Energy transition and the future of energy research: Innovation and Education

Carbon Capture Utilization & Storage

A case study

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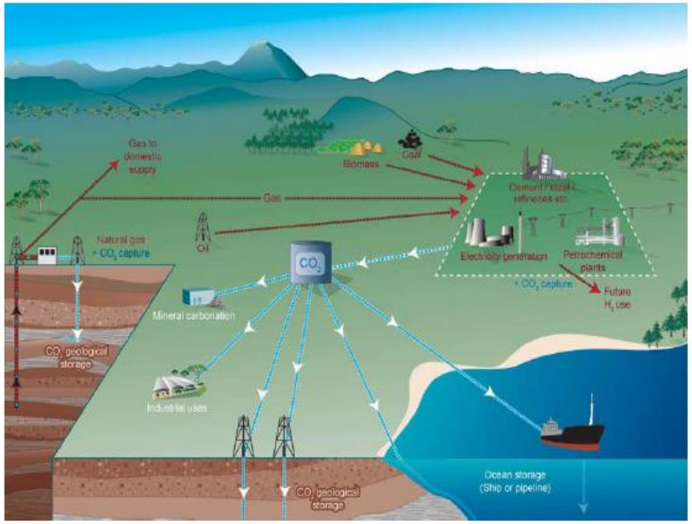
Outline

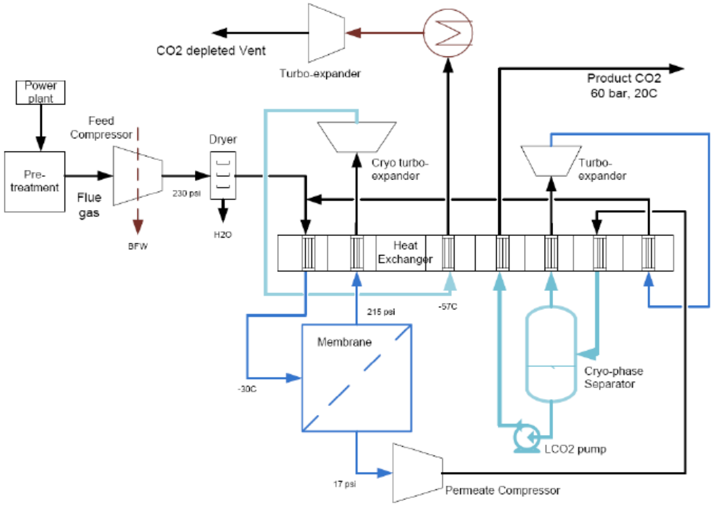
i) Introduction: Framework

ii) Energy & education

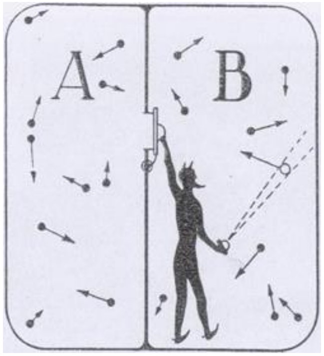
iii) One step further

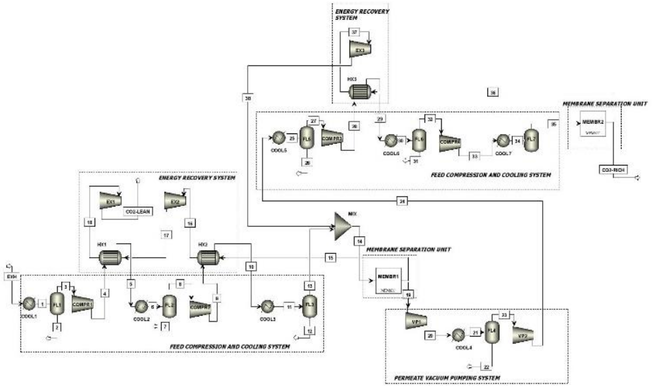
iv) Conclusion





Introduction: Framework

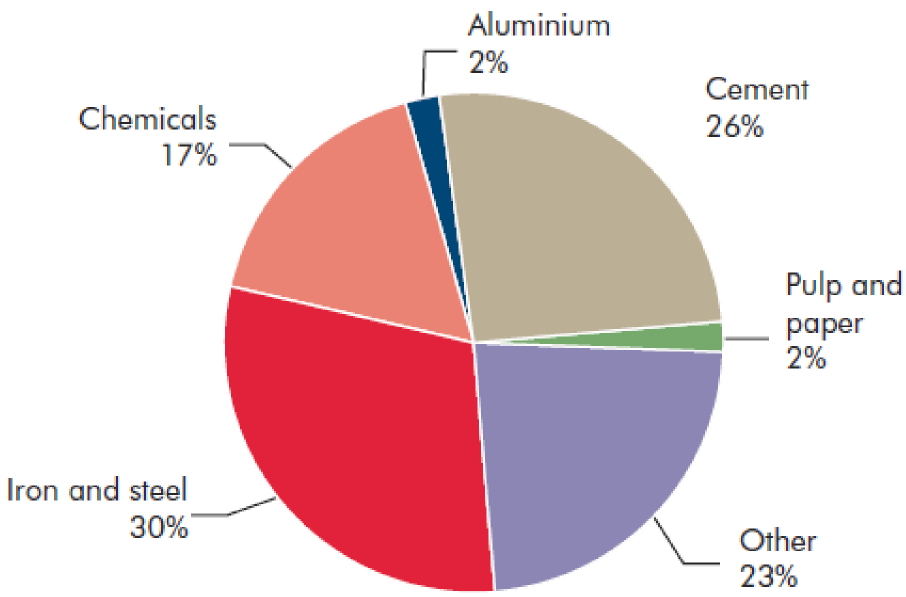




Framework: Global warming & CCUS

Steelmaking industry and CO_2 emissions

Direct CO_2 emissions in industry by sector, 2007



Source: International Energy Agency (IEA) (2010), Energy Technology Perspectives 2010, Scenarios and Strategies to 2050.

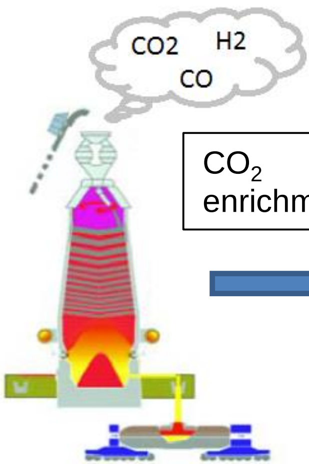
- **Second largest industrial user of energy and largest industrial source of CO_2 emissions (2,3 $GtCO_2$ in 2009)[1].**
- **Integrated steel mills based on blast furnace-basic oxygen furnace technology dominate global steel production.**
- **Most of emissions come from the blast furnace gas. Typical composition:**

17-25% CO_2
20-28% CO
1-5% H_2
50-55% N_2

VALORCO

Framework: VALORCO Project

Input



CO_2 enrichment

Blast Furnace Gas (BFG)

Separation and conversion processes

Gas filtration

CO_2 separation via solvents

CO_2 separation via membranes

Carbonation

Fermentation

Methanation

Methanol production

Formic acid production

Output

Aggregates for construction industry

Chemical industry, polymers

Biomethane

Chemical industry, Biofuels.

