Integrated Electrochemical Systems for Scalable CO_2 Conversion to Chemical Feedstocks

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Project Members :
The University of Tokyo, Osaka University, RIKEN, UBE Corporation, Shimizu Corporation, Chiyoda Corporation, Furukawa Electric Co. Ltd., Maxell, Ltd.

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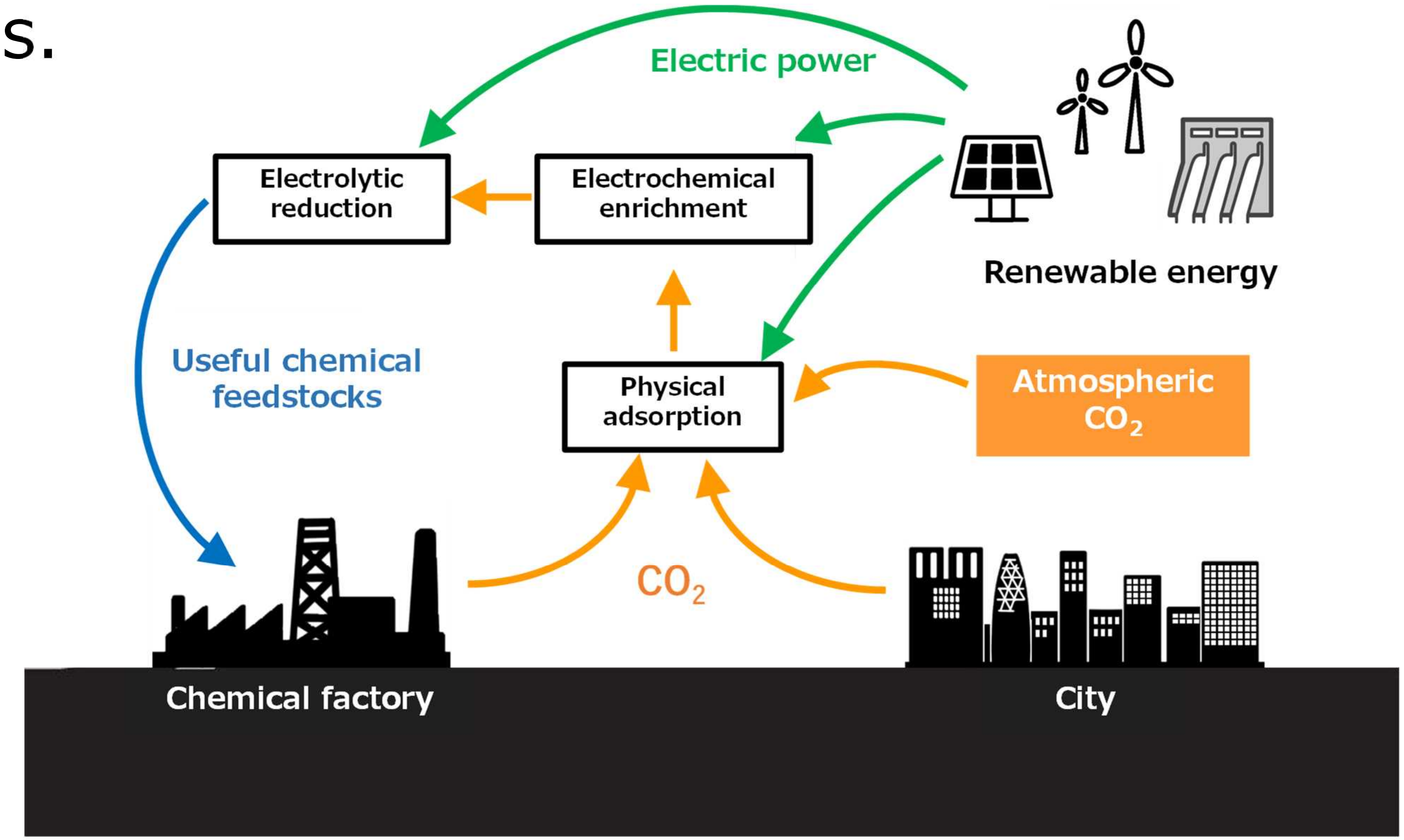
Project Goals

(Goals in FY 2029)

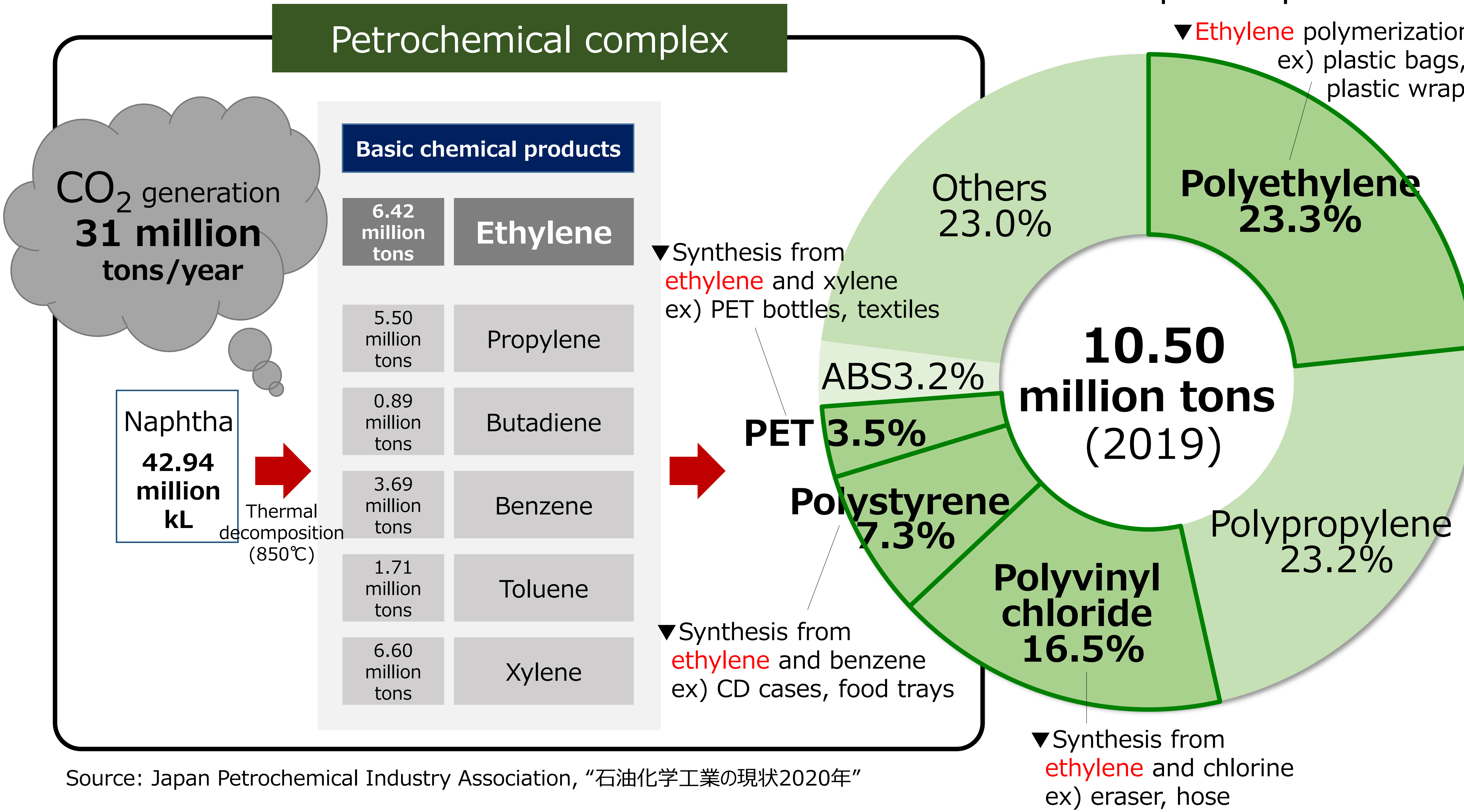
Development of a system to convert atmospheric CO_2 into useful chemical feedstocks based on electrochemical processes.



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 ～

Products : Ethylene

Ethylene is used in about half of all plastic products.

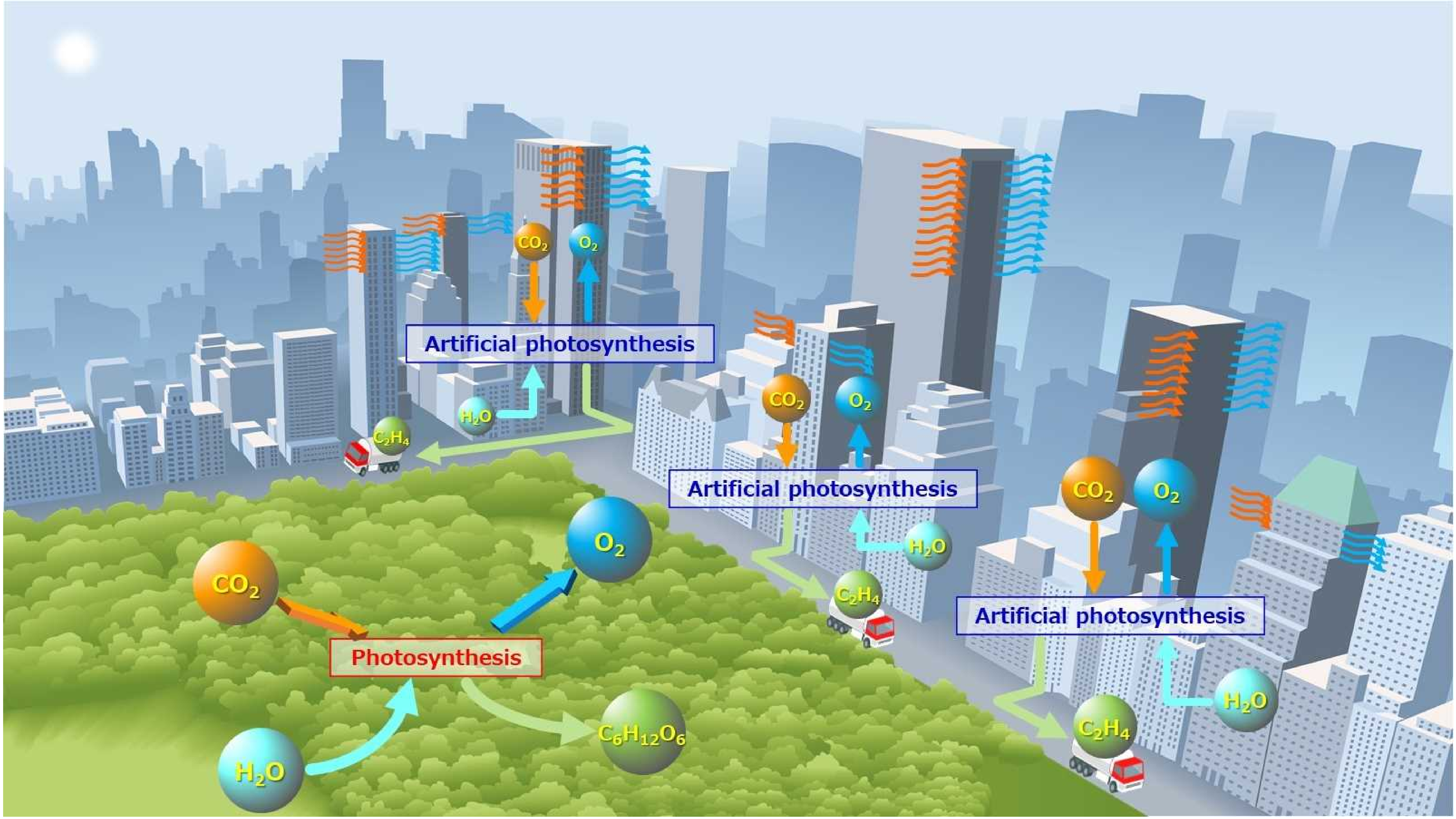


Source: Japan Petrochemical Industry Association, "石油化学工業の現状2020年"

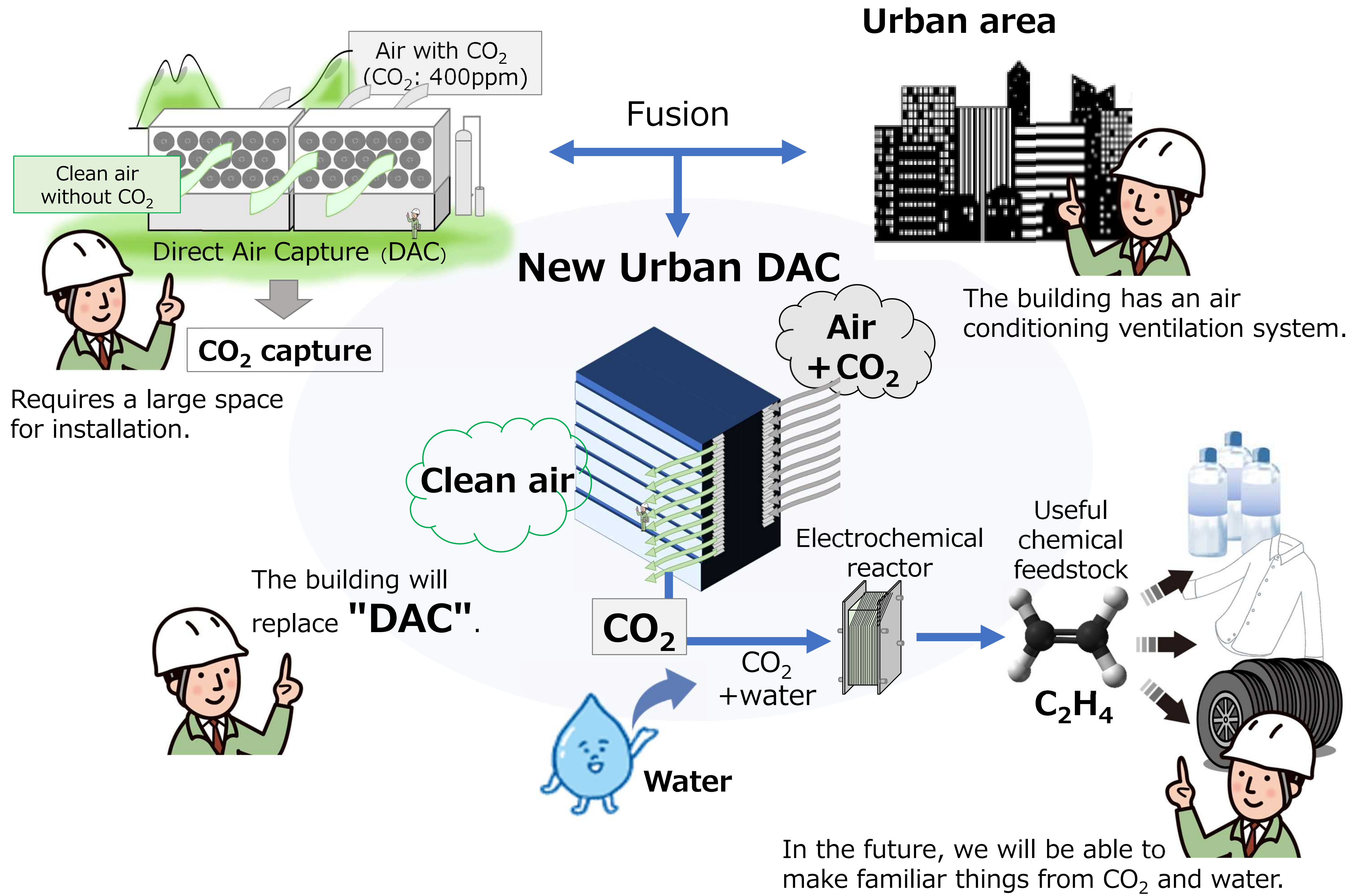
Source: Plastic Waste Management Institute, "プラスチックリサイクルの基礎知識2020"
http://www.pwmi.or.jp/pdf/panf1.pdf

Our Future Vision

Urban DAC-U System (Artificial Photosynthesis)

