Integrated Electrochemical Systems for Scalable CO_2 Conversion to Chemical Feedstocks

PM : SUGIYAMA Masakazu
Director / Professor
Research Center for Advanced Science and Technology (RCAST),
The University of Tokyo

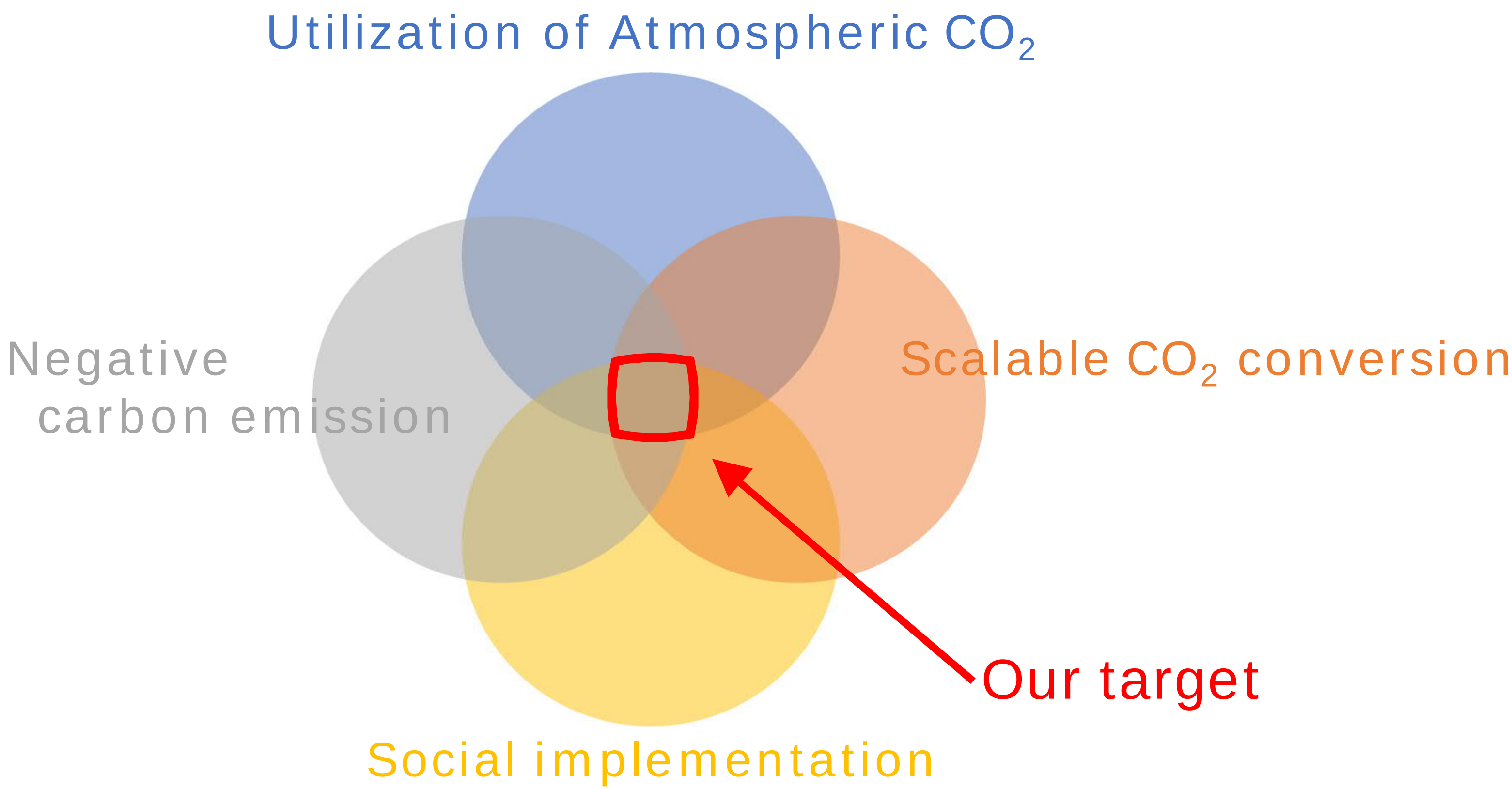
Implementing organizations:

The University of Tokyo, Osaka University,
Institute of Physical and Chemical Research (RIKEN),
UBE Corporation, Shimizu Corporation,
Chiyoda Corporation, Furukawa Electric Co., Ltd.

Project concept

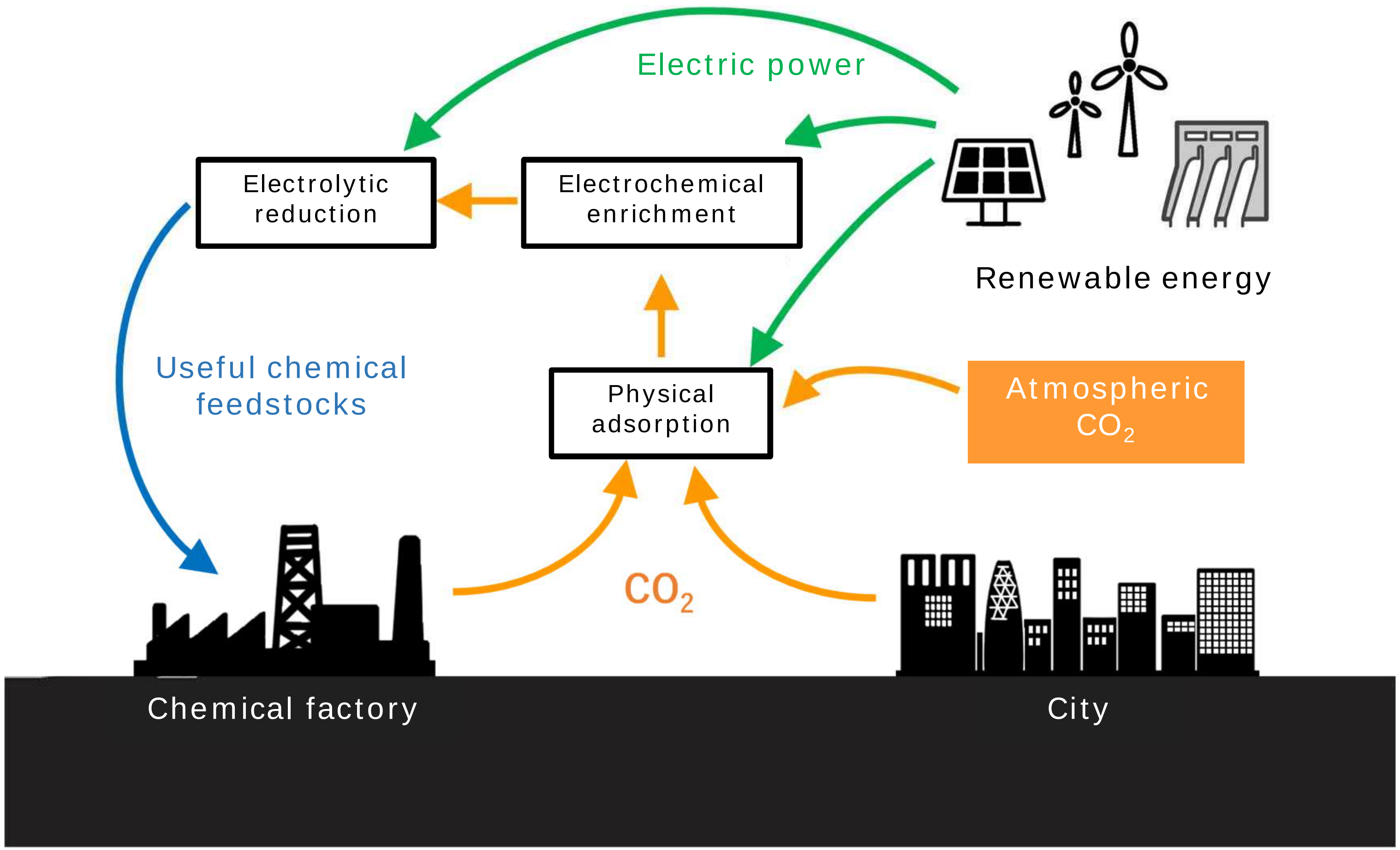
■ The technology developed by this project aims at:

- ☐ Utilization of atmospheric CO_2
- ☐ Negative carbon emission
- ☐ Scalable CO_2 conversion (100 million tons / year @ 2050)
- ☐ Social implementation, industrialization



Final target at FY2029

Development of a system to convert atmospheric CO_2 into useful chemical feedstocks based on electrochemical processes.



Achievement of carbon cycle based on electricity which is a platform of future energy system
～ Toward 100 million ton/year reduction of CO_2 emissions @ 2050 ～