Chemical industry, Fuel cells.

Issues:

Feasibility (separation performances)?

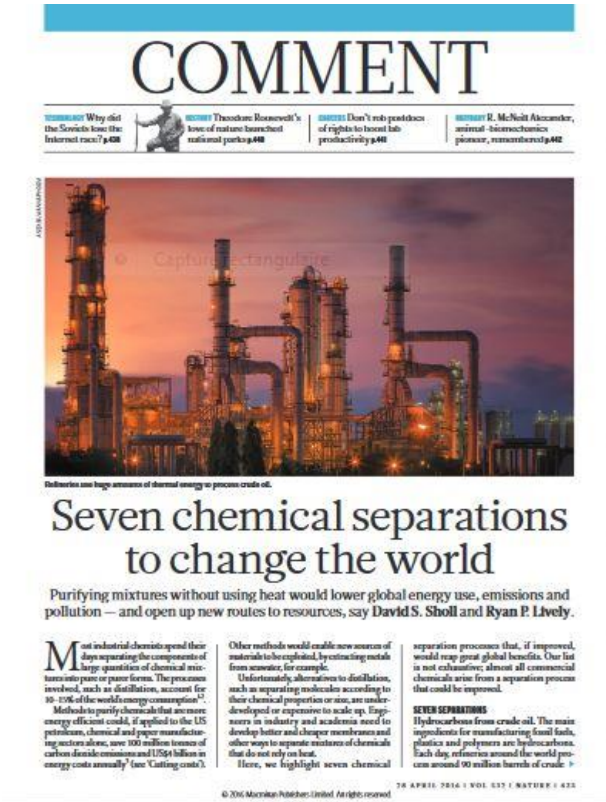
Energy requirement?

Cost ?

VALORCO

Separations processes are costly:

Energy requirement is one of the key issue of process selection



COMMENT

TECHNOLOGY Why did the Soviets lose the Internet race? p.438 | HISTORY Theodore Roosevelt's love of nature launched national parks p.440 | CAREERS Don't rob postdocs of rights to boost lab productivity p.441 | OBITUARY R. McNeill Alexander, animal-biomechanics pioneer, remembered p.442

Refineries use huge amounts of thermal energy to process crude oil.

Seven chemical separations to change the world

Purifying mixtures without using heat would lower global energy use, emissions and pollution — and open up new routes to resources, say **David S. Sholl** and **Ryan P. Lively**.

Most industrial chemists spend their days separating the components of large quantities of chemical mixtures into pure or purer forms. The processes involved, such as distillation, account for 10–15% of the world's energy consumption[1,2].

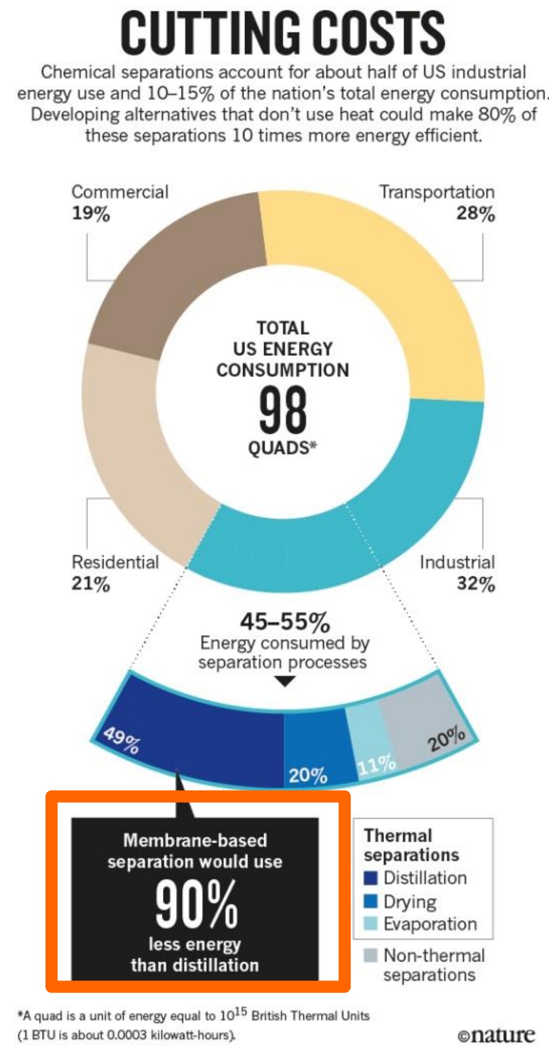
Methods to purify chemicals that are more energy efficient could, if applied to the US petroleum, chemical and paper manufacturing sectors alone, save 100 million tonnes of carbon dioxide emissions and US$4 billion in energy costs annually[3] (see 'Cutting costs'). Other methods would enable new sources of materials to be exploited, by extracting metals from seawater, for example.

Unfortunately, alternatives to distillation, such as separating molecules according to their chemical properties or size, are underdeveloped or expensive to scale up. Engineers in industry and academia need to develop better and cheaper membranes and other ways to separate mixtures of chemicals that do not rely on heat.

Here, we highlight seven chemical separation processes that, if improved, would reap great global benefits. Our list is not exhaustive; almost all commercial chemicals arise from a separation process that could be improved.

SEVEN SEPARATIONS

Hydrocarbons from crude oil. The main ingredients for manufacturing fossil fuels, plastics and polymers are hydrocarbons. Each day, refineries around the world process around 90 million barrels of crude ▸



D.S.Sholl, R.P. Lively Seven chemical separations to change the world. Nature (2016) 532, 435-437.

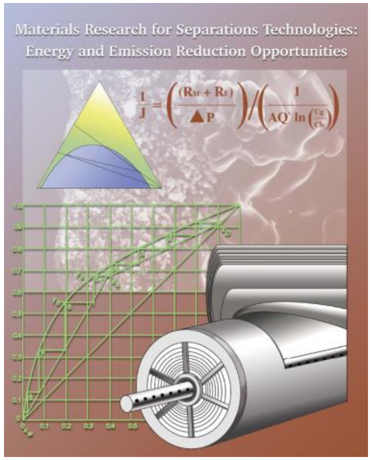
W.J. Koros, R.P. Lively Water and beyond: Expanding the spectrum of large scale energy efficient separation processes, AIChE J. (2012) 58, 9, 2624-2633.

