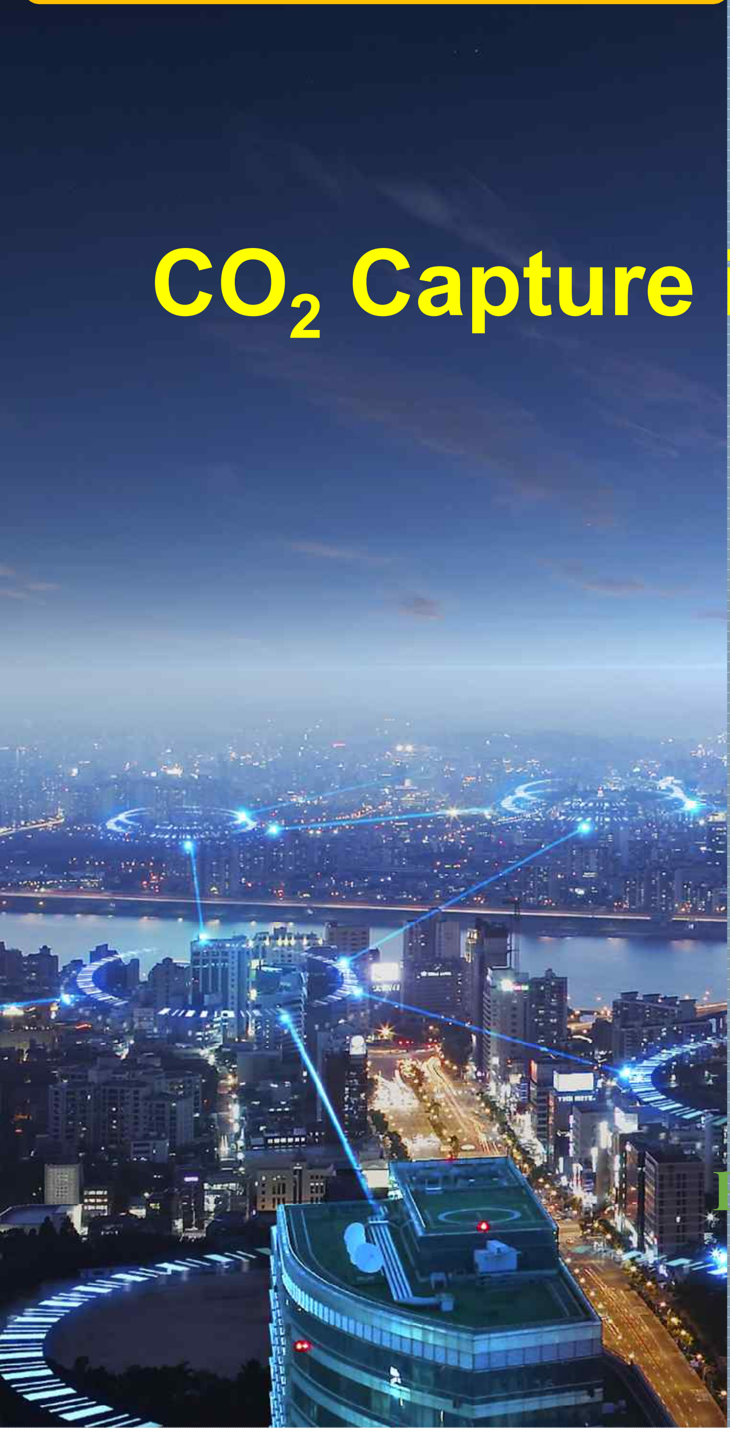
1st GCCUS Conference

CO_2 Capture in Power and Industrial Sectors



Dec. 1, 2023

Kunwoo Han, *Ph.D*

POSCO N.EX.T Hub

POSCO HOLDINGS

POSCO N.EX.T Hub : At a glance!

POSCO HOLDINGS

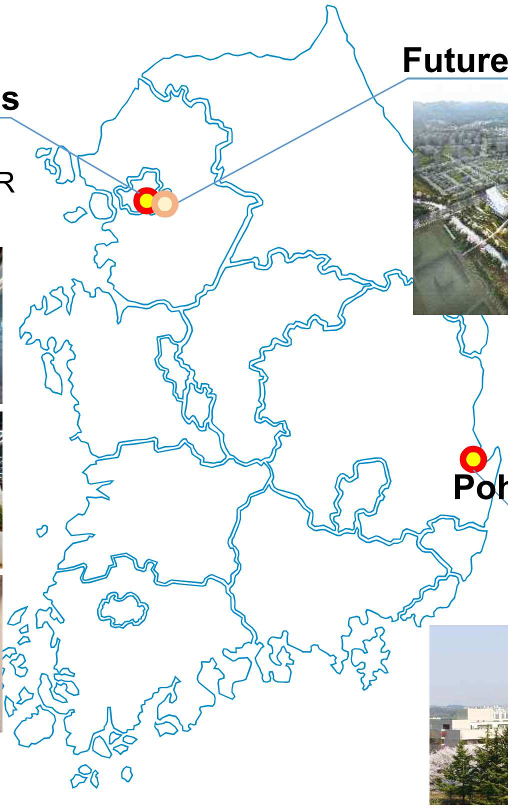
Opened in Jannuary 2021
to lead a low-carbon society through carbon neutrality

Location

- **Seoul Campus : Future-leading tech. development**
- **Pohang Campus : Development of core tech. for commercialization**

Seoul Campus

Teheran-ro 440
POSCO CENTER
West Wing 18th



Future Campus('27~)

Pohang Campus

67, Cheongam-ro,
Nam-gu, RIST
2 Research BLD

Organization

- **One of three research Labs under the POSCO N.EX.T Hub**

POSCO Holdings

POSCO N.EX.T Hub

- AI Lab.
- **Hydrogen & Low Carbon Research Lab.**
  - Research Planning Group
  - **Hydrogen R&D Center**
    - Hydrogen production using ammonia cracking
    - Water electrolysis
    - NH_3/H_2 utilization
    - Novel H_2 production, storage & transportation tech.
  - **Low Carbon R&D Group**
    - CCUS
    - Separation and purification of by-product gases
    - Co-firing(Combustion) of NG, by-product gases and ammonia(hydrogen)
    - Energy/Fuel transformation
- LiB Material Lab.

