Demonstration Activity of the Bio-Jet Fuel Contributing for the Carbon Neutrality in the Aviation Industry

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Having set the target limit increase of CO_2 emissions after 2021 for the decarbonization of the aviation industry, the International Civil Aviation Organization (ICAO) proposes, as the main measures, the introduction and spread of sustainable aviation fuel (SAF). SAF includes the bio-jet fuel (BJF) produced by biomass gasification technology combined with Fischer-Tropsch (FT) synthesis. Between 2017 and 2021, Mitsubishi Heavy Industries, Ltd. (MHI), in collaboration with JERA Co., Inc. (JERA), Toyo Engineering Corporation (TOYO) and Japan Aerospace Exploration Agency (JAXA), built a pilot plant for the biomass gasification and FT synthesis process to produce BJF and conduct combustion and engine tests. The produced BJF was used in a flight by Japan Airlines (JAL). Our biomass gasification technology is an energy conversion technology that plays a part in energy transition. Using this technology, we will provide solutions for decarbonization in the aviation industry.

1. Introduction

In relation to aviation fuel, the development of hydrogen, ammonia and electric aircraft are under way as alternatives to fossil-derived jet fuel (kerosene). However, none of these have yet found their way to commercialization. Especially when it comes to long-haul flights, there are, as yet, no alternatives to jet fuel. In the aircraft industry, with a view to not increasing CO_2 emissions after 2021, ICAO, a United Nations specialized agency, has laid out the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) until 2035. In order to fulfill the goals, SAF is expected to be indispensable as one of the key measures in addition to improving the efficiency of flight control and introducing new equipment. Neat SAF refers to the fuel produced from plant-derived feedstocks, animal oils and captured CO_2 with electrolytic hydrogen using renewable electricity. When blended with Jet A-1 fuel, it is called SAF. Neat SAF is a fuel that enables sustainable energy circulation of CO_2 generated by combustion. As Neat SAF, what is currently being tested for practical application is one synthesized from oils or alcohols and one produced by FT synthesis using syngas produced by gasification of plants.

Since around the end of the 1990s, we have worked on the development of gasification technology that is pivotal to the carbon-neutral thermochemical conversion of biomass. Commissioned by the New Energy and Industrial Technology Development Organization (NEDO), we conducted a joint research project with JERA, TOYO and JAXA from 2017 until 2021. A pilot facility for the gasification and FT synthesis process using woody feedstock was built on the premises of JERA's Shin-Nagoya Thermal Power Station, to demonstrate the viability of integrated BJF production from wood. The produced BJF was used in a JAL commercial flight from Haneda

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to Shin-Chitose in June 2021. This report describes this project, focusing on the use of BJF as well as our energy transition technology based on biomass gasification.

2. Features of the biomass gasification and FT synthesis plant

2.1 Features of the gasifier

Sustainable feedstock is needed to produce sustainable BJF. Forest resources can be sustainable when afforestation is appropriately managed and the cut timber is proportional to the amount of growth. The gasification and FT synthesis process, which is shown in **Figure 1**, is a BJF synthesis technology using such woody biomass. The key lies in the gasification technology to produce syngas that enables stable and highly efficient FT synthesis. As shown in **Figure 2**, there are three types of gasification depending on the mode of solid-gas (powder-gas) multiphase flow: fixed bed, fluidized bed and entrained bed. Fixed bed and fluidized bed are advantageous in terms of handling of biomass, as 20-30mm chips can be used in these types. Fluidized bed is favorable when using high-moisture biomass, thanks to its large thermal capacity. On the other hand, biomass gasification has the issue of tar production. Less tar is produced with higher temperatures, although higher temperatures increase the risk of clinker formation from biomass ash. Entrained bed is of use in this regard because, in this type of gasification, solids are less likely to make contact with each other, thereby reducing the clinker formation risk. The advantage is enhanced when the temperature of gasification is elevated, as this results in less production of tar. As described so far, the preferable conditions for biomass handling and gasification stability are at odds with each other, which makes it difficult to simultaneously bring out the best in both of them.

