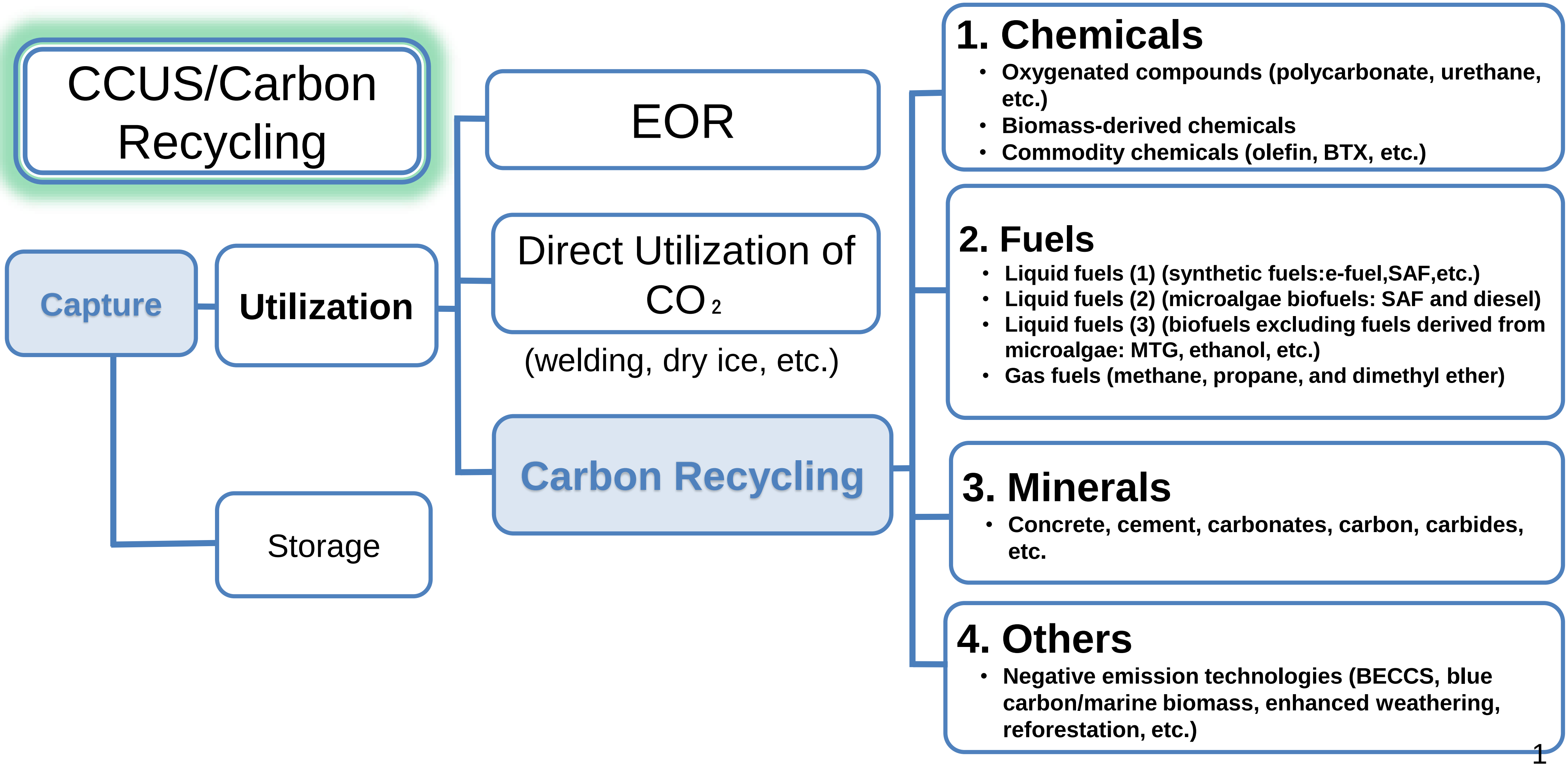
Roadmap for
Carbon Recycling Technologies

June 2019 (July 2021 Revision)

Ministry of Economy, Trade and Industry
In cooperation with the of Cabinet Office,
Ministry of Education, Culture, Sports, Science and Technology,
& Ministry of the Environment

CCUS/Carbon Recycling

- With the concept of Carbon Recycling technology, we consider carbon dioxide as a source of carbon, and promote capturing and recycling this material. Carbon dioxide (CO_2) will be recycled into concrete through mineralization, into chemicals through artificial photosynthesis, and into fuels through methanation to reduce CO_2 emissions into the atmosphere.
- Carbon Recycling technology advances research and development of CO_2 utilization promoting collaborations among industries, academia, and governments around the world while also stimulates disruptive innovation.
- Carbon Recycling is one of the key technologies for society, together with energy saving, renewable energy, and CCS.



CCUS/Carbon Recycling

Capture

Utilization

Storage

EOR

Direct Utilization of CO_2

(welding, dry ice, etc.)

Carbon Recycling

1. Chemicals

- **Oxygenated compounds (polycarbonate, urethane, etc.)**
- **Biomass-derived chemicals**
- **Commodity chemicals (olefin, BTX, etc.)**

2. Fuels

- **Liquid fuels (1) (synthetic fuels:e-fuel,SAF,etc.)**
- **Liquid fuels (2) (microalgae biofuels: SAF and diesel)**
- **Liquid fuels (3) (biofuels excluding fuels derived from microalgae: MTG, ethanol, etc.)**
- **Gas fuels (methane, propane, and dimethyl ether)**

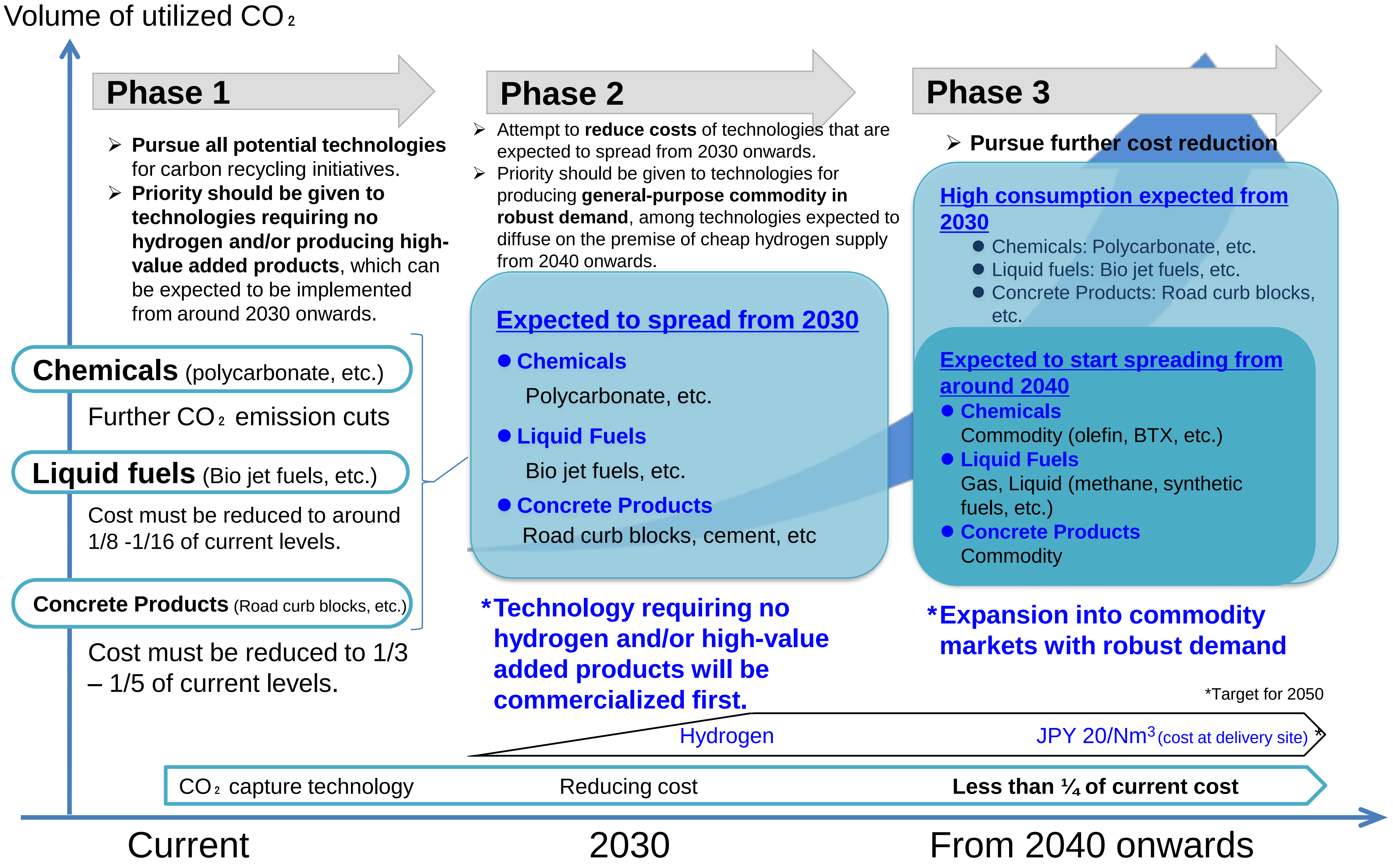
3. Minerals

- **Concrete, cement, carbonates, carbon, carbides, etc.**

4. Others

- **Negative emission technologies (BECCS, blue carbon/marine biomass, enhanced weathering, reforestation, etc.)**

Roadmap for Carbon Recycling Technologies



Volume of utilized CO_2

Phase 1

- **Pursue all potential technologies** for carbon recycling initiatives.
- **Priority should be given to technologies requiring no hydrogen and/or producing high-value added products**, which can be expected to be implemented from around 2030 onwards.