Outline

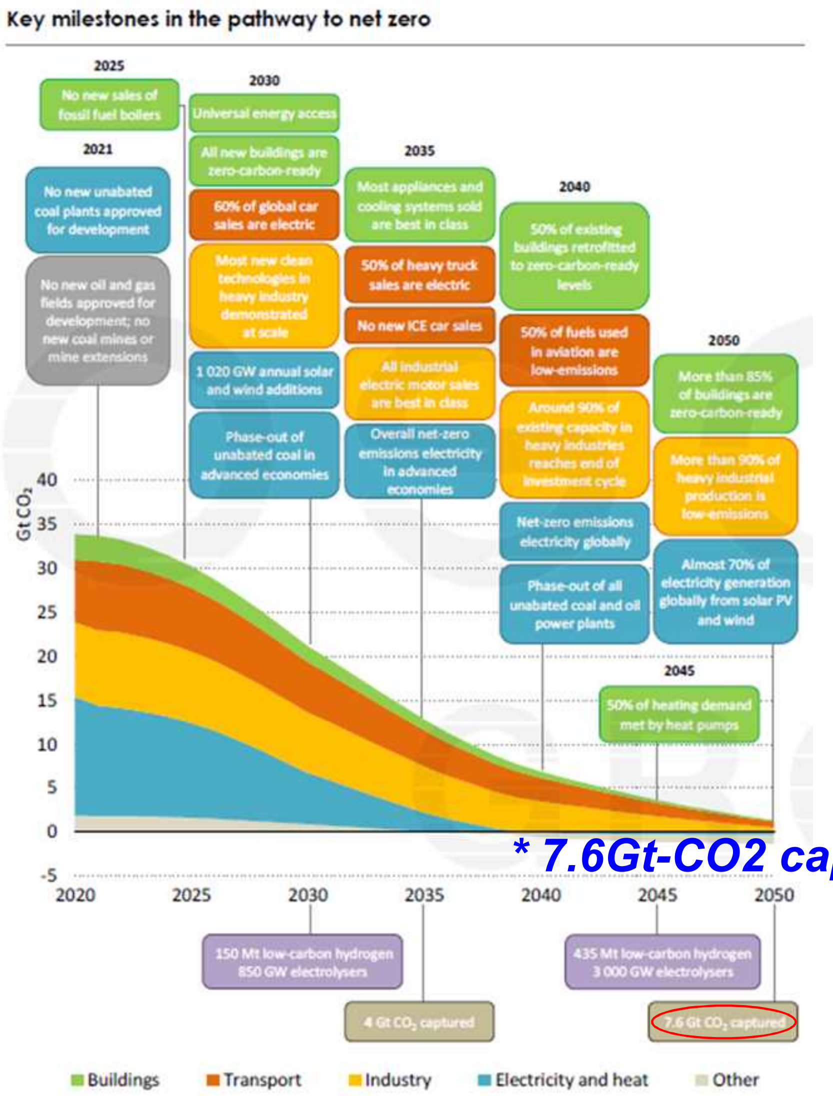
Carbon Neutrality and CCUS

CO_2 Capture: Principles and Practices

CO_2 Capture: Future Directions

Summary

Importance of CCUS



<NZE by 2050, IEA (2021)>

*** 7.6Gt-CO2 capture in 2050**

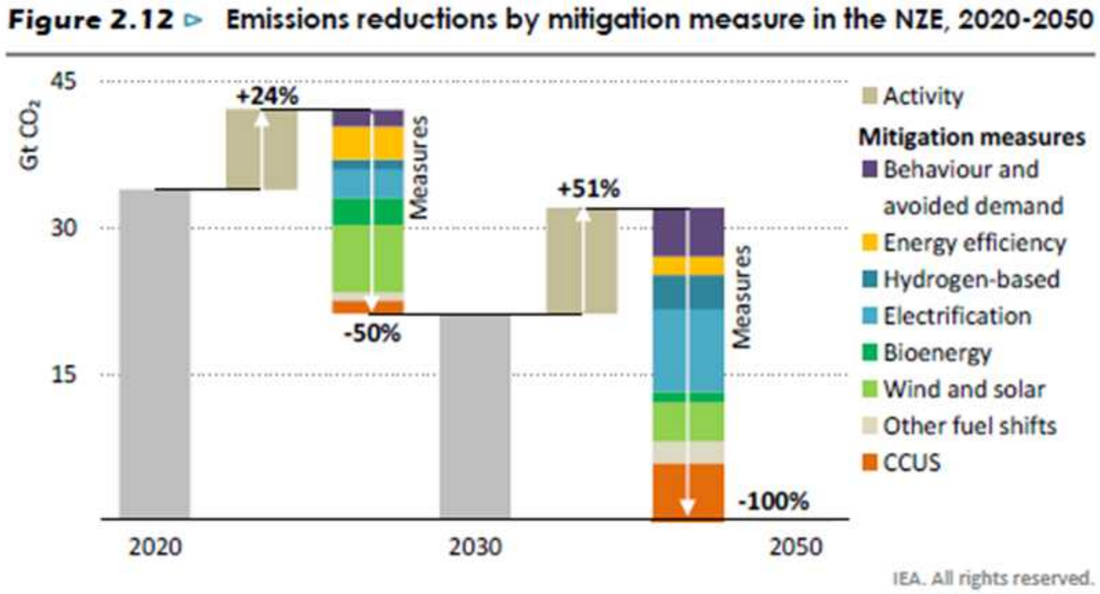


Table 2.9 ▷ Key global milestones for CCUS

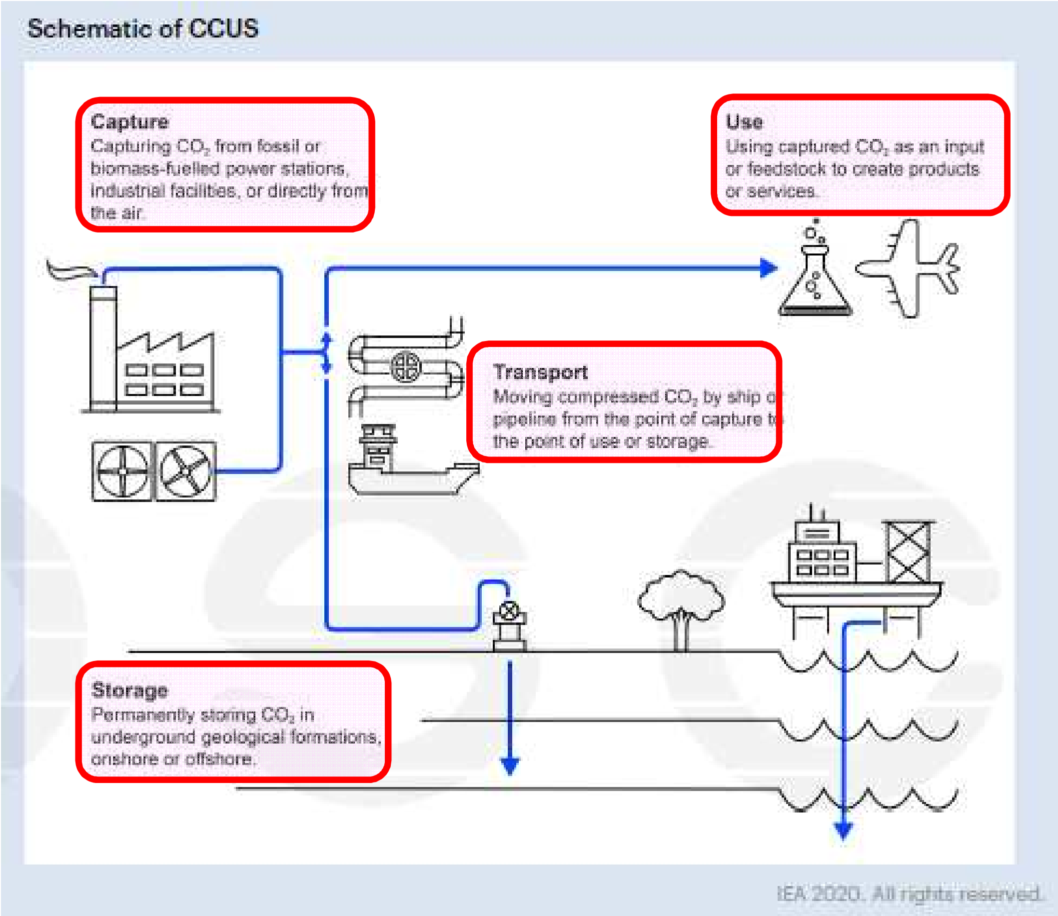
	2020	2030	2050
Total CO_2 captured (Mt CO_2)	40	1 670	7 600
CO_2 captured from fossil fuels and processes	39	1 325	5 245
Power	3	340	860
Industry	3	360	2 620
Merchant hydrogen production	3	455	1 355
Non-biofuels production	30	170	410
CO_2 captured from bioenergy	1	255	1 380
Power	0	90	570
Industry	0	15	180
Biofuels production	1	150	625
Direct air capture	0	90	985
Removal	0	70	630

√ **CCUS: Necessary option for "Carbon Neutrality"**

* **Reduction measures in 2050: Behaviro and avoided demand 16%, Electrification 27%, Solar and Wind 12%, Hydrogen 11%, …, CCUS 18%**

What is CCUS?