Target product: Ethylene

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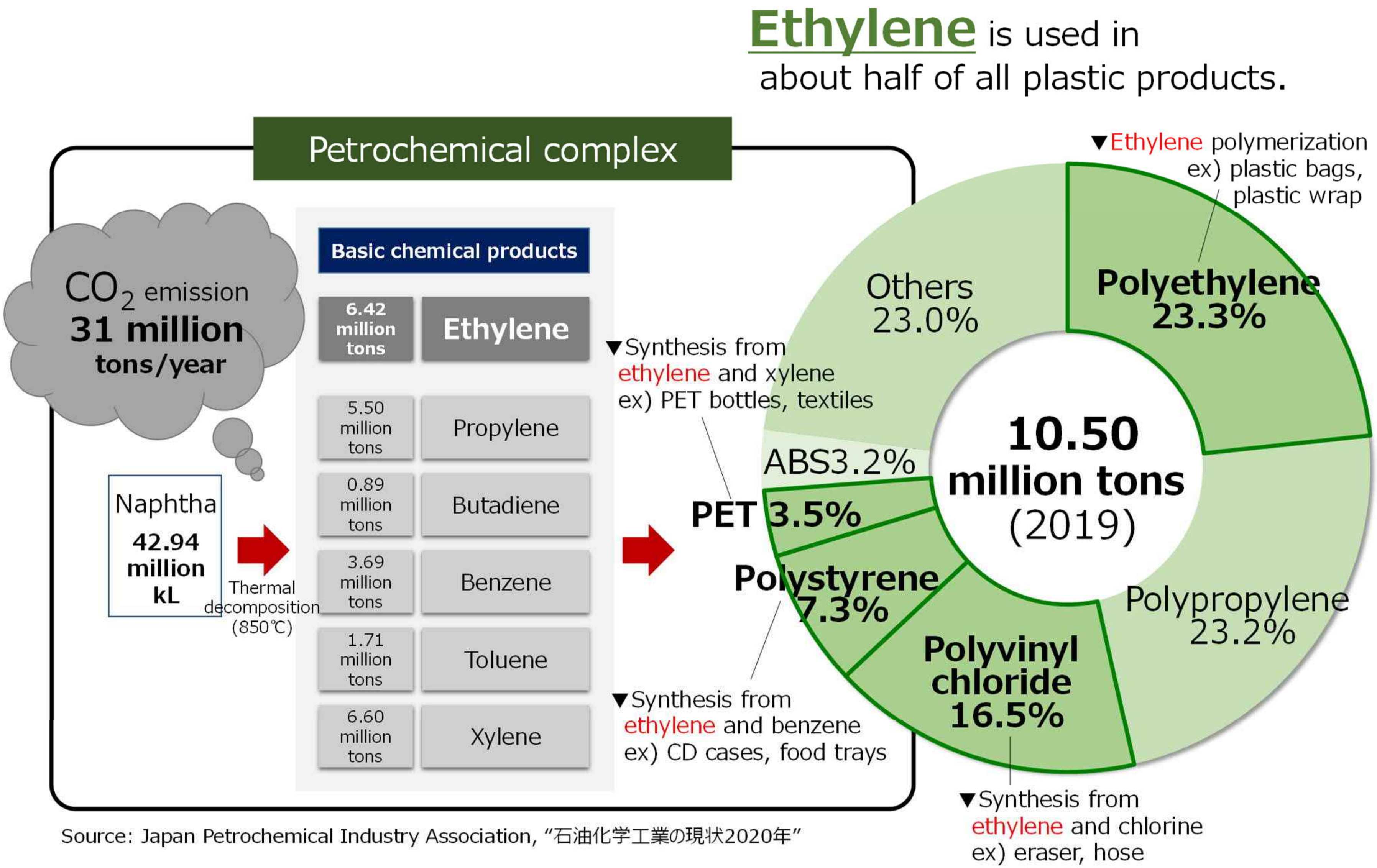
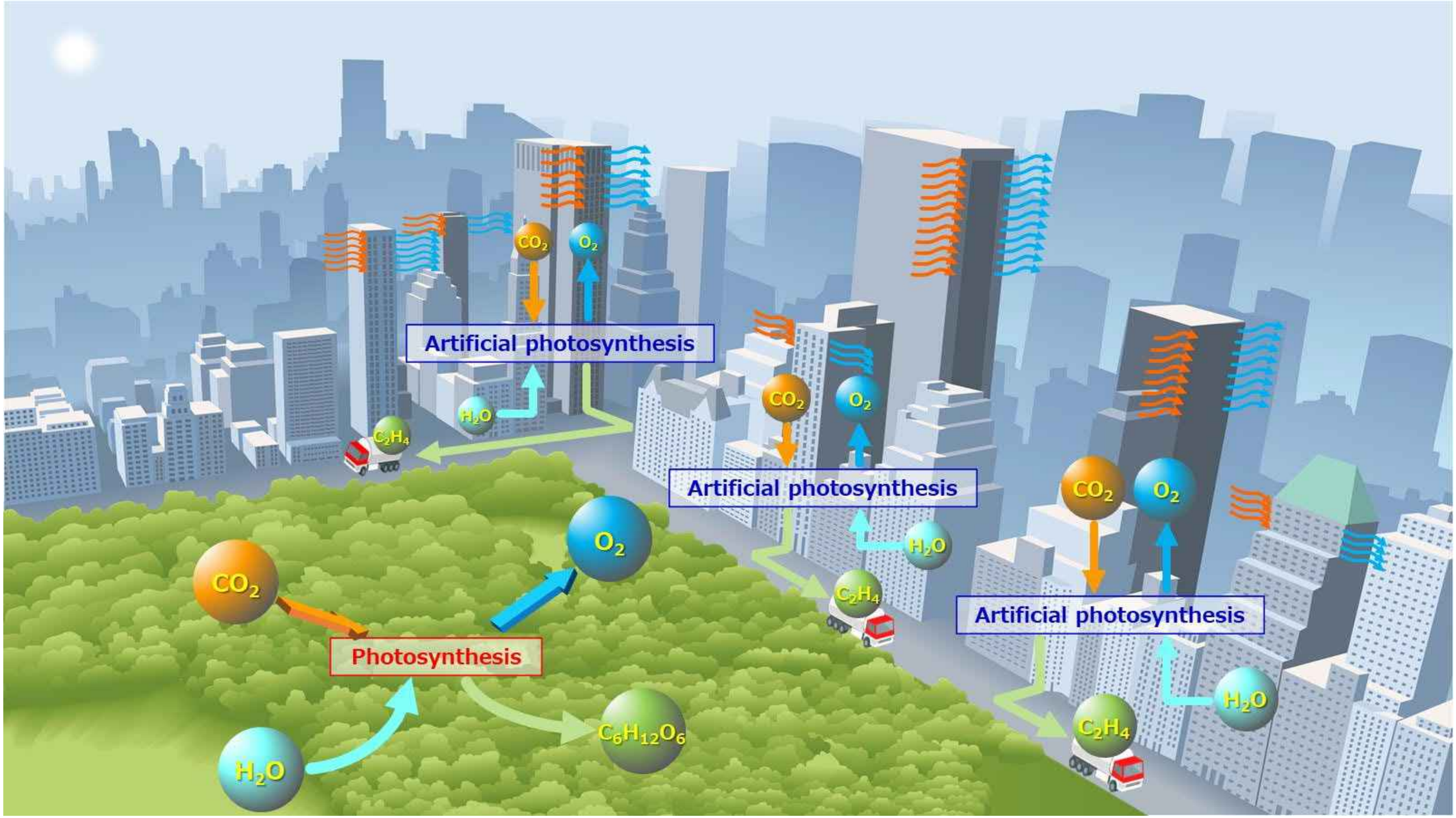


Source: Japan Petrochemical Industry Association, "石油化学工業の現状2020年"

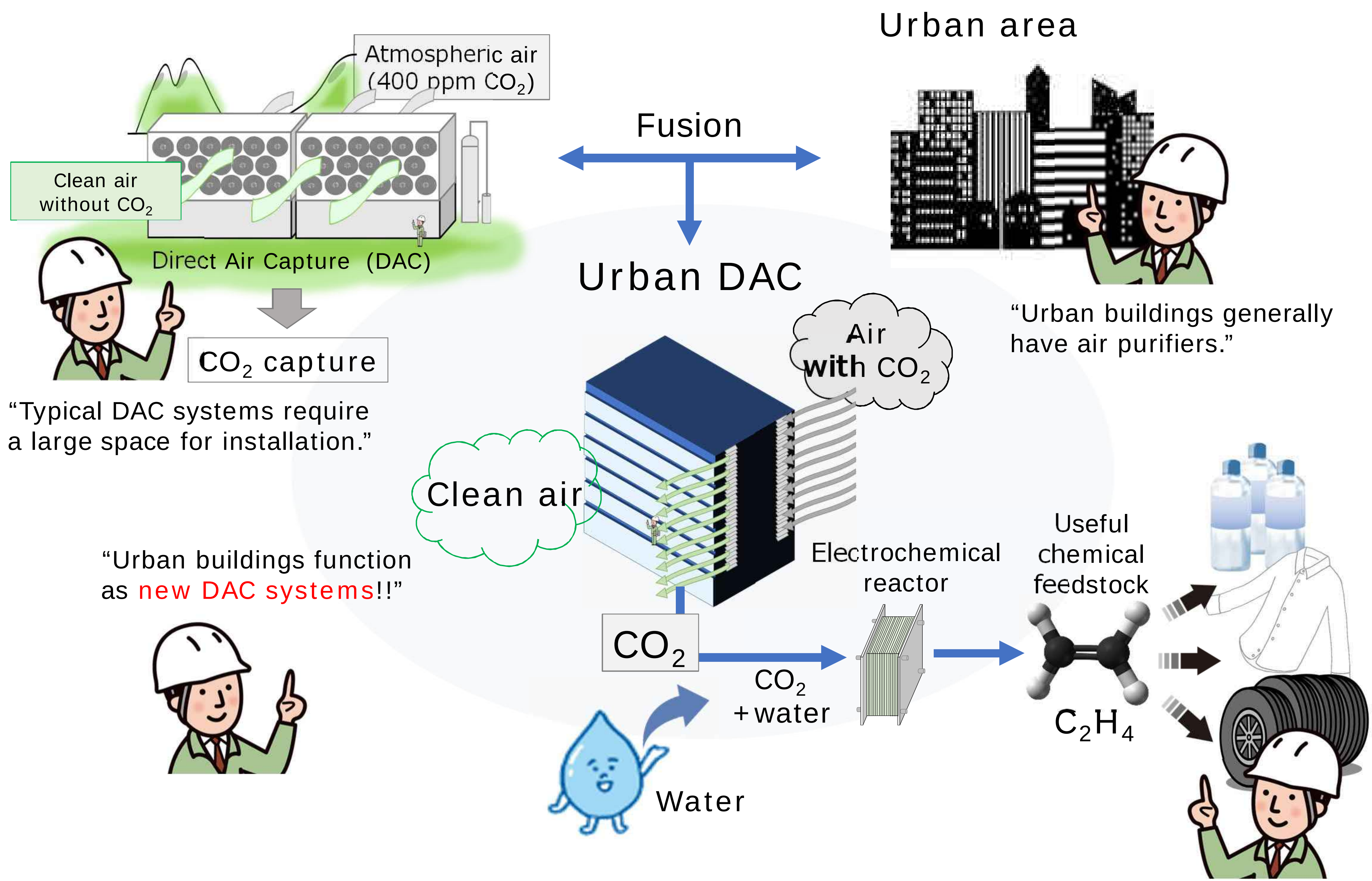
Source: Plastic Waste Management Institute, "プラスチックリサイクルの基礎知識2020"
http://www.pwmi.or.jp/pdf/panf1.pdf

Future vision of social implementation

Urban DAC-U System (Artificial Photosynthesis)



