The Present Status and Future Scope of Bioenergy in Japan

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Situations of Japanese biomass in terms of resource, utilization technology, and system evaluation are reviewed. The feed-in tariff system can be another driving force to introduce biomass. The utilization of biomass in Japan is not large now, but its potential amount is 1.2 EJ/year, while world biomass availability is expected to be 200 EJ/year. Technologies are being developed for electricity generation, production of 1st, 2nd, and 3rd generation biofuel, as well as fuel gas production. In addition to these single conversion technologies, biorefinery is to be studied where biomass is fully utilized to produce both value added and common products. Latest information is introduced for each topics.

Key Words
Biomass, Availability, Conversion technology, Biorefinery

1. Introduction

In developing countries, biomass is utilized mainly for cooking and heating. In developed nations, however, biomass is also used in sophisticated ways to generate power, as well as to produce alternative gaseous and liquid fuels, chemicals, and other bio-based materials. In Japan, a feed-in tariff (FIT) system was introduced in 2012 to enhance the introduction of renewable electricity, and several wood-fired power stations have been built, each with a capacity greater than 5 MW. The number of such power stations is expected to increase 1). In other power plants, dry biomass is mixed with coal for use as fuel to generate heat and electricity. This co-firing is often employed by the large scale coal fire plant. Additionally, the Japanese government intends to distribute 850 dam³ (850,000 kL) of bioethanol (equivalent to 500,000 m³ of oil) as E3 by 2017 2), although ethanol is blended with gasoline only after conversion to ethyl tertiary butyl ether. On the other hand, biodiesel fuels, produced mainly from waste cooking oil, has been used to replace diesel in small towns and communities, either as B5 (5 % blend of biodiesel in diesel oil) or B100 (neat biodiesel). The amount of biodiesel consumed is around 15 dam³ 3). Finally, anaerobic technologies have been employed to treat waste properly and to recover energy for it, but these processes are not economically viable without adequate support mechanisms like FITs or subsidies.

As the reason of these situations, incentives to utilize biomass in Japan are numerous and diverse: depletion of fossil fuels, reduction of greenhouse gas (GHG) emissions, revitalization of the forestry industry, utilization and disposal of unused and waste biomass, and creation of new businesses and jobs. In our opinion, the strategy to utilize biomass in Japan should focus on specific purposes to make domestic and international situation better.

The main purpose of the domestic strategy should be to revitalize primary industries, particularly forestry, by converting waste and unused biomass to heat and electricity. To illustrate this strategy, we examine 1st generation bioethanol as an example, since 2nd generation bioethanol still remains in research and development. Bioethanol can be produced rather easily from sugars and starch and its production from rice, wheat, and sugar beet has been demonstrated in Hokkaido and Niigata 4). Thus, it should be plausible to also produce bioethanol from rice planted in Fukushima Prefecture where nuclear accident occurred. The advantages of bioethanol production in this region have been described previously 5) 6).
new businesses and jobs, particularly in Fukushima and neighboring Prefectures.

Alternatively, bioethanol could be produced in foreign countries, where inexpensive feedstock is available on a large scale, so that production cost becomes competitive with international market price. In the end, this foreign bioethanol could help alleviate global warming, create new industries, and reduce consumption of fossil fuels, particularly in Asian regions, where energy demand will increase due to rapid economic growth.

2. Potential Biomass Supply

Estimates of biomass potential in the world vary greatly due to variability in methods to measure food demand, soil and water constraints, biodiversity, resource management restrictions, and a number of other sustainability issues. Thus, potential biomass supply is believed to range from the current level of production (about 50 EJ) to levels significantly beyond the current global primary energy consumption (500 EJ). According to the International Energy Agency (IEA), sustainable biomass potential in 2050 will be 200 to 500 EJ/year. This potential comes from agricultural and forestry residues (ca. 100 EJ), surplus forest production (ca. 80 EJ), energy crop production on possible surplus good quality agricultural and pasture lands (ca. 120 EJ), and the potential contribution of water-scarce, marginal and degraded lands for energy crop production (ca. 70 EJ). If agricultural productivity increases faster than historic trends, another ca. 140 EJ may become available for use. In the end, it seems that 200 EJ is more plausible, because of competition for land, but effort should nevertheless be expended to achieve 500 EJ through technological development and international collaboration.