Chemicals (polycarbonate, etc.)

Further CO_2 emission cuts

Liquid fuels (Bio jet fuels, etc.)

Cost must be reduced to around 1/8 -1/16 of current levels.

Concrete Products (Road curb blocks, etc.)

Cost must be reduced to 1/3 – 1/5 of current levels.

Phase 2

- Attempt to **reduce costs** of technologies that are expected to spread from 2030 onwards.
- Priority should be given to technologies for producing **general-purpose commodity in robust demand**, among technologies expected to diffuse on the premise of cheap hydrogen supply from 2040 onwards.

Expected to spread from 2030

- **Chemicals**
  Polycarbonate, etc.
- **Liquid Fuels**
  Bio jet fuels, etc.
- **Concrete Products**
  Road curb blocks, cement, etc

***Technology requiring no hydrogen and/or high-value added products will be commercialized first.**

Phase 3

- **Pursue further cost reduction**

High consumption expected from 2030

- Chemicals: Polycarbonate, etc.
- Liquid fuels: Bio jet fuels, etc.
- Concrete Products: Road curb blocks, etc.

Expected to start spreading from around 2040

- **Chemicals**
  Commodity (olefin, BTX, etc.)
- **Liquid Fuels**
  Gas, Liquid (methane, synthetic fuels, etc.)
- **Concrete Products**
  Commodity

***Expansion into commodity markets with robust demand**

Hydrogen — JPY 20/Nm³ (cost at delivery site)*

*Target for 2050

CO_2 capture technology — Reducing cost — **Less than ¼ of current cost**

Current — 2030 — From 2040 onwards

Summary of Carbon Recycling Technologies and Products

*1 Price researched by secretariat
*2 Basic substances, chemicals (excluding some oxygenated compounds), and many technologies for fuels require large amounts of inexpensive CO_2-free hydrogen. Biomass-derived fuels may require hydrogen for hydrogenation treatment, etc.

	Substance After CO_2 Conversion	Current Status*1	Challenges	Price of the Existing Equivalent Product*1	In 2030	From 2040 Onwards
Basic Substance	**Syngas/ Methanol, etc.**	Partially commercialized. Innovative process (light, electricity utilization) is at R&D stage	Improvement of conversion efficiency and reaction rate, improvement in durability of catalyst, etc.	–	Reduction in process costs	Further reduction in process costs
Chemicals	**Oxygenated Compounds**	Partially commercialized (e.g., polycarbonates). Others are at R&D stage. [Price example] Price of the existing equivalent product (Polycarbonate)	Reduce the amount of CO_2 emission for polycarbonate. Other than polycarbonate, etc. commercialized (Improvement in conversion rate/selectivity, etc.)	Approx. JPY 300-500/kg (polycarbonate (domestic sale price))	Costs: similar to those of existing energy/products	Further reduction in costs
	Biomass-derived Chemicals	Technical development stage (non-edible biomass)	Cost reduction/effective pretreatment technique, conversion technologies, etc.	–	Costs: similar to those of existing energy/products	Further reduction in costs
	Commodity Chemicals (olefin, BTX, etc.)	Partially commercialized (e.g., Syngas, etc. produced from coal)	Improvement in conversion rate/selectivity, etc.	JPY 100/kg (ethylene (domestic sale price))	–	Costs: similar to those of existing energy/products
Fuels	**Liquid Fuel** (microalgae biofuel)	Demonstration Stage [Price example] Bio jet Fuels: JPY 1600/L	Improvement productivity, cost reduction, effective pretreatment technique, etc.	Approx. JPY 100/L level (bio jet fuels (domestic sale price))	Costs: similar to those of existing energy/products (JPY 100-200/L)	Further reduction in costs
	Liquid Fuel (CO_2-derived fuels or biofuels; excluding microalgae-derived ones)	Technical Development stage (e-fuel, SAF). Partially commercialized for edible biomass-derived bioethanol. [Price example] Synthetic fuels: about JPY300-700/L	Improvement in current processes, system optimization, etc.	JPY 50-80/L (alcohol as raw material (imported price) Approx. JPY 130/L Industrial alcohol (domestic sale price)	–	Synthetic fuels: Less than gasoline price costs: similar to those of existing energy/products
	Gas Fuels (methane, propane, dimethyl ether)	Technical Development/Demonstration Stage	System optimization, scale-up, efficiency improvement, etc.	JPY 40-50/Nm^3 (Natural gas (imported price))	Reduction in costs for CO_2–derived CH_4	Costs: similar to those of existing energy/products
Minerals	**Concrete, cement, carbonates, carbon, carbides**	Partially commercialized. R&D for various technologies and techniques for cost reduction are underway. [Price example] order of JPY 100/t (Road curb block)	Separation of CO_2-reactive and CO_2-unreactive compounds, comminution, etc.	JPY 30/kg (Road curb block (domestic sale price))	Road curb block costs: similar to those of existing energy/products	Other products, except road curb block costs: similar to those of existing energy/products
Common Technology	**CO_2 capture (including DAC)**	Partially commercialized (chemical absorption). Other techniques are at research/ demonstration stage [Price example] Approx. JPY 4000/t-CO_2 (Chemical absorption)	Reduction in the required energy, etc.	–	Approx. JPY 1000-2000 /t-CO_2 (chemical absorption, solid absorption, physical absorption, membrane separation)	≤JPY 1000/t-CO_2 ≤JPY 2000/t-CO_2 (DAC)
Basic Substance	**Hydrogen**	Technologies have been roughly established (e.g., water electrolysis). R&D for other techniques and cost reduction are also underway.	Cost reduction, etc.		JPY 30/Nm^3	JPY 20/Nm^3 (cost at delivery site)

Scope : Roadmap for Carbon Recycling Technologies

We expect carbon recycling technology, where we consider CO_2 as a resource, will begin as relatively small volume activities. We expect this initiative will continue to expand into different application areas as cost effectiveness improves. We set relatively short-term targets for 2030 and mid- to long-term targets for 2040 onwards.

2030: Technologies aiming at achieving commercialization as soon as possible.

(1) Establish an environment that fosters easy utilization of CO_2 (reducing costs for capture and recycle of CO_2)

(2) Processes whose basic technology is established can replace existing products by reducing costs (products that do not require inexpensive hydrogen supply, as well as high-value added)

2040 onwards: Technologies aiming at achieving commercialization in the mid- to long-term.