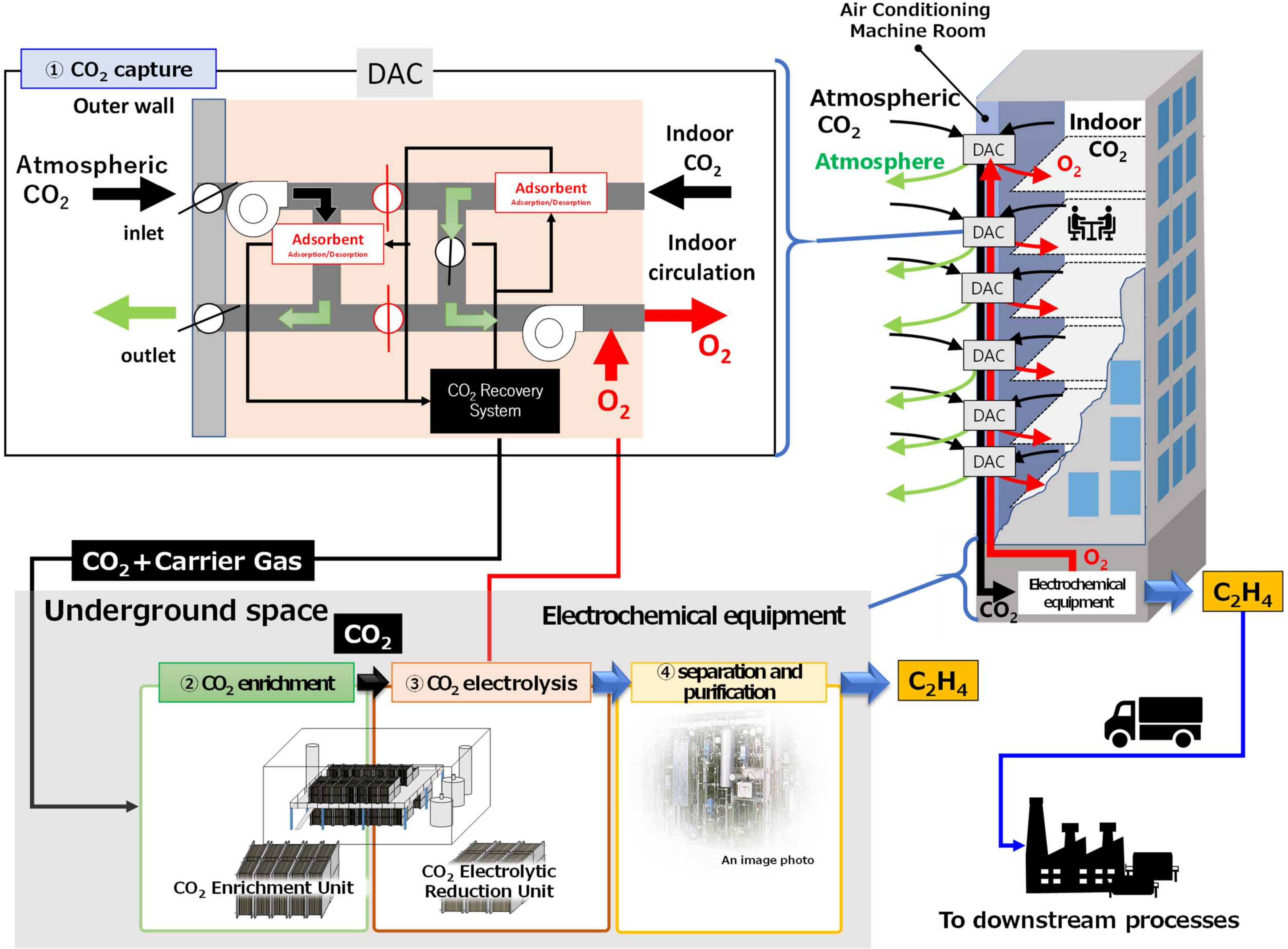


Buildings Function as "Air purifiers for a city"



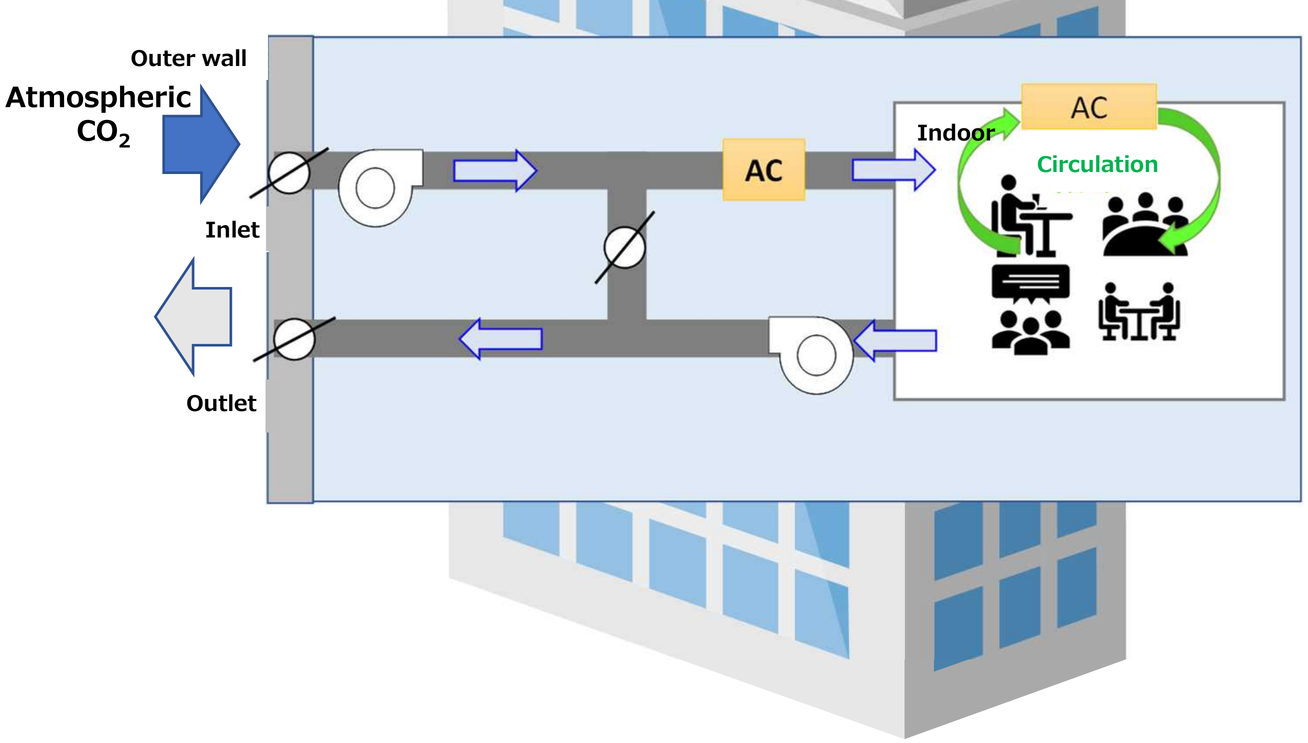
Urban Artificial Photosynthesis

CO_2 and O_2 circulation

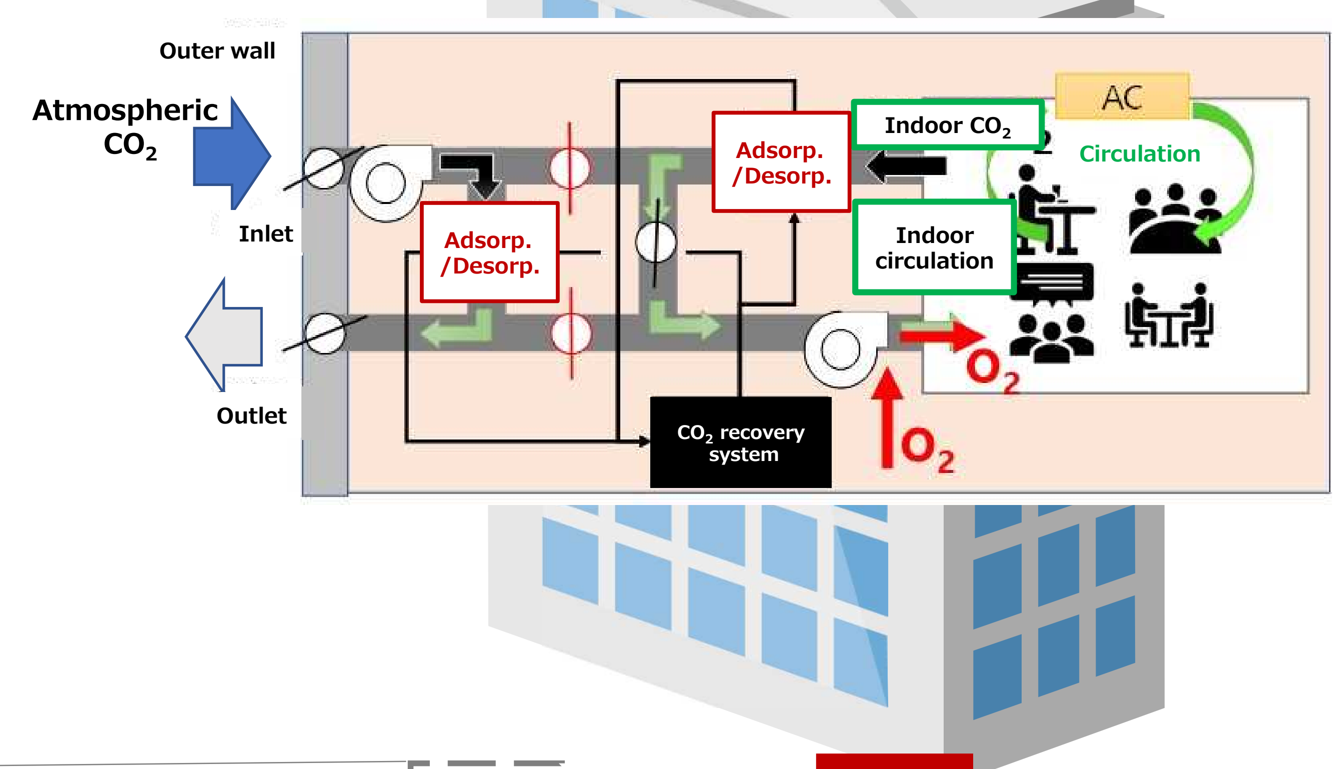


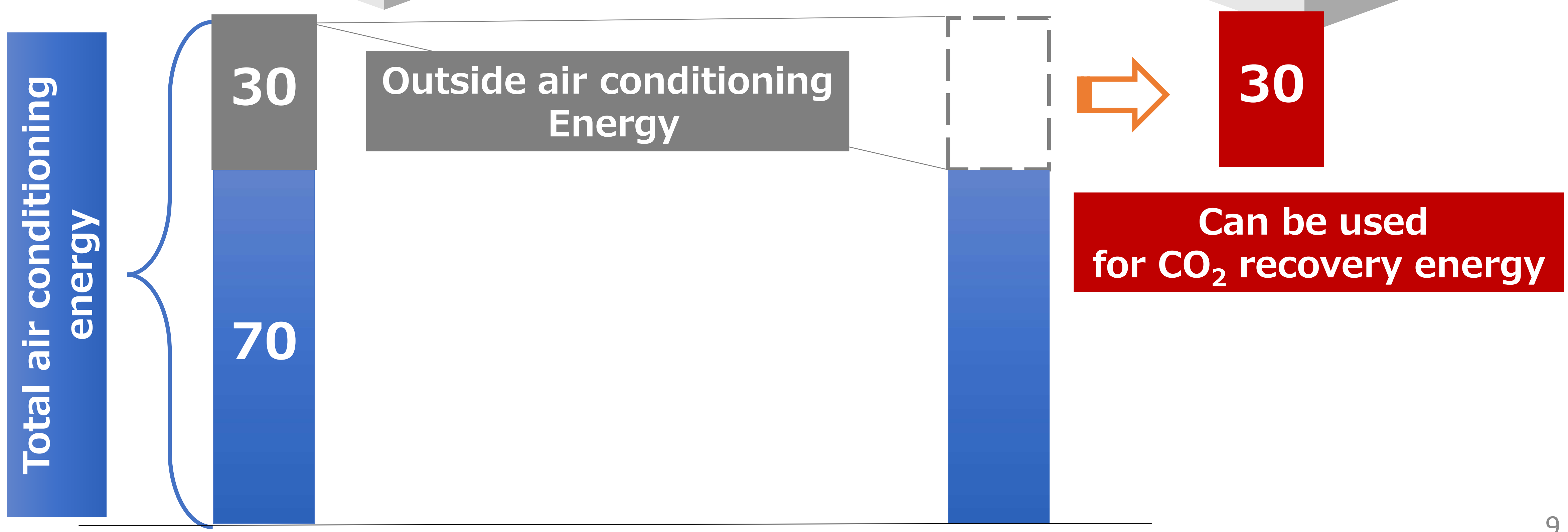
Energy Savings in Air Conditioning and Ventilation Systems

