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## A Comparative Study of the Effect of CO<sub>2</sub> Emission Reduction by Several Bioenergy Production Systems

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**Abstract** – Biomass can contribute to sustainable development and globally environmental preservation since it is renewable and carbon neutral. Unused biomass such as oil palm trunk, which is discharged in large quantities when palm trees are cut down, could be converted to useful energy. This paper evaluates the effect of CO<sub>2</sub> emission reduction by four biomass conversion systems within the framework of the Clean Development Mechanism (CDM). These systems are power generation by direct combustion, power generation by the biomass integrated gasification combined cycle (BIGCC), an alternative method of diesel oil production by Fischer-Tropsch synthesis, and an ethanol production by saccharification of cellulose followed by fermentation. Power generation by BIGCC gives the highest CO<sub>2</sub> emission reduction. Taking the maturity of technology into account, however, power generation by direct combustion is the most favorable for the CDM project in the short term. The emission reduction of liquid fuel production is lower than that of power generation. Biomass is the only organic form of renewable energy, so it is important to convert biomass into liquid fuel for displacing fossil liquid fuel.

**Keywords** – Clean Development Mechanism, ethanol, F-T diesel, IGCC, oil palm trunk.

### 1. INTRODUCTION

#### *Effect of Biomass Utilization*

Biomass is considered to be renewable and carbon neutral insofar as its production and consumption are balanced, and so it can contribute to stabilization of greenhouse gas emissions in the atmosphere. In order to prevent global warming, more renewable energy should be used. Biomass has a unique characteristic compared with other forms of renewable energy: it can take various forms such as liquid, gas and solid, and so can be used for electricity or mechanical power generation and heat.

Tropical and semitropical areas like Southeast Asia are blessed with favorable climatic conditions for biomass production, so a large quantity of unused biomass is produced every year through agricultural activity. In addition, it is forecasted that energy demand will increase in these areas. If biomass could be converted into useful energy, the consumption of fossil fuel and greenhouse gas emissions would be decreased. Furthermore, the use of biomass could lead to the creation of a new biomass industry, which would help revitalize agriculture and forestry leading to social stability as well as economic stimulus.

#### *Clean Development Mechanism*

Three mechanisms (Emission Trading, Joint Implementation, and Clean Development Mechanism) are established in the Kyoto Protocol, which are expected to provide grate flexibility and reduce the costs of mitigation measures [1]. In terms of creating a new relationship between developing and developed countries, the Clean Development Mechanism (CDM) is attracting attention. The CDM is intended to assist developing countries in

achieving sustainable development, and to assist developed countries in achieving compliance with emission reduction targets [2]. The CDM can thus accelerate the utilization of abundant unused biomass, for example, in Southeast Asia.

The contribution of projects to reduce emissions entails the issuing of certificates, Certified Emissions Reductions (CERs), which can be traded internationally after proper validation of the project, and verification of the emissions reductions achieved. To administer this mechanism, it is necessary to estimate the exact amount of GHG emission reductions achieved by each project.

#### *By-products from the oil palm industry*

Over the last few decades, the Malaysian palm oil industry has grown to become a very important agriculture-based industry. Malaysia is today the world's leading producer and exporter of palm oil. There are two main products produced by the oil palm fruit, that is, crude palm oil (CPO) and crude palm kernel oil (CPKO). The palm oil is used for food, industrial raw material, and biodiesel.

Tables 1 and 2 show the availability of by-product in tons per hectare [3]. The main by-products from an oil palm mill are empty fruit bunch (EFB), palm oil mill effluent (POME), palm fiber and palm kernel shell. EFB has been used extensively as mulch and organic fertilizer in oil palm areas while palm fiber and shell are used as fuel which makes the palm oil mill self-sufficient in energy.

The main by-products from a plantation are oil palm frond (OPF) and oil palm trunk (OPT). OPF is produced regularly during harvesting, pruning, and replanting, while OPT is discharged as waste only periodically during replanting. The amount of OPF is large, and it contains a very sufficient nutrient. To maintain sustainable oil palm plantations, it should be used as a fertilizer.