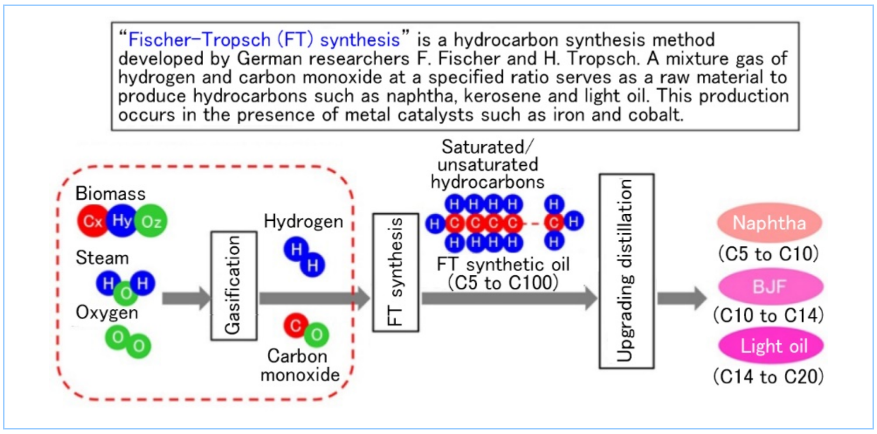

Figure 1　BJF production by gasification and FT synthesis

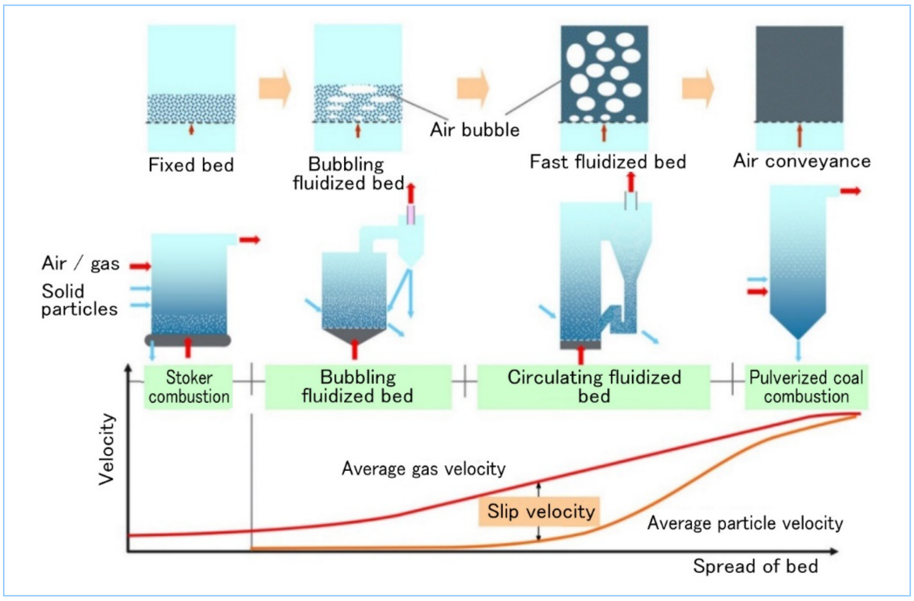

Figure 2　Solid-gas multiphase flow technology for gasification

An entrained bed gasifier is employed in our coal gasification technology. However, as a lock hopper system is used to feed pulverized coal into a pressurized gasifier, blockage prevention is needed by pulverizing coal to a particle diameter/shape achieving high fluidity. Because of it being fibrous, biomass generally has poor grindability and therefore needs a lot of power to grind it into fine particles, if required as in the case of coal. For this reason, we have developed an entrained bed gasification technology in which relatively rough pulverization to a diameter of about 10 mm can suffice. As shown in **Figure 3**, the structure of the gasifier was designed in such a way as to ensure the retention times required for both large and fine particles in the gasifier, whereby gasification can be performed successfully. In this way, less power is required for grinding biomass, while the advantage of a high gasification temperature can be maintained.

