<Provisional translation>

Roadmap for Carbon Recycling Technologies

June 2019

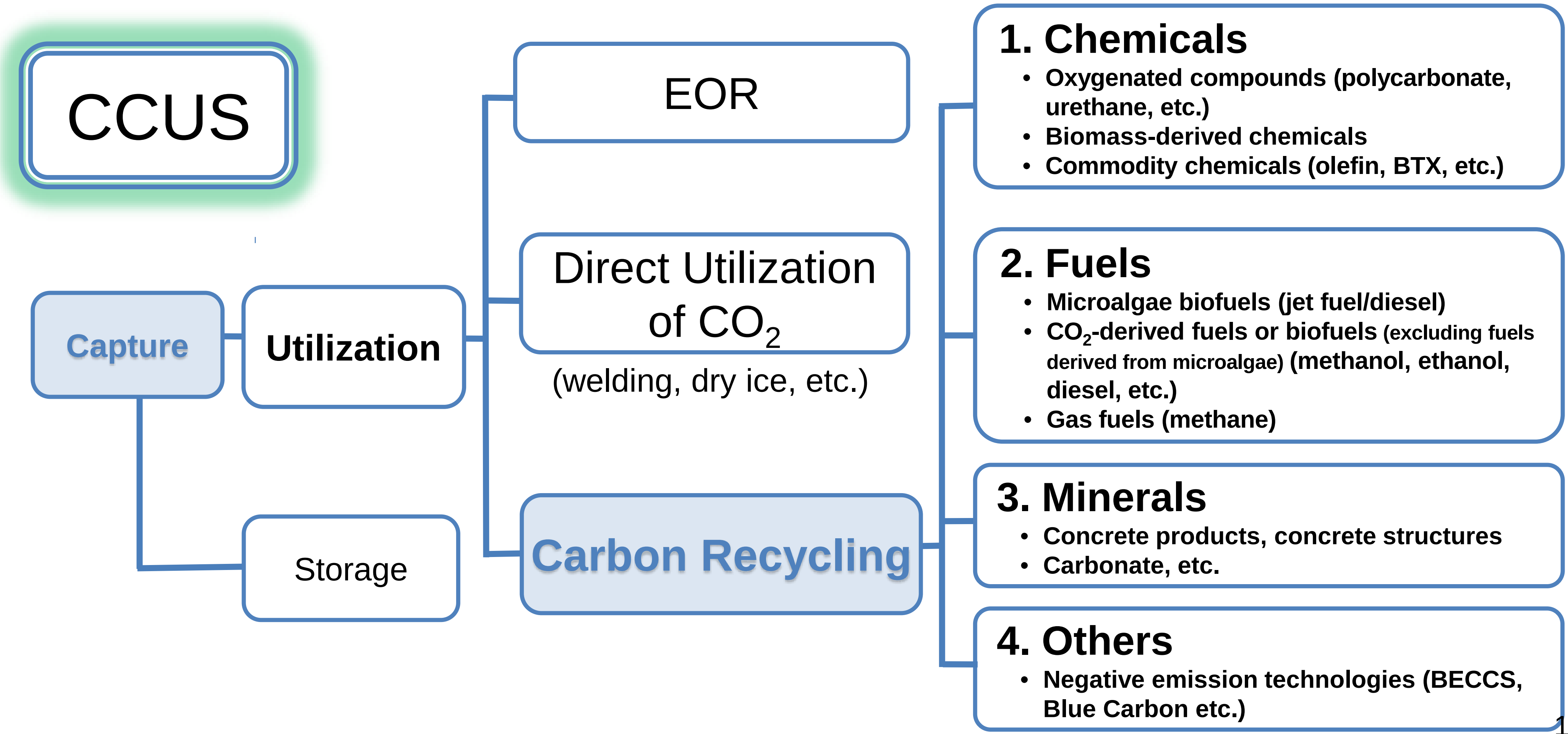
Ministry of Economy, Trade and Industry

Cooperation of Cabinet Office,
Ministry of Education, Culture, Sports, Science and Technology &
Ministry of the Environment

※ In the event of any doubts arising as to the contents, the original Japanese version is to be the final version.

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 utilized for producing recycled materials and fuels by mineralization, artificial photosynthesis and methanation and this will also control CO_2 emissions to the air.
- Carbon Recycling technology advances research and development of CO_2 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.



Roadmap for Carbon Recycling Technologies

Volume of utilized CO_2

Chemicals (polycarbonate, etc.)