It is easy to use the by-products from oil palm mills such as EFB, fiber, shell, and POME, because these by-products have already been collected. The economic life of the oil palm is about 25 years after which it has to be

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replanted. Since 75.5 dry-tons of oil palm trunk are generated per hectare every 25 years, the amount of OPT is expected to be 3.0 dry-tons on average every year. This value is higher than the by-products from oil palm mills. If OPT can be collected and transported efficiently, it has a great potential to become a useful energy.

**Table 1. Availability of by-products after milling**

Item	Dry Matter (t/ha/year)
Fresh fruit bunch	10.6
Empty fruit bunch	1.55
Fiber	1.63
Shell	0.99
Palm Oil mill effluent	0.67

**Table 2. Availability of by-products from oil palm plantation**

Period	Part	Dry Matter (t/ha)
Annual	Pruned frond	10.4
At replanting	Oil palm trunk	75.5
	Frond and rachis	14.4

### Objective

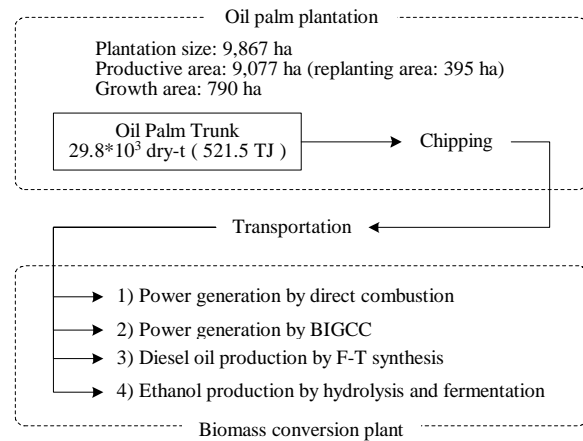
This paper evaluates the effect of CO<sub>2</sub> emission reduction by four bioenergy production systems. These systems are: (1) power generation by direct combustion; (2) power generation by the biomass integrated gasification combined cycle (BIGCC); (3) an alternative method of diesel oil production by Fischer-Tropsch synthesis, and (4) ethanol production by saccharification of cellulosic material followed by fermentation. The target material is the oil palm trunk (OPT) which is discharged from oil palm plantations during replanting. The methodology for estimating CO<sub>2</sub> emission reduction is constructed within the framework of the CDM.

## 2. SPECIFICATION OF BIOENERGY PRODUCTION SYSTEMS

### Overview of Bioenergy Production Systems

The system flow of bioenergy production is shown in Figure 1. The system is composed of three processes, chipping, transportation, and conversion, from the oil palm plantation to the conversion plant.

The size of oil palm plantations and available amount of OPT is also shown in Figure 1. The average capacity of a palm oil mill is about  $188.8 \times 10^3$  tons of fresh fruit bunch (FFB) per year. The FFB yield from productive area is 20.08 tons per hectare per year. The productive area is estimated to be 9,077 ha. The economic life of the oil palm is about 25 years, and the productive period for the palm tree that bears fruit is 23 years. The average size of a plantation is estimated to be 9,867 ha which is composed of productive area (9,077 ha) and growth area (790 ha). The productive area includes the replanting area (395 ha). The available amount of OPT in this system is  $29.8 \times 10^3$  dry-tons per annum, whose calorific value is 521.5 TJ. The characteristics of OPT are shown in Table 3 [4]-[5].



**Fig. 1. System flow of bioenergy production**

**Table 3. Characteristics of OPT**

Item	Value
Calorific value (LHV)	17.5 GJ/dry-t
Moisture content	50%
Specific gravity	0.76

### Chipping process

The moisture content of fresh OPT is about 50%. If fresh OPT is chipped, its bulk density decreases. This decrease of the bulk density makes its outside dimensions large, leading to a decrease of its moisture content. During transportation and storage, the moisture content of chipped OPT decreases to about 20%. The CO<sub>2</sub> emissions from combustion of fossil fuels for chipping of biomass are calculated by multiplying the amount of OPT measured in m<sup>3</sup> (78,421) by the average CO<sub>2</sub> emission factor for the chipping machine measured in kg-CO<sub>2</sub>/m<sup>3</sup> (1.605) [6]-[7]. The CO<sub>2</sub> emission from the chipping OPT is estimated at 126 t-CO<sub>2</sub> as given in Table 4.

