Roadmap for Carbon Recycling Technologies

June 2019 (July 2021 Revision)

Ministry of Economy, Trade and Industry
In cooperation with the Cabinet Office, Ministry of Education, Culture, Sports, Science and Technology, & Ministry of the Environment
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 (CO₂) will be recycled into concrete through mineralization, into chemicals through artificial photosynthesis, and into fuels through methanation to reduce CO₂ emissions into the atmosphere.

Carbon Recycling technology advances research and development of CO₂ 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**

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**

### 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 CO₂ 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.

### Chemicals
- Polycarbonate, etc.

### Liquid Fuels
- Bio jet fuels, etc.

### Concrete Products
- Road curb blocks, cement, etc.

### 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 spread from 2030
- **Chemicals**
  - Polycarbonate, etc.
- **Liquid Fuels**
  - Bio jet fuels, etc.
- **Concrete Products**
  - Road curb blocks, cement, etc.

### Expected to start spreading from around 2040
- **Chemicals**
  - Commodity (olefin, BTX, etc.)
- **Liquid Fuels**
  - Gas, Liquid (methane, synthetic fuels, etc.)
- **Concrete Products**
  - Commodity

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

### *Expansion into commodity markets with robust demand

---

**Current**

**2030**

**From 2040 onwards**

**CO₂ capture technology**

**Reducing cost**

**Less than ¼ of current cost**

**Hydrogen**

JPY 20/Nm³ (cost at delivery site)

---

*Target for 2050*
### Summary of Carbon Recycling Technologies and Products

<table>
<thead>
<tr>
<th>Substance After CO₂ Conversion</th>
<th>Current Status</th>
<th>Challenges</th>
<th>Price of the Existing Equivalent Product</th>
<th>In 2030</th>
<th>From 2040 Onwards</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Basic Substance</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Syngas/ Methanol, etc.</td>
<td>Partially commercialized. Innovative process (light, electricity utilization) is at R&amp;D stage</td>
<td>Improvement of conversion efficiency and reaction rate, improvement in durability of catalyst, etc.</td>
<td>–</td>
<td>Reduction in process costs</td>
<td>Further reduction in process costs</td>
</tr>
<tr>
<td><strong>Oxygenated Compounds</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Partially commercialized (e.g., polycarbonates). Others are at R&amp;D stage.</td>
<td>Reduce the amount of CO₂ emission for polycarbonate. Other than polycarbonate, etc. commercialized (Improvement in conversion rate/selectivity, etc.)</td>
<td>Approx. JPY 300-500/kg (polycarbonate (domestic sale price))</td>
<td>Costs: similar to those of existing energy/products</td>
<td>Further reduction in costs</td>
<td></td>
</tr>
<tr>
<td>Price of the existing equivalent product (Polycarbonate)</td>
<td></td>
<td>–</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Chemicals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technical development stage (non-edible biomass)</td>
<td>Cost reduction/effective pretreatment technique, conversion technologies, etc.</td>
<td>JPY 100/kg (ethylene (domestic sale price))</td>
<td>Costs: similar to those of existing energy/products</td>
<td>Costs: similar to those of existing energy/products</td>
<td></td>
</tr>
<tr>
<td><strong>Biomass-derived Chemicals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Partially commercialized (e.g., Syngas, etc. produced from coal)</td>
<td>Improvement in conversion rate/selectivity, etc.</td>
<td>–</td>
<td>–</td>
<td>Costs: similar to those of existing energy/products</td>
<td></td>
</tr>
<tr>