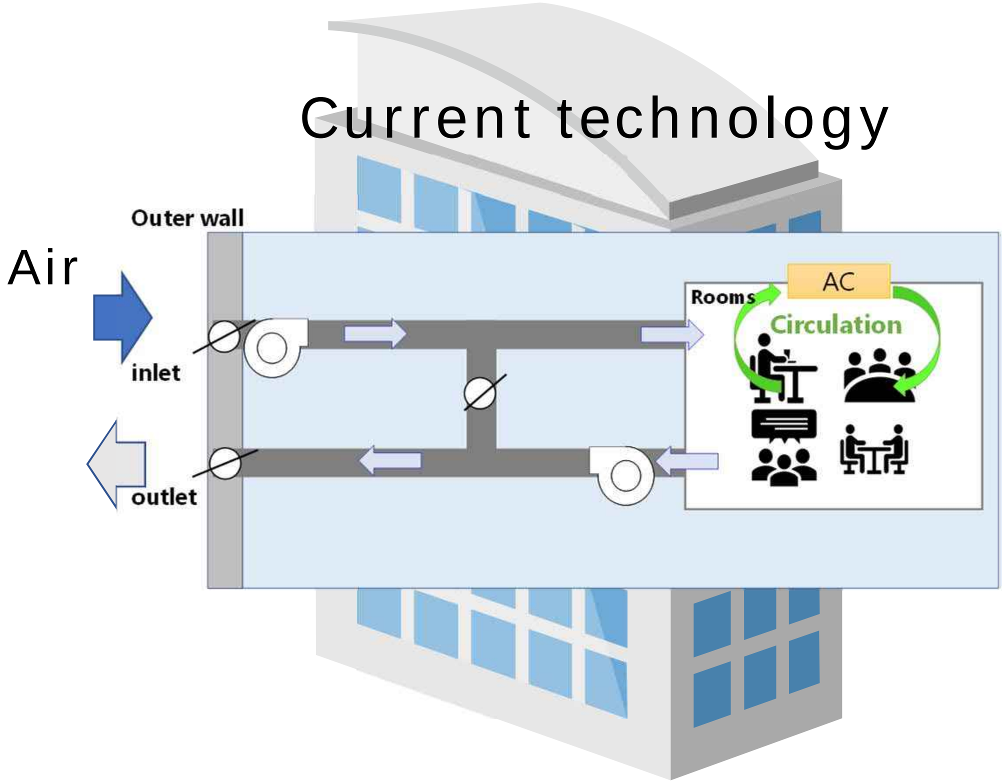
Urban buildings as “air purifiers of a city”

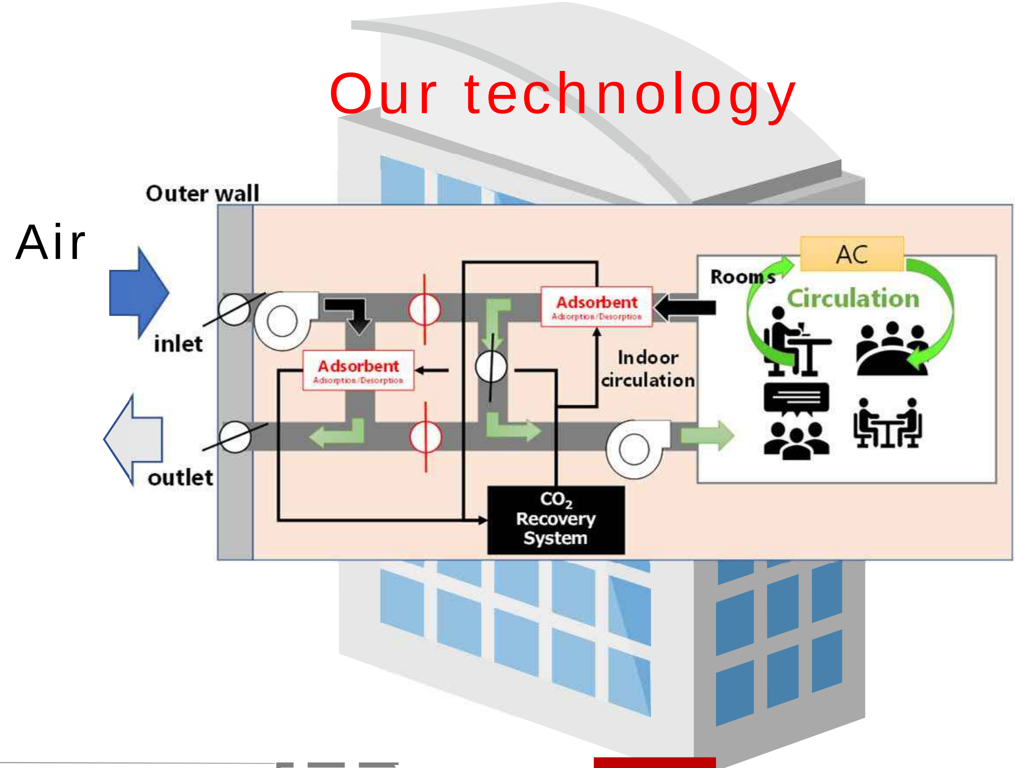


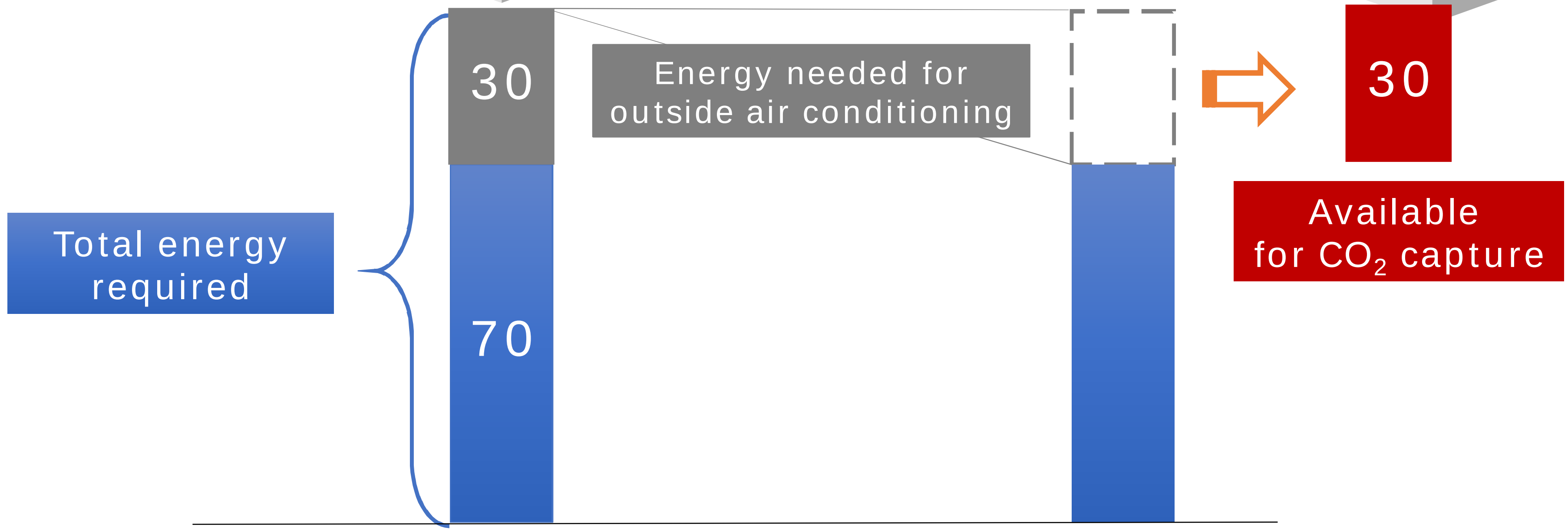
“We will be able to make various materials from CO_2 and water in the future.”

CO_2 capture from both outdoor and indoor air

[redacted]

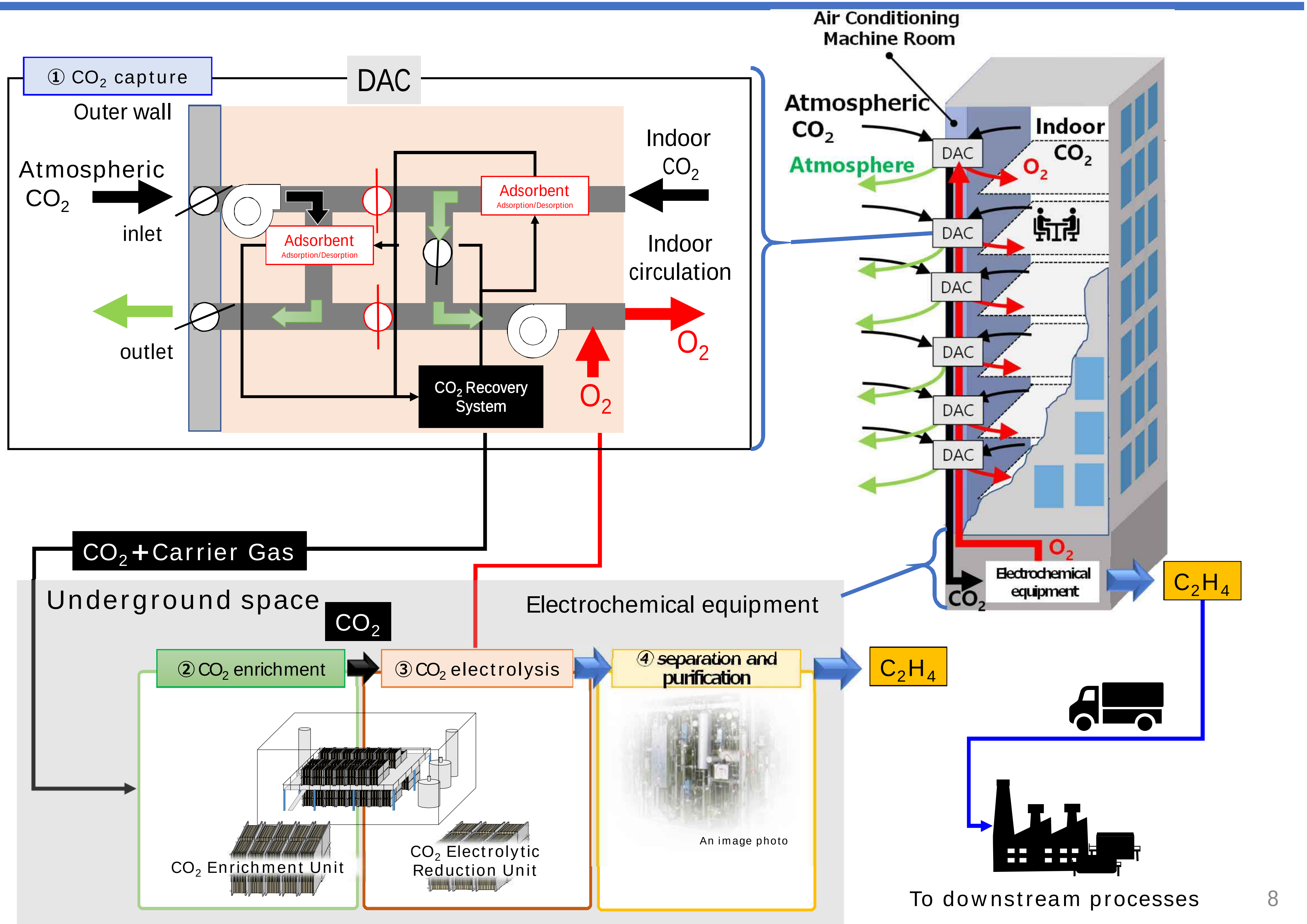






Urban artificial photosynthesis (circulation of both CO_2 and O_2)