**Table 4. CO<sub>2</sub> emissions by chipping OPT**

Item	Value
Chipped biomass/year	78,421 m <sup>3</sup> (fresh)
Emission factor for crusher	1,605 kg-CO <sub>2</sub> /m <sup>3</sup>
CO <sub>2</sub> emissions/year	126 t-CO <sub>2</sub>

### Transportation process

The CO<sub>2</sub> emissions for transportation to the project plant are calculated on the basis of distance and the number of trips. The OPT loaded onto a 15-ton truck is transported from the plantation site, about 3 km away from the project plant site. As the total biomass supply from the plantation site is  $59.6 \times 10^3$  tons/year, the truck will make the return trip 3,973 times per year. The CO<sub>2</sub> emission factor for heavy truck is measured in kg-CO<sub>2</sub>/km (1.108) [8]. The CO<sub>2</sub> emission from the transportation process is estimated as 26 t-CO<sub>2</sub> as given in Table 5.

**Table 5. CO<sub>2</sub> emissions by transportation**

Item	Value
Transported biomass/year	59,600 t (fresh)
Truck capacity	15 t
Average of return trip distance	6 km
Return trips to the plant/year	3,973
Distance traveled/year	23,839 km
Emission factor for heavy truck	1.108 kg-CO <sub>2</sub> /km
CO <sub>2</sub> emissions/year	26 t-CO <sub>2</sub>

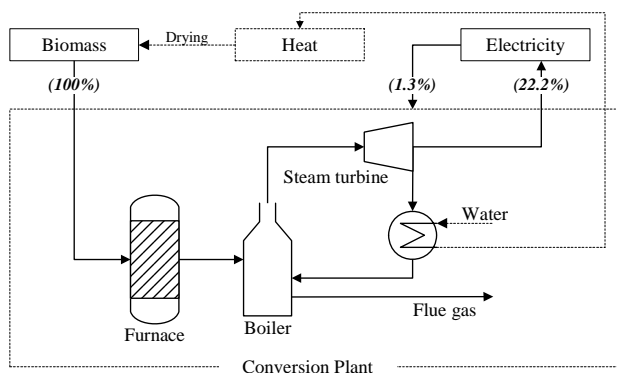
### Biomass Conversion Process

To consider the conversion efficiency of each conversion process, the production energy and conversion energy are quantified as a percentage of biomass energy input on a lower heat value (LHV) basis in Figures 2 to 5. The conversion efficiency is the ratio of production energy to biomass calorific value. These percentages are based on several studies of biomass conversion technology.

#### 1) Power generation by direct combustion

At present, power generation from biomass is generally done by direct combustion. Power generation by direct combustion is composed of two processes: steam generation by boiler and power generation by steam turbine. The diagram of power generation by direct combustion is shown in Figure 2.

The conversion efficiency of power generation by direct combustion is also given in Figure 2. The conversion efficiency is 22.2% electricity, but 1.3% electricity is used for the process itself, so the overall efficiency of this process is 20.9%. Discharged heat is used for drying OPT. These values are based on the conversion efficiencies when a conventional direct combustion technology is applied to biomass [9]-[10].



**Fig. 2. Scheme and conversion efficiency of power generation by direct combustion**

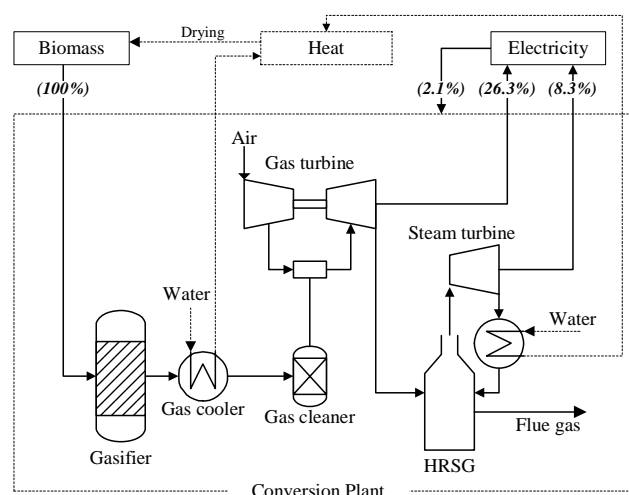
#### 2) Power generation by biomass IGCC