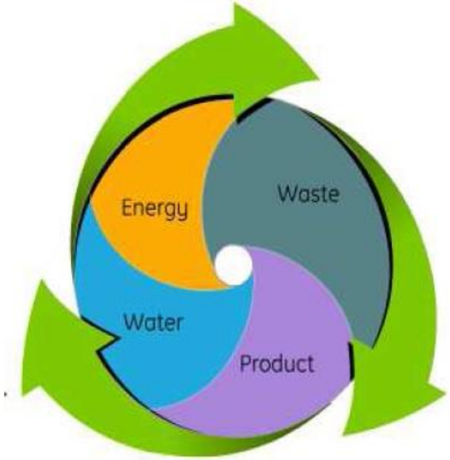
Membrane Separations

Table 5.1: Industrial Applications with Potential for Alternative Low-Energy Intensity Separation Technologies

	Distillation	Evaporation	Membranes	Extraction	Adsorption & Ion Exchange	Absorption	Filtration	Gas Treatment†	Hybrid Systems	Untreated Waste
Petroleum Industry										
Gas recovery	*		Δ			Δ				
Hydrogen recovery			Δ							*
Chemicals Industry										
Phenol/Cumene	*		Δ	Δ		Δ			Δ	
Ethylene	*		Δ	Δ	Δ				Δ	
Methanol	*			Δ				*	Δ	
Styrene/Ethybenzene	*		Δ						Δ	
Ammonia			Δ	Δ	Δ	*				
Caustic Soda		*	Δ							
Nitrogen/Oxygen	*		Δ						Δ	
Phosphoric Acid		*	Δ	Δ						
Lime			Δ					*		
Sodium Carbonate			Δ					*		
Forest Products Industry										
Black Liquor Concentration		*	Δ				Δ		Δ	

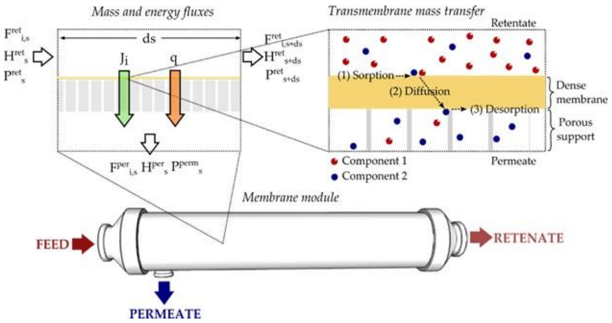
** - Existing technology*
Δ - Energy-saving alternative technology
† - Generated from air-fueled furnaces to be replaced by oxygen-fueled furnaces with pretreated oxygen-enriched feed





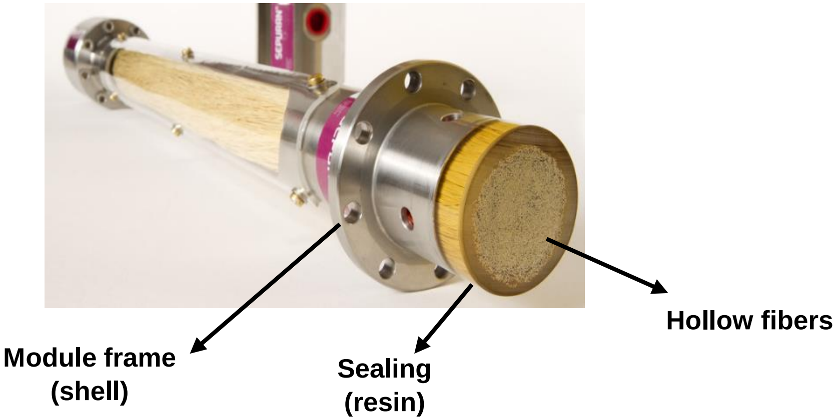
Membranes: a key technology for energy efficient processes…

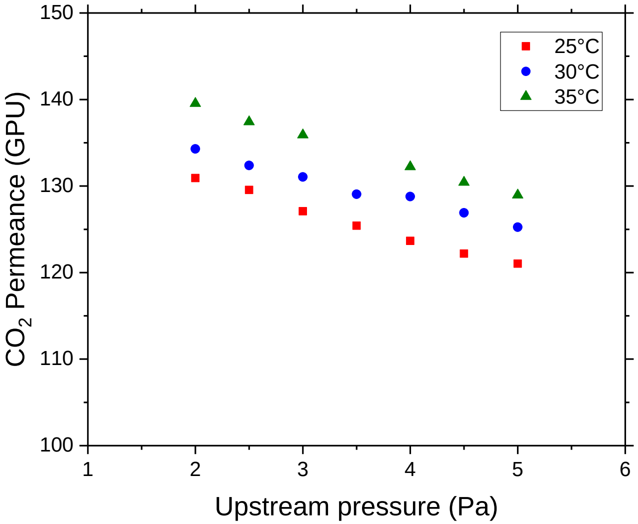
Energy & education: a Master research project case study



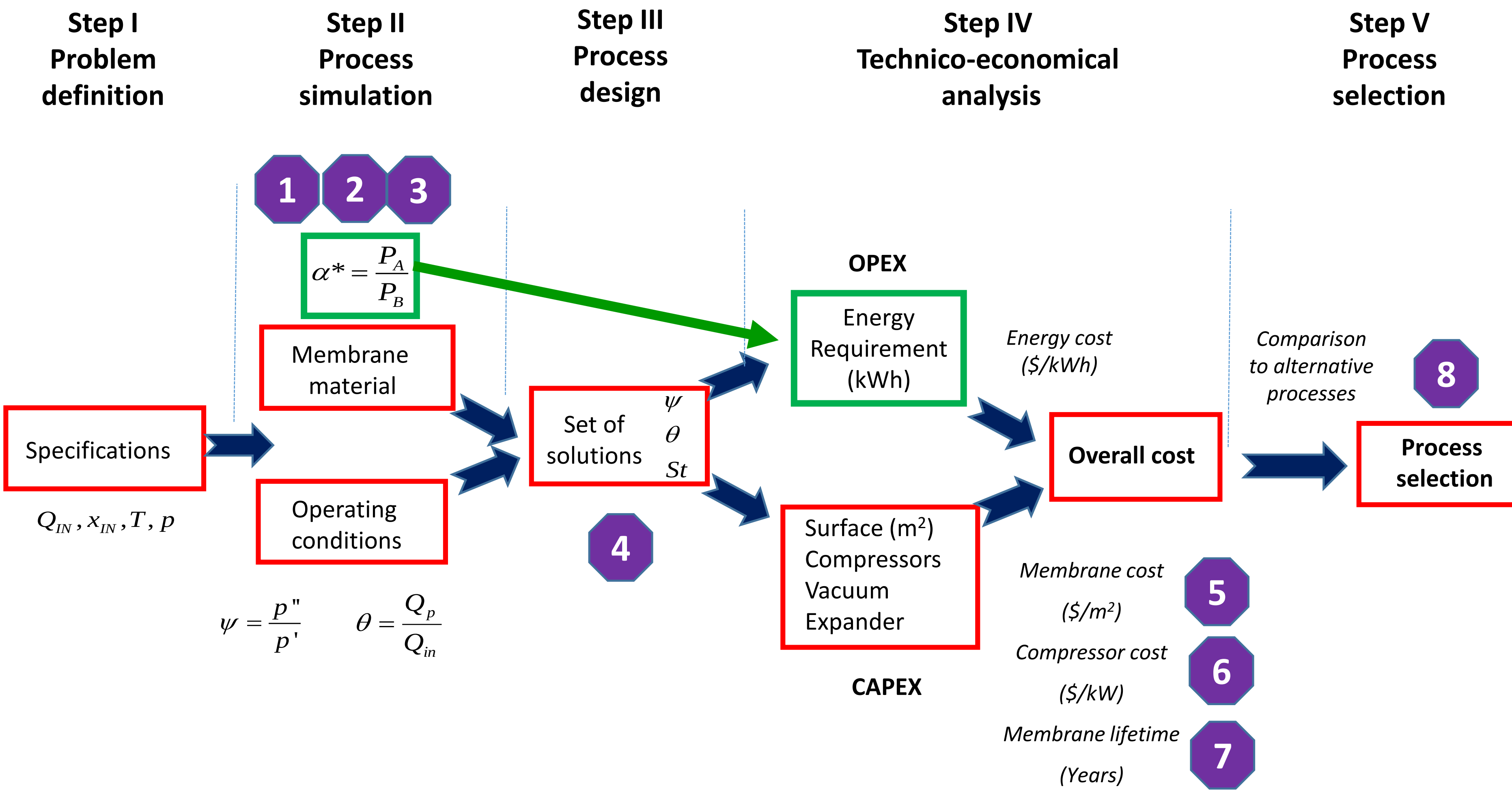
Master research program (Energy & Fluids)