<td><strong>Commodity Chemicals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(olefin, BTX, etc.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technical Development/Demonstration Stage</td>
<td>System optimization, scale-up, efficiency improvement, etc.</td>
<td>JPY 40-50/Nm³ (Natural gas (imported price))</td>
<td>Reduction in costs for CO₂-derived CH₄</td>
<td>Costs: similar to those of existing energy/products</td>
<td></td>
</tr>
<tr>
<td><strong>Fuels</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demonstration Stage</td>
<td>Improvement productivity, cost reduction, effective pretreatment technique, etc.</td>
<td>Approx. JPY 100/L level (bio jet fuels (domestic sale price))</td>
<td>Costs: similar to those of existing energy/products (JPY 100-200/L)</td>
<td>Further reduction in costs</td>
<td></td>
</tr>
<tr>
<td>[Price example] Bio jet Fuels: JPY 1600/L</td>
<td></td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td><strong>Liquid Fuel</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(microalgae biofuel)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technical Development stage (e-fuel, SAF). Partially commercialized for edible biomass-derived bioethanol.</td>
<td>Improvement in current processes, system optimization, etc.</td>
<td>JPY 50-80/L (alcohol as raw material (imported price))</td>
<td>Synthetic fuels: Less than gasoline price costs: similar to those of existing energy/products</td>
<td>Synthetic fuels: Less than gasoline price costs: similar to those of existing energy/products</td>
<td></td>
</tr>
<tr>
<td>[Price example] Synthetic fuels: about JPY300-700/L</td>
<td></td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td><strong>Gas Fuels</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(methylene, propane, dimethyl ether)</td>
<td>Technical Development/Demonstration Stage</td>
<td>System optimization, scale-up, efficiency improvement, etc.</td>
<td>JPY 30/kg (Road curb block (domestic sale price))</td>
<td>Road curb block costs: similar to those of existing energy/products</td>
<td>Other products, except road curb block costs: similar to those of existing energy/products</td>
</tr>
<tr>
<td><strong>Minerals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete, cement, carbonates, carbon, carbidies</td>
<td>Separation of CO₂-reactive and CO₂-unreactive compounds, comminution, etc.</td>
<td>JPY 30/kg (Road curb block (domestic sale price))</td>
<td>Road curb block costs: similar to those of existing energy/products</td>
<td>Other products, except road curb block costs: similar to those of existing energy/products</td>
<td></td>
</tr>
<tr>
<td>Partially commercialized. R&amp;D for various technologies and techniques for cost reduction are underway.</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>[Price example] order of JPY 100/t (Road curb block)</td>
<td></td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td><strong>Common Technology</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ capture (including DAC)</td>
<td>Partially commercialized (chemical absorption). Other techniques are at research/demonstration stage</td>
<td>Reduction in the required energy, etc.</td>
<td>–</td>
<td>Approx. JPY 1000-2000/t-CO₂ (chemical absorption, solid absorption, physical absorption, membrane separation)</td>
<td>≤JPY 1000/t-CO₂ (DAC)</td>
</tr>
<tr>
<td>[Price example] Approx. JPY 4000/t-CO₂ (Chemical absorption)</td>
<td></td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td>Technologies have been roughly established (e.g., water electrolysis). R&amp;D for other techniques and cost reduction are also underway.</td>
<td>Cost reduction, etc.</td>
<td>JPY 30/Nm³ (cost at delivery site)</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
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)

