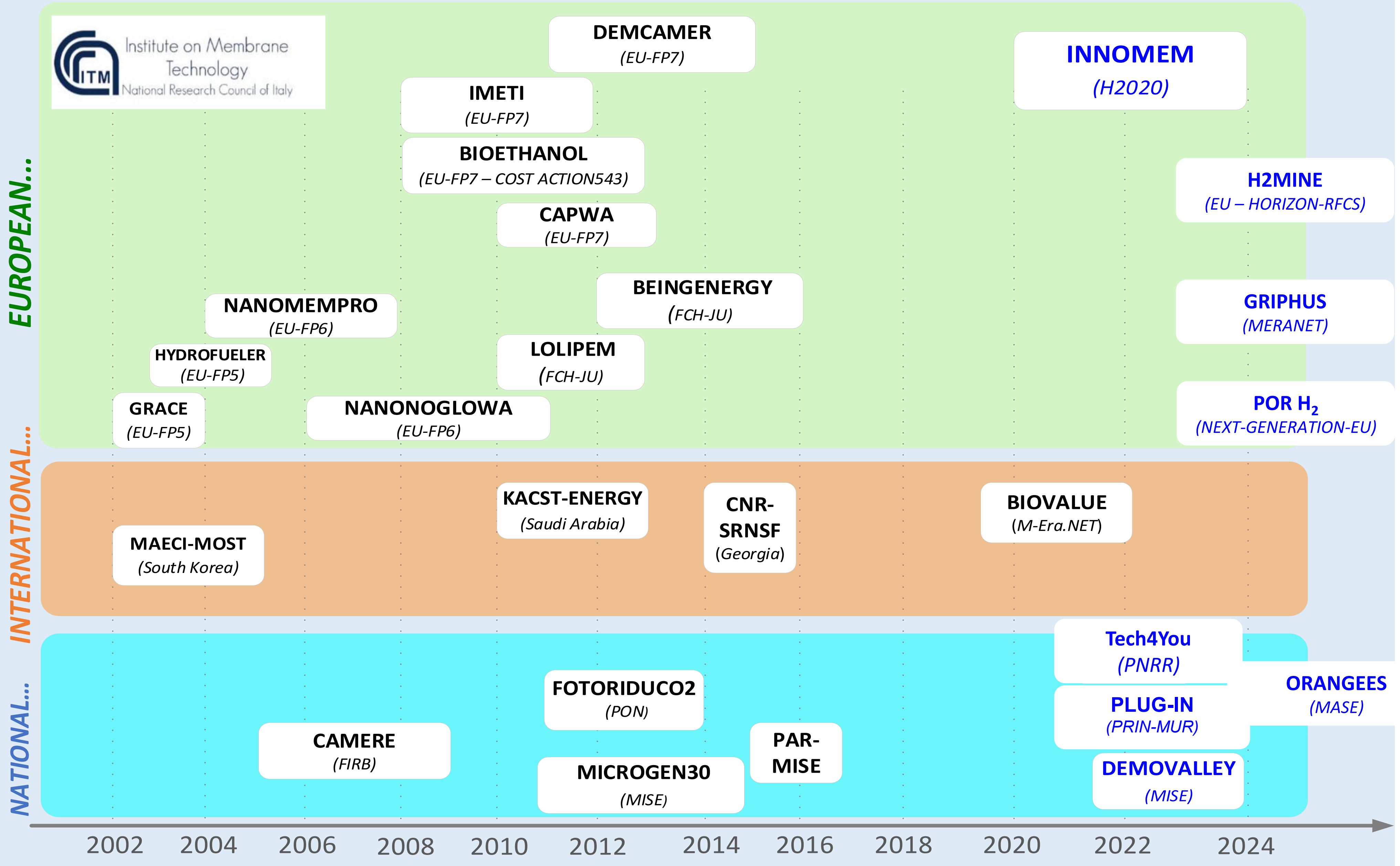


Membrane Engineering in H_2 & CO_2 activities @ CNR-ITM



Consiglio Nazionale delle Ricerche

SOME OF MOST RELEVANTS PROJECTS ON HYDROGEN&GAS @ CNR-ITM



H_2 production: definitions

Unofficial H_2 production methods classification

	Terminology	Technology	Feedstock/ Electricity source	GHG footprint*
PRODUCTION VIA ELECTRICITY	Green Hydrogen	Electrolysis	Wind | Solar | Hydro Geothermal | Tidal	Minimal
	Purple/Pink Hydrogen		Nuclear	
	Yellow Hydrogen		Mixed-origin grid energy	Medium
PRODUCTION VIA FOSSIL FUELS	Blue Hydrogen	Natural gas reforming + CCUS Gasification + CCUS	Natural gas | coal	Low
	Turquoise Hydrogen	Pyrolysis	Natural gas	Solid carbon (by-product)
	Grey Hydrogen	Natural gas reforming		Medium
	Brown Hydrogen	Gasification	Brown coal (lignite)	High
	Black Hydrogen		Black coal	

*GHG footprint given as a general guide but it is accepted that each category can be higher in some cases.

European Commission

Renewable Hydrogen is defined by reference to the definition of the Proposed Directive to Amend RED II, e., as hydrogen that (i) derives its energy content from renewable sources other than biomass; and (ii) achieves a 70% GHG emission reduction compared to fossil fuels.

Low-Impact Hydrogen Emissions is defined as hydrogen with an energy content that is derived from non-renewable sources, and that meets a GHG emission reduction threshold of 70% compared to fossil-based hydrogen.

Official H_2 production methods classification

CLEAN HYDROGEN, Examples

- Clean Hydrogen encompasses clean hydrogen generated from both renewables and fossil fuels through the use of carbon capture and storage (CCS) technology.

LOW-CARBON HYDROGEN, Examples

UN environment programme | copenhagen climate centre

- Low-carbon hydrogen encompasses:
  - Fossil-based hydrogen with carbon capture and
  - Electricity-based hydrogen, with significantly reduced full life-cycle greenhouse gas emissions compared to existing hydrogen production.

RENEWABLE HYDROGEN DEFINITION, Example

- Renewable hydrogen is hydrogen produced through the electrolysis of water (in an electrolysers, powered by electricity), and with the electricity stemming from renewable sources;
- The full life-cycle greenhouse gas emissions of the production of renewable hydrogen are close to zero;
- Renewable hydrogen may also be produced through the reforming of biogas (instead of natural gas) or biochemical conversion of biomass, if in compliance with sustainability requirements;

Hydrogen strategy in Italy

Dedicated budget

> **3.5B EUR** of investment on H_2-chain and R&D

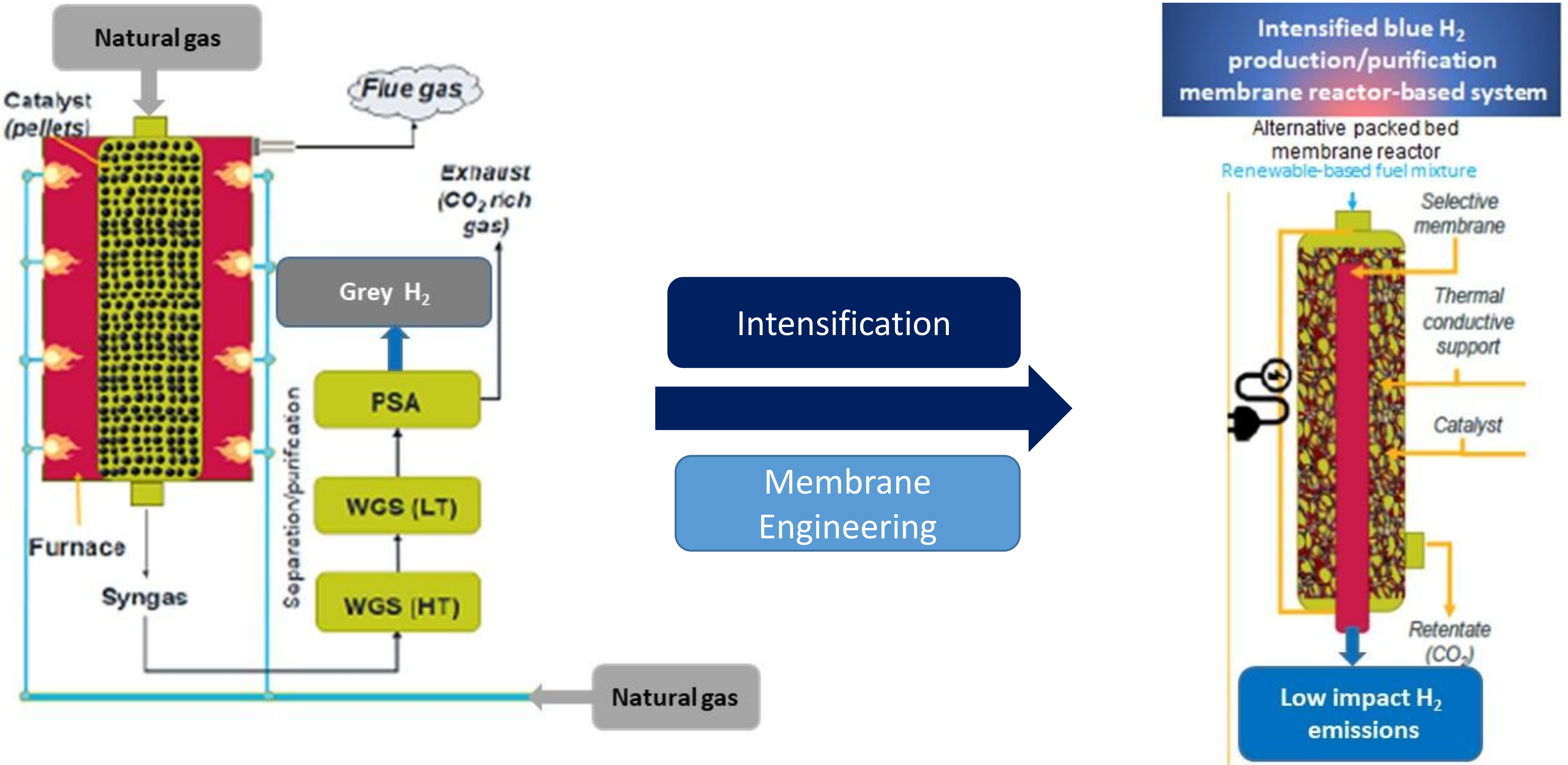
PNRR – Mission 2, Componen 2.3 – **Renewable Energy, Hydrogen, Networks and Mobility System**
Investments 3.1-3.5: *Promotion of the Production, Distribution, and Final Uses of Hydrogen*
Budget: 3,19 B€

PNRR – Missione 2, Component 2.5 – **International Industrial and R&D Leadership Development in the key Transition Networks**
Investment 5.2: *Hydrogen*
Budget: 0,45 B€

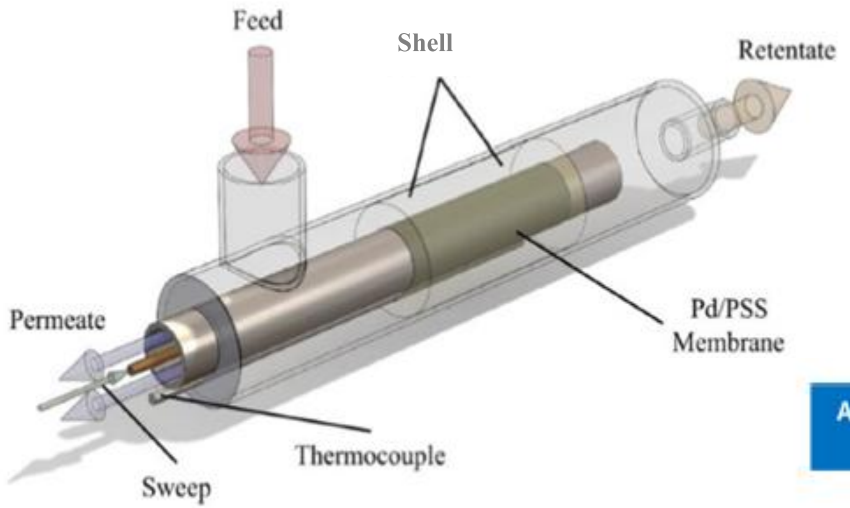
The National Recovery and Resilience Plan NextGenerationEU REPowerEU Plan's

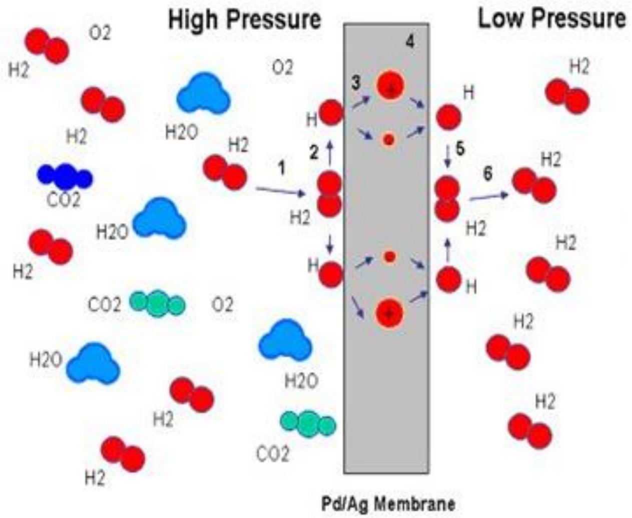
> **200B EUR** investments and infrastructures

Process intensification by membrane engineering

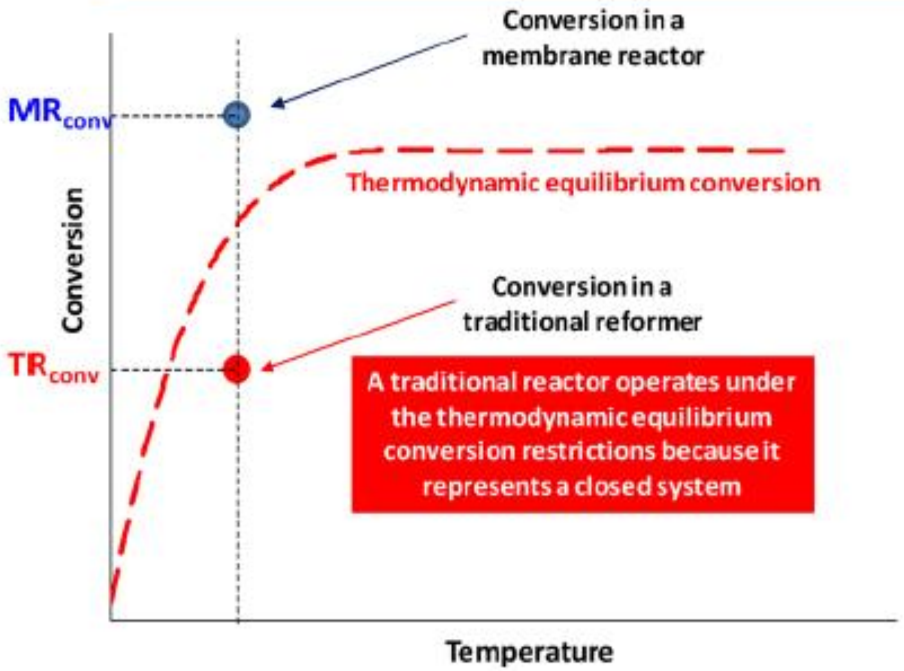


H_2 separation/purification by membrane technology – *Inorganic membranes*





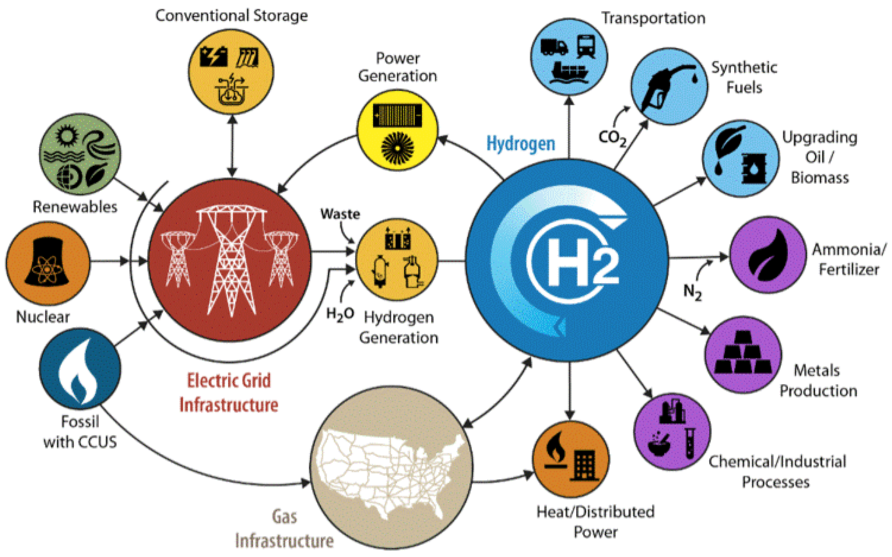
A membrane reactor is not limited by the thermodynamic equilibrium conversion because it does not represent a closed system



Membrane technologies in Hydrogen production, separation/purification and chemical storage

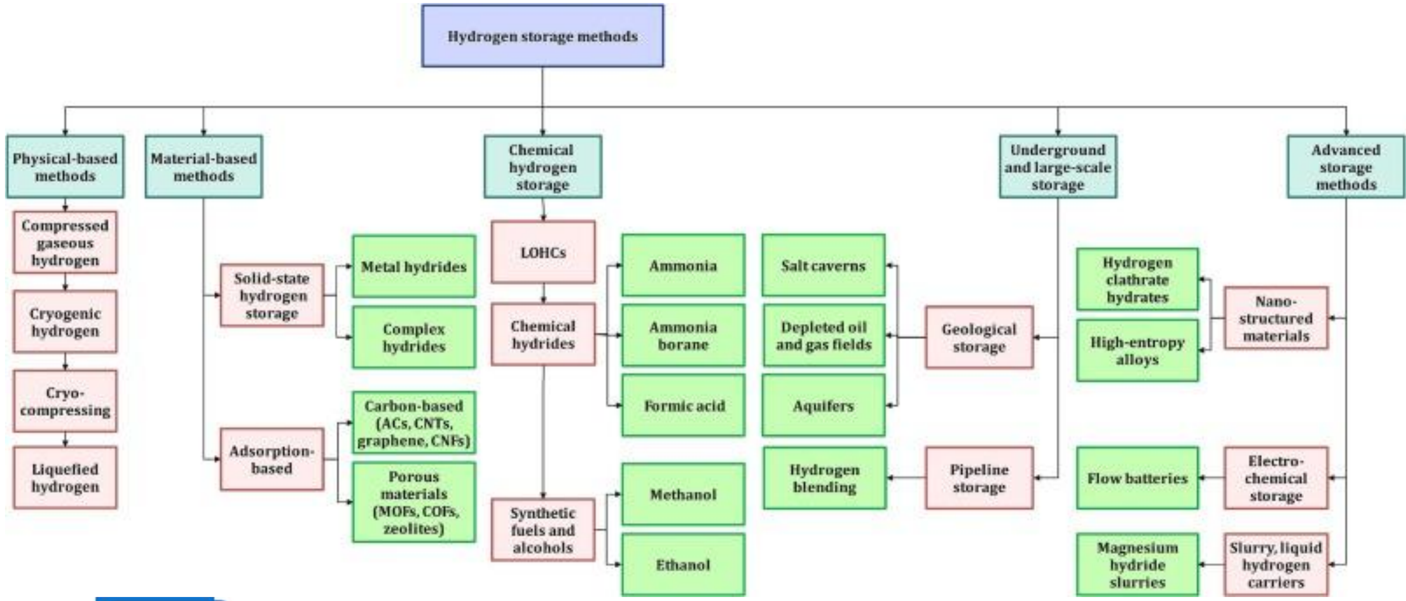
CNR

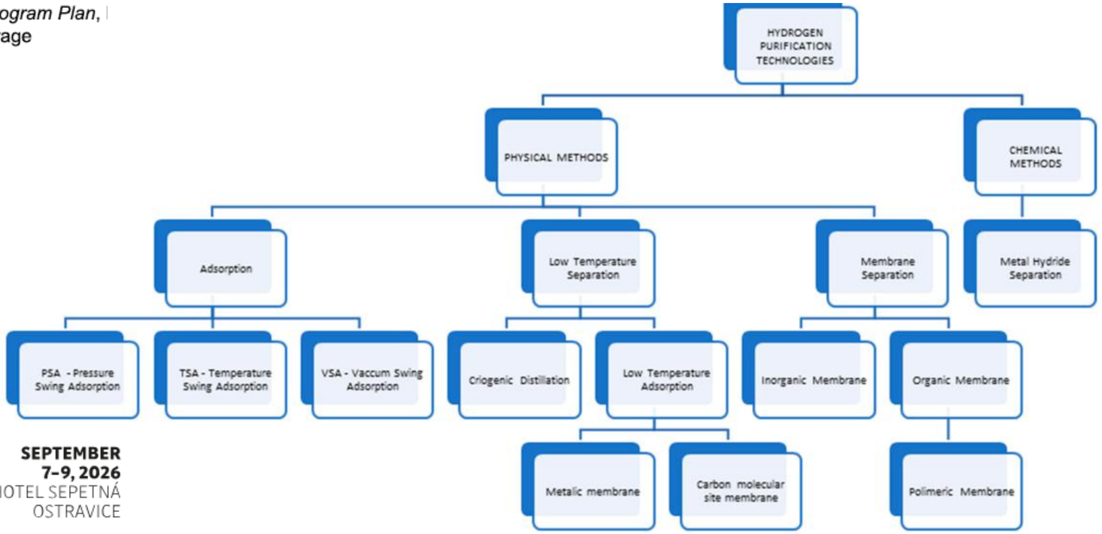
HYDROGEN PRODUCTION & UTILIZATION



Source: U.S. Department of Energy, *Hydrogen Program Plan*,
Note: CCUS=carbon, capture, utilization, and storage