- **Carbon dioxide Capture, Utilization and Storage**



<ETP 2020: Special Report on CCUS, IEA(2020)>

(Capture) Separation of CO_2

(Transport) Transporation via pipeline or shipping

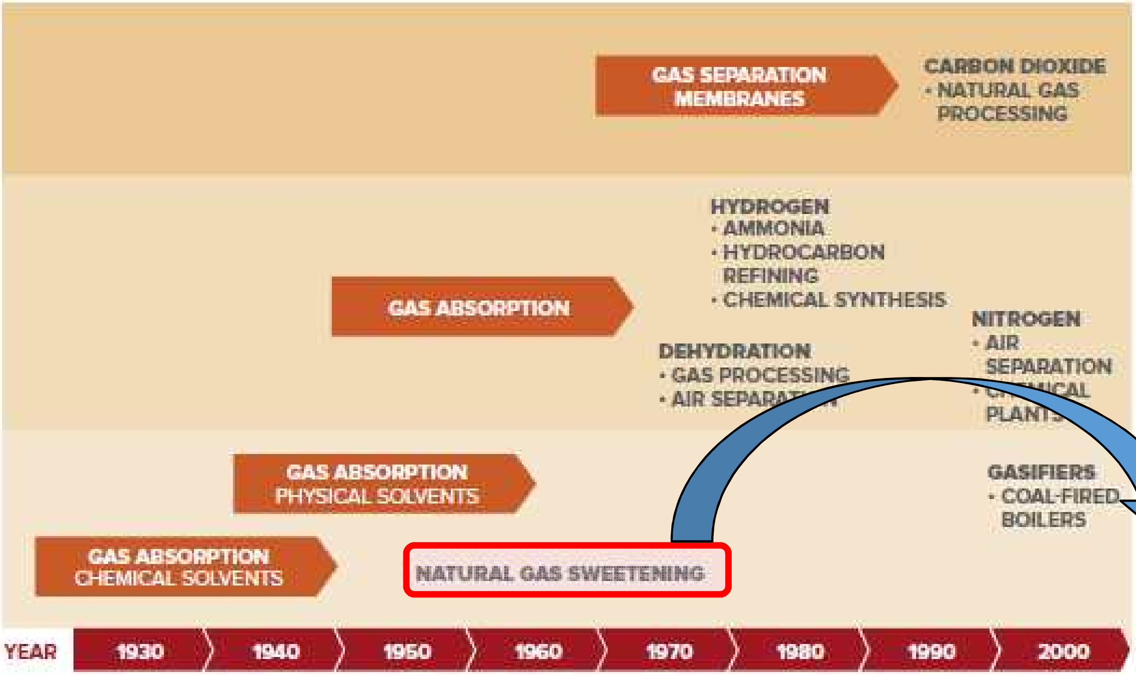
(Storage) Permament storage of CO_2

(Utilization) Use of CO_2 via conversion/non-conversion

CO_2 Capture: A brief history

- **Selective separation of CO_2 from flue/exhaust gas**

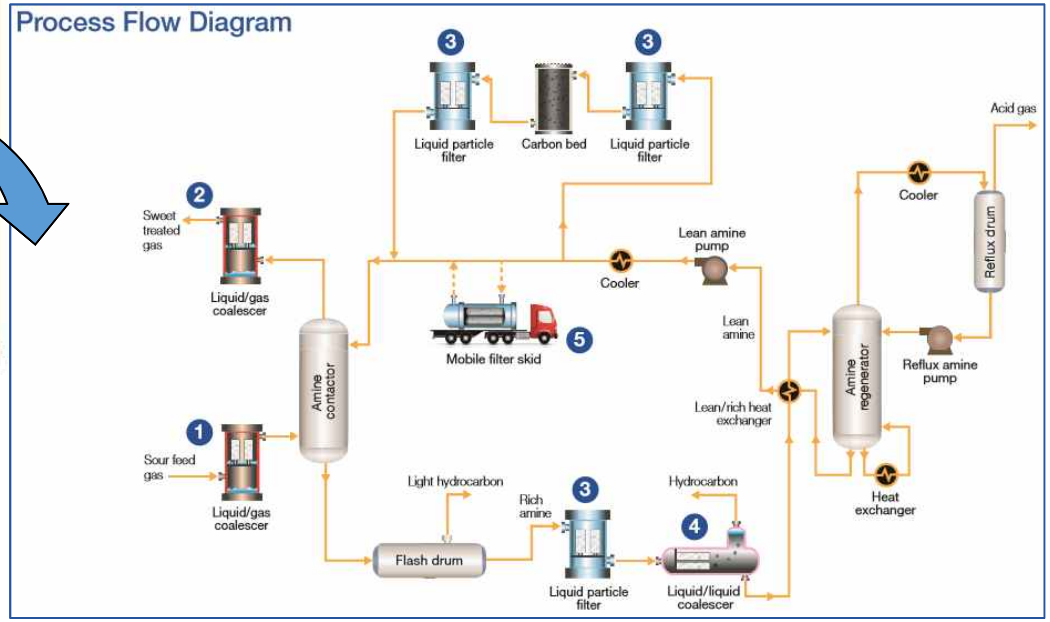
Figure 2 - Development of carbon captures technologies (Global CCS Institute 2016).



<Technology Readiness and Costs of CCS, GCCSI(2021)>

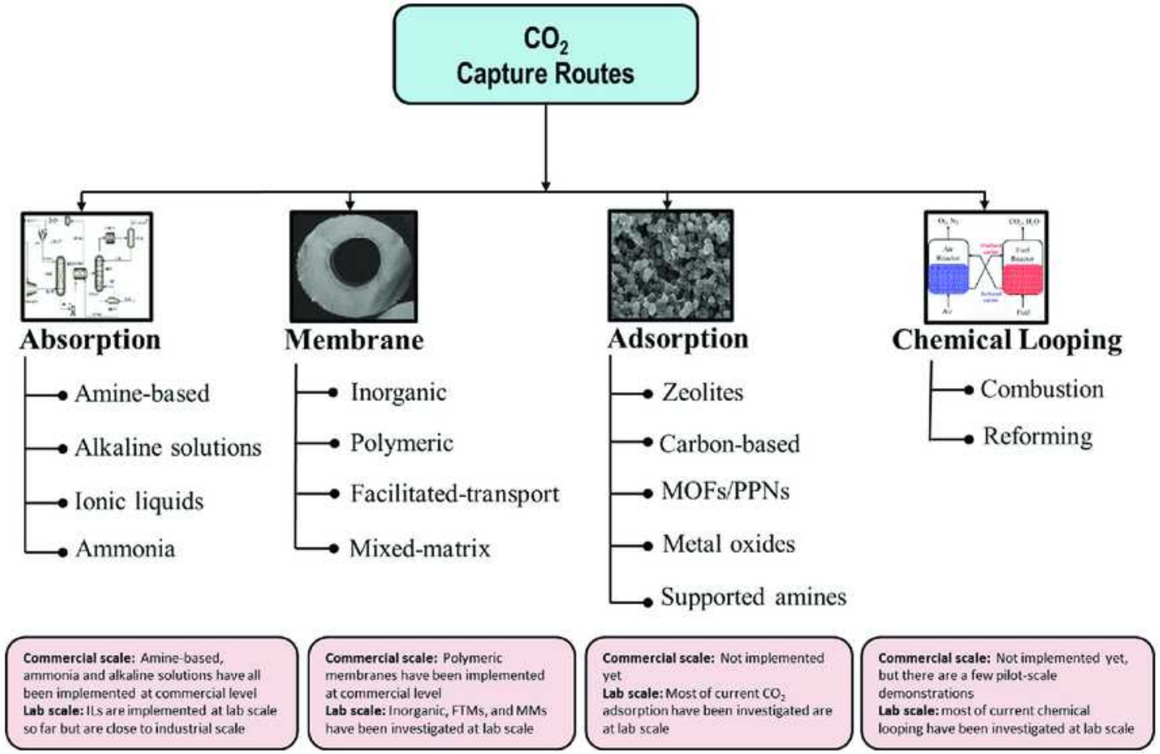
CAPTURE MECHANISM

- Absorption
- Adsorption
- Membrane
- Hydrate, …



<https://www.pall.com/en/oil-gas/midstream/lng-acid-gas.html>

Classification of CO_2 Capture and Its Application



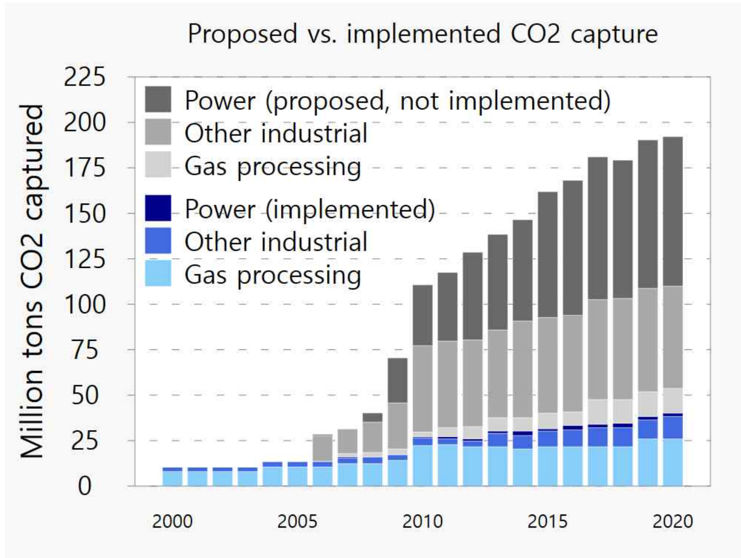
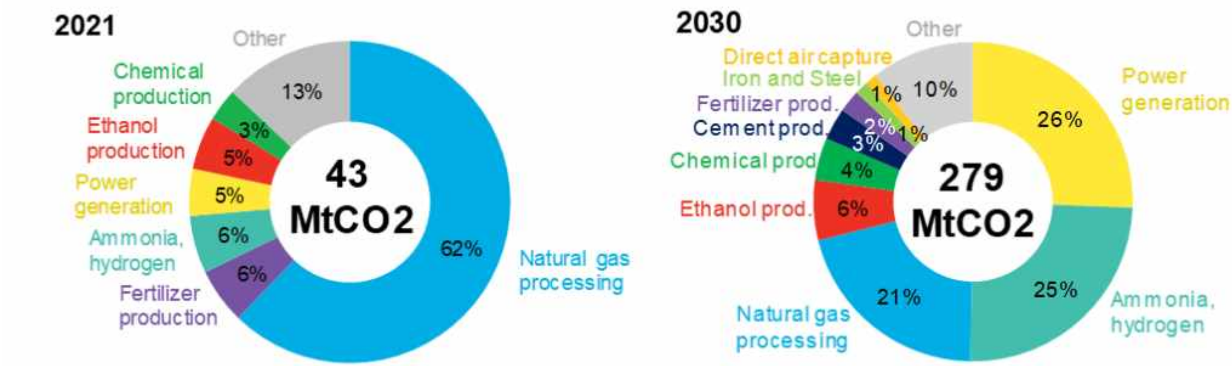