<table>
<thead>
<tr>
<th>Field</th>
<th>2030 (short-term)</th>
<th>2040 onwards (mid-to long-term)</th>
</tr>
</thead>
</table>
|       | 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
**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 (CO₂) will be recycled into concrete through mineralization, into chemicals through artificial photosynthesis, and into fuels through methanation to reduce CO₂ emissions into the atmosphere.

- **Emissions etc.**
  - Chemical or physical ab/adsorption, membrane separation, etc.
  - **Direct Air Capture (DAC)**
  - CO₂ transportation (vehicles, pipelines, ships, etc.)

- **Storage**
  - EOR*¹
  - Direct utilization (Welding, dry ice)

- **Utilization**
  - **Basic substances**
    - CO/H₂ Syngas
    - Methanol, etc.
  - **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.)

*¹ EOR: Enhanced Oil Recovery
*² SAF: Sustainable aviation fuel
*³ MTG: Methanol to Gasoline
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
- Full-fledged spread of CO\(_2\) separation, capture, and transportation systems
- Develop CO\(_2\) networks (covering capture/transportation/utilization infrastructure, hubs & clusters, etc.)

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\(_2\)

Target from 2040 onwards

- 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.)

<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.)
Common technology

**DAC (Direct Air Capture)**

- **Technological challenges: 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 CO₂ 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 CO₂ separation and capture
  - JPY 30,000-60,000/t-CO₂
  - 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 CO₂.
  - Selection of DAC locations (suitable climate for CO₂ capture, proximity to energy sources and CO₂ 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 CO₂ separation and capture systems**
  - Achieve competitive CO₂ separation and capture costs in the 2030s market
  - Example targets
    - JPY 10,000/t-CO₂: ICEF (Innovation for Cool Earth Forum) roadmap
    - JPY 10,000/t-CO₂: 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-CO₂
  - Improve DAC system durability and reliability
  - Full-fledged spread of DAC system
## Common technology

### Explanations of CO₂ separation/capture and DAC technologies

<table>
<thead>
<tr>
<th>Capture technologies</th>
<th>Principle</th>
<th>Application areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical absorption</td>
<td>• Chemical reaction between CO₂ and liquid.</td>
<td>thermal power plants, cement manufacture, iron and steel production, petroleum refining, chemical production, and fossil fuel extraction</td>
</tr>
<tr>
<td>Physical absorption</td>
<td>• Dissolution of CO₂ into liquid.</td>
<td>thermal power plants (high gas pressure), petroleum refining, chemical production and fossil fuel extraction</td>
</tr>
<tr>
<td>Solid absorption</td>
<td>• Absorption into solid absorbents.</td>
<td>thermal power plants, cement manufacture, petroleum refining, and chemical production</td>
</tr>
<tr>
<td></td>
<td>• Absorbents include porous materials impregnated with amines (for low temperature separation) or other solid absorbents for high temperature separation.</td>
<td></td>
</tr>
<tr>
<td>Physical adsorption</td>
<td>• Adsorption onto a porous solid such as zeolite and metal-organic complex (e.g., MOFs).</td>
<td>thermal power plants, cement manufacture, iron and steel production, petroleum refining and chemical production</td>
</tr>
<tr>
<td></td>
<td>• Realized by increase and decrease of pressure (pressure swing) or temperature (temperature swing).</td>
<td></td>
</tr>
<tr>
<td>Membrane separation</td>
<td>• Separation of CO₂ by using permeation through zeolite, carbon, organic, or other membranes which have selective permeability for different gas species.</td>
<td>thermal power plants (high gas pressure), petroleum refining, chemical production and fossil fuel extraction</td>
</tr>
<tr>
<td>DAC (Direct Air Capture)</td>
<td>• Technology for direct capture of dilute CO₂ from the atmosphere using the abovementioned separation and capture technology.</td>
<td>Capture CO₂ at very low concentration (400 ppm) in the atmosphere</td>
</tr>
<tr>
<td></td>
<td>• The DAC technology is an advanced version of the CO₂ separation and capture technology. Further cuts in costs and energy consumption are required for commercialization.</td>
<td></td>
</tr>
</tbody>
</table>
Basic substances

- Methane Chemistry, etc. (Until inexpensive hydrogen can be supplied, methane (CH₄) or waste plastics will be used instead of CO₂.)

[CH₄ → 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.

[CH₄ → 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 CO₂-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>**
- CH₄ → 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

**<CO₂ Emission Intensity>**
- In LCA, the amount of emissions must be equal to or lower than the CO₂ emission intensity from the current process

**Target from 2040 Onwards**

**<Costs>**
- Raw materials are replaced with CO₂ (Slides 11 and 12) and the costs are similar to those for existing energy/products

**<CO₂ Emission Intensity>**
- Further reduction

### Flow chart:

- **Natural Gas** → **Syngas** → **Methanol** → **Chemicals**
- **Waste plastics** → **Ethanol** → **Fuels**
- **CO₂, H₂** → **Carbon** → **H₂O**
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)
  - Capture and reuse of the CO₂ produced as a byproduct in reaction system
- **Other Challenges**
  - Improvement in steam reforming processes (processes, catalysts and separation), thermal cracking of methane, thermal cracking of CO₂ 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, CO₂-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)**
  - CO₂ processing speed 6t/yr/m²
    - Achievement of current density 500mA/cm² at ordinary temperature/normal pressure, electrolytic efficiency 50% (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)**
  - CO₂ processing speed 11 t/yr/m²
    - Achievement of current density 1000mA/cm² 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 CO₂ free Hydrogen is important
Basic substances

Technologies to produce Methanol, etc.