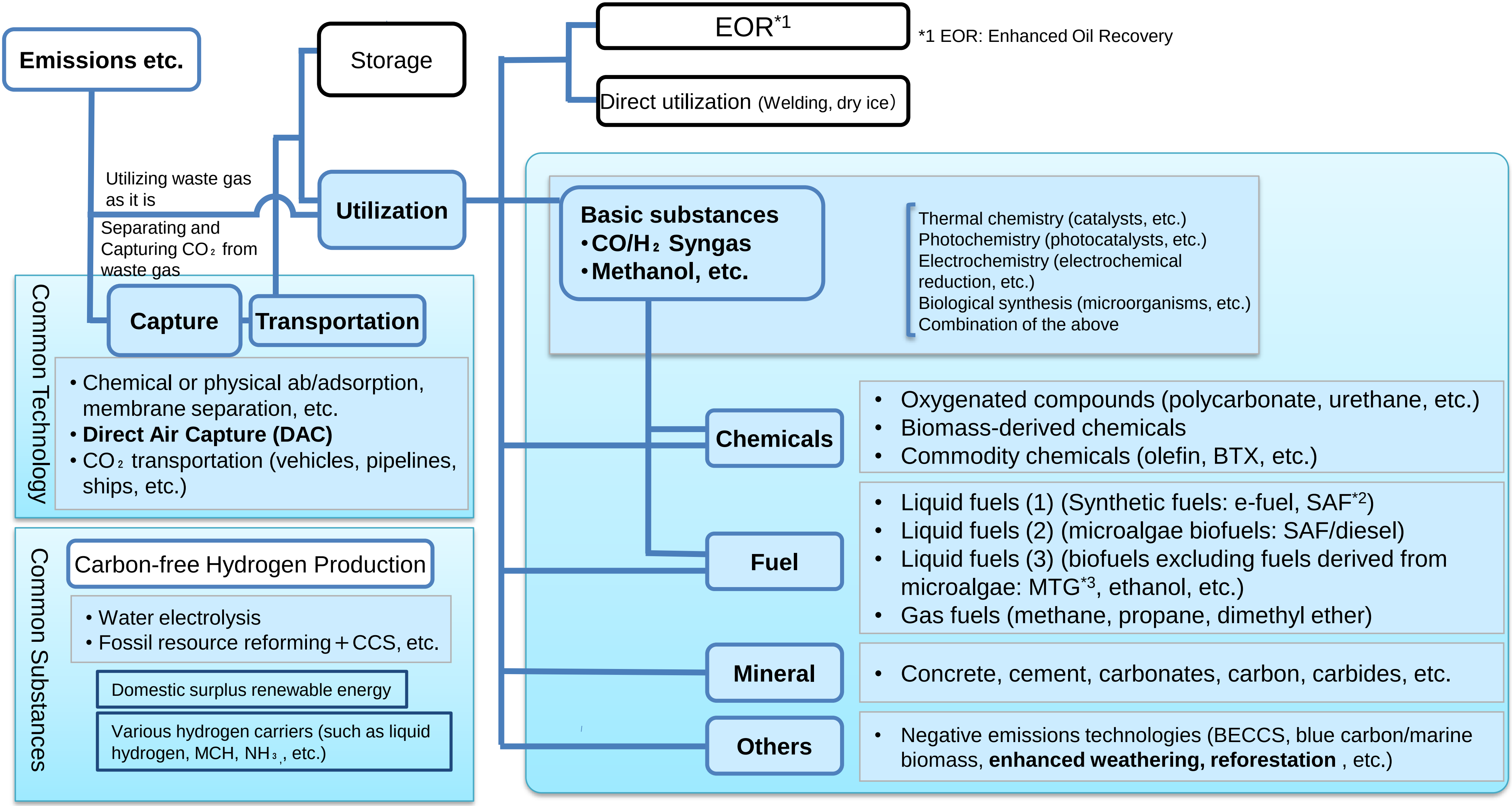
○ Early-stage technologies that have greater impacts by using a large amount of CO_2 (possibly enabled by inexpensive hydrogen)

	2030 (short-term)	2040 onwards (mid-to long-term)
Field	**Technologies producing high-value added products and/or requiring no hydrogen will be commercialized first:** • Chemicals (polycarbonate, etc.) • Liquid fuels (bio jet fuels, etc.) • Concrete products (Road curb blocks, etc.)	**Expanded to products that have large demand:** • Chemicals (commodity: olefin, BTX, etc.) • Fuels (gas, liquid: methane, synthetic fuels, etc.) • Concrete products (commodity)

Individual technologies

CCUS/Carbon Recycling

- **Carbon Recycling**: With the concept of Carbon Recycling technology, we consider carbon dioxide as a source of carbon, and promote separating, capturing, and recycling of this material. Carbon dioxide (CO_2) will be recycled into concrete through mineralization, into chemicals through artificial photosynthesis, and into fuels through methanation to reduce CO_2 emissions into the atmosphere.



Emissions etc.

Storage

EOR[*1]

*1 EOR: Enhanced Oil Recovery

Direct utilization (Welding, dry ice)

Utilizing waste gas as it is

Separating and Capturing CO_2 from waste gas

Utilization

Common Technology

Capture

Transportation

- Chemical or physical ab/adsorption, membrane separation, etc.
- **Direct Air Capture (DAC)**
- CO_2 transportation (vehicles, pipelines, ships, etc.)

Common Substances

Carbon-free Hydrogen Production

- Water electrolysis
- Fossil resource reforming＋CCS, etc.

Domestic surplus renewable energy

Various hydrogen carriers (such as liquid hydrogen, MCH, NH_3, etc.)

Basic substances
•CO/H_2 Syngas
•Methanol, etc.

Thermal chemistry (catalysts, etc.)
Photochemistry (photocatalysts, etc.)
Electrochemistry (electrochemical reduction, etc.)
Biological synthesis (microorganisms, etc.)
Combination of the above

Chemicals

- Oxygenated compounds (polycarbonate, urethane, etc.)
- Biomass-derived chemicals
- Commodity chemicals (olefin, BTX, etc.)

Fuel

- Liquid fuels (1) (Synthetic fuels: e-fuel, SAF[*2])
- Liquid fuels (2) (microalgae biofuels: SAF/diesel)
- Liquid fuels (3) (biofuels excluding fuels derived from microalgae: MTG[*3], ethanol, etc.)
- Gas fuels (methane, propane, dimethyl ether)

Mineral

- Concrete, cement, carbonates, carbon, carbides, etc.

Others

- Negative emissions technologies (BECCS, blue carbon/marine biomass, **enhanced weathering, reforestation** , etc.)

*2 SAF: Sustainable aviation fuel
*3 MTG: Methanol to Gasoline

Common technology

● CO_2 Capture Technology

<Technological Challenges>

- Reduction in capital and operational costs and in required energy
  - Development of new materials (absorbers, adsorbents, separation membrane)
  - Reduction in production costs of functional materials
  - Optimization of processes (in terms of heat/substance/power, etc.)
- Selection of the types of CO_2 capture technologies based on the CO_2 emission source/application
- Establishing CO_2 capture and conversion systems by matching CO_2 supply and demand with co-production opportunities
- Establishing assessment baseline for energy consumption and cost
- Transportation and storage
  - Transportation cost reduction (large-scale transportation, liquefaction technology)
  - Control and management of CO_2 supply and demand matching

<Individual Technologies>

- Chemical absorption (temperature swing (current process))
  - Approx. JPY 4,000/t-CO_2
  - Required energy: Approx.2.5GJ/t-CO_2
- Physical absorption (pressure swing (demonstration stage))
- Solid absorption (temperature swing) (R&D stage)
- Physical adsorption (pressure/temperature gaps, advantageous in smaller scales, selectivity/capacity/durability improvements, development of new materials)
- Membrane separation (pressure difference)
- Others: cryogenic separation technique, Direct Air Capture, etc.

<Process Technologies to facilitate CO_2 Capture>

- Oxygen-enriched combustion, closed IGCC
  - Development of low cost oxygen supply technology
- Chemical Looping combustion
  - Development of low-cost and durable oxygen carriers

<Specific initiatives>

- Development of low-cost CO_2 separation and capture technology
- Development of technology for transporting liquefied CO_2 by ships

Target for 2030

- For low-pressure gas (CO_2 separation from flue gas, blast furnace gas, etc. at several percent and under normal pressure)
  - JPY2,000 level/t-CO_2
  - Required energy 1.5 GJ/t-CO_2
  - Chemical absorption, solid absorption, physical absorption, etc.
- For high-pressure gas (CO_2 separation from chemical process/fuel gas, etc. several percent and several MPa)
  - JPY1,000 level/t-CO_2
  - Required energy 0.5GJ/t-CO_2
  - Physical absorption, membrane separation, physical adsorption ,etc.
- Overall review of other processes (power generation and chemical synthesis systems with CO_2 separation and capture)
  - Closed IGCC/Chemical looping, etc.
  - JPY1,000 level/t-CO_2
  - Required energy 0.5GJ/t-CO_2

<Establishing a CO_2 capture systems>

- Realization of an energy-saving, low cost CO_2 capture system that is designed for each CO_2 emission source/usage
- Realization of 10,000 hour continuous operation (to demonstrate the robustness and reliability)

<Establish assessment standards for separation materials>

- Establish assessment protocols to accelerate material development

<Develop CO_2 transportation and storage systems>

- Establish energy-saving, low-cost CO_2 transportation and storage infrastructure matching CO_2 emission sources and usages
  - Liquefaction (cooling, compression), storage (containers, tank), transportation (vehicles, pipelines, ships, etc.)

Target from 2040 onwards

<Commercialization of CO_2 capture technology>

- Achieve JPY 1,000/t-CO_2 or lower
- Improve the durability and reliability of CO_2 separation and capture systems and downsize these systems
- Optimize CO_2 capture systems according to the emission source and application
- Full-fledged spread of CO_2 separation, capture, and transportation systems
- Develop CO_2 networks (covering capture/transportation /utilization infrastructure, hubs & clusters, etc.)