[redacted]



Scalable system adaptable to various situations

Transported chemicals

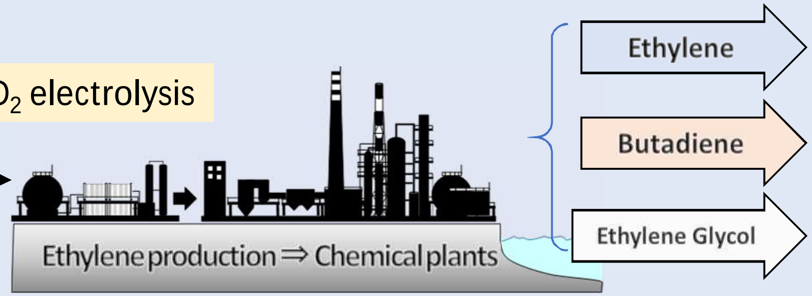
CO_2

Carbon dioxide

CO_2 capture + Enrichment

→ CO_2 →

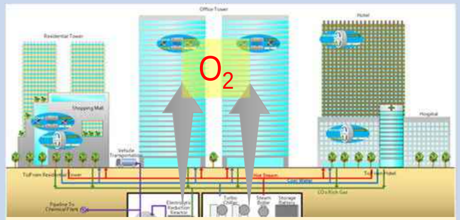
CO_2 electrolysis



Electrolyzers are installed away from urban areas.

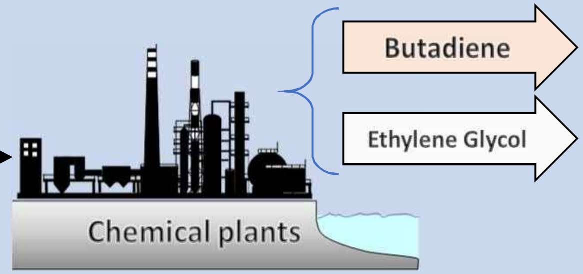
C_2H_4

Ethylene



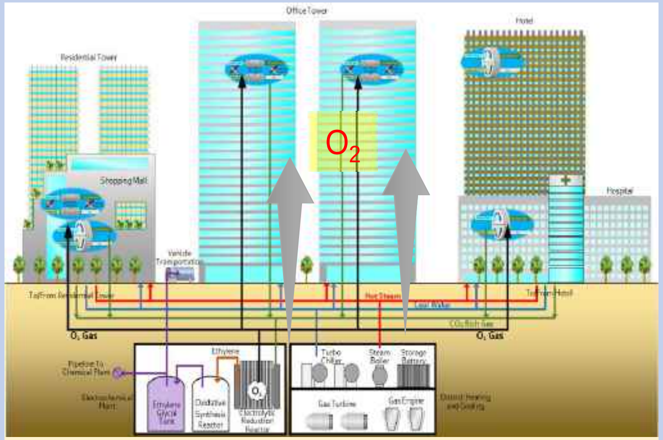
CO_2 capture + Enrichment + Electrolytic reduction

→ C_2H_4 →



$C_2H_6O_2$

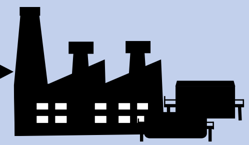
Ethylene Glycol (EG)



CO_2 capture + Enrichment + Electrolytic reduction + Chemical production

→ EG →

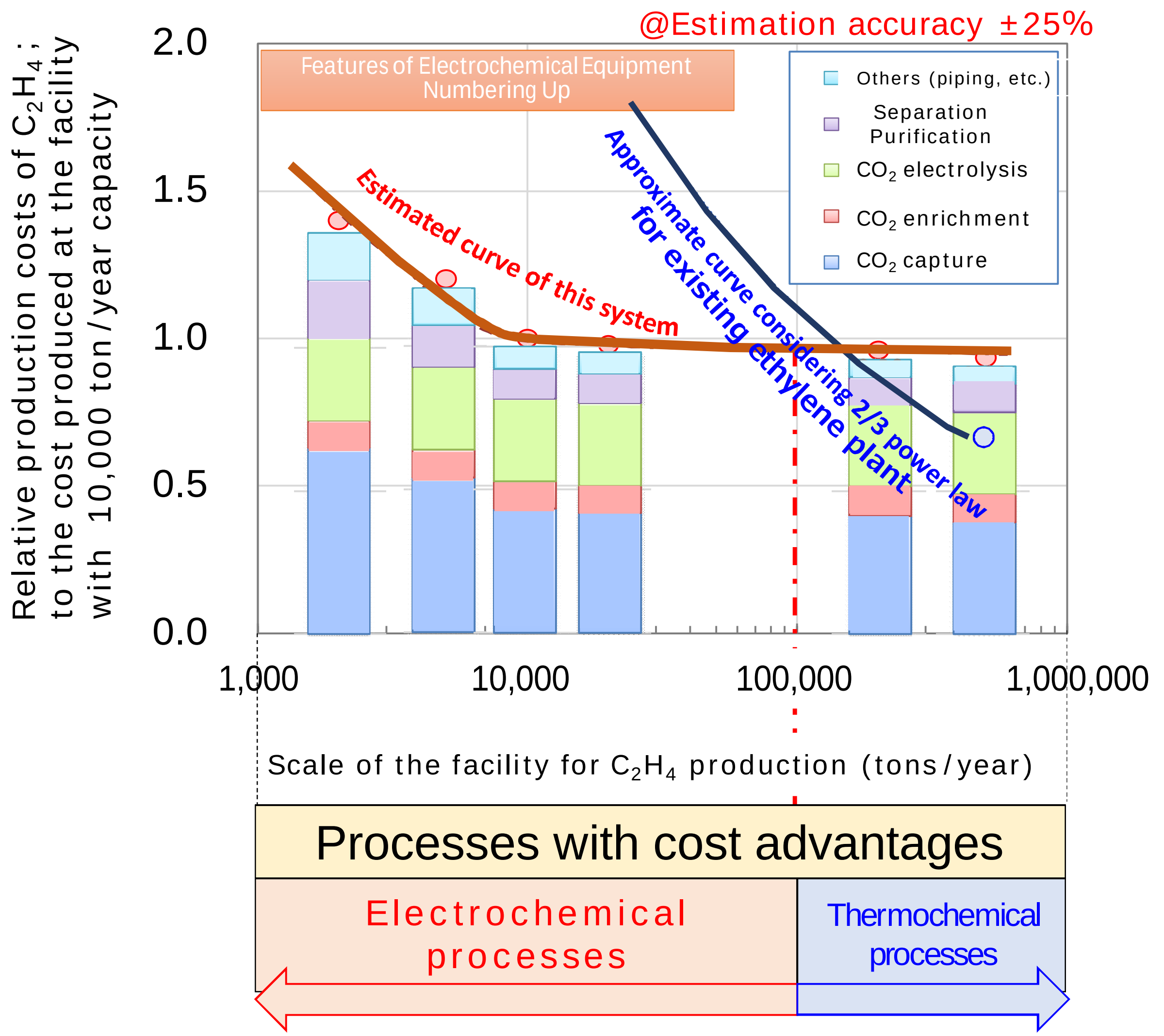
Antifreeze, solvents, cosmetics, polyester raw materials, etc.



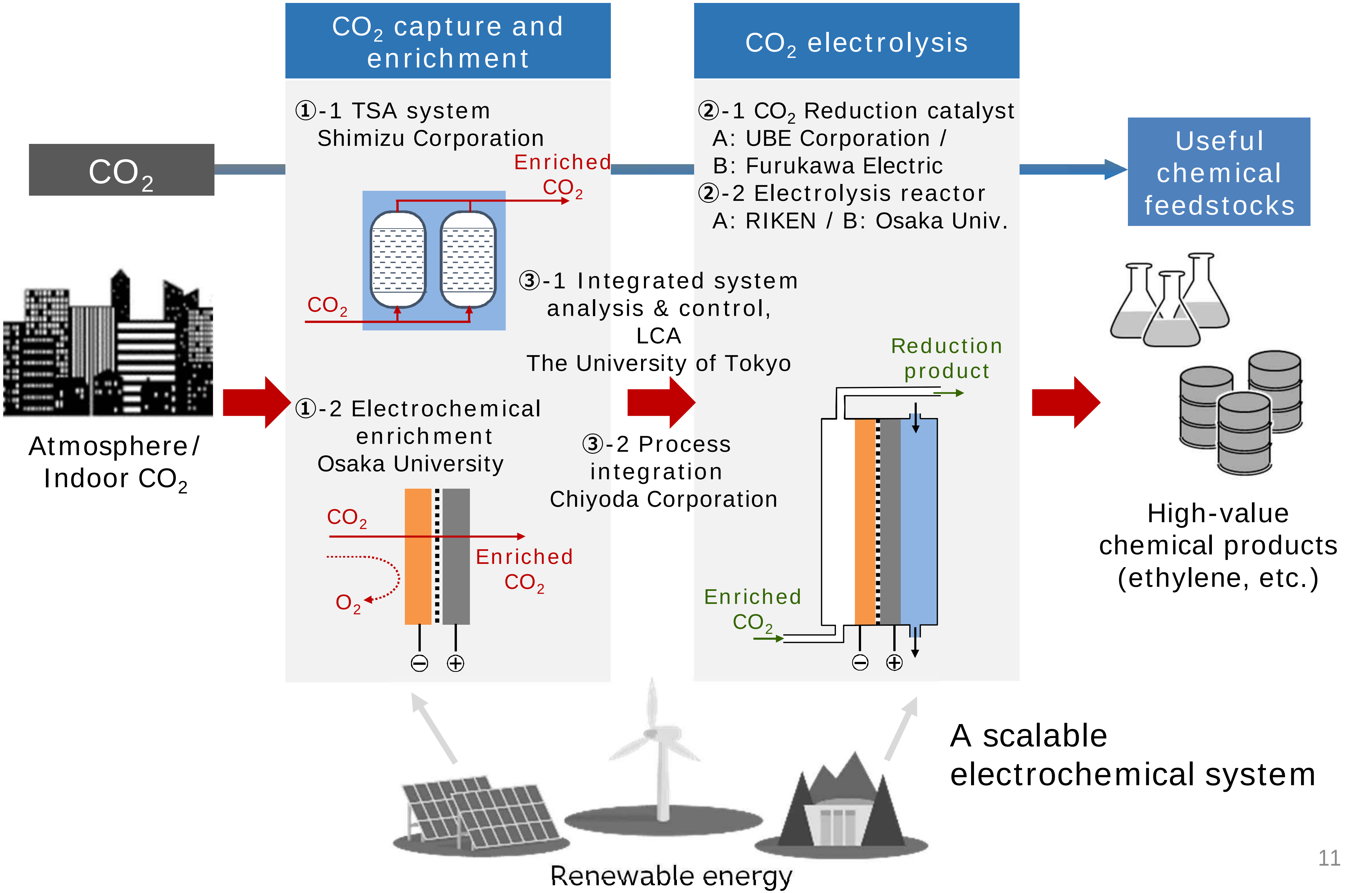
Industrial Factories

Origin of the scalability: electrochemical processes

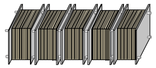
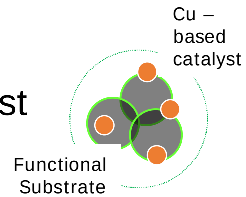
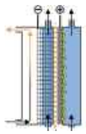
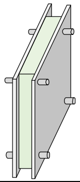
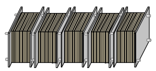
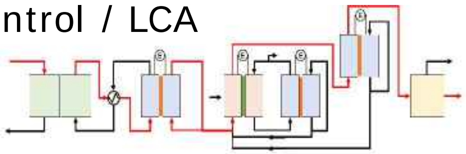
Estimated relative production cost of ethylene