Figure 1: Global carbon capture capacity by source, 2021 and 2030



Source: BloombergNEF.

https://about.bnef.com/blog/global-carbon-capture-capacity-due-to-rise-sixfold-by-2030/

Carbon Neutrality Scenarios and Industrial Effort

< 2050 탄소중립 시나리오 최종(안) 총괄표 >

(단위 : 백만톤CO_2eq)

구분	부문	'18년	초안 1안	초안 2안	초안 3안	최종본 A안	최종본 B안	비고
배출량		686.3	25.4	18.7	0	0	0	
배출	전환	269.6	46.2	31.2	0	0	20.7	· (A안) 화력발전 전면중단 · (B안) 화력발전 중 LNG 일부 잔존 가정
	산업	260.5	53.1	53.1	53.1	51.1	51.1	
	건물	52.1	7.1	7.1	6.2	6.2	6.2	
	수송	98.1	11.2 (9.4)	11.2 (9.4)	2.8	2.8	9.2	· (A안) 도로부문 전기·수소차 등으로 전면 전환 · (B안) 도로부문 내연기관차의 대체연료(e-fuel) 등 사용 가정
	농축수산	24.7	17.1	15.4	15.4	15.4	15.4	
	폐기물	17.1	4.4	4.4	4.4	4.4	4.4	
	수소	-	13.6	13.6	0	0	9	· (A안) 국내생산수소 전량 수전해 수소(그린 수소)로 공급 · (B안) 국내생산수소 일부 부생·추출 수소로 공급
	탈루	5.6	1.2	1.2	0.7	0.5	1.3	
흡수 및 제거	흡수원	-41.3	-24.1	-24.1	-24.7	-25.3	-25.3	
	이산화탄소 포집 및 활용·저장 (CCUS)	-	-95	-85	-57.9	-55.1	-84.6	
	직접공기포집 (DAC)	-	-	-	-	-	-7.4	· 포집 탄소는 차량용 대체 연료로 활용 가정

* 시나리오 간 내용이 상이한 부문은 파란색으로 표시

< 2050 탄소중립 시나리오 (2021)>

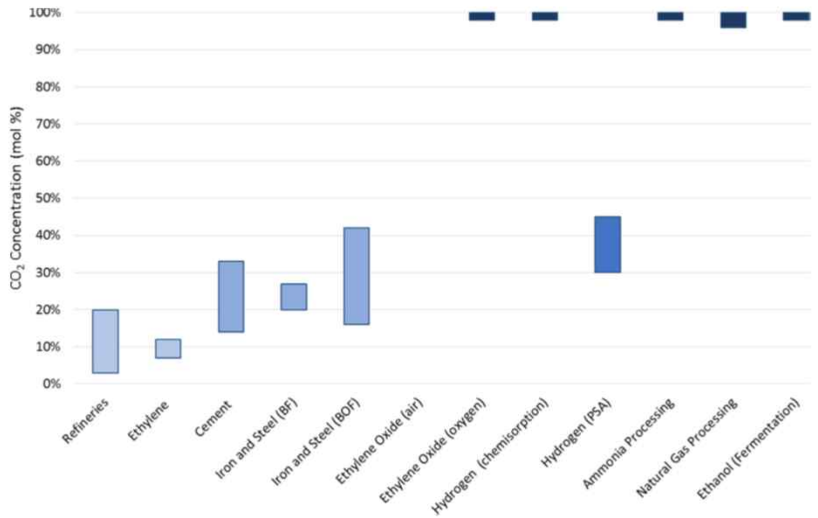
부 문		감축목표(백만톤)	대표 감축기술
전 환 (에너지)		('18)269.6 → ('50)20.7(△92.3%)	· 재생에너지 효율화 관련 차세대 기술 · 수소터빈 등 신규 발전원 상용화 기술 · 재생에너지 중심 전력체계 안정성 확보 기술
산업	全 업종 : ('18)260.5 → ('50)51.1(△80.4%)		· 저탄소 산업구조로 대전환 - 탈탄소 공정 · 핵심 감축기술 실증화 및 상용화
	철강		· 탄소계공정, 수소환원제철로 100% 대체 · 철스크랩 전기로 조강 확대 기술
	석유화학(정유)		· 연료(전기 가열로) 및 원료(바이오 납사) 전환기술 고도화
	시멘트		· 100% 친환경 연료 전환 기술 · 석회석 대체 및 혼합재 원료 확대 고도화
	기타(반도체·디스플레이 등)		· 불소계 온실가스 저감 기술 · 전력 다소비업종 에너지 효율화 기술
수 송		('18)98.1 → ('50)9.2(△90.6%)	· 친환경 교통 전환 및 도로부문 전기·수소화 · 대체연료(e-fuel) 기술 상용화
CCUS		('18) 0 → ('50)-84.6	· 이산화탄소 포집, 활용, 저장 상용화 기술