Gasification is currently considered to be an important technology for increasing the efficiency of biomass power generation. There are several competing technologies for gasification which can be classified as different types such as pressurized or atmospheric, oxygen-blown or air-blown, fixed bed or fluidized bed, up-draft type or down-draft type, and so on. The gasifier and gas cleaner, in combination with the gas turbine, are the crucial units.

One concept for advanced power generation includes the use of pressurized biomass gasification to produce fuel gas for a gas turbine engine (topping cycle). Waste heat from the turbine can be recovered for use in a

steam cycle (bottoming cycle) to produce additional power. The system of integrated gasification combined cycle (IGCC) power generation is conceptually illustrated in Figure 3. The efficiency of this cycle is calculated to be higher than those of conventional Rankine cycles. Major engineering challenges include hot-gas cleaning to provide a gas of adequate quality to the turbine, and the development of reliable high-pressure reactors and fuel feeding systems.

The conversion efficiency of power generation of BIGCC is also given in Figure 3. The conversion efficiency, 26.3% for the gas turbine and an additional 8.3% for the steam turbine, is 34.6%. However, 2.1% electricity is used for the process itself, so the overall efficiency of this process is 32.5%. Discharged heat is used for drying OPT as in the case of power generation by direct combustion. These values are based on the result of a demonstration plant in Värnamo, Sweden, where dried and crushed wood fuel is used. The operating temperature of the gasifier is 950 °C and the pressure is approximately 18 bar. The gasifier is a circulating bed type and an air-blown type. The hot flue gas from the gas turbine is ducted to the heat recovery steam generator (HRSG). The steam temperature and pressure are 455 °C, 40 bar respectively [11].



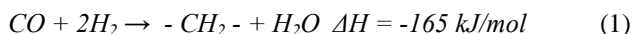
**Fig. 3. Scheme and conversion efficiency of power generation by BIGCC**

#### 3) Diesel oil production by Fischer-Tropsch synthesis

A variety of biomass liquefaction processes are under development, including direct processes, such as fermentation, fast pyrolysis and hydrothermal upgrading. In indirect liquefaction processes, biomass is first gasified to produce synthesis gas followed by conversion to methanol, DME, or Fischer-Tropsch liquids.

The F-T synthesis is a process capable of producing liquid hydrocarbon fuel from synthesis gas. The F-T synthesis was introduced by Fischer and Tropsch in 1923 using Fe-alkaline metal as catalyst. F-T liquid can be used as alternative diesel oil for transportation fuel.

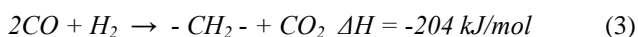
A scheme of the main process steps to convert biomass to F-T liquid is shown in Figure 4. In the F-T synthesis one mole of CO reacts with two moles of H<sub>2</sub> to yield a hydrocarbon chain extension (-CH<sub>2</sub>-). The oxygen from the CO is released as product water:



An important design parameter for integrating a biomass gasifier and F-T reactor is the hydrogen to carbon monoxide ( $\text{H}_2/\text{CO}$ ) ratio. The  $\text{H}_2/\text{CO}$  ratio in the raw gas from the biomass gasifier typically is between 0.8 and 1.6, while the FT reactor consumes at least two times more hydrogen than carbon monoxide. The reaction implies a  $\text{H}_2/\text{CO}$  ratio of at least 2 for the synthesis of the hydrocarbons. Therefore it has to be adjusted in the reactor with the catalytic Water-Gas Shift (WGS) reaction:



When catalysts are used with WGS activity, the water produced in the reaction can react with CO to form additional  $\text{H}_2$ . Oxygen from the CO is released as  $\text{CO}_2$ :



The reaction yields mainly aliphatic straight-chain hydrocarbons ( $\text{C}_x\text{H}_y$ ). In addition to these straight-chain hydrocarbons, also branched hydrocarbons, unsaturated hydrocarbons (olefins), and primary alcohols are formed in minor quantities. The kind of liquid obtained is determined by the process parameters (temperature, pressure), the kind of reactor, and the catalyst used. Typical operation conditions for the F-T synthesis are a temperature range of 200-350 °C and pressures of 15-40 bar, depending on the process.