- ***Transport phenomena (mass & heat transfer)***
- ***Fluid mechanics (CFD)***
- ***Thermodynamics & Energy***
- ***Modelling & simulation (methods & tools)***
- ***Process Systems Engineering (PSE)***
- ***Experiments (design, planning, error analysis…)***
- ***Materials science, chemistry***

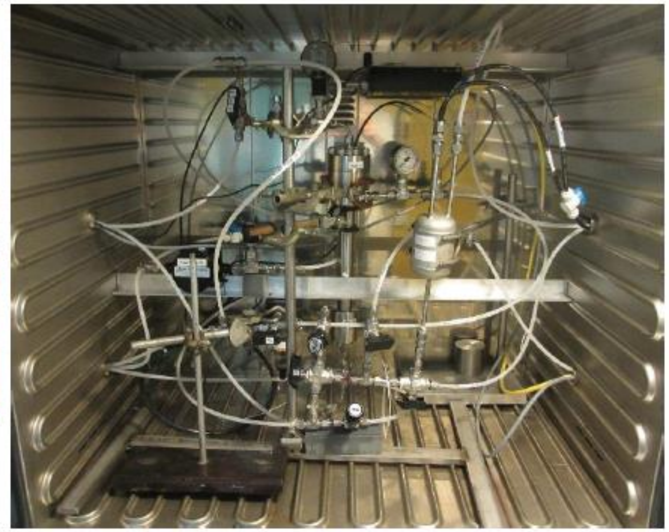


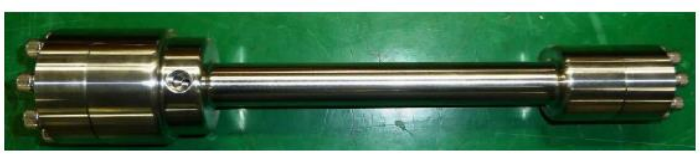


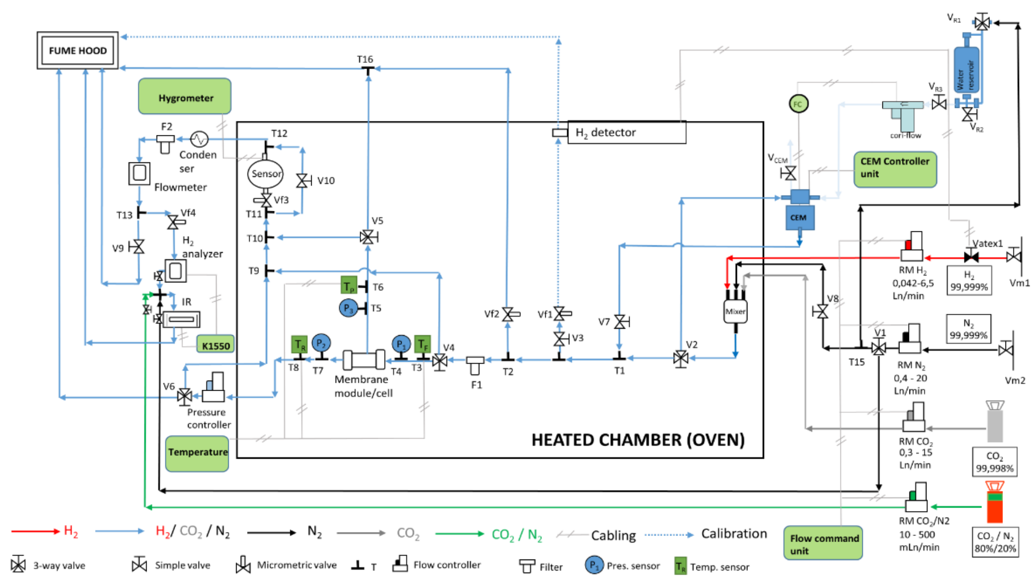
Membrane gas separations: the long & complex road to industrial development