Further reduction volume of CO_2, for the polycarbonate.

Liquid Fuels (Bio-jet fuel, etc).

Cost must be reduced to around1/8 -1/16 of current one.

Concrete Products (Road curb blocks, etc.)

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

Phase 1

- Ø Pursue all potential technologies for carbon recycling initiatives.
- Ø 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.

Expected to Spread from 2030

- Chemicals
  - Polycarbonate, etc.
- Liquid Fuels
  - Bio-jet fuel, etc.
- Concrete Products
  - Road curb blocks, etc.

Phase 2

- Ø Attempt to reduce costs of technologies that are expected to spread from 2030 onwards.
- Ø 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

- Ø Pursue further cost reduction

Expected to be highly consumed from 2030

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

Expected to Spread from 2050

- Chemicals
  - Commodity (Olefin, BTX, etc.)
- Fuels
  - Gas, Liquid
- Concrete Products
  - Commodity

Hydrogen JPY20/Nm^3 (cost at delivery site)

CO_2 capture technology Reducing cost Less than ¼ of current cost

Current 2030 From 2050 onwards

<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)” .

Summary of Carbon Recycling Technologies R&D

※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 hydrogens. Biomass-derived fuels may require hydrogen for hydrogenation treatment, etc.

Category	Substance After CO_2 Conversion	Current Status※1	Challenges	Price of the Existing Equivalent Product※1	In 2030	From 2050 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 (polycarbonates, etc.), 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, etc. conversion technologies, etc.	—	Costs: similar to those of existing energy/products	Further reduction in costs
	Commodity Chemicals (olefin, BTX, etc.)	Partially commercialized (Syngas, etc. produced from coal, etc. is utilized)	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] Biojet Fuel: JPY 1600/L	Improvement productivity, cost reduction/ effective pretreatment technique, etc.	JPY 100/L level (bio-jet fuel (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))	Demonstration stage (E-Fuel, etc.), partially commercialized for edible biomass-derived bioethanol	Improvement in current processes, system optimization, etc.	JPY 50-80/L (alcohol as raw material (imported price) JPY approx. 130/L Industrial alcohol (domestic sale price)	—	Costs: similar to those of existing energy/products
	Gas Fuel (Methane)	Demonstration Stage	System optimization, scale-up, 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	Carbonates/Concrete Products, Concrete Structures	Partially commercialized. R&D for various technologies techniques are underway towards cost reduction. [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	Partially commercialized (chemical absorption). Other techniques are at research/ demonstration stage [Price example] Approx. JPY4000/t-CO_2 (Chemical absorption)	Reduction in the required energy, etc.	—	JPY 1000-2000 level /t-CO_2 (chemical absorption, solid absorption, physical absorption, membrane separation)	JPY 1000/t-CO_2 or lower
Basic Substance	Hydrogen	Technologies have been roughly established (water electrolysis, etc.) R&D for other techniques are also underway towards cost reduction.	Cost reduction, etc.		JPY 30/Nm^3	JPY 20/Nm^3 (cost at delivery site)

Scope : Roadmap for Carbon Recycling Technologies

The carbon recycling technology, where we consider CO_2 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 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 products can replace existing products)

2050: 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 (enabled by inexpensive hydrogen)

	2030 (short-term)	2050 onward (mid-to long-term)
Field	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

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 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.

Storage

Utilization

Direct utilization

EOR※

Welding, dry ice

※EOR：Enhanced Oil Recovery

Carbon Recycling

Basic substances
- **CO/H_2 Syngas**
- **Methanol, etc.**

(Until inexpensive Hydrogen can be supplied, methane (CH_4) will be used instead of CO_2)

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 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.)

Capture

Common Technology

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

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.)

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

Common technology

Ⅰ CO_2 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 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 approaching co-production
- Transportation and storage

<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 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 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

Target for 2030

- For low-pressure gas (CO_2 separation from flue gas, blast furnace gas, etc.)
  JPY2,000 level/t-CO_2
  Required energy 1.5 GJ/t-CO_2
  Chemical absorption, solid absorption, etc.
- For high-pressure gas (CO_2 separation from chemical process/fuel gas, etc.)
  JPY1,000 level/t-CO_2
  Required energy 0.5GJ/t-CO_2
  Physical absorption, membrane separation, etc.
- Overall review of other processes
  Closed IGCC/Chemical looping, etc.
  JPY1,000 level/t-CO_2
  Required energy 0.5GJ/t-CO_2