Several types of catalyst can be used for the F-T synthesis. The most important are based on iron (Fe) or cobalt (Co). Cobalt catalysts have the advantage of a higher conversion rate and a longer life (over five years). The Co catalysts are in general more reactive for hydrogenation and therefore produce less unsaturated hydrocarbons and alcohols compared to iron catalysts. Iron catalysts have a higher tolerance for sulfur, are cheaper, and produce more olefin products and alcohols. The lifetime of the Fe catalysts is short and in commercial installations generally is limited to eight weeks.

The conversion efficiency of F-T synthesis is given in Figure 4. The yield of the F-T synthesis is 36.5% F-T diesel oil. The energy consumption for conversion is 10.6% electricity. Heat from the gas cooling process is used for OPT drying. These values are based on the result of exergy analysis of the biomass integrated gasification F-T process. Sawdust is considered as a feedstock, which is autothermally gasified with air at a temperature of 900 °C at atmospheric pressure. The feed gas is converted to gaseous and liquid hydrocarbons at a temperature of 260 °C by a cobalt catalyst [12].

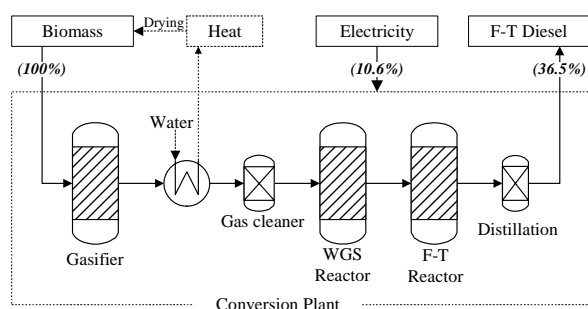


Fig. 4. Scheme and conversion efficiency of diesel oil production by F-T synthesis

#### 4) Ethanol production by saccharification and fermentation

Ethanol-added gasoline is called gasohol. The heating value of gasoline per kg is 44.37 MJ while that of ethanol is 26.79 MJ, which indicates that the heating value of ethanol per unit weight is 60% of that of gasoline. The molecular formula shows that the weight percentages of C, H, and O for ethanol are 52%, 13% and 35%, respectively, while for gasoline ( $\text{C}_n\text{H}_{2n+2}$ ) those of C and H are 84% and 16%, respectively. Therefore, unlike gasoline, ethanol contains 35% oxygen, which reduces the heating value per unit weight and effectively activates the combustion efficiency. In addition, the presence of oxygen gives ethanol a lower combustion temperature than gasoline, resulting in the production of no soot and less  $\text{NO}_x$ .

Woody biomass such as OPT mainly consists of cellulose, hemicellulose and lignin. To produce ethanol from woody biomass, cellulose and hemicellulose must be saccharized to fermentable sugar prior to the fermentation. Saccharification can be performed with diluted acid, concentrated hydrochloric acid or enzyme, lignin cannot be broken down to sugar by hydrolysis. Saccharification yields hexoses and pentoses, which are then fermented. Hexoses can be fermented by yeast, while pentoses cannot be fermented. The schematic diagram of the diluted acid process is shown in Figure 5.

The conversion efficiency of this process is also given in Figure 5. The process using diluted acid yields 27% ethanol and 44% lignin as a by-product. The energy consumption for conversion is estimated to be 0.05% electricity. These values are based on the results of simulation studies. Pine is considered as a feedstock. The dilute acid process is composed of sulfur dioxide in the first step and hydrochloric acid in the second hydrolysis step. The feedstock is first steamed with waste steam (4 bar) from the process, in order to remove air and other inert gases, and then impregnated with  $\text{SO}_2$ . The feedstock is further contacted with saturated backpressure steam (12 bar, 188 °C). In the first step, semicellulose is almost converted to sugars, while the lignin is lumped together and the cellulose fibers are separated. The cellulose fibers are heated to 230°C, and then fed to the second hydrolysis reactor. Dilute hydrochloric acid catalytically converts cellulose to glucose, and 66% of cellulose is fed in the hydrolysis step [13]-[14].