Available biomass resources in Japan are shown in Table 1, based on information from the Ministry of Agriculture, Forestry and Fisheries. The maximum available biomass is believed to be 11 Tg-C, or 11 million tons on a carbon basis, based on the assumption that biomass currently not in use will become partly available in 2020. In this table, black liquor is already almost fully exploited to produce heat and chemicals, so no additional energy is expected from this source even in 2020, unless current technology is replaced with more efficient alternatives. On the other hand, available forest residue is 1.2 Tg-C, which is 30% of its potential, 4 Tg-C. Availability will increase if artificial forests are thinned properly and regularly. In 2011, only 5%, or 5,500 km² (550,000 ha), of national and privately owned forests was thinned. Since the total area of artificial forest is 103,500 km², and thinning is usually done every 6 years, 17,300 km² may be safely targeted, which is three times larger than the present area. Available forest residue will increase by 30% in 2020, but will grow up and eventually approach 4 Tg-C. In any case, forests should be properly managed, because more residue will be consumed when thinning is increased.

The total potential biomass is about 30 Tg-C, corresponding to roughly 1.2 EJ. It is important to fully utilize these biomass resources with the greatest efficiency in order to revitalize forestry and local economies, as well as to reduce greenhouse gas (GHG) emissions. Unfortunately, it is hardly possible for Japan to rely on energy crops because of limited land and prohibitive production cost.

3. Biomass Conversion Technologies

3.1 Power generation and co-generation

With the implementation of FIT in Japan in 2012, power generation from biomass became economically attractive because electricity can be sold between 13.65 JPY/kWh (1 USD=120 JPY, as of Mar. 6, 2015) and 40 JPY/kWh when generated from thinned wood and in small scale, respectively. At present, the number of wood-fired power plants operating under FIT is limited; however, more are expected to come online in the future.

Fig. 1 depicts the relationship between the available biomass and the technology suitable to convert it to energy. If the available biomass is around 10 Mg/d (10 tons per day) or so, it should be used as feedstock to generate heat from stove and boiler. On the other hand, if available biomass is around 170 Mg/d, power can be generated by ordinary steam turbine. However, when the available biomass is less, power generation by steam turbine is unacceptable because of low efficiency. In this case, power is generated by gasification, which produces combustible gases that fuel gas engines or turbines. Nonetheless, gasification has not been adopted so far because of higher construction cost per kW, and because of unstable operation due to factors like
There are numerous types of gasifiers, including downdraft and updraft fixed-bed, entrained bed, fluidized bed, and rotary kiln, each with its own advantages and disadvantages. Reaction conditions such as temperature, operating pressure, feeding system, and gasification agent are also variable. In any case, the tar inevitably produced in the process presents a big operational challenge, because it fouls up in the power generator, and additional cost may be required to maintain the plant. Another factor that contributes to unstable operation is heterogeneity of feedstock in terms of wood species, size, moisture content, heating value, and ash content. Thus, there is a strong need to build compact and efficient gasifiers at reasonable cost, in accordance with FIT requirements.

Co-firing is the process of burning a blend of biomass and coal. In this case, biomass is used as a supplement, and represents about 3% or less of the fuel burned. Co-firing is easy to implement, because most coal-fired power plants in operation can burn biomass directly, even though existing boilers may have to be retrofitted to maximize efficiency. In Japan, all of 10 electric companies operate or plan to operate co-fired power plants.}

### 3.2 2nd generation bioethanol

Bioethanol can be produced from sugars, starch, and cellulosic materials. Bioethanol produced from sugars and starch is called 1st generation bioethanol, while 2nd generation bioethanol is produced from cellulosic materials, as shown in Fig. 2. Bioethanol production from corn in the United States and from sugar cane in Brazil has accelerated rapidly in the past years. Bioethanol from sugar was criticized on grounds that it can raise food prices by competing directly with the food supply, and by competing for land.

Hence, 2nd generation bioethanol is produced from feedstock that is not edible, including cellulosic materials like wood and grass, as well as agricultural waste such as bagasse, rice straw, and rice husk. In comparison with 1st generation bioethanol, the 2nd generation requires an additional step to produce the same, as shown in Fig. 2. Lignocellulosic materials must be pretreated to delignify and saccharify to C6 and C5 sugars. Notably, life cycle GHG emissions of 2nd generation bioethanol is less, in spite of the energy required for additional processes. GHG emissions from 2nd generation bioethanol are reduced, because lignin separated from cellulosic materials can be utilized to generate heat and power, and because no energy is expended to cultivate, fertilize, harvest, and transport waste biomass. Thus, to estimate GHG emissions from 2nd generation bioethanol, it is only necessary to evaluate the energy required to pretreat and hydrolyze cellulose. Unfortunately, this estimation cannot yet be properly done, because 2nd generation bioethanol has never been produced yet on a large scale. Hence, GHG emissions from 2nd generation bioethanol are likely underestimated at present.

