Workshop on Non-Electric and Hybrid Applications of Nuclear Energy,
Bexco, Busan

Nuclear Process Heat for Decarbonizing of Korean Chemical Process Industries?

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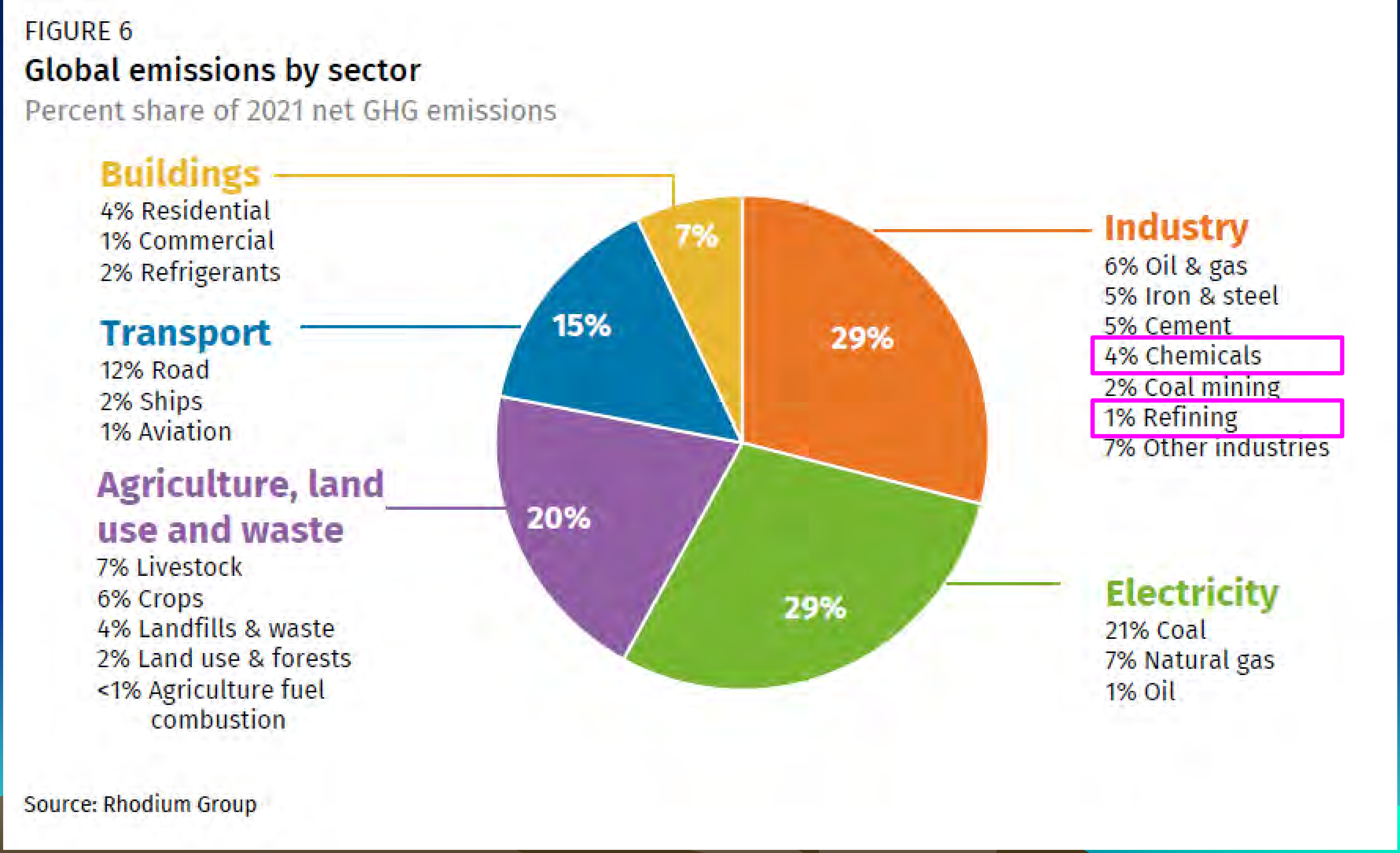
Outline

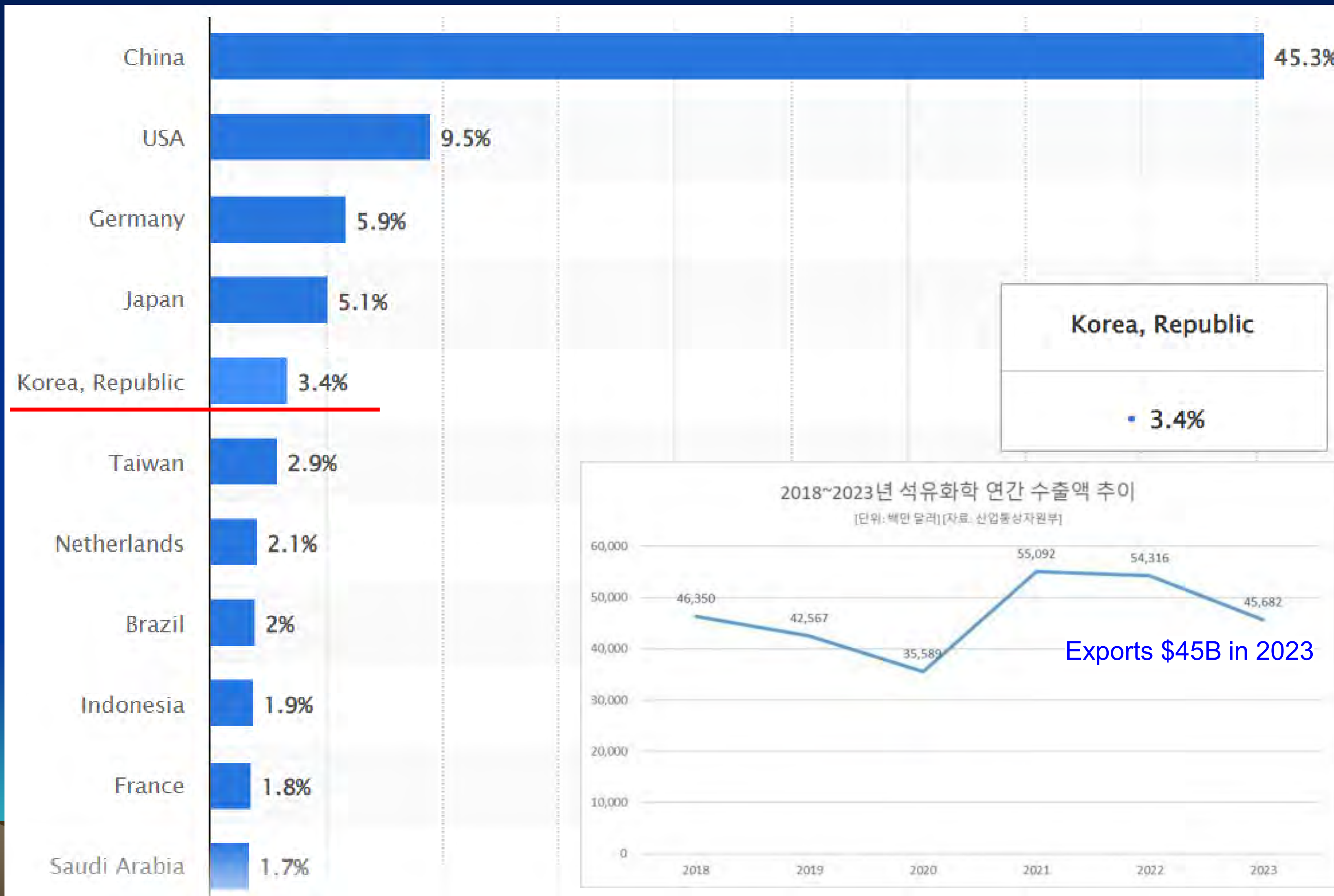
- Korean Chemical Process Industries
  - Energy consumption, CO_2 emission
- Emissions Reduction Roadmap
- Chemical Plant Characteristics
  - Driven by steam
  - Ex: Toluene hydrodealkylation process
- Conclusions