* 자원순환도 핵심 감축기술로 제시

<탄소중립 산업·에너지 R&D 전략, 산업부 (2021)>

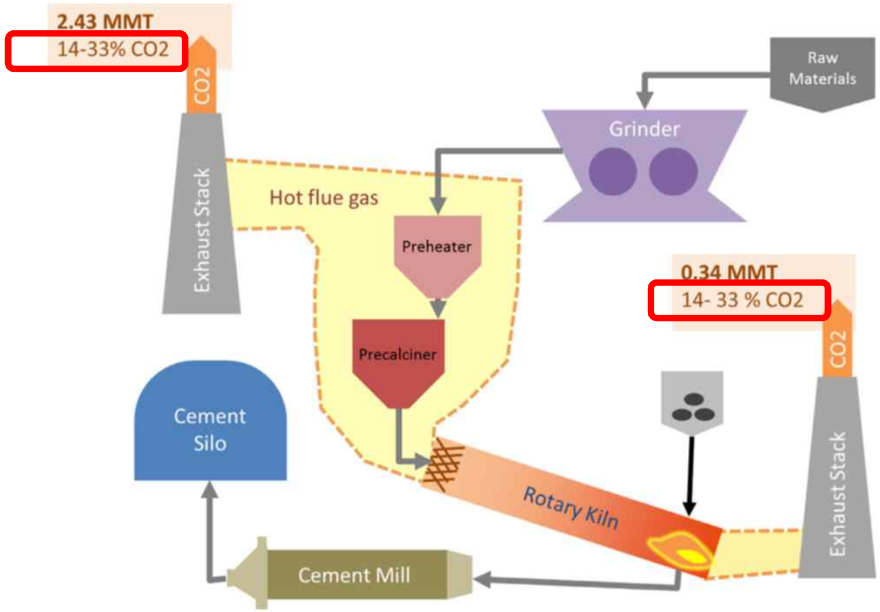
CO_2 Capture in Industrial Sector

CO_2 source	CO_2 content	CO_2 process unit	Temperature (°C)	Flue gas component	% of U.S. emissions
Petroleum power plant	3–8%	Furnace	40 – 65	CO_2, NOx, SOx, O_2, N_2	0.5
Natural gas power plant	3–5%	Gas turbine	93–106 (after HRSG)	CO_2, NOx, SOx, CO, O_2, N_2, Hg, As, Se	8.0
Coal power plant	10–15%	Steam boiler furnace	40 – 65	CO_2, NOx, SOx, CO, O_2, N_2, Hg, As, Se	28.3
Cement production	30%	Precalciner	150 – 350	CO_2, H_2O, N_2, hydrocarbons, volatiles (K_2O, Na_2O, S, Cl)	1.2
	14–33%	High T Kiln (calcination)	150 – 350	CO_2, H_2O, N_2, hydrocarbons, volatiles (K_2O, Na_2O, S, Cl)	
Petroleum refineries	8–10%	Process heaters	160–190	Depends on fuel used	3.1
	3 – 5%	Utilities (steam, electricity)	160–190	Depends on fuel used	
	10–20%	Fluid catalytic cracker (FCC) (regeneration of catalyst)	160–190	O_2, CO_2, H_2O, N_2, Ar, CO, NOx, SOx	
	30 – 45%, 98–100%	H_2 purification	20-40 (for PSA), 100–120 (for chemisorption)	CO_2, H_2, CO, CH_4	
Iron and steel manufacturing	20 - 27%	Blast furnace (high CO_2 if BFG is burned)	100	H_2, N_2, CO, CO_2, H_2S	1.0
	16 – 42%	Basic oxygen Furnace (high CO_2 from burning BOF gas)	~100	H_2, N_2, CO, CO_2, H_2S	
Ethylene production	7–12%	Steam cracking	160–215	H_2O, CO, NOx, SOx, O_2, N_2, CO_2	0.3
Ethylene oxide production	~30%, 98 – 100%	Absorption unit to purify EO (lower end is air oxidation, higher end is oxygen oxidation)	16–32 (for water adsorption), 100 – 120 (chemisorption)	Mainly CO_2, H_2O, N_2, (air oxidation) some CH_4, ethylene, EO	0.02
Ammonia processing	98–100%	H_2 purification	100–120 (chemisorption)	CO_2, H_2, O_2, CH_4	0.3
Natural gas processing	96–99%	Acid gas removal/CO_2 absorption (low P stripper)	100–120	96 - 99% CO_2, 1-4% CHx (mainly methane, trace amounts ethane, propane, butane), H_2O, N_2	0.3
Hydrogen production	30 – 45%, 98–100% (15–20% in stream before purification)	H_2 purification (lower end is PSA, higher end for CO_2 specific separation)	20–40 (for PSA), 100–120 (for chemisorption)	CO_2, H_2, CO, CH_4, After chemisorption: ~100% CO_2	0.8
Ethanol production	98 – 99%	Fermentation	35	CO_2, ethanol, methanol, H_2S, dimethyl sulphide, acetaldehyde, ethyl acetate	0.7



<Bains et al., PECS(2017)>

CO_2 Capture in Cement Industry



$$CaCO_3 + heat \rightarrow CaO + CO_2$$

<Bains et al., PECS(2017)>

- √ **Globally, CO_2 emission in cement industry ~ 64.3Mt in 2014**
- √ **Main source of CO_2 ~ cement kiln (heating + calcination)**
- √ **Higher CO_2 conc. than flue gas, however, … little profit**

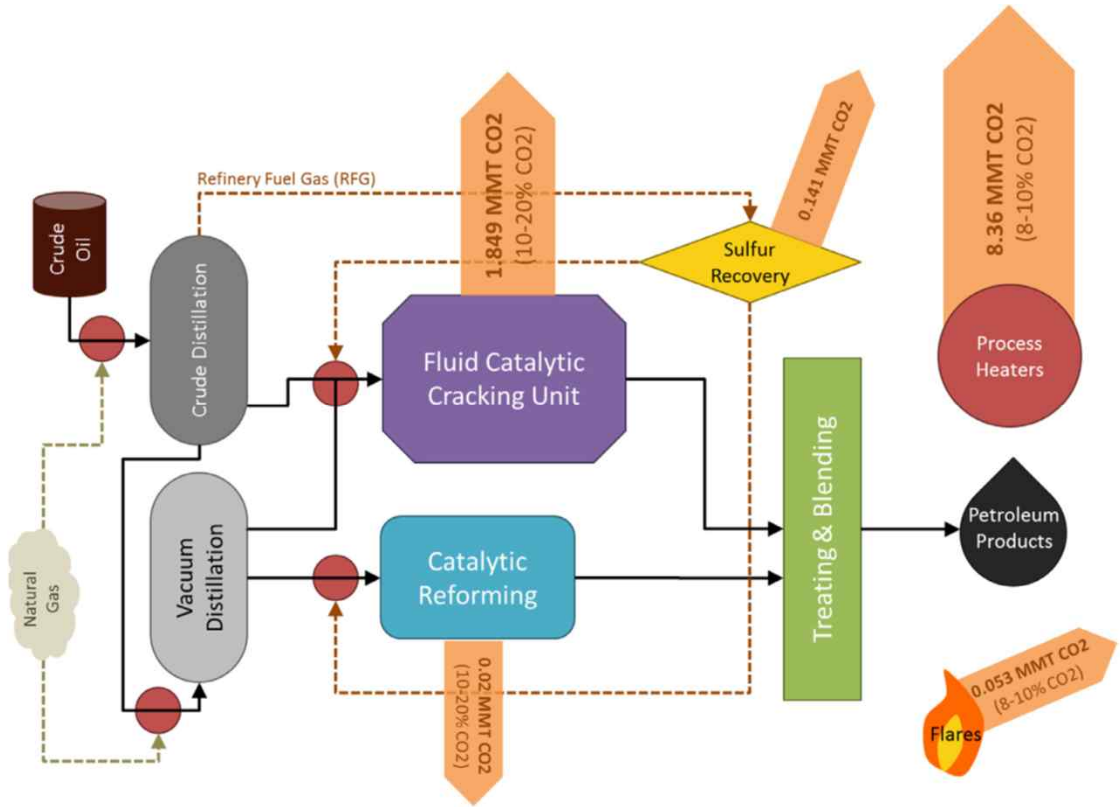


Table 4
Breakdown of 2014 CO_2 emissions from ExxonMobil's petroleum refinery in Baytown, TX [38].

CO_2 source	CO_2 emissions (metric tons)	% of facility emissions
Process heaters	8359,658	80.30%
Fluid catalytic cracking	1849,208	17.80%
Sulfur recovery	140,722	1.40%
Flares	52,751	0.51%
Catalytic reforming	2046	0.02%
Process vents	1693	0.02%
TOTAL	***10,406,077***	***100%***

<Bains et al., PECS(2017)>

Heating

$$CH_4 + O_2 \rightarrow CO_2 + 2H_2O$$

$$C_2H_6 + O_2 \rightarrow 2CO_2 + H_2O$$

Decoking

$$C(deposit) + O_2 \rightarrow \ldots \rightarrow CO_2$$

√ **Globally, CO_2 emission in refinery industry ~ 818Mt in 2008**

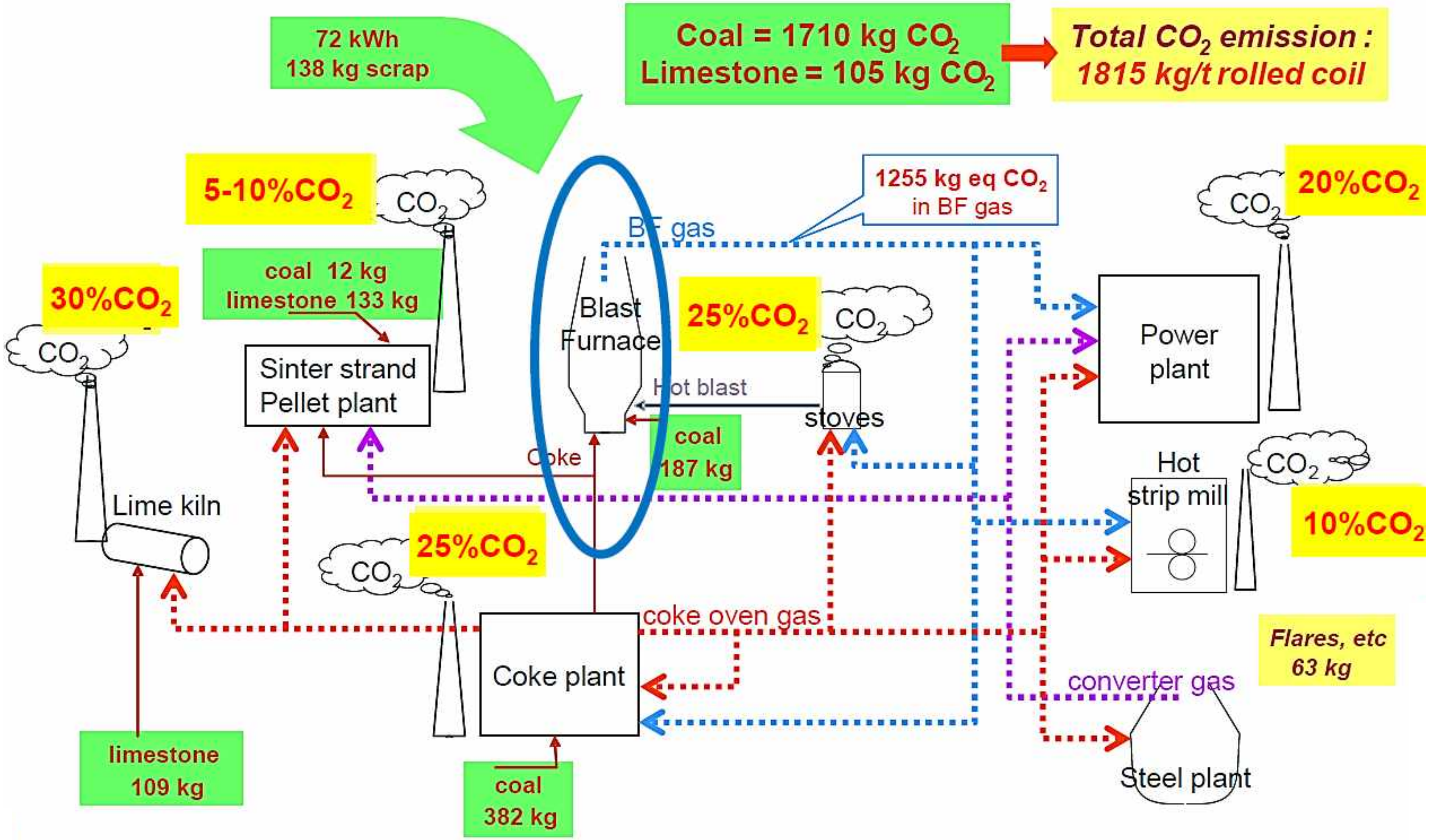
√ **Main source of CO_2 emission ~ combustion(fluid catalytic cracking, process heaters)**