It is noteworthy to examine the history of bioethanol production from lignocellulosic materials, as depicted in Table 2. The discovery that sugar is produced when wood is reacted with sulfuric acid was made in 1819. Since then,
tremendous effort was devoted to the production of ethanol from wood. In Germany, the first plant was constructed to produce ethanol from wood using dilute hydrochloric acid in Tornesch. The second and third were constructed subsequently in Rheinau and Manheim which employed concentrated hydrochloric acid. In the late 1890s, these plants produced a little less than 76 cm³/kg-feedstock (76 L/t), but soon improved to generate around 190 cm³/kg17).

In Japan, anhydrous ethanol was produced from wood at the scale of 50-60 Mg/d via the Scholler process. It should be emphasized that 2nd generation bioethanol was produced in wartime even at very high production cost. In 1957, 1 Mg/d of sugar was produced by the Hokkaido process, but scale up to 80 Mg/d was unsuccessful. In 1980 and 1983, the Japanese government tried to produce 2nd generation bioethanol through the national projects RAPAD (Research Association for Petroleum Alternative Development) and FARA (Fuel Alcohol Research Association), respectively. Recently, New Energy and Industrial Technology Development Organization (NEDO) again initiated a project to attempt to produce 2nd generation bioethanol at 40 JPY/L.

An ideal process to pretreat biomass should produce high rates of hydrolysis, high yields of sugar, minimal degradation of carbohydrate, and minimal or zero production of chemicals that inhibit the microorganisms used in subsequent steps. The process should also be mild to reduce capital cost, should recycle chemicals to reduce running cost, and should generate minimal waste. Research and development is expected to develop a combination of the right technologies. These include, in addition to enzyme hydrolysis, hydrolysis in concentrated and dilute sulfuric acid; steam explosion; treatment with ammonia, lime and alkaline peroxide; wet oxidation; fractionation in organosolv, concentrated phosphoric acid, or ionic liquid; and microwave treatment18).

3.3 Biodiesel fuel

Biodiesel is a combustible fuel based on vegetable oil and composed of fatty acid methyl ester (FAME). Fatty acids are long-chain molecules that react to produce glycerol ester called triglycerides, which is the main component of fats and oils in animals and plants. Triglycerides are too viscous to use in a diesel engine. Thus, triglycerides are usually broken down into smaller molecules through transesterification, a process achieved by mixing with methanol and an alkaline catalyst, such as sodium or potassium hydroxide, at about 60 °C under atmospheric pressure. Rapeseed and sunflower oil are used as feedstock in the EU, while soybean oil is mainly used in the United States. Waste cooking oil and rapeseed oil are used in Japan to produce around 10 dam³ (10,000 kL) of biodiesel. Out of this, 1 dam³ is produced in Kyoto City, and used as B5 and B100. The use of biodiesel fuel has been shown to significantly reduce emissions of harmful air pollutants, although it emits slightly more nitrogen oxide than petroleum diesel19).

Saka and co-workers20) proposed a novel technology that uses supercritical methanol, does not require alkaline catalyst, and does not produce glycerol as byproduct. An improvement of this process, called the Saka-Dadan method21), involves two-step supercritical esterification, and has the advantage of requiring milder conditions. The technique is expected to be commercialized.

Recently, research and development has focused on direct production of hydrocarbons instead of FAME, hydrocarbons being superior in compatibility with engines and stability during storage22). Hydrocarbons are produced through hydrogenation, a process that costs less and uses a more flexible range of feedstock. The technology is in demonstration, and requires integration into an oil refinery to avoid building a unit dedicated to hydrogen production, as well as to maintain excellent fuel quality. Co-processing plants exploit the hydrotreating capacity of conventional
oil refineries, and produce pure or blended diesel. Such plants not only reduce capital costs, but also reduce output of petroleum-based diesel, although the process demands a large quantity of feedstock. Presently, stand-alone and co-processing hydrogenation plants already exist.