Petrochemical Industry: 5% share of global emissions



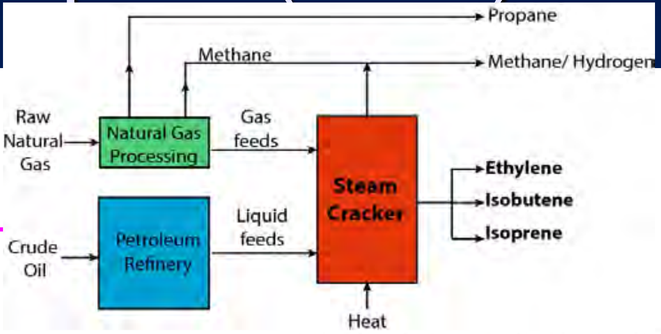
https://rhg.com/research/global-greenhouse-gas-emissions-2022/

Petrochemical sales worldwide in 2022



https://www.statista.com/statistics/1330657/global-petrochemical-sales-share-by-country/

Petrochemical Energy Consumption (2019)



- 최종 에너지 사용 비중 : 31.1%
- 비에너지 사용 비중 : 94.8%
- 비에너지(Naphtha 등 산업원료용 에너지원) 제외 시 사용 비중 : 9.3% (16M TOE)
- 석유화학은 세계 최고의 에너지 효율성 유지

에너지 사용 통계(2019년)

(단위: 천toe / 괄호안은 비중(%)) [kTOE]

		최종에너지 (A)		비에너지 (B)		비에너지제외(a-b)	
산업전체		231,353	100%	59,091	100%	172,262	100.0%
제조업		127,431	55.1%	57,297	97.0%	70,134	40.7%
	석유&화학	72,003	31.1%	56,003	94.8%	16,000	9.3%
	철강	29,529	12.8%	-	0.0%	29,529	17.1%
	조립금속	11,414	4.9%	3	0.0%	11,411	6.6%
	기타	14,485	6.3%	1,291	2.2%	13,194	7.7%
비제조업		5,502	2.4%	1,689	2.9%	3,813	2.2%
수송		42,975	18.6%	6	0.0%	42,969	24.9%
가정·상업		40,088	17.3%	84	0.1%	40,004	23.2%
공공·기타		5,388	2.3%	15	0.0%	5,373	3.1%

자료 : 에너지경제연구원, 에너지통계연보(2020)

Energy consumption by industrial sector (2021)

(단위 : 천toe)

[kTOE]

Refinery

Petrochem.

년도	제조업											광업	합계
	음식료업	섬유제품업	펄프,종이	정유	화학	비금속광물 제품	제1차금속 산업	전자장비 제조업	자동차제조업	그외 기타 제조업	소계		
2015	2,329	1,634	2,809	33,002	32,673	6,538	31,583	4,162	1,926	4,529	121,185	140	121,325
2016	2,539	1,673	2,817	35,278	33,329	6,759	31,158	4,169	2,011	4,868	124,600	154	124,754
2017	2,529	1,491	2,993	37,686	34,823	6,634	31,749	4,484	1,903	4,967	129,258	150	129,408
2018	2,759	1,620	2,929	37,076	35,964	6,284	33,815	5,055	2,144	5,683	133,328	144	133,472
2019	2,374	1,001	2,628	36,325	35,864	6,378	33,538	5,600	1,979	4,975	130,662	132	130,794
2020	2,598	1,018	2,595	32,661	36,524	5,898	33,668	5,542	1,850	5,911	128,264	116	128,380
2021	2,466	1,074	2,357	30,290	45,023	6,004	34,004	5,556	1,809	4,992	133,574	128	133,702

EG-TIPS 에너지온실가스 종합정보 플랫폼 https://tips.energy.or.kr/statistics/statistics_view1115.do

Emissions by industrial sector based on national inventory (2020)

(단위: 천CO2eq.)
[ktCO2eq]