√ **Lots of refineries have on-site hydrogen production units**

CO_2 Capture in Iron and Steel Industry

Key reaction in "Iron and Steelmaking"

Fe_2O_3, Fe_3O_4 + Carbon → Fe + CO_2

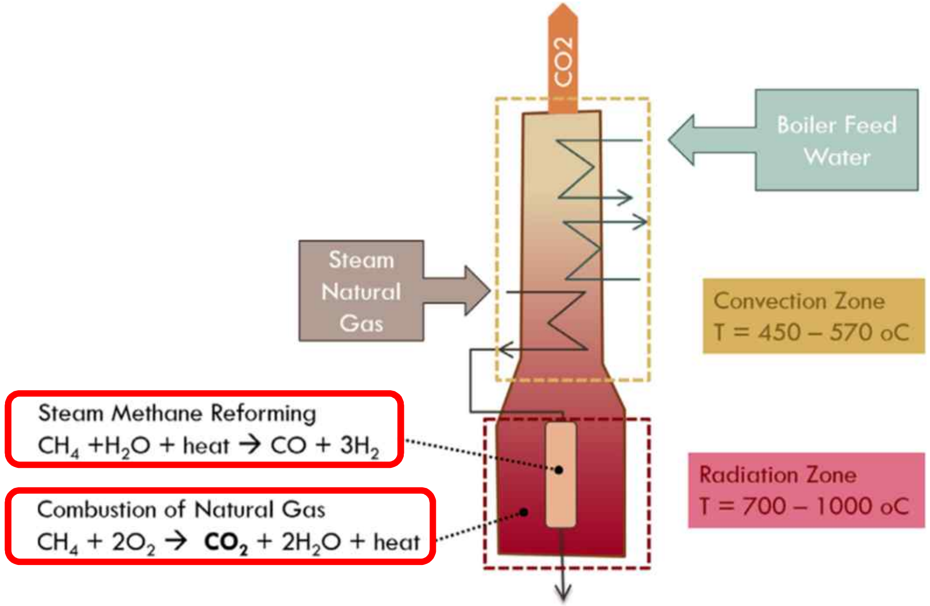


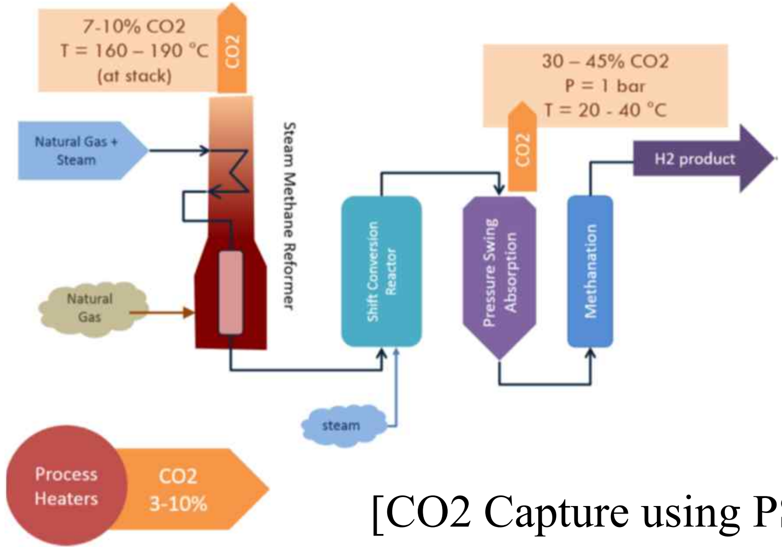
< CO_2 capture technologies for industry Iron & Steel, Oil Refinery & Cement
CO_2 capture and Storage Regional Awareness-Raising Workshop, 2012 >

√ **Major CO_2 emission : iron-making(Coking/Sintering/BF)**

√ **CO_2 capture ~ practices in BFG**

CO_2 Capture in Hydrogen Production





[CO2 Capture using PSA]

Table 7
Estimated 2008 CO_2 emissions from hydrogen production [30]. Production type from [77].

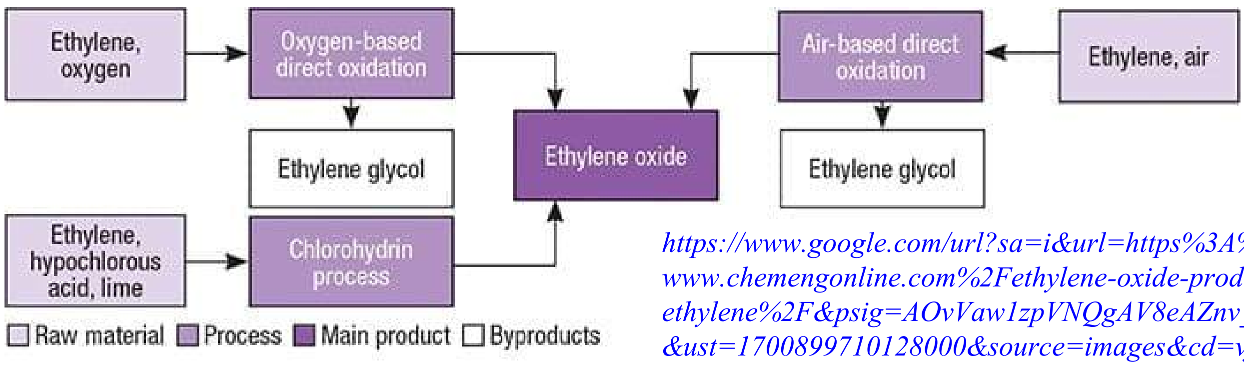
Hydrogen production type	Business sector	Estimated CO_2 emissions (MMT per year)	CO_2 breakdown
On-purpose merchant	Merchant H_2	17	28.3%
On-purpose captive	Oil refineries	25	41.7%
On-purpose captive	Ammonia plants	18	30.0%
On-purpose captive	Methanol plants	None	0.0%
Byproduct	Chlorine plants	None	0.0%
	Other	< 1	< 1%
–	*TOTAL*	*60*	**100%**

<Bains et al., PECS(2017)>

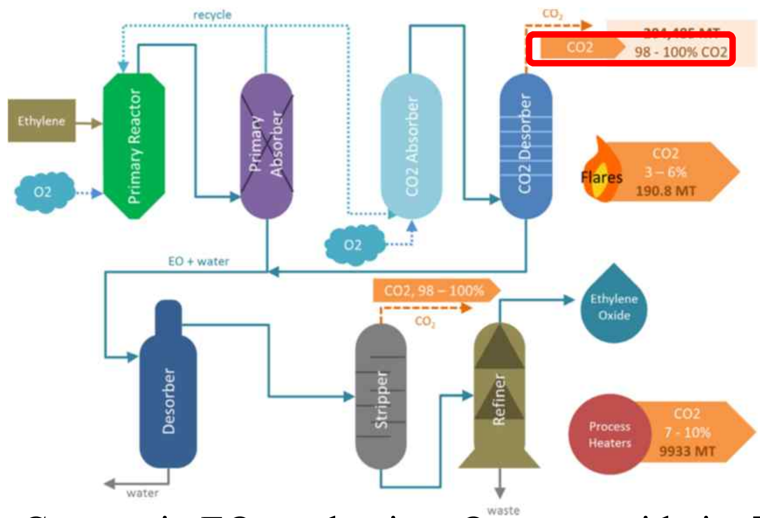
√ **Majority production : on-purpose captive**