Team formation



Roles of each player

R&D items				Player	
CO_2 capture and enrichment	CO_2 capture by TSA method 			SC	Collaborative member
	Electrochemical CO_2 enrichment 			OSU	Collaborative member
CO_2 electrolysis	Reactor member	Catalyst 	Substrates	OSU	UBE
			Cu-based materials		FKW
		Gas-Diffusion Electrode (GDE) 			Collaborative member
		MEA-based reactor 	Membrane	RIKEN	Collaborative member
			Reactor		New member
		Stack 			
System integration	Reaction process development / Process integration Integrated system analysis & control / LCA 			UTK	CYD

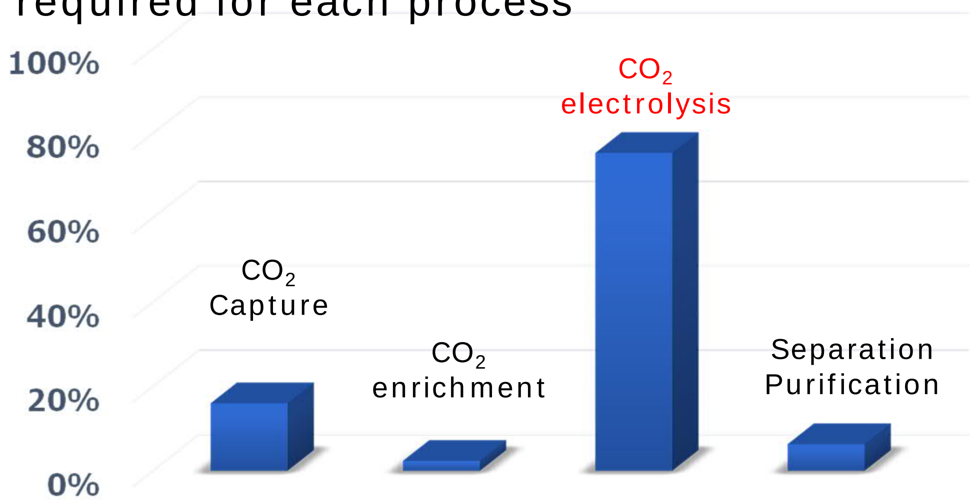
*UTK: The University of Tokyo, OSU: Osaka University,
RIKEN: Institute of Physical and Chemical Research,
UBE: UBE Corporation, SC: Shimizu Corporation,
CYD: Chiyoda Corporation, FKW: Furukawa Electric Co., Ltd

KPIs

	2022	2024	2029
CO_2 emission※ ($t\text{-}CO_2/t\text{-}C_2H_4$)	+1.0 ～ +1.5 at device level	+0.5 ～ +1.0 at laboratory scale 1,000 hours	<－0.5 at pilot plant scale 5,000 hours
CO_2 emission during operation	－0.5 ～ 0.0 (5.0～4.5 V, FE= 55 ～65%)	－1.0 ～ －0.5 (4.5～3.8 V, FE= 55 ～80%)	<－2.0 (3 V, FE= 80%)
CO_2 emission upon equipment manufacturing	+1.5	+1.5	+1.5

※CO_2 emission of the entire system from atmospheric CO_2 capture to ethylene production (including emission upon manufacturing of equipment)

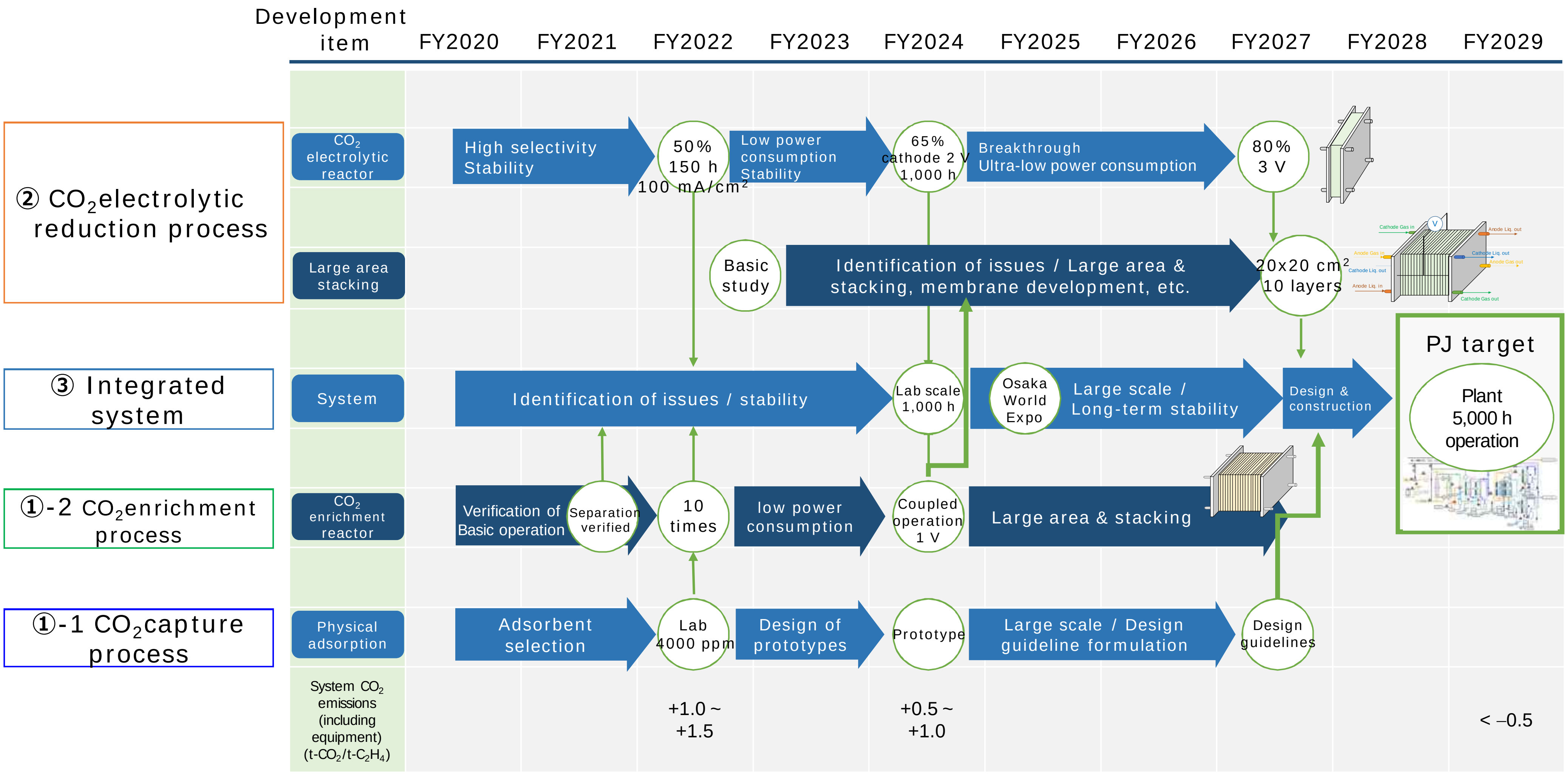
Energy required for each process



- Rough estimation with ±20% accuracy
- Assuming solar power generation of 30g-CO_2/kWh as CO_2 emission from electricity
- Includes CO_2 emission from equipment manufacturing

Schedule for development

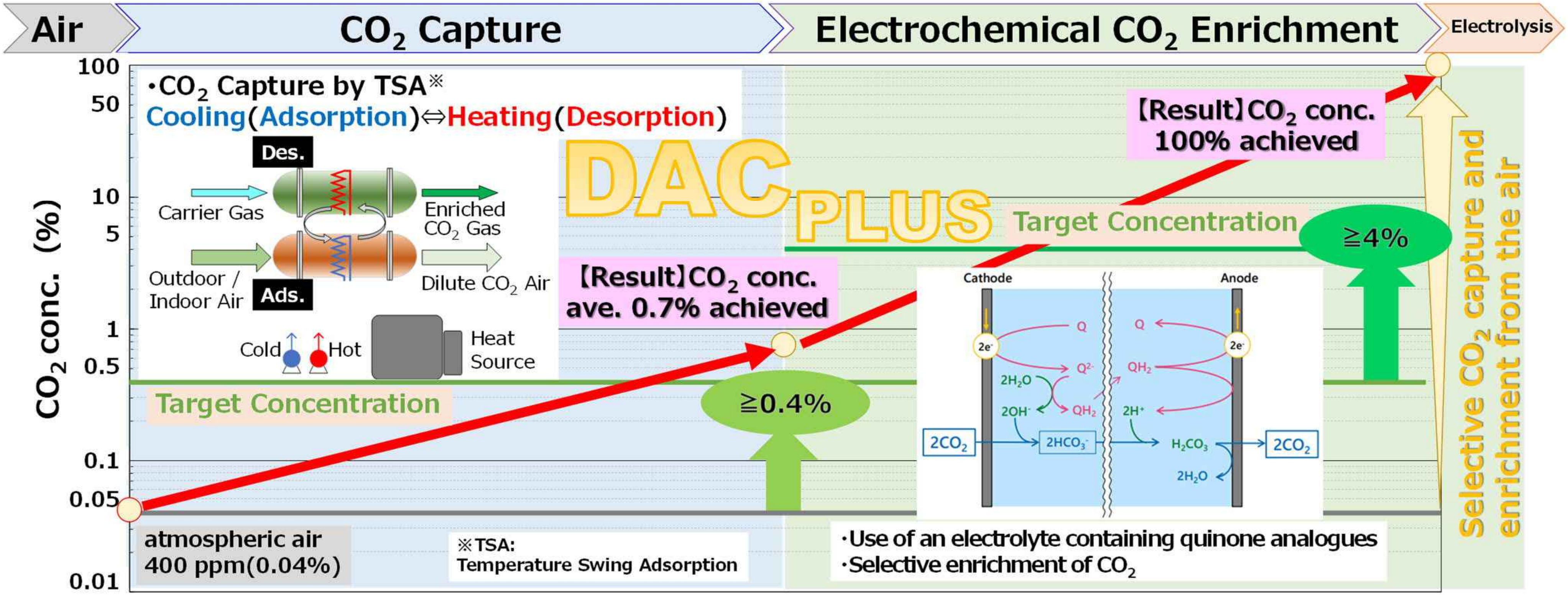
- Target at FY2029: Pilot demonstration for 5,000 h