Experimental permeation tests in laboratory unit

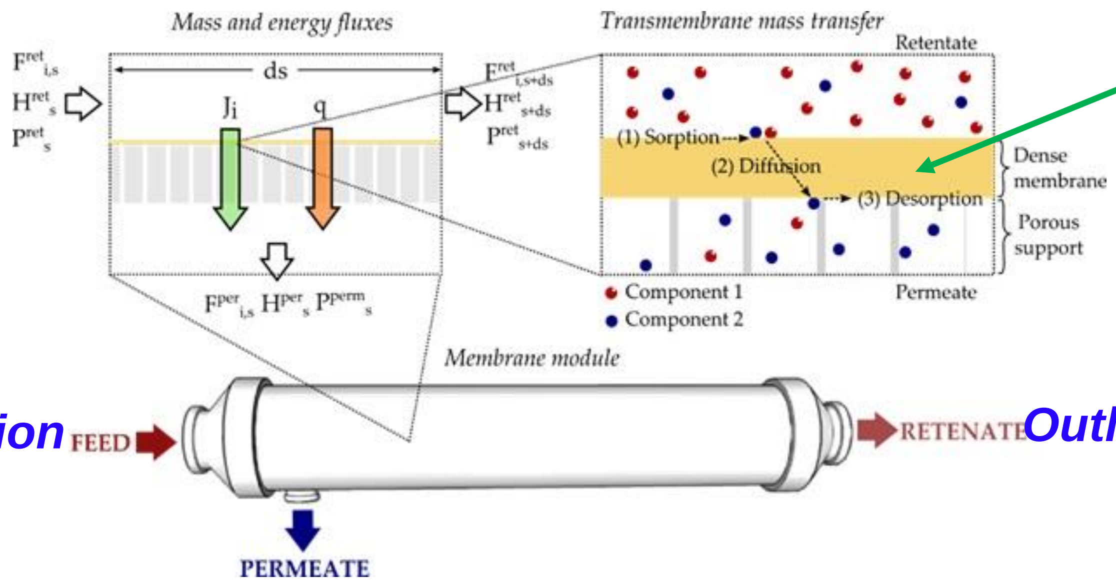






The separation challenge: purity, recovery, energy, productivity, cost

Selectivity α



Feed composition x_{in}

Outlet composition x_{out}

Permeate composition y

Purity y ***or*** x_{out}

Recovery R

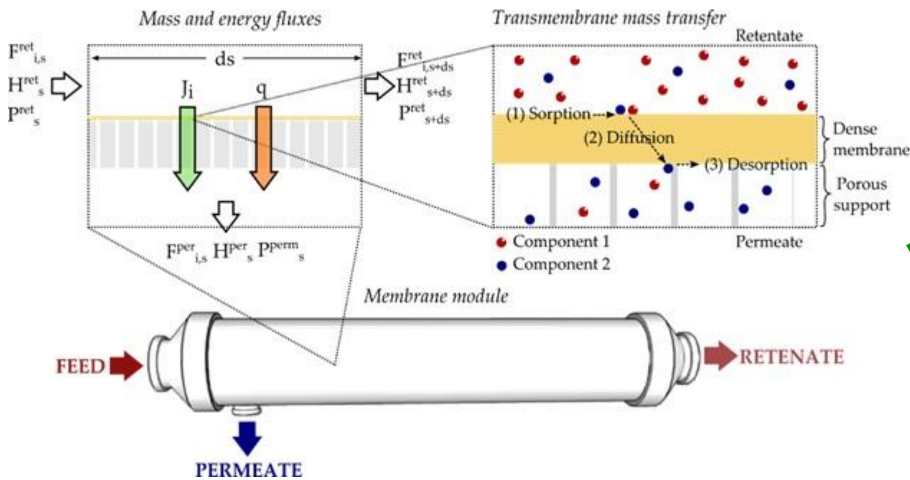
Separation factor

Productivity

Energy efficiency

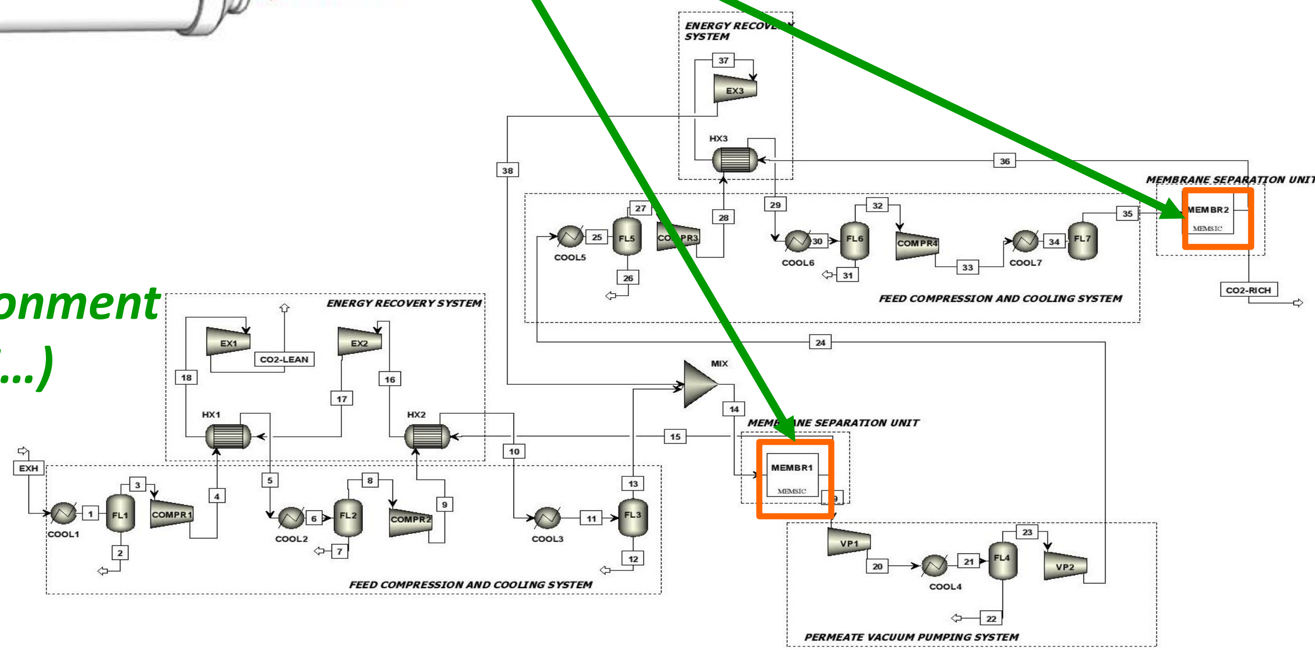
Cost

Pushing process energy efficiency performances through PSE

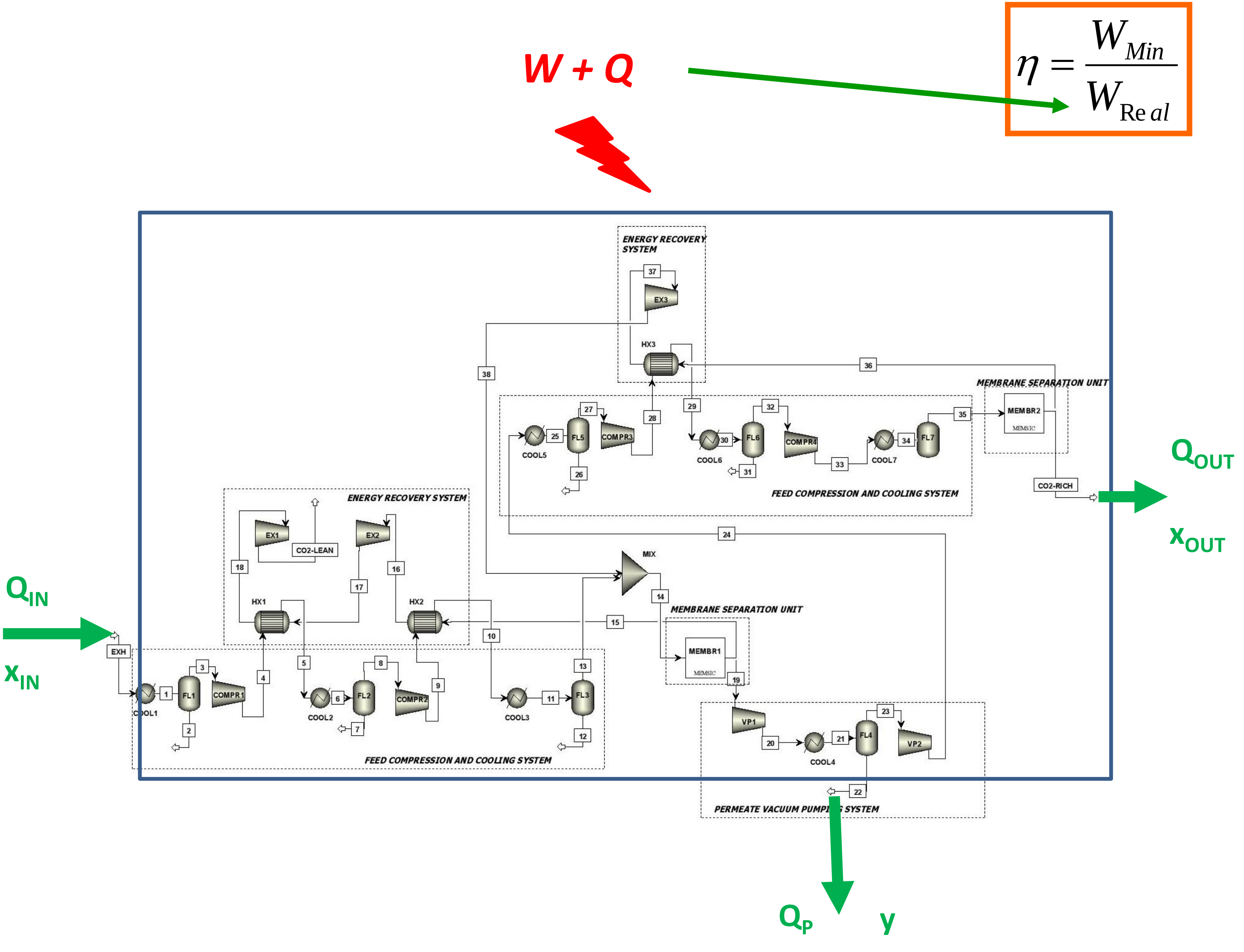


MEMSIC simulation toolbox

PSE software environment (Aspen, ProII, COFE…)



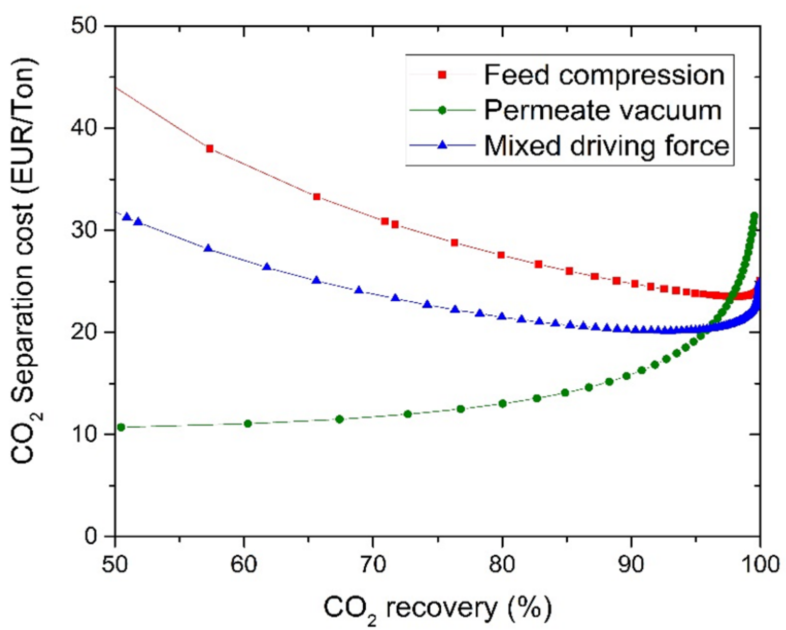
Bounaceur, R., Berger, E., Pfister, M., Ramirez, A., Favre, E. (2017) Rigorous variable permeability modelling and process simulation for the design of polymeric membrane gas separation units: MEMSIC simulation tool. *Journal of Membrane Science*, 513, 236-249.


W + Q
η = W_Min / W_Real
Q_IN
x_IN
Q_OUT
x_OUT
Q_P
y
ENERGY RECOVERY SYSTEM
EX3
HX3
MEMBRANE SEPARATION UNIT
MEMBR2
MEMSIC
FEED COMPRESSION AND COOLING SYSTEM
COOL5
FL5
COMPR3
COOL6
FL6
COMPR4
COOL7
FL7
CO2-RICH
ENERGY RECOVERY SYSTEM
EX1
EX2
CO2-LEAN
HX1
HX2
MIX
MEMBRANE SEPARATION UNIT
MEMBR1
MEMSIC
EXH
COOL1
FL1
COMPR1
COOL2
FL2
COMPR2
COOL3
FL3
FEED COMPRESSION AND COOLING SYSTEM
VP1
COOL4
FL4
VP2
PERMEATE VACUUM PUMPING SYSTEM

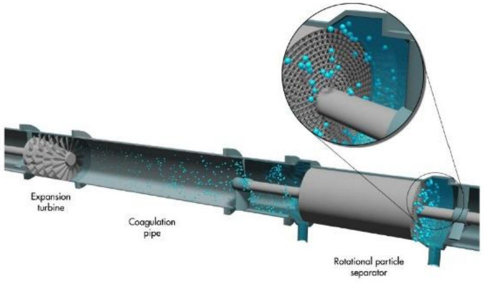
The ultimate target: cost analysis