HYDROGEN STORAGE





HYDROGEN PURIFICATION

Our objectives: H_2 targets set by the European Clean Hydrogen Alliance

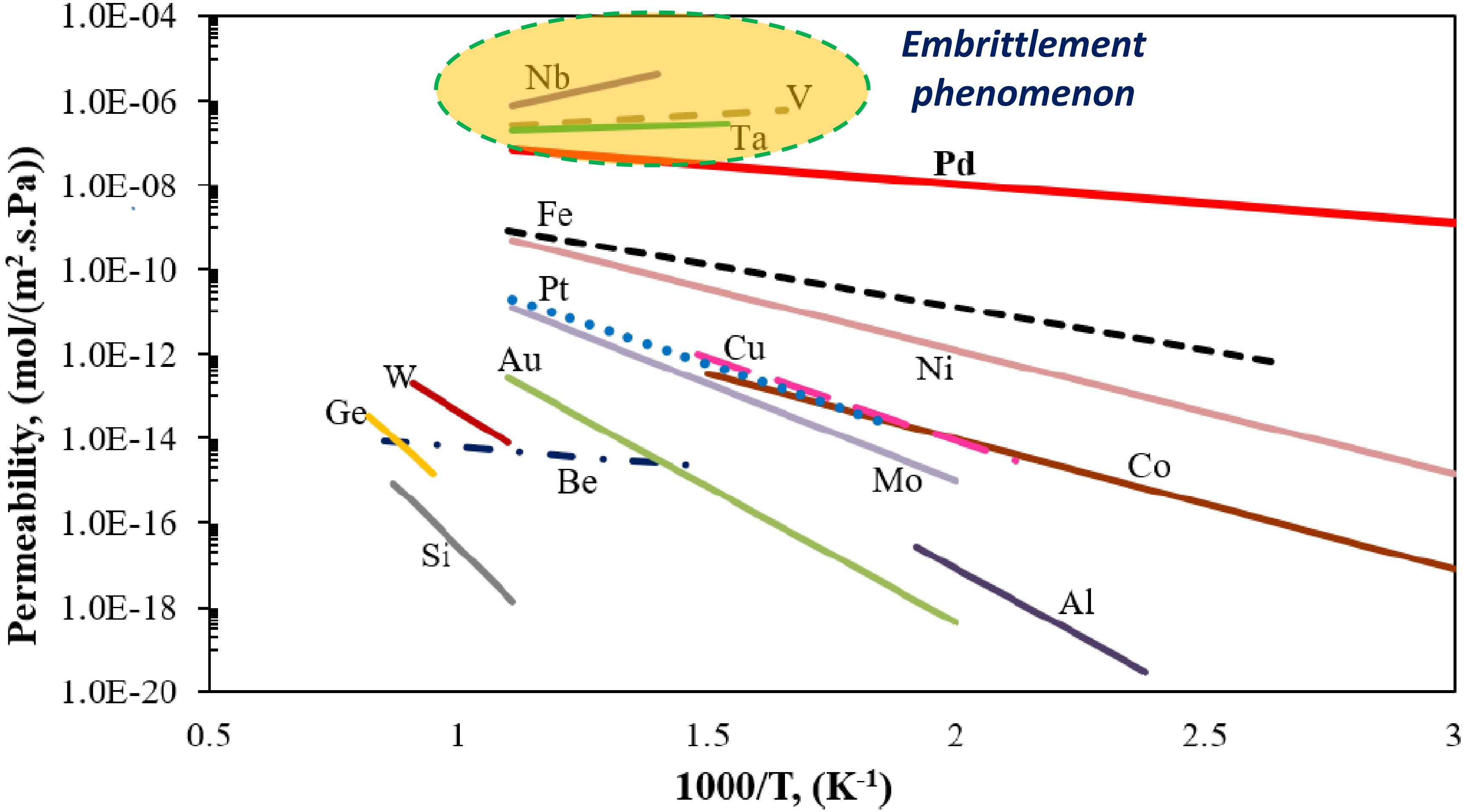
EU TARGETS

H_2 recovery: **80%** (2024); **90%** (2027); **95%** (2030)

H_2 purity: **99.99%**

Clean Hydrogen Alliance under the Strategic Research & Innovation Agenda 2021-2027

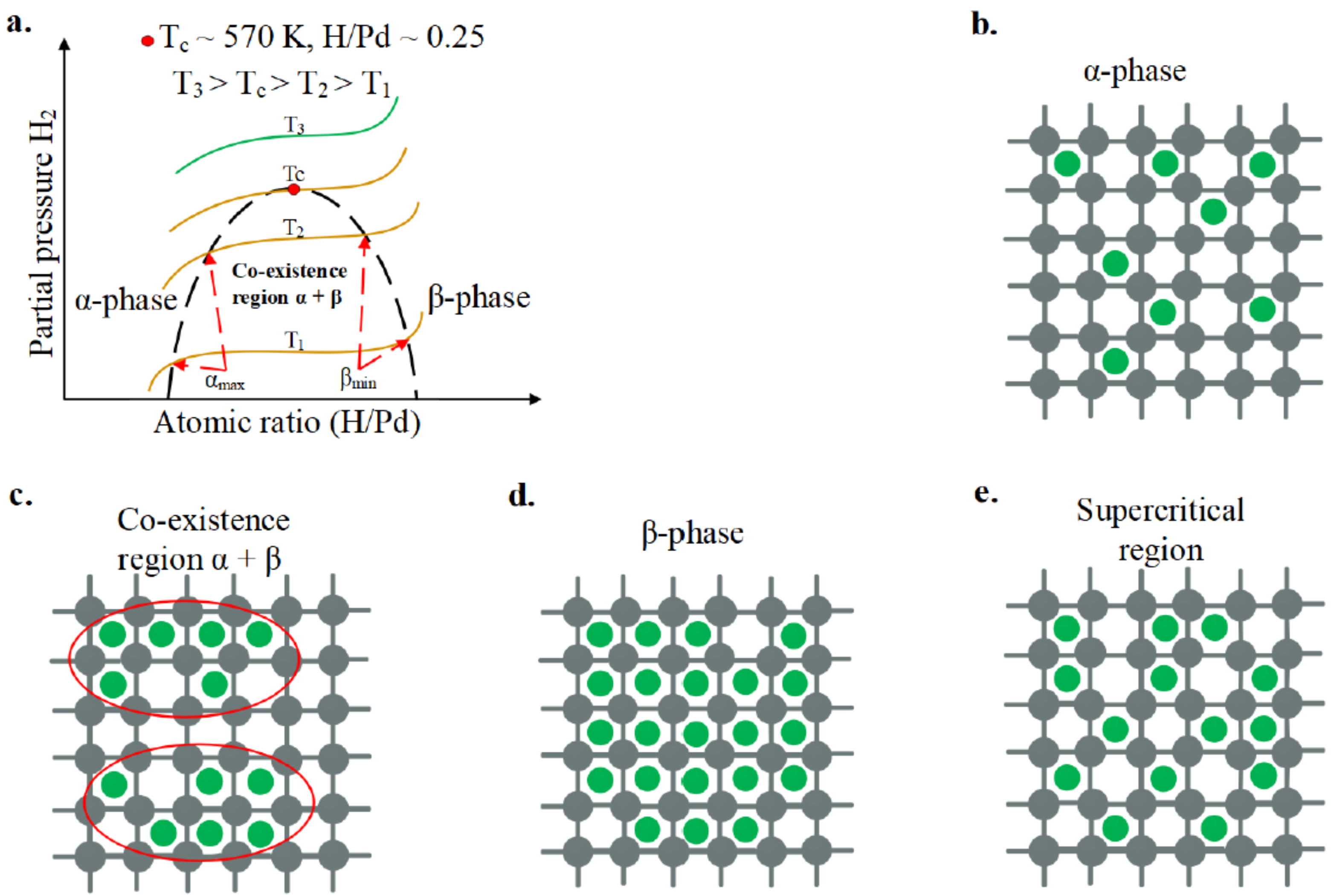
Metallic membranes for H_2 separation/purification

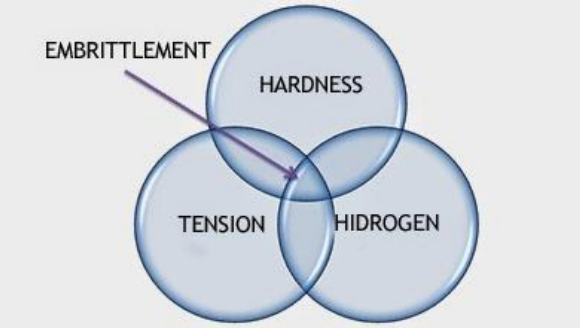


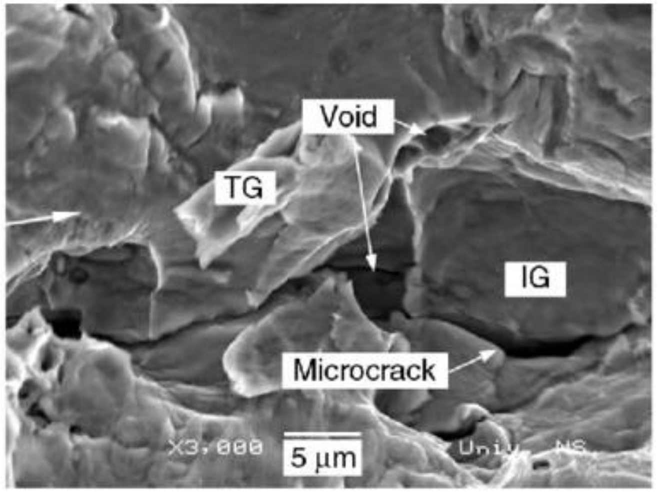
Palladium: dominant membrane material in hydrogen separation/purification

Consiglio Nazionale delle Ricerche

Pd hydride phases: **a.** P-C-T diagram, **b.** α-phase, **c.** α-phase and β-phase, **d.** β-phase and **e.** supercritical region. *Green and gray dots are hydrogen and Pd, respectively*

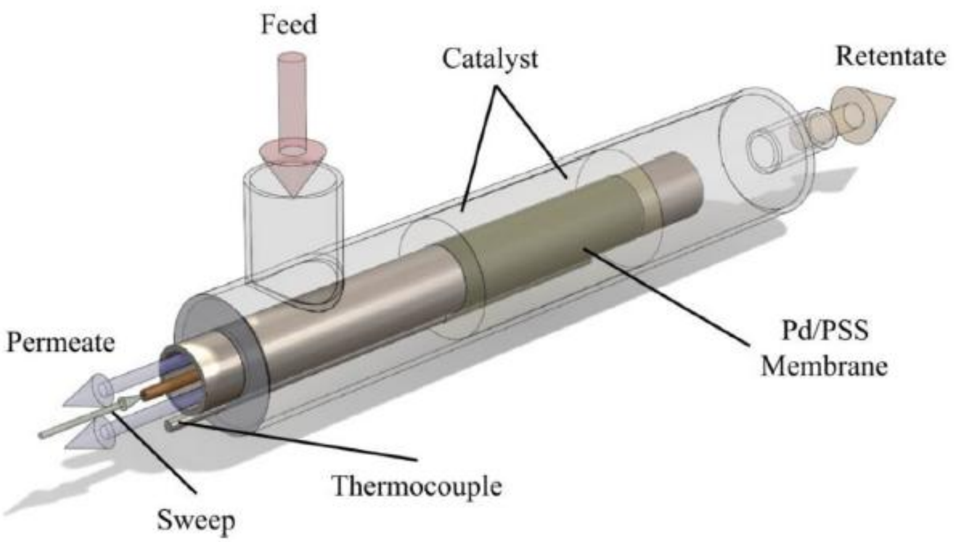


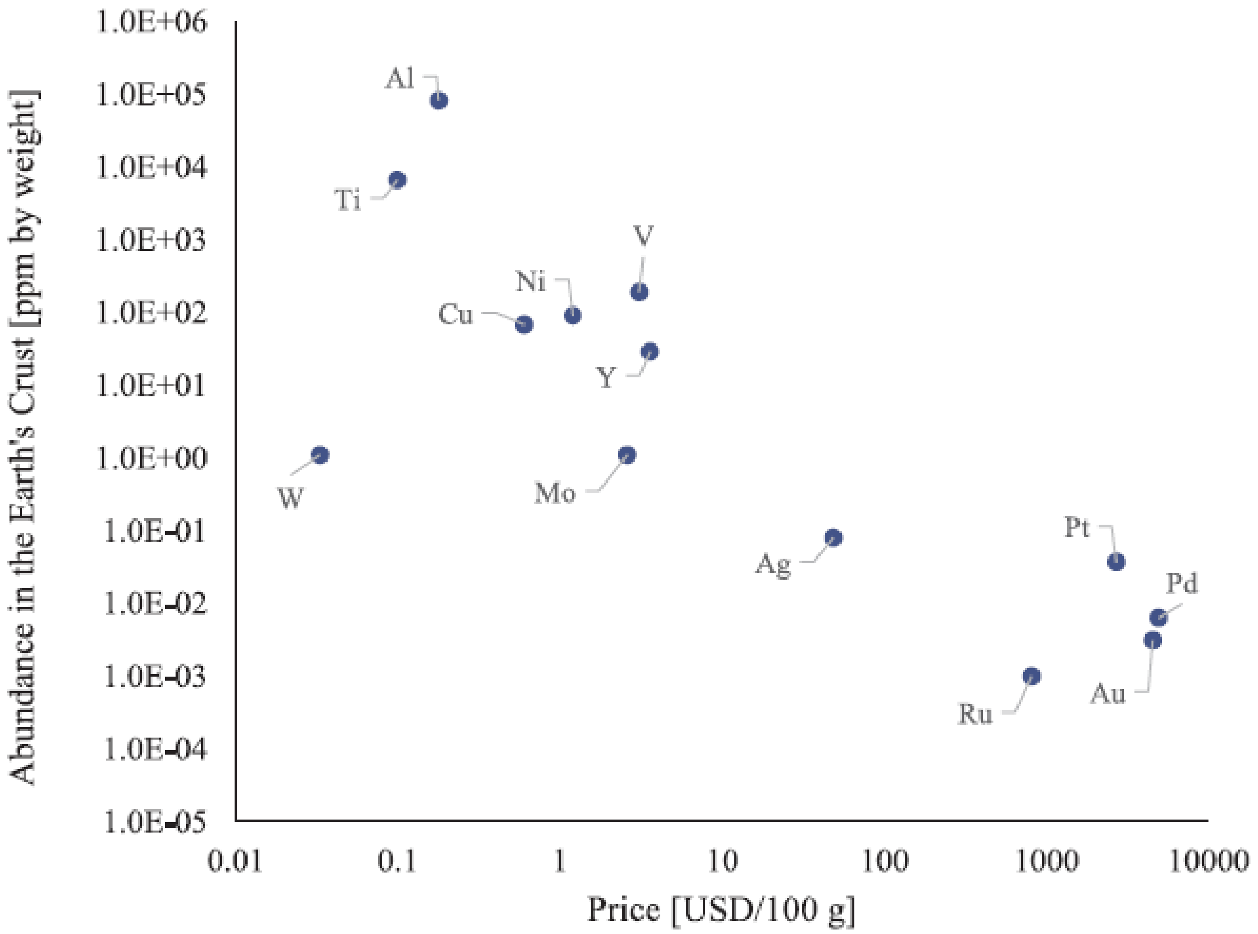




U.S. DOE 2015 targets for hydrogen separation and purification by dense metallic membranes [129]

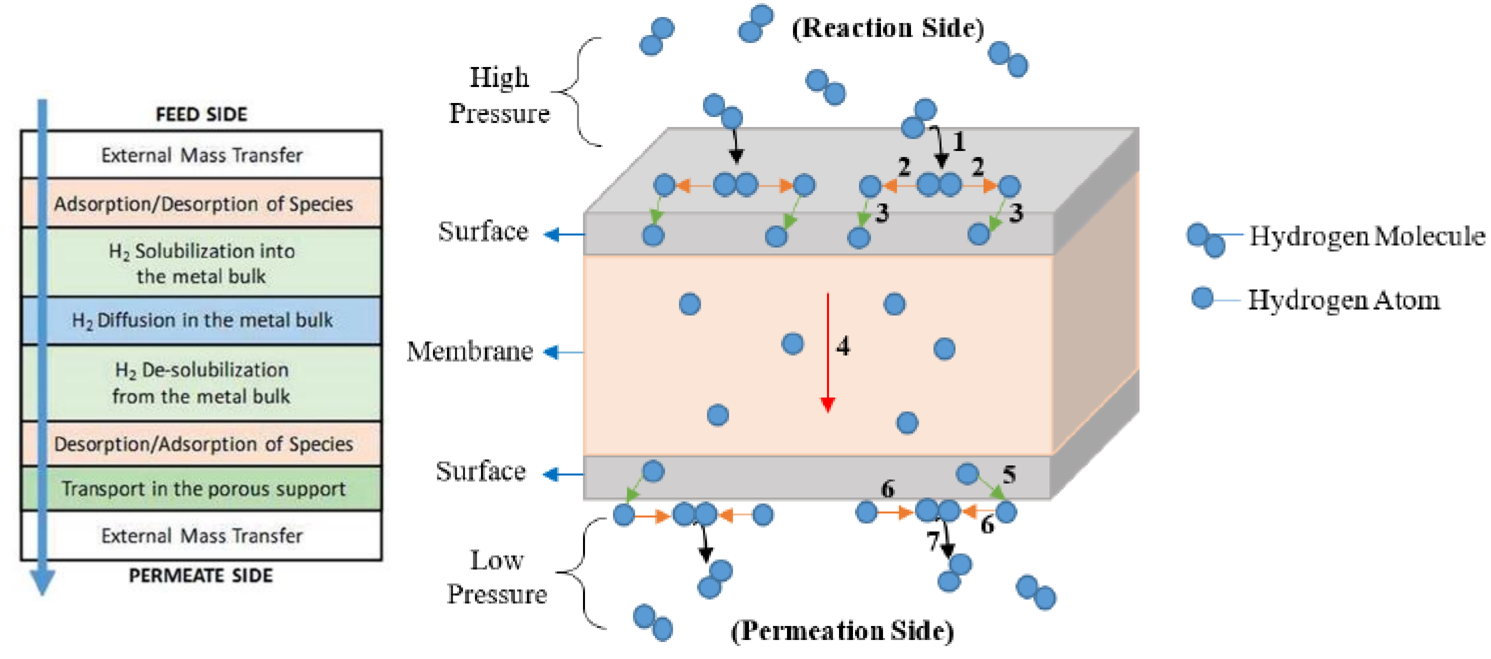
Performance criteria	Target
Flux	1.135 $mol/m^2.s$ (300 $Scfh/ft^2$)
Cost of membrane	< 5,400 $\$/m^2$ (< 500 $\$/ft^2$)
Durability	> 5 years
H_2 recovery	90 %
Hydrogen purity	99.99%





Hydrogen permeation through Pd-based membranes

Consiglio Nazionale delle Ricerche



Schematic representation of the hydrogen permeation through dense Pd-based membranes via solution/diffusion mechanism;

Hydrogen permeation by solution/diffusion mechanism (Fick-Sieverts law)

$$J_{H_2} = \frac{K_{H_2}}{\delta}\left(p_{H_2,ret}^{0.5} - p_{H_2,perm}^{0.5}\right)$$

J_{H2} is the hydrogen permeating flux; K_{H2} hydrogen permeability; $p_{H2,ret}$ and $p_{H2,perm}$ are partial pressure of hydrogen in the retentate and permeate sides; δ is the membrane thickness.