Existing technology



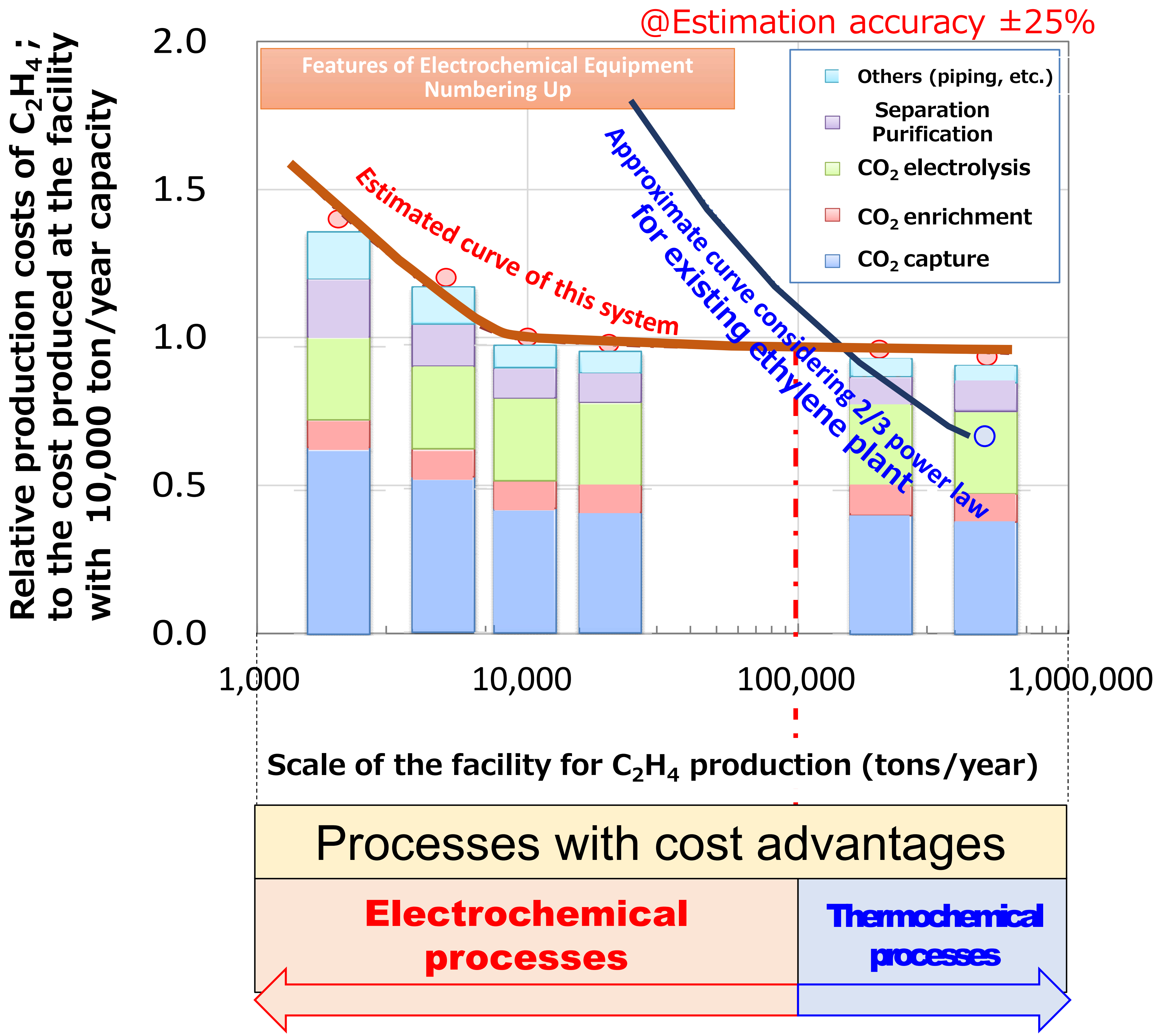
Novel technology



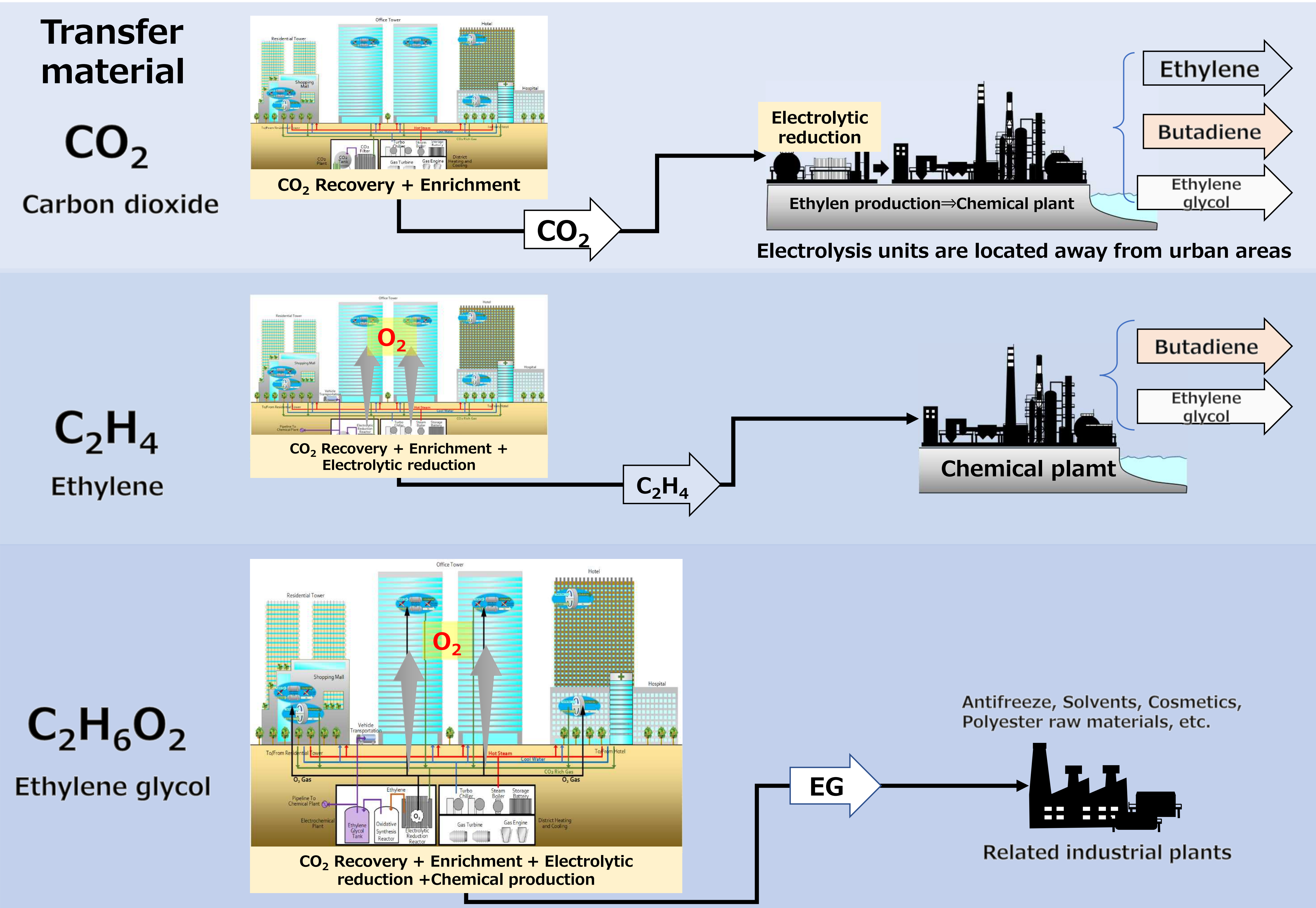


Scalability Based on Electrochemical Processes

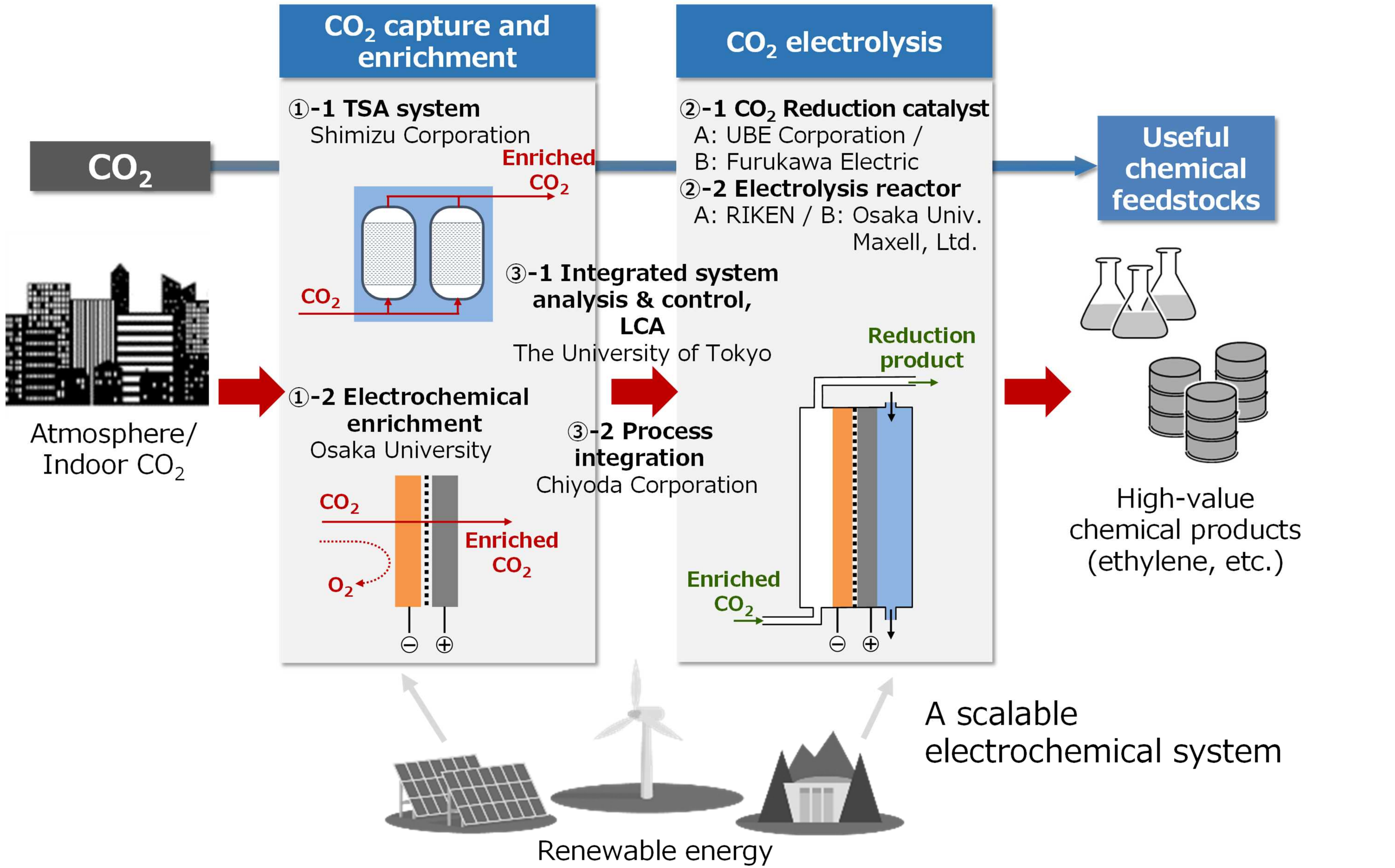
Estimated relative production cost of 1 ton ethylene



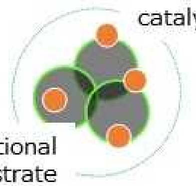
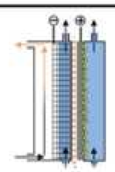
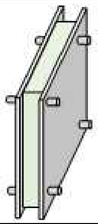
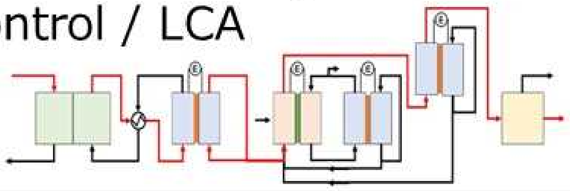
Scalable Social Implementation for Various Scenes



Work Packages of the Project



R&D Items and Players

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 UTK	UBE
			Cu-based materials		FKW
		Gas-Diffusion Electrode (GDE) 			UBE, FKW, Maxell
		MEA-based reactor 	Membrane	RIKEN	Collaborative member
			Reactor		
		Stack 			
System integration	Reaction process development / Process integration Integrated system analysis & control / LCA 			UTK	CYD

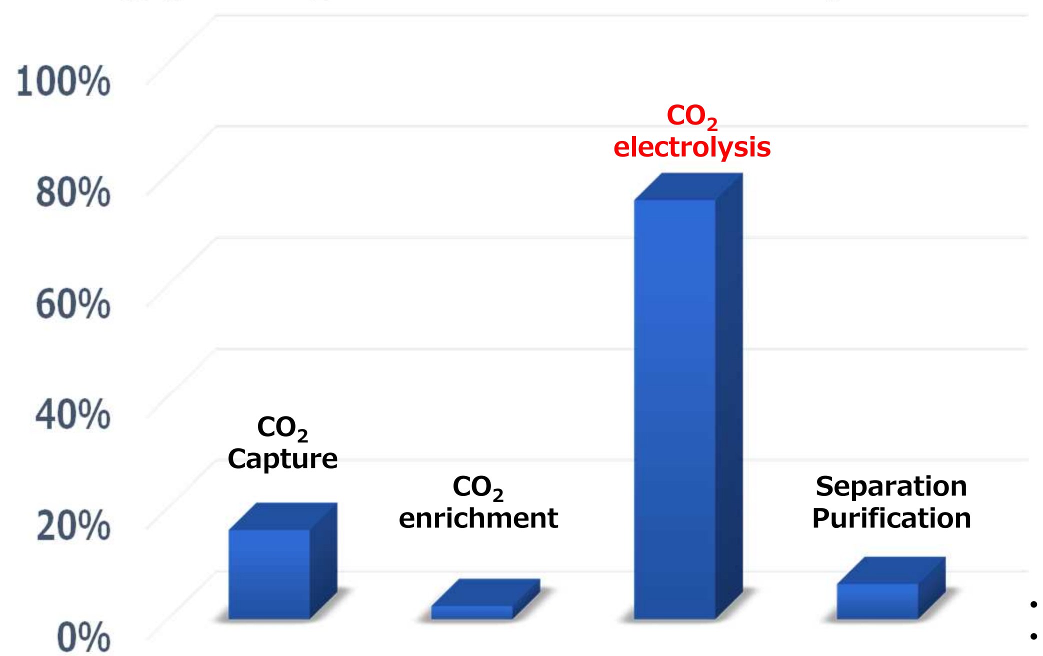
*UTK: The University of Tokyo, OSU: Osaka University,
RIKEN: Institute of Physical and Chemical Research,
UBE: UBE Corporation, SC: Shimizu Corporation,
CYD: Chiyoda Corporation, FKW: Furukawa Electric Co., Ltd, Maxell : Maxell, Ltd.

KPI

	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

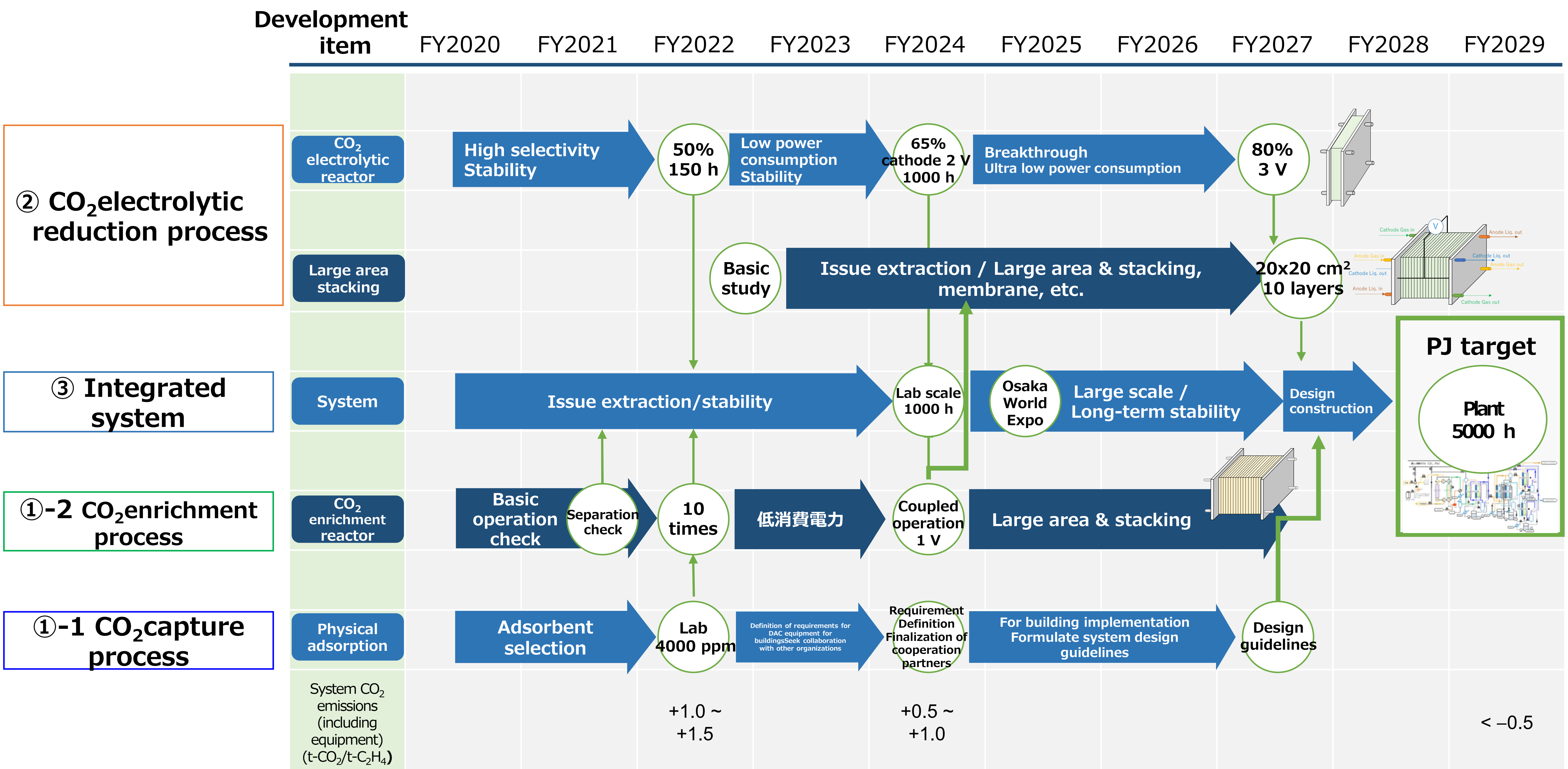
※CO_2 emission of the entire system from atmospheric CO_2 capture to ethylene production (including emission upon manufacturing of equipment)

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

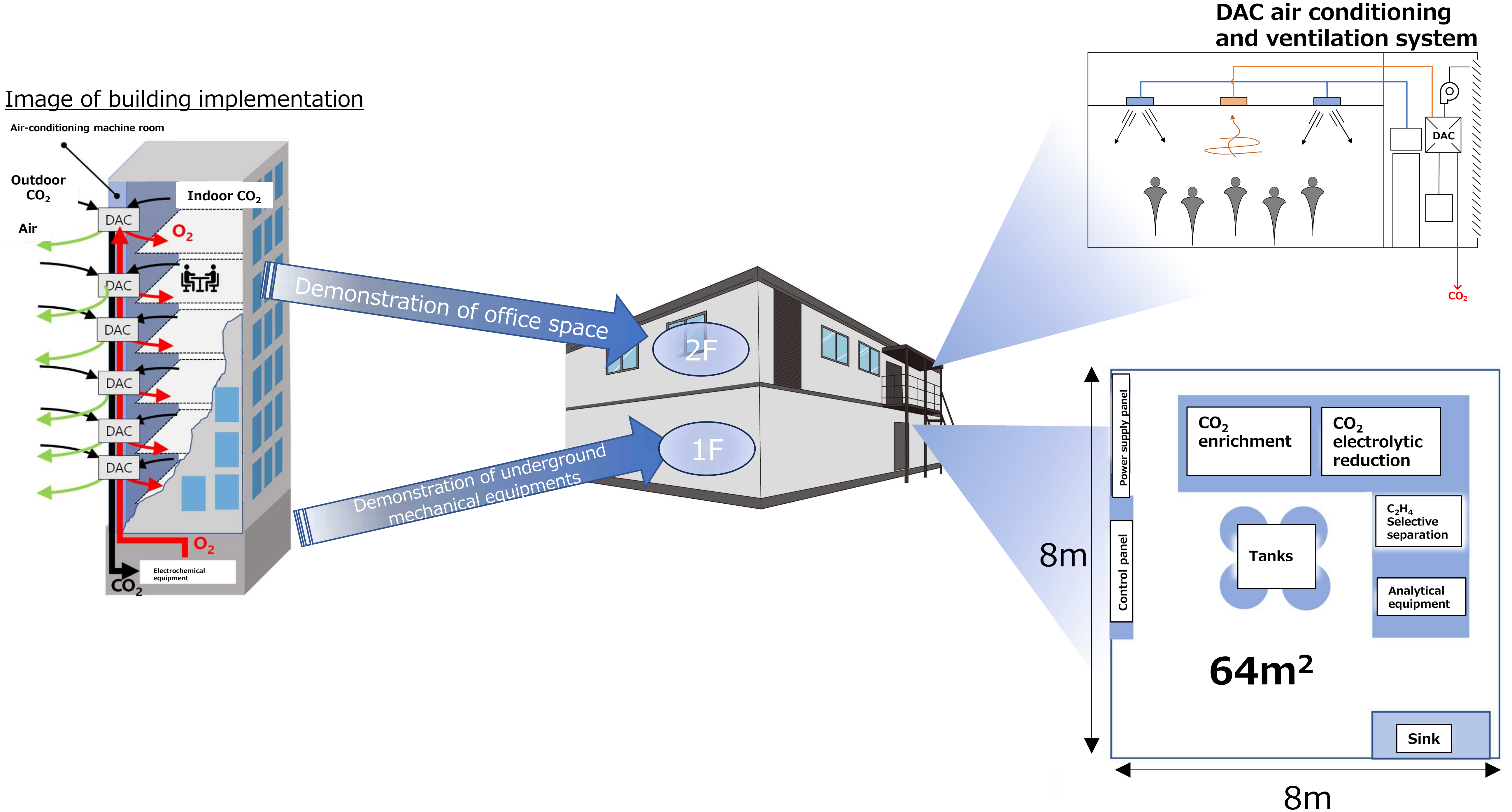
Development Schedule



Pilot Demonstration Image

Pilot Implementation Image

- CO_2 throughput : ～10 kg/day
- Ethylene production : ～ 3 kg/day



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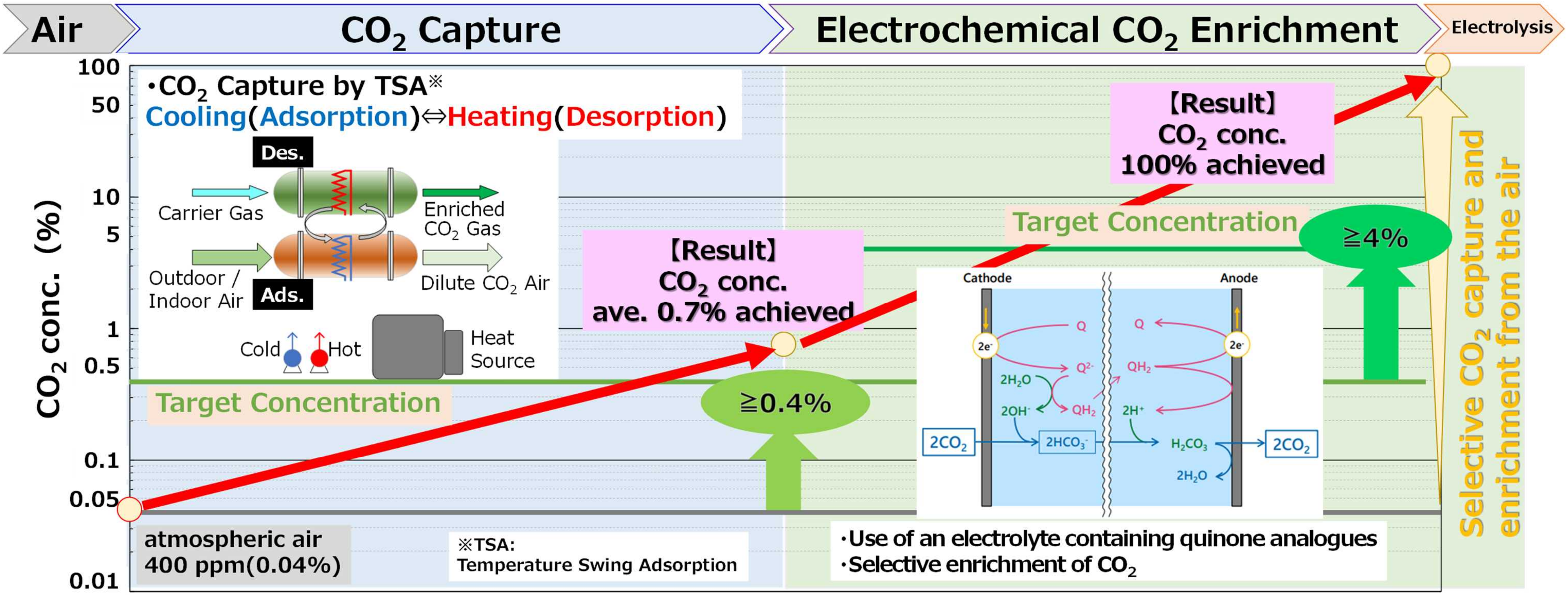
CO_2 Capture and Enrichment : Basic Performance Achieved