부문	업종	직접	간접(전기, 열)	산업공정	계
	철강	93,137	11,359	4,418	108,914
Petrochem.	석유화학	46,899	21,439	907	69,245
Refinery	정유	15,173	4,021	-	19,194
	시멘트	9,184	2,520	22,703	34,407
	요업	616	879	-	1,495
	유리	736	1,367	-	2,103
	디스플레이	516[illegible]	[illegible]	[illegible]	[illegible]
	전기전자	731[illegible]	[illegible]	[illegible]	[illegible]
	반도체	71[illegible]	[illegible]	[illegible]	[illegible]
제조업	자동차	1,36[illegible]	[illegible]	[illegible]	[illegible]
	기계	1,348	15,370		16,718
	조선	239	1,336		1,575
	비철금속	2,881	4,235	25	7,142
	음식료품	1,991	5,365		7,355
	제지	717	3,933		4,650

- Global: 정유 및 석유화학 분야가 석유 및 가스 등의 생산·운송·정제 과정에서 발생하는 탄소는 전세계 배출량의 ~15%
- Korea: 국내 석유화학산업은 한국의 온실가스 배출량의 ~17-18%

https://tips.energy.or.kr/carbon/Ggas_industry.do

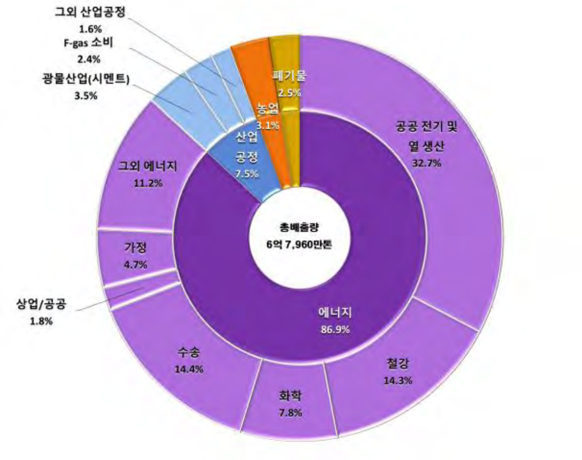
www.sisajournal-e.com/news/articleView.html?idxno=305828

Greenhouse gas emissions in industrial sector (2021)

(단위 : 천tCO_2eq)

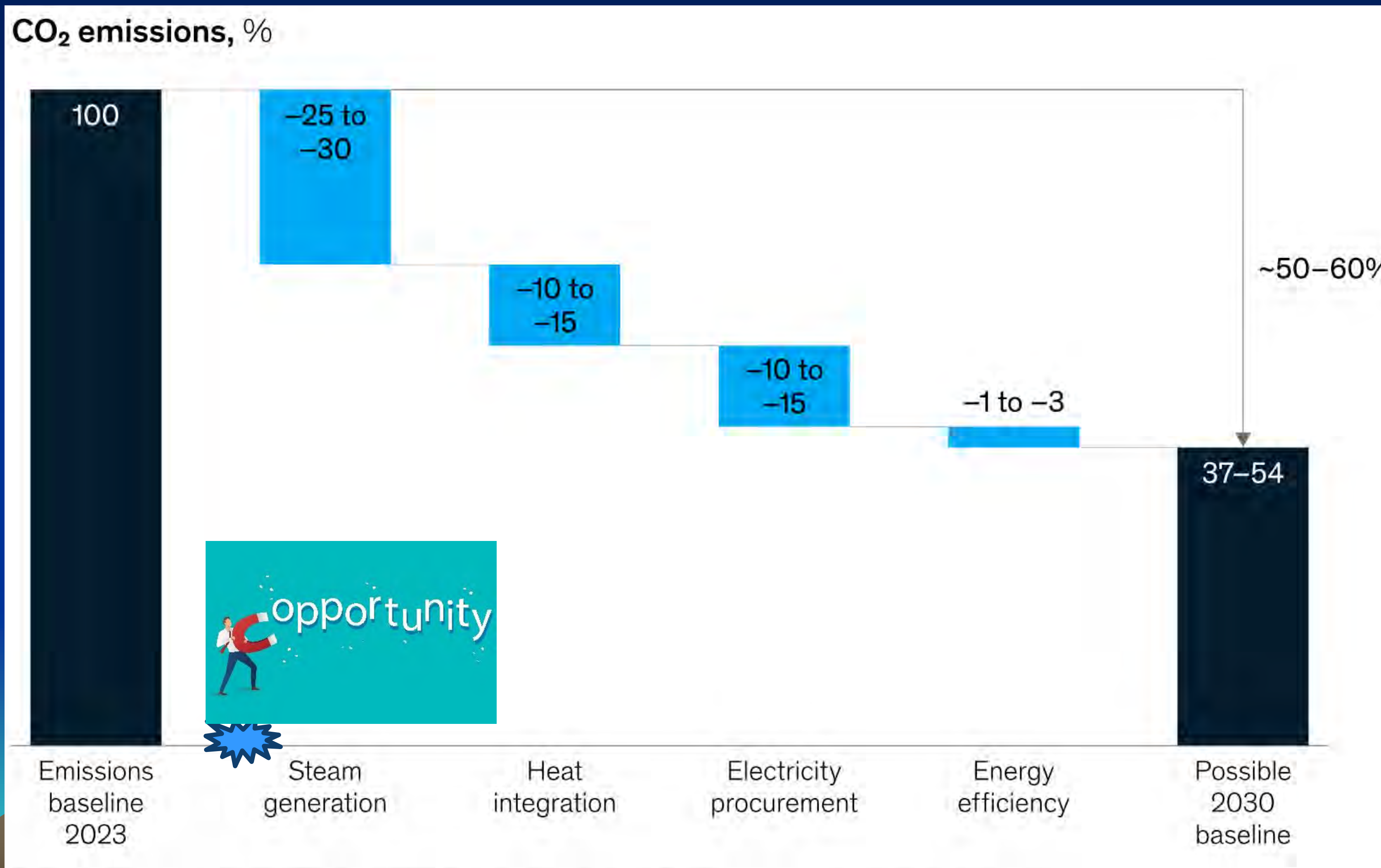
[ktCO2eq]