$$K_{H_2} = K_{H_2}^0.\exp\left(-\frac{E_{a.H_2}}{RT}\right)$$

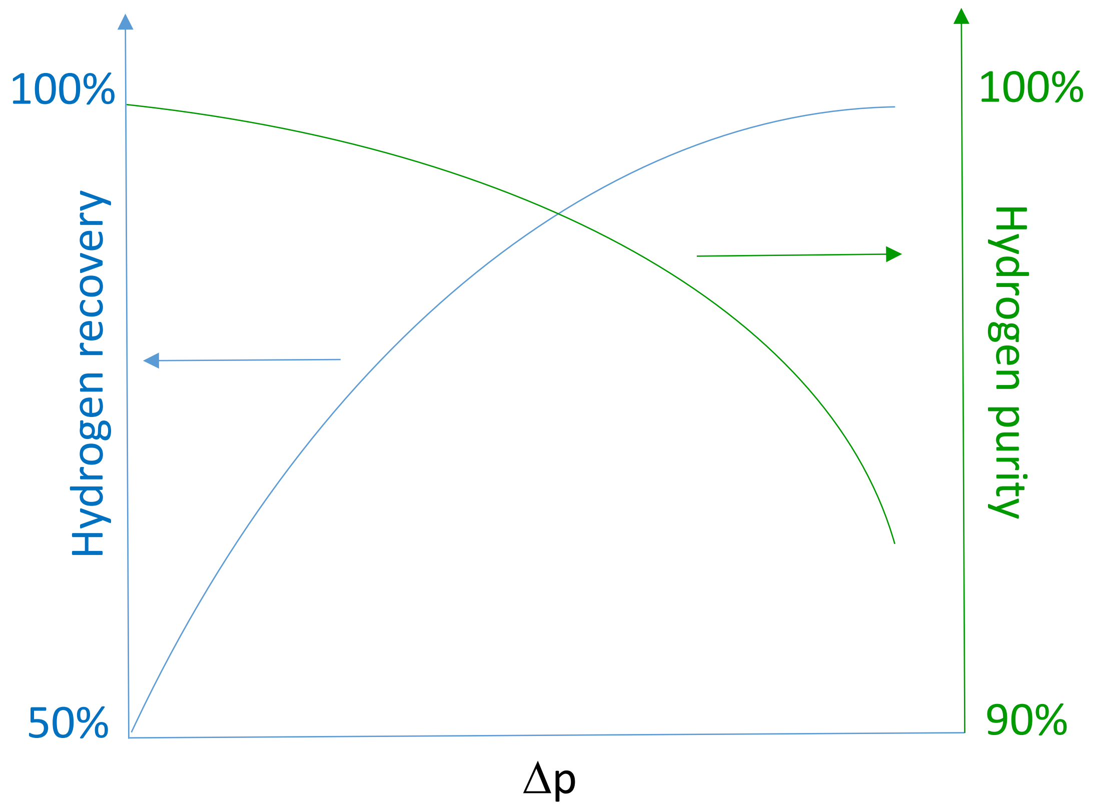
K_{H2}^0 is a pre-exponential membrane permeability constant, $E_{a.H2}$ is the activation energy of hydrogen permeation, R is the universal gas constant and T is the absolute temperature

Richardson equation

$$J_{H_2} = \frac{K_{H_2}^0.\exp\left(-\frac{E_{a.H_2}}{RT}\right)}{\delta}\left(p_{H_2,ret}^{n} - p_{H_2,perm}^{n}\right)$$

Y. Nalbant Atak, C.O. Colpan, A. Iulianelli, A review on mathematical modeling of packed bed membrane reactors for hydrogen production from methane, International Journal of Energy Research, 45 (2021) 20601-20633

Hydrogen recovery vs purity trade-off



Membrane Technologies in H_2 separation/purification

Bench-scale membrane modules used in Hybrid Membrane Separation Systems

Parameter	Hollow Fiber	PdAu/α-Al_2O_3
Length	0.25 m	0.25 m
Outer diameter	0.015 m	0.012 m
Material	Polyimide (Membrain s.r.o.)	Pd-Au alloy on α-Al_2O_3
Sealing	—	Graphite gaskets

a) Hollow fiber polyimide-based membrane module

VSB TECHNICAL UNIVERSITY OF OSTRAVA | CENTRE FOR ENERGY AND ENVIRONMENTAL TECHNOLOGIES

b) Pd-Au/α-Al_2O_3 tubular membrane module

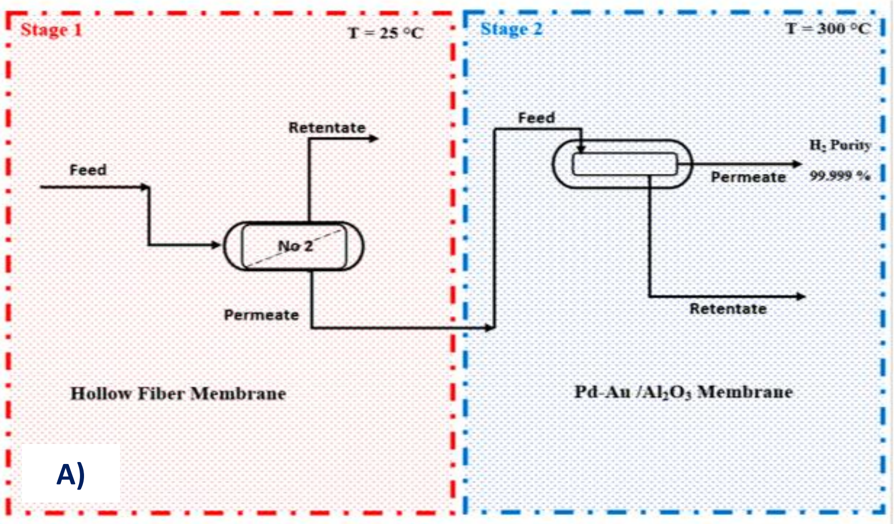
南京工業大學 NANJING TECH UNIVERSITY

H_2 separation/purification by membrane technology

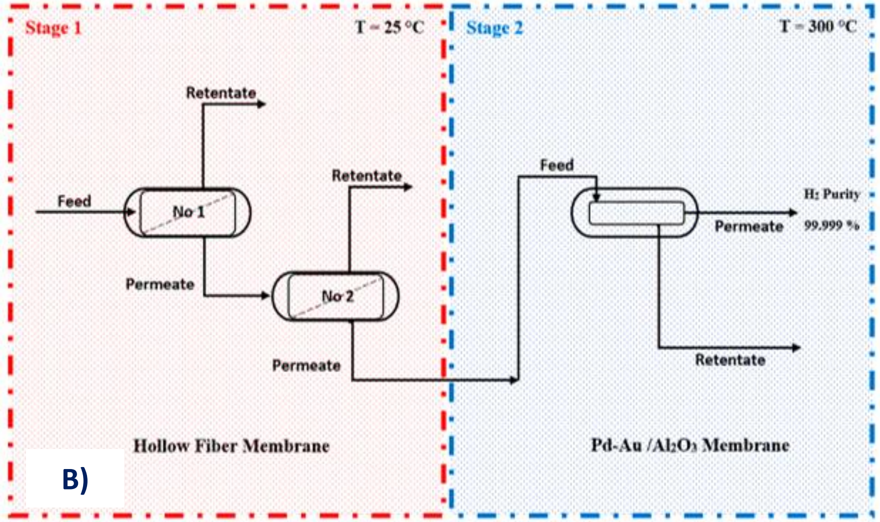
REFRESH

CNR

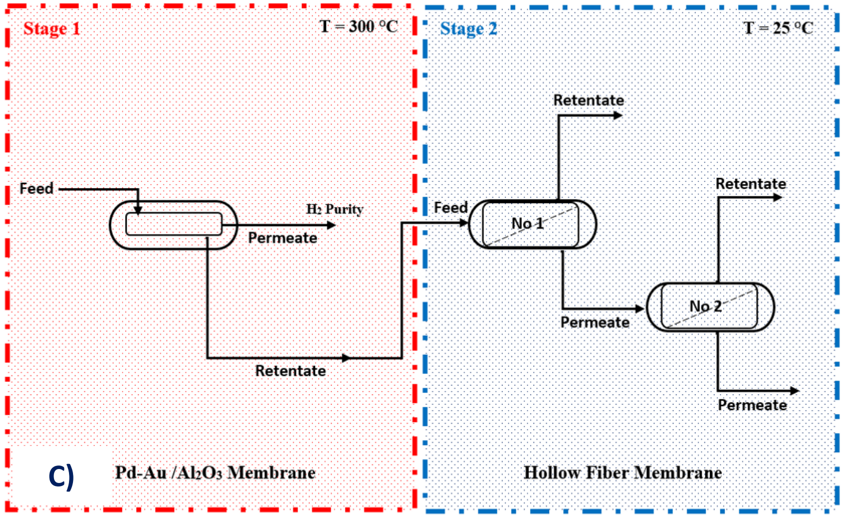
Case (A)



Case (B)

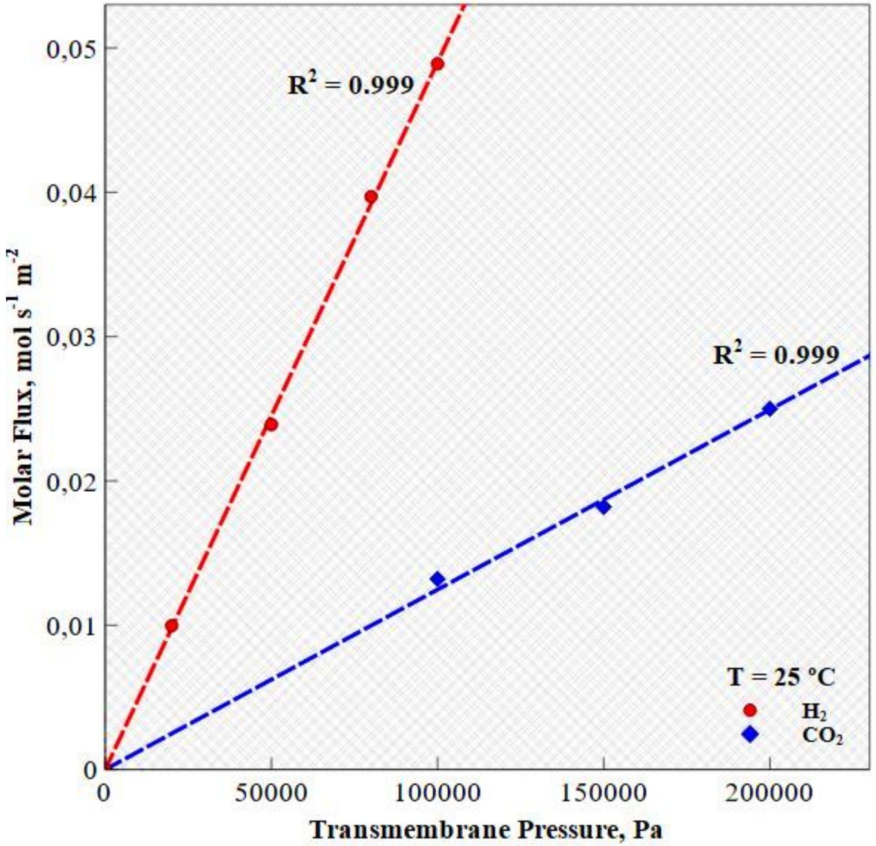


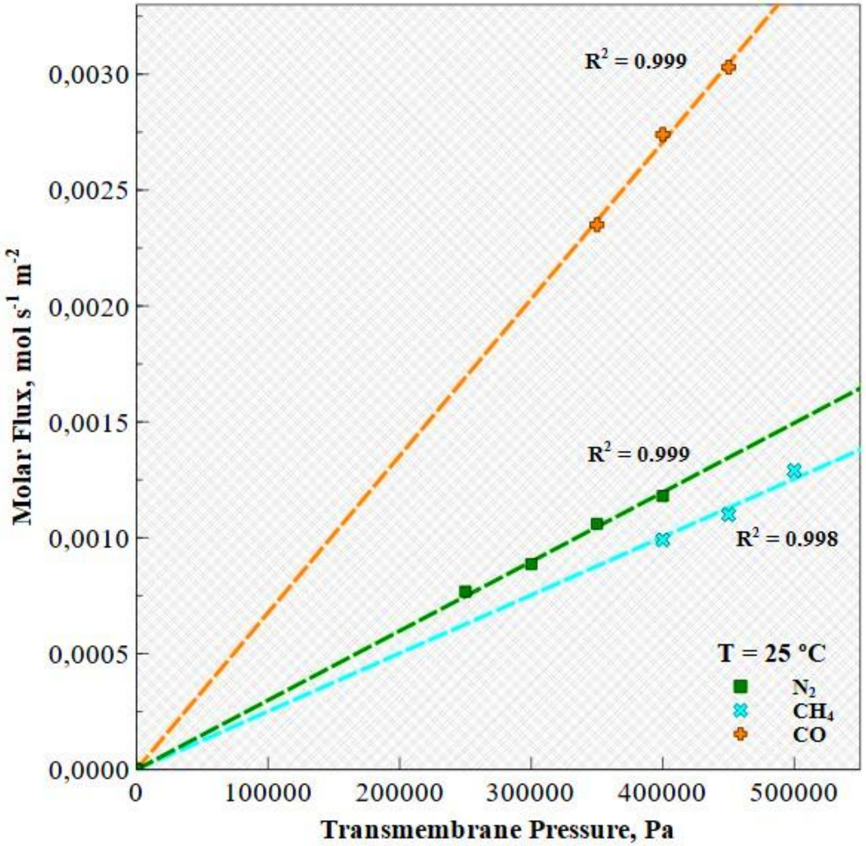
Case (C)



Three Hybrid Configurations Tested

Hollow Fiber Membranes — Permeance at 25 °C

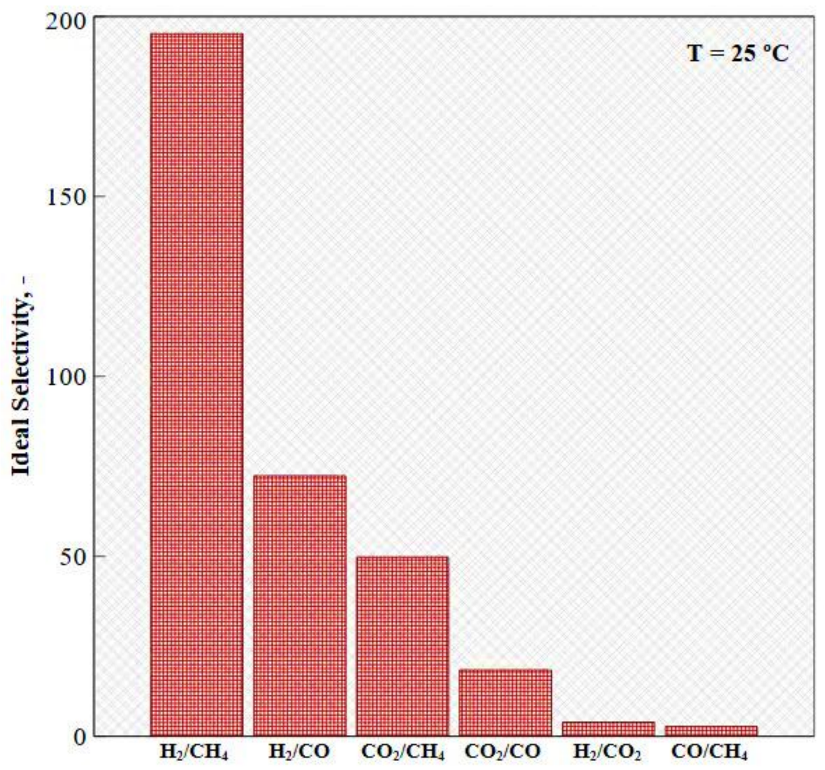




Component	Permeance (mol s^{-1} m^{-2} Pa^{-1})
H_2	4.90×10^{-7}
CO_2	1.25×10^{-7}
CO	6.77×10^{-9}
N_2	3.00×10^{-9}
CH_4	2.51×10^{-9}

Molar flux vs. transmembrane pressure difference, single-gas conditions (H_2, CO_2 and N_2, CH_4, CO)

Hollow Fiber Membranes — Ideal Selectivity



195

H_2 / CH_4 selectivity

Above Robeson's upper bound (2008)

72

H_2 / CO selectivity

4.0

H_2 / CO_2 selectivity

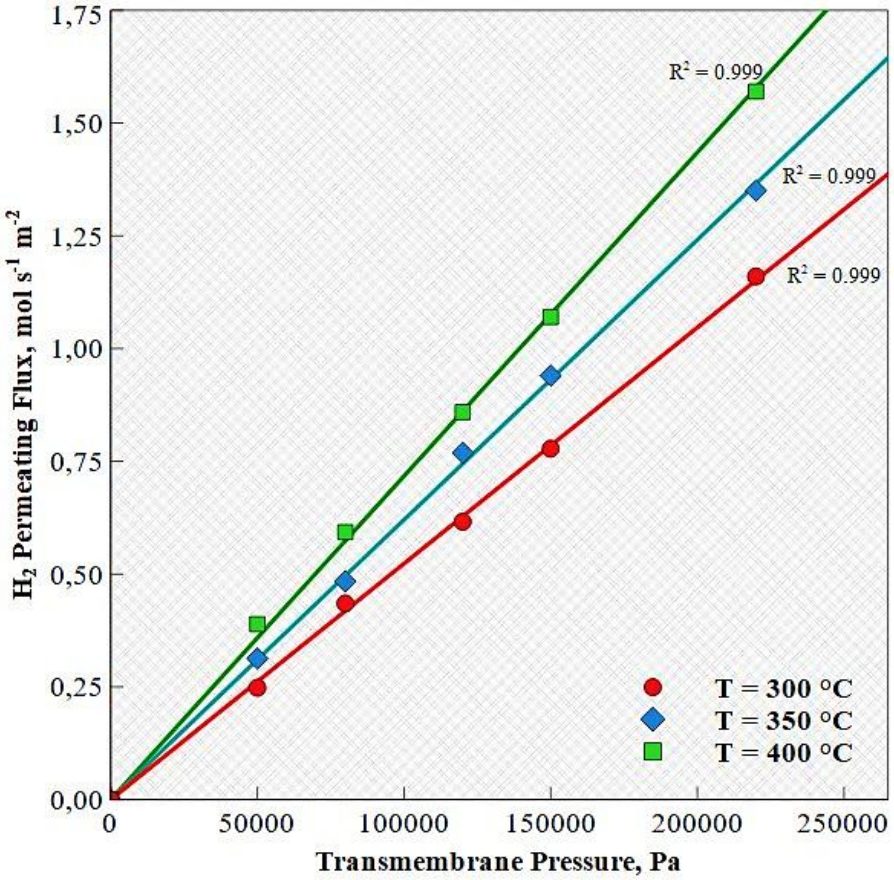
Below Robeson's upper bound (2008)

25 °C

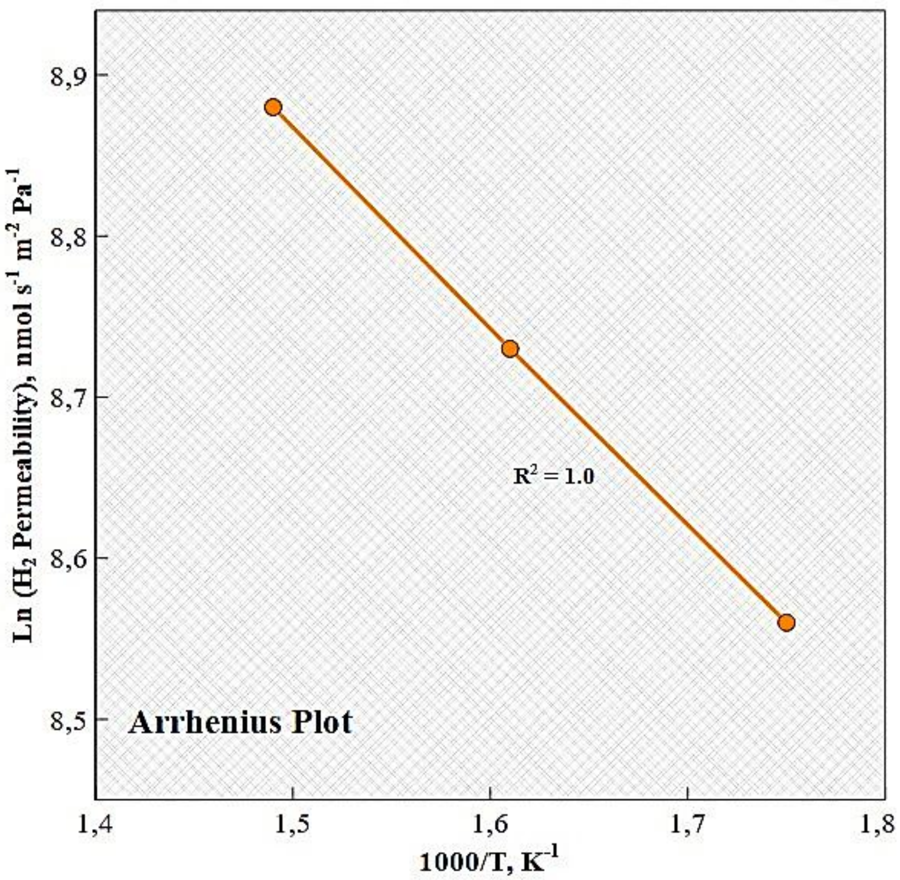
Testing temperature

Selectivity governed by the solution-diffusion mechanism: hydrogen's small kinetic diameter and high diffusivity dominate over CH_4 and CO, while moderate H_2/CO_2 selectivity reflects CO_2's higher condensability/sorption in the polyimide matrix.