□ CO_2 capture :

Concentration 0.04% ➡ ave. 0.7%   **Target for FY2022 (0.4%) achieved**

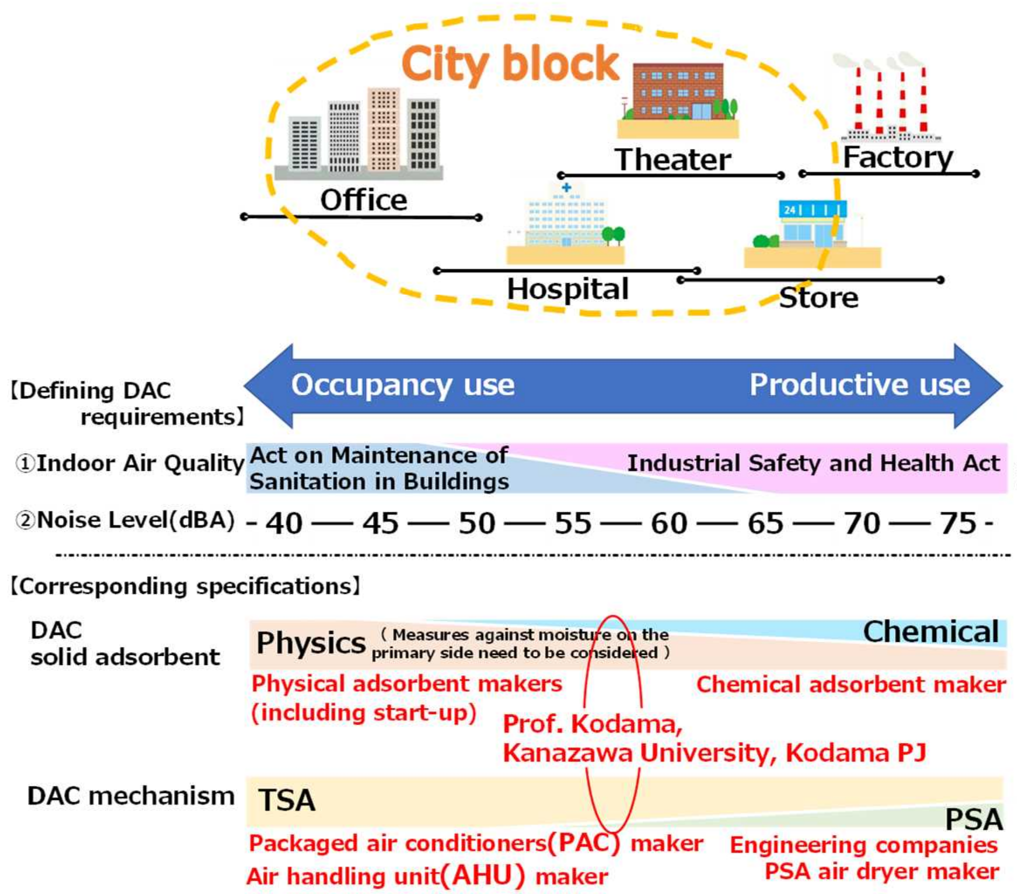
□ CO_2 enrichment

Concentration 0.7% ➡ 100%   **Target for FY2022 (10 times enrichment) achieved**

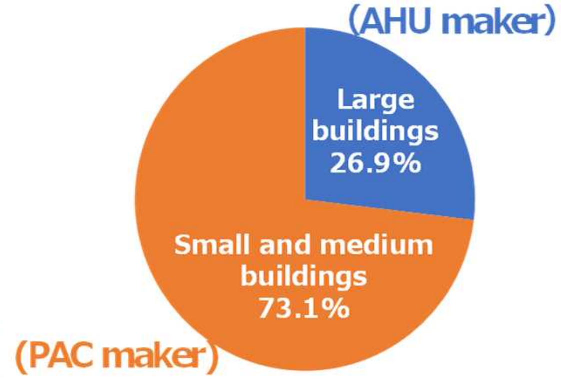


CO_2 Capture： DAC Requirement Definition for Buildings

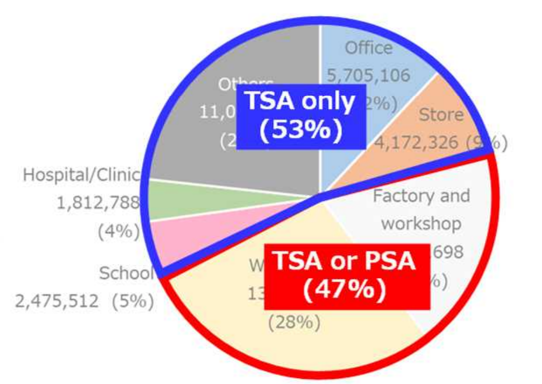
□ Concept of DAC requirement definition for buildings



※1) Japanese market for air conditioning systems and partners' positioning



※2) Percentage of applied DAC mechanism in Japanese construction start floor area



2022 Annual construction start floor area (m²)

Ref.) MLIT: Statistical survey of construction starts 2022

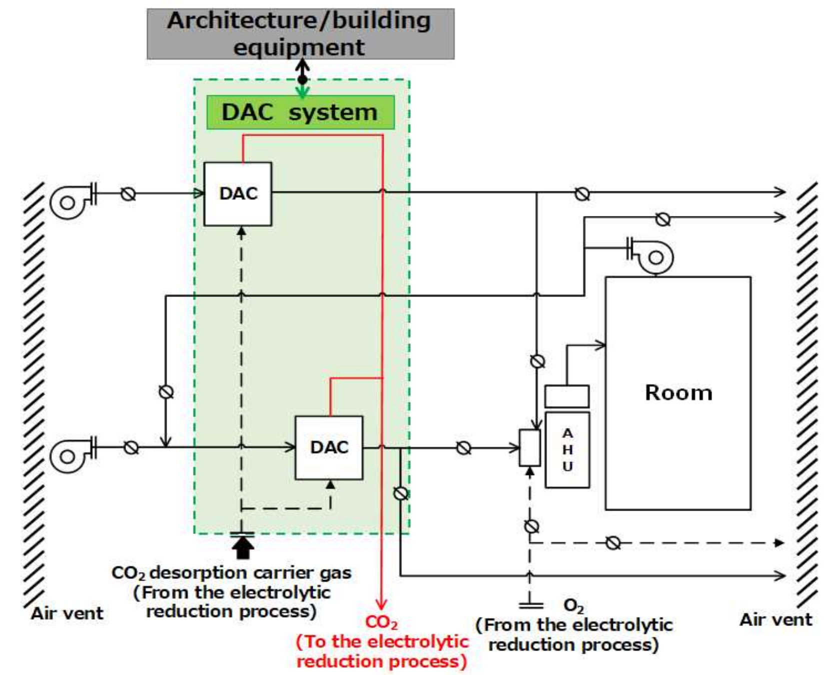
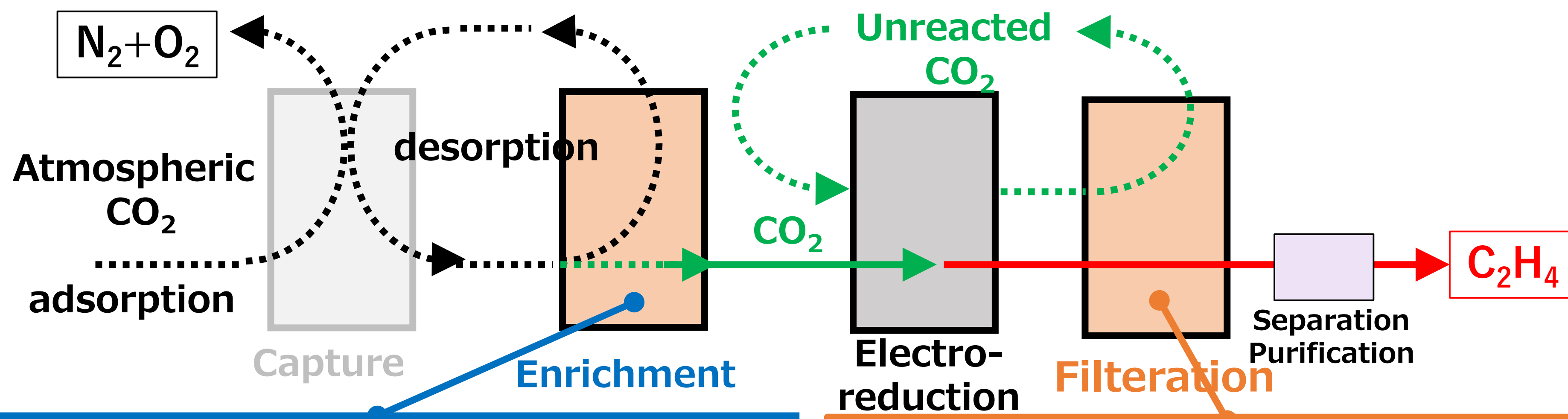


Diagram with the boundary

		Office: Complex	Office: Large	Office: Below medium	Theater	Store	Hospital	Factory
Requirements	CO_2 conc.	≦1,000 ppm					≦1,000 ppm	≦5,000 ppm
	Noise /Vibration	NC45/VAL≦			NC45/VAL ≦		NC45/VAL≦	NC45/VAL≦
	Space	4～6% of floor area						
	Temp. /Humi.	17～28℃/40～70%R.H.						
	Air quality	HCHO:100 μg/m³, TVOC:400 μg/m³ or less						
	Odor	―						Offensive Odor Control Law
	Energy type	Electricity					Electricity /heavy oil/gas	Electricity /heavy oil/gas
	Special facilities	District heating and cooling					Private power generation	※ cogeneration
DAC mechanism	Adsorbent	Solid adsorbent					Solid adsorbent	Solid adsorbent
	DAC mechanism	TSA			TSA/PSA	PSA /TSA	TSA/PSA	PSA/TSA
	Partner candidate							

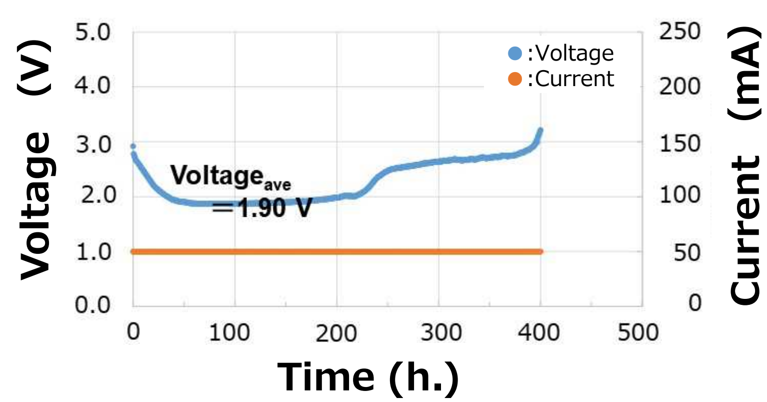
Requirements definition table

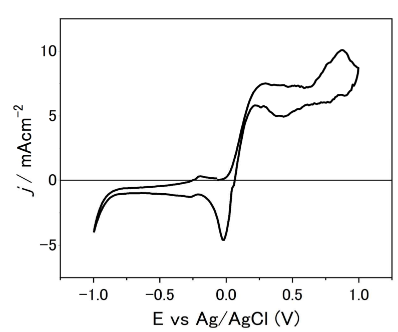
CO_2 Enrichment : Stability and Scale-up



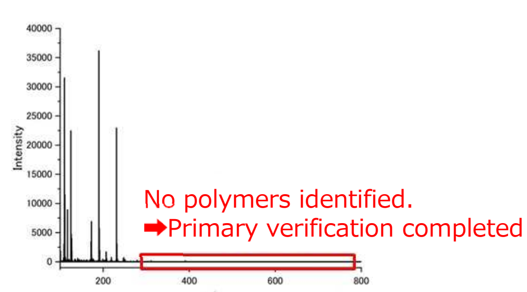
Extract Issues

- ☐ Asymmetric Electrochemical Properties in the High pH Region (Near the Electrode)