<Establishing a CO_2 capture system>
- 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)

Target from 2050 Onwards

<Commercialization of CO_2 capture technology>
- Achieve JPY1,000/t-CO_2 or lower
- Improve the robustness and reliability of CO_2 capture systems
- Optimize CO_2 capture systems according to the emission source and application
- Full-fledged spread of CO_2 capture systems

Common technology

Explanations on CO_2 capture technologies

Capture technologies	Principle	Application areas
Chemical absorption	• Chemical reaction between CO_2 and liquid.	thermal power plants, cement manufacturer, iron and steel production, petroleum refining, chemical production and fossil fuel extraction
Physical absorption	• Dissolution 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 manufacturer, petroleum refining and chemical production
Physical adsorption	• Adsorption onto porous solid such as zeolite. • Realized by increase and decrease of pressure (i.e. pressure swing) or temperature (i.e. temperature swing).	thermal power plants, cement manufacturer, iron and steel production, petroleum refining and chemical production
Membrane separation	• Permeation through a membrane, which has selective permeability for different gas species	thermal power plants(high gas pressure), petroleum refining, chemical production and fossil fuel extraction

Basic substances

Ⅰ Methane Chemistry, etc.

(Until inexpensive Hydrogen can be supplied, methane (CH_4) 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)

[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 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

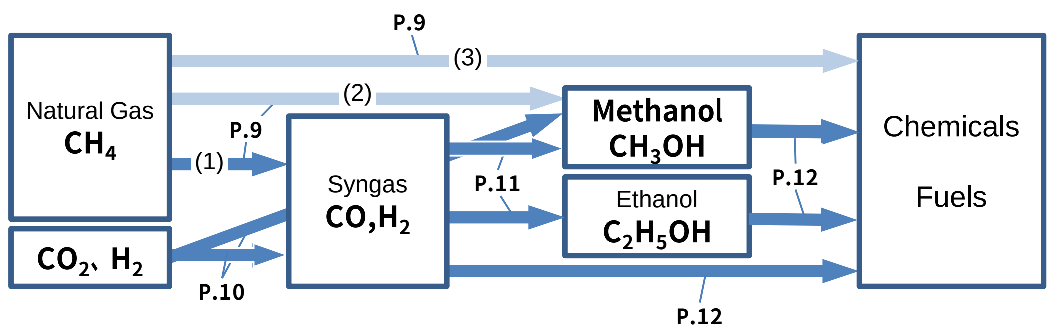
<Costs>
- Costs are similar to those for existing energy/products

<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 2050 Onwards

<Costs>
- Raw materials are replaced with CO_2 (Slide 10and11) and the costs are similar to those for existing energy/products

<CO_2 Emission Intensity>
- Further reduction



Basic substances

Ⅰ 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>
- 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.)

Artificial Photosynthesis (PV-electrochemical cell)
<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 reasonable and stable, large amounts of power derived from renewable energy

Synthesis utilizing organisms (such as microorganisms)

- Implement various types of R&D

Target for 2030

<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: 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)>
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.

Note1) 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)
Note2) Supplying inexpensive CO_2 free Hydrogen is important

Basic Substances

Ⅰ Technologies to produce Methanol, etc.

Thermal Chemistry(catalysts, etc.)

[CO_2 → 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 CO_2 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)

Photochemistry (photocatalysts, 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

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 CO_2 free Hydrogen is important

Chemicals

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

<Technological Challenges>
[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 CO_2 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

<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 2050 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

Chemicals

Ⅰ Technologies to produce oxygenated compounds

<Technological Challenges>
- Reduce cost in the current process or for commercialization (polycarbonate synthesis, etc.)
- Further reduction of CO_2 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 CO_2 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

<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 2050 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, polycarbonate, polyester, salicylic acid, urethane, etc.

Chemicals

Ⅰ 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 2050 Onwards

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

<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 (Marine 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)
- 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

Ⅰ Technologies to produce liquid fuel (1) *Microalgae Biofuel (Jet Fuel/Diesel)

<Technological Challenges>
(Microalgae→Biojet fuel/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 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)

<CO_2 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 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 2050 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

(FYI) If a biojet fuel 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.

*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

l Technologies to produce liquid fuel (2)
*CO_2-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

<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 2050 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 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 CO_2 free Hydrogen is important

Fuels

Ⅰ Technologies to produce gas fuel (Methane)

<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 (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 CO2 emission from coal fired thermal power plants

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 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

<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

Minerals

Technologies to produce carbonates, concrete products and concrete structures, etc.