년도	음식료업	섬유제품업	펄프,종이	정유 (Refinery)	화학 (Petrochem.)	비금속광물 제품	제1차금속 산업	전자장비 제조업	자동차제조업	그외 기타 제조업	소계	광업	합계
	제조업												
2015	8,672	6,664	11,368	36,226	58,341	24,781	122,246	20,292	7,969	20,477	317,035	647	317,682
2016	9,531	6,736	11,074	36,491	61,343	25,515	122,086	20,337	8,338	22,162	323,611	723	324,335
2017	9,668	5,794	11,860	38,871	62,884	25,078	123,314	21,819	7,725	22,722	329,735	693	330,428
2018	10,624	6,315	11,230	38,019	66,363	23,864	133,665	24,403	8,500	26,135	349,118	674	349,791
2019	9,201	4,427	10,362	37,415	69,470	24,465	132,632	25,987	8,219	23,710	345,887	654	346,541
2020	9,219	4,100	10,215	34,248	69,308	22,395	132,367	26,28					343,992
2021	9,435	4,514	9,342	33,223	78,736	22,798	133,792	27,07					350,487



EG-TIPS 에너지온실가스 종합정보 플랫폼 https://tips.energy.or.kr/statistics/statistics_view1115.do https://www.mckinsey.com/industries/chemicals/our-insights/decarbonizing-the-chemical-industry

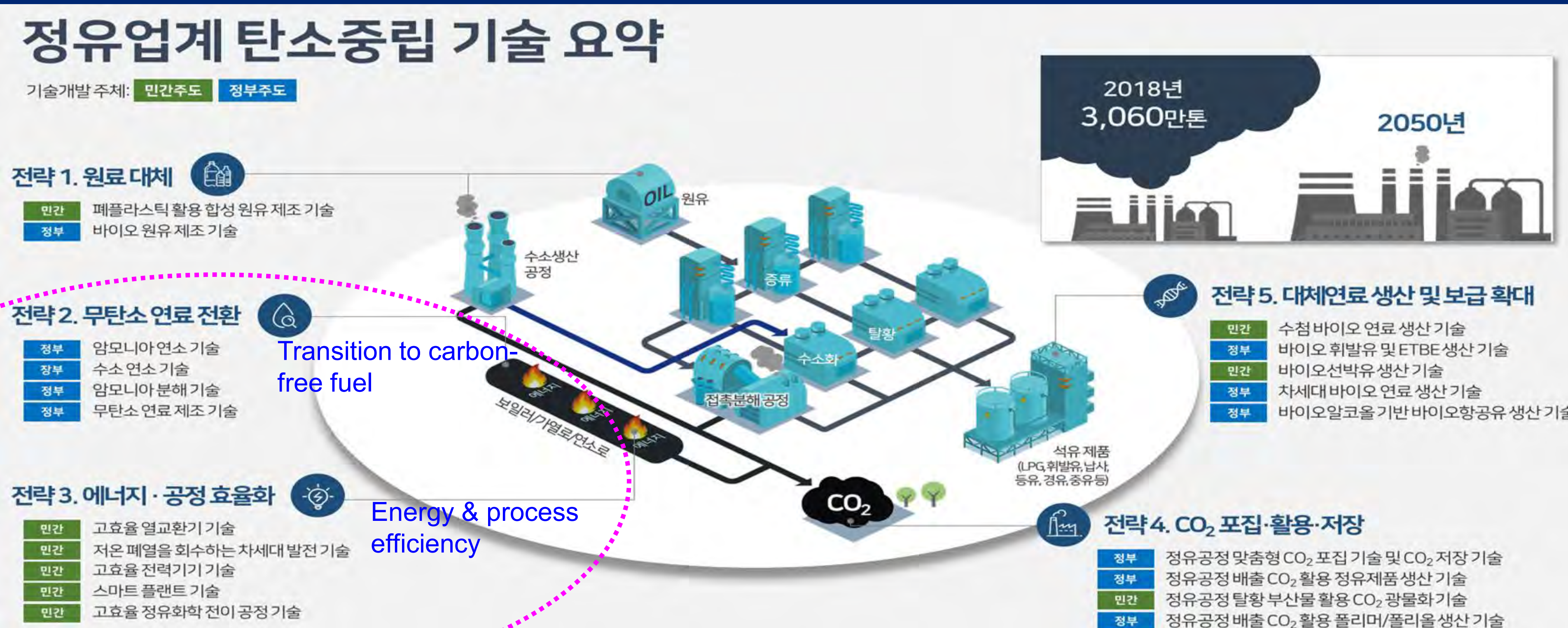
Four levers of the highest potential for emissions reduction



Note: Countries included are Belgium, Finland, France, Germany, Italy, Netherlands, Norway, Spain, and Sweden.

Carbon neutral technology development roadmap for the oil refining industry (2022)

- Possibility in fuel change?



https://www.investkorea.org/ik-en/bbs/i-308/detail.do?ntt_sn=490765

The Korean government set its national greenhouse emissions target (40% reduction compared to 2018) in 2030 and 2050 carbon neutrality, with **the petrochemical sector aiming to cut 20.2% compared to 2018 levels by 2030**.

Chemical Plant Characteristics

- Operational Mode:
  - Batch (Recipes), up to 1M kg/yr
  - Continuous, 1M to 1$^+$B kg/yr (may run months or years between shutdowns)

- Energy Requirements:
  - Mostly Thermal
    - Condensing steam, up to 250C (Latent Heat)
    - Hot oil, 250-350C (Sensible Heat)
    - Fired furnace, 350-1000C (Mostly Radiation)
    - Direct contact (Blast Furnace, Gasifiers, etc.), up to 1500C
    - Electric arc furnace (Steel Recycling)
    - Water cooling
  - Some Power
    - Pumps, Compressors, Refrigeration Systems (Compressors), Agitators, Rotating/Moving Equipment (Centrifuges, Dryers, Conveyors, etc.): Motive Steam or Electricity
    - Electrochemistry (Chlorine, Caustic, Aluminum, etc.): Electricity

Ex: Spirax steam table

	HPS	MPS	LPS
Pressure, kg/cm^{2}g	40	10.6	3.5
Temperature, ℃	250.7	183	147

Chemical Plants were Historically Driven by Steam, Cooling Water, and Compressed Air

- Early chemical process industries predated electricity
- Chemical reaction rates are temperature-dependent
- Many separation technologies (distillation, crystallization, etc.) are also driven by phase changes and temperature differences
- Some vapor chemical reactions are favored by high pressures; steam turbines supplied the motive power for pumps and compressors
- Sensor and control information was encoded into pneumatically transmitted air pressures
-