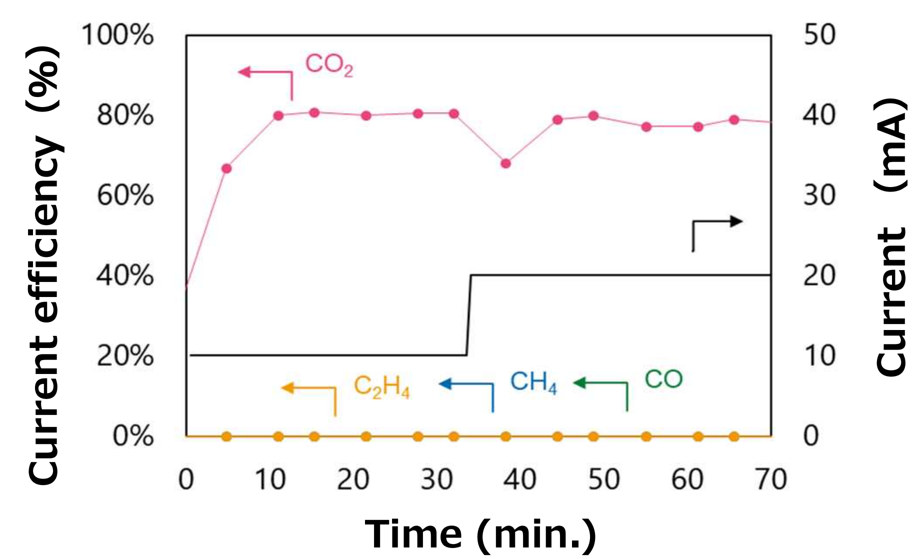




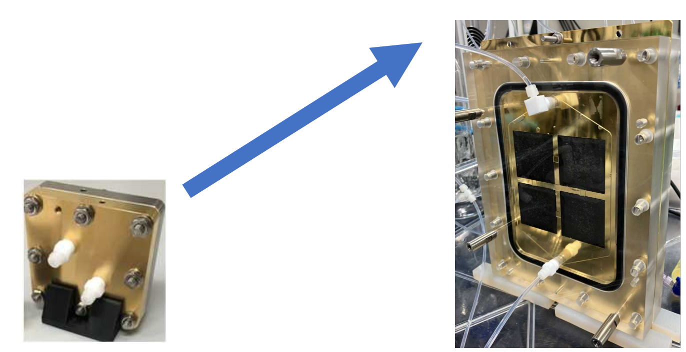
Asymmetric electrochemical properties



MS spectrum results of post-reaction solutions



■ Selective separation of CO_2 from the mixture of CO_2/C_2H_4



2.5 cm Square

10 cm Square

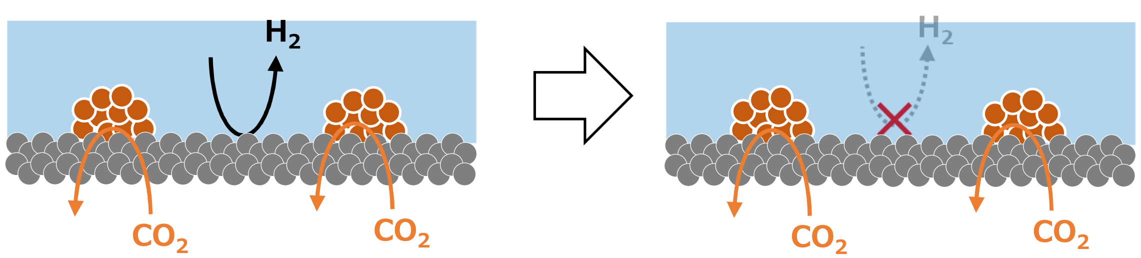
Improved reactor and larger area

CO_2 Electrolytic Reduction : Cathode Electrode Design Guidelines

■ Measures to improve current efficiency

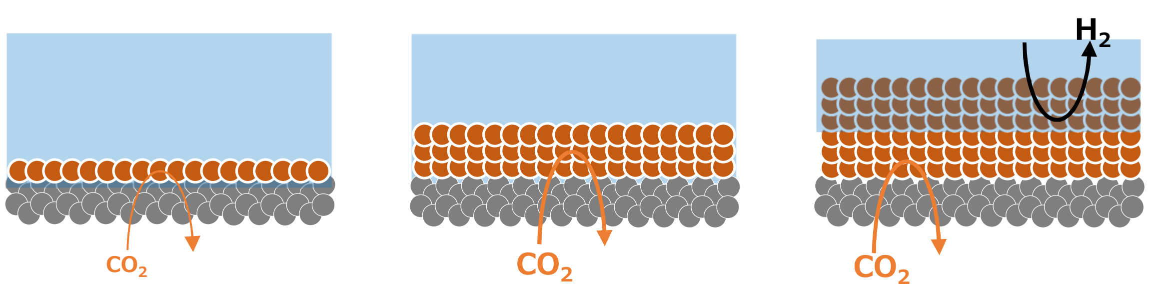
□ vs. Hydrogen

① Thorough elimination of macro hydrogen generation sites



② Appropriate catalyst structure control according to target current value

Example: Appropriate catalyst loading according to target current value

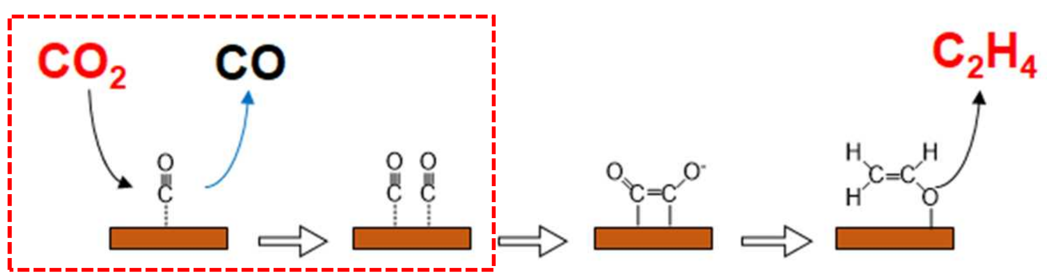


Current density : small
Current efficiency : Large

Current density : Large
Current efficiency : Large

Current density : Large
Current efficiency : small

□ vs. Other CO_2 reduction products



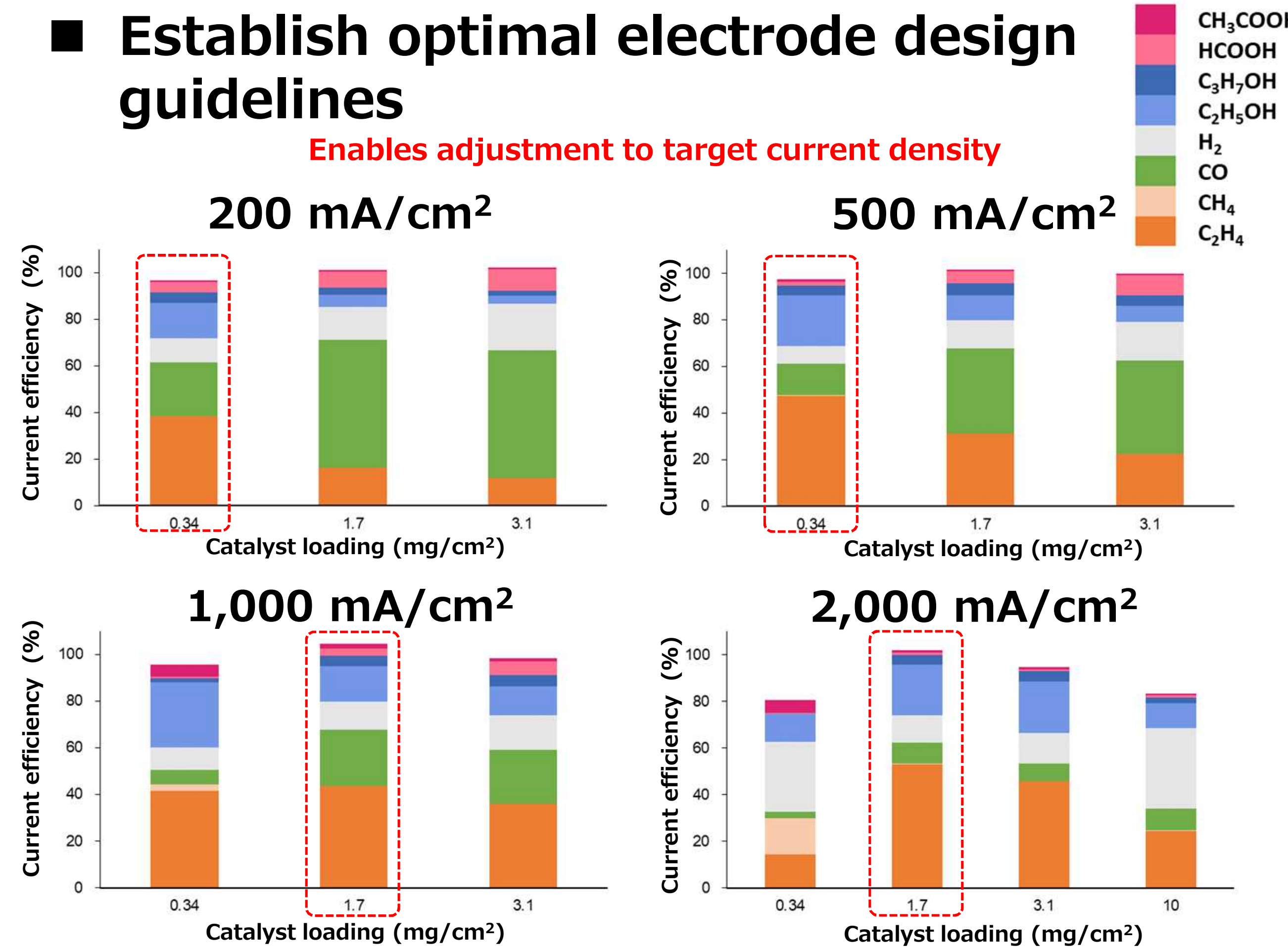
CO dimerization promotion

Counter measures

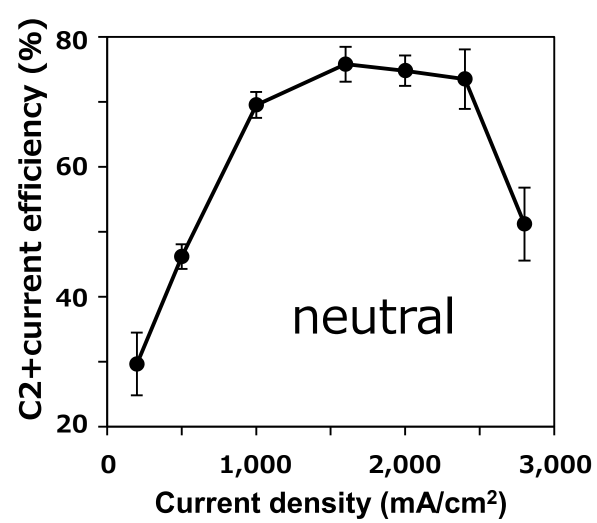
Improvement of local partial pressure of CO by increasing catalyst/electrode porosity
Improvement of CO local partial pressure by increasing current density

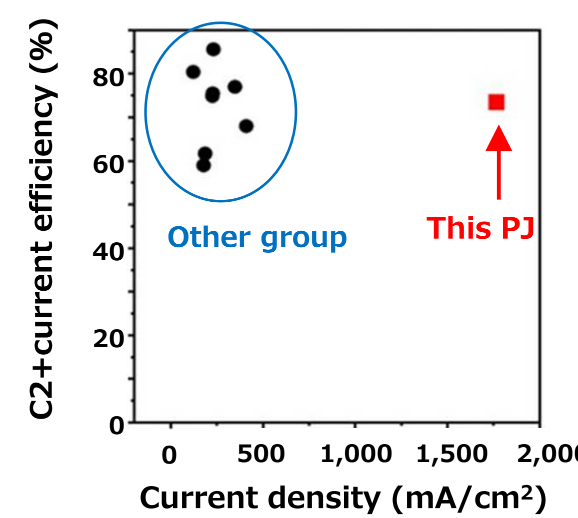
■ Establish optimal electrode design guidelines

Enables adjustment to target current density



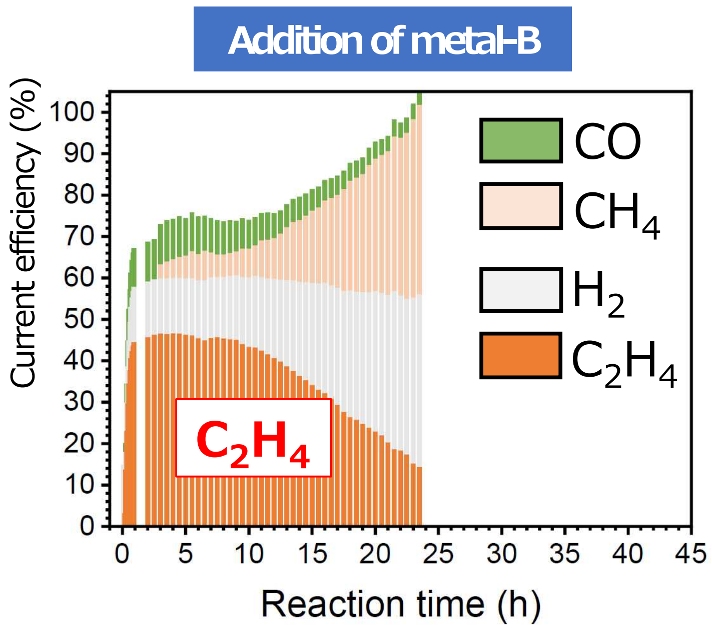
■ Compatibility of current efficiency with current density

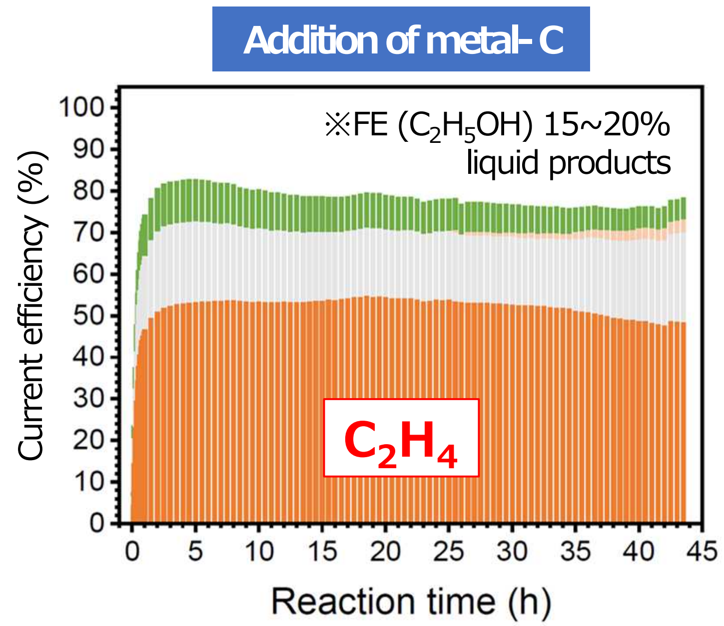


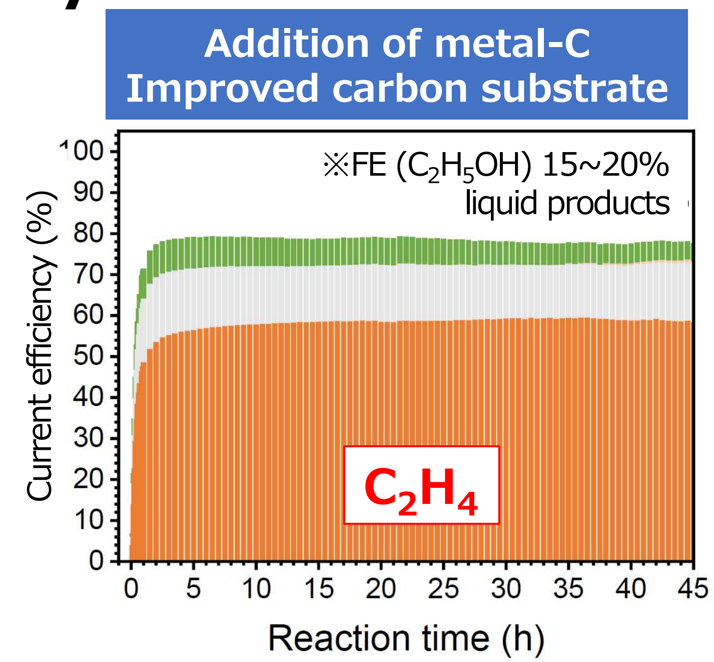


CO_2 Electrolytic Reduction: Cathode Electrode Catalyst Development

Attaining both high current efficiency and high stability

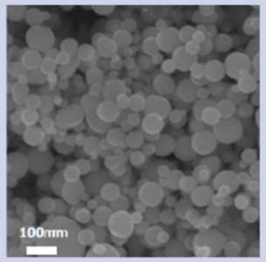
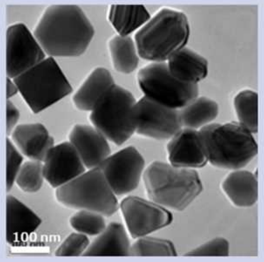


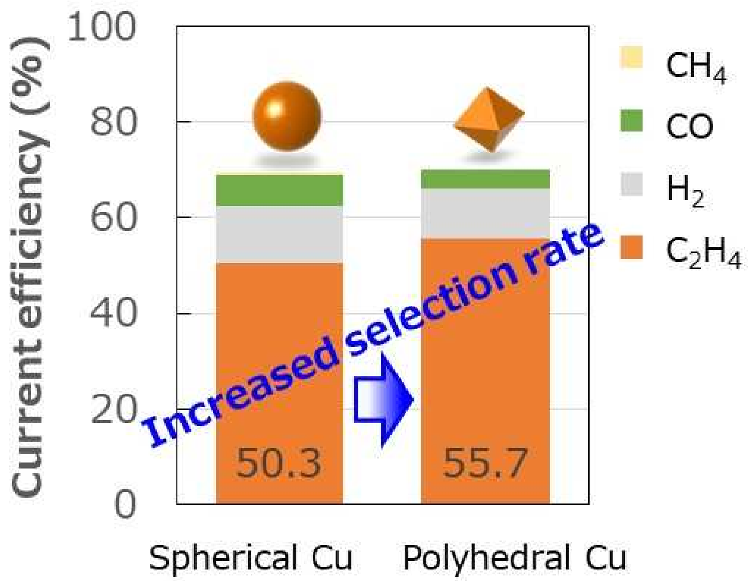




Efforts to achieve a high current efficiency

- Ethylene current efficiency of 56% with polyhedral Cu
- Factors are being identified and design guidelines are being developed

	Spherical Cu	Polyhedral Cu
Particle image		
Production method	Sintering	Wet reduction
State of purchase	Powder	Dispersion



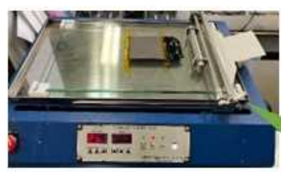
CO_2 Electrolytic Reduction: Cathode Electrode Study for Industrialization

□Start of electrode prototyping through institutional collaboration / Preliminary report of results (Prototype 1)

UBE

【 MPL/GDL production 】

Water repellent treatment, etc.



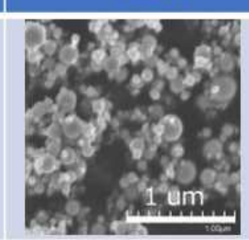
Substrate area 6cm square

Research Center for Advanced Science and Technology The University of Tokyo

FURUKAWA ELECTRIC

【 Catalyst Development & Preparation 】

Cu-Al alloy catalyst preparation

Image	SEM
	
Preparation Method	Thermal plasma method

maxell Within, the Future

【 Catalyst coating /GDE fabrication 】

Coating treatment, etc.