Equipment cost		
$I_m = A_m * K_m$	(4.1)	Membrane cost
$I_{mf} = (A_m/2000)^{0.7} * K_{mf} * (P_{mf}/55)^{0.875}$	(4.2)	Membrane frame cost
$I_C = C_{oc} * \left(\frac{P_{cpr}}{7460}\right)^{0.8} * (P_{out}/69)^{0.18} * MF_C * MDF_C * UF * ER$	(4.3)	Centrifugal compressor cost
$I_C = C_{or} * \left(\frac{P_{cpr}}{7460}\right)^{0.8} * (P_{out}/69)^{0.18} * MF_C * MDF_C * UF * ER$	(4.4)	Reciprocating compressor cost
$I_{vp} = P_{vp} * C_{vp}$	(4.5)	Vacuum pump cost
$I_{Hex} = HX_o * \left(\frac{A_H}{139.4}\right)^{0.68} * MF_{Hx} * MDF_{HX} * PF * UF * ER$	(4.6)	Heat exchangers cost
Capital expenditures		
$CAPEX = \left(\sum I_c + \sum I_{vp} + \sum I_{Hex} + \sum I_{mf} + \sum I_m\right) * ICF$	(4.7)	Total capital cost
Operational expenditures		
$C_{O\&M} = A_m * \nu * K_{mr} + 0.036 * \left(\sum I_c + \sum I_{vp} + \sum I_{Hex}\right) + 0.01 * (I_m + I_{mf})$	(4.8)	O&M Cost
$C_{en} = t_{op} * P_{tot} * K_{el}$	(4.9)	Energy cost
$C_{cw} = t_{op} * W_{tot} * K_{cw}$	(4.10)	Cooling water cost
$OPEX = C_{en} + C_{cw} + C_{O\&M}$	(4.11)	Total operational expenditures
Annual and specific separation costs		
$C_{cap} = \left[\left(\sum I_c + \sum I_{vp} + \sum I_{Hex} + I_{mf}\right) * 1.31 + 0.31 * \sum I_m\right] * a + I_m * a_m$	(4.12)	Annual capital costs
$C_{tot} = C_{cap} + OPEX$	(4.13)	Total annual costs
$C_{product\,gas} = C_{tot}/M_{product\,gas-year}$	(4.14)	Specific separation cost