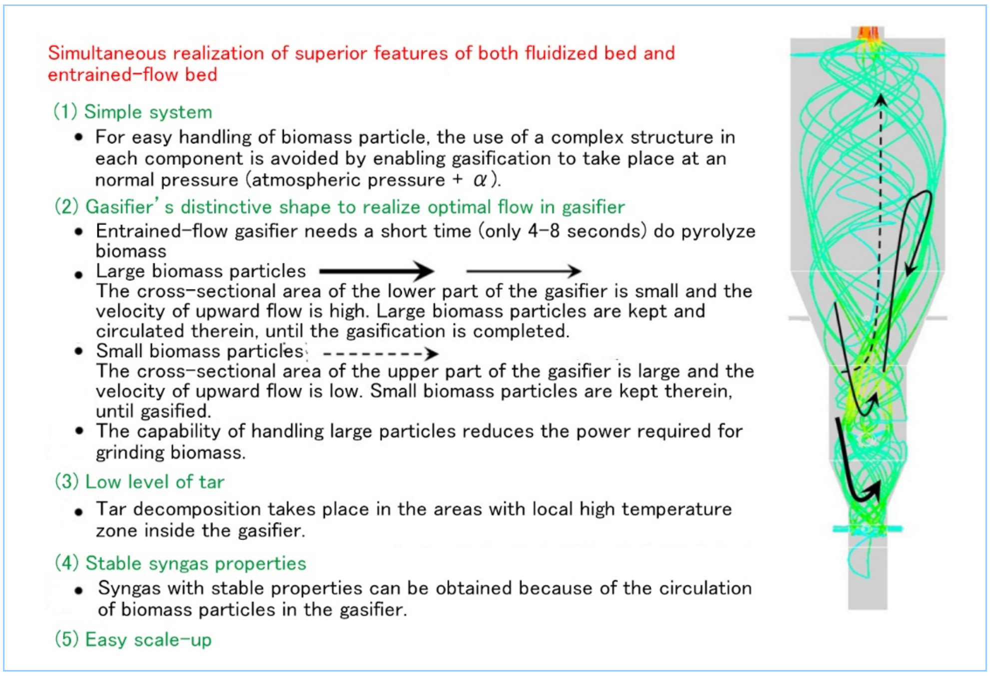

Figure 3　Features of entrained-flow gasifier for biomass

2.2　Pilot testing of bio-jet fuel production system

During the project period between 2017 and 2021, we built a pilot plant to perform the integrated production from biomass to jet fuel, in which this gasification technology was used in combination with TOYO's FT synthesis system based on Velocys's proprietary FT technology shown in **Figure 4**. The produced fuel was used in a commercial flight.