Progress and results: CO_2 capture and enrichment（1/2）

FY’22 Target
0.04% to 0.4**%**
10 times enrichment

- ☐ CO_2 Capture ：0.04% ➡ ave. 0.7**%** achieved
- ☐ CO_2 Enrichment： 0.7% ➡ 100**%** achieved



Successful enrichment of CO_2 from 400 ppm to 100%

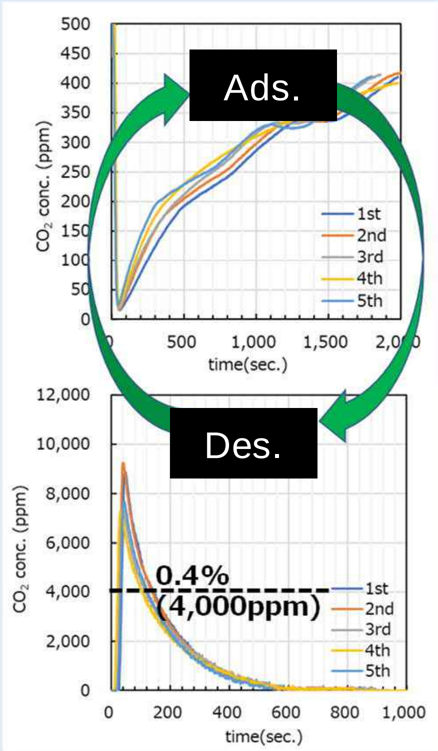
Progress and results: CO_2 capture and enrichment（2/2）

CO_2 Capture

- Selection of effective adsorbents
- 10-fold enrichment of atmospheric CO_2
- Adsorption/desorption cycle performance

High-precision evaluation of adsorbed gas volume

System for evaluating adsorption/desorption cycle performance

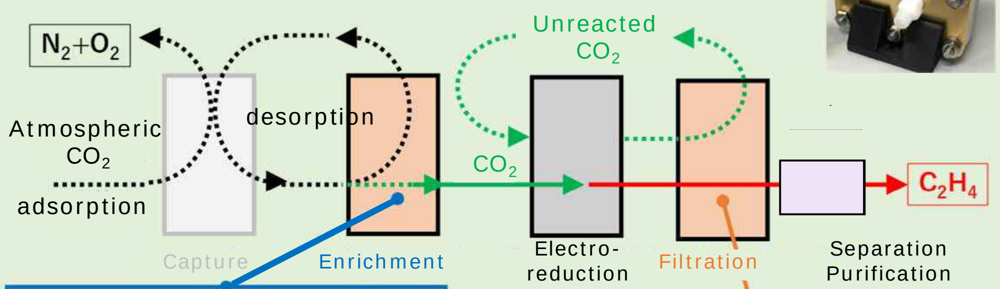


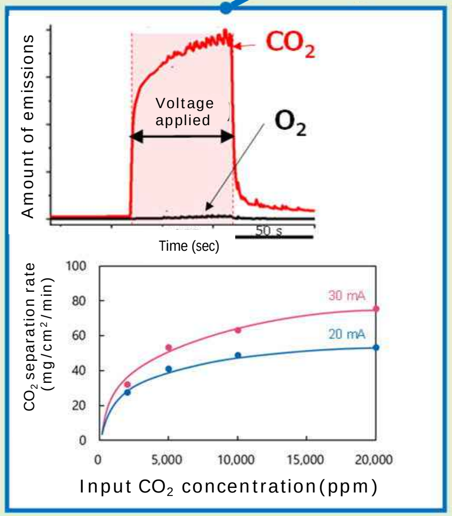
Ex.) Outlet CO_2 conc. upon repeated adsorption/desorption

Adsorption : 15℃ CO_2 400ppm
Desorption : 90℃

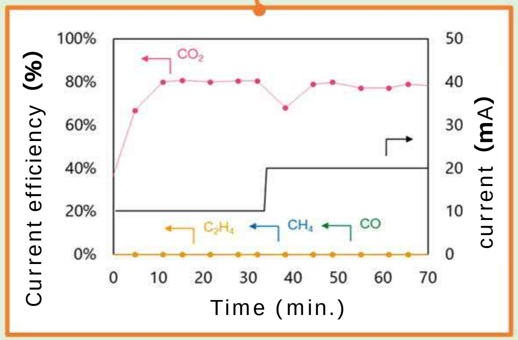
Electrochemical CO_2 Enrichment

- Enrichment of CO_2 from 0.2% to 100%
- Selective electro-filtration of CO_2 from a mixture of unreacted CO_2 and C_2H_4 emitted from the electrolysis reactor
- Reducing the cell voltage by improving the electrode and reactor structures
- Identifying the key factors for performance degradation





CO_2 enrichment from CO_2/O_2 mixture



Selective separation of CO_2 from the mixture of CO_2/C_2H_4

Confirmation of repeated adsorption/desorption performance
Confirmation of CO_2 selective separation

Progress and results: CO_2 electrolytic reduction （1/3）

☐ Ultra-high rate electrolysis

- High current density (2,000 mA/cm²) at the 80% of FE (for C2+ products) was achieved.

☐ High FE and low operation voltage

- 60% of FE (C_2H_4) was achieved at the 4 V of operation voltage.

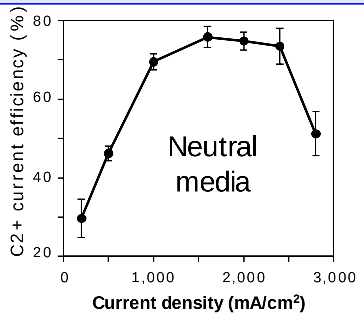
※FE: faradaic efficiency

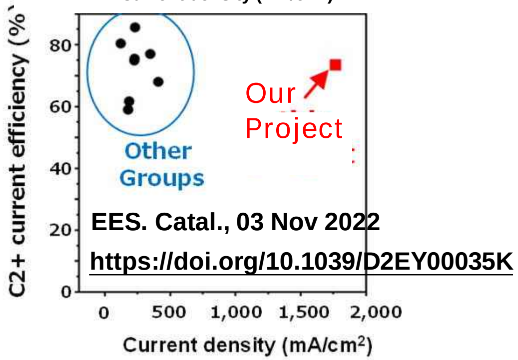
The world record

FY22 target cleared
100 mA/cm²

FY24 KPI target cleared
CO_2 emissions (t-CO_2/t-C_2H_4)
＋0.5～＋1.0

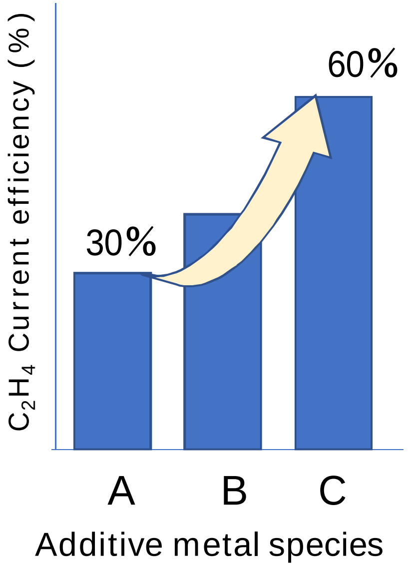
☐ FE for C2+: 80**%**
☐ Current density:
2,000 mA/cm²

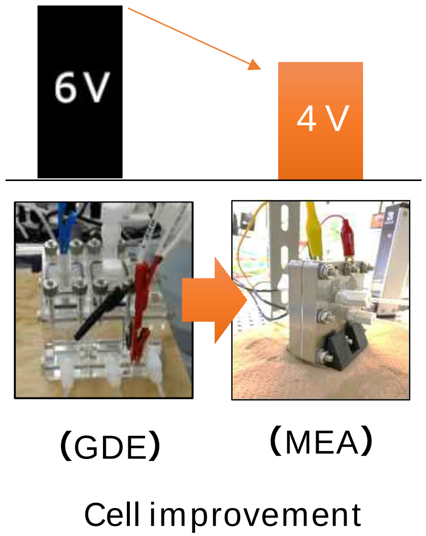




Achievement of both high FE and high current density

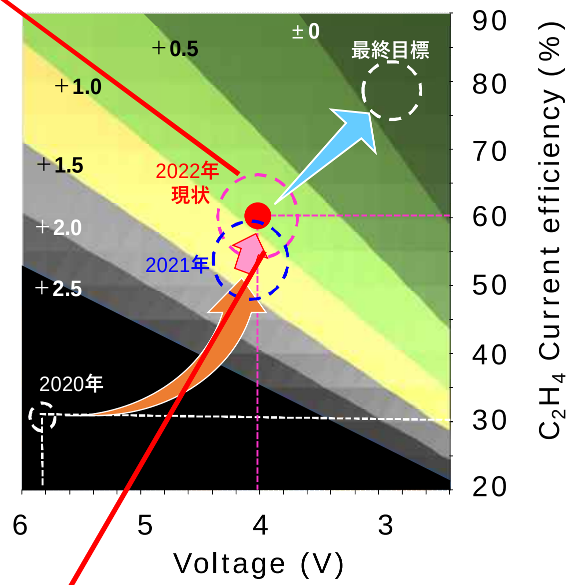
☐ FE for C_2H_4: 60**%**
☐ Operation voltage: **4** V





Improved reaction selectivity

Reduced operation voltage



CO_2 emissions from the whole system (t-CO_2/t-C_2H_4)

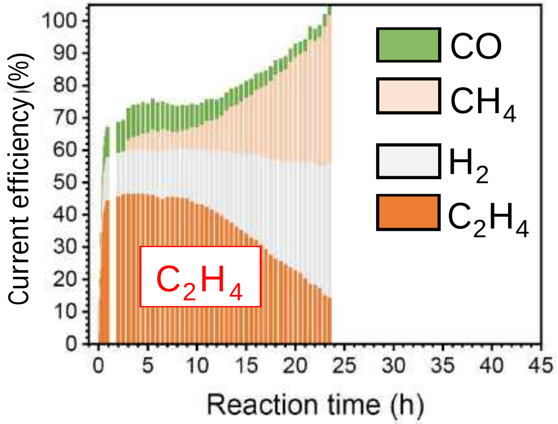
High current density, improved current efficiency, reduced operating voltage achieved.