3.4 Liquid fuel from algae

Algae has attracted attention for various reasons as a source of 3rd generation liquid biofuel, including higher productivity compared to terrestrial biomass, high lipid and hydrocarbon content, and utilization of wastewater and flue gas for cultivation. Algae also do not compete with food crops, grow in aqueous cultures that are stable in temperature, and are not subject to water restrictions, especially if seawater is used\(^{23}\). In spite of such advantages, a number of challenges must be resolved to achieve commercial production. Even though systems analysis indicates that there could be significant economies of scale, the economics remain challenging unless improvements in productivity and performance are achieved, along with reduction in energy use.

In addition, algal production remains too expensive for fuel production alone. Hence, there is a need to produce products or services with higher value in addition to fuel and low-grade bulk chemicals. One possibility is wastewater treatment, with the added advantage that growing algae can consume carbon dioxide from an existing power plant that uses fossil fuels. Unfortunately, the seasonality of algal growth does not go well with the constancy of emissions from such power plants, so algae are unlikely to provide a complete solution to such emissions.

Algae are cultivated in either closed- or an open-pond systems. The advantages and disadvantages of each, as well as recent trends in algae research, were well summarized in a report from the IEA Bioenergy ExCo64 Workshop \(^{26}\). Open pond systems are likely to be cheaper than photobioreactors, because they require minimal plant construction, artificial lighting, and maintenance. Cost and performance principles are well understood, although the room for further development and innovation is probably limited. However, contamination with other microorganisms remains an issue, one that should be avoided or managed because crops may get damaged. Although there is room to improve performance and productivity via genetic modification, its application is necessarily restricted.

On the other hand, photobioreactors face their own issues. Current work centers on closed photobioreactor designs, and on ways to maximize photosynthetic efficiency and control metabolism and productivity. These can be achieved by shading, employing a vertical design, or increasing biomass density. However, high-density cultures perform better with more vigorous mixing, and thus require more energy, so an optimum balance must be sought. Furthermore, more vigorous mixing can generate shear effects through bubbling or flow, which eventually can lead to high incidence of fouling. Finally, some algae produce inhibitors at high densities, so such phenomenon needs to be avoided. Another factor being examined is the use of light guides, and research is being conducted to understand the flashing light effect as algae traverse light and dark zones. A key and related issue is light density, as maximum productivity is obtained only in bright light.

Recently, applied and basic studies by the programs of the Japan Science and Technology Agency have examined a variety of microorganisms, mainly cyanobacteria \(^{26}\). These studies include gene modification and mutation to induce higher production and stress tolerance, to manipulate substrate selectivity, to accelerate growth, and to exploit circadian rhythms. Although it will take some time before these studies are applied, we anticipate that novel technologies derived from them will be implemented.

3.5 Anaerobic digestion

Anaerobic digestion is biological degradation of organic matter in the absence of oxygen. The main product is biogas, a mixture of methane and carbon dioxide. Biogas generation involves hydrolysis, acidogenesis, and methanogenesis. In the final step, methanobacteria consume acetic acid to produce biogas, and the methane content of the product is 60-70 %. The rest is carbon dioxide and trace amounts of other gases.

Anaerobic digestion is classified as mesophilic if it occurs at 25-40 °C, and thermophilic if it occurs at 50-70 °C. Biogas production is improved by increasing the temperature. In Japan, 40 and 23 anaerobic plants digest animal waste to generate electricity and heat, respectively. Food waste has also been used \(^{30}\). Both dry and wet processing technologies are well established with good track records, and have been proven at commercial scale worldwide, although the latter is more widely used \(^{27}\).

Biogas can be used essentially in the same manner as natural gas, and is considered renewable. Biogas can power an internal combustion engine or a micro gas turbine that drives a generator to produce electricity or heat. Biogas can also be used in transportation as fuel for modified internal combustion engines. Furthermore, biogas technology can be applied to advanced applications such as microbial fuel cells, in which specialized microorganisms digest biomass to generate hydrogen-rich biogas \(^{28}\). Although this technology
is still in infancy, it could have interesting prospects in the long term.

The economic viability of biogas operations is highly sensitive to plant capacity and feedstock price. Small-scale plants are often uneconomic, but centralized digestion may also be limited because of the distances over which animal waste would have to be transported. Transportation would necessarily increase the price of feedstock. Also, farm-based biogas digestion in rural Japan is often associated with challenges in selling surplus heat, and with exorbitant grid connection fees in remote areas. Thus, the country has adopted an FIT system for electricity generated by biogas\textsuperscript{10}). Nevertheless, operations will only become economically feasible if processes become more efficient; plants become less expensive to construct and feedstock less expensive to transport; and operations are scaled up appropriately.