Pd-Au/α-Al_2O_3 Membrane — Temperature Effect



H_2 flux vs. Δp at 300 / 350 / 400 °C



Arrhenius plot (ln P vs. 1/T)

10.13

Apparent E_a (kJ·mol^{-1})

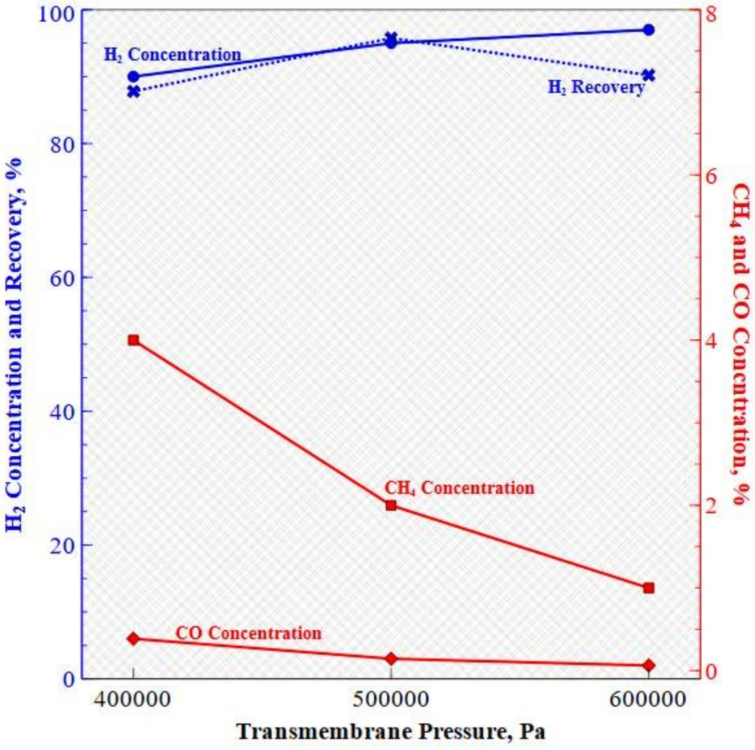
No CO_2, CH_4 or CO permeation detected up to 6×10^5 Pa — defect-free, fully H_2-selective Pd layer.

H_2 separation/purification by membrane technology

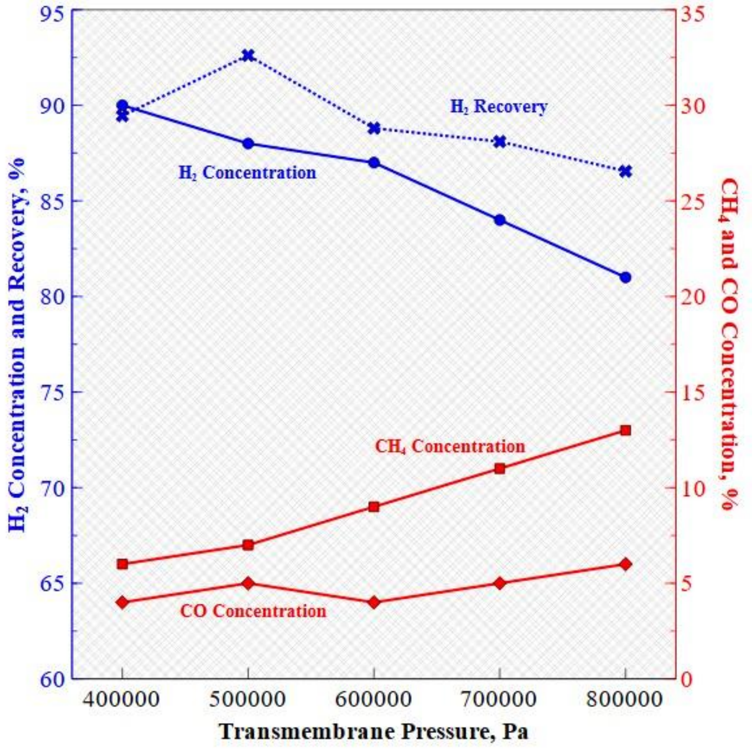
Coke Oven Gas, Feed

H_2 = 60 %
CH_4 = 30 %
CO = 10 %

Hollow Fiber Membrane Performance



a) Two HF membranes in series, Configuration (i)— 25 °C



b) Single HF membrane, Configuration (ii) — 25 °C

H_2 a)

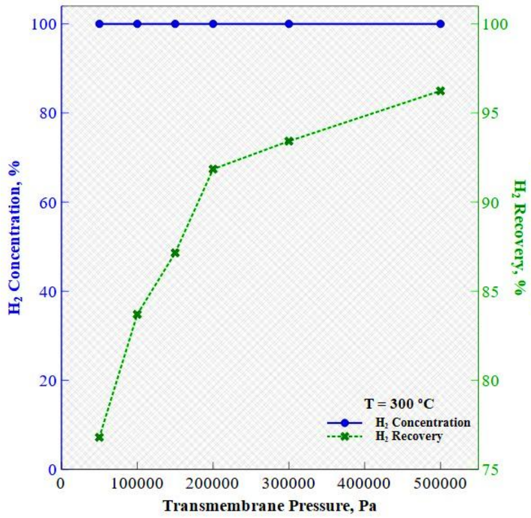
96.1%	95.8%
Purity (i)	max. recovery (i)

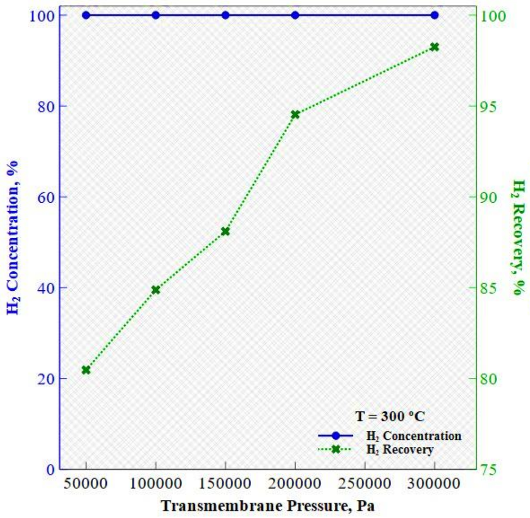
H_2 b)

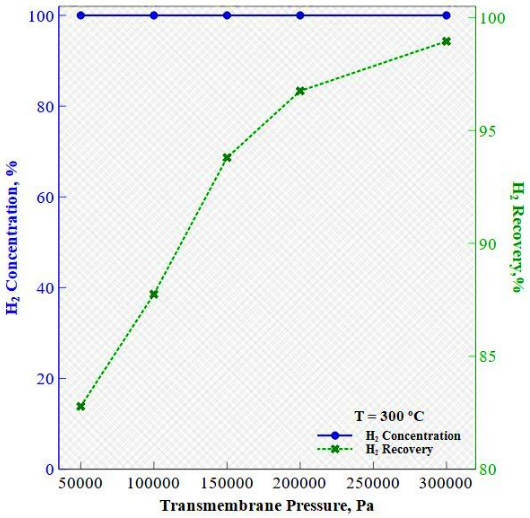
90.0%	92.3%
Purity (ii)	max. recovery (ii)

H_2 separation/purification by membrane technology

Configuration (B): HF-Series Permeate → Pd-Au Membrane







Feed from HF-series permeate at

a) 4×10^5 b) 5×10^5 c) 6×10^5 Pa

94.7%

Best global H_2 recovery — Case B (meets the 2030 Clean Hydrogen Alliance target)

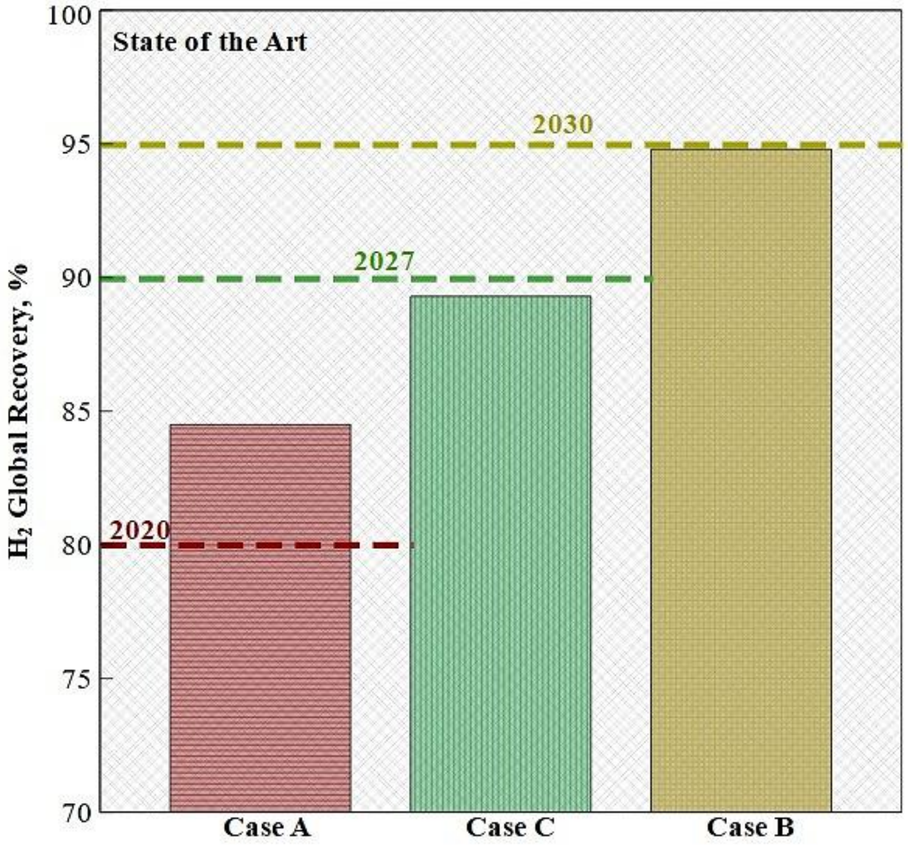
~ 600 h under operation

Stage-wise and overall H_2 recovery, Configuration (i)

Case	Δp, Stage 1	Δp, Stage 2	Recovery Stage 1	Recovery Stage 2	Global Recovery	Purity
A	4×10^5 Pa	5×10^5 Pa	87.8 %	96.2 %	84.5 %	>99.99 %
B	5×10^5 Pa	3×10^5 Pa	95.8 %	98.8 %	94.7 %	>99.99 %
C	6×10^5 Pa	3×10^5 Pa	90.2 %	98.9 %	89.3 %	>99.99 %

Configuration (i): Global H_2 Recovery vs Clean Hydrogen Alliance Targets

All three cases surpass the 2024 target; Case B approaches the 2030 target while keeping a single ultrapure H_2 stream (>99.99%).



94.7%

Case B — nearly meets 2030 target (95%)

89.3%

Case C — exceeds 2024 target (80%)

84.5%

Case A — exceeds 2024 target (80%)

Membrane Technologies in decarbonized H_2 production

PLUG-IN project: Process for Low-carbon blUe/hydrogen Generation via Intensified electrified reforming of biogas/natural gas; Project budget: 1.8 MEuros

Renewable Energy 210 (2023) 472–485

Contents lists available at ScienceDirect

Renewable Energy

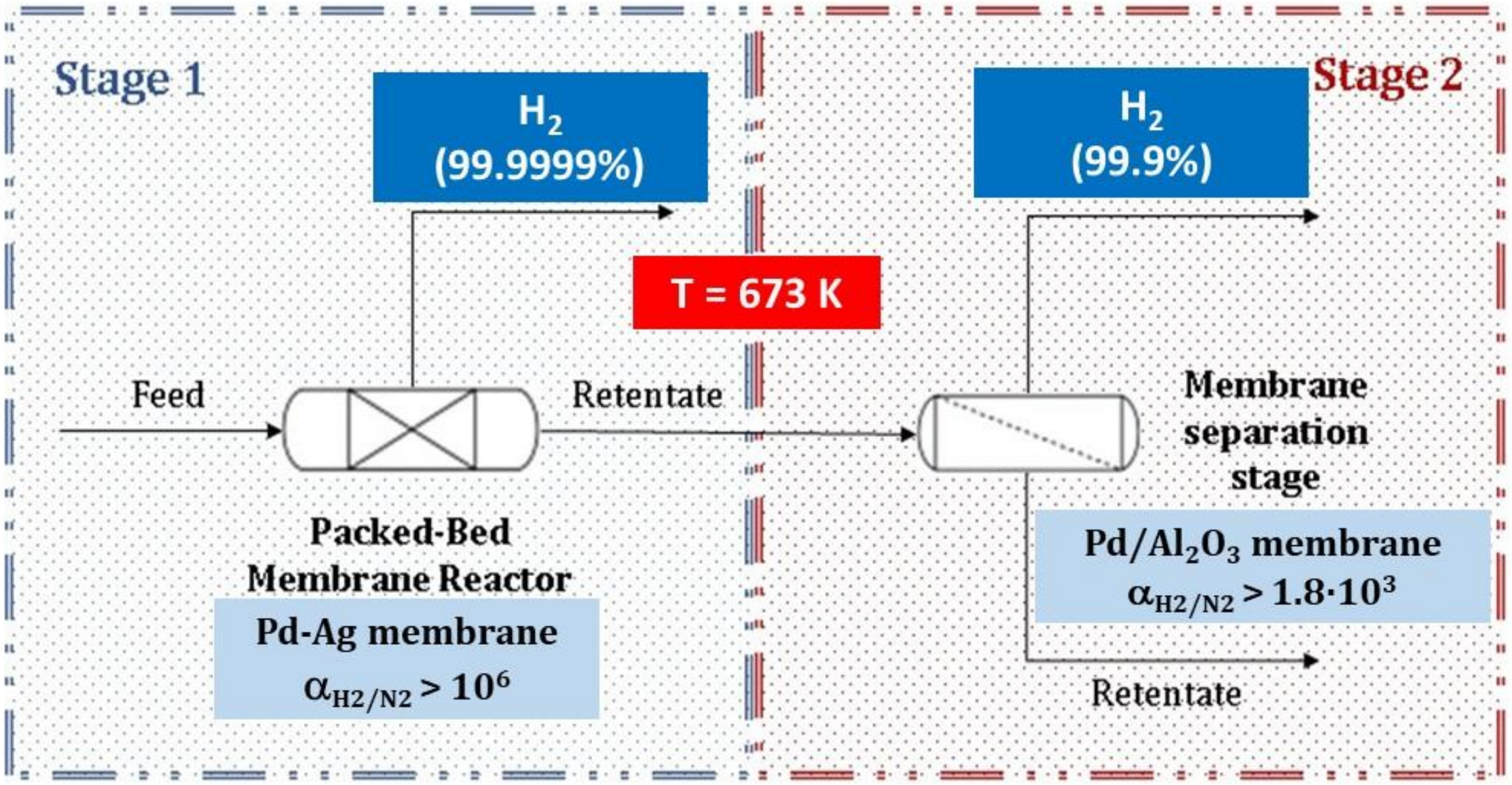
journal homepage: www.elsevier.com/locate/renene

An integrated two stages inorganic membrane-based system to generate and recover decarbonized H_2: An experimental study and performance indexes analysis

Adolfo Iulianelli [a,*,1], Adele Brunetti [a,1], Lidia Pino [b], Cristina Italiano [b,**], Giovanni Drago Ferrante [b], Mario Gensini [a], Antonio Vita [b]

[a] Institute on Membrane Technology of the National Research Council of Italy (CNR-ITM), via P. Bucci 17C, 87036, Rende, CS, Italy
[b] The Advanced Energy Technology Institute of the National Research Council of Italy (CNR-ITAE), Salita Santa Lucia Sopra Contesse 5, 98126, Messina, ME, Italy

Parameter	Stage 1	Stage 2	Target	Integrated system
CH_4 conversion	> 99%	-	-	> 99%
H_2 recovery	40%	67%	80%	80%
H_2 recovered stream purity	> 99.9999%	99.9%	99.99%	99.99%
Net CO_2 reduction	92%	-	-	92%
Conversion index	18[a]	-	-	18[a]
H_2 yield index	5	-	-	5



VSB TECHNICAL UNIVERSITY OF OSTRAVA

INTERNATIONAL ENERGY AND ENVIRONMENT CONFERENCE
SEPTEMBER 7–9, 2026
HOTEL SEPETNÁ OSTRAVICE

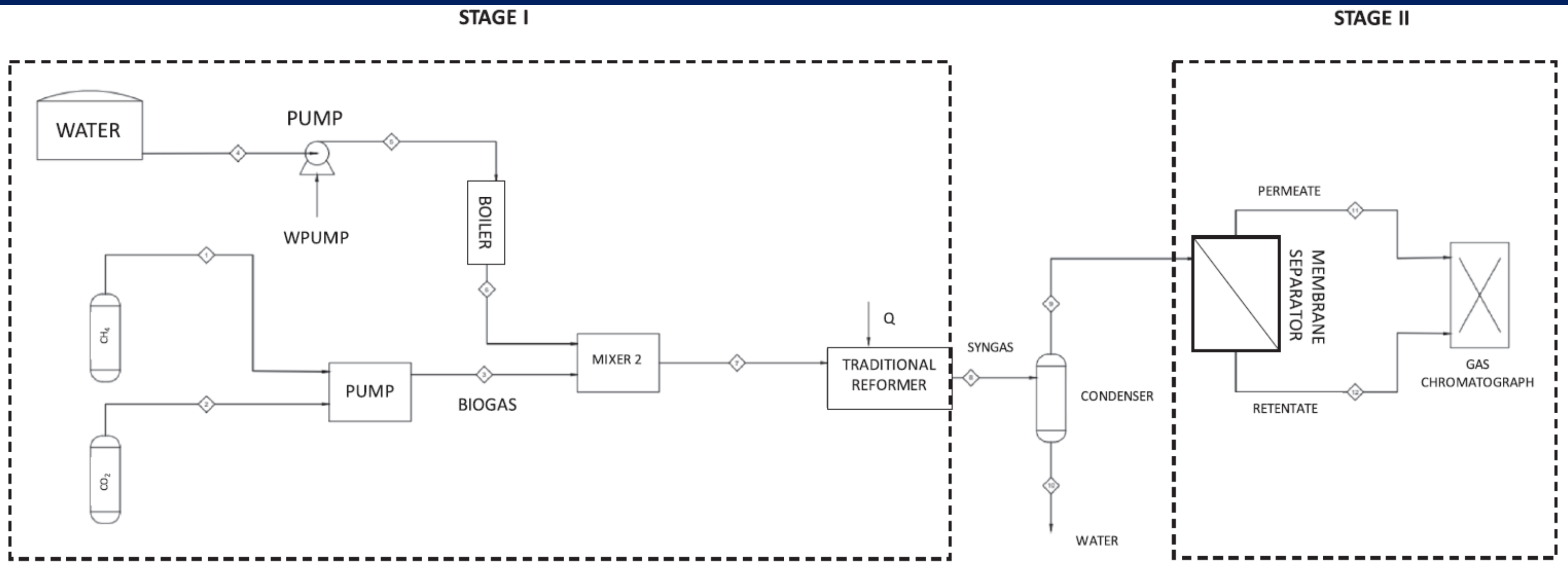
Consiglio Nazionale delle Ricerche

Operational Plan for H_2 Research

NextGenerationEU – Program Agreement MASE/ENEA/CNR/RSE, M2C2 Investiment 3.5 – PNRR, Project: Research & Development on H_2
Total budget: 110M EUR

Integrated reformer + Pd-membrane-separation system to recover decarbonised H_2 from biogas reforming

Finanziato dall'Unione europea
NextGenerationEU
MINISTERO DELL'AMBIENTE E DELLA SICUREZZA ENERGETICA