√ **CO_2 capture ~ absorption/adsorption after shift reactor**

CO_2 Capture in Ethylene Oxide Production

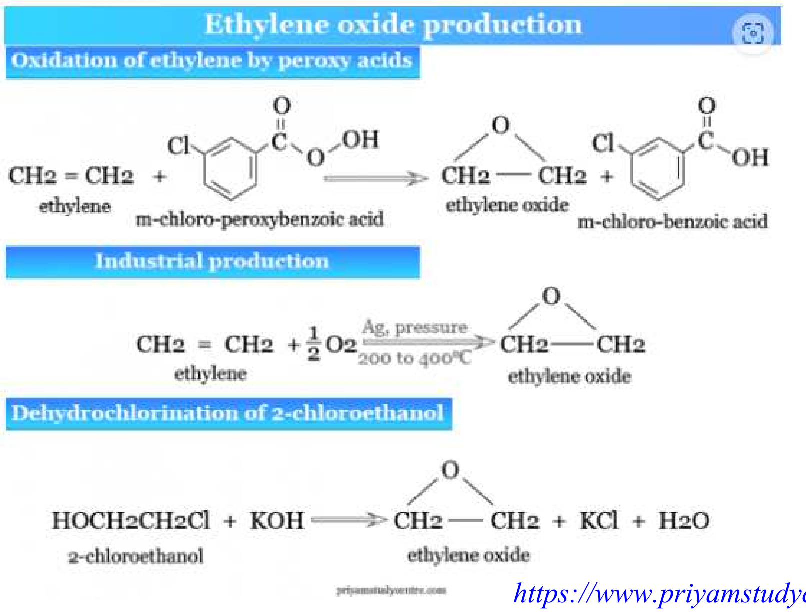


https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.chemengonline.com%2Fethylene-oxide-production-ethylene%2F&psig=AOvVaw1zpVNQgAV8eAZnv_YklEmT&ust=1700899710128000&source=images&cd=vfe&opi=89978449&ved=0CBEQjhxqFwoTCJDmnKyX3IIDFQAAAAAdAAAAABAI

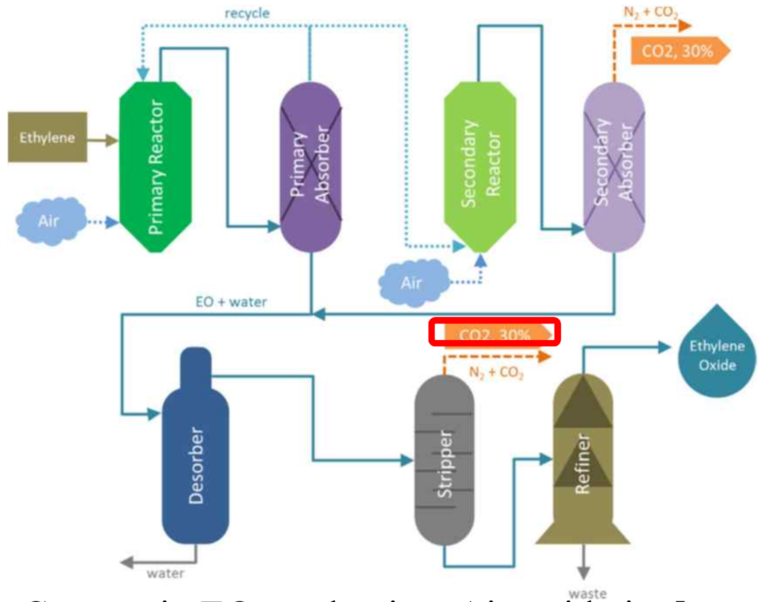


[CO_2 Capture in EO production, Oxygen-oxidation]

Ethylene oxide production



https://www.priyamstudycentre.com/2021/05/ethylene-oxide.html

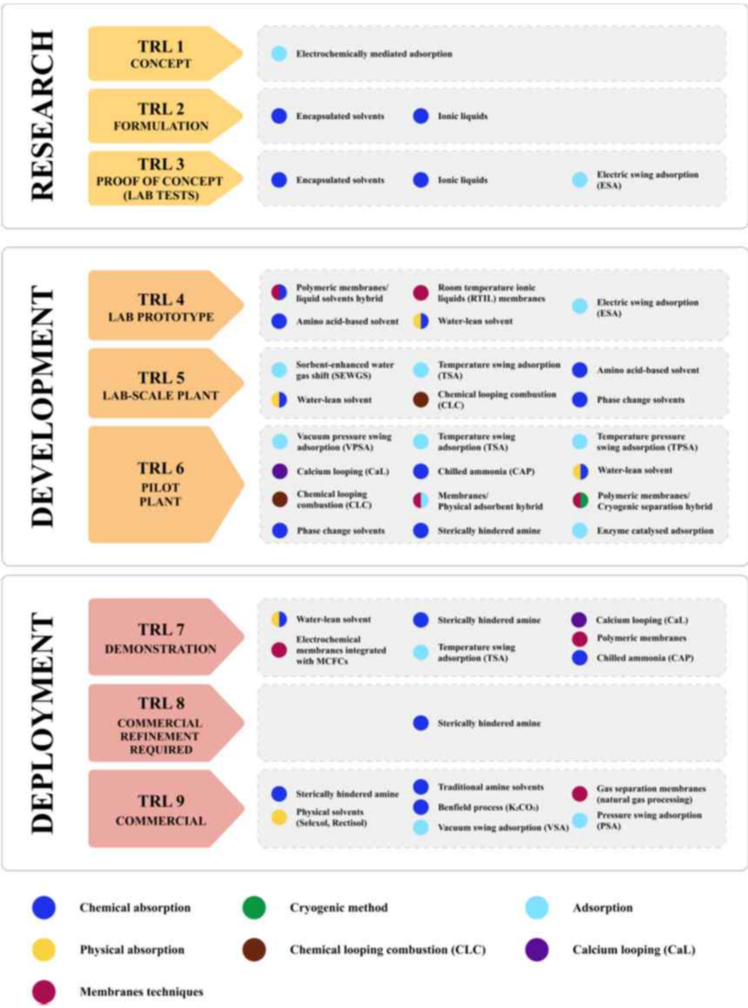


[CO_2 Capture in EO production, Air-oxidation]

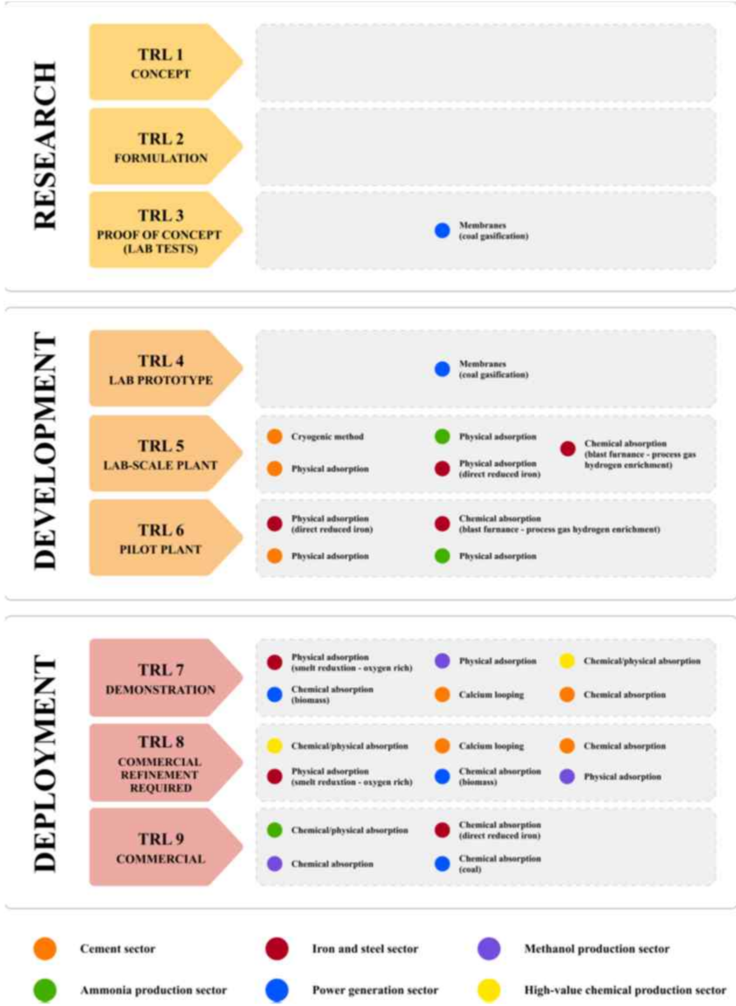
<Bains et al., PECS(2017)>

- √ **CO_2 emissions in EO or EG production**
- √ **Two types of oxidation: direct oxygen or air**