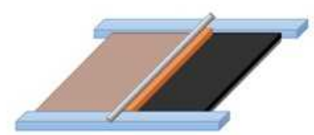
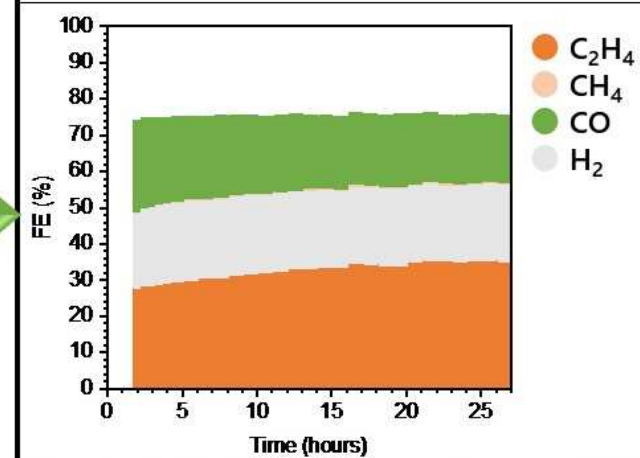


Image of catalyst coating treatment on substrate

CHIYODA CORPORATION

【 Device evaluation 】



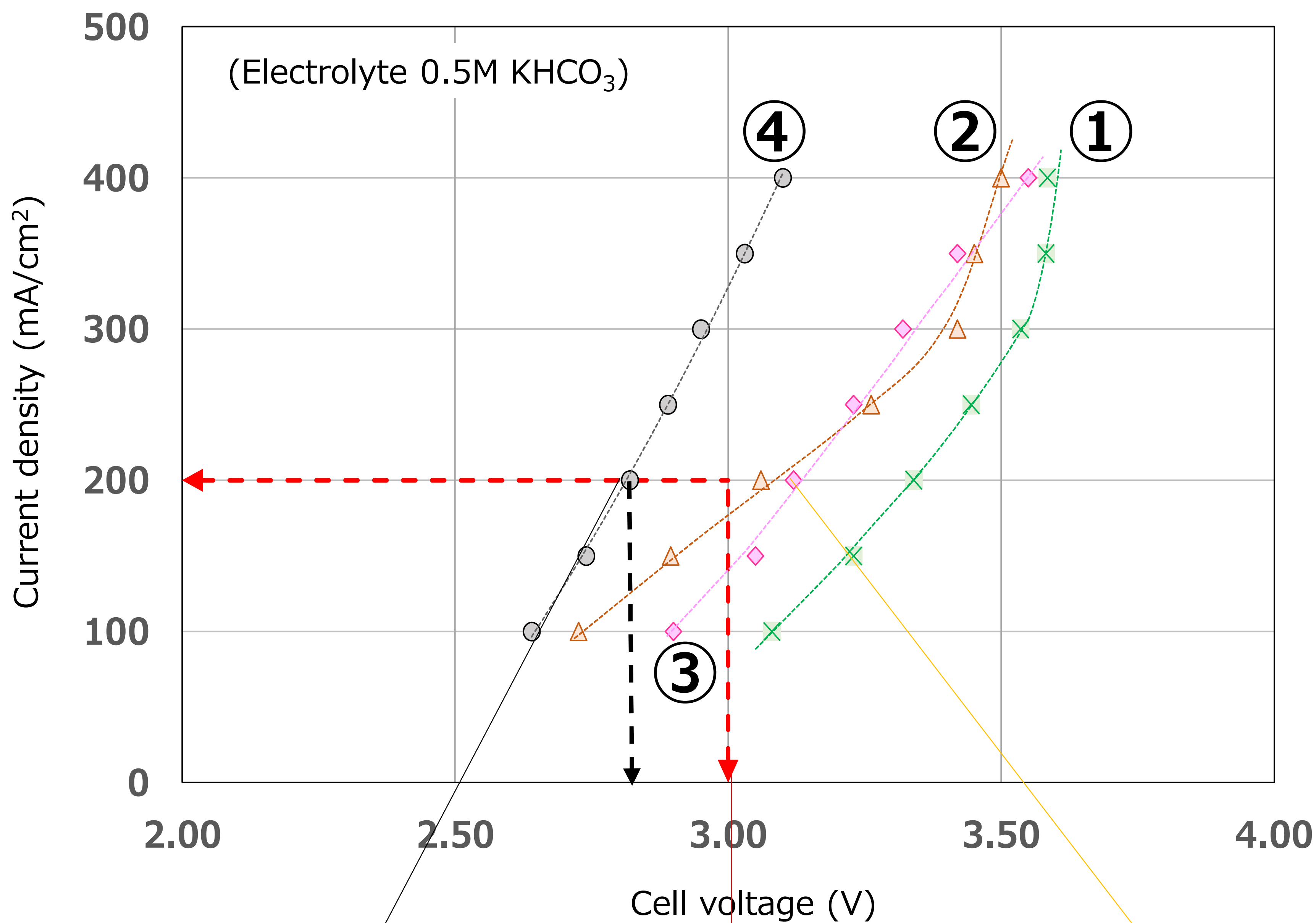
Electrolytic Cell: 2.5 cm Square MEA

Evaluation results of the first prototype of the catalyst addition electrode

【Future】
Aiming to implement roll-to-roll coating prototypes

CO_2 Electrolytic Reduction: Anode Electrode Development

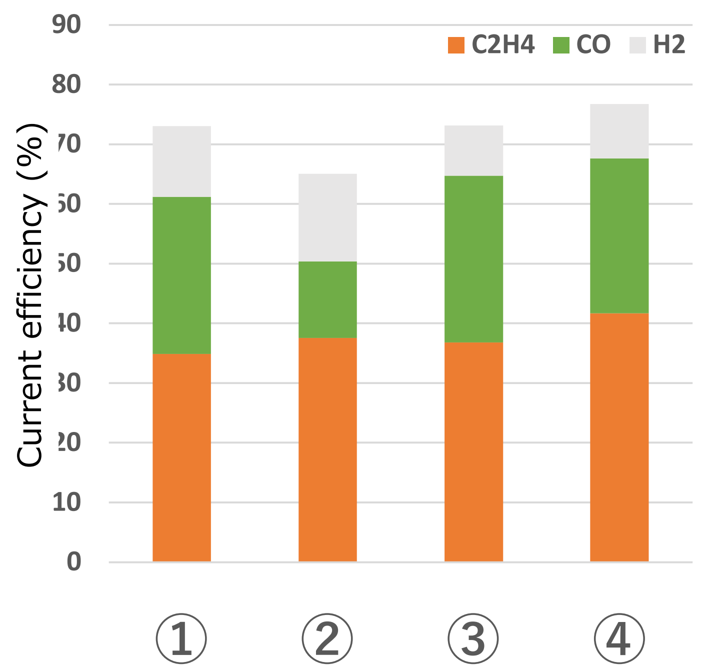
□Cell voltage of 2.82V @ 200mA/cm² was confirmed by optimizing the anode electrode structures



④Cell voltage: **2.82 V** @200 mA/cm²

Target : 3.0V @200mA/cm²

②Cell voltage 3.06 V @200 mA/cm²



(Ref.) Cathode product @ 200 mA/cm²

	structure
①	Commercial
②	Catalyst α
③	Catalyst β
④	Catalyst γ

CO_2 Electrolytic reduction : Reactor Performance Improved

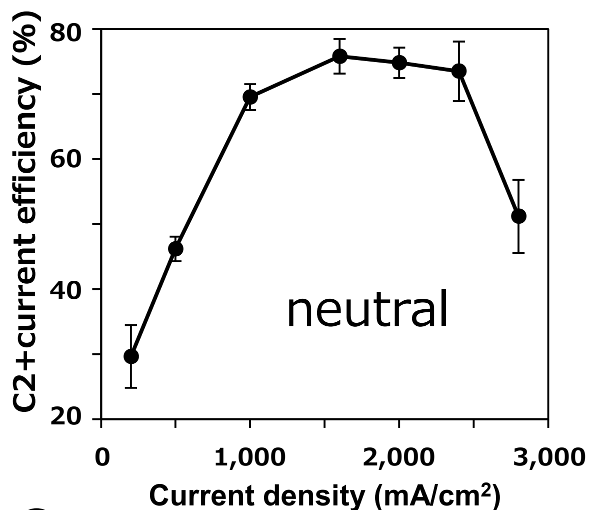
- **World's highest level of high current density**
  - C2+ FE 80% @ 2,000 mA/cm²
- **Higher current efficiency / lower operating voltage**
  - C_2H_4 FE 60% @ cell voltage of 2.8 V

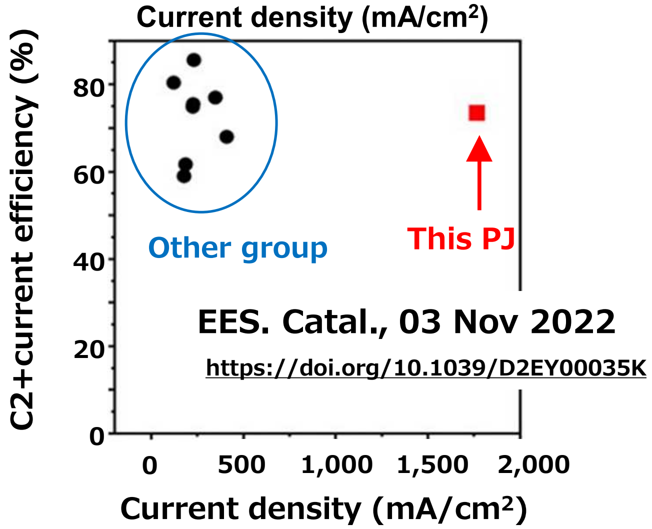
World's top

FY2022 Target : 100 mA/cm²

FY2024 KPI
CO_2 emissions (t-CO_2/t-C_2H_4)
+0.5～+1.0

- Current density: 2,000 mA/cm²
- C2+ Current efficiency 80%

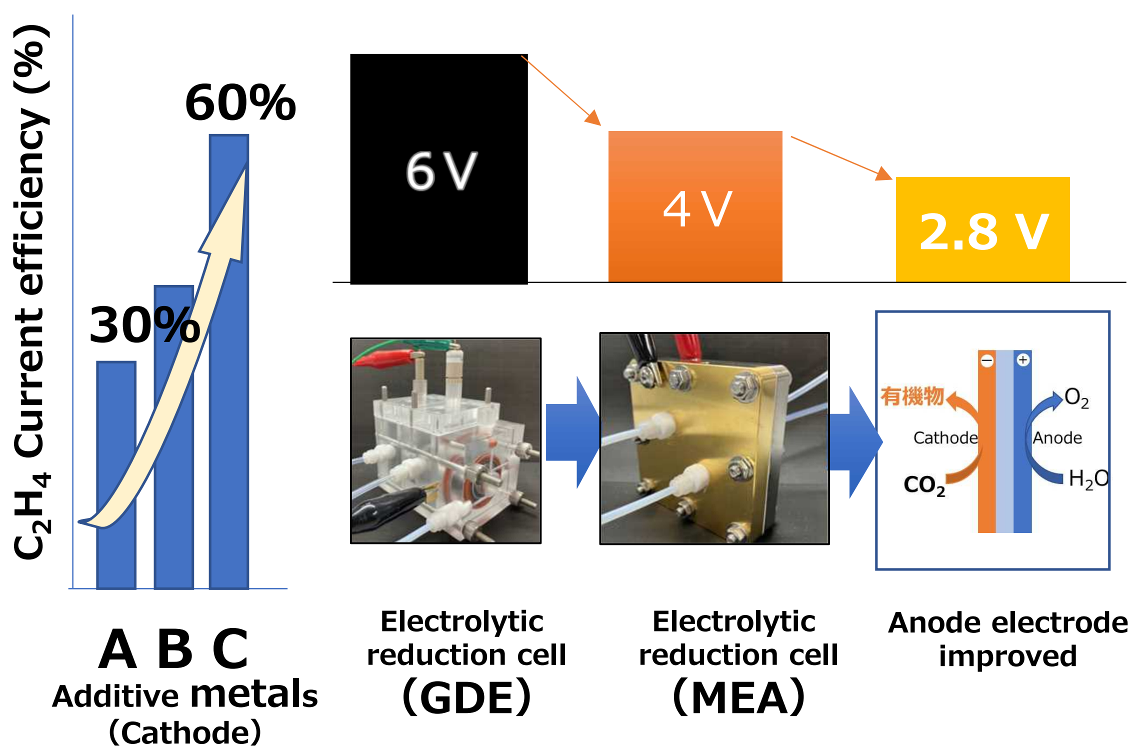




EES. Catal., 03 Nov 2022
https://doi.org/10.1039/D2EY00035K

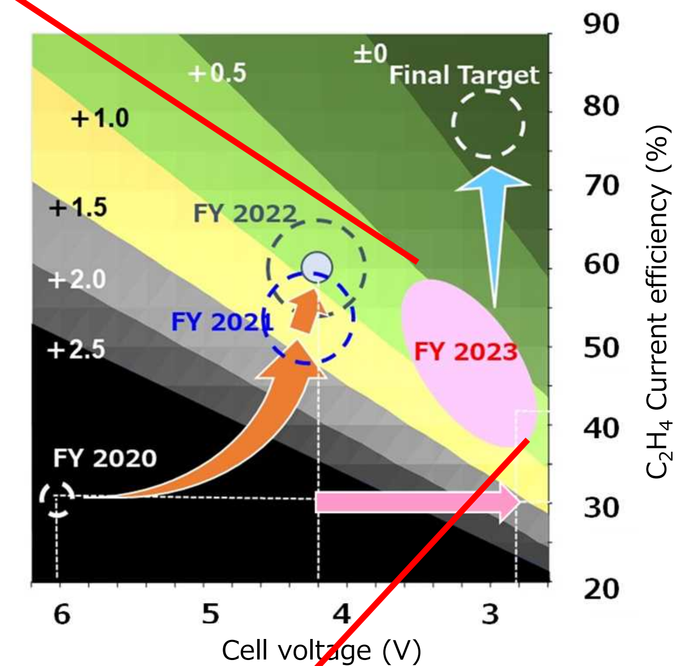
High current efficiency at high current density

- Current efficiency 60%
- Cell voltage of 2.8 V



Selectivity improved

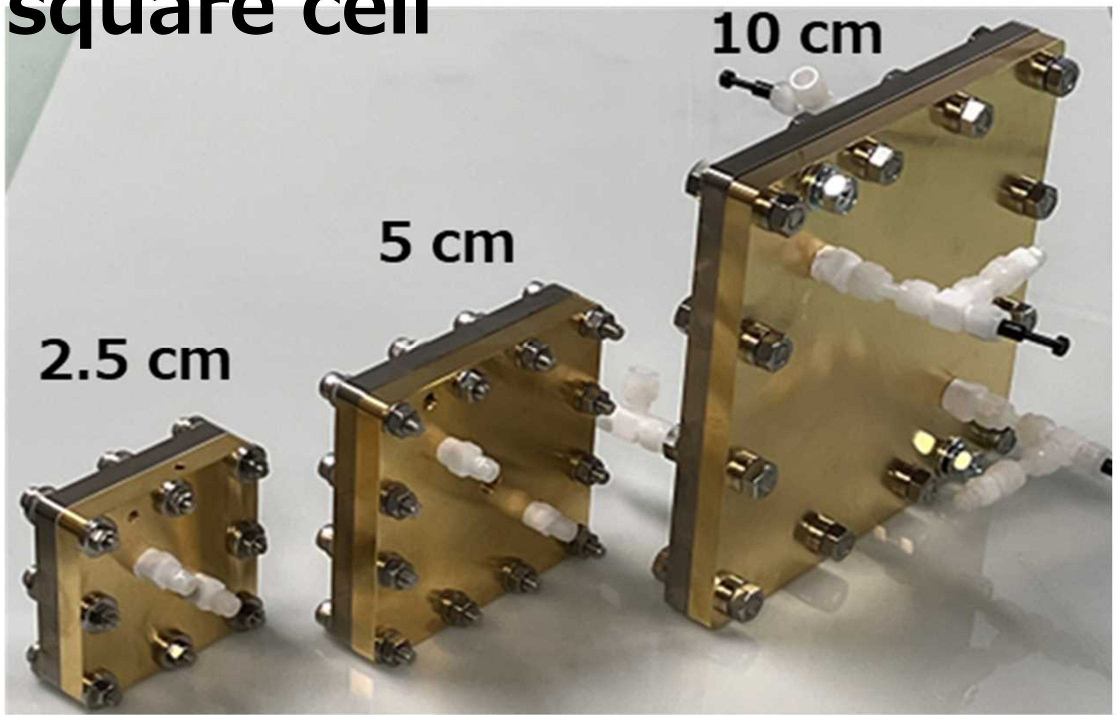
Cell voltages reduced

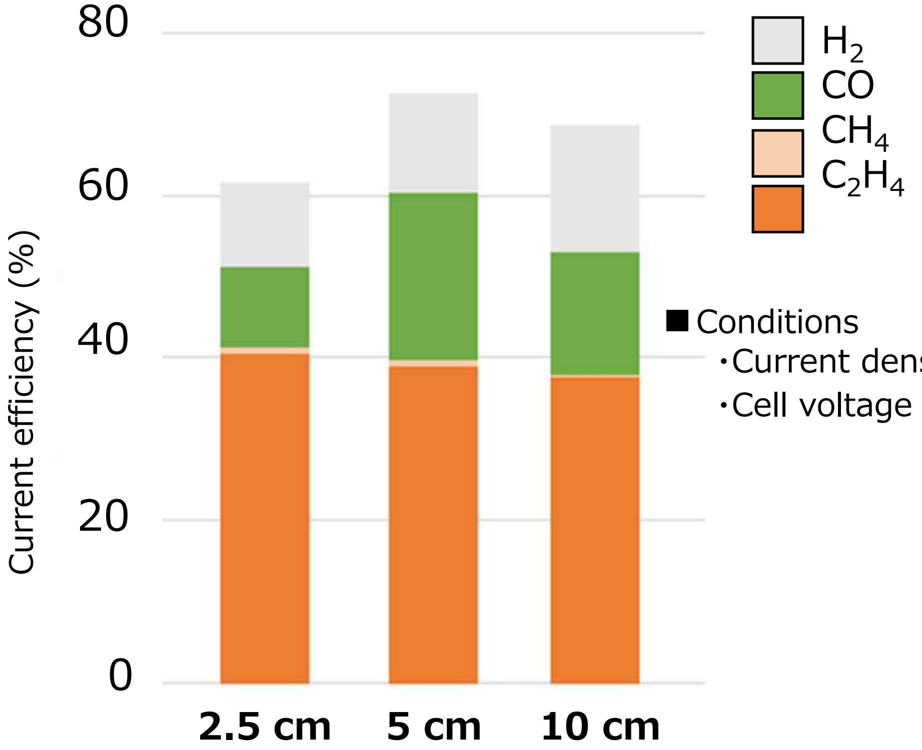


Overall system CO_2 emissions (t-CO_2/t-C_2H_4)