Process Industry	Examples of Processes Using Heat
Petroleum Refining	Feedstock heating, distillation, hydrocarbon cracking, hydrocarbon reforming (i.e., steam-methane reforming)
Chemicals (includes ammonia, fertilizers, pharmaceuticals, alcohols, detergents, resins, polymers, textiles, paints/pigments/dyes)	Endothermic chemical reactions, hydrogenation, pyrolysis, distillation, purification, evaporation, crystallization, polymerization, drying, prilling

J. Siirola (2021), https://www.nationalacademies.org/documents/embed/link/LF2255DA3DD1C41C0A42D3BEF0989ACAECE3053A6A9B/file/DA13DD514C735D9A943DEAD247358F8CD29774127A16?noSaveAs=1

https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_29023.pdf

Thermal requirements >> Electricity

Electricity is Relatively Expensive and its Use within the Chemical Industry is Still Minimized

- Thermally-driven separations (like distillation) remain favored over pressure-driven separations (exploiting membranes)
- Some work-driven operations (like compressors) are expensive; extraordinary design measures (like multiple effect distillation) are employed in processes with high refrigeration needs (like air separation plants) in order to minimize compressor work requirements
- Although common in laboratory settings, electrical process heating is rare (but is used, for example in electric arc furnaces)
- Many chemical plants co-generate their own electricity in steam boiler topping cycles, but in general thermal requirements far exceed electricity requirements
  - Some plants cogenerate as much electricity as possible given their thermal steam requirement and sell the excess, although most plants scale back cogeneration to just meet internal electrical needs

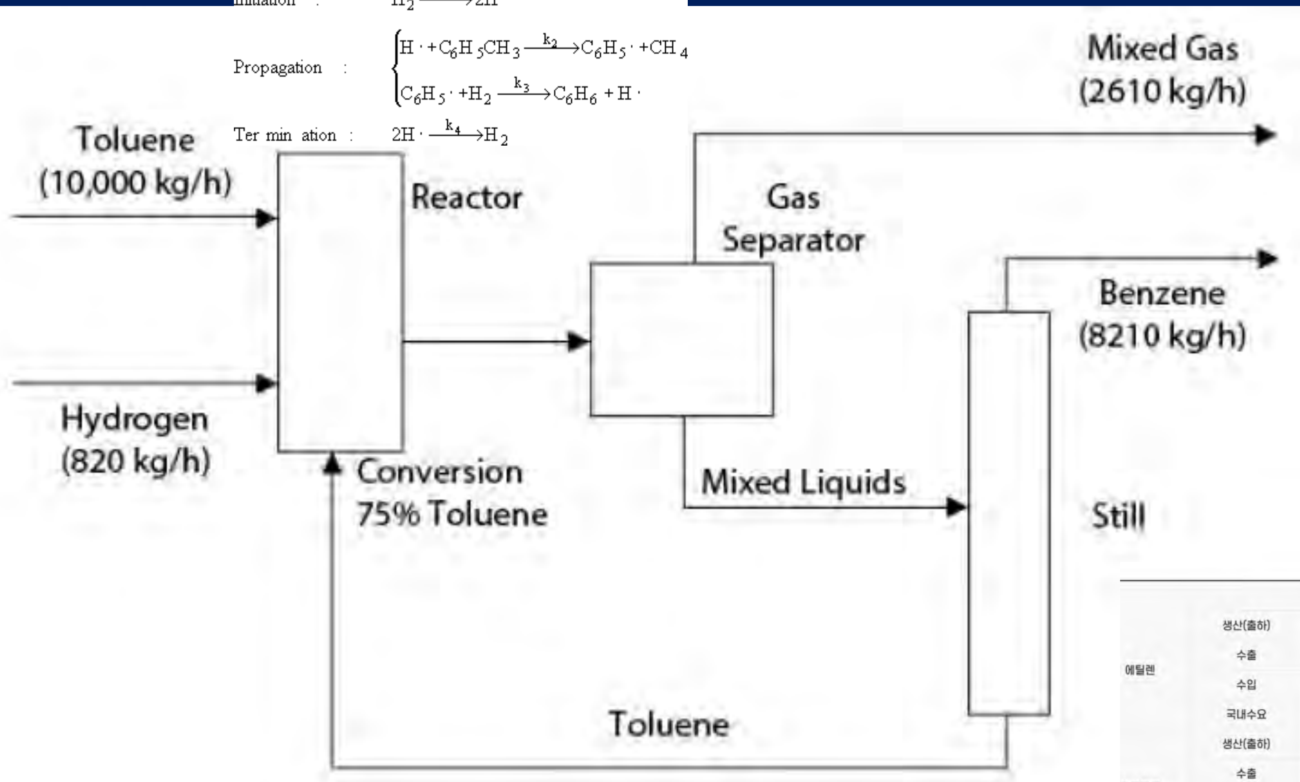
J. Siirola (2021), https://www.nationalacademies.org/documents/embed/link/LF2255DA3DD1C41C0A42D3BEF0989ACAECE3053A6A9B/file/DA13DD514C735D9A943DEAD247358F8CD29774127A16?noSaveAs=1

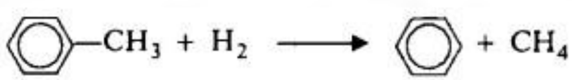
Ex: Toluene hydrodealkylation plant
(Benzene production in Korea: ~6 MMT/yr)

Initiation : $H_2 \xrightarrow{k_1} 2H\cdot$

Propagation : $\begin{cases} H\cdot + C_6H_5CH_3 \xrightarrow{k_2} C_6H_5\cdot + CH_4 \\ C_6H_5\cdot + H_2 \xrightarrow{k_3} C_6H_6 + H\cdot \end{cases}$