Common technology

● DAC (Direct Air Capture)

<Technological challenge: DAC>

- Development of air contactor technology for contact between absorbers/adsorbents/membranes and air
- Development of distributed (small-scale) systems
  Development of large-scale (highly efficient) systems

<Technological challenges: common with other CO_2 separation and capture technology>

- Reduction of equipment/operation costs and energy consumption
  Development of new materials (absorbers, adsorbents and separation membranes) (improve selectivity, capacity and durability)
  Reduction of material production costs
  Optimization of processes (e.g., heat, mass, power, etc.), etc.

<Other challenges>

- Development of technologies to raise capture efficiency and cut energy consumption to improve CO_2 separation and capture
- JPY 30,000-60,000/t-CO_2

* In the absence of large-scale demonstration tests, costs vary significantly depending on the system and technologies as well as on scales

- DAC technology should be to utilization renewable energy and other non-fossil power sources, considering storage and utilization of captured CO_2.
- Selection of DAC locations (suitable climate for CO_2 capture, proximity to energy sources and CO_2 utilization demands)
- Establishing assessment baseline for energy consumption and cost

<Specific initiatives>

- Moonshot Research & Development Program
  Chemical absorption, physical absorption, solid absorption, physical adsorption, and membrane separation methods

Target for 2030

<Development of CO_2 separation and capture systems>

- Achieve competitive CO_2 separation and capture costs in the 2030s market
  Example targets
  JPY 10,000/t-CO_2: ICEF (Innovation for Cool Earth Forum) roadmap
  JPY 10,000/t-CO_2: Published as corporate target for 2025 or 2030

- Confirm the effectiveness from the lifecycle assessment (LCA) through pilot projects

Target from 2040 onwards

<DAC system commercialization>

- Achieve capture costs less than JPY 2,000/t-CO_2
- Improve DAC system durability and reliability
- Full-fledged spread of DAC system

Common technology

Explanations of CO_2 separation/capture and DAC technologies

Capture technologies	Principle	Application areas
Chemical absorption	• Chemical reaction between CO_2 and liquid.	thermal power plants, cement manufacture, iron and steel production, petroleum refining, chemical production, and fossil fuel extraction
Physical absorption	• Dissolution of CO_2 into liquid. • Efficiency depends on the solubility of CO_2 in the absorbent.	thermal power plants (high gas pressure), petroleum refining, chemical production and fossil fuel extraction
Solid absorption	• Absorption into solid absorbents. • Absorbents include porous materials impregnated with amines (for low temperature separation) or other solid absorbents for high temperature separation.	thermal power plants, cement manufacture, petroleum refining, and chemical production
Physical adsorption	• Adsorption onto a porous solid such as zeolite and metal-organic complex (e.g., MOFs). • Realized by increase and decrease of pressure (pressure swing) or temperature (temperature swing).	thermal power plants, cement manufacture, iron and steel production, petroleum refining and chemical production
Membrane separation	• Separation of CO_2 by using permeation through zeolite, carbon, organic, or other membranes which have selective permeability for different gas species.	thermal power plants (high gas pressure), petroleum refining, chemical production and fossil fuel extraction
DAC (Direct Air Capture)	• Technology for direct capture of dilute CO_2 from the atmosphere using the abovementioned separation and capture technology. • The DAC technology is an advanced version of the CO_2 separation and capture technology. Further cuts in costs and energy consumption are required for commercialization.	Capture CO_2 at very low concentration (400 ppm) in the atmosphere

Basic substances

- **Methane Chemistry, etc.** (Until inexpensive hydrogen can be supplied, methane (CH_4) or waste plastics will be used instead of CO_2.)

[CH_4→Syngas (1)]

- Established as a commercial process
- Partial oxidation/ATR, dry reforming: There is a room for improvement, such as making the reaction temperature lower, searching suitable catalysts, improving durability, etc.

[CH_4→Others]

- Separation under high temperature conditions (hydrogen and benzene, etc.)
- Direct synthesis of methanol (2) and of ethylene (3) are still at R& D stage.
- Methane thermal cracking where CO_2-free hydrogen can be obtained is still at R&D stage (catalyst development, carbon removal/utilization technology)

[Waste plastic or rubber depolymerization – olefin]

- Develop technologies for waste plastic pretreatment (removing impure substances)
- Develop catalysts (to improve conversion rate/selectivity)

<Other Challenges>

- Heat management, equipment costs, development of low-cost oxygenation (such as the utilization of oxygen concurrently produced during electrolysis)

Target for 2030

<Technological Goal>

- CH_4→Syngas Reaction temperature: 600°C or lower
  (Catalyst: life of approx. 8000hr)
- Development a hydrogen separation membrane
  that is usable even at 600°C

<Costs>

- Costs are similar to those for existing energy/products

<CO_2 Emission Intensity>

- In LCA, the amount of emissions must be equal to or lower than the CO_2 emission intensity from
  the current process

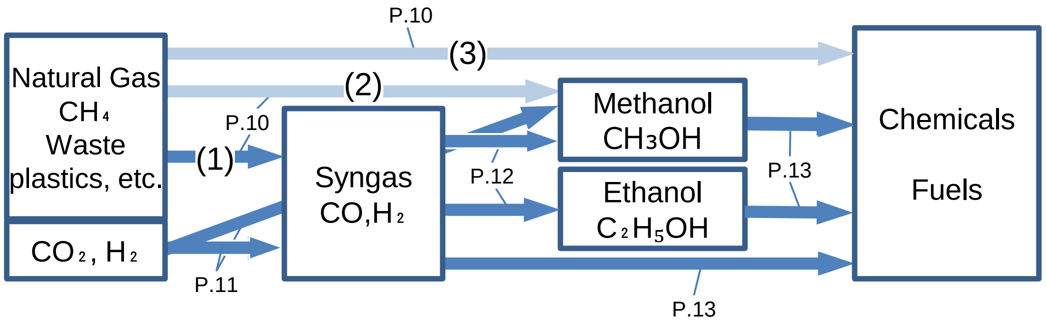
Target from 2040 Onwards

<Costs>

- Raw materials are replaced with CO_2 (Slides 11 and 12) and the costs are similar to those for existing energy/products

<CO_2 Emission Intensity>

- Further reduction



Basic substances

● Technologies to produce syngas containing Carbon Mono-oxide and Hydrogen

Thermal Chemistry (catalysts, etc.)

<Technological Challenges>

- Further improvement in current processes (reverse-shift reaction)

<Other Challenges>

- Capture and reuse of the CO_2 produced as a byproduct in reaction system

<Example of specific efforts>

- Improvement in steam reforming processes (processes, catalysts and separation), thermal cracking of methane, thermal cracking of CO_2 utilizing solar heat

Photochemistry (photocatalysts, etc.)

Artificial Photosynthesis (photocatalysts)

<Technological Challenges>

- Catalyst Development
  Hydrogen synthesis (photocatalysts) → Reverse shift reaction
  Direct synthesis of CO
    Improvement in conversion efficiency and separation of gas generated

<Other Challenges>

- System design of a plant whose commercialization is viable
- Examination and comparison with the current CO production process (methane-derived)

Electrochemistry (electrochemical reduction, etc.)

Electrolytic reduction

<Technological Challenges>

- Development of a catalyst electrode that is suitable for high current density (improve reaction rate)
- Development of integration technology for catalyst electrodes (improve the current density per unit volume)
- Production of syngas through co-electrolysis (respond to load change, equipment scale)

<Other Challenges>

- System design of a plant whose commercialization is viable
- Examination and comparison with the current CO production process (methane-derived)
- Securing massive, stable, CO_2-free electricity supply at reasonable prices

Synthesis utilizing organisms (such as microorganisms)

- Implement various types of R&D

Target for 2030

<Common Challenges>

- Reduction in process cost

<Conversion Efficiency (Photochemistry)>

- Solar energy conversion efficiency: 10% achievement

<Reaction Rate (Current Density)>

- CO_2 processing speed 6t/yr/m^2

(Achievement of current density 500mA/cm^2 at ordinary temperature/normal pressure, electrolytic efficiency50%) (Electrochemistry) Note 1)

<Catalysts>

- Further improvement in durability and Reduction in costs

(Others)

- Development of renewable energy combined systems
- Development of hybrid systems (Photo ＋ Electricity, etc.)
- Sector coupling: Introducing the accommodation of basic substances and Carbon Recycling projects through inter-industry cooperation, including industrial complex operation

Target from 2040 Onwards

<Common Challenges>

- Further reduction in process cost

<Conversion Efficiency (Photochemistry)>

- Further improvement of conversion efficiency

<Reaction Rate (Current Density)>

- CO_2 processing speed 11 t/yr/m^2

(Achievement of current density 1000mA/cm^2 at ordinary temperature/normal pressure, electrolytic efficiency 50%) (Electrochemistry) Note 1)

(Others)

- Synthesis that utilizes thermal chemistry/photochemistry/electrochemistry/organisms is the best mix of various reactions/technologies.