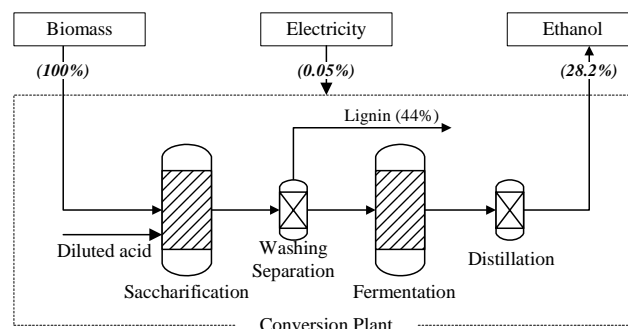


Fig. 5. Scheme and conversion efficiency of ethanol production from cellulosic biomass

### 3. METHODOLOGY FOR ESTIMATING EMISSION REDUCTION

To compare the CO<sub>2</sub> emission reduction (ER) by the four conversion systems, a methodology for estimating the ER is constructed based on methodologies approved by the CDM Executive Board [2]. The approved consolidated baseline methodology linked to biomass utilization is ACM0006 "Consolidated baseline methodology for grid-connected electricity generation from biomass residues" [15]. This consolidated methodology is based on a rice husk power project in Thailand, a bagasse cogeneration project in Brazil, and so on.

The ER by the CDM project activity per annum is the difference between baseline emissions (BE), project emissions (PE), and emissions due to leakage (L) as follows:

$$ER = BE - PE - L \quad (4)$$

The baseline for a CDM project activity is the scenario that reasonably represents the anthropogenic emissions by sources of greenhouse gases that would occur in the absence of the proposed project activity. The BE is equivalent to amount of CO<sub>2</sub> emission in the absence of bioenergy production activity. Therefore the BE is calculated by multiplying the quantity of produced energy generated from biomass as a result of the project activity (EG) with the CO<sub>2</sub> emission factor of the displaced electricity and fossil liquid fuel due to the project activity (EF) as follows:

$$BE = EG \times EF \quad (5)$$

where: EG is the quantity of produced electricity and biomass liquid fuel as a result of the project activity in GJ.

EF is the CO<sub>2</sub> emission factor for the displaced electricity and fossil liquid fuel due to the project activity in tons CO<sub>2</sub>/GJ.

The PE includes CO<sub>2</sub> emissions from transportation of biomass to the project site (PET) and CO<sub>2</sub> emissions from on-site energy consumption due to the project activity (PEFF) as follows:

$$= PET + PEFF \quad (6)$$

where: PET is the CO<sub>2</sub> emissions due to transportation process in tons of CO<sub>2</sub>

PEFF is the CO<sub>2</sub> emissions due to chipping process and conversion process in tons of CO<sub>2</sub>.

The Leakage (L) is defined as the net change of anthropogenic emissions by source of greenhouse gas which occurs outside the project boundary, which is measurable and attributable to the CDM project activity. The main potential source of leakage for a biomass residue conversion project is an increase in CO<sub>2</sub> emissions due to fossil fuel combustion which offsets biomass combustion. Therefore it has to be demonstrated that there is an abundant surplus of the biomass in the region of the project activity which is not utilized. In this study, Leakage is assumed to be zero.

### Determination of Emission Factor

The emission factors (EF) for displacement of electricity and fossil fuel are shown in Table 6. Calculation of EF for displacement of electricity is defined in the "Consolidated baseline methodology for grid-connected electricity generation from renewable sources" (ACM002). The EF for displacement of electricity is calculated as a combined margin (CM), consisting of the combination of operating margin (OM) and building margin (BM) factors. The OM reflects a displacement of electricity from system, while the BM reflects a displacement of power plant.