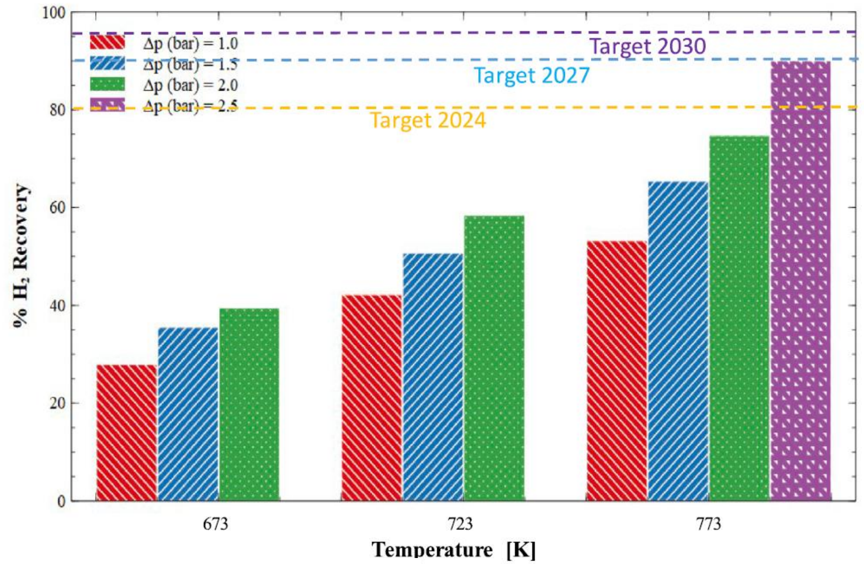


EU TARGETS

H_2 recovery: **80%** (2024); **90%** (2027); **95%** (2030)

H_2 purity: **99.99%**

Clean Hydrogen Alliance under the Strategic Research & Innovation Agenda 2021-2027



Energy Conversion and Management 315 (2024) 118748

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

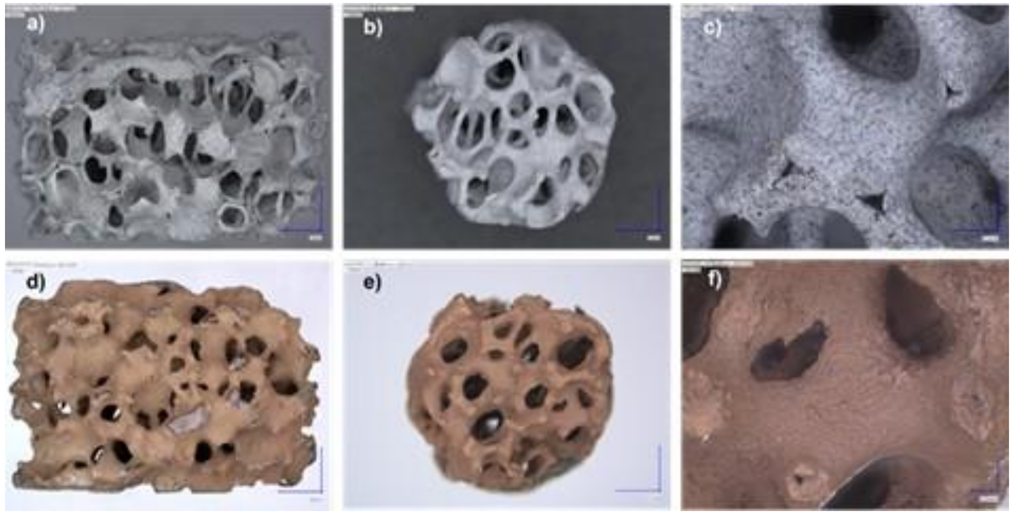
ELSEVIER

Reformer + Membrane separator plant for decarbonized hydrogen production from Biogas/Biomethane: An experimental study combined to energy efficiency and exergy analyses

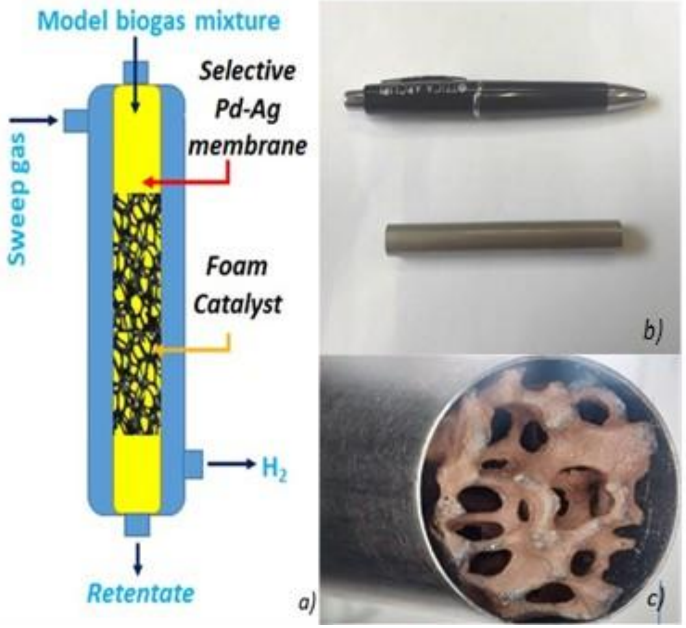
Henry Bryan Trujillo Ruales [a], Alex Spadafora [a,b], Piergiuseppe Fiore [a], Jan Veres [c], Alessio Caravella [b], Adolfo Iulianelli [a,*]

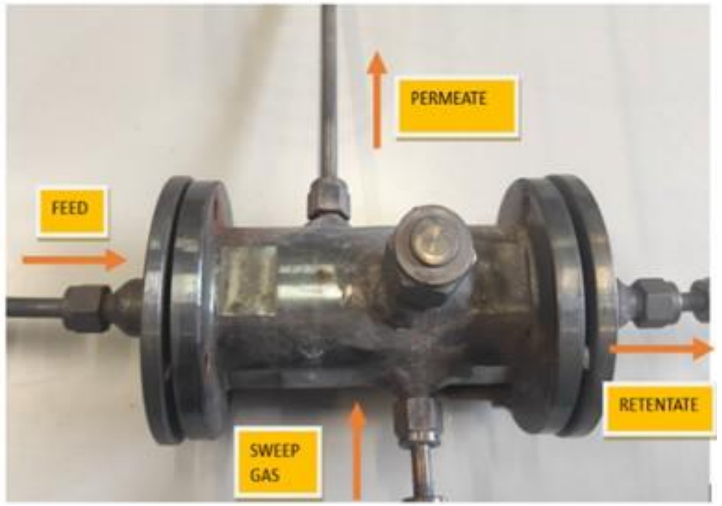
Foam structured membrane reactor

Finanziato dall'Unione europea
NextGenerationEU

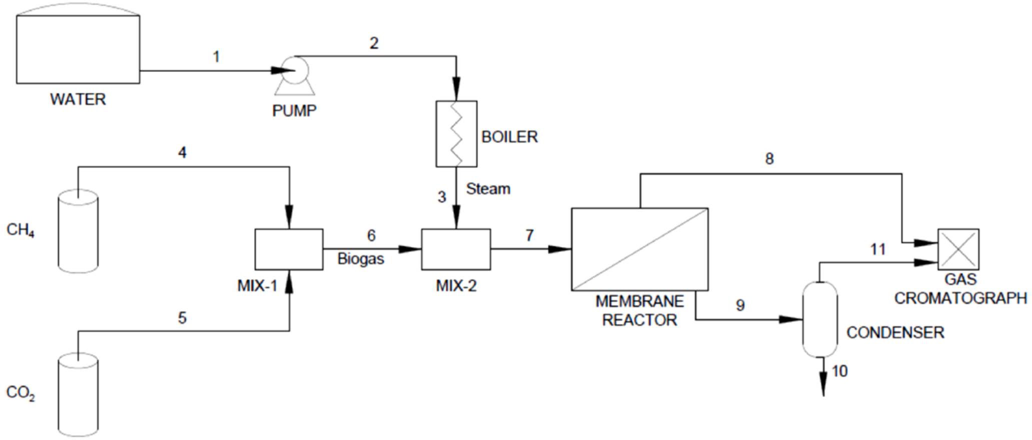


Images of bare (a – c) coated (d – f) 40PPI SIC foam after calcination step (by CNR-ITAE)





a) schematic view of the foam structured membrane reformer; b) Pd-Ag tubular membrane; c) Ni-Ru foam structured catalyst inserted in the lumen of the Pd-Ag membrane



Energy Conversion and Management 326 (2025) 119504

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

ELSEVIER

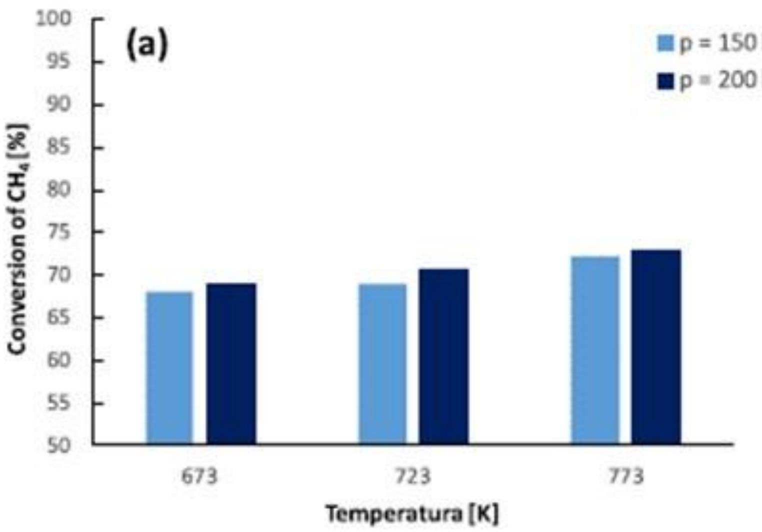
Research Paper

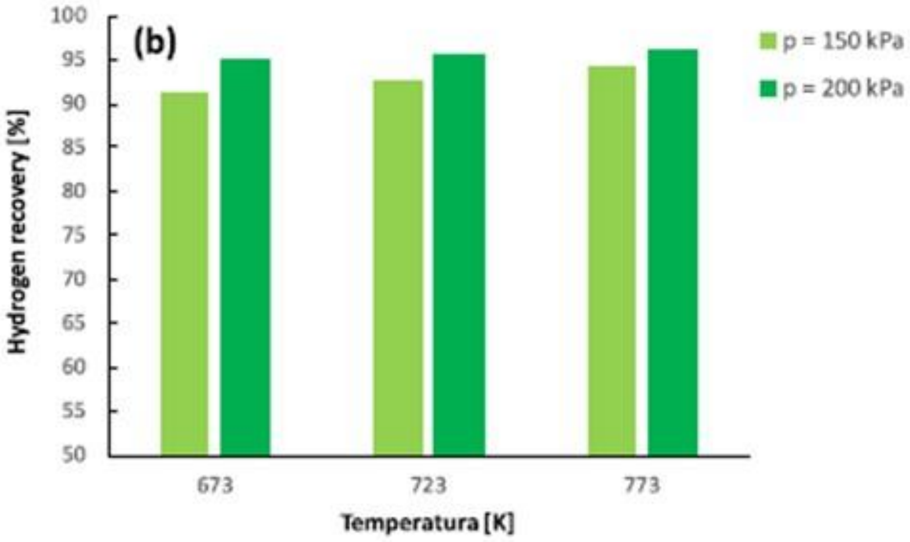
Low impact emissions H_2 production via biogas steam reforming in a foam structured membrane reactor: Energy efficiency and exergy analyses, and H_2 production cost assessment

H.B.Trujillo Ruales [a], C. Italiano [b], A. Vita [b], A. Iulianelli [a,*]

[a] National Research Council - Institute on Membrane Technology (CNR-ITM), via P. Bucci 17C, 87036 CS, Italy
[b] National Research Council - Institute for Advanced Energy Technologies (CNR-ITAE), Via Salita S. Lucia sopra Contesse, 5 - 98126 Messina, ME, Italy

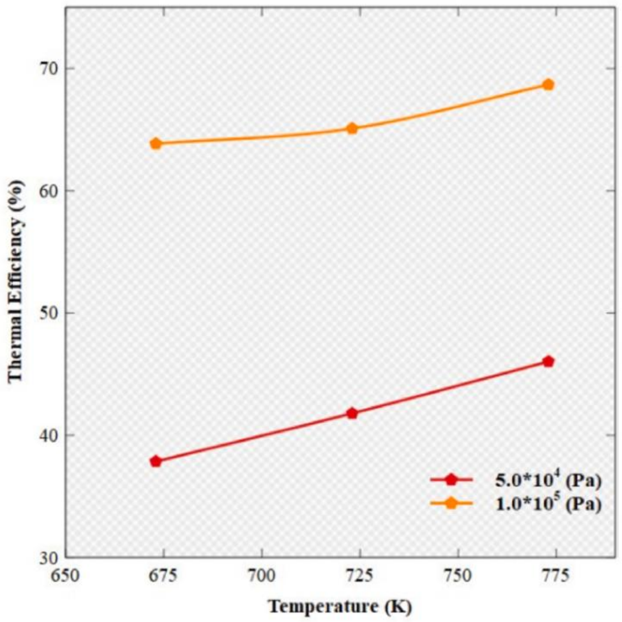
Foam structured membrane reactor

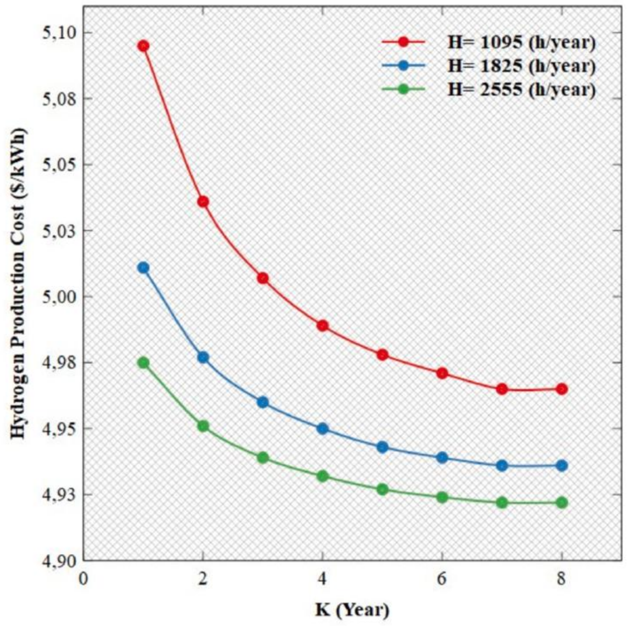




H_2 purity
> 99.99%

Energy Efficiency
~ 70%





EU TARGETS

H_2 recovery: **80%** (2024); **90%** (2027); **95%** (2030)

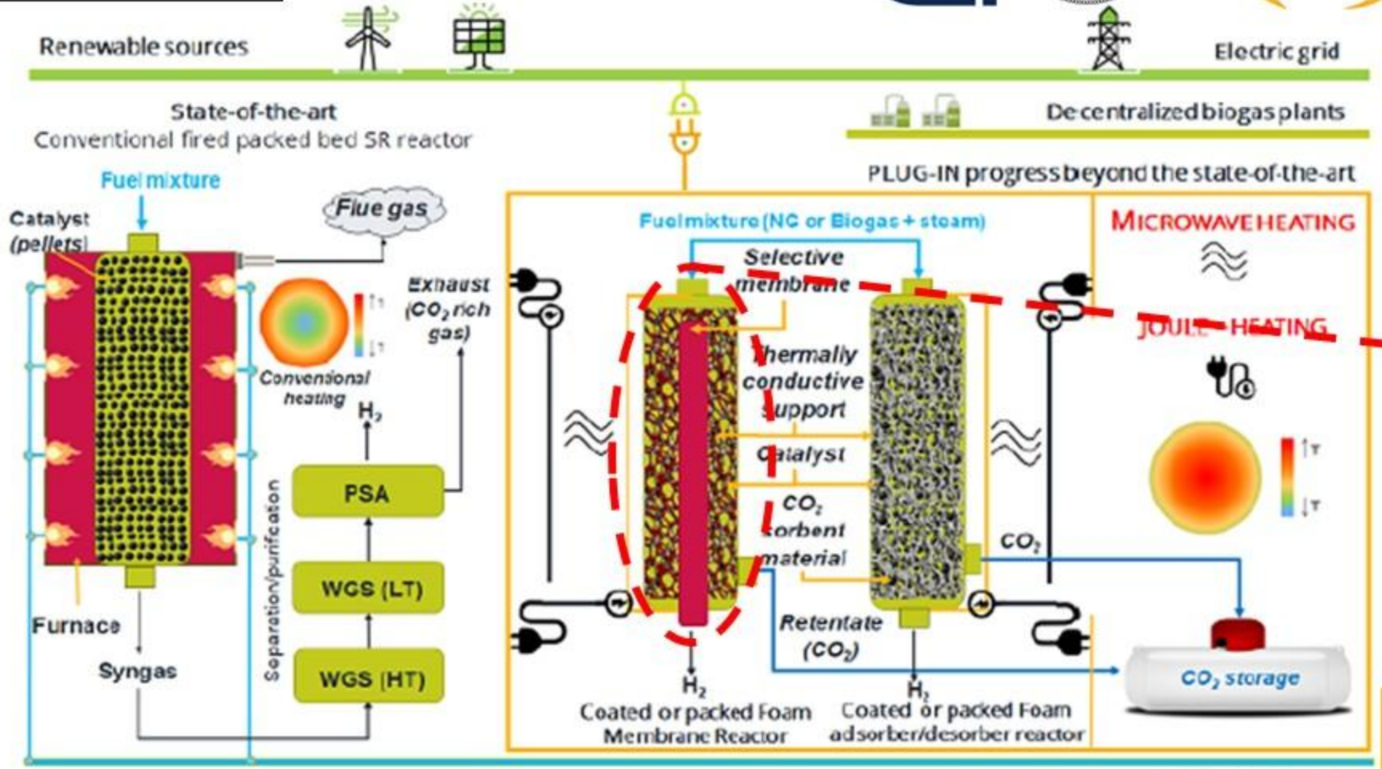
H_2 purity: **99.99%**

Clean Hydrogen Alliance under the Strategic Research & Innovation Agenda 2021-2027

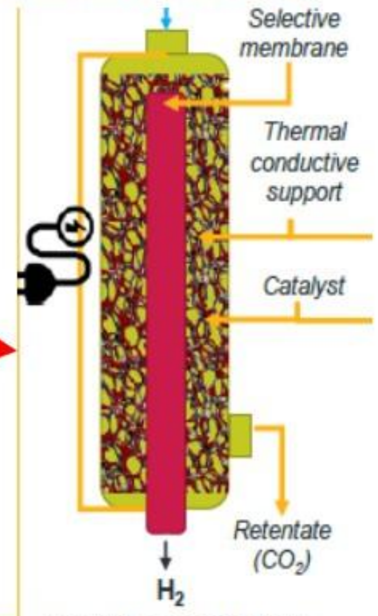
Consiglio Nazionale delle Ricerche

Electrification of a foam structured membrane reformer to generate pure H_2

PRIN 2020



Intensified blue H_2 production/purification membrane reactor-based system



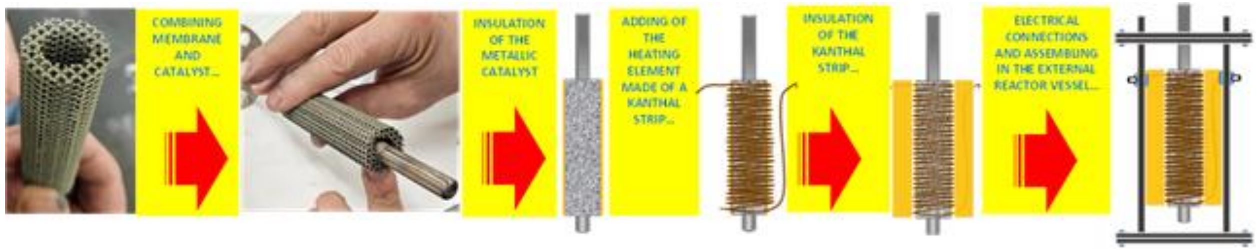
Institute on Membrane Technology
National Research Council of Italy

- *Study of generation and simultaneous H_2 purification of H_2 from biogas as bio-alternative to natural gas by Pd/Pd-alloys membranes housed in membrane reformers*
- *Electrification of the membrane reformer with the renewable energy surplus of the grid to generate decarbonized H_2*