3.6 Biorefinery

A biorefinery, as shown in Fig. 3, integrates various processes and equipment to produce fuel, electricity, heat, and chemicals from biomass resources such as wood, grass, organic waste, seaweed, and microalgae. This biorefinery concept is basically identical to the one proposed by National Renewable Energy Laboratory, United States\textsuperscript{29}), and analogous to petroleum refineries. Industrial biorefineries are believed to be the most promising route to a new domestic bio-based industry, and their development is driven by the need to replace fossil fuels. Indeed, the feasibility of petroleum exploitation is predicted to worsen in the near future, because of the expected increase in price of fossil fuels, and their unpredictable availability and environmental impact. Thus, sustainable production of biofuels and other high-value chemicals from biomass needs to be established, through integration of green chemistry into biorefineries, and through application of low-impact technologies.

Notably, the marine industry also stands to benefit from biorefineries, because marine algae such as kelp, and microalgae such as \textit{Botryococcus braunii}, are candidate feedstock. In Fig. 3, seaweed and microalgae are consumed as feedstock to produce value-added chemicals, along with methane\textsuperscript{30}). Indeed a combined marine and biorefinery industry would be expected to produce a variety of fine chemicals, pharmaceuticals, and polymers in addition to food and energy. Since the Japanese exclusive economic zone is sixth largest in the world, coastal and offshore resources should be utilized as much as possible toward biorefinery operations\textsuperscript{31}). Recently it was shown that genetic modification and engineering can greatly enhance production of biofuels from microalgae\textsuperscript{32--33}).

In the end, it is important to examine the size of biomass plant that would be required to be market-competitive and to progressively replace products from petroleum refineries. One of the smallest petroleum refineries in Japan produces 15.9 \text{dam}^3/\text{d} (100,000 \text{bbl per day}) by atmospheric distillation. In contrast, one of the biggest petroleum refineries in Saudi Arabia outputs 95.4 \text{dam}^3/\text{d}. In South Africa, the Sasol process has been implemented in a plant to gasify coal in order to produce syngas, which is ultimately converted to hydrocarbons by the Fischer-Tropsch process. This plant has capacity of 30,000 \text{t/d}, which is 30 \text{dam}^3 of hydrocarbons produced from 50,000 \text{t/d} of coal\textsuperscript{34}). In any case, an oil refinery or a coal-derived oil production plant is significantly larger than a biomass-fired plant. For example, a large power station fueled by biomass generates around 50,000 kW, and consumes 2,000 to 3,000 \text{t/d} of biomass, depending on efficiency and heating value of the feedstock, and assuming 50\% moisture content. This small scale of biomass plant is one of the cause of economic difficulties.
4. Conclusion

It is important to consider the feasibility of biomass utilization, in light of feedstock availability, technical maturity of various processes, and economic support systems such as FITs. Biomass is broadly categorized into waste and green biomass. Waste biomass such as food and animal waste, sewage sludge, and demolition timber should be converted to energy, heat and other chemicals as a way to dispose of waste. On the other hand, green biomass such as forest residue should be utilized in cooperation with housing manufacturers to revitalize forestry and to create new industries and jobs. It should be emphasized that an industry based on biomass is renewable. Needless to say, conversion of biomass into energy can contribute to the reduction of GHGs.

Technologies to convert biomass to energy should be categorized according to maturity. Generally, processes to gasify biomass seem mature, but small-scale gasifiers require further improvements in efficiency, ease and stability of operation, tar removal, and cost-effectiveness of construction. As for advanced technologies such as 2nd and 3rd generation biofuels, different strategies for commercialization should be implemented in Japan and beyond. While it takes time to commercialize technologies on a large scale, the efficiency of each process should be improved in the mean time, and smaller scale plants should be able to operate continuously without serious disruptions.

Three years after an FIT system was adopted, several wood-fired plants with capacity around 5 MW have become operational. However, the market might already be approaching a ceiling due to unavailability of woody biomass. Thus, power generation by gasification at a scale smaller than 1 MW is strongly recommended. Furthermore, it is imperative that society should increasingly adopt FITs, and should review and revise the electricity price from time to time.

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