Journal of Membrane Science 526 (2017) 191-204



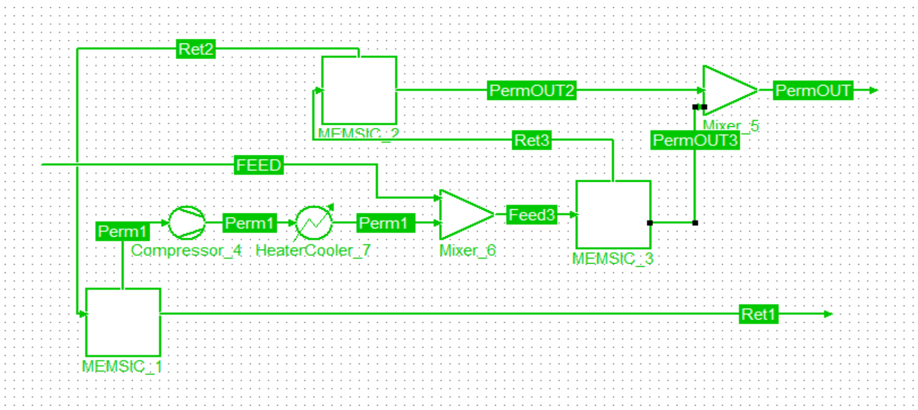
Energy & education: One step further…

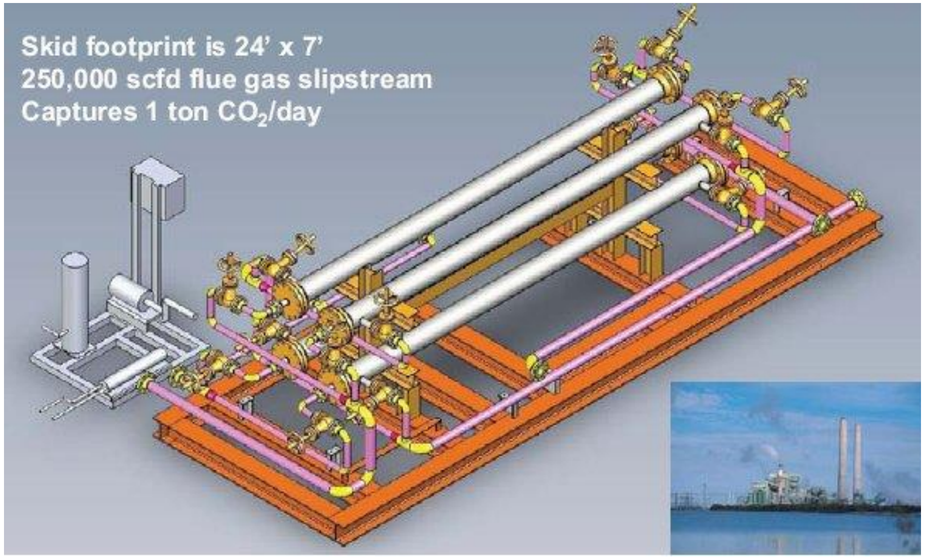


Energy engineering & education…

- *Advanced thermodynamics (IPT, Energy)*
- *Technico-economical analysis*
- *Optimization methods (process synthesis)*
- *Environmental impact evaluation*

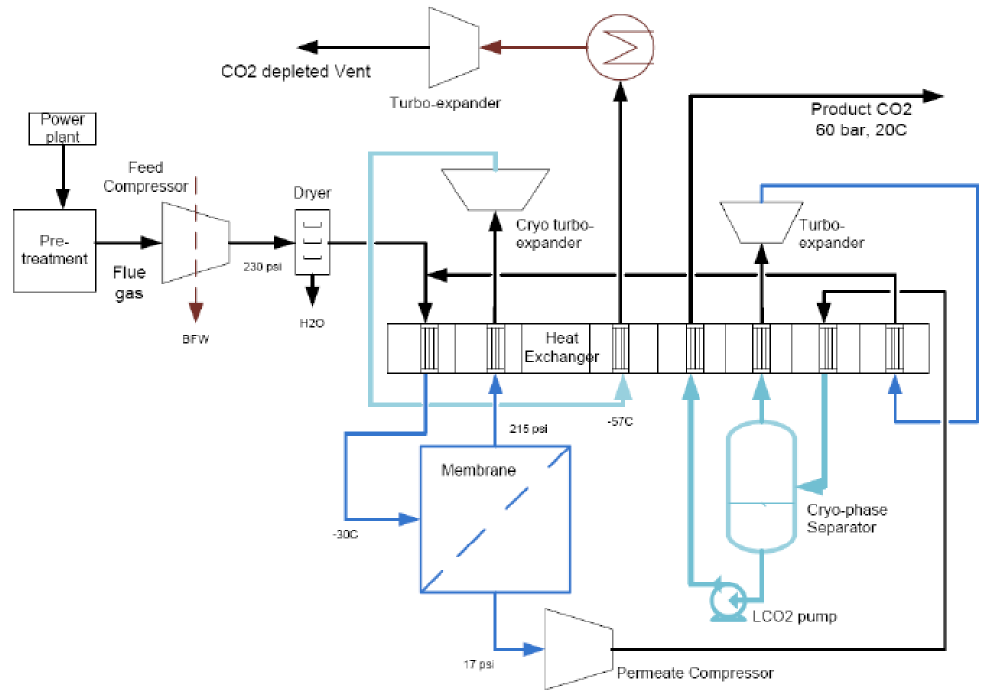
  (LCA, C footprint, water foot print…)
- *Innovation methodology*
- *Systems analysis*





Advanced energy integration concepts

Project DE-FE004278



US005679133A

United States Patent [19]

Moll et al.

[11] **Patent Number: 5,679,133**

[45] **Date of Patent: Oct. 21, 1997**

[54] **GAS SEPARATIONS UTILIZING GLASSY POLYMER MEMBRANES AT SUB-AMBIENT TEMPERATURES**

[75] Inventors: **David J. Moll; Alan F. Burmester**, both of Midland, Mich.; **Thomas C. Young**, Walnut Creek, Calif.; **Kent B. McReynolds; James E. Clark**, both of Midland, Mich.; **Charles Z. Hotz**, Walnut Creek; **Ritchie A. Wessling**, Berkeley, both of Calif.; **George J. Quarderer**, Midland, Mich.; **Ronald M. Lacher**, Midland, Mich.; **Stephen E. Bales**, Midland, Mich.; **Henry Nelson Beck**, Walnut Creek; **Thomas O. Jeanes**, Antioch, both of Calif.; **Bethanne L. Smith**, Freeland, Mich.

[73] Assignee: Dow Chemical Co., Midland, Mich.

OTHER PUBLICATIONS

S. Srinivasan, Gordon Research Conference On Synthetic Membranes, Jul. 10, 1990, "An Extraordinary Membrane That Rejects Light Gases".

Thorogood, International Gas Separation Meeting, Austin, Tex., Apr. 23, 1991.

S.R. Auvil et al, "Book of Abstracts, The Fourth Chemical Congress of North America", Aug. 25–30, 1991, Item 119.