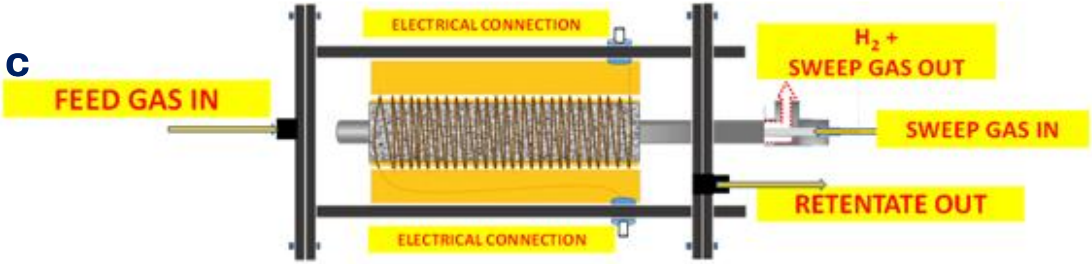
PRIN (Research Program of relevant National Interest) Project – Bando MUR 2020 Prot. 2020N38E75, D.D. 2436 del 20/10/2021. **Budget: 893.000 €.**
CNR-ITM Scientific Responsible:
Dr. Adolfo IULIANELLI

Electrification of the foam structured membrane reactor

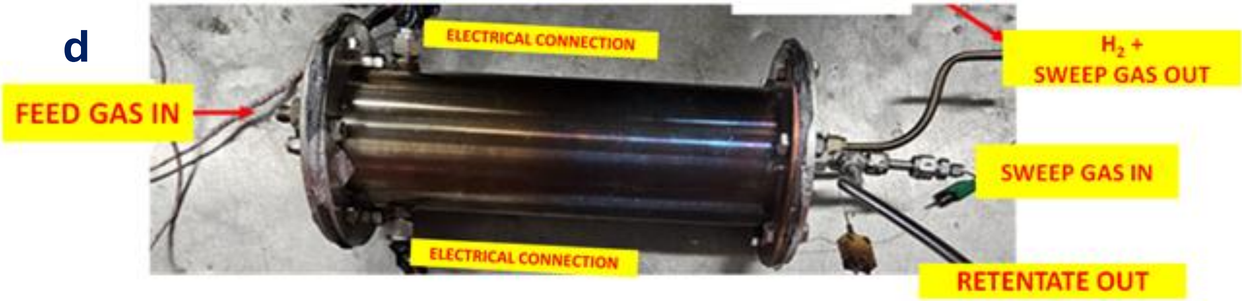
b



c



d



Chemical Engineering Journal 531 (2026) 174263

Contents lists available at ScienceDirect

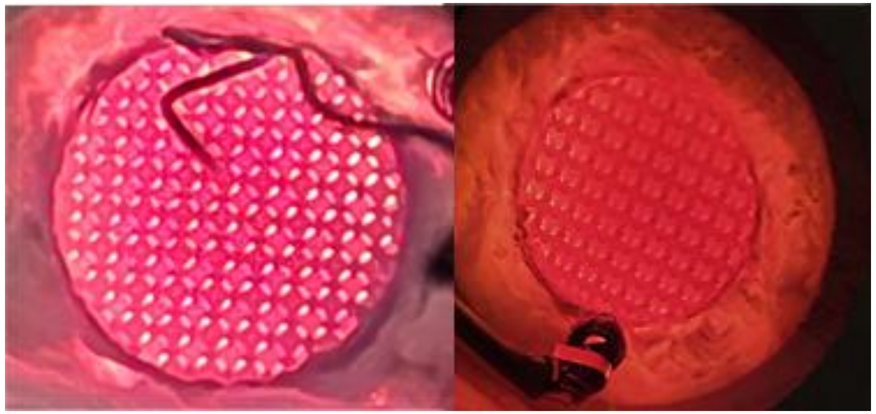
Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

Electrically assisted POCS-catalytic reactor with integrated dense Pd—Ag membrane for low-carbon hydrogen production via dry reforming of methane☆

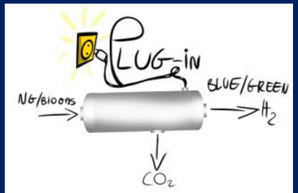
C. Ruocco[a,1], E. Meloni[a,*], A. Vita[b], C. Italiano[b,1], H. Brahim[b], A. Iulianelli[c,1], V. Palma[a]

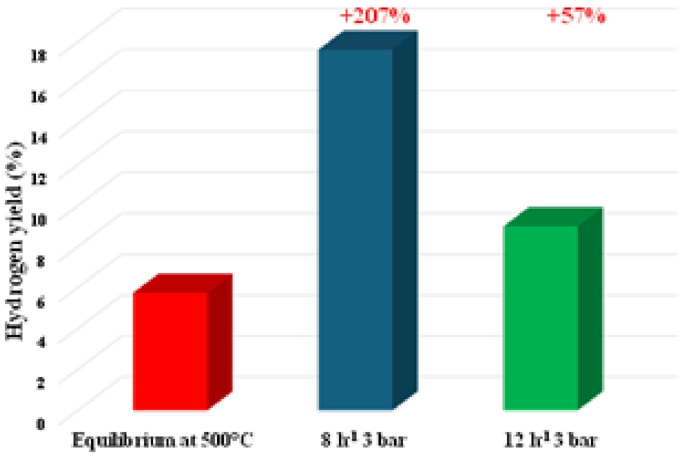
a

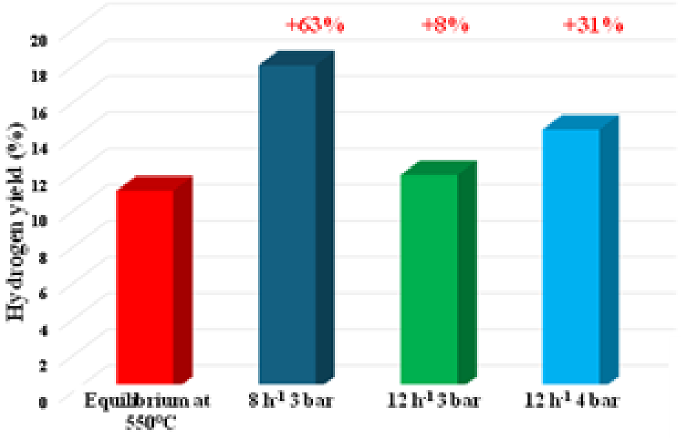


(a) Preliminary Joule-heating tests on cylindrical POCS samples at about 800°C, evidencing the absence of T gradients; (b) Schematic representation of the assembling steps of the electrically heated POCS-based MR and flow directions; (c) scheme of the final integrated MR; (d) photograph of the electrified MR used for the experiments.

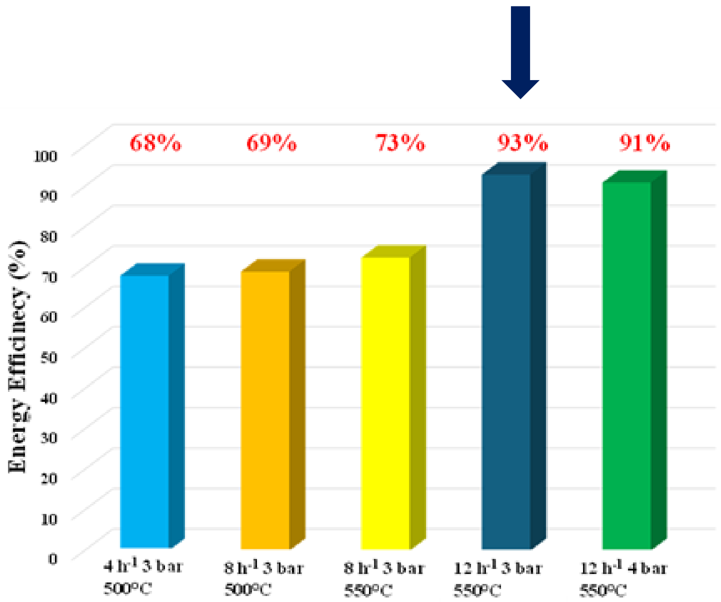
Electrification of the foam structured membrane reactor

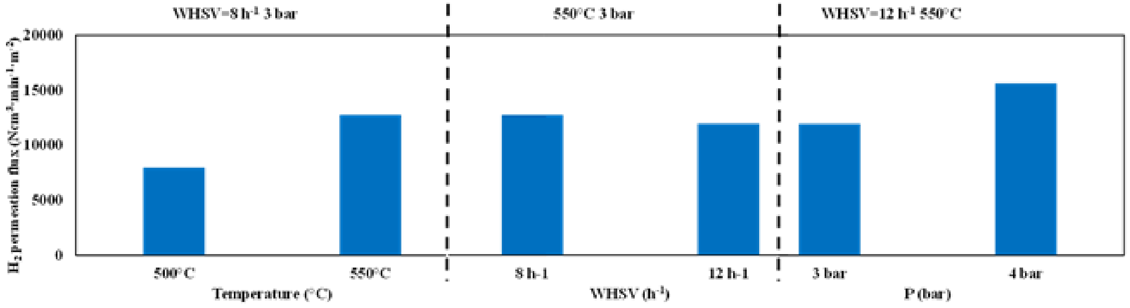






Comparison of hydrogen yields recorded at 500°C (left) and 550°C (right) as a function of space velocity between the electrically assisted foam structured membrane reactor and the equilibrium value of the equivalent conventional reactor





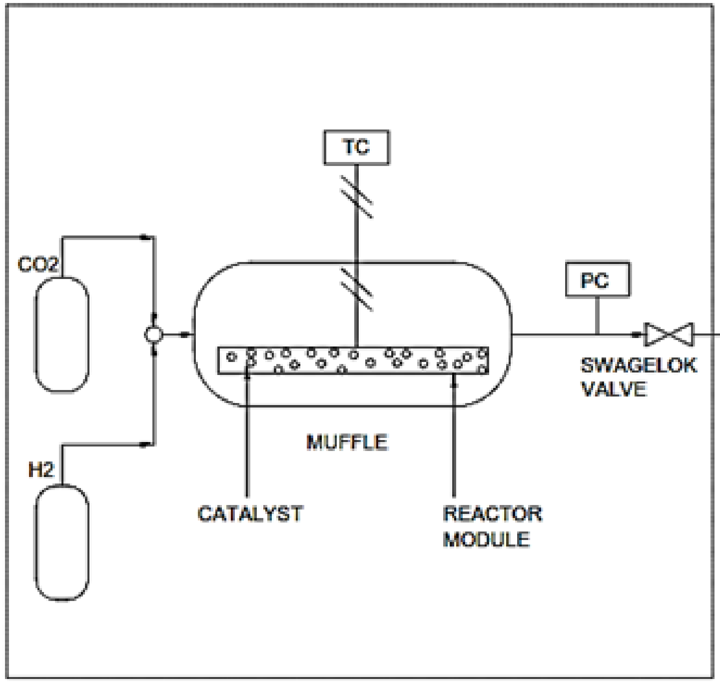
Effect of temperature (left), space velocity (middle) and pressure (right) on the hydrogen permeation flux through the Pd-Ag membrane

Consiglio Nazionale delle Ricerche

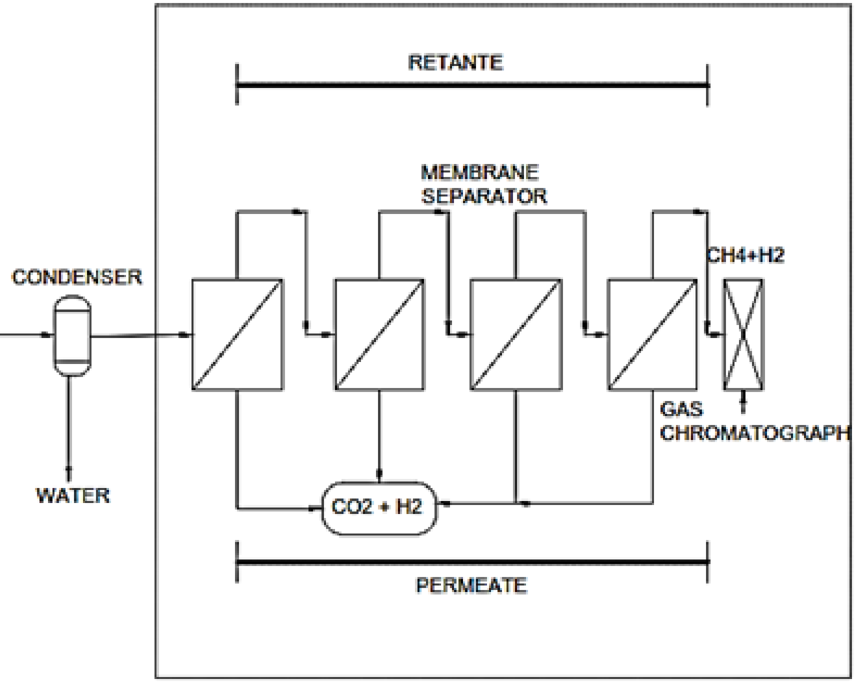
Membrane Technologies in H_2 chemical storage

Consiglio Nazionale delle Ricerche

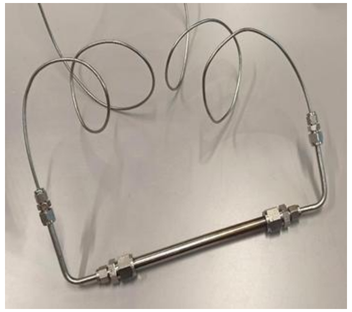
Hydrogen chemical storage through the CO_2 valorisation to e-methane generation



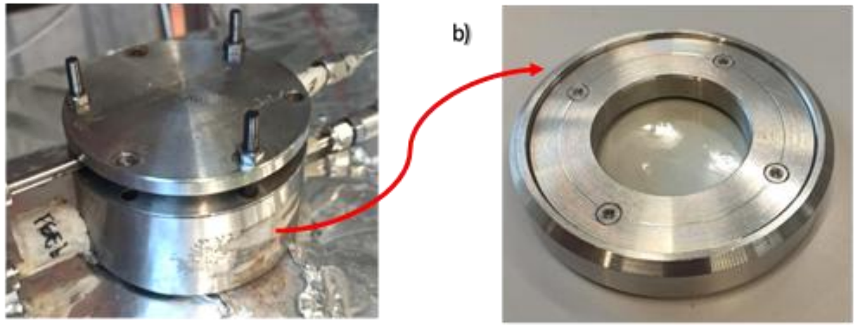
STAGE I: METHANATION REACTION



STAGE II: MEMBRANE SEPARATION



a)



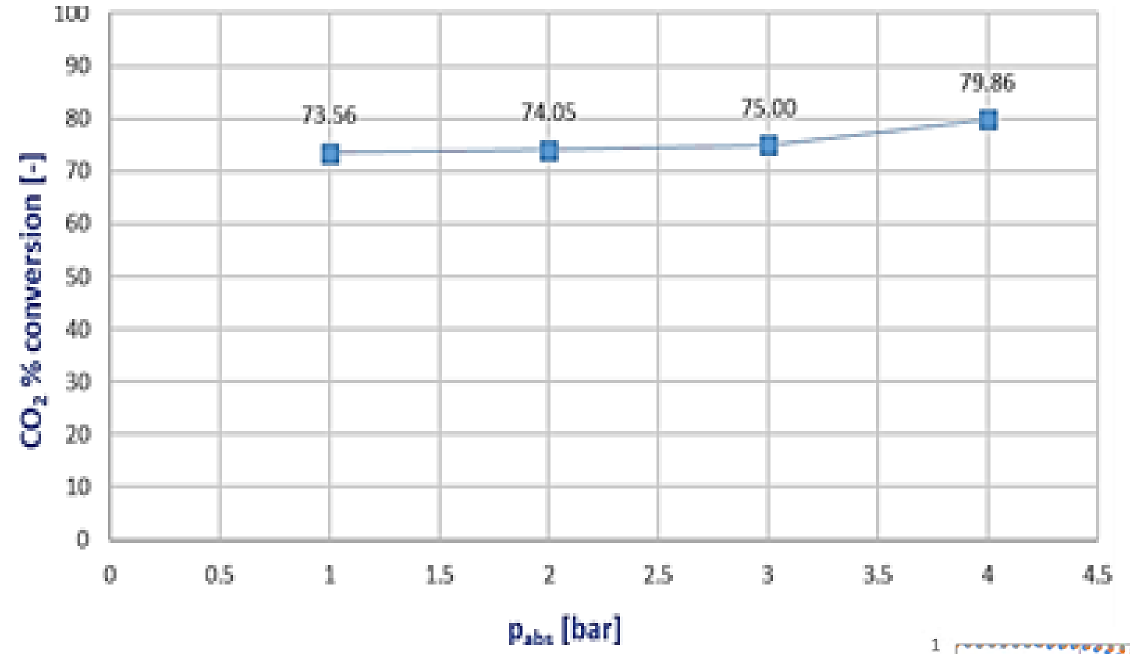
b)

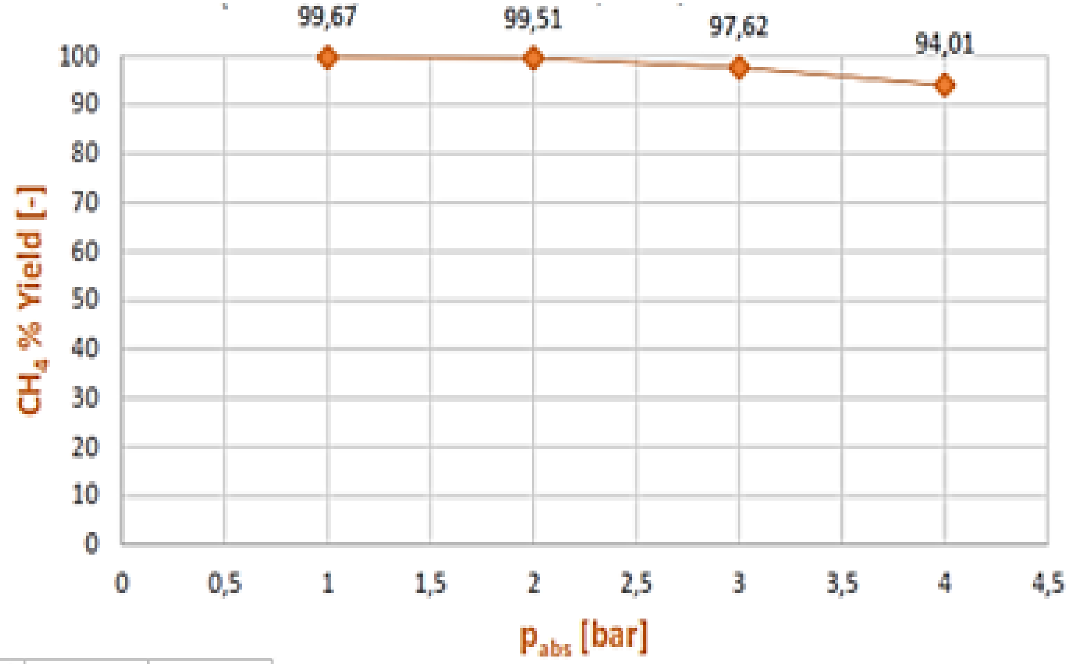
Expected outcomes (thermo-chemical)

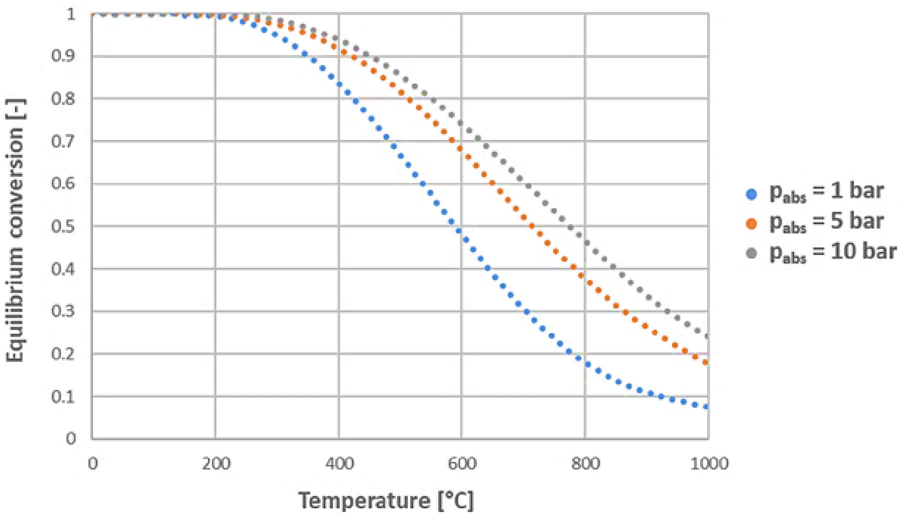
CO_2 conversion to a bioCH_4 grade stream:
($x_{CH4} \geq 97\%$; $x_{CO2} < 2\%$)
Energy efficiency > 70%;
Exergy efficiency > 90%
CO_2 conversion > 80%