Termination : $2H\cdot \xrightarrow{k_4} H_2$





$$\left(\Delta H = -\frac{30\ \text{kcal}}{126\ \text{kJ}}/\text{mol}\right)$$

Figure

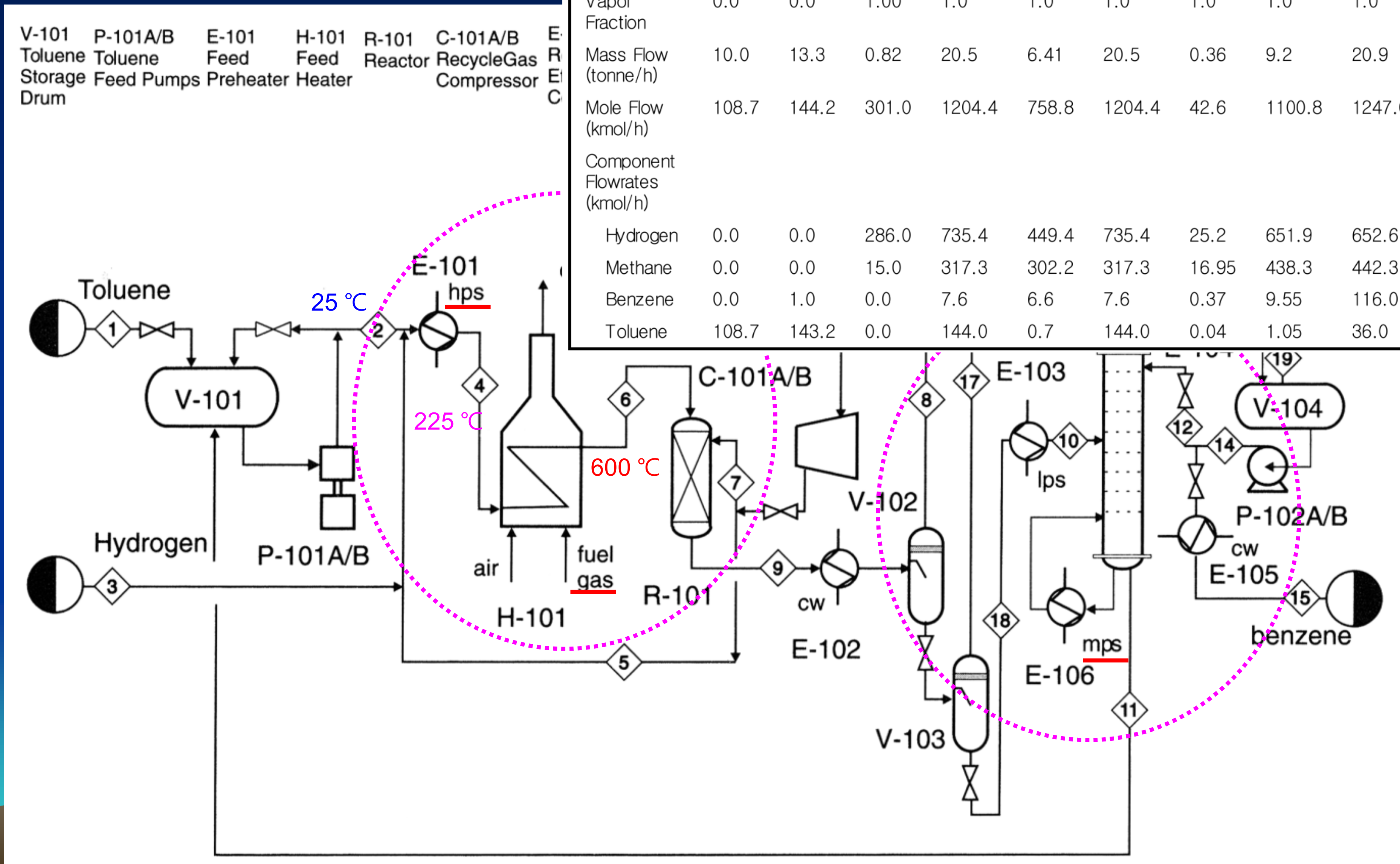
(단위 : 천톤)

		2019	2020	2021	2022	2023
에틸렌	생산(출하)	8,907	8,738	10,349	10,410	9,437
	수출	1,091	848	1,175	1,585	1,115
	수입	109	283	207	142	162
	국내수요	7,925	8,173	9,381	8,966	8,484
프로필렌	생산(출하)	8,704	8,644	9,879	9,116	8,540
	수출	1,657	1,506	1,653	1,633	1,589
	수입	132	124	105	95	112
	국내수요	7,180	7,262	8,331	7,578	7,064
부타디엔	생산(출하)	1,271	1,209	1,434	1,396	1,210
	수출	98	92	125	181	171
	수입	406	474	337	206	313
	국내수요	1,579	1,591	1,646	1,421	1,353
벤젠	생산(출하)	6,565	5,999	6,699	6,055	5,544
	수출	2,627	2,220	2,477	2,575	2,922
	수입	56	66	58	95	96
	국내수요	3,994	3,845	4,280	3,576	2,718

https://www.kpia.or.kr/petrochemical-industry/statistics

Heating: Fuel g

Stream Number	1	2	3	4	5	6	7	8	9
Temperature (°C)	25	59	25	225	41	600	41	38	654
Pressure (bar)	1.90	25.8	25.5	25.2	25.5	25.0	25.5	23.9	24.0
Vapor Fraction	0.0	0.0	1.00	1.0	1.0	1.0	1.0	1.0	1.0
Mass Flow (tonne/h)	10.0	13.3	0.82	20.5	6.41	20.5	0.36	9.2	20.9
Mole Flow (kmol/h)	108.7	144.2	301.0	1204.4	758.8	1204.4	42.6	1100.8	1247.0
Component Flowrates (kmol/h)									
Hydrogen	0.0	0.0	286.0	735.4	449.4	735.4	25.2	651.9	652.6
Methane	0.0	0.0	15.0	317.3	302.2	317.3	16.95	438.3	442.3
Benzene	0.0	1.0	0.0	7.6	6.6	7.6	0.37	9.55	116.0
Toluene	108.7	143.2	0.0	144.0	0.7	144.0	0.04	1.05	36.0