CO_2 Electrolytic Reduction: Larger Area and Stacked Reactors

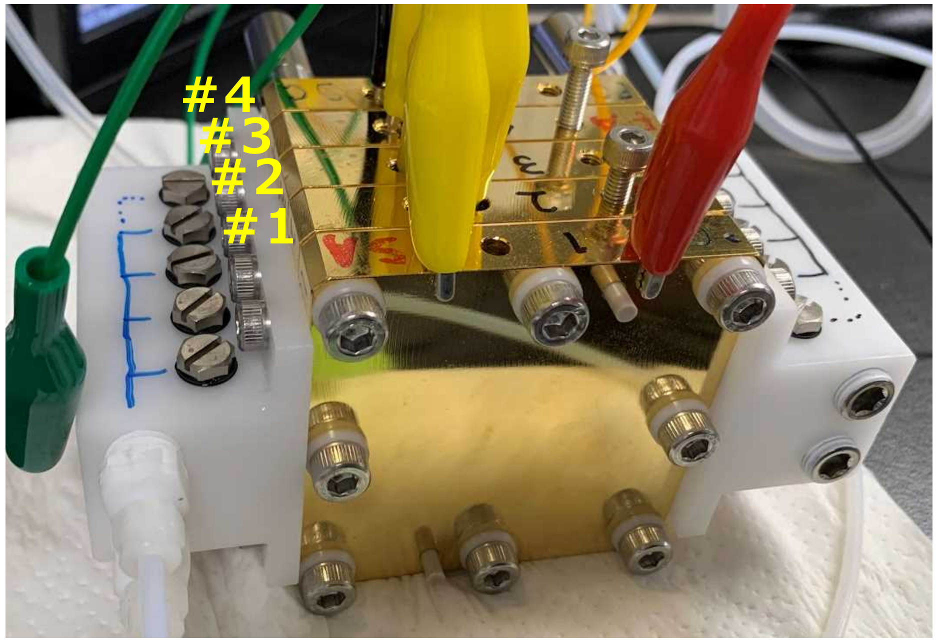
□10 cm square cell achieves performance equivalent to 2.5 cm square cell

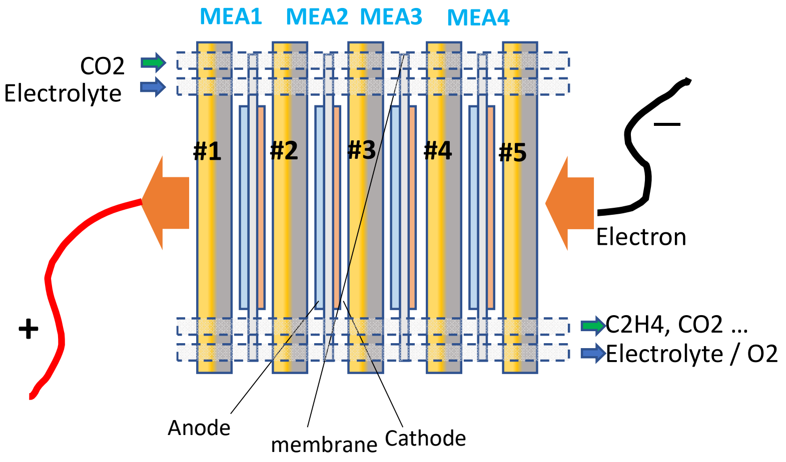


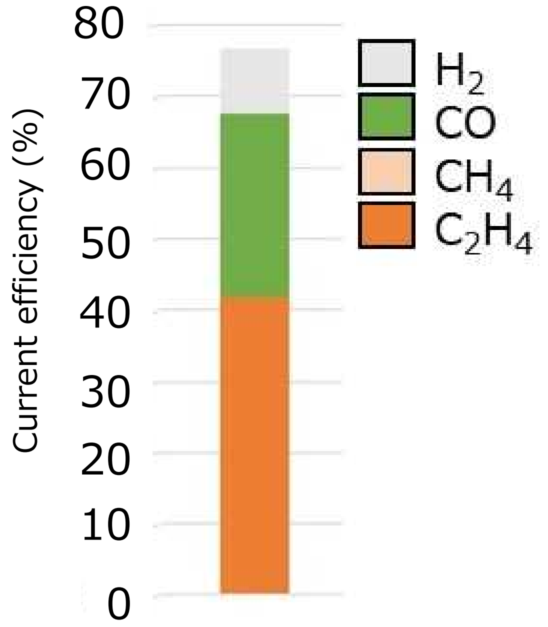


■Conditions
・Current densities : 200 mA/cm²
・Cell voltage : 3.3 ～ 3.8 V

□Ethylene formation was confirmed in a 2.5 cm square x 4 stack







CO_2 Electrolytic Reduction: Simulation Development

◻ Development of a simulation model was initiated

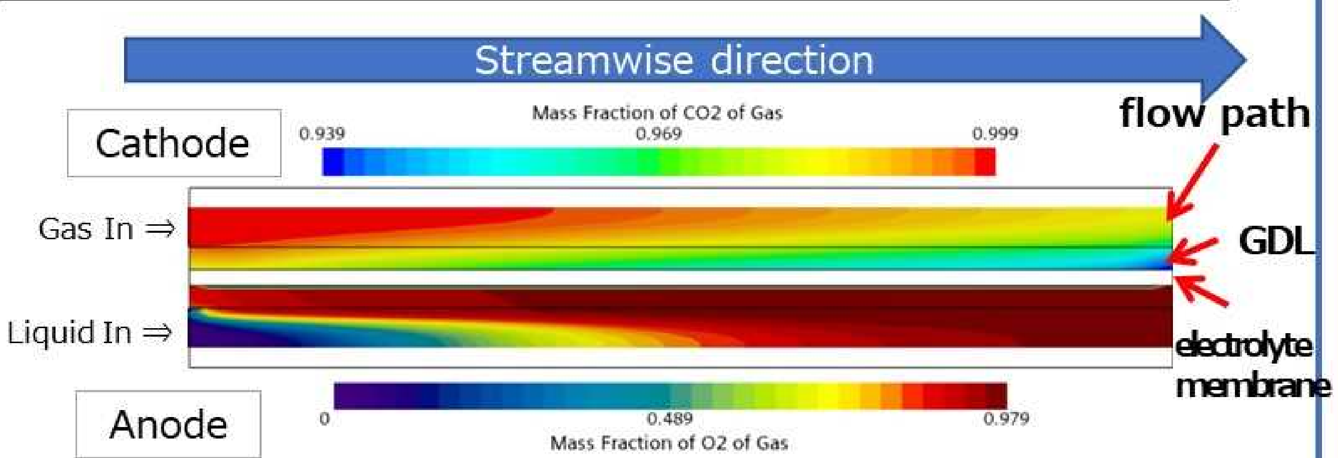
Electrolytic reaction model

[Review]

- ◻ Development of reaction process model between cathode and anode
- ◻ Consideration and reflection of CO_2 crossover

○Example of response analysis in the basic study model

Distribution of CO_2 and O_2 concentration between Anode and Cathode

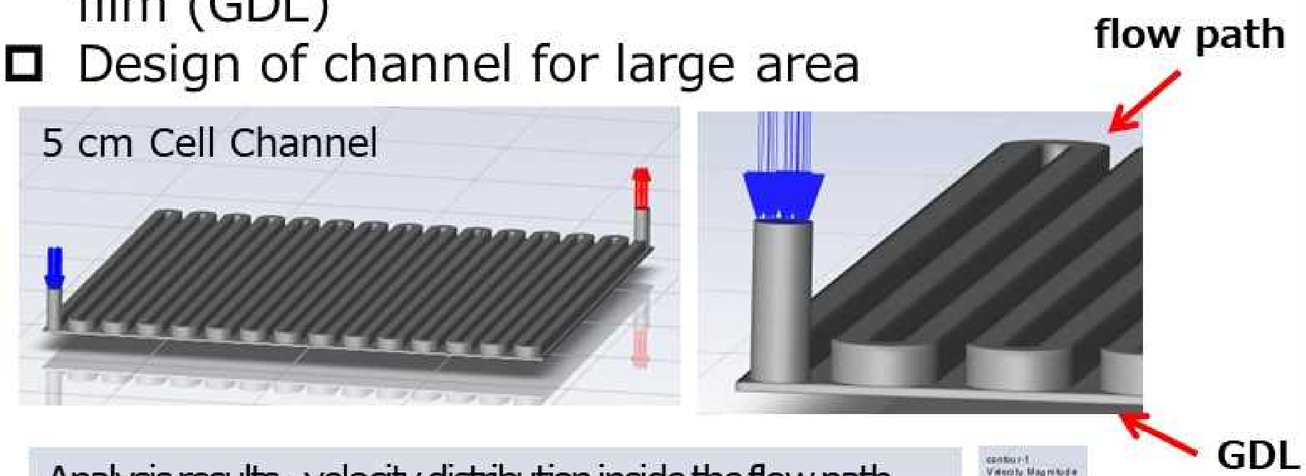


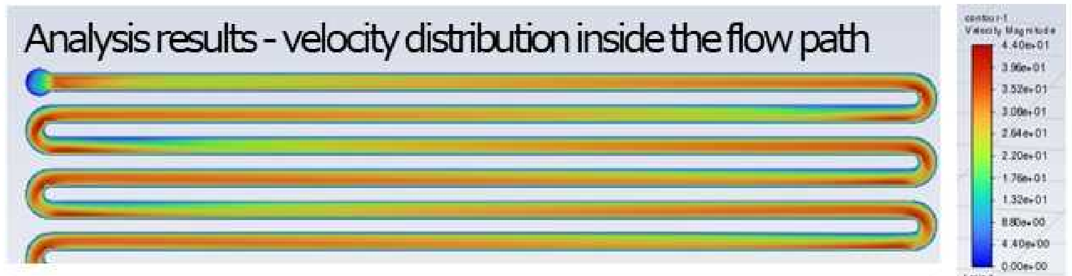
Reproduce the reduction of CO_2 concentration (reduction reaction) as you go downstream in Cathode.
→Analysis of the effect of flow on reaction efficiency.

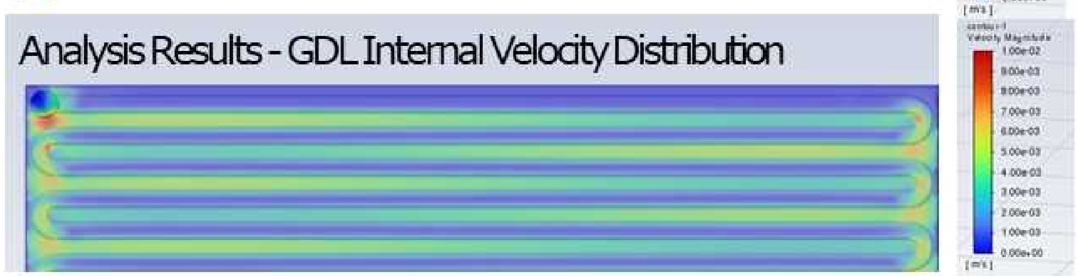
Fluid model

[Review]

- ◻ Flow analysis in cell channel and diffusion layer film (GDL)
- ◻ Design of channel for large area



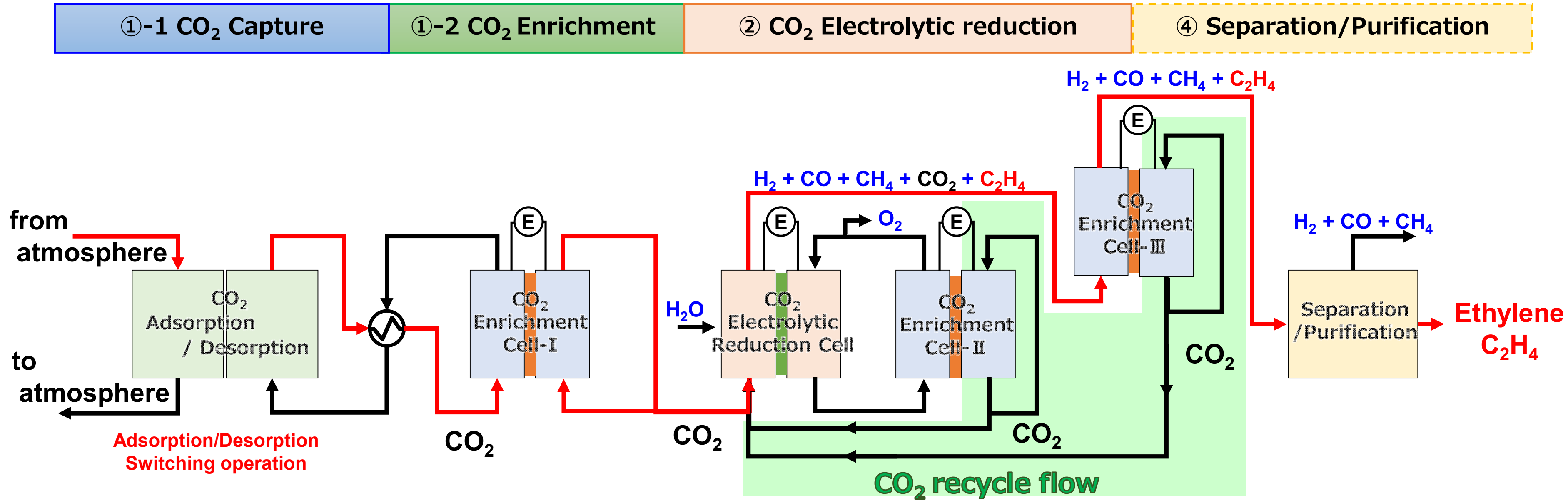




Optimal flow path design for large-area cells based on flow paths and flow conditions inside the GDL.

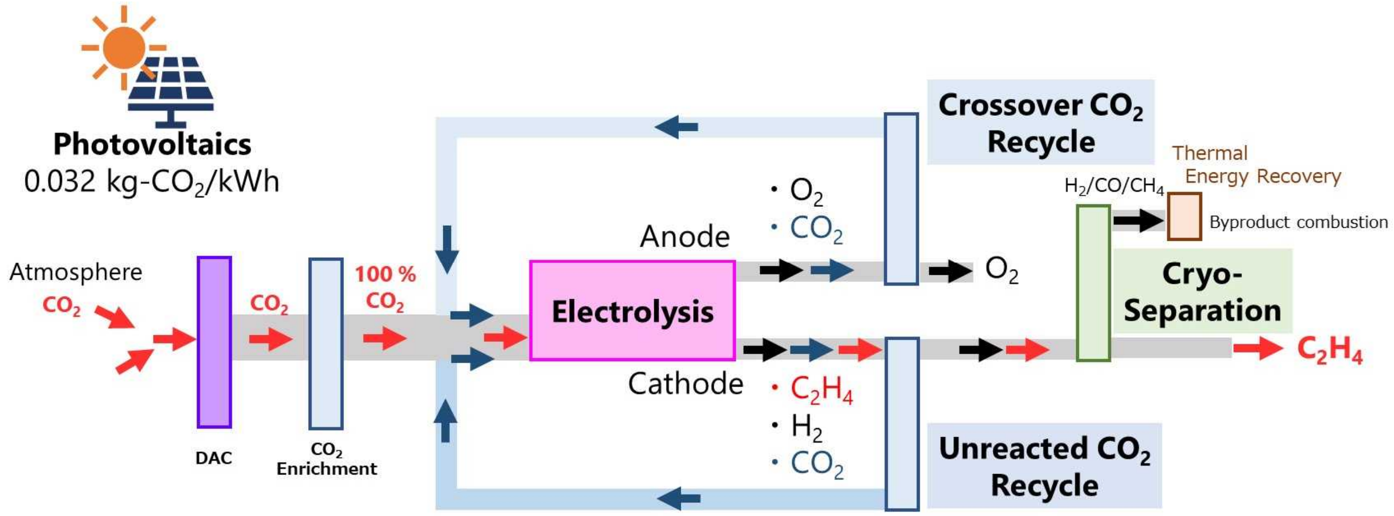
Integrated Systems: Conceptual Design and LCA

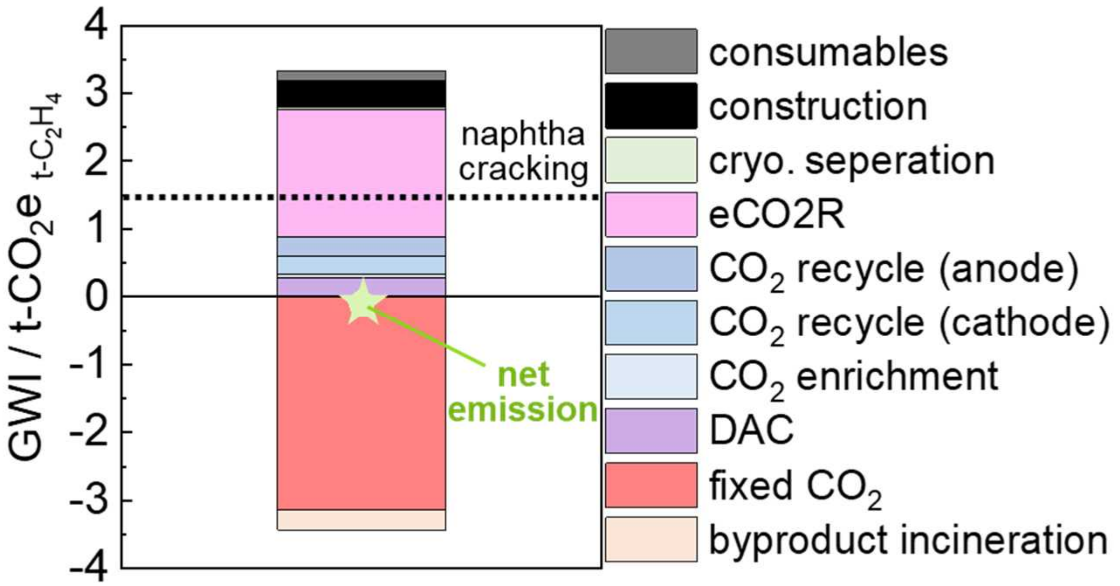
◻ Integrated system design: introduction of CO_2 recycling flow using enrichment cells