**Thermal Chemistry (catalysts, etc.)**

[CO₂ → 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 CO₂ 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, CO₂-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 500~1,000 kL/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 CO₂ and H₂ 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 CO₂ 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 CO₂, methane and heavy oil

[CO₂ → 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

[CO₂ → olefins]
- Further improvement of energy conversion efficiency and generation speed

<CO₂ Emission Intensity>
- In LCA, the amount of emissions must be equal to or lower than the CO₂ emission intensity from the current process

Supplying inexpensive CO₂ free Hydrogen is important

Target from 2040 Onwards

<Expected Cost>
- The costs are similar to those for existing energy/products

<CO₂ Emission Intensity>
- In LCA, the amount of emissions must be equal to or lower than half of the CO₂ emission intensity from the current process
**Technological Challenges**

- 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.
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

**CO₂ 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 CO₂ 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

**CO₂ 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 CO₂ emission intensity from the current process

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

* 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 CO₂ generated during their consumption with CO₂ used for their overseas production.

<Specific initiatives>
• Developing innovative technology to integrally produce synthetic fuels from CO₂ 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 (CO₂ 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

*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)*

---

**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)

**CO₂ 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 CO₂ 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 CO₂ free hydrogen increases the GHG reduction impact

---

**Target from 2040 onwards**

**Expected Cost**
- Further reductions in costs

**CO₂ Reduction Amount**
- Must contribute to 50% CO₂ reduction relative to that for 2005 in aviation sectors

(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 CO₂ 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*

**CO₂ Emission Intensity**
- In LCA, the amount of emissions must be equal to or lower than the CO₂ emission intensity from the current process

**Other Challenges**
- Wondering what impact a CO₂-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

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

**CO₂ Emission Intensity**
- In LCA, the amount of emissions must be equal to or lower than half of the CO₂ emission intensity from the current process

*Costs for biofuels and target for CO₂ 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 CO₂ emissions intensity from the current process.*

Supplying inexpensive CO₂ free Hydrogen is important
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 CO₂
- Improvement of energy conversion efficiency

<Expected Cost>
- Reduction in costs for CO₂ derived CH₄

<CO₂ Emission Intensity>
- In LCA, the amount of emissions must be equal to or lower than the CO₂ emission intensity from the current process

<Others>
- Demonstrate synthetic natural gas injection into gas introduction pipes at a commercial scale (several tens of thousands Nm³/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

Other Challenges

- System’s optimization (introducing renewable energy)
- Upsizing/cost reduction
- Equipment cost
- A framework should be developed to offset CO₂ generated during methane consumption with CO₂ used during for methane production.

<Expected Cost>
- The costs are similar to those for existing energy/products

<CO₂ Emission Intensity>
- In LCA, the amount of emissions must be equal to or lower than half of the CO₂ emission intensity from the current process

Supplying inexpensive CO₂ free Hydrogen is important
<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 CO₂ (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 CO₂>
• 500 kWh/t-CO₂ (e.g., utilizing iron and steel slag, dry processes)

<Other Challenges>
• Establish a supply system from CO₂ emission sources to mineralization process (optimized to net CO₂ 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 CO₂ 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 CO₂>
• 200 kWh/t-CO₂ (regardless of a raw material and reaction process)

<CO₂ Utilization>
• CO₂ 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 CO₂ reaction quantity and speed
• Expanding the range of applications for concrete products that effectively use CO₂
• 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)

<CO₂ Utilization>
• CO₂ mineralization must be applied to ~50% of iron & steel slag and coal ash
Inexpensive CO\textsubscript{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\textsuperscript{3}
- While the problem of hydrogen supply remains, 1) R&D for biomass and other technologies not dependent on hydrogen should continue, 2) CH\textsubscript{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\textsubscript{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\textsubscript{2} will have a positive feedback on Carbon Recycling.
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 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

<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
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**

CO₂ → CO (reverse shift reaction)
\[ CO₂ + H₂ → CO + H₂O \quad ΔH= +41.2 \text{ kJ/mol (endothermic reaction)} \]
600–700℃

CO₂ → Methanol
\[ CO₂ + 3H₂ → CH₃OH + H₂O \quad ΔH= -49.4 \text{ kJ/mol (exothermic reaction)} \]
200–300℃

Syngas → Methanol
\[ CO + 2H₂ → CH₃OH \quad ΔH= -90.6 \text{ kJ/mol (exothermic reaction)} \]

CO₂ → Ethanol
\[ CO₂ + 3/2H₂O → 1/2C₂H₅OH + 3/2O₂ \quad ΔH= +683.4 \text{ kJ/mol (endothermic reaction)} \]

