Roadmap for Carbon Recycling Technologies
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 utilized for producing recycled materials and fuels by mineralization, artificial photosynthesis and methanation and this will also control CO₂ emissions to the air.

Carbon Recycling technology advances research and development of CO₂ utilization promoting collaborations among industries, academia and governments around the world and stimulates disruptive innovation.

Carbon Recycling is one of key technologies for the society, together with energy saving, renewable energy and CCS.

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

**2. Fuels**
- Microalgae biofuels (jet fuel/diesel)
- CO₂-derived fuels or biofuels (excluding fuels derived from microalgae) (methanol, ethanol, diesel, etc.)
- Gas fuels (methane)

**3. Minerals**
- Concrete products, concrete structures
- Carbonate, etc.

**4. Others**
- Negative emission technologies (BECCS, Blue Carbon etc.)
Phase 1
- Pursue all potential technologies for carbon recycling initiatives.
- Special effort should focus on technologies requiring no hydrogen and producing high-value added materials, both of which shall be expected to spread from around 2030 onwards.

Phase 2
- Attempt to reduce costs of technologies that are expected to spread from 2030 onwards.
- Special effort should focus on technologies for large-volume commodity, which will be enabled by inexpensive hydrogen supply from 2050 onwards. Attempts should be made to reach equivalent cost of existing energy and products from 2050 onward.

Phase 3
- Pursue further cost reduction

Expected to be highly consumed from 2030
- Chemicals: Polycarbonate, etc.
- Liquid Fuels: Bio-jet fuel, etc.
- Concrete Products: Road curb blocks, etc.

Expected to be highly consumed from 2050
- Chemicals: Commodity (Olefin, BTX, etc.)
- Fuels: Gas, Liquid
- Concrete Products: Commodity

<Review process> Be flexible in the addition of technologies based on the state of international technology development obtained through the International Conference on Carbon Recycling among Industry-Academia-Government, or proposals of new technologies. The roadmap should be reviewed in five years as needed, take into account the revision of the “Long term Strategy for Growth strategy based on the Paris Agreement (provisional translation)” .
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</thead>
<tbody>
<tr>
<td>Basic Substance</td>
<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></td>
<td>Oxygenated Compounds</td>
<td>Partially commercialized (polycarbonates, etc.), 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>
</tr>
<tr>
<td></td>
<td>Biomass-derived Chemicals</td>
<td>Technical development stage (non-edible biomass)</td>
<td>Cost reduction/effective pretreatment technique, etc. conversion technologies, etc.</td>
<td>—</td>
<td>Costs: similar to those of existing energy/products</td>
<td>Further reduction in costs</td>
</tr>
<tr>
<td></td>
<td>Commodity Chemicals (olefin, BTX, etc.)</td>
<td>Partially commercialized (Syngas, etc. produced from coal, etc. is utilized)</td>
<td>Improvement in conversion rate/selectivity, etc.</td>
<td>JPY 100/kg (ethylene (domestic sale price))</td>
<td>—</td>
<td>Costs: similar to those of existing energy/products</td>
</tr>
<tr>
<td></td>
<td>Liquid Fuel (microalgaebiofuel)</td>
<td>Demonstration Stage</td>
<td>Improvement productivity, cost reduction/ effective pretreatment technique, etc.</td>
<td>JPY 100/L level (bio-jet fuel (domestic sale price))</td>
<td>Costs: similar to those of existing energy/products (JPY 100-200/L)</td>
<td>Further reduction in costs</td>
</tr>
<tr>
<td></td>
<td>Liquid Fuel (CO₂-derived fuels or biofuels (excluding microalgaebiofuel derived ones))</td>
<td>Demonstration stage (E-Fuel, etc.), 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)) JPY approx. 130/L Industrial alcohol (domestic sale price)</td>
<td>—</td>
<td>Costs: similar to those of existing energy/products</td>
</tr>
<tr>
<td></td>
<td>Gas Fuel (Methane)</td>
<td>Demonstration Stage</td>
<td>System optimization, scale-up, 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>
</tr>
<tr>
<td>Minerals</td>
<td>Carbonates/Concrete Products, Concrete Structures</td>
<td>Partially commercialized. R&amp;D for various technologies techniques are underway towards cost reduction.</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>
</tr>
<tr>
<td>Common Technology</td>
<td>CO₂ Capture</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>JPY 1000-2000 level /t-CO₂ (chemical absorption, solid absorption, physical absorption, membrane separation)</td>
<td>JPY 1000/t-CO₂ or lower</td>
</tr>
<tr>
<td>Basic Substance</td>
<td>Hydrogen</td>
<td>Technologies have been roughly established (water electrolysis, etc.) R&amp;D for other techniques are also underway towards cost reduction.</td>
<td>Cost reduction, etc.</td>
<td>JPY 30/Nm³</td>
<td>JPY 20/Nm³ (cost at delivery site)</td>
<td></td>
</tr>
</tbody>
</table>