The OM is calculated as the weighted average emissions of all generating sources serving the system, excluding hydro, geothermal, wind, low-cost biomass, nuclear and solar power generation. The BM is calculated as the weighted average emissions of recent capacity additions to the system, defined as the lower of the most recent 20% of plants built. Calculations for this combined margin must be based on an official source. It is a default IPCC value from the IPCC 1996 Revised Guidelines and the IPCC Good Practice Guidance for net calorific values and carbon emission factors for fuels instead of plant-specific values [8]. In this study, the data of power generation in Peninsular Malaysia is adopted [17].

The EF for displaced electricity is calculated as the weighted average of the Operating Margin emission factor (EF<sub>OM</sub>) and the Building Margin emission factor (EF<sub>BM</sub>), as follows:

$$EF_{electricity} = w_{OM} \times EF_{OM} + w_{BM} \times EF_{BM} \quad (7)$$

where: The weights  $w_{OM}$  and  $w_{BM}$ , by default, are 50% (i.e.,  $w_{OM} = w_{BM} = 0.5$ ), and EF<sub>OM</sub> and EF<sub>BM</sub> are expressed in t-CO<sub>2</sub>/GJ.

**Table 6. Emission factor for electricity, diesel, and gasoline**

Item	Emission factor (t-CO <sub>2</sub> /GJ)	
Electricity	Operating margin	0.176 (0.635 t-CO <sub>2</sub> /MWh)
	Building margin	0.173 (0.635 t-CO <sub>2</sub> /MWh)
	Combined margin	0.174 (0.635 t-CO <sub>2</sub> /MWh)
Diesel	0.074	
Gasoline	0.069	

### 4. RESULTS AND DISCUSSION

The energy balances of the four biomass conversion processes are presented in Figure 6. The net production energy (production energy minus conversion energy) is an important index for adoption of bioenergy production system. The net production energy is related to overall conversion efficiency, so the power generation by BIGCC achieves the highest net production energy. The production energy of diesel oil production by F-T synthesis is the highest, but its conversion energy is also highest. Therefore the net production energy of ethanol is higher than that of diesel oil.

The CO<sub>2</sub> emission reductions achieved by the four biomass conversion systems are presented in Figure 7. The project emission due to the chipping process (126 t-CO<sub>2</sub>/yr) and transportation process (26 t-CO<sub>2</sub>/yr) is small

relative to the emission from the conversion process, excluding the ethanol production project.

It is clear that the largest emission reduction is achieved through power generation by BIGCC. The net production energy of power generation by direct combustion is lower than that of liquid fuel production. However, the ER of power generation is larger than that of

liquid fuel production. This result is strongly linked to the emission factor (EF). The EF of electricity is approximately 2.4 times as large as that of liquid fuel. The EF of electricity strongly reflects the power generation condition of the host country of the project country. The value of ER for displaced electricity varies country by country.