CO₂ + 3H₂ → 1/2 CH₃CH₂OH (liquid) + 3/2H₂O \quad ΔH = -174.1 \text{ kJ/mol (exothermic reaction)}

CO₂ → Methane (methanation; Sabatier reaction)
\[ CO₂ + 4H₂ → CH₄ + 2H₂O \quad ΔH= -164.9 \text{ kJ/mol (exothermic reaction)} \]
250–550℃

Methane + CO₂ → Syngas (dry reforming)
\[ CH₄ + CO₂ → 2CO + 2H₂ \quad ΔH= +247 \text{ kJ/mol (endothermic reaction)} \]
800℃–

Methane → Syngas (steam reforming)
\[ CH₄ + H₂O → CO + 3H₂ \quad ΔH= +206 \text{ kJ/mol (endothermic reaction)} \]
750–900℃

Methane → Syngas (partial oxidation)
\[ CH₄ + 1/2O₂ → CO + 2H₂ \quad ΔH= -35 \text{ kJ/mol (exothermic reaction)} \]
800℃–, without a catalyst 1300–1500℃

Thermal cracking of methane
\[ CH₄ → C + 2H₂ \quad ΔH= +75 \text{ kJ/mol (endothermic reaction)} \]
700–1000℃

FT synthesis
\[ CO + 2H₂ → (1/n)(CH₂)n + H₂O \quad ΔH= -167 \text{ kJ/mol-CO (exothermic reaction)} \]
Flowchart for CO₂ Utilization (for chemicals/fuels/carbonates)

- Methane CH₄
  - Methanation
  - Adding CO₂ from syngas (CO + H₂)
  - FT Synthesis for Fuels (diesel, etc.)

- Syngas CO + H₂
  - Methane CH₄
  - Methanation
  - Adding CO₂ from syngas (CO + H₂)
  - FT Synthesis for Fuels (diesel, etc.)

- H₂
  - Methane CH₄
  - Methanation
  - Adding CO₂ from syngas (CO + H₂)
  - FT Synthesis for Fuels (diesel, etc.)

- Methanol CH₃OH
  - Ethanol C₂H₅OH
  - DMC (Liquid Fuel)
  - Polycarbonate, etc.
  - Carbonates (Utilized as concrete materials, etc.)

- Ethylene/propylene
  - MTG
  - MTA
  - DME (Gas Fuel)
  - BTX
  - Various Chemicals

- Polymerization Reaction
  - Methane CH₄
  - Methanation
  - Adding CO₂ from syngas (CO + H₂)
  - FT Synthesis for Fuels (diesel, etc.)

- Natural Gas
  - Methane CH₄
  - Methanation
  - Adding CO₂ from syngas (CO + H₂)
  - FT Synthesis for Fuels (diesel, etc.)

- CO₂
  - Methane CH₄
  - Methanation
  - Adding CO₂ from syngas (CO + H₂)
  - FT Synthesis for Fuels (diesel, etc.)

- H₂O, O₂
  - Methane CH₄
  - Methanation
  - Adding CO₂ from syngas (CO + H₂)
  - FT Synthesis for Fuels (diesel, etc.)
Flowchart: CO₂ Utilization (for Bio-derived fuels/chemicals)

CO₂

- Gasification
  - Syngas CO + H₂
  - FT Synthesis
    - Fermentation/Chemical Conversion
      - Alcohols
        - FT Synthetic Oil
          - Hydroprocessing
            - Hydrocarbon Fuels

- Component Separation
  - Cellulose-type Biomass, etc.
    - Cellulose
      - Hemicellulose
      - Lignin
      - Saccharification
      - Fermentation w/catalyst
        - C6 Sugar
        - C5 Sugar
        - Cellulose Nano Fiber (CNF)
          - Fermentation w/catalyst
            - Organic Acid
              - Chemicals/Polymers /Composite materials*

- Vegetable oil, waste cooking oil, etc.
  - Hydrocarbon (Crude Oil)
  - Fats and Oils
    - Fatty Acid Methyl Ester
      - Hydrocracking
        - H₂
      - Hydroprocessing
        - Monomers of Fats and Oils
          - Catalyst
            - LMW Lignins
              - Aromatic Monomer
                - Polymer Intermediates
                  - Bioethanol
                    - Hydrocracking
                      - H₂

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