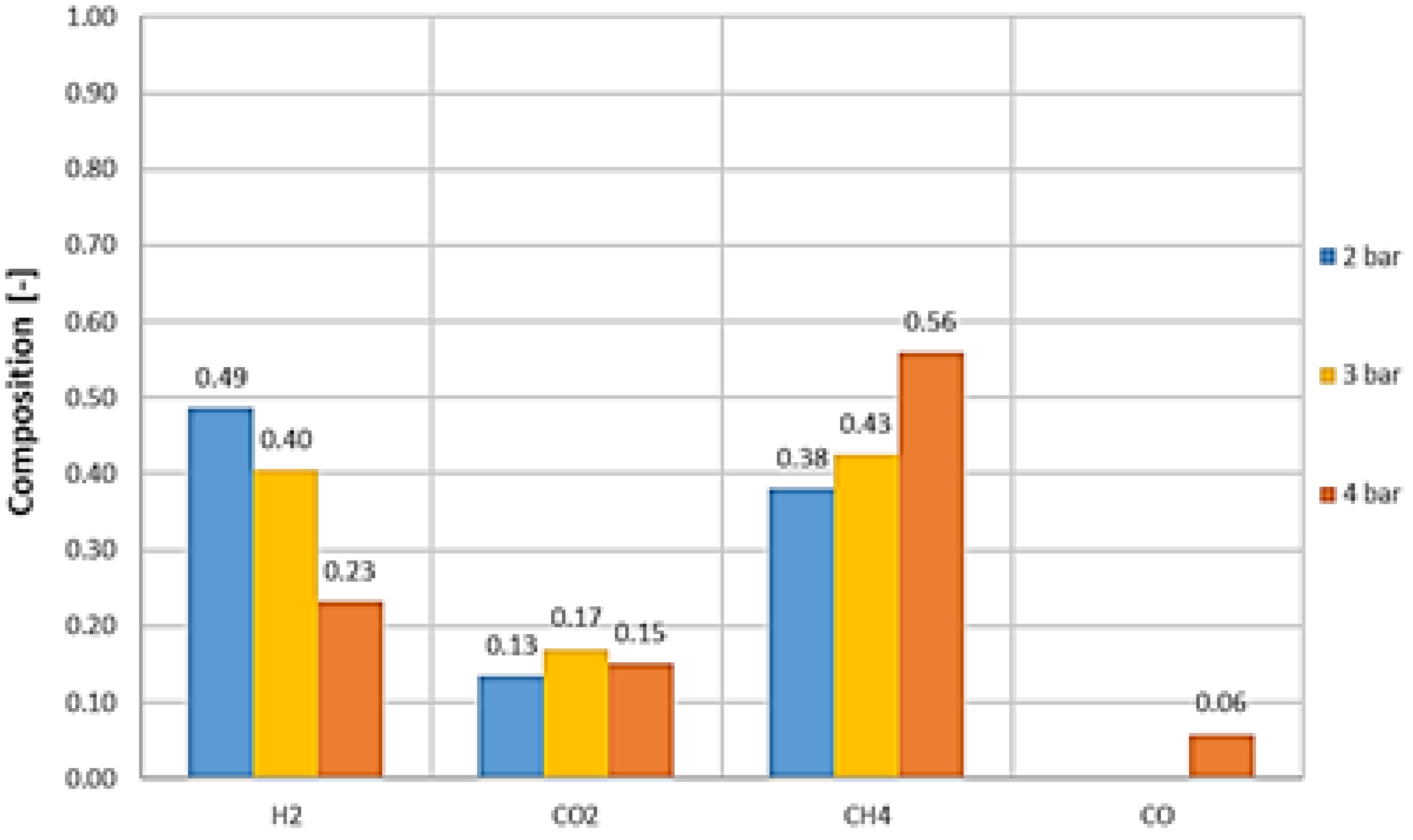
Hydrogen chemical storage: CO_2 valorisation for e-methane generation – *First stage process*

First stage: *methanation reactor*

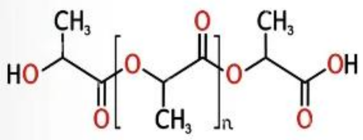




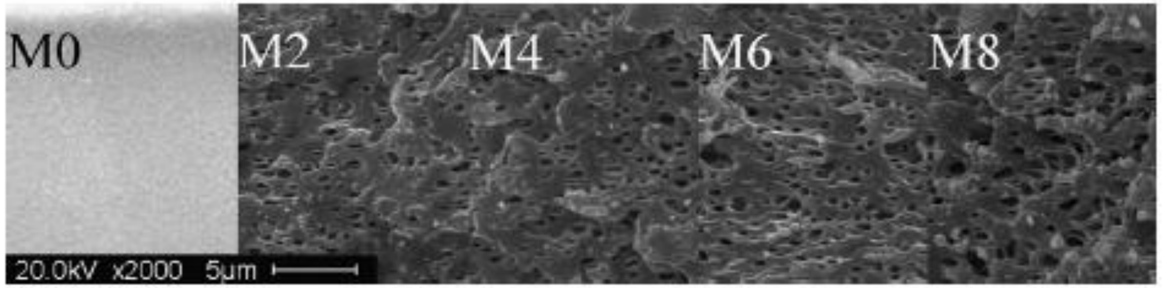



1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Composition [-]
0.49
0.40
0.23
0.13
0.17
0.15
0.38
0.43
0.56
0.06
H2
CO2
CH4
CO
2 bar
3 bar
4 bar

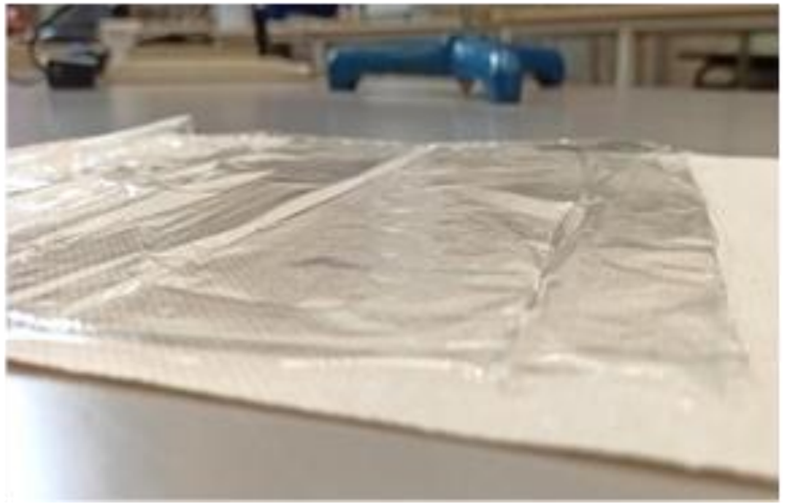
Sustainable polymeric membrane gas separation – *Bio-polymeric membranes*



Polylactic acid (PLA)



PLA dense and porous membranes



International Journal of Greenhouse Gas Control 117 (2022) 103657

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

ELSEVIER

Novel bio-polymer based membranes for CO_2/CH_4 separation

A. Iulianelli [†,*], F. Russo [†], F. Galiano, M. Manisco, A. Figoli [*]

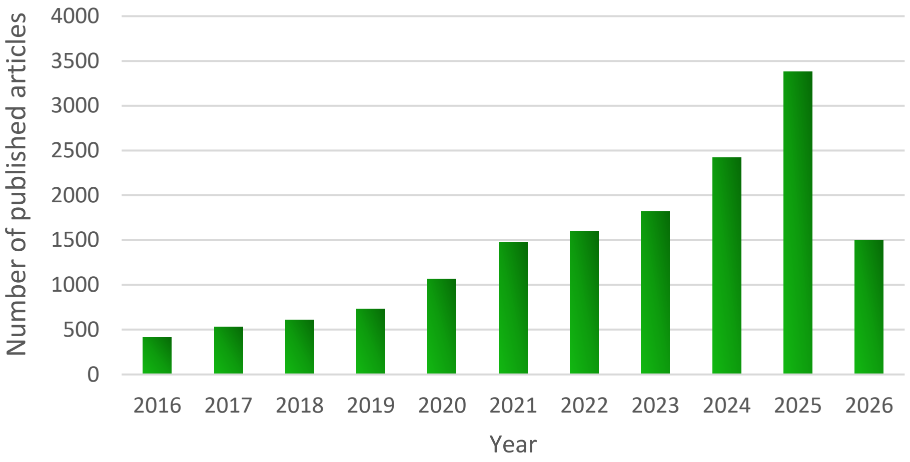
Institute on Membrane Technology of the National Research Council of Italy (CNR-ITM), via P. Bucci 17/C, Rende, (CS) 87036, Italy

Advantages of biopolymer membrane

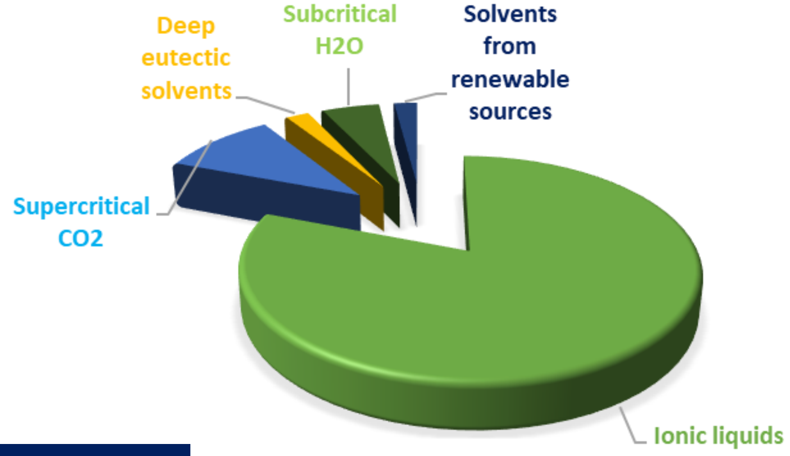
- **Biodegradability**
- **Biocompatibility**
- **Low Environmental impact**

Sustainable polymeric membrane gas separation – *Bio-polymeric membranes preparation by green solvent*

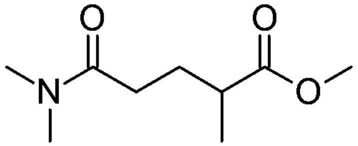
The interest in the use of biopolymers for membrane preparation is steadily increasing, as demonstrated by the trend in the number of publications over the last 10 years.



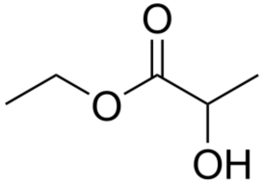
Proportion of articles addressing different classes of green solvents.



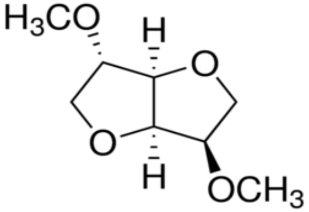
Most used green solvents in mebrane preparation



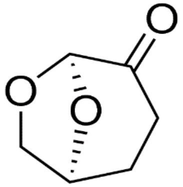
Polarclean®



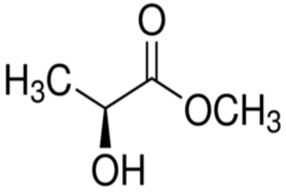
Ethyl lactate



Dimethyl isosorbide



Cyrene™



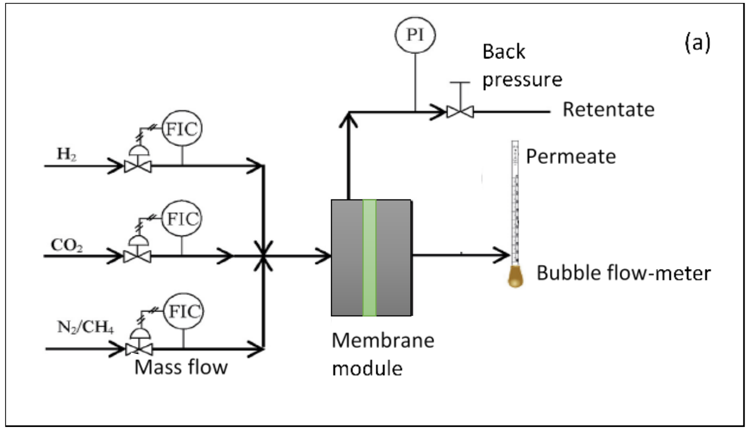
Methyl lactate

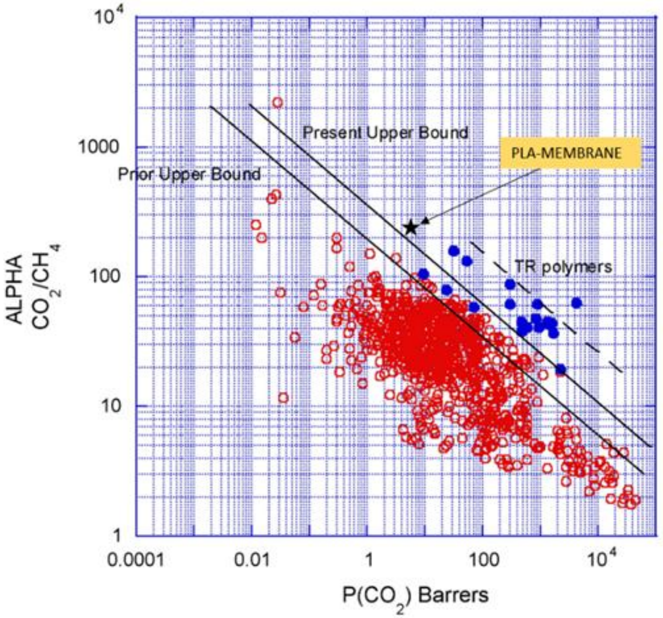
VSB TECHNICAL UNIVERSITY OF OSTRAVA
INTERNATIONAL ENERGY AND ENVIRONMENT CONFERENCE
SEPTEMBER 7–9, 2026
HOTEL SEPETNÁ OSTRAVICE

A. Figoli, T. Marino, S. Simone, E. Di Nicolò, X.-M. Li,T. He, S. Tornaghi, E. Drioli, Towards non-toxic solvents for membrane preparation: a review, Green Chem., 16 (2014) 4034

Consiglio Nazionale delle Ricerche

PLA membranes performance in CO_2/CH_4 separation





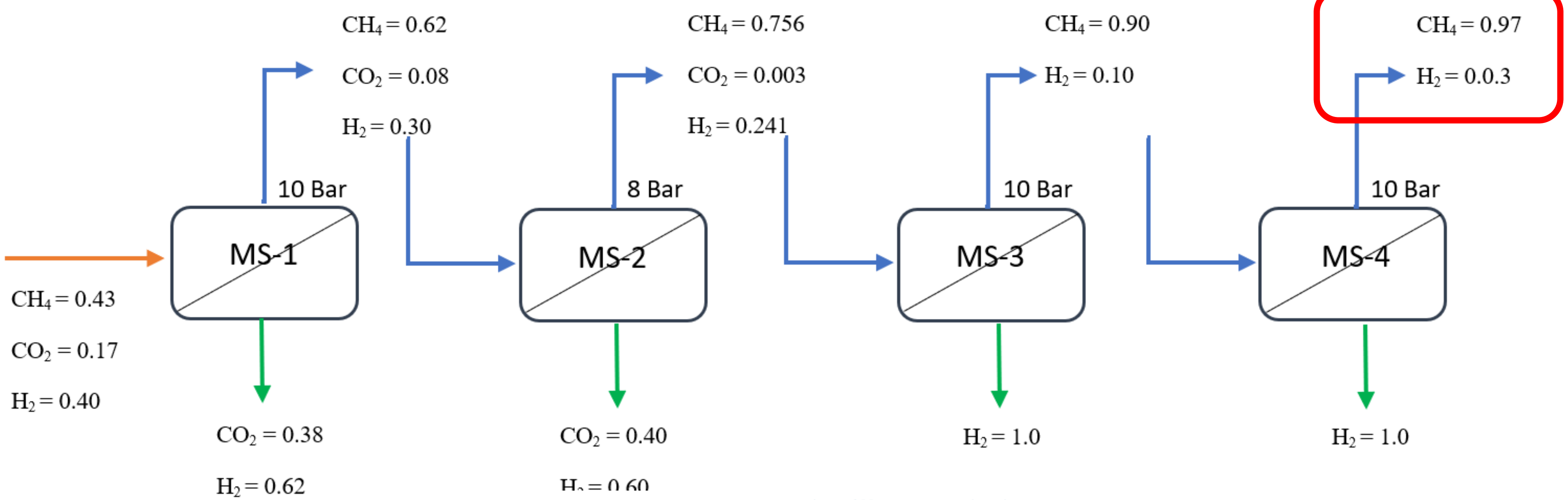
Biogas products	Concentration [%]	Farm biogas plant [%]	Sewage digester [%]	Landfill [%]
CH_4	40 - 75	55 - 58	57.8	47 - 57
CO_2	25 - 55	37 - 38	38.6	37 - 41
H_2S	0.005 - 0.5	0.0032 - 0.0169	0.00629	0.0036 - 0.0115
NH_3	0 - 1	-	-	-
H_2O	0 - 10	4 - 7	4 - 7	4 - 7
N_2	0 - 5	2	3.7	1
O_2	0 - 2	1	0	1
H_2	0 - 1	-	-	-

Bio-polymers and blends used for membrane preparation and utilization in CO_2/CH_4 separation.

Bio-polymers & blends	CO_2 permeability [Barrer]	α_{CO_2/CH_4}	Reference
CA (semi-crystalline)	1.8 - 6	32	(Nguyen et al., 2019)
CA/HFMs	~ 1.3	~ 8	(Mubashir, Yeong, Lau, and Chew, 2019)
ZIF8/Cellulose nanofiber	550	~ 36	(Jia et al., 2020)
PES/water insoluble Amino-Starch	7.6 (GPU)	58	(Saedi et al., 2013)
CSgraphitic carbon nitride (g-C3N4)/ ZIF-8/PES	-	25	(Jomekian, Bazooyar, Esmaeilzadeh, and Behbahani, 2020)
PLA/PHBV/ncry cellulose	0.3	-	(Dasan, Bhat, and Ahmad, 2017)
PLA/PBS multilayer film	~ 0.9	-	(Messin et al., 2020)
PHB	10-14	-	(Follain et al., 2014)
PVA/Cellulose nanocrystal	107 (GPU)	43	(Jahan, Niazi, Hägg, and Gregersen, 2018)
CNTs-PVAm/PVA blend nanoco	129 (GPU)	45	(Deng and Hägg, 2014)
PU	332	13	(Molki, Aframehr, Bagheri, and Salimi, 2018)
PU/NiO	78-135	9-24	(Molki, Aframehr, Bagheri, and Salimi, 2018)
Ils-PEG-PU	104	19	(Ghadimi, Gharibi, Yeganeh, and Sadatnia, 2019)
PLA-2100 NatureWorks	11	220-230	This work

Hydrogen chemical storage: CO_2 valorisation for e-methane generation – *Second stage process*

Second stage: *bio-polymeric membrane methanation reactor downstream treatment*



Energy Conversion and Management 365 (2026) 121798

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

ELSEVIER

CO_2 valorization into SNG through a methanation reactor combined with a multi-stages bio-polymeric membrane separation system: An experimental study, with exergy and cost analyses

A. Iulianelli [a,*], H.B.Trujillo Ruales [a], J. Veres [b], F. Russo [a], F. Galiano [a], A. Figoli [a]

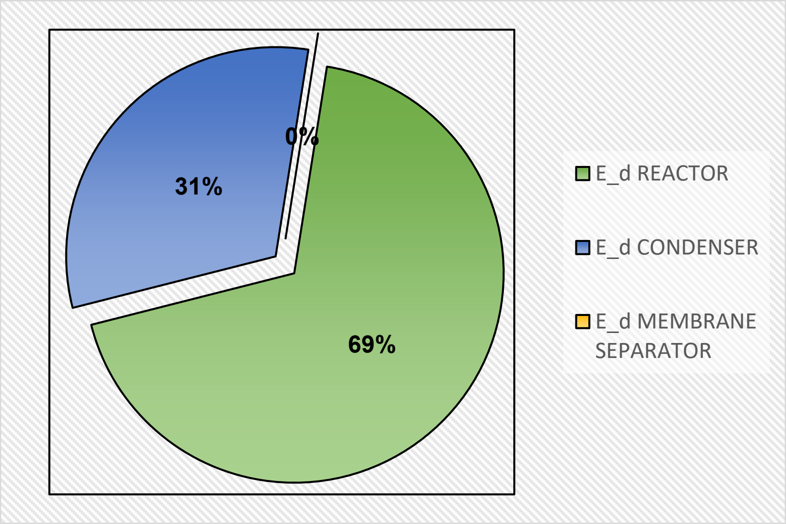
[a] National Research Council - Institute On Membrane Technology (CNR-ITM), Via P. Bucci 17C, Rende CS 87036, Italy