Note 1) Estimate under the following conditions: 100MW plant, availability factor:16.3%, and JPY 2/kWh.
Source of the available factor: Materials owned by ANRE (Agency for Natural Resources and Energy)

Note 2) Supplying inexpensive CO_2 free Hydrogen is important

Basic substances

● Technologies to produce Methanol, etc.

Thermal Chemistry (catalysts, etc.)

[CO_2 → Methanol]

<Technological Challenges>

- Reaction at low temperature (improvement in conversion rate/selectivity)
- Separation/removal of the water arising from the reaction
- Direct utilization of low quality exhaust gas (at a research stage)
  Measures against deterioration/improvements of durability of catalysts

<Other Challenges>

- Examination and comparison with the current practical process (reaction through syngas)
- Utilization of CO_2 in existing methanol production equipment

[Syngas → Methanol (or DME)]

<Technological Challenges>

- Improvement of yields in methanol production
- Methanol and DME production control technology

Photochemistry (photocatalysts, etc.)

Electrochemistry (electrochemical reduction, etc.)

Synthesis utilizing organisms (such as microorganisms)

Implement various types of R&D

<Technological Challenges>

- Direct synthesis of formic acid/methanol(by utilizing the protons in water)
- Improvement in reaction rate and efficiency

<Other Challenges>

- Securing massive, stable, CO_2-free electricity supply at reasonable prices (in the case of utilizing electricity)

<Specific Practical Example>

- Demonstration of integrated bioethanol production from syngas (derived from waste incineration facilities) using microorganisms (The technology to be established by 2023: Goal 500～1,000kL/y scale demonstration to be implemented)

* some processes require no further hydrogen

Target for 2030

<Common Challenges>

- Reduction in process cost

<Others>

- Development of renewable energy combined systems
- Development of hybrid systems (Photo ＋ Electricity, etc.)
- Considering large-scale methanol supply chain
- Apply the technology to existing production systems/secure affinity

<Challenges to be taken up when methanol is utilized as a raw material>

- Demonstrate the technology for methanol to be used in an actual environment
- Expand mixed utilization of existing fuels and methanol as well as the mixed ratio

<Technological Goal>

- Establish a reaction control technology for large-scale processes
- Develop production technologies responding to CO_2 and H_2 supply and demand fluctuations

Target from 2040 Onwards

<Common Challenges>

- Further reduction in process cost

<Expected Cost>

- The expected costs are roughly equal to those incurred for the product synthesized from natural gas-derived methanol

Supplying inexpensive CO_2 free Hydrogen is important

Chemicals

● Technologies to produce basic chemicals (olefins, BTX, etc.)

<Technological Challenges>

[MTO (Methanol to Olefins)]

[ETO (Ethanol to Olefins)]

- Develop catalysts (to improve conversion rate/selectivity)
  E.g.: Controlling a generation rate for plastic materials (C2 ethylene, C3 propylene, C4 butene, etc.) and rubber materials (C4 butadiene, C5 isoprene)
- Countermeasures against catalyst poisoning (controlling carbon precipitation)

[MTA-BTX] (R&D projects exist)

- Developing catalysts (improvement in conversion rate/selectivity)
  E.g.: Controlling generation ratio of benzene, toluene, xylene, etc.
- Mass production technology for catalysts (influences of materials, shapes, sizes, etc.)
- Lengthening service lives of catalysts
- Poisoning countermeasures for improving catalysts lifetime

[Syngas → olefins, BTX]

- Develop catalysts (to improve conversion rate/selectivity)
  E.g.: Controlling a generation rate for plastic materials (C2 ethylene, C3 propylene, C4 butene, etc.) and BTX (C6 benzene, C7 toluene and C8 xylene)
- Suppression of the generation of CO_2, methane and heavy oil

[CO_2 → olefins]

- Develop electrochemical reaction technology
- Develop electrode catalysts, electrolytes and reactor vessels

Target for 2030

[MTO, ETO, syngas → olefins]

- Establish C2-C5 selective synthesis technology
- Further improvement of yield and control of selectivity
- Establish mass production and cost reduction technologies for catalysts
- Establish olefin distillation and separation processes

[MTA-BTX]

- Further improvement of yield, control of selectivity and improvement of durability
- Establish processes for commercial plants

[CO_2→olefins]

- Further improvement of energy conversion efficiency and generation speed

<CO_2 Emission Intensity>

- In LCA, the amount of emissions must be equal to or lower than the CO_2 emission intensity from the current process

Target from 2040 Onwards

<Expected Cost>

- The costs are similar to those for existing energy/products

<CO_2 Emission Intensity>

- In LCA, the amount of emissions must be equal to or lower than half of the CO_2 emission intensity from the current process

Supplying inexpensive CO_2 free Hydrogen is important

Chemicals

● Technologies to produce functional chemicals (oxygenated compounds)

<Technological Challenges>
[Polycarbonate, polyurethane]

- Direct synthesis from CO_2 to further reduce CO_2 emissions
- Develop synthesis processes that do not use highly poisonous materials such as phosgene and ethylene oxide
- Establishment of mass production and cost reduction technologies

Basic research level, under low TRL Process (acrylic acid synthesis, etc.)

- Catalyst development (improvement in conversion rate/selectivity)
- Realization of low LCA for reaction partners (such as utilizing biomass/waste plastics, etc.)

<Other Challenges>

- Considering another CO_2 storage technique based on chemicals (such as oxalic acid, etc.)
- Consider processes to use microbes for fixing CO_2 to organic acid or oils and lipids

Target for 2030

<Expected Cost>

- The costs are similar to those for existing energy/products

<CO_2 Emission Intensity>

- In LCA, the amount of emissions must be equal to or lower than the CO_2 emission intensity from the current process

<Others>

- Establish processes for commercial plants

Target from 2040 Onwards

<Expected Cost>

- Further reduction in costs

<CO_2 Emission Intensity>

- In LCA, the amount of emissions must be equal to or lower than half of the CO_2 emission intensity from the current process

Oxygenated compounds include (in alphabetical order):
Acetic acid, acetic acid ester, acrylic acid, ethanol, ethylene glycol, oxalic acid, polyamide , polyurethane, polycarbonate, polyester, salicylic acid, urethane, etc.

Chemicals

● Technologies to produce biomass-derived chemicals

<Technological Challenges>

(Cellulose-type biomass)

- Low cost, effective pretreatment technique (separation of cellulose, lignin, etc.)
- Establish the related techniques such as dehydration/drying, removal of impurities, etc.
- Production process of high-value added chemicals from non-edible biomass
- Screening and culture techniques for new microorganisms resources
- Utilization of biotechnology (Genome editing/synthesis), establishment of separation/purification/reaction process techniques
- Fermentation technology and catalyst technology that are not susceptible to impurities
- Development of effective materials conversion technologies for biomass materials
- High functionality in biomass-derived chemicals (adding marine biodegradable functions, etc.)

<Other Challenges>

- Establishing integrated production processes (securing production scale, stability in quality, etc.)
- Expanding the scope of target products including derivatives (oxygenated compounds→olefin, etc.)
- Expanding the scope of application of biomass-derived chemicals and verify their economic performance
- Establishing an effective collection system for biomass materials
- Standardization of biomass-derived chemicals/intermediates

Target for 2030

<Expected Cost>

- The costs are similar to those for existing energy/products

<CO_2 Emission Intensity>

- In LCA, as compared to alternative petrochemical products (such as oxygenated compounds, etc.), the amount of emissions must be equal to or lower than half of the CO_2 emission intensity from the current process

<Others>

- Diversification and high functionality of biomass-derived chemicals (Controlling marine biodegradable functions, etc.)
- Hydrogen is necessary in hydrogenation treatment

Target from 2040 Onwards

<Common Challenges>

- Large-scale production (geographically-distributed chemicals production that utilizes papermaking infrastructure/agriculture and forestry/wastes, etc.)

<Expected Cost>

- Further reduction in costs

<CO_2 Emission Intensity>

- In LCA, as compared to alternative petrochemical products (such as olefin, etc.), the amount of emissions must be equal to or lower than half of the CO_2 emission intensity from the current process

- Introduction into global markets (Biodegradable plastics : JPY 850 billion (Global market share of Japan: 25%))

Image of expansion

- Utilize edible biomass (mainly, ethanol and amino acid)
- Utilize oils and fats
- Bio and waste power generation
- Synthesize high-value added chemicals (functional chemicals)

⇨

- Utilize non-edible biomass/microalgae
- Bio power generation (ultimately, BECCS, BECCU)
- Diversification of biomass chemicals/fuels

* Such technological development is also common to that in fuel sector (bioethanol, etc.)