[1] Price researched by secretariat
[2] Basic substances, chemicals(excluding some oxygenated compounds), and many technologies for fuels require large amounts of inexpensive CO₂-free hydrogens. Biomass-derived fuels may require hydrogen for hydrogenation treatment, etc.
The carbon recycling technology, where we consider CO₂ as a resource, will begin with a smaller recycle volume. We expect this initiative will continue to expand into different application areas as achieving cost effectiveness. We set relatively short-term targets in 2030 while 2050 onward is seen as a mid- to long-term target.

### 2030:
- Technologies aiming at achieving commercialization as early stage as possible.
  1. Establish an environment that fosters easy utilization of CO₂ (reducing costs for capture and recycle of CO₂)
  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 products can replace existing products)

### 2050:
- Early-stage technologies that have greater impacts by using a large amount of CO₂ (enabled by inexpensive hydrogen)

<table>
<thead>
<tr>
<th>Field</th>
<th>2030 (short-term)</th>
<th>2050 onward (mid-to long-term)</th>
</tr>
</thead>
</table>
| Technologies producing high-value added products and/or not requiring inexpensive hydrogen will be commercialized first: | Chemicals (polycarbonate, etc.)  
Liquid fuels (bio-jet fuel, etc.)  
Concrete products (road curb blocks, etc.) | Extended to products that have large demand:  
- Chemicals (commodity: olefin, BTX, etc.)  
- Fuels (gas, liquid)  
- Concrete products (commodity) |
Individual technologies
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 utilized for producing recycled materials and fuels by mineralization, artificial photosynthesis and methanation and this will also control CO$_2$ emissions to the air.

**Emissions etc.**

**Capture**
- Chemical or physical absorption/membrane separation, etc.
- Direct Air Capture (DAC)

**Storage**

**Utilization**

**Carbon Recycling**

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

**Basic substances**
- CO/H$_2$ Syngas
- Methanol, etc.

(Until inexpensive Hydrogen can be supplied, methane (CH$_4$) will be used instead of CO$_2$)

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

**Fuel**
- Liquid fuel (1) (microalgae biofuels: bio-jet fuel/diesel)
- Liquid fuel (2) (CO$_2$-derived fuels or biofuels (excluding fuels derived from microalgae): methanol, ethanol, etc.)
- Gas fuels (methane)

**Mineral**
- Concrete products, concrete structure, carbonate, etc.

**Others**
- Negative emissions technologies (BECCS, Blue Carbon, etc.)

**Common Issues:**
- Overall optimization of heat/pressure/materials (cost reduction, etc.) and LCA (comparison with the current processes)

**Carbon-free Hydrogen Production**

**Common Substances**
- Water electrolysis
- Fossil resource reforming + CCS, etc.

**Domestic surplus renewable energy**
- Various hydrogen carriers (such as liquid hydrogen, MCH, NH$_3$, etc.)
CO₂ Capture Technology

<Technological Challenges>
- Reduction in capital and operational costs and in required energy
  - Development of new functional materials (absorbents, adsorbents, separation membrane)
    (improvements in selectivity/capacity/durability improvements)
  - Reduction in production costs of functional materials
  - Optimization of processes (in terms of heat/substance/power, etc.)
- Selection of the types of CO₂ capture technologies based on the CO₂ emission source/application
- Establishing CO₂ capture and conversion systems by matching CO₂ supply and demand with approaching co-production
- Transportation and storage