<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 CO_2 (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 CO_2 >
- 500 kWh/t-CO_2 (utilizing iron and steel slag, dry process)

<Other Challenges>
- Establish a supply system from CO_2 emission sources to mineralization process (optimized to net CO_2-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

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 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.)

Target from 2050 Onwards

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

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

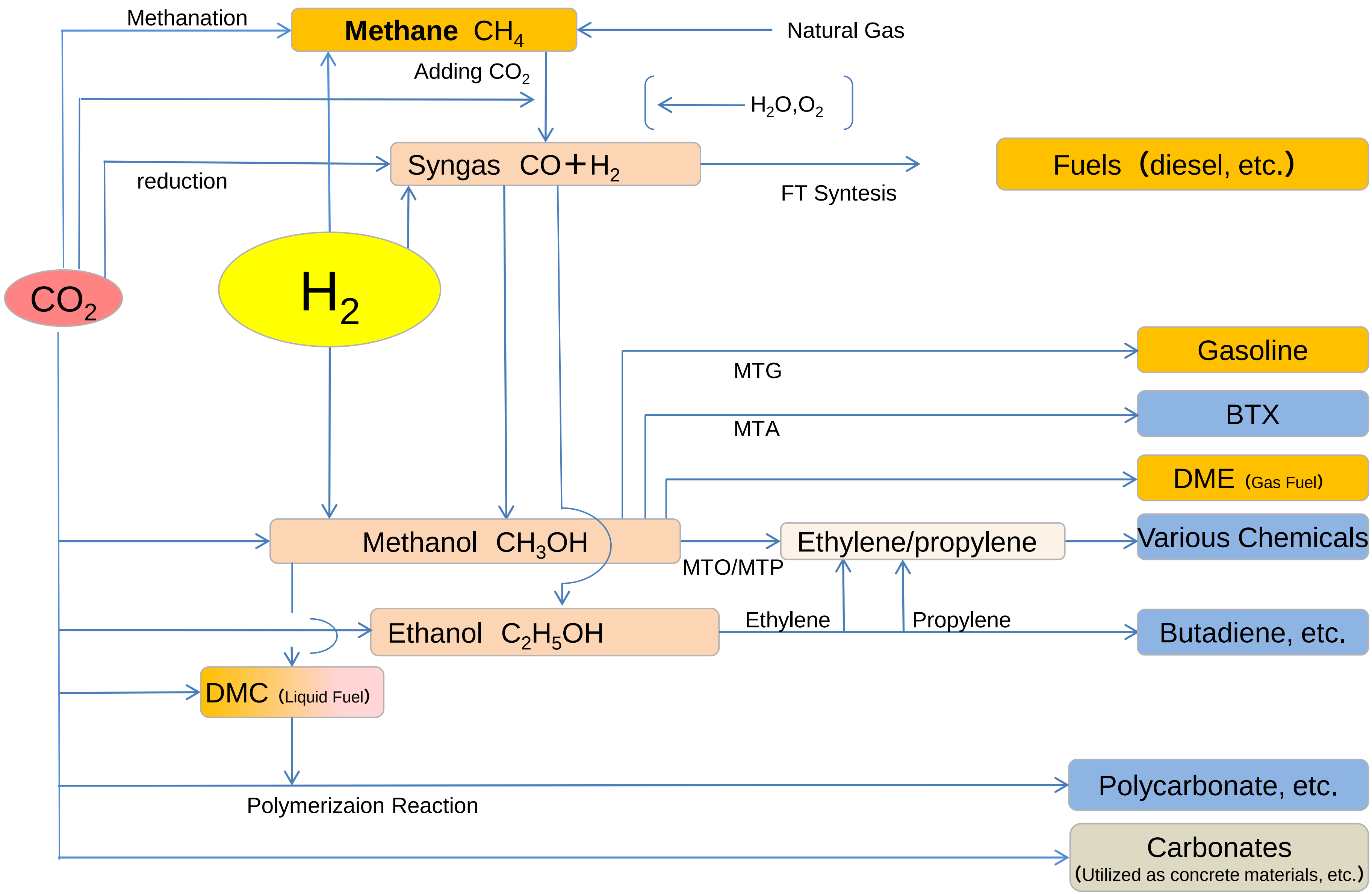
Important points for Carbon Recycling Technologies

- 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.