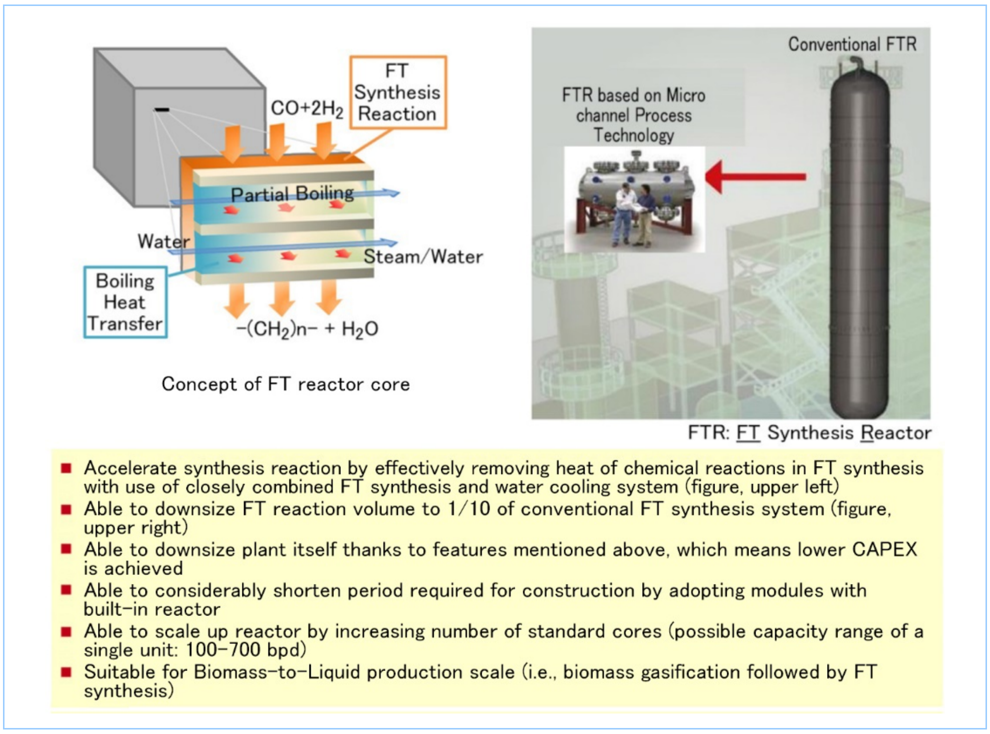

Figure 4　Overview of FT synthesis system

Verification testing using the pilot plant was conducted under the organizational structure shown in **Figure 5**. Built on the premises of JERA's Shin-Nagoya Thermal Power Station, the pilot plant had a biomass processing capacity of 0.7 tons/day shown in **Figure 6**. We were responsible for the gasification facility, while TOYO was responsible for the FT synthesis system. The produced bio-jet fuel was tested by JAXA for its combustion and engine characteristics.

The gasification facility achieved 3,079 hours of operation, while the FT synthesis system achieved 1,543 hours of operation including 30 days of continuous operation exclusively by JERA operators. The production of reformate totaled 4,233 liters, of which Neat BJF amounted to 2,366 liters and satisfied the ASTM standard requirements. Thus, this pilot testing is considered to have successfully demonstrated the viability of the process(1).