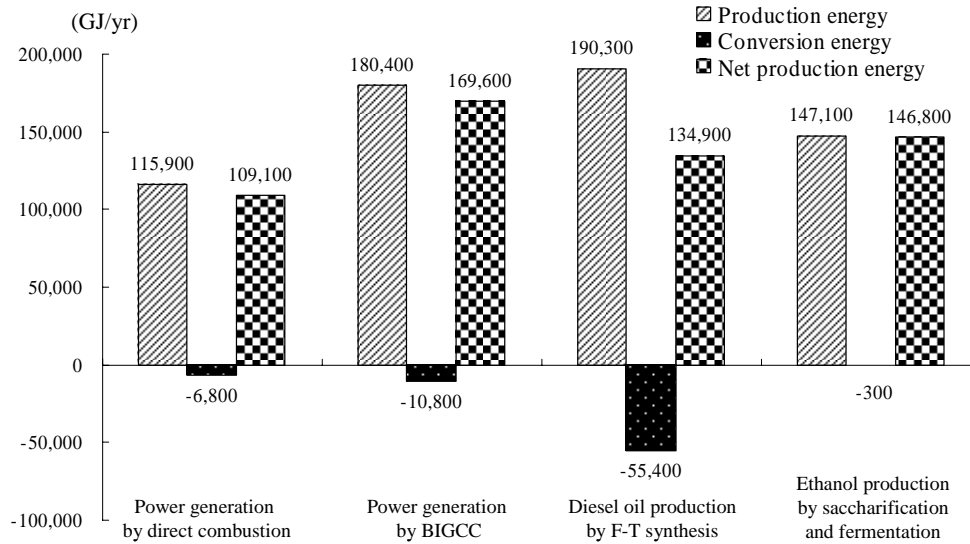


Fig. 6. Energy balances of four biomass conversion processes

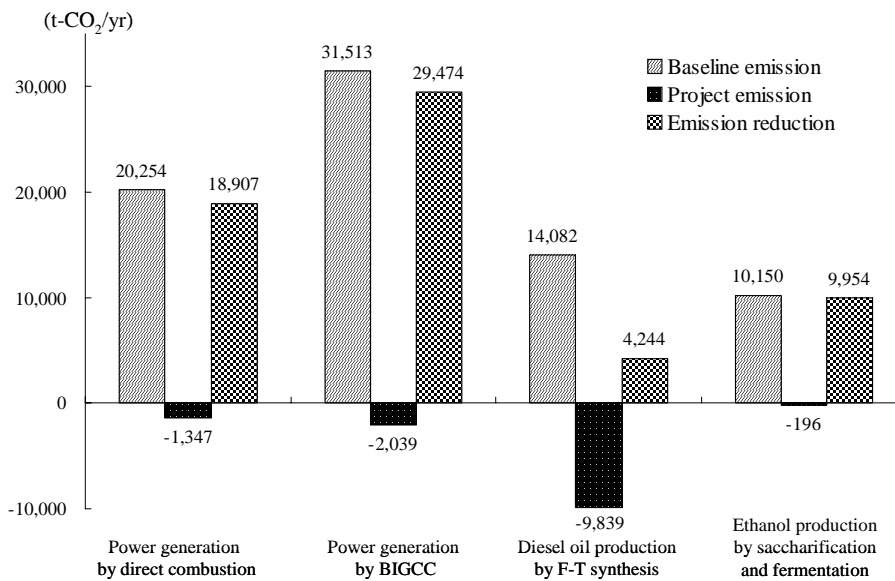


Fig. 7. CO<sub>2</sub> emission reductions by four bioenergy production systems

**Development level of biomass conversion technologies**

Biomass conversion technologies are divided into three main groups: (1) technology at the commercial stage, (2) technology at the development stage, and (3) technology at the research stage.

Power generation by BIGCC achieves the highest ER, but this technology currently belongs to the group (2). Power generation by direct combustion is already available. At present, therefore, power generation by direct combustion is the most favorable for CDM projects due to the lower risk. Power generation by BIGCC thus offers good potential for CDM projects in the near future.

The liquid fuel production technologies considered in this paper belong to group (2). F-T liquid production

from natural gas and coal is already available. Shell (natural gas based) and Sasol (coal based) apply F-T synthesis on a commercial scale. The optimal F-T synthesis from biomass-derived syngas, however, is under development. Ethanol production from woody biomass has two major problems. First, the sugar yields have to be improved. The other problem concerns pentose fermentation.

Group (3) includes hydrogen fermentation, acetone butanol ethanol (ABE) fermentation, ozone oxidation, two-stage supercritical methanol treatment, and so on. To evaluate biomass conversion potential adequately, all biomass conversion technologies should be compared from a long-term perspective.

### **Importance of liquid fuel production from biomass residues**

Petroleum occupies about 40% of energy consumption in the world, and is necessary for transportation fuel and chemical engineering. As a result of economic development, in Asia the energy demand far exceeds supply, and so import volume of petroleum is rising drastically.

Biomass is the only organic form of renewable energy, so it is important to convert biomass into renewable liquid fuel. At present, the main liquid fuels produced from biomass in the world are biodiesel and bioethanol. Biodiesel is produced from vegetable oil crops such as palm, sunflower, soybean, rapeseed, and so on. Bioethanol is produced from sugar (sugar cane, sugar beet) and starch (potato, corn, cassava).

The feedstocks of biodiesel and bioethanol compete with food, and the productivities of these feedstocks are lower than those of lignocellulosic materials. To avoid competition with cultivated fields for food production, in the future biomass liquid fuel has to be produced from cellulosic materials such as agricultural residues.

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