<Individual Technologies>
- Chemical absorption (temperature swing (current process))
  Approx. JPY 4,000/t-CO₂
  Required energy: Approx. 2.5GJ/t-CO₂
- Physical absorption (pressure swing (demonstration stage))
- Solid absorption (temperature swing) (R&D stage)
- Physical adsorption (pressure/temperature swing, less advantages in scale-up, improvements needed in selectivity/capacity/endurance life)
- Membrane separation (pressure difference)
- Others: cryogenic separation technique, Direct Air Capture, etc.

<Process Technologies to facilitate CO₂ Capture>
- Oxygen-enriched combustion, closed IGCC
  Development of low cost oxygen supply technology
- Chemical Looping combustion
  Development of low-cost and durable oxygen carriers

Target for 2030
- For low-pressure gas (CO₂ separation from flue gas, blast furnace gas, etc.)
  JPY 2,000 level/t-CO₂
  Required energy 1.5 GJ/t-CO₂
  Chemical absorption, solid absorption, etc.
- For high-pressure gas (CO₂ separation from chemical process/fuel gas, etc.)
  JPY 1,000 level/t-CO₂
  Required energy 0.5GJ/t-CO₂
  Physical absorption, membrane separation, etc.
- Overall review of other processes
  Closed IGCC/Chemical looping, etc.
  JPY 1,000 level/t-CO₂
  Required energy 0.5GJ/t-CO₂

<Establishing a CO₂ capture system>
- Realization of an energy-saving, low cost CO₂ capture system that is designed for each CO₂ emission source/usage
- Realization of 10,000 hour continuous operation (to demonstrate the robustness and reliability)

Target from 2050 Onwards
- Achieve JPY 1,000/t-CO₂ or lower
- Improve the robustness and reliability of CO₂ capture systems
- Optimize CO₂ capture systems according to the emission source and application
- Full-fledged spread of CO₂ capture systems
## Explanations on CO₂ capture 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 manufacturer, iron and steel production, petroleum refining, chemical production and fossil fuel extraction</td>
</tr>
<tr>
<td>Physical absorption</td>
<td>• Dissolution CO₂ into liquid. Efficiency depends on the solubility of CO₂ in the absorbent.</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 manufacturer, petroleum refining and chemical production</td>
</tr>
<tr>
<td>Physical adsorption</td>
<td>• Adsorption onto porous solid such as zeolite.</td>
<td>thermal power plants, cement manufacturer, iron and steel production, petroleum refining and chemical production</td>
</tr>
<tr>
<td>Membrane separation</td>
<td>• Permeation through a membrane, which has selective permeability for different gas species</td>
<td>thermal power plants(high gas pressure), petroleum refining, chemical production and fossil fuel extraction</td>
</tr>
</tbody>
</table>
Basic substances

I Methane Chemistry, etc.
(Until inexpensive Hydrogen can be supplied, methane (CH₄) 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)

[Wastes→Useful Substances]
• Sophisticate a recycling technology that utilizes waste plastics (physical selection of plastics, removal of impurities, halogen-resistant catalysts, etc.)
• Establishment of industrialized process

<Other Challenges>
• Heat management, equipment costs, development of low-cost oxygcnation (such as the utilization of oxygen concurrently produced during electrolysis)

Target for 2030

<Technological Goal>
• CH₄→Syngas Reaction temperature: 600 ºC or lower
  (Catalyst: life of approx. 8000hr)
• Development a hydrogen separation membrane that is usable even at 600 ºC

<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 2050 Onwards

<Costs>
• Raw materials are replaced with CO₂ (Slide 10and11) and the costs are similar to those for existing energy/products