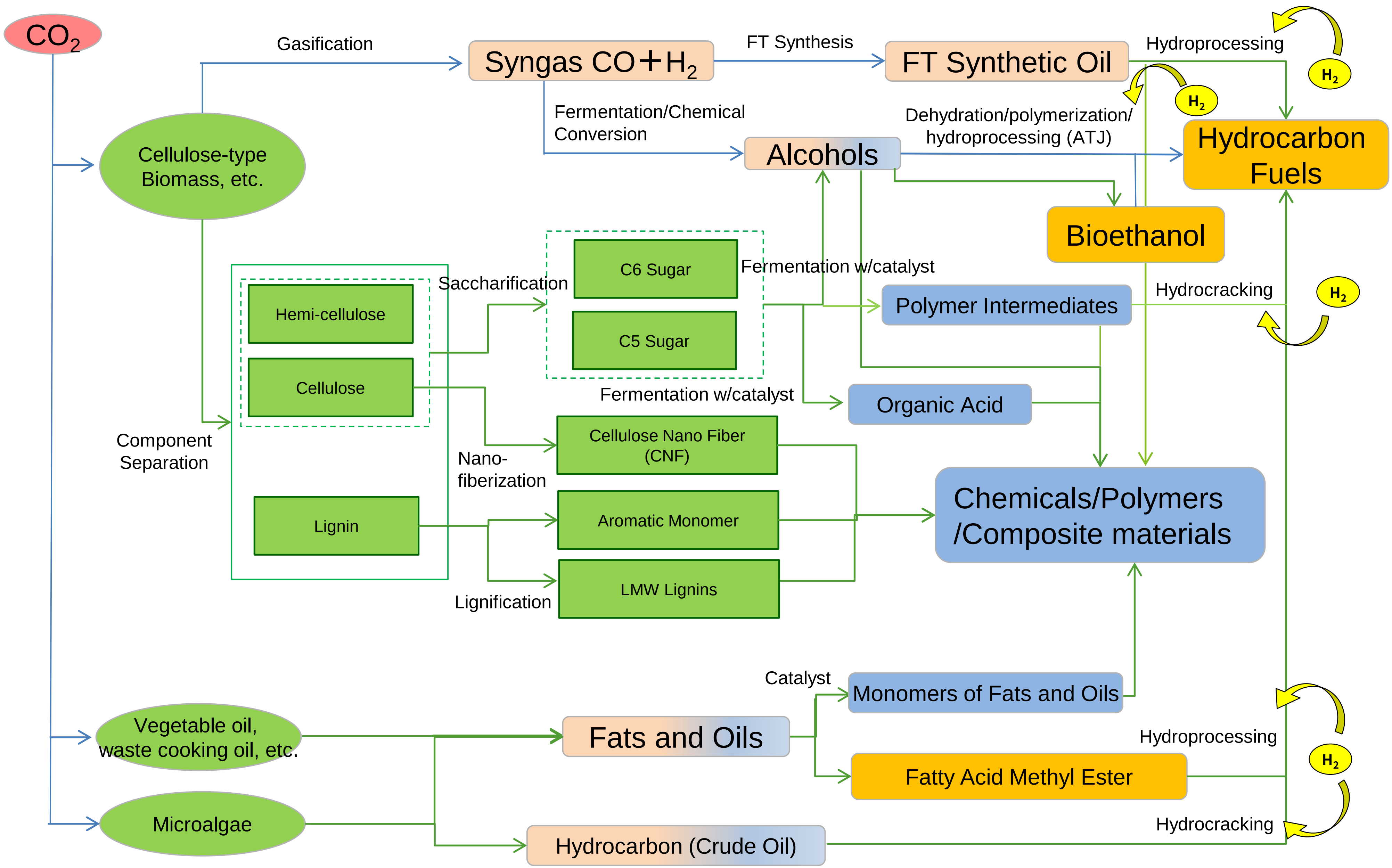
- Inexpensive CO_2 free Hydrogen is important for many technologies
  - Under the hydrogen and fuel cells strategy roadmap in 'Hydrogen Basic Strategy', the target at costs at delivery site for 2050 is JPY 20/Nm^3
  - While the problem of hydrogen supply remains, 1) R&D for biomass and other technologies not dependent on hydrogen should be continue, 2) CH_4 (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, CO_2, 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 CO_2 will positively feedback into Carbon Recycling.

Reference

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



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



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