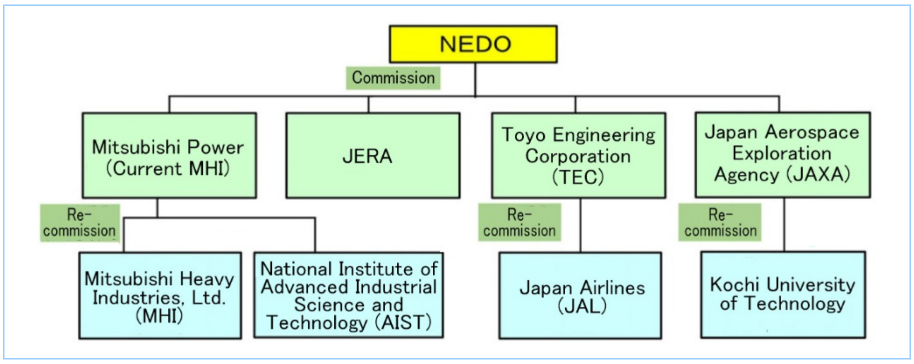

Figure 5 Organizational structure for pilot plant research project

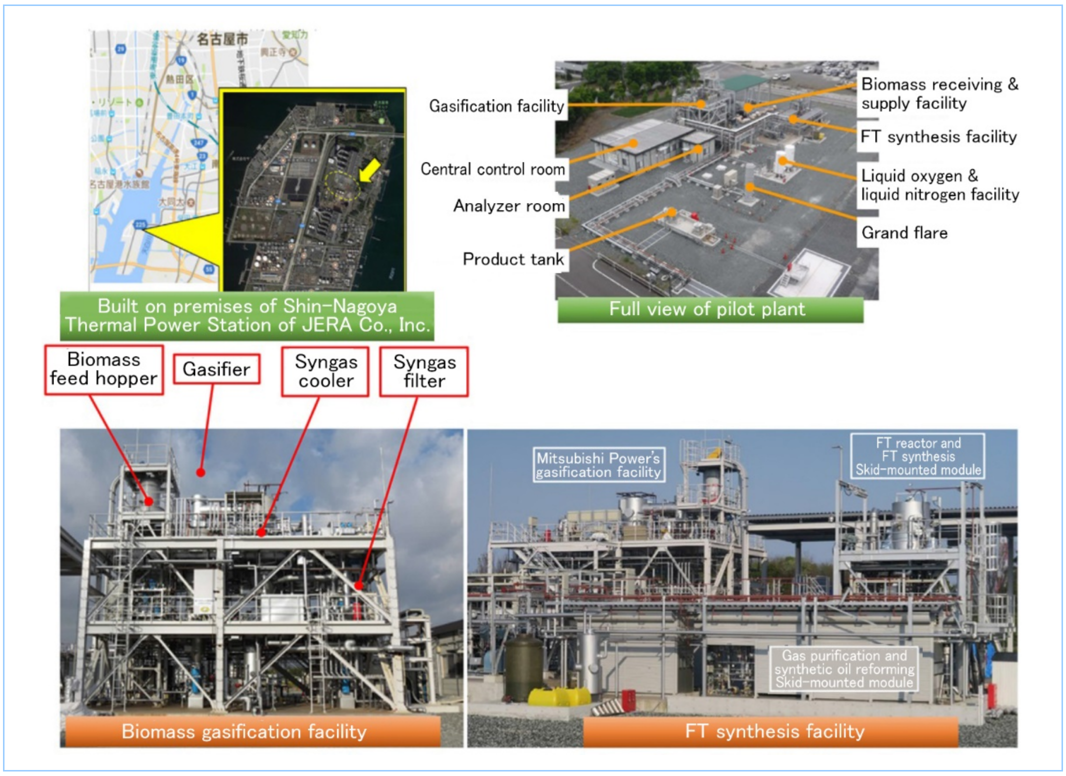

Figure 6 Pilot plant facilities

The combustion characteristics of the produced fuel were assessed under the conditions in which the blending ratio with the conventional JET A-1 fuel varies from 0% to 100%. As shown in **Figure 7**, the results indicate that the combustion characteristics such as exhaust gas component are comparable to those of JET A-1. Especially because of the low content of aromatic hydrocarbons, the formation of particle matter (PM) is greatly less than JET A-1. Thus, the superiority of BJF is also indicated from a viewpoint of PM reduction measures. Although it was not possible to test on a turbofan engine because of the coronavirus pandemic, the performance was measured using a model turbojet engine by Kochi University of Technology. The results have also confirmed that there is no difference between our BJF and JET A-1 in terms of performance, specifically including thrust, intake air flow, thrust specific fuel consumption rate, and exhaust gas temperature(2).