CO_2 Capture Development Status



[CO_2 Capture – by Separation Methods]



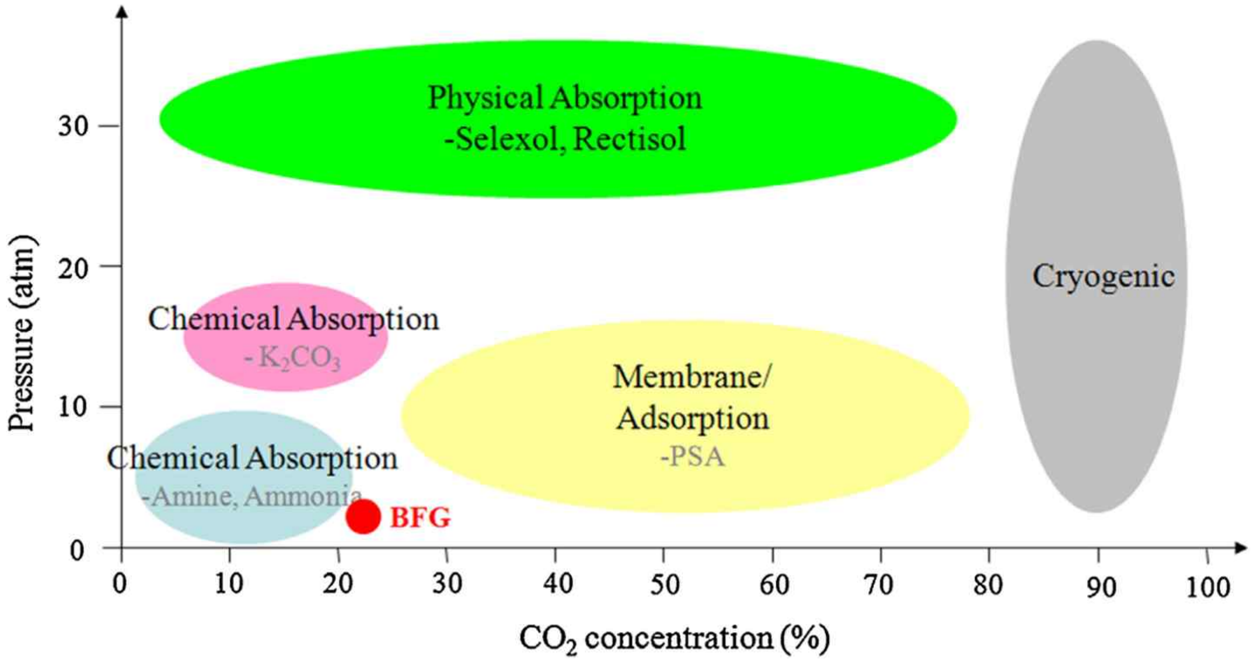
[CO_2 Capture – by Industrial Sector]

√ **Chemical absorption ~ widely studied and commercialized**

√ **Commercialized in various fields**

<Bains et al., PECS(2017)>

Directions for CO_2 Capture



<Han et al., JGGC(2014)>

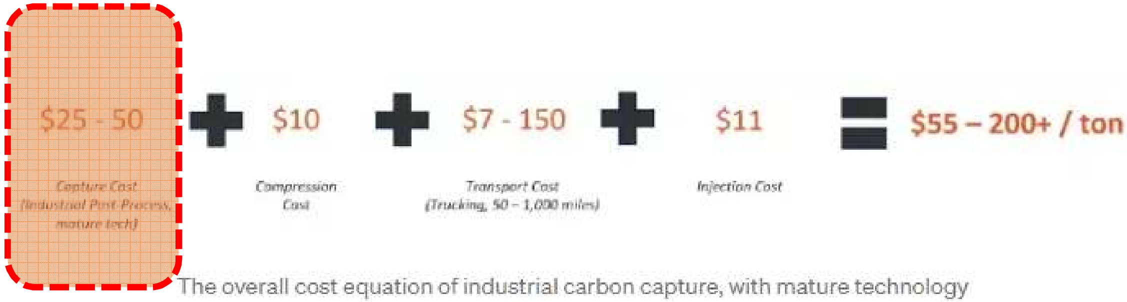
	MOFs	Liquid Amines	Amine Grafted MOFs	Zeolites	Ionic Liquids	Hybrid Ultraporous Materials (HUMs)	Soda Lime	Amine Grafted Inorganics
Selectivity	Low	High	High	Low	High	Very high	High	High
Stability	Low	Low	Medium	High	High	Medium	High	High
Humidity effect	High	Low	Medium	High	Low	Medium	Low	Low
Material cost	Medium/high	Low	High	Low	Low	Low	Low	Medium
Process cost	Medium	Low	High	Low	Medium	Low	Low	Medium
Recycling cost	High	High	Medium	High	Medium/high	Low	Very high	Medium
Working capacity	High	Medium	Medium	Medium	Low	Medium	Medium	Medium
Kinetics	Medium	Fast	Medium	Medium	Fast	Fast	Fast	Medium
Upside potential	High	Low	Medium	Low	Medium	High	Low	Medium

<Catalysts(2020)>

√ No Silver Bullet!

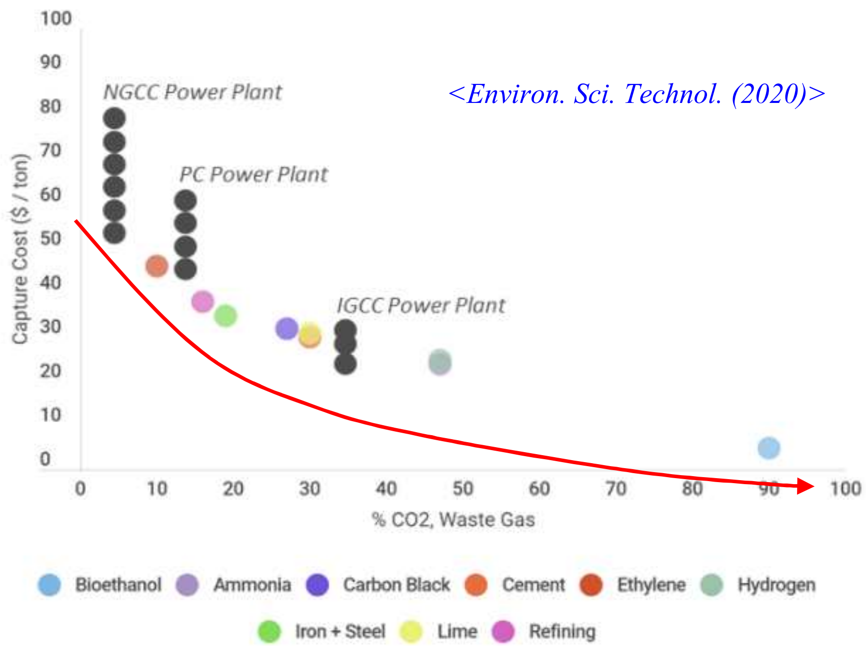
Directions for CO_2 Capture

* Why should we develop?



The overall cost equation of industrial carbon capture, with mature technology

<We are close to a tipping point in industrial carbon capture>



<Environ. Sci. Technol. (2020)>

* Thermodynamics tells…

$$W_{min} = RT[n_B^{CO2}\ln(y_B^{CO2}) + n_B^{B-CO2}\ln(y_B^{B-CO2})] + RT[n_C^{CO2}\ln(y_C^{CO2}) + n_C^{C-CO2}\ln(y_C^{C-CO2}) - RT[n_A^{CO2}\ln(y_A^{CO2}) + n_A^{A-CO2}\ln(y_A^{A-CO2})]] \quad ($$

"A 90% CO2 capture rate at 95% CO2 purity was assumed for all CO2-relevant gas streams, except for those with initial(feed) stream purities greater than 95%. In this case, CO2 purity that matched the initial feed stream's purity were assumed, resulting in zero theoretical minimum work required for separation."

<CO2 Capture, Wilcox(2014)>

Summary

- CCUS ~ pillar for "Carbon Neutrality"
- Capturing CO_2 ~ long history with lots of practices around the globe
  - Absorption(Wet/Dry), Adsorption, Membranes, Cryogenics, etc.
  - Natural gas processing, Hydrogen production, EO production, …
  - Moving toward Power and Other Industrial Sectors
- Industrial CO_2 Capture
  - (Refinery) FCC, Process Heaters
  - (Cement) Kiln exhaust gas with relatively high concentration
  - (Iron and Steel) Iron-making process with wide range of CO_2 conc.
  - (Hydrogen Production) Various possible points of capture, relatively high CO_2 conc.
- Different CO_2 emission conditions → Different methods for capture
- Research direction: Reducing the energy(thermal) consumption


Thanks!
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