<CO₂ Emission Intensity>
• Further reduction
Basic substances

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

<table>
<thead>
<tr>
<th>Thermal Chemistry (catalysts, etc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technological Challenges</strong></td>
</tr>
<tr>
<td>• Further improvement in current processes (reverse-shift reaction)</td>
</tr>
<tr>
<td><strong>Other Challenges</strong></td>
</tr>
<tr>
<td>• Capture and reuse of the CO₂ produced as a byproduct in reaction system</td>
</tr>
<tr>
<td>• Thermal cracking of CO₂ utilizing solar heat</td>
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</table>

<table>
<thead>
<tr>
<th>Photochemistry (photocatalysts, etc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technological Challenges</strong></td>
</tr>
<tr>
<td>• Catalytic cracking of CO₂ utilizing solar heat</td>
</tr>
<tr>
<td><strong>Other Challenges</strong></td>
</tr>
<tr>
<td>• System design of a plant whose commercialization is viable</td>
</tr>
<tr>
<td>• Examination and comparison with the current CO production process (methane-derived)</td>
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<table>
<thead>
<tr>
<th>Electrochemistry (electrochemical reduction, etc.)</th>
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</thead>
<tbody>
<tr>
<td><strong>Technological Challenges</strong></td>
</tr>
<tr>
<td>• Development of a catalyst electrode that is suitable for high current density (improve reaction rate)</td>
</tr>
<tr>
<td>• Development of integration technology for catalyst electrodes (improve the current density per unit volume)</td>
</tr>
<tr>
<td>• Production of syngas through co-electrolysis (respond to load change, equipment scale)</td>
</tr>
<tr>
<td><strong>Other Challenges</strong></td>
</tr>
<tr>
<td>• System design of a plant whose commercialization is viable</td>
</tr>
<tr>
<td>• Examination and comparison with the current CO production process (methane-derived)</td>
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<tr>
<td>• Securing reasonable and stable, large amounts of power derived from renewable energy</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Synthesis utilizing organisms (such as microorganisms)</th>
</tr>
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<tbody>
<tr>
<td>• Implement various types of R&amp;D</td>
</tr>
</tbody>
</table>

**Target for 2030**

**Conversion Efficiency (Photochemistry)**
- Solar energy conversion efficiency: 10% achievement

**Reaction Rate (Current Density)**
- CO₂ processing speed 6 t/yr/m²
  (Achievement of current density 500 mA/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: Demonstrate a case where CO is used as a reducing agent for steelmaking

**Target from 2050 Onwards**

**Conversion Efficiency (Photochemistry)**
- Further improvement of conversion efficiency

**Reaction Rate (Current Density)**
- CO₂ processing speed 11 t/yr/m²
  (Achievement of current density 1000 mA/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.

[CO₂ → Methanol]

<Technological Challenges>
- Reaction at low temperature
  - Catalyst development/improvement in catalyst’s 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
- A system for concurrent production of methanol and DME where syngas is used as a raw material (production adjustment technique)

Thermal Chemistry (catalysts, etc.)

Electrochemistry (electrochemical oxidation/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 reasonable and stable, large amounts of power derived from renewable energy (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

Photochemistry (photocatalysts, etc.)

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

<Other Challenges>
- Securing reasonable and stable, large amounts of power derived from renewable energy (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)

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

Target from 2050 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

I Technologies to produce commodity chemicals (Olefins, BTX, etc.)

<MTO-olefin> (production plants exist)
- Developing catalysts (improvement in conversion rate/selectivity)
  E.g., Controlling generation ratio of Ethylene, propylene, butane, etc.
- 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.

Regarding MTO and MTA, methanol derived from coal is implemented or under implemented in China.

[Syngas → olefin, BTX]
Basic research level
- Developing catalysts (improvement in conversion rate/selectivity)
  E.g., Controlling generation ration of Benzene, toluene, xylene, etc.
- Suppression of the generation of CO₂ and methane

Target for 2030

[MTO-olefin]
<Catalyst>
Establish C2-C4 selective synthesis technology
- Further improvement in yield and Control of selectivity
- Establish a small-pilot-scale process

[MTA-BTX]
<Catalyst>
- Further improvement of yield and control of selectivity

[Syngas → Olefin, BTX]
<Catalyst>
- Further improvement of yield and control of selectivity

<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 2050 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

Supplying inexpensive CO₂ free Hydrogen is important
Chemicals

Technological Challenges

- Reduce cost in the current process or for commercialization (polycarbonate synthesis, etc.)
- Further reduction of CO₂ emissions
- Reduction in production costs

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 CO₂ storage technique based on chemicals (such as oxalic acid, etc.)