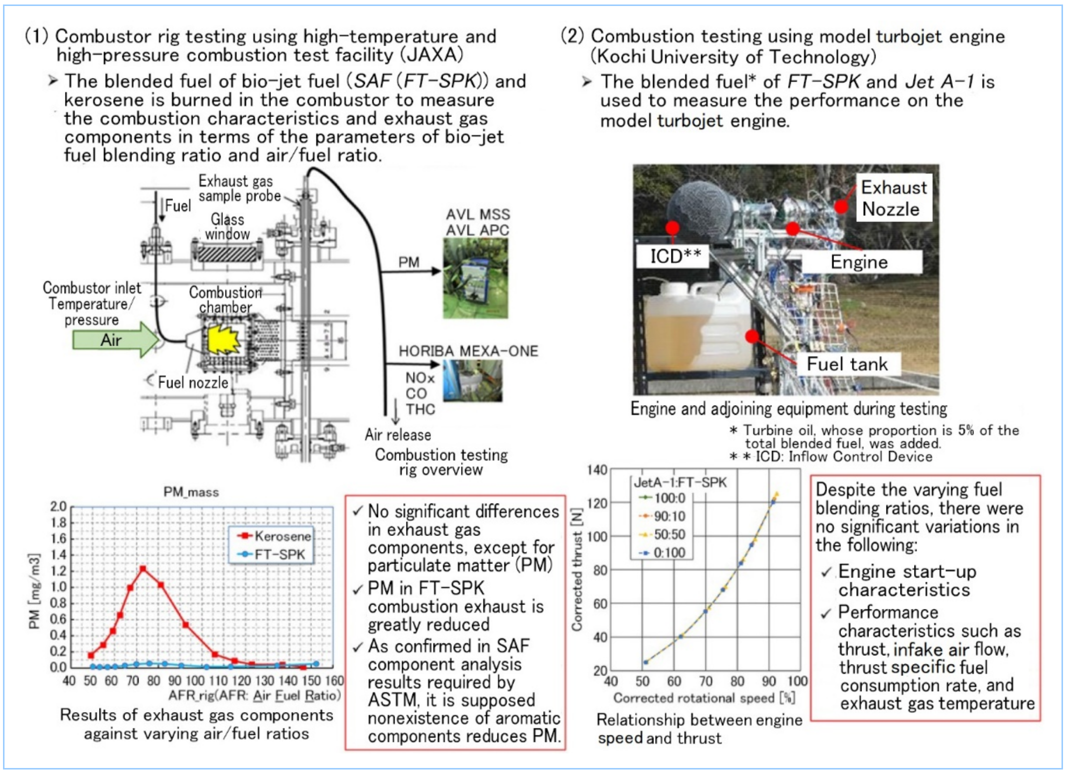

Figure 7 SAF combustion characteristics testing

2.3 Application in commercial flight

Of the produced BJF, 283 liters was blended with JET A-1 at an oil company's plant, and 2,195 liters was used as a SAF drop-in fuel for the JAL 515 flight from Tokyo/Haneda to Shin-Chitose on June 17, 2021. We proceeded with this application, while ascertaining that both the Neat SAF and the JET A-1 blended SAF met the ASTM standards. The blending ratio was 3%, which was made public by a press release of the Japanese Ministry of Land, Infrastructure, Transport and Tourism[3]. This was the world's first commercial aircraft flight in which bio-jet fuel produced from woody biomass using an integrated production system was used. Thus, a series of processes from the bio-jet fuel production to the fueling of aircraft, which are shown in **Figure 8**, have been demonstrated.

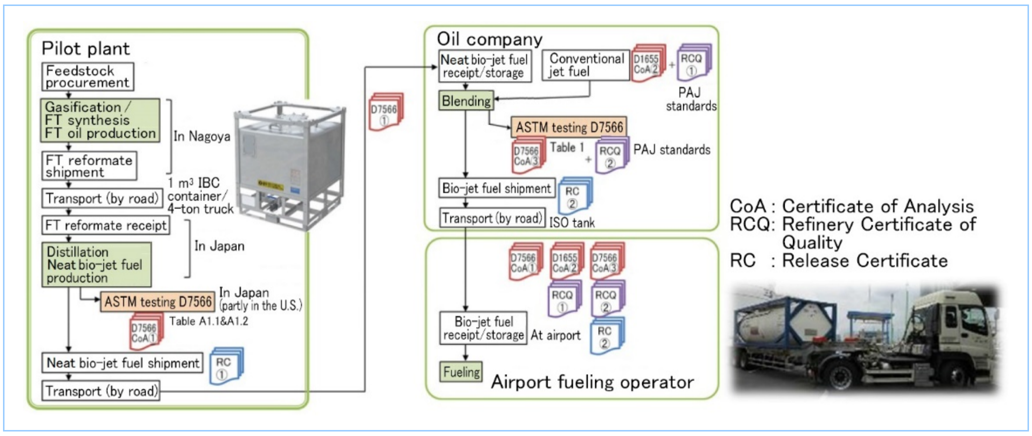

Figure 8 Series of processes from bio-jet fuel production to fueling of aircraft

3. SAF standards and certification

The SAF standards are set out in ASTM D7566, which prescribes in its Annexes the permissible feedstocks and production methods, and the upper limit of blending ratio with conventional jet fuel for each of the production methods. Adopting a new production method requires approval from the ASTM Standards Committee. The gasification and FT synthesis process is a technology already registered in Annex 1, in which blending of up to 50% is allowed. **Table 1** lists the approved technologies as of 2020[4].