* Cultivation and capturing biomass technologies include marine use as well (fuel sector as well)

Fuels

● Technologies to produce liquid fuel (1) *Synthetic fuels (e-fuel, SAF)

<Technological challenges>

- Challenges towards the introduction of synthetic fuels include the reduction of costs and the establishment of production technologies (synthetic fuel production costs with current technologies are estimated at about JPY300-700/L).
- The hydrogen cost accounts for a major part of synthetic fuels production costs. Need to tackle technological development and demonstrations for improving production efficiency without waiting until a hydrogen cost decline.

<Other challenges>

- Need to establish an international assessment of synthetic fuels as decarbonized fuels and develop a framework for offsetting CO_2 generated during their consumption with CO_2 used for their overseas production.

<Specific initiatives>

- Developing innovative technology to integrally produce synthetic fuels from CO_2 emitted by power and other plants and hydrogen from renewable energy.

Target for 2030

<Establishment of production technology>

- Establish highly efficient, large-scale production technology by 2030
- To this end, intensify technological development and demonstration regarding synthetic fuels until 2030. The following are specific targets:

(1) Development of technology to improve the efficiency of the existing synthetic fuels production technology (reverse conversion reaction + Fischer-Tropsch (FT) synthesis process), and design development and demonstration of equipment to realize large-scale production

(2) Development of innovative production technologies (CO_2 electrolysis, co-electrolysis, direct synthesis (Direct FT)

<Technological goals>

- Achieve a liquid fuels yield of 80% with a pilot-scale (assumed at 500 BPD) plant
- Upgrade electrolysis syngas production technology, improve production performance with next-generation FT catalysts, conduct demonstration operation tests for optimization, scale up pilot plant capacity (semi-plant demonstration), and proceed to the commercialization stage

Target from 2040 onwards

<Synthetic fuels commercialization>

- Diffuse synthetic fuels and cut their costs in the 2030s for independent commercialization (based on environmental values) by 2040

<Costs>

- Realize synthetic fuels costs below gasoline prices in 2050

Fuels

● Technologies to produce liquid fuel (2) *Microalgae biofuel (SAF, diesel)

<Technological Challenges>
(Microalgae→Bio jet fuels/Biodiesel)

- Improve productivity (culture system/ gene recombination)
- Low cost, effective pretreatment technique
- Establish the related techniques such as dehydration/drying, oil extraction, removal of impurities, etc.
- Develop the technology for utilizing oils/fats residues
- Scale-up (from bench-scale to pilot-scale, followed by demonstration level)
- Large-scale technological demonstration
- Pursuit of cost reduction

<Other Challenges>

- Expanding the scope of application and verify economic performance
- Establishing an effective collection system for raw materials

Target for 2030

<Expected Cost>

- Bio jet Fuels: costs: similar to those for existing energy/products, JPY 100-200/L (Currently, JPY1600/L)

<Production Rate>

- 75 L-oil/day･ha (Currently, 35 L-oil/day·ha)

<CO_2 Emission Intensity>

- With regard to bio jet fuels, in LCA, as compared to existing jet fuels, the amount of emissions must be equal to or lower than half of the CO_2 emission intensity from the current process

<Others>

- Compliance with fuel standards
- Scale up to the demonstration level and establish the supply chain
- Expand mixed utilization of the liquid fuel and an existing fuel as well as the mixed ratio
- Since hydrogen is used in relatively small amounts for oil reforming, the presence of CO_2 free hydrogen increases the GHG reduction impact

Target from 2040 onwards

<Expected Cost>

- Further reductions in costs

<CO_2 Reduction Amount>

- Must contribute to 50% CO_2 reduction relative to that for 2005 in aviation sectors

*Such technological development is also common to that in the chemicals sector
(High value added products, such as cosmetics and supplements derived from microalgae are partially commercialized)

(FYI) If a bio jet fuels with a greenhouse gas emission reduction rate of 50% continues to be introduced at 100 thousand kL/yr, a CO_2 reduction of 123 thousand t/yr will be achieved.

Fuels

Technologies to produce liquid fuel (3) *Biofuels (excluding fuels derived from microalgae) (MTG, ethanol, diesel, jet, DMC, OME, etc.)

<Technological Challenges>

- Improvement in FT Synthesis (current process) (Improvement in conversion rate/selectivity)
- Improvement in other synthetic reaction (current process)

<Other Challenges>

- System's optimization (Renewable energy introduction

<Specific Practical Example>

- Demonstration of integrated bioethanol production from syngas (derived from waste incineration facilities) using microorganisms (The technology to be established by 2023: Goal 500-1,000kL/y scale demonstration to be implemented)

* some processes require no further hydrogen

Target for 2030

<CO_2 Emission Intensity>

- In LCA, the amount of emissions must be equal to or lower than the CO_2 emission intensity from the current process

<Other Challenges>

- Wondering what impact a CO_2-derived fuel may have on the regulations/ device/equipment on which naphtha-/crude oil-derived fuels had no effect
- Demonstrate the technology in an actual environment
- Expand mixed utilization of the liquid fuel and existing fuels as well as the mixed ratio

Target from 2040 onwards

<Expected Cost>

- The costs are similar to those for existing energy/products

<CO_2 Emission Intensity>

- In LCA, the amount of emissions must be equal to or lower than half of the CO_2 emission intensity from the current process

* Costs for biofuels and target for CO_2 emissions, the same as biomass derived chemicals and microalgae biofuels attempt to reduce the cost equivalent to those existing energy/products in 2030 as well as in LCA the amount of emissions must be lower than half of the CO_2 emissions intensity from the current process.

Fuels

● Technologies to produce gas fuels (methane, propane, dimethyl ether)

<Technological Challenges>
Existing Techniques (Sabatier Reaction)

- Long lasting of catalysts
- Heat management (utilizing the generation of heat)
- Activity management
- Considering scale-up

R&D of Innovative Technology (co-electrolysis, etc.)

[Power to Methane]

- Production of electrolytic methane and propane through co-electrolysis (utilization as city gas, etc.)
- Integrate the synthesis/power generation of electrolytic methane that utilizes CO_2
- Improvement of energy conversion efficiency

<Other Challenges>

- System's optimization (introducing renewable energy)
- Upsizing/cost reduction
- Equipment cost
- A framework should be developed to offset CO_2 generated during methane consumption with CO_2 used during for methane production.

<Specific Practical Example>

- Commercial scale (125Nm^3/h) demonstration that utilizes CO_2 contained in exhaust gas from a cleaning plant
- Development of basic technology towards practical-scale (60 thousand Nm^3/h) demonstration of introducing city gas that utilizes CO_2 emission from coal fired thermal power plants
- Cutting-edge research to utilize co-electrolysis for synthesizing methane and propane more efficiently

Target for 2030

<Expected Cost>

- Reduction in costs for CO_2 derived CH_4

<CO_2 Emission Intensity>

- In LCA, the amount of emissions must be equal to or lower than the CO_2 emission intensity from the current process

<Others>

- Demonstrate synthetic natural gas injection into gas introduction pipes at a commercial scale (several tens of thousands Nm^3/h)
- Develop sales channel/use application
- Expand mixed utilization of the gas fuel and an existing fuel as well as the mixed ratio
- Improve the energy conversion efficiency further

Target from 2040 onwards

<Expected Cost>

- The costs are similar to those for existing energy/products

<CO_2 Emission Intensity>

- In LCA, the amount of emissions must be equal to or lower than half of the CO_2 emission intensity from the current process

Supplying inexpensive CO_2 free Hydrogen is important

Minerals

- Technologies to produce concrete, cement, carbonates, carbon, carbides, etc.