Target for 2030

- 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 the CO₂ emission intensity from the current process

Target from 2050 Onwards

- Expected Cost: Further reduction in costs
- 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

Oxygenated compounds include (in alphabetical order):
acetic acid, acetic acid ester, acrylic acid, ethanol, ethylene glycol, oxalic acid, polyamide, polycarbonate, polyester, salicylic acid, urethane, etc.
Technologies to produce biomass-derived chemicals

**Technological Challenges**
- 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**
- The costs are similar to those for existing energy/products
- 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
- Diversification and high functionality of biomass-derived chemicals (Controlling marine biodegradable functions, etc.)
- Hydrogen is necessary in hydrogenation treatment

**Target from 2050 Onwards**
- Large-scale production (geographically-distributed chemicals production that utilizes papermaking infrastructure/agriculture and forestry/wastes, etc.)
- 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 (Marine biodegradable plastics: JPY 850 billion (Global market share of Japan: 25%))

- 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)
- 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) *Microalgae Biofuel (Jet Fuel/Diesel)

**Target for 2030**

- **Expected Cost**
  - Bio-jet Fuel: 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 biojet 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 2050 Onwards**

- **Expected Cost**
  - Further reductions in costs

- **CO₂ Reduction Amount**
  - Must contribute to 50% CO₂ 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)*
Fuels

Technologies to produce liquid fuel (2)
*CO₂-derived fuel or Biofuel (excluding microalgae-derived fuels) (such as methanol, 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 (E-Fuel))

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

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

Target from 2050 Onwards

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
- Thermal 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 through co-electrolysis (utilization as city gas, etc.)
- Integrate the synthesis/power generation of electrolytic methane that utilizes CO2
- Improvement of efficiency

Other Challenges
- System’s optimization (introducing renewable energy)
- Upsizing/cost reduction
- Equipment cost

Specific Practical Example
- Commercial scale (125Nm³/h) demonstration that utilizes CO₂ contained in exhaust gas from a cleaning plant
- Development of basic technology towards practical-scale (60 thousand Nm³/h) demonstration of introducing city gas that utilizes CO2 emission from coal fired thermal power plants

Target for 2030

- 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 injection into gas introduction pipes
  - Develop sales channel/use application
  - Expand mixed utilization of the gas fuel and an existing fuel as well as the mixed ratio

Target from 2050 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

Supplying inexpensive CO₂ free Hydrogen is important
Technological Challenges
- Separation of effective components (Ca or Mg compounds) from industrial byproducts (such as 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 process)
- Energy-saving of the pretreatment (for example, comminution of effective components) that helps to enhance the reactivity with CO₂ (dry process)
- Energy-saving in wet process (inexpensive treatment for waste water containing heavy metals, etc.)
- Development of inexpensive aggregates, admixtures, etc.
- Scale up

Energy required to mineralize 1 ton of CO₂
- 500 kWh/t-CO₂ (utilizing iron and steel slag, dry process)

Other Challenges
- Establish a supply system from CO₂ emission sources to mineralization process (optimized to net CO₂-fixiation 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 the performance as a civil-engineering/building material as well as organize standards/guidelines

Specific Practical Example
- Development of a technology that is used to convert unused highly reactive industrial byproducts into carbonates (e.g., coal ash), which pretreated by energy saving process
- Even now, iron and steel slags and coal ash are used as materials for concrete but not in the form of carbonates

Expected Cost
- Other products: The 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 work 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 (e.g., brine) utilization (lye water), etc.)