Table 1 Annexes of the ASTM D7566 standards (as of 2020)

Annex	Conversion process	Blending ratio
Annex 1	Fischer-Tropsch hydroprocessed synthesized paraffinic kerosene (FT-SPK)	Up to 50%
Annex 2	Synthesized paraffinic kerosene from hydroprocessed esters and fatty acids (Bio-SPK or HEFA)	Up to 50%
Annex 3	Synthesized iso-paraffins from hydroprocessed fermented sugars (SIP)	Up to 10%
Annex 4	Synthesized kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources (SPK/A)	Up to 50%
Annex 5	Alcohol to jet synthetic paraffinic kerosene (ATJ/SPK)	Up to 50%
Annex 6	Catalytic hydrothermolysis jet fuel (CHJ)	Up to 50%
Annex 7	Synthesized paraffinic kerosene from hydrocarbon hydroprocessed esters and fatty acids (HC-HEFA SPK)	Up to 10%

Source: MANUAL FOR PROPER HANDLING OF SUSTAINABLE AVIATION FUEL (SAF) ISSUE 1, Aug. 2021 by the Aviation Fuel Expert Committee of the Petroleum Association of Japan,

To be used for CORSIA, SAF should be produced in compliance with the criteria that prove the produced SAF is a CORSIA eligible fuel (CEF). The production process is to be reviewed and approved by a third-party certification organization. CEF can be classified as SAF or low carbon aviation fuel (LCAF). In either case, CEF has to meet the CORSIA sustainability criteria, which demand, for validation, the assessment on a life cycle basis including indirect land use change associated with fuel production, require the achievement of net greenhouse gas emission reductions of at least 10% compared to the level of fossil fuel, and specify that biomass obtained from land with high carbon stock should not be used. The land with high carbon stock pertains to the land that was primeval forest, wetlands or peat lands and was converted after January 1, 2008. If land use was indeed converted after January 1, 2008, the Intergovernmental Panel on Climate Change (IPCC) land categories should be used to calculate the induced land use change (ILUC) emissions; the result will be added to the emissions associated with production (core lifecycle assessment or Core LCA). In the LCA of CEF, an ICAO default value may be used, or an actual value may be calculated following the ICAO methodologies. **Figure 9** shows some examples of the default values for LCA of CEF[5]. The default value of the gasification and FT synthesis process (as indicated by FTJ in the figure) is lower than other production methods.