Progress and results: CO_2 electrolytic reduction （2/3）

[redacted]

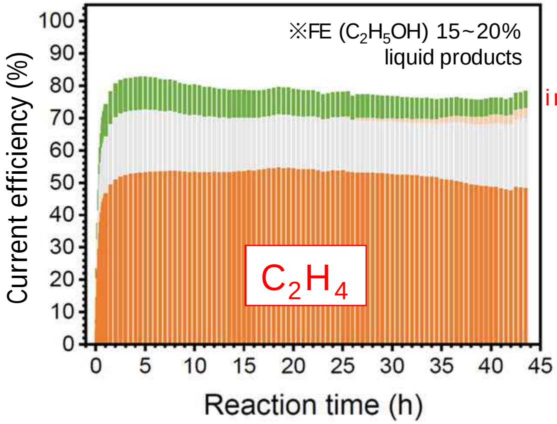
☐ Achievement of both FE (for C_2H_4) and stability

Addition of metal-B



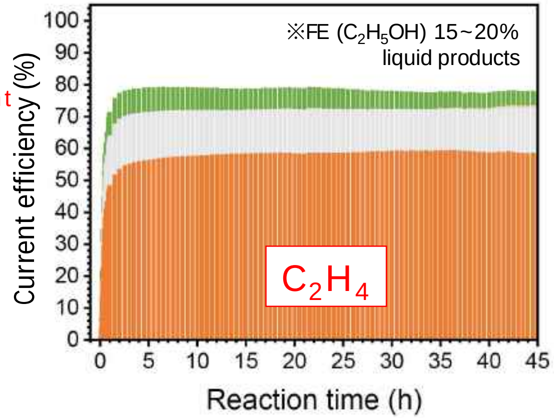
Catalyst improvement

Addition of metal-C



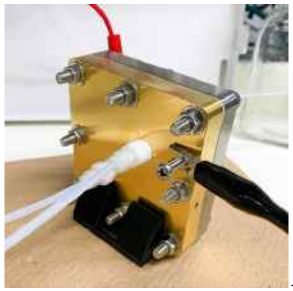
Substrate improvement

Addition of metal-C
Improved carbon substrate

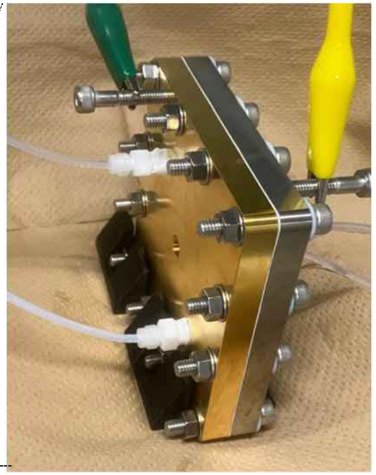


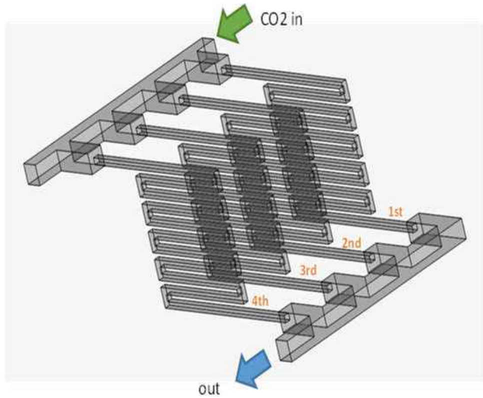
☐ Development of cell stacks

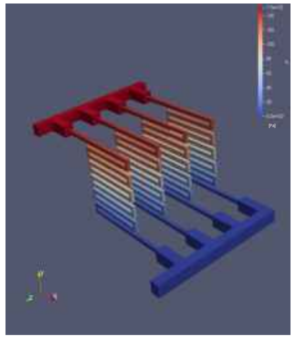
2.5 cm square



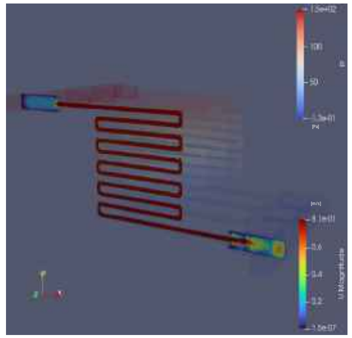
5.0 cm square







Pressure distribution



Flow velocity distribution

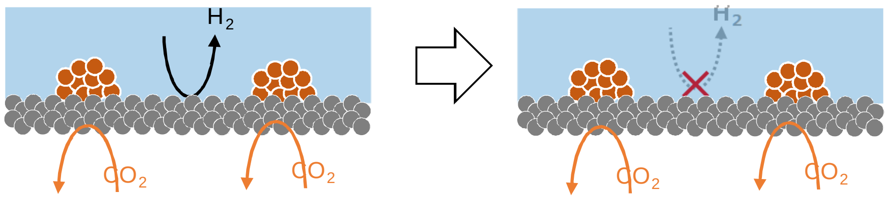
- Started operation of 5.0 cm square size reactor with developed electrodes
- CFD evaluation of gas/liquid distribution with common inlet/outlet flow channels

Enhancement in C_2H_4 current efficiency & stability
Design of larger area cells and stacks of MEA-type cells

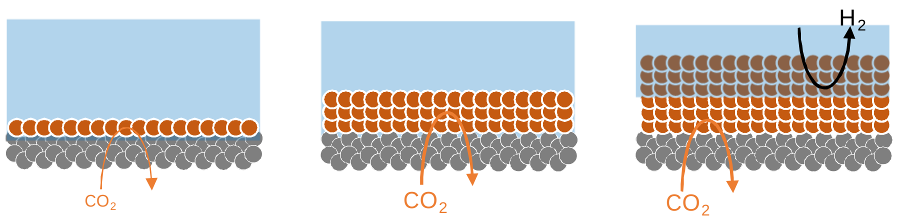
Progress and results: CO_2 electrolytic reduction (3/3)

■ Strategies for enhancing FE (for C_2H_4)

① Suppression of parasitic H_2 evolution by surface modification of a carbon substrate.

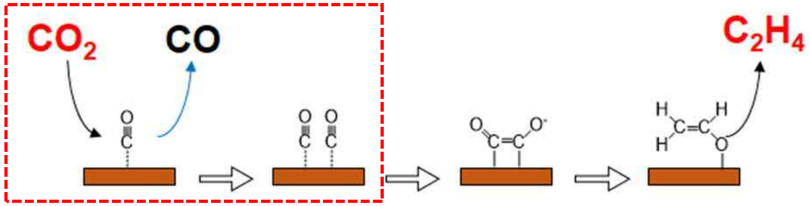


② Thickness optimization of the catalyst layer to meet the target current density.



Current density: Low Current efficiency: High	**Current density:** High Current efficiency: High	**Current density:** High Current efficiency: Low

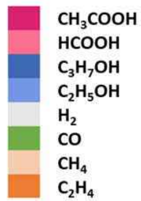
③ Increasing the local concentration of CO

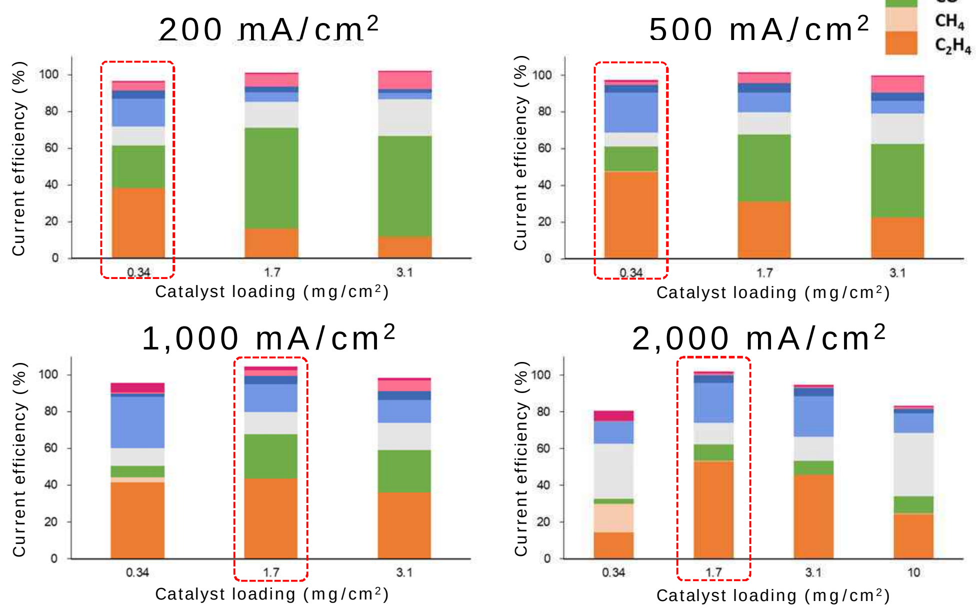


Promoting dimerization of CO

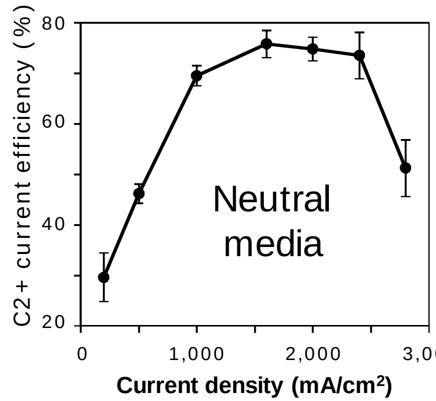
- CO dimerization is the key for the improvement of C_2H_4 generation
- Preparation of an appropriate porous electrode that allows to increase the local CO concentration