Integration Processes of Benzene-Toluene-Xylene Fractionation, …

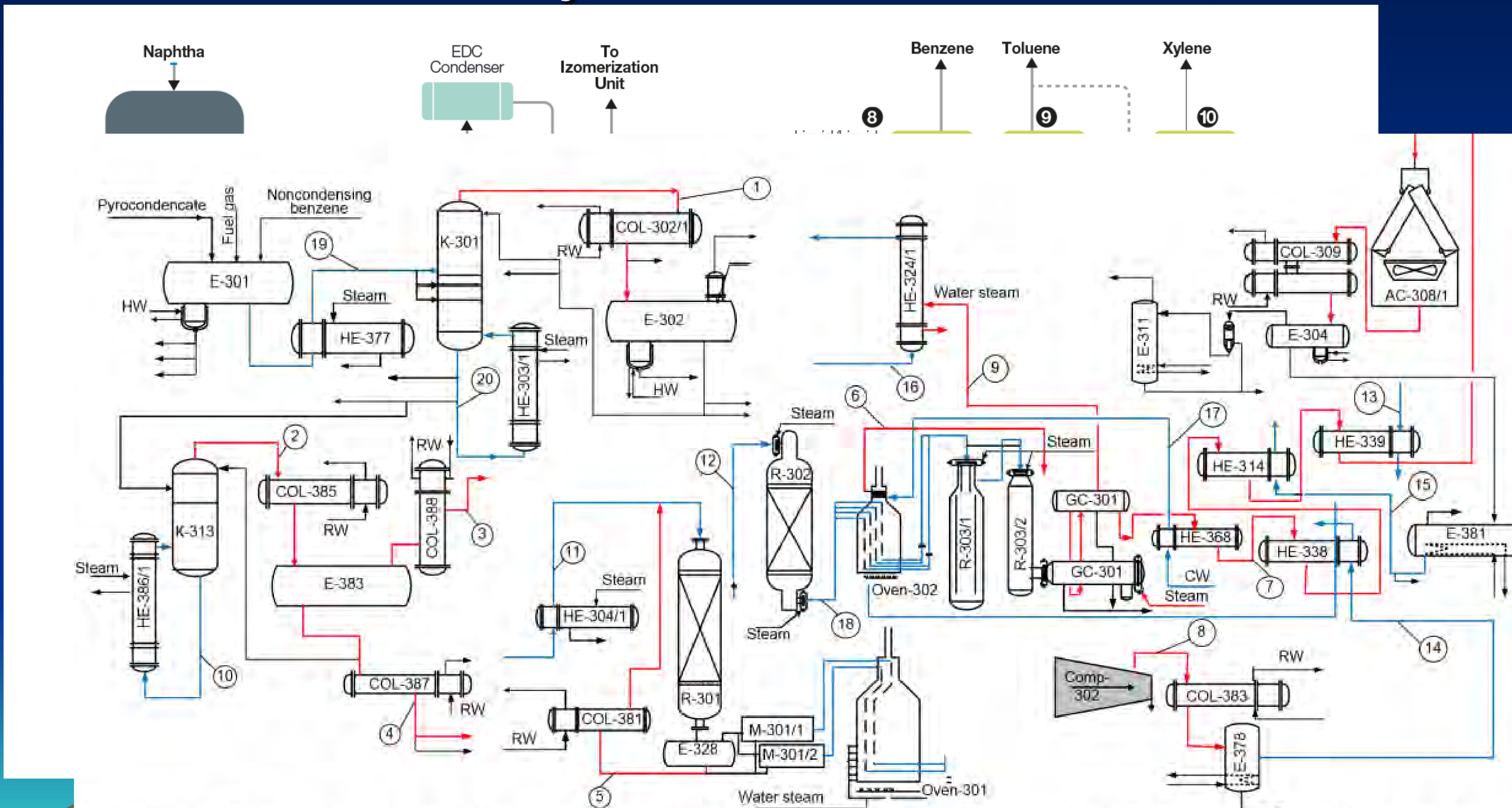


Figure 1: The flowchart of the existing process (COMP – compressors; R – reactors; K – distillation

https://www.semanticscholar.org/paper/Integration-Processes-of-Benzene-toluene-xylene-and-Kapustenko-Ulyev/9eb46b5782f361295dd1895c906e39a3d8970017

Temperature ranges of heat application: 200-900 ℃

- Heat inputs at 800C for some endothermic cracking, reforming, and other reactions
- Most chemical plant thermal energy is supplied by condensing steam at 250C (600 psi, 41 bar) or lower: The less common energy requirements at higher temperatures could be supplied by non-nuclear alternatives

https://world-nuclear.org/information-library/non-power-nuclear-applications/industry/nuclear-process-heat-for-industry.aspx

Dow Nuclear Energy Design (1970s)

- Twin 650 Mw(e) light water reactors each also providing 2M lb/hr process steam
  - Project ultimately cancelled and replaced by 12-unit natural gas fired cogeneration

Totally Electrical Chemical Processing

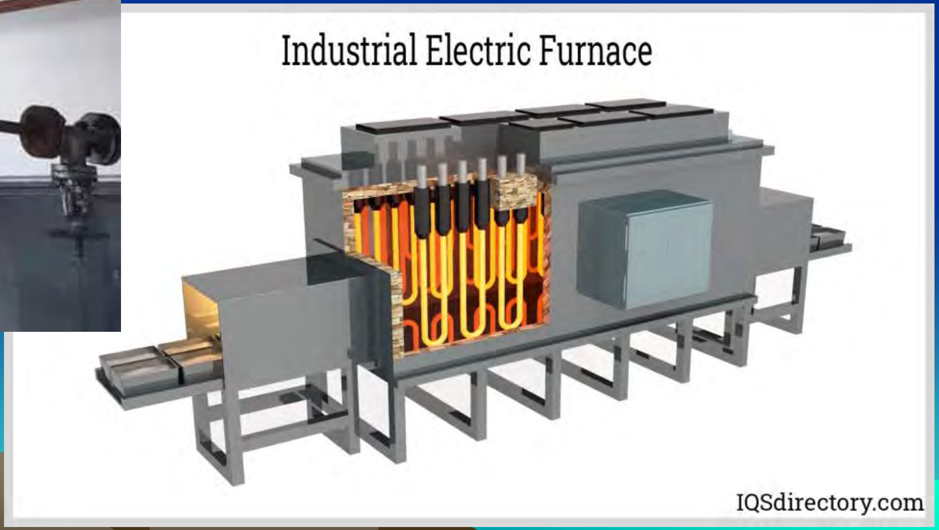
- An approach to decarbonize chemical production by using mostly carbon-emission-free electricity
  - Yes, you can run a chemical plant with a windmill (lots of them)
  - Or, conventional nuclear and electrical grid technology