<Technological Challenges>

- Separation of effective components (Ca or Mg compounds) from industrial byproducts (e.g., iron and steel slag, waste concrete, coal ash, etc.) and/or mine tailings, produced water (e.g., brine), etc. (including the treatment of byproducts arising from the separation processes)
- Improving the energy efficiency of pretreatments, such as the pulverization and separation of effective components to enhance reactivity with CO_2 (dry processes)
- Energy-saving in wet processes (inexpensive treatment for waste-water containing heavy metals, etc.)
- Development of inexpensive aggregates, admixtures, etc.; optimization of composition; composite manufacturing technology using these materials
- Reducing energy consumption for carbon and carbide generation, separating and refining carbon and carbides
- Scale-up

<Energy required to mineralize 1 ton of CO_2>

- 500 kWh/t-CO_2 (e.g., utilizing iron and steel slag, dry processes)

<Other Challenges>

- Establish a supply system from CO_2 emission sources to mineralization process (optimized to net CO_2 fixation and economic performance)
- Expand the scope of application and verify economic performance (development and demonstration of the technologies designed to utilize carbonates – verify the scope of application to concrete products, develop high-value added articles such as luminous materials, etc.)
- Long-term evaluate of performance as a civil-engineering/ building material as well as organize standards/guidelines

<Specific Practical Example>

- Development of carbonation technology using calcium and magnesium contained in waste concrete and other industrial byproducts, waste brine-etc.
- Development of technology to expand the range of applications to cover concrete aggregates, soil improvement agents, glass materials, etc.
- Development of technologies for CO_2 reduction and carbonization

∗Iron slag, steel slag, and coal ash are already used as materials for concrete, but not in the form of carbonates

Target for 2030

<Expected Cost>

- Road curb blocks: costs are similar to those for existing energy/products

<Energy required to mineralize 1 ton of CO_2>

- 200 kWh/t-CO_2 (regardless of a raw material and reaction process)

<CO_2 Utilization>

- CO_2 mineralization must be applied to ~10% of iron & steel slag and coal ash

<Others>

- Large-scale demonstration
- Pursuit of cost reduction
- Survey on appropriate sites within/outside the country
- Promotion of demands by providing some incentive (such as procurement for a public works project, etc.)

<Specific Practical Example>

- Expand raw materials (Coal ash, biomass mixed combustion ash, waste concrete, etc. → Iron and steel slag, mine tailings, produced water, brine, lye water, etc.)

<Technological Goal>

- Development of effective carbonation processes to enhance CO_2 reaction quantity and speed
- Expanding the range of applications for concrete products that effectively use CO_2
- High value-added products (carbon fiber, nanocarbon, etc.)
- Development of cement manufacturing processes capturing carbon dioxide

Target from 2040 onwards

<Expected Cost>

- Products other than road curb blocks : The costs are similar to those for existing energy/products
- Reduction of costs to levels for consistent with commodities (electrodes, activated charcoal)

<CO_2 Utilization>

- CO_2 mineralization must be applied to ~50% of iron & steel slag and coal ash

Important points for Carbon Recycling Technologies

- In order to effectively advance R&D in Carbon Recycling technologies to address climate change and the security of natural resources, the following points need to be considered;

- ➢ Inexpensive CO_2 free Hydrogen is important for many technologies
  - Under the hydrogen and fuel cells strategy roadmap in ‘Hydrogen Basic Strategy’, the target cost for on-site delivery in 2050 is JPY 20/Nm^3
  - While the problem of hydrogen supply remains, 1) R&D for biomass and other technologies not dependent on hydrogen should continue, 2) CH_4 (methane) should be used in place of hydrogen until the establishment of cheap hydrogen.

- ➢ Using zero emission power supply is important for Carbon Recycling
  - ➢ Conversion of a stable substance, CO_2, into other useful substances will require a large amount of energy.

- ➢ Life Cycle Analysis (LCA) perspective is critical to evaluate Carbon Recycling technologies. These analysis methods should be standardized.

- ➢ Reducing the costs for capturing CO_2 will have a positive feedback on Carbon Recycling.

(Reference) Initiatives to promote Carbon Recycling technology development

- Japan devised the “Carbon Recycling 3C Initiative” at the 2019 International Conference on Carbon Recycling to accelerate Carbon Recycling technology development and commercialization through international cooperation. The 3C’s are described below.

1. Caravan (mutual exchange)

   Enhance bilateral and multilateral relationships by sharing information at any possible opportunities such as international conferences* and workshops.

   *International Conference on Carbon Recycling, World Future Energy Summit, etc.

2. Center of Research (R&D and demonstration base)

   Promote the outcomes of Carbon Recycling at R&D sites of Osakikamijima and Tomakomai, and the cooperate with other R&D sites.

3. Collaboration (international joint research)

   Japan-Australia MOC* (Signed on September 25, 2019)

   Establishment of regular meetings, sharing of research achievements, consideration of potential joint projects, etc.

   Japan-U.S. MOC (Signed on October 13, 2020)

   Sharing of technological information, mutual dispatch of experts, exchange of test samples, etc.

   Japan-UAE MOC (Signed on January 14, 2021)

   Sharing of information and research achievements, meetings for information exchange, exploration of potential for cooperation, etc.

   *Memorandum of Cooperation

Japan-U.S. Climate Partnership (April 16, 2021)

- **Japan and the United States, at their summit meeting on April 16** committed to enhancing cooperation on climate ambition, decarbonization and clean energy, and will lead on climate action in the international community.
- **Enhancing bilateral cooperation in Carbon Recycling** and other priority areas

Japan-U.S. Climate Partnership (excerpts)

<Climate and clean energy technology and innovation>

Japan and the United States **commit to** addressing climate change and **working together towards the realization of green growth by enhancing cooperation on innovation**, including in such areas as renewable energy, energy storage (such as batteries and long-duration energy storage technologies), smart grid, energy efficiency, hydrogen, **Carbon Capture, Utilization and Storage/Carbon Recycling**, industrial decarbonization, and advanced nuclear power.

This cooperation will also promote the development, deployment, and utilization of climate friendly and adaptive infrastructure through collaboration in areas including renewable energy, grid optimization, demand response and energy efficiency.

Reference

Glossary

Basic substances (methane chemistry, etc.)

Methane chemistry…A technique to reform natural gas-derived methane into single-carbon compounds, such as syngas (mixed gas of carbon monoxide and hydrogen) or methanol, and by using this as a material, perform interconversion with single-carbon compounds or synthesis of multi-carbon compounds.

ATR…Auto Thermal Reaction

Basic substances (methanol, etc.)

DME…Dimethyl Ether

Chemicals (commodity chemicals: olefins, BTX, etc.)

MTO…Methanol to Olefins
MTA…Methanol to Aromatics
BTX…Benzene, Toluene, Xylenes

Fuel

MTG: Methanol to Gasoline

Reaction Formulae

CO_2 → CO (reverse shift reaction)
$CO_2 + H_2 \rightarrow CO + H_2O$ ΔH= +41.2 kJ/mol (endothermic reaction)
600–700℃

CO_2 → Methanol
$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$ ΔH= -49.4 kJ/mol (exothermic reaction)
200–300℃

Syngas → Methanol
$CO + 2H_2 \rightarrow CH_3OH$ ΔH= -90.6 kJ/mol (exothermic reaction)

CO_2 → Ethanol
$CO_2 + 3/2H_2O \rightarrow 1/2C_2H_5OH + 3/2O_2$ ΔH= +683.4 kJ/mol (endothermic reaction)

$CO_2 + 3H_2 \rightarrow 1/2\ CH_3CH_2OH$ (liquid) $+ 3/2H_2O$ ΔH =-174.1 kJ/mol (exothermic reaction)

CO_2 → Methane (methanation; Sabatier reaction)
$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ ΔH= -164.9 kJ/mol (exothermic reaction)
250–550℃

Methane + CO_2 → Syngas (dry reforming)
$CH_4 + CO_2 \rightarrow 2CO + 2H_2$ ΔH= +247 kJ/mol (endothermic reaction)
800℃–