◻ LCA evaluation of CO_2 recycling

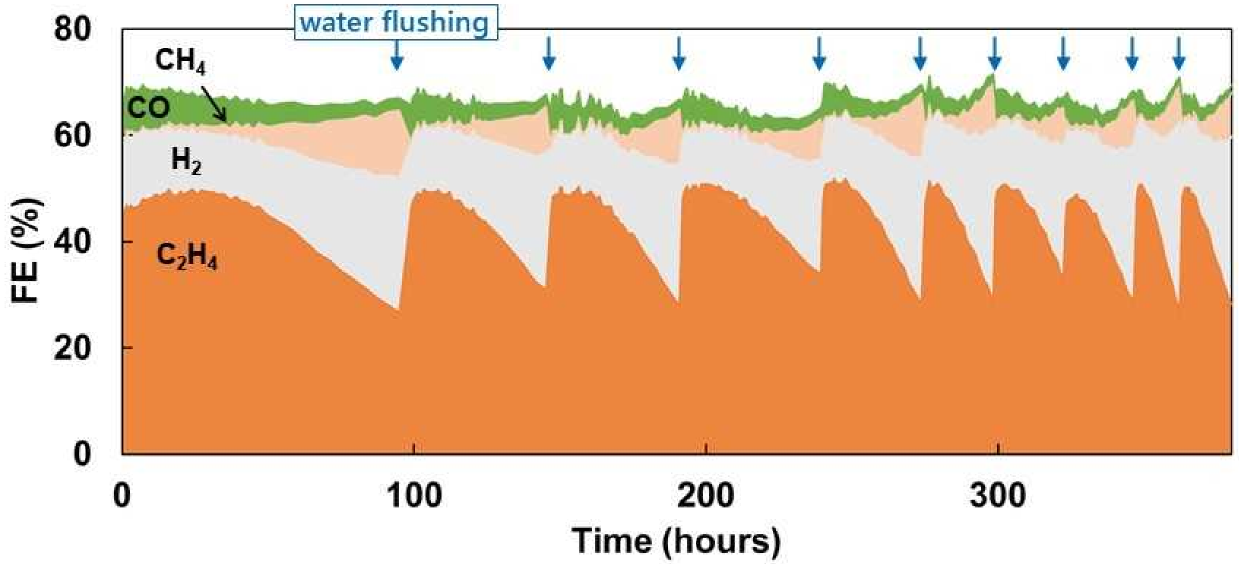
- ◻ Study LCA for a system that reuses heat from combustion of by-products as heat for CO_2 desorption in DAC



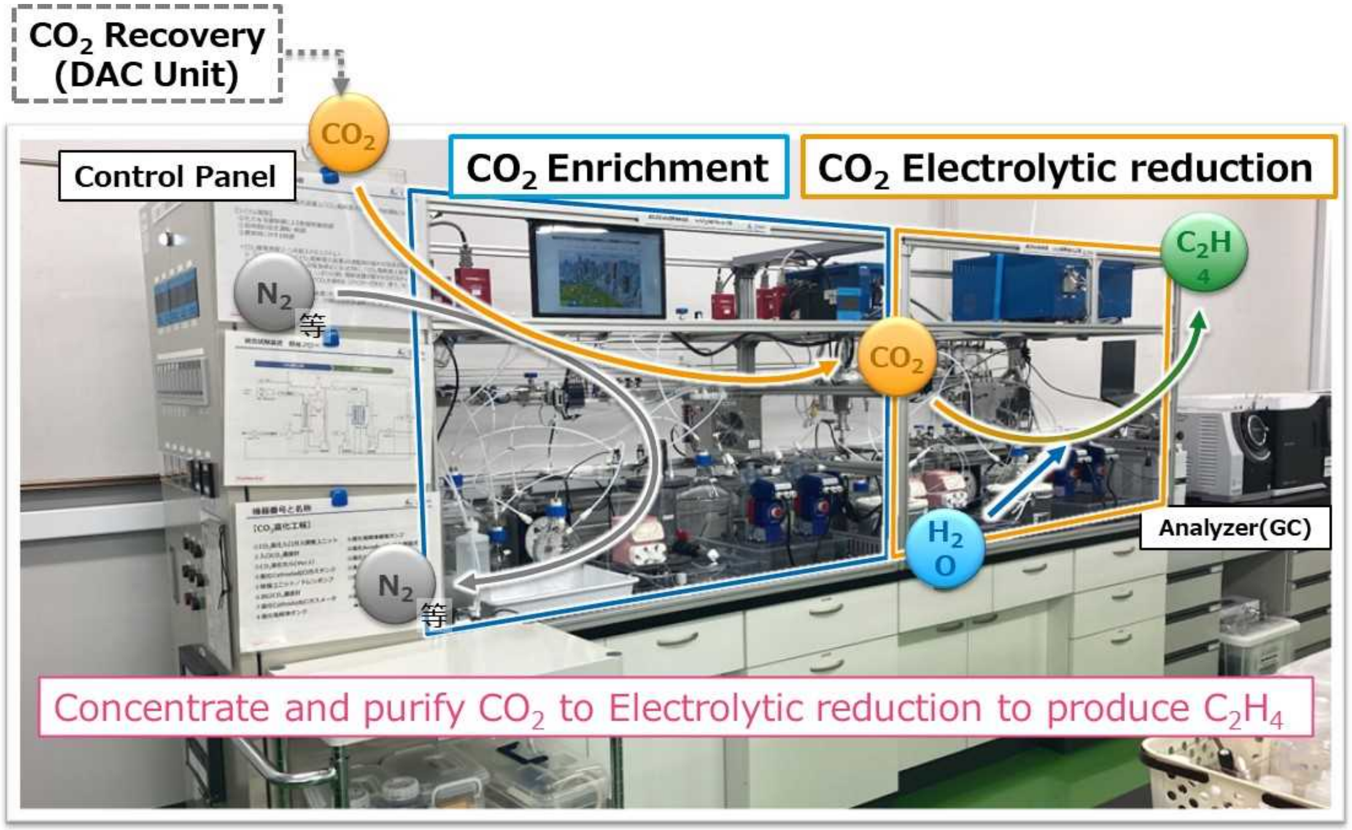


Integrated Systems: Control and Evaluation

□Study on system control for continuous operation
➡Confirmed the impact of operation control



□ Started evaluation of "CO_2 enrichment + CO_2 electrolysis" coupled operation at lab. scale



International Collaborations

MOONSHOT RESEARCH & DEVELOPMENT PROGRAM / NEDO

Exchanges with Embassies

MOONSHOT / NEDO

東大先端研
Research Center for Advanced Science and Technology The University of Tokyo

The Director and Prof. Sugiyama

Information Exchange Meetings with European Embassies and Others
/Embassy of Norway
/Trade and Investment Promotion Agency of the German State of NRW, etc.
/Consulate of Switzerland in Osaka

BERKELEY LAB

Prof. Joel.Ager

大阪大学

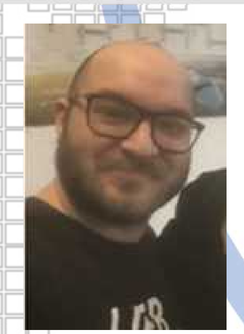
Prof. Nakanishi

Study Abroad

Study Abroad

collaborative research

DLR Institute of Engineering Thermodynamics



Dr. Seyed Schwan Hosseiny

理化学研究所 RIKEN

Dr. Fujii

DLR Institute of Engineering Thermodynamics: Dr. Seyed Schwan Hosseiny
Study abroad【Osaka Univ. : Prof. Nakanishi】

Lawrence Berkeley National Laboratory, Materials Science & Engineering : Prof. Joel Ager
Collaborative research【RIKEN : Dr. Fujii】
Study abroad【Osaka Univ. : Prof. Nakanishi】

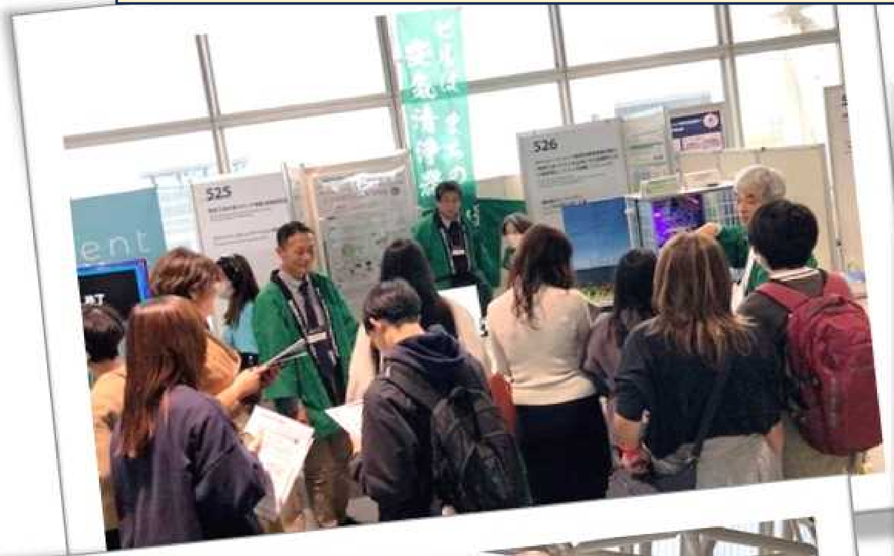
Outreach Activities

Exhibited at SCIENCE AGORA 2023 organized by JST

Nov. 18 - 19, 2023, at Telecom Center

Number of visitors to the project booth: over 400

Exchange of business cards: about 15 companies



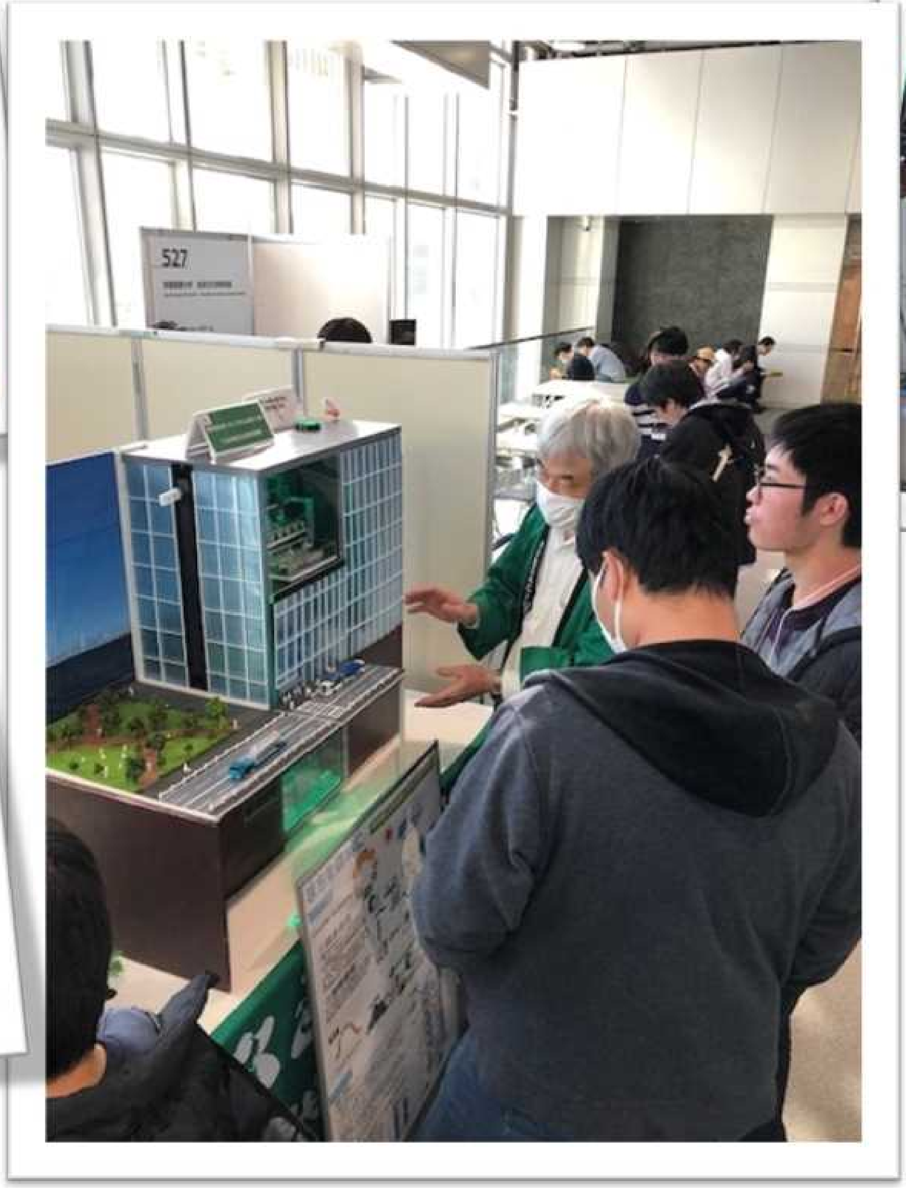


Table of Contents

Summary and Future Challenges

☐ Summary

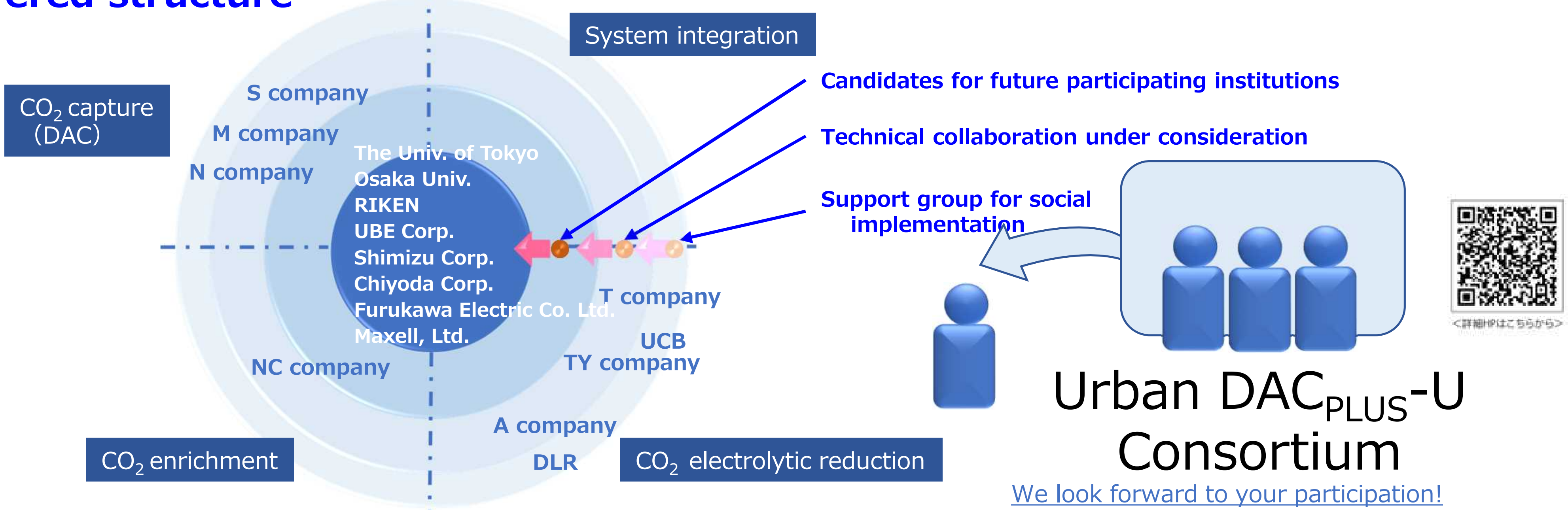
Theme	Major Results	Future Works
CO_2 Capture and Enrichment	・Clarified the concept (requirements) of the implementation model for buildings ・Successful enrichment of atmospheric CO_2 from 400 ppm to 100% (pure CO_2)	・Design and manufacturing of prototypes ・Low drive voltage and long-term stable operation
CO_2 Electrolysis	・FE to ethylene 60%, 2.8 V operating potential between 2 poles achieved ・Efforts to achieve large area / 10cm square cell evaluation and institutional collaboration	・Development of electrodes that simultaneously satisfy current efficiency, current density, and 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

☐ Targets

Fiscal Year	Scale	CO_2 throughput (kg/y)	CO_2 emission reduction target (per ton of ethylene produced)
2024	Laboratory	25	+0.5 ～+1.0 ton
2027	Bench	250	±0.0～+0.5 ton
2029	Pilot	3,300	< -0.5 ton (Carbon negative and 5,000 hours of continuous operation achieved)

☐ Efforts toward social implementation

Establish a four-layered structure



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