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

CO₂ Utilization
- CO₂ mineralization must be applied to ~50% of iron & steel slag and coal ash
- steel slag and coal ash

Target for 2030
- Road curb blocks: costs are similar to those for existing energy/products

Target from 2050 Onwards
- Road curb blocks: costs are similar to those for existing energy/products
**Important points for Carbon Recycling Technologies**

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

- **Inexpensive CO₂ free Hydrogen is important for many technologies**
  - Under the hydrogen and fuel cells strategy roadmap in ‘Hydrogen Basic Strategy’, the target at costs at delivery site for 2050 is JPY 20/Nm³
  - While the problem of hydrogen supply remains, 1) R&D for biomass and other technologies not dependent on hydrogen should be continue, 2) CH₄ (methane) should be used in place of hydrogen until the establishment of a cheap hydrogen.

- **Using zero emission power supply is important for Carbon Recycling**
  - Conversion of a stable substance, CO₂, into other useful substance will require a large amount of energy.

- **Life Cycle Analysis (LCA) perspective is critical to evaluate Carbon Recycling technologies.**

- **Reducing the costs for capturing CO₂ will positively feedback into Carbon Recycling.**
Flowchart for CO₂ Utilization (for chemicals/fuels/carbonates)

- Methanation
- Methane CH₄
- Natural Gas
- Adding CO₂
- Syngas CO + H₂
- FT Syntesis
- Fuels (diesel, etc.)
- Ethanol C₂H₅OH
- Methanol CH₃OH
- Ethylene/propylene
- Gasoline
- BTX
- DME (Gas Fuel)
- Various Chemicals
- Butadiene, etc.
- DMC (Liquid Fuel)
- Polymerization Reaction
- Methanol CH₃OH
- MTG
- MTA
- MTO/MTP
- Ethylene
- Propylene
- Butadiene, etc.
- DME (Gas Fuel)
- Various Chemicals
- Carbonates

CO₂

H₂

CO₂ (Utilized as concrete materials, etc.)
Flowchart: CO₂ Utilization (for Bio-derived fuels/chemicals)

- **CO₂**
  - Gasification
  - Syngas CO + H₂
    - FT Synthesis
      - Fermentation/Chemical Conversion
        - FT Synthetic Oil
          - Dehydration/polymerization/hydroprocessing (ATJ)
            - Hydroprocessing
              - Hydrocracking
                - Reduction reaction or hydrocracking during the process to produce "chemicals, polymer products or composite materials", may require hydrogen.

- **Cellulose-type Biomass, etc.**
  - Component Separation
    - Saccharification
      - Hemicellulose
        - C6 Sugar
          - Polymer Intermediates
            - Hydrocracking
              - Monomers of Fats and Oils
                - Catalyst
                  - Polymer Intermediates
                    - Hydrocracking
                      - Chemicals/Polymers/Composite materials

- **Cellulose**
  - Nano-fiberization
    - Cellulose Nano Fiber (CNF)
      - Organic Acid
        - Hydrocracking
          - Chemicals/Polymers/Composite materials

- **Lignin**
  - Lignification
    - LMW Lignins
      - Monomers of Fats and Oils
        - Catalyst
          - Fats and Oils
            - Monomers of Fats and Oils
              - Hydrocracking
                - Fatty Acid Methyl Ester
                  - Hydroprocessing
                    - Chemicals/Polymers/Composite materials

- **Vegetable oil, waste cooking oil, etc.**
  - Component Separation
    - Fermentation w/catalyst
      - alcohol
        - Bioethanol
          - Hydrocracking
            - Chemicals/Polymers/Composite materials

- **Microalgae**
  - Component Separation
    - Saccharification
      - Fermentation w/catalyst
        - Hydroprocessing
          - Chemicals/Polymers/Composite materials

- **Fats and Oils**
  - Component Separation
    - Hydrocarbon (Crude Oil)
      - Fatty Acid Methyl Ester
        - Hydrocracking
          - Chemicals/Polymers/Composite materials

- **Cellulose Nano Fiber**
  - Aromatic Monomer
    - Chemicals/Polymers/Composite materials

- **Hydrocarbon Fuels**
  - Chemicals/Polymers/Composite materials

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