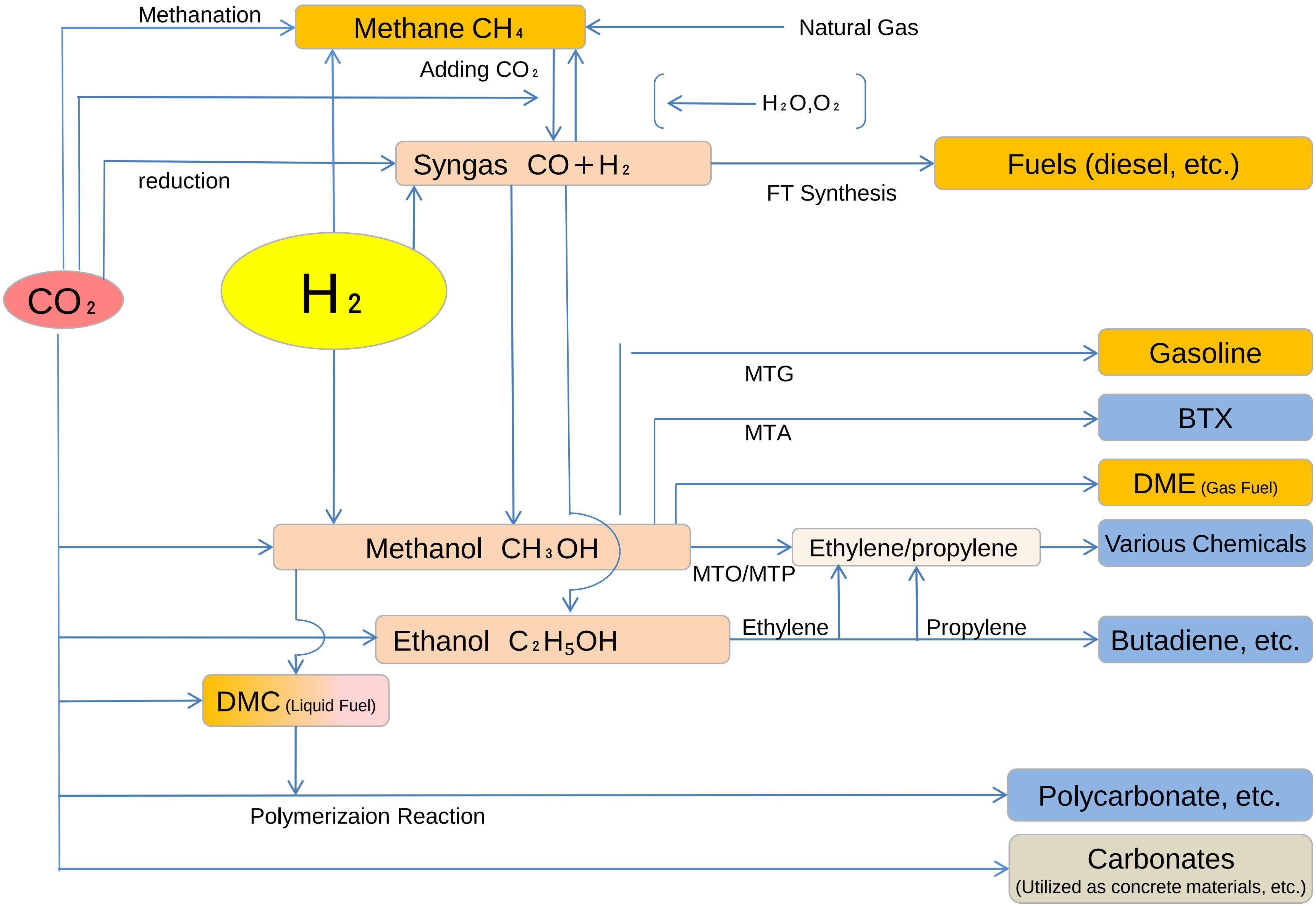
Methane → Syngas (steam reforming)
$CH_4 + H_2O \rightarrow CO + 3H_2$ ΔH= +206 kJ/mol (endothermic reaction)
750–900℃

Methane → Syngas (partial oxidation)
$CH_4 + 1/2O_2 \rightarrow CO + 2H_2$ ΔH= -35 kJ/mol (exothermic reaction)
800℃–, without a catalyst 1300–1500℃

Thermal cracking of methane
$CH_4 \rightarrow C + 2H_2$ ΔH= +75 kJ/mol (endothermic reaction)
700–1000℃

FT synthesis
$CO + 2H_2 \rightarrow (1/n)(CH_2)_n + H_2O$ ΔH= -167 kJ/mol-CO (exothermic reaction)

Flowchart for CO_2 Utilization (for chemicals/fuels/carbonates)



Methanation

Methane CH_4

Natural Gas

Adding CO_2

H_2O,O_2

reduction

Syngas $CO+H_2$

FT Synthesis

Fuels (diesel, etc.)

CO_2

H_2

MTG

Gasoline

MTA

BTX

DME (Gas Fuel)

Methanol CH_3OH

MTO/MTP

Ethylene/propylene

Various Chemicals

Ethanol C_2H_5OH

Ethylene

Propylene

Butadiene, etc.

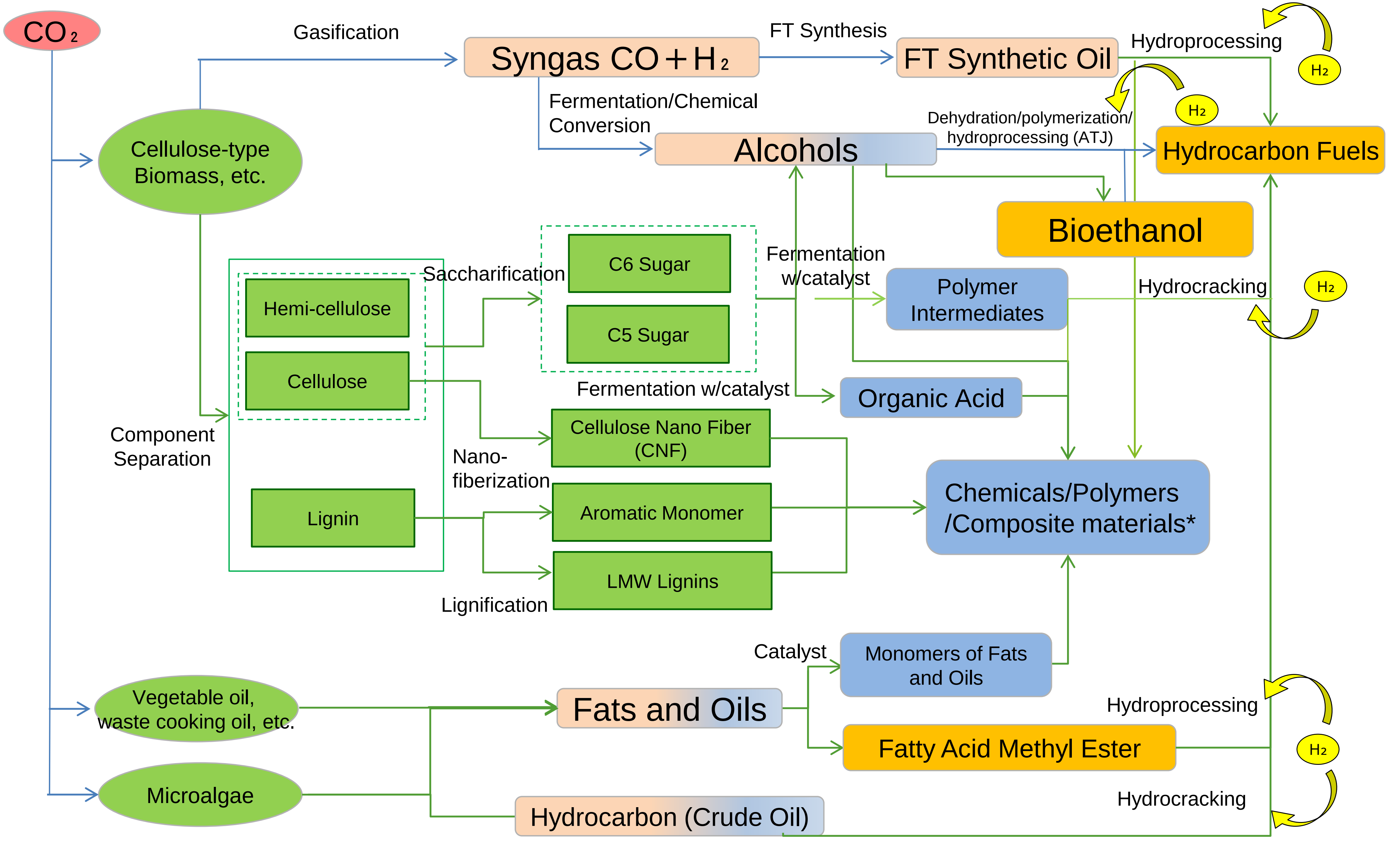
DMC (Liquid Fuel)

Polymerizaion Reaction

Polycarbonate, etc.

Carbonates
(Utilized as concrete materials, etc.)

Flowchart: CO_2 Utilization (for Bio-derived fuels/chemicals)



CO_2

Gasification

Syngas $CO + H_2$

FT Synthesis

FT Synthetic Oil

Hydroprocessing

H_2

Fermentation/Chemical Conversion

Alcohols

Dehydration/polymerization/ hydroprocessing (ATJ)

H_2

Hydrocarbon Fuels

Cellulose-type Biomass, etc.

Bioethanol

Saccharification

C6 Sugar

C5 Sugar

Fermentation w/catalyst

Polymer Intermediates

Hydrocracking

H_2

Hemi-cellulose

Cellulose

Component Separation

Fermentation w/catalyst

Organic Acid

Cellulose Nano Fiber (CNF)

Nano-fiberization

Lignin

Aromatic Monomer

LMW Lignins

Lignification

Chemicals/Polymers /Composite materials*

Catalyst

Monomers of Fats and Oils

Vegetable oil, waste cooking oil, etc.

Fats and Oils

Hydroprocessing

Fatty Acid Methyl Ester

H_2

Microalgae

Hydrocracking

Hydrocarbon (Crude Oil)

*Reduction reaction or hydrocracking during the process to produce "chemicals, polymer products or composite materials", may require hydrogen.