K.K. Hsu et al., AIChE Conference, Nov. 18, 1991.

D.J. Moll et al., First Annual National Meeting of the North American Membrane Society, Jun. 3–5, 1987.

D.J. Moll et al., Gordon Research Conference on Reverse Osmosis, Ultrafiltration, and Gas Separation, Jul. 31, 1989.

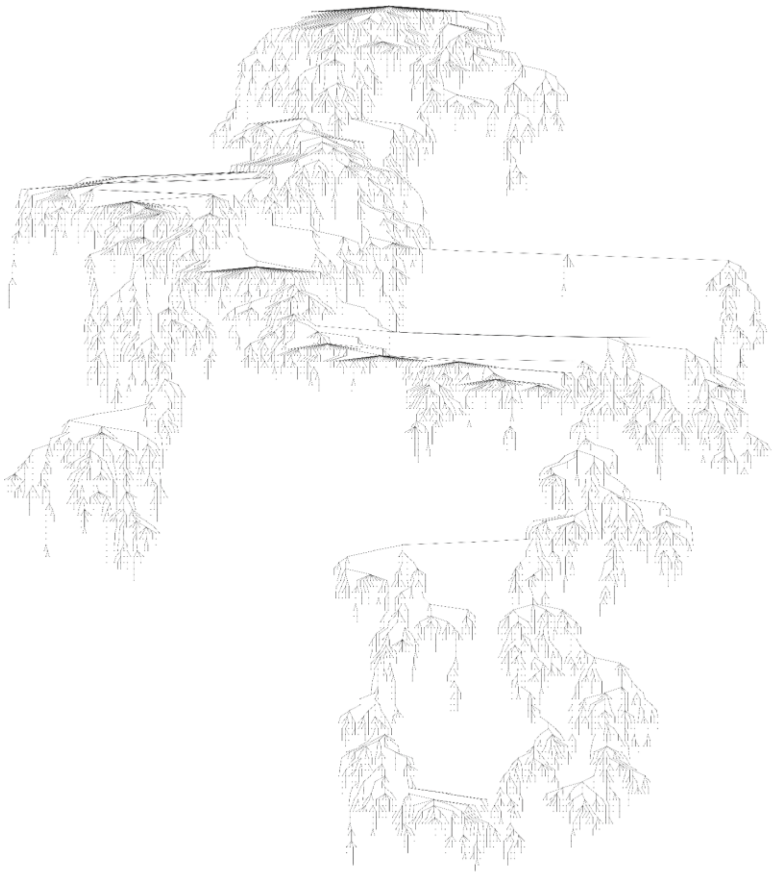
D. Parro, *Energy Process*, vol. 5, No.1, pp. 51–54, 1985.

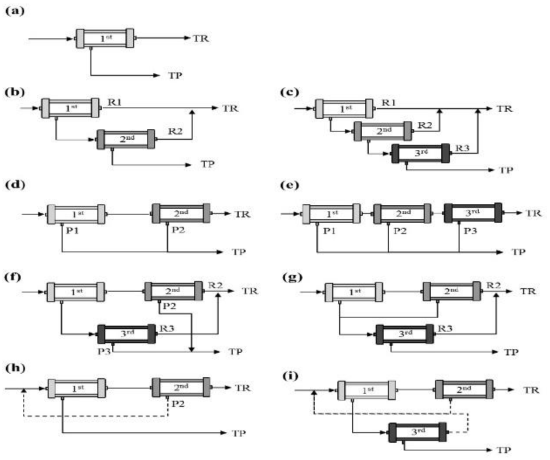
D. Parro, *Technology, Oil and Gas Journal*, pp. 85–88, Sep. 24, 1984.

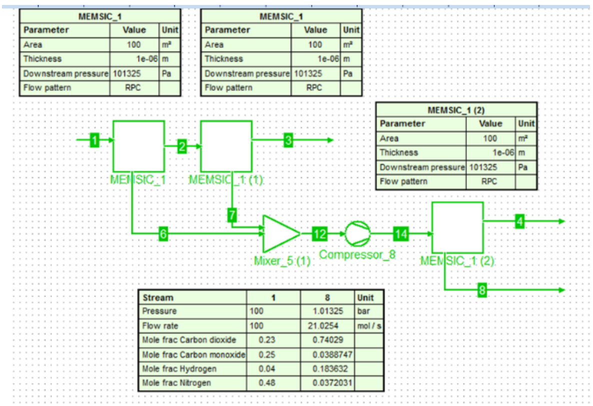
Low temperature (-30 C)
Compression + ERS
Hybrid membrane / cryogenic process
Energy requirement ~ 204 kWh/ton (1.9 GJ/ton)

Air Liquide DOE project

Towards process synthesis







MEMSIC_1		
Parameter	Value	Unit
Area	100	m²
Thickness	1e-06	m
Downstream pressure	101325	Pa
Flow pattern	RPC	

MEMSIC_1		
Parameter	Value	Unit
Area	100	m²
Thickness	1e-06	m
Downstream pressure	101325	Pa
Flow pattern	RPC	

MEMSIC_1 (2)		
Parameter	Value	Unit
Area	100	m²
Thickness	1e-06	m
Downstream pressure	101325	Pa
Flow pattern	RPC	

Stream	1	8	Unit
Pressure	100	1.01325	bar
Flow rate	100	21.0254	mol / s
Mole frac Carbon dioxide	0.23	0.74029	
Mole frac Carbon monoxide	0.25	0.0388747	
Mole frac Hydrogen	0.04	0.183632	
Mole frac Nitrogen	0.48	0.0372031	

Example of a phylogenetic process synthesis tree
(starting from a blank page)
Courtesy of T. Neveux (EDF)



Thank you for your attention!

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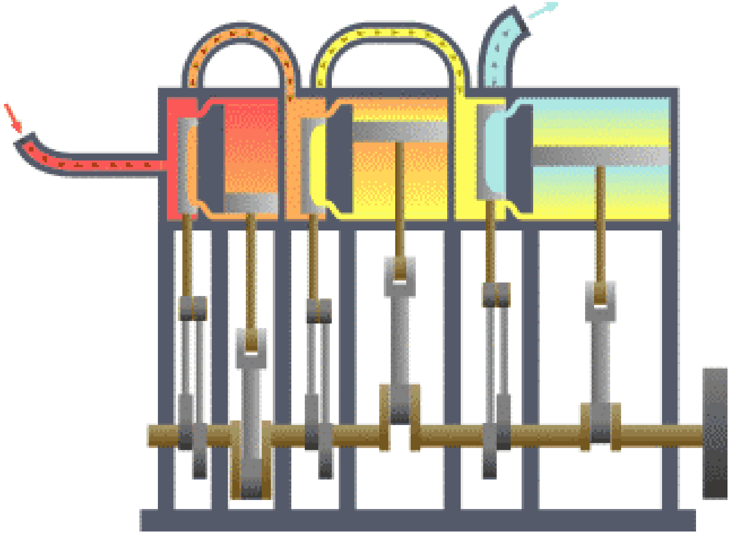
LRGP

ENSIC

Questions?



Eric.Favre@univ-lorraine.fr