[b] VSB-Technical University of Ostrava, Energy and Environmental Technology Centre, Energy Research Centre, 17. Listopadu 2172/15, 708 00 Ostrava-Poruba, Czech Republic

Hydrogen chemical storage: CO_2 valorisation for e-methane generation – *exergy efficiency*

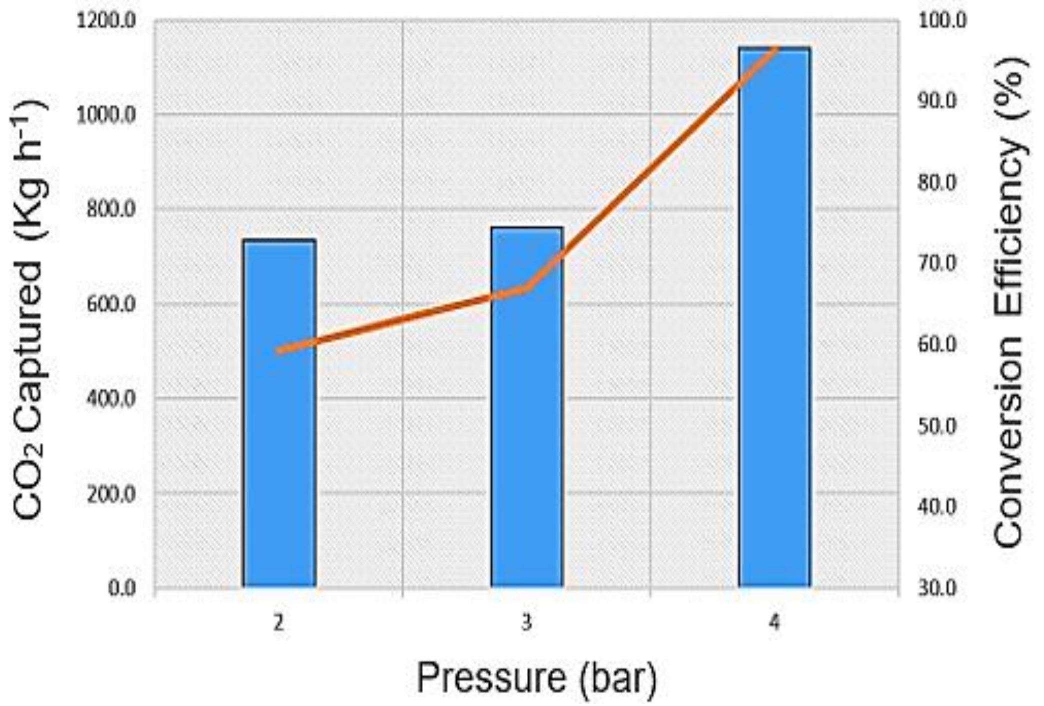
CO_2 methanation reactor					
T (°C)	P (bar)	Reactor (W)	η_{ex} (%)	Condenser (W)	η_{ex} (%)
300	2	$2.04\cdot10^6$	86.0	$4.03\cdot10^5$	94.08
	3	$7.54\cdot10^5$	89.9	$7.59\cdot10^5$	89.29
	4	$4.22\cdot10^5$	94.4	$9.11\cdot10^5$	82.85

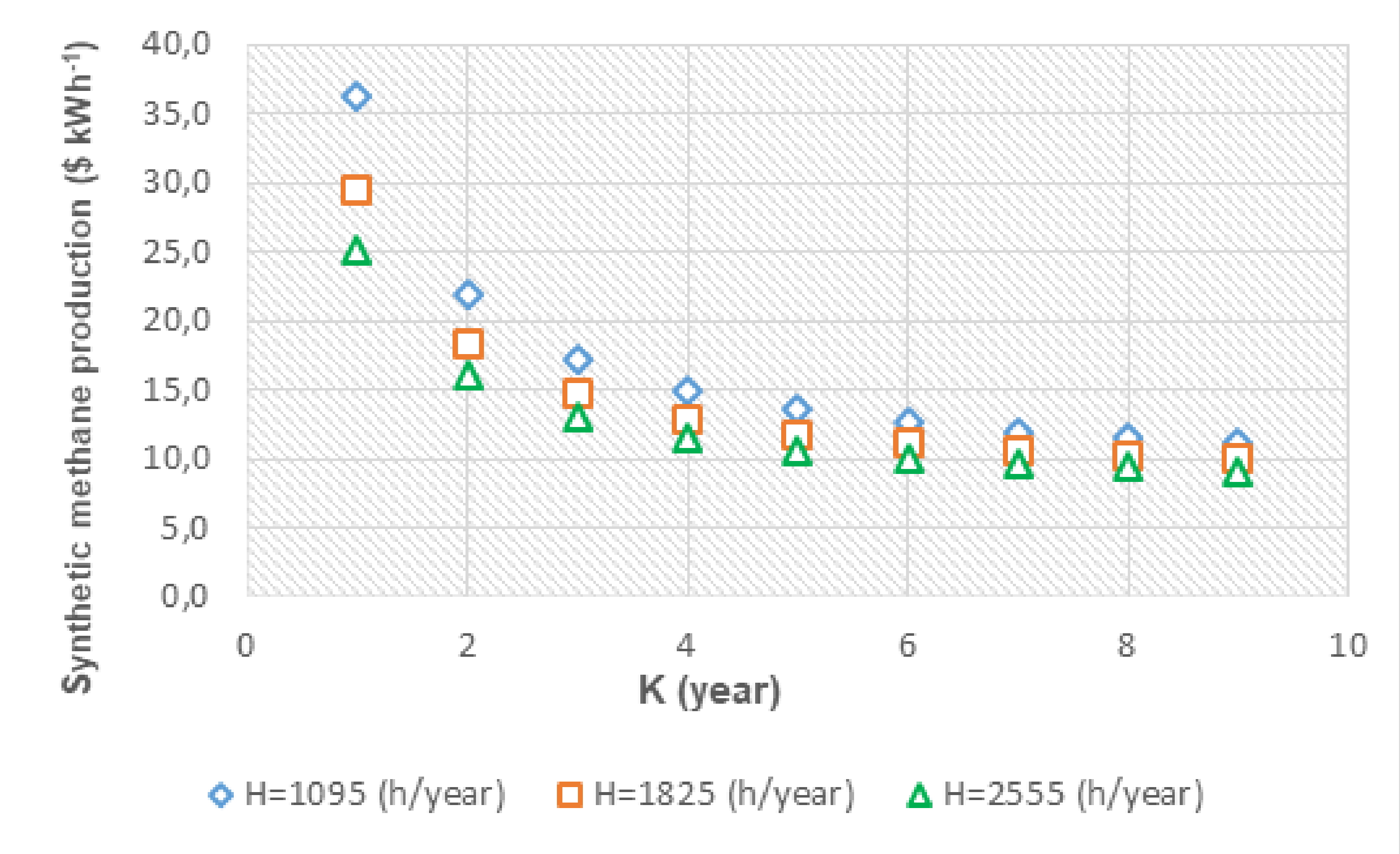
Membrane Gas Separation Modules											
T (°C)	P (bar)	MS-1 (W)	η_{ex} (%)	MS-2 (W)	η_{ex} (%)	MS-3 (W)	η_{ex} (%)	MS-4 (W)	η_{ex} (%)	MS-G (W)	η_{ex} (%
25	2	2.11	78.08	2.859	70.34	3.164	67.28	3.482	63.68	**9.15**	**94.9**
	4	1.96	79.71	2.857	70.36	3.163	67.19	3.481	63.89		
	6	1.89	80.43	2.856	70.38	3.163	67.19	3.480	63.90		
	8	1.86	80.66	2.852	70.41	3.162	67.20	3.479	63.91		
	10	1.81	81.25	-	-	3.157	67.25	-	-		



A. Iulianelli, H.B. Trujillo Ruales, J. Veres, F. Russo, F. Galiano, A. Figoli, CO_2 capture and valorization into synthetic methane production through an integrated CO_2-methanation reactor combined with a bio-polymeric membrane separation system: an experimental study, with exergy and cost analyses, **Energy Conversion and Management**, 365 (2026) 121798

Hydrogen chemical storage: CO_2 valorisation for e-methane generation – *CO_2 captured and synthetic methane production cost*





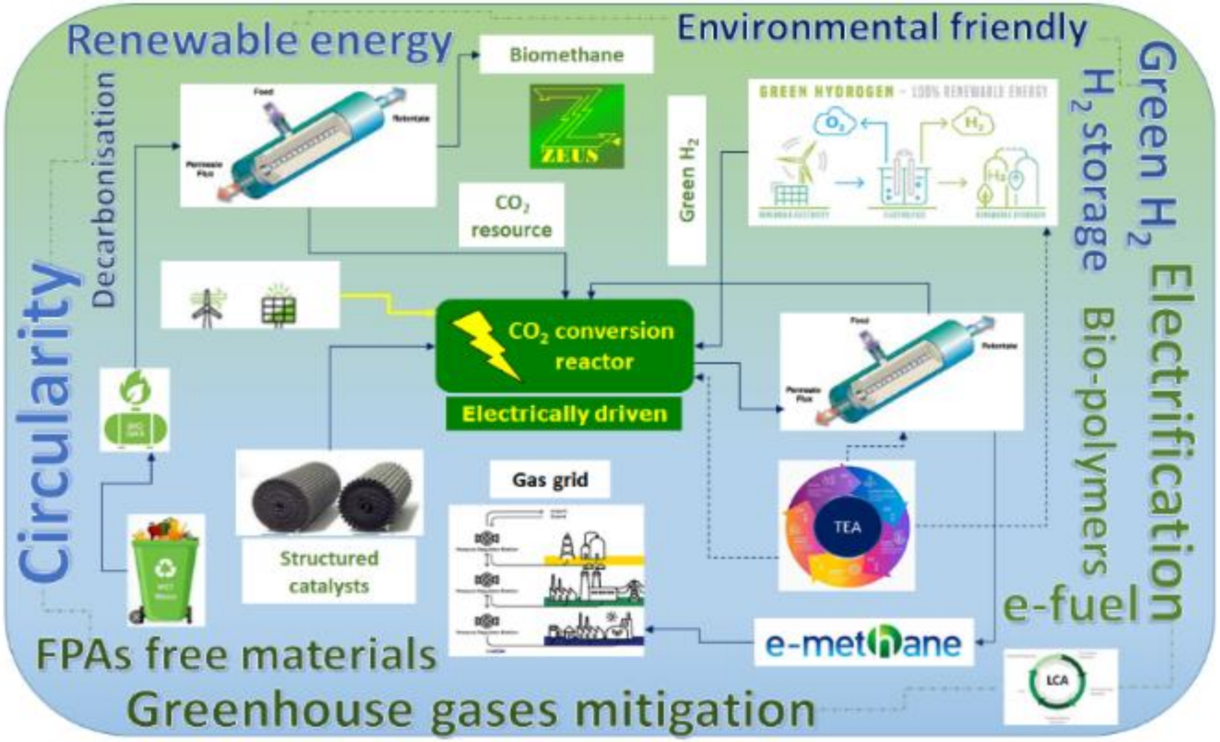
VSB TECHNICAL UNIVERSITY OF OSTRAVA

INTERNATIONAL ENERGY AND ENVIRONMENT CONFERENCE SEPTEMBER 7–9, 2026 HOTEL SEPETNÁ OSTRAVICE

A. Iulianelli, H.B. Trujillo Ruales, J. Veres, F. Russo, F. Galiano, A. Figoli, CO_2 capture and valorization into synthetic methane production through an integrated CO_2-methanation reactor combined with a bio-polymeric membrane separation system: an experimental study, with exergy and cost analyses, **Energy Conversion and Management**, 365 (2026) 121798

Consiglio Nazionale delle Ricerche

Perspectives in the hydrogen chemical storage: : *electrification of the CO_2 conversion reactor to e-fuel production*



Expected Outcomes (electrically-assisted)

(Electrically-driven FBR + biopolymeric membrane separation):

CO_2 conversion to a bioCH_4 grade stream ($x_{CH4} \geq 97\%$; $x_{CO2} < 2\%$)

Energy efficiency > 90%;

Exergy efficiency > 90%

CO_2 conversion > 90%

Consiglio Nazionale delle Ricerche

INDUSTRIA 2015

Ministero dello Sviluppo Economico

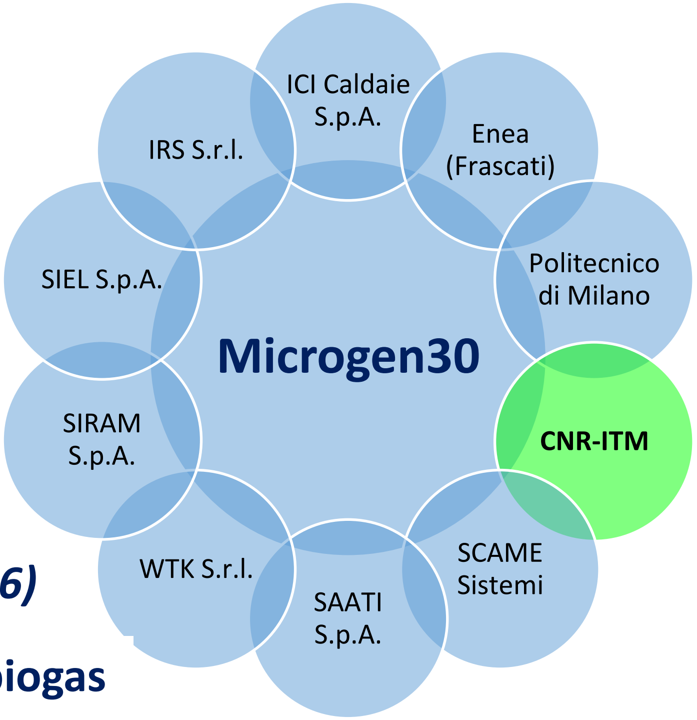
Project budget = 15 M€

Institute on Membrane Technology
National Research Council of Italy

Then (2015)

ICI
POWERING EVOLUTION

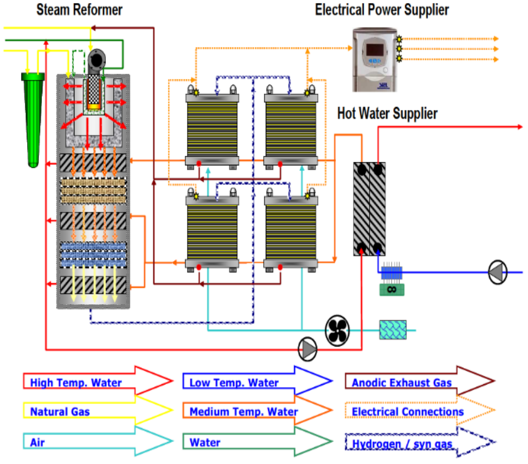
Now (2025/26)



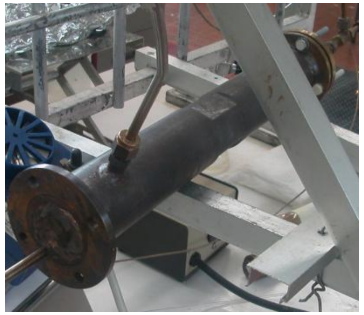
CNR-ITM in the first ranke Projects "Industrial Innovation INDUSTRY2015"

"MICROGEN30 - Medium-small Microcogeneration System based on Fuel Cells for Residential Applications" (Italian Economic Development Ministry, D.M. 5 March 2008)

100 kg/day of pure hydrogen from biogas



Functional layout of the micro-cogeneration MICROGEN30



H_2 research and decarbonisation: a new economy?

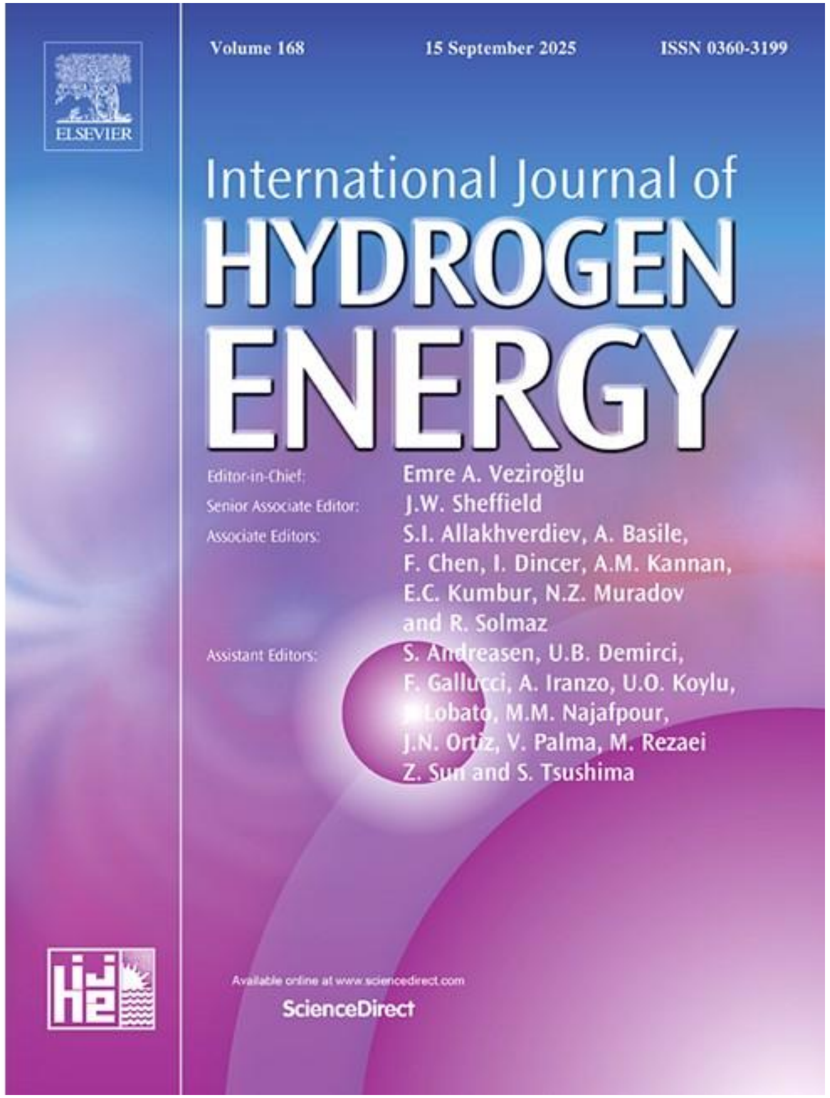
Hydrogen Europe Research

Clean Hydrogen Partnership

Co-funded by the European Union

Italian National Research Council

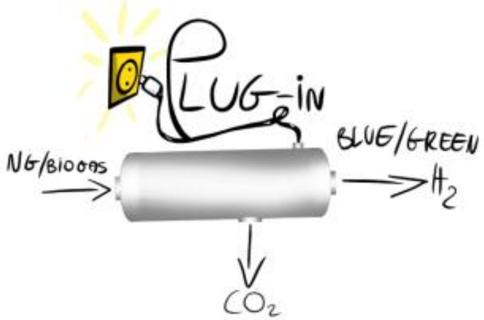
Special issue: *Global Perspectives on Hydrogen Technologies: Innovations, Challenges, and Pathways to a Hydrogen Economy*



Acknowledgements

Operational Plan for H_2 Research

NextGenerationEU – Program Agreement MASE/ENEA/CNR/RSE, M2C2 Investiment 3.5 – PNRR, Project: Research & Development on H_2
Total budget: 110M EUR



PRIN2020 – Bando MUR 2020 Prot. 2020N38E75, D.D. 2436 del 20/10/2021
Project: **Process for Low-carbon blUe/hydrogen Generation via Intensified electrified reforming of biogas/natural gas (PLUG-IN)**

REFRESH

EU Horizon Europe - Research and innovation programme under grant agreement no. 101096858
Project: **Research Excellence For Region Sustainability and High-ech Industries (REFRESH)**

Consiglio Nazionale delle Ricerche

Dr. Adolfo IULIANELLI, Ph.D.

Senior Researcher at the Institute on Membrane Technology of the Italian National Research Council (ITM-CNR), Via P. Bucci, Cubo 17/C, University of Calabria, Rende (CS) – 87036 – Italy
Ph.: +39 0984 492011, Cell.: +39 348 3908649
Web-site: www.itm.cnr.it; http://areacs.cnr.it/adolfo-iulianelli/
e-mail: a.iulianelli@itm.cnr.it, adolfo.iulianelli@cnr.it