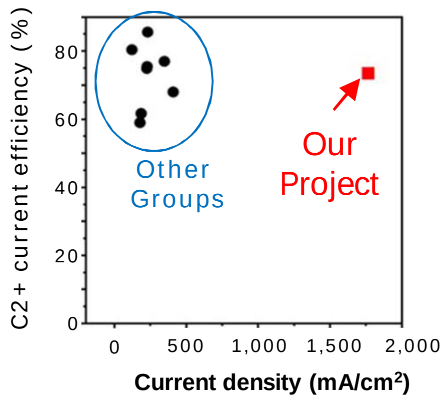
■ Optimal electrode design (catalyst load) to meet the target current density





■ Achievement of both high FE and high current density



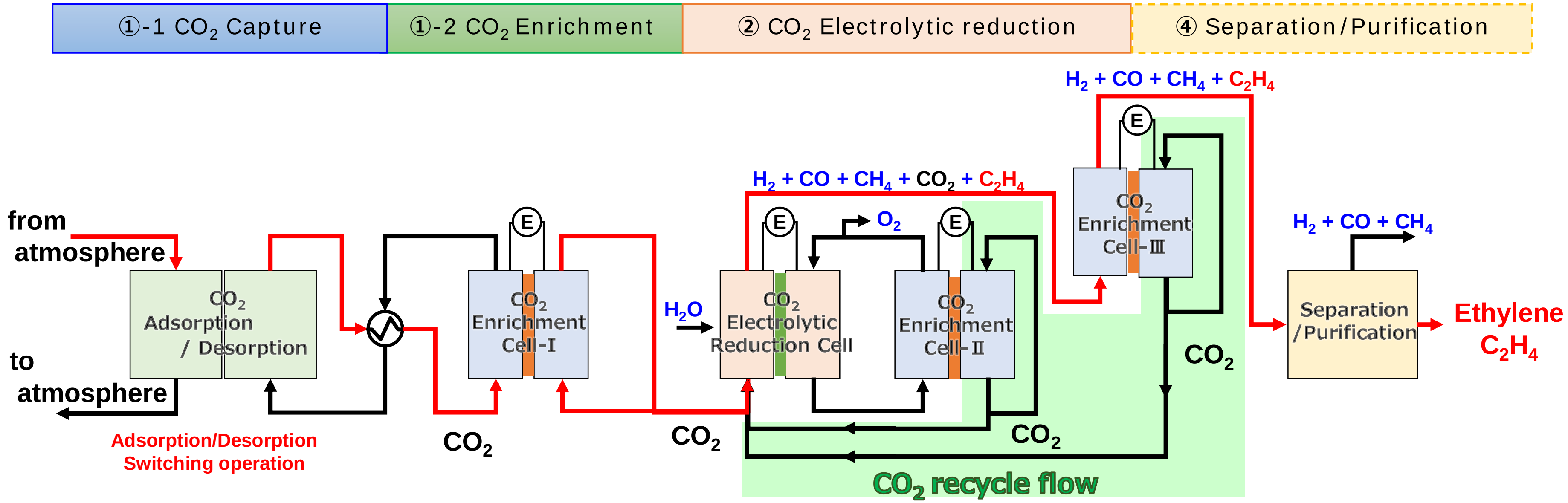


Established optimal design guidelines for electrodes

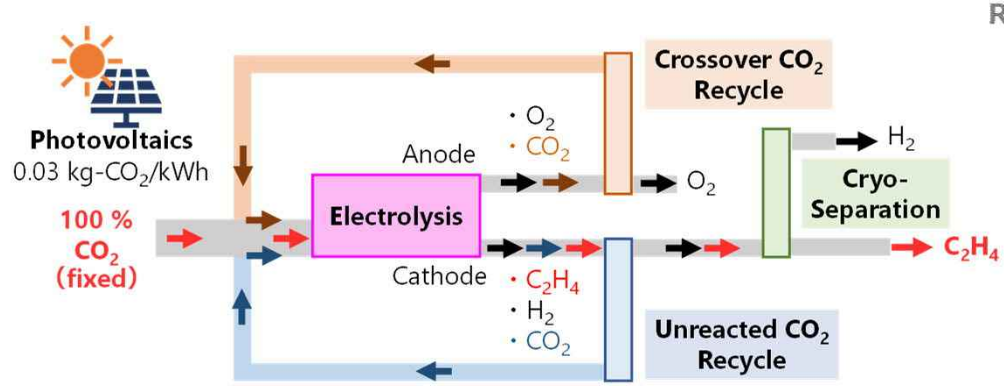
Progress and results: Integrated system (1/1)

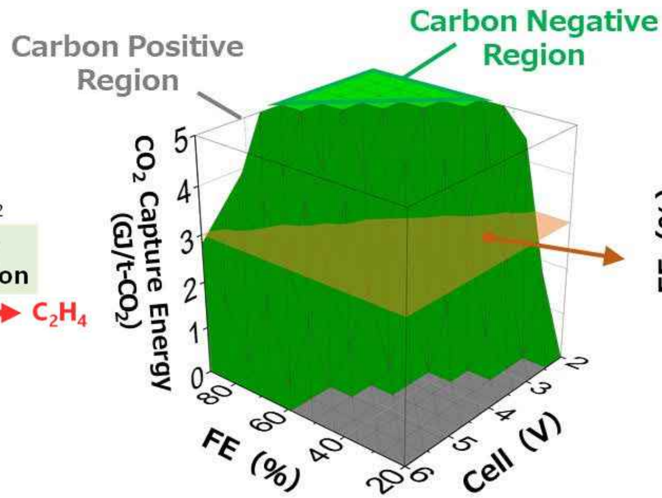
[redacted]

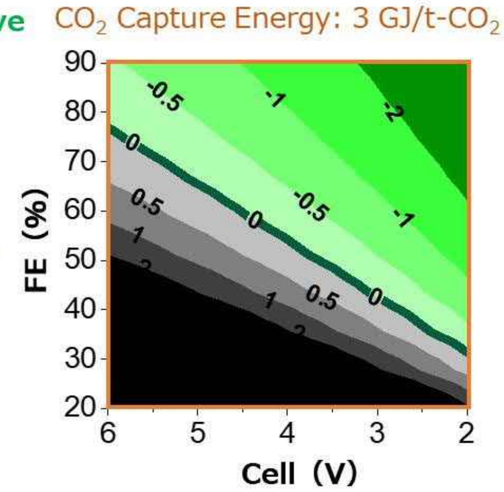
☐ Integrated system design: introduction of CO_2 recycling flow using CO_2 enrichment cells



☐ LCA evaluation of CO_2 recycling







Evaluation of CO_2 emission in the electrolytic reduction process with CO_2 recycling

Operating conditions necessary to achieve carbon negativity (emitted CO_2 < fixed CO_2) is identified.

Publications and intellectual properties

◻ **Conference presentations**, papers, newspapers, etc. (2020.9-2022.8)

	number of events	note
Conference Presentations	**27**	The Electrochemical Society of Japan, The Chemical Society of Japan, The Japan Society of Applied Physics, ECS, etc.
Journal papers	**8**	EES Catalysis、ACS Applied Nano Materials, etc.
Magazines, Newspapers, Exhibitions, etc.	**15**	Magazine (1) Press (8) Release (2) Exhibition (2) Interview/HP (1) etc.

◻ **Conference presentations**

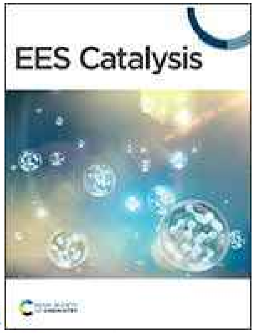
- Electrochemical Society: 5 presentations
- PVSEC-33: 1 presentation

◻ Symposiums held and exhibitions

- CEATEC2022
- PVSEC-33
- Distributed Carbon Neutral Symposium Using Electrochemistry

Ultra-high-rate CO_2 reduction reactions to multicarbon products with a current density of 1.7 A cm^{-2} in neutral electrolytes †

Asato Inoue,[a] Takashi Harada,[ab] Shuji Nakanishi *[ab] and Kazuhide Kamiya



Ultra-high rate electrolysis results by Osaka Univ. published in EES Catalysis (Royal Society of Chemistry, UK)

EES. Catal., 03 Nov 2022

Intellectual property (cumulative) : 9 applications filed

Dissemination to the public through various media and promotion of intellectual property rights

Summary and future perspective

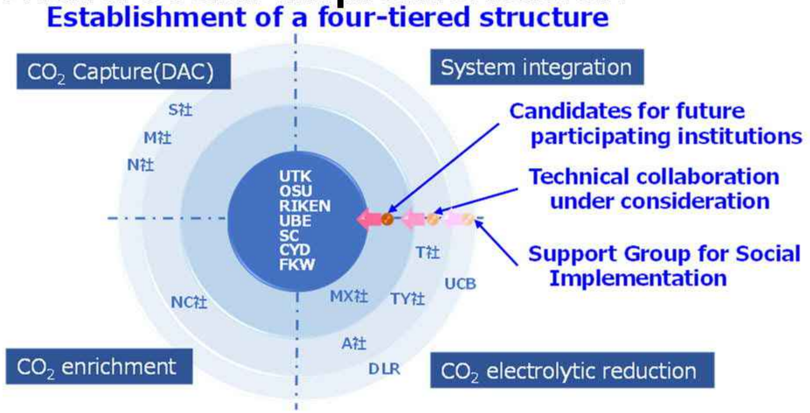
☐ Major results

Theme	Major Results	Future Works
CO_2 Capture and Enrichment	・Successful enrichment of atmospheric CO_2 from 400 ppm to 100% (pure CO_2).	・Design and manufacturing of prototypes ・Low drive voltage and long-term stable operation
CO_2 Electrolysis	・High current density (2,000 mA/cm^2) at the 80% of FE (for C2+ products) was achieved. ・60% of FE (for C_2H_4) was achieved at the operation voltage of 4V.	・Preparing electrodes that satisfy all the required factors simultaneously (i.e., high FE, high current density, and high stability)
System Integration LCA	・Conceptual system design from atmospheric CO_2 capture to ethylene production and LCA for CO_2 emission	・Continuous process benchmark of "CO_2 Enrichment + Electrolysis." ・Improvement of LCA accuracy

☐ Future Development Goals

	Scale of the system	CO_2 emissions (per ton of ethylene produced)
FY2024	Laboratory scale	Less than +0.5~+1.0 ton
FY2029	Pilot plant	Less than –0.5 ton (Carbon negative process and continuous operation for 5,000 h)

☐ Efforts toward social implementation



*UTK: The University of Tokyo, OSU: Osaka University, RIKEN: Institute of Physical and Chemical Research, UBE: UBE Corporation, SC: Shimizu Corporation, CYD: Chiyoda Corporation, FKW: Furukawa Electric Co., Ltd

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