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Nuclear carbonization and gasification of biomass for effective removal of atmospheric CO_2

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ABSTRACT

By the process of carbonization of biomass a portion of carbon element in biomass is stabilized as solid carbon, and the remaining portion of carbon, which is the volatile product from carbonization, is converted by the subsequent gasification and conversion process to carbon-neutral synthetic fuels, which can replace the fossil derived fuels currently used.

In these processes, nuclear energy can effectively be utilized for supplying energy, thus avoiding the CO_2 emission from any biomass or fossil combustion. By utilizing nuclear energy, most of the carbons in biomass are converted to either stabilized solid carbon or carbon-neutral fuels.

Thus, significant amount of CO_2 can efficiently be removed from the atmosphere by processing a part of annual growth of biomass, which leads to the decrease of atmospheric CO_2 concentration.

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1. Introduction

The increase of CO_2 concentration in atmosphere is the major cause of global warming. To cope with this issue, it is necessary not only to reduce the emission of CO_2 to atmosphere, but also to actually remove the excessive quantity of CO_2 from the atmosphere.

For removing atmospheric CO_2, processes of nuclear carbonization and gasification of biomass can be utilized. By the process of carbonization of biomass and subsequent gasification of the volatile product from carbonization, a portion of carbon element in biomass is stabilized as solid carbon, and the remaining portion of carbon is converted by gasification and conversion process to synthetic fuels, which can replace fossil fuels for energy supply (Hori, 2007a,b). Thus, biomass, which otherwise eventually decays in soil or in waste to emit CO_2, becomes stabilized solid carbon and carbon-neutral synthetic fuels.

In this process, nuclear energy can effectively be utilized, avoiding the CO_2 emission from any biomass or fossil combustion. Thus, significant amount of CO_2 can efficiently be removed from the atmosphere by processing a certain amount (1/10 of annual growth in the following estimation) of biomass (preferably, plant residue in soil or waste), which leads to the decrease of atmospheric CO_2 concentration. The 1/10 amount of annual growth is tentatively selected as a reference amount of processing which may exert appreciable effect on global carbon budget, but may need extensive efforts to collect the widely dispersed biomass in vegetation, soil and waste.

2. Global carbon cycle

Carbon is exchanged between the Earth and atmosphere. The global carbon budget for Year 2000–2005 is shown in Table 1 (These values on the CO_2 flux and reservoir are cited from IPCC AR4 Final Report and other reports (IPCC, 2007; Watanabe, 2010).The values cited here are rounded by the author for approximate evaluation.).

The plant growth by photosynthesis absorbs CO_2 at the rate of about 110 GtonC/y (GtonC = 10^9 ton of carbon) globally from atmosphere, and the plant respiration discharges CO_2 at the rate of about 50 GtonC/y back to the atmosphere. Therefore the net rate of CO_2 fixed as 'plant growth' by the photosynthesis/respiration processes is about 60 GtonC/y. The decay of plant residue discharges CO_2 as the soil respiration back to the atmosphere at the rate of about 60 GtonC/y.

The reaction formula of photosynthesis is expressed as;

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$

where $C_6H_{12}O_6$ (glucose) represents biomass.

The reaction formula of decay of plant residue is expressed as;

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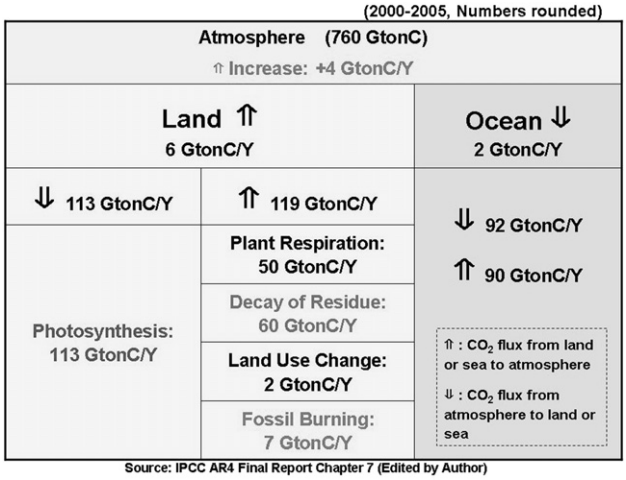
Table 1
Global carbon budget.