- It has not been economical in the past
  - On an energy basis, electricity is generally more expensive that thermal energy
    - Electricity is conventionally generated from thermal energy at about 35% Carnot efficiency (and less if carbon capture and sequestration is required)
    - Compressors in particular are very expensive to buy and to operate and are generally avoided
    - This is why refrigeration and high pressure vapor processes are so expensive
  - Most chemical processes today remain thermal energy dominated

- But it may be competitive in the future
  - If Carbon Taxes approximating the cost of fluegas CCS or direct air capture are imposed and could thereby be avoided

Electrification: Reactor, furnace

Induction Heating Chemical Reactor



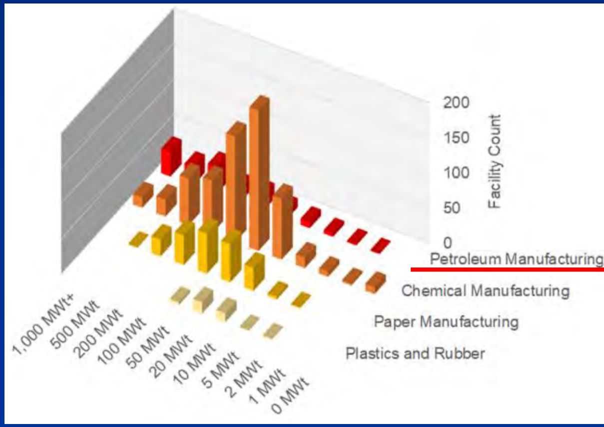
https://dw-inductionheater.com/product/induction-heating-chemical-reactor

https://www.iqsdirectory.com/articles/furnace.html

Conclusions

- Opportunity: The use of nuclear power as a heat source is positive for the carbon neutrality of the chemical process industry:
  - Most chemical thermal requirements are below 250C (currently met by condensing steam), well within the capabilities of most nuclear reactor concepts.
  - There are aspects in which CAPEX can be reduced when expanding facilities in the future, but OPEX and safety issues remain.
- Domestic heat demand analysis is needed: quality, quantity and time variability.

- Threat: Electrification
  - To meet environmental goals exploiting carbon-emission-free electricity, **chemical plants could be redesigned to substitute work-based operations for currently thermally-driven operations**.
  - Conventional nuclear electricity might prove more applicable to an appropriately modified chemical industry than on-site nuclear thermal energy might be.

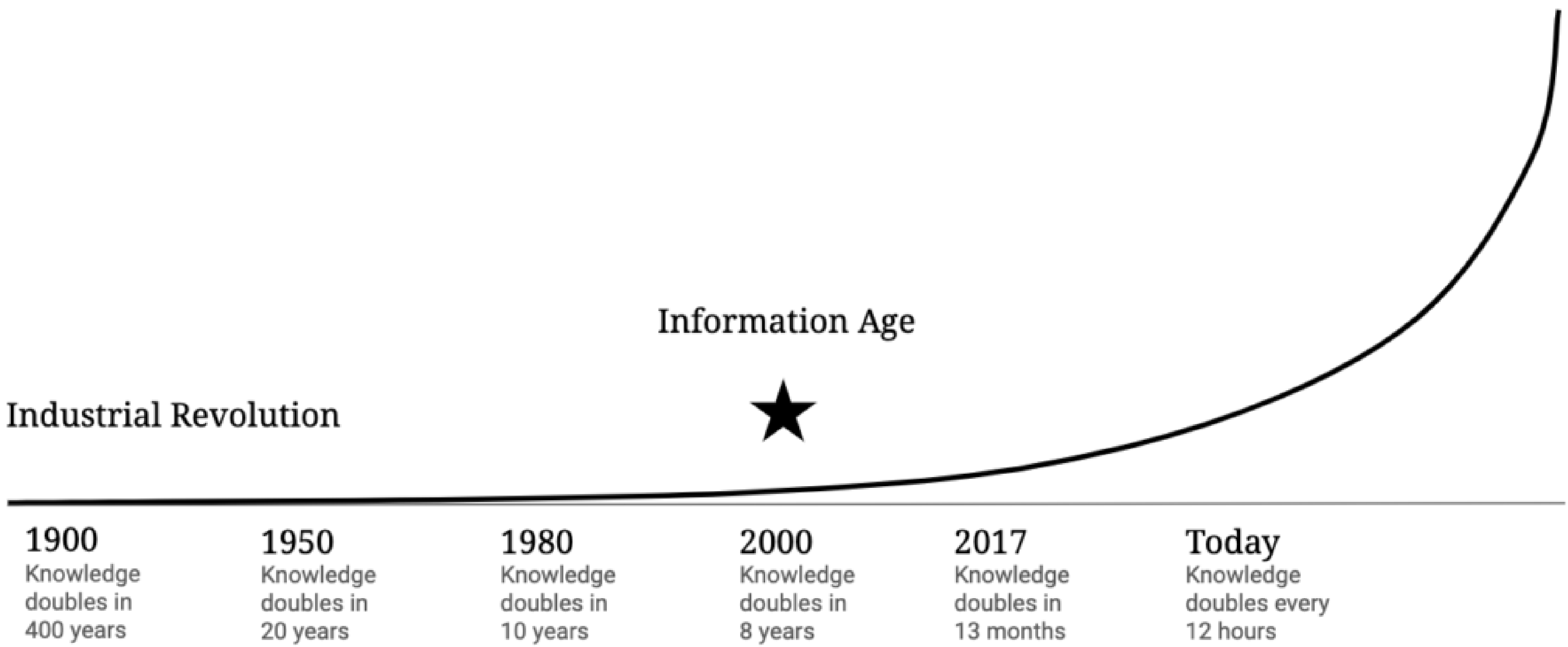


Heat consumption analysis of EPA (2020)

Summary

- 원전 열원 사용은 화학공정산업의 탄소중립에 긍정적
- 국내 열 수요 분석 필요: 품질, 양 및 시간 변동성
- 향후 증설시 CAPEX 줄일 수 있는 측면, OPEX와 안전 문제

지식 증가: 12시간마다 2배로



Computer IT Big Data AI GPT

https://nesslabs.com/brain-limitations