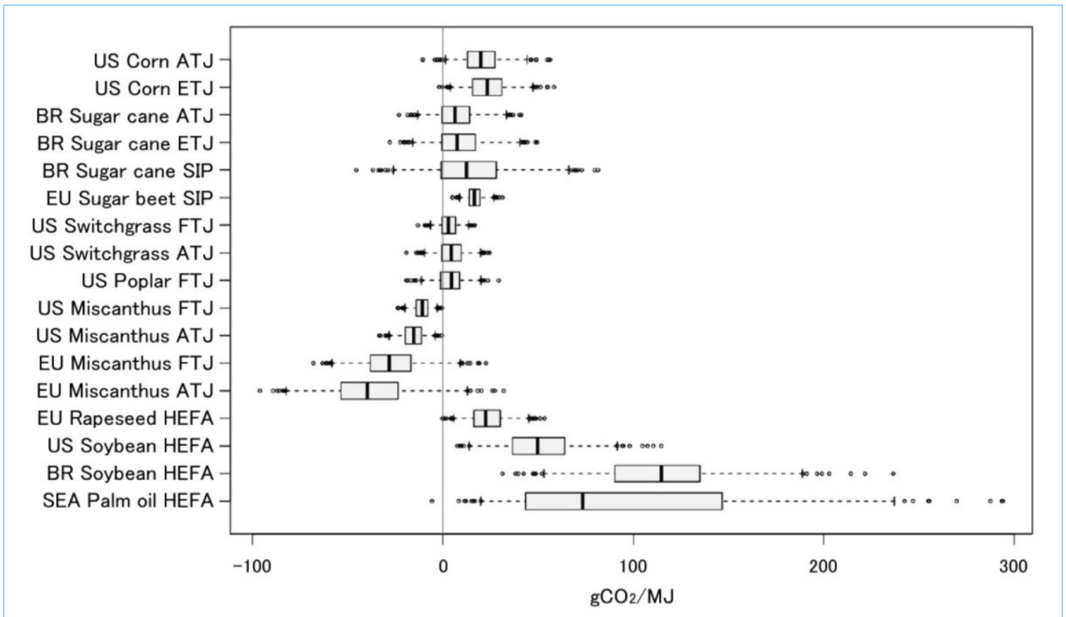

Figure 9 Examples of default values for ICA of CEF

At present, there are two certifying authorities with standards: the International Sustainability and Carbon Certification (ISCC) and the Roundtable on Sustainable Biomaterials (RSB). These two certifying authorities have their own recognized certification organizations, which review the third-party certification organizations and accordingly accredit them for handling a certification process[6][7]. The certification is based on chain of custody (CoC) standards. The CoC certificate ensures transparency throughout the supply chain including feedstock's point of origin, collection, processing and traders and, at each transaction point along the supply chain, assures that the ISCC/RSB-certified products were made from the feedstock procured from the certified producers. The CoC standards basically requires having a management system that meets the requirements prescribed by the CoC standards, checking up on the suppliers registered on the ISCC/RSB certificate, checking on the transactional documents and the quantities of traded products, confirming the traceability, and having product identification and labeling systems. Producers seeking certification need to submit the application form to a third-party certification organization for a contract and be examined via internal audit to prove that the requirements set by the standards are satisfied.

4. Energy transition by biomass gasification

In gasification and FT synthesis, by-products such as diesel oil, naphtha and LPG are obtained in addition to bio-jet fuel. These by-products are also green fuels derived from biomass. For example, the quality of naphtha is high enough to be suitable for chemical synthesis, and it can be used as a raw material to produce plastics. Moreover, if captured, the CO_2 generated in the production process, which is of course derived from biomass, can be expected to be a new source of domestic CO_2 supply, as the mergers and closures of domestic oil refineries are causing a shortage. Since the char removed from the gasifier is also derived from biomass, underground carbon fixation or use as a fertilizer can be considered. If such hydrocarbons can be synthesized from carbon monoxide and hydrogen, they can be produced by replacing FT synthesis with the relevant processes.

As described so far, it can be said that biomass gasification is one of the energy transition technologies capable of replacing the chemical industrial processes that have been conventionally carried out using fossil fuels. Because of the recent implementation of the feed-in tariff (FIT) system for renewable energy, many biomass power generation facilities have been built in Japan. Since biomass is a solid like coal, it is used as an alternative to coal or a fuel for decarbonization in power generation. If we aspire to zero emissions in the years to come, the replacement of petroleum and its decarbonization will also be discussed. In this case, the possible alternatives are considered to be biomass or hydrocarbons synthesized using atmospheric CO_2 and renewable hydrogen. It would be possible to use CO_2 and renewable hydrogen as feedstocks, if renewable electricity prices decline and CO_2 can be extracted from the atmosphere at low cost. However, in the meantime, biomass will be the feedstock. The synthesis of chemical products by means of biomass gasification will first be advanced technologically through the production of aviation fuel, which has no alternative means, and will be implemented in society. Depending on how decarbonization will progress, biomass may also serve as a major raw material in chemical production. When this happens, biomass gasification is expected to play a critical role as the key energy transition technology.

5. Conclusion

Since around the end of the 1990s, we have developed the biomass gasification technology. Having applied the technology to the production of bio-jet fuel (one type of SAF), we verified its viability through a demonstration of the process involved. With this technology, syngas with stable properties can be produced. This is therefore a gasification technology suitable for the processes of chemical synthesis and is also a carbon energy conversion technology that will substitute petroleum in the future and produce environmentally superior fuels and raw materials suitable for chemical production.

While promoting the practical application of gasification technology for the production of bio-jet fuel, we expect that it will also become a technology to supply raw materials for chemical production.

Some of the results presented in this report is based on results obtained from a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO) (JPNP17005).

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