Source: IPCC AR4 Final Report Chapter 7 (Edited by Author)

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$

3. Concept of the nuclear–biomass processes

The purpose of nuclear carbonization and gasification of biomass is to convert, using nuclear energy, a part of biomass into solid carbon (elementary substance) and synthetic fuels before the biomass is decayed into CO_2 and emitted to atmosphere.

The concept of this process is shown in Fig. 1. The carbon in biomass which is fixed by photosynthesis from atmospheric CO_2 is converted into;

1. Solid carbon (various kinds of charcoal, carbon and graphite), which is a stable form of carbon element. Such solid carbon products can be used as materials for industry, agriculture, construction and other purposes, or can be stored on earth in atmospheric condition for the carbon sequestration purpose.
2. Synthetic fuels such as Fischer–Tropsch (FT) diesel oil, DME (Dimethyl ether) or hydrogen, which are carbon-neutral alternate fuels. These synthetic fuels can replace fossil derived fuels such as gasoline and diesel oil currently used.

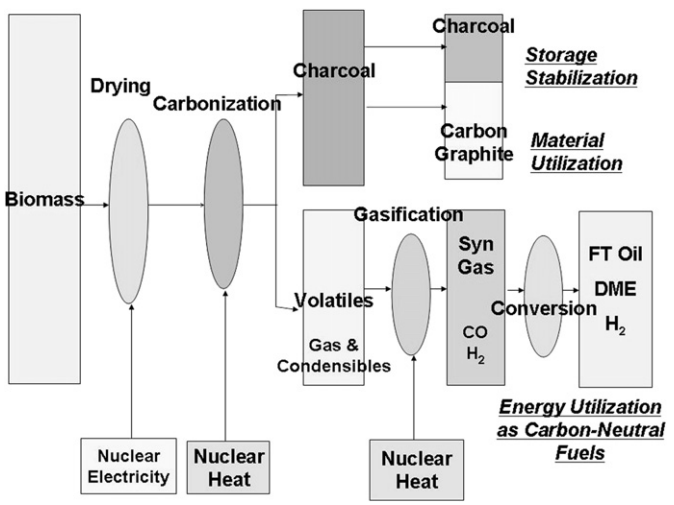


Fig. 1. Concept of the proposed biomass–nuclear process.

First, biomass is dried to a suitable dryness to be carbonized. Then, biomass is carbonized in 400–500 °C which is a typical temperature range (FAO Forestry Paper 63, 1985a) in industrial processes, while the carbonization is usually conducted in 270–800 °C.

The reaction formula of carbonization (conversion of an organic substance into carbon or a carbon-containing residue through pyrolysis) is expressed as;

$$C_6H_{12}O_6 \rightarrow C\ (\text{charcoal}) + \text{Volatiles, Gas and Condensibles}\ (\text{carbon} - \text{containing residue})$$

where $C_6H_{12}O_6$ (glucose) represents biomass.

The carbon-containing residue is then converted to synthetic gas by steam gasification (conversion of carbon-containing compounds into mixture of carbon monoxide (CO) and hydrogen (H_2) by reacting with steam) usually in 700–850 °C temperature. This reaction is an 'endothermic' reaction which absorbs energy from surroundings in the form of heat.

The reaction formula of steam gasification is expressed as;

$$C + H_2O \rightarrow CO + H_2$$

where C (carbon) represents carbon contents in volatiles, gas and condensibles, and ($CO + H_2$) is synthetic gas (Syn gas).

Then Syn gas is converted into synthetic fuels. The typical conversion process is the Fischer–Tropsch (FT) synthesis (a set of chemical reactions that convert Syn gas into liquid hydrocarbons fuels).

The reaction formula of FT synthesis is expressed as;

$$CO + 2H_2 \rightarrow CH_2 + H_2O$$

where CH_2 represents synthetic fuels (FT diesel oil, typically).

As the necessary energy in the processes is supplied by nuclear energy, the conversion ratios of energy and mass from biomass to the products become high, besides avoiding CO_2 emission, thus contributing to the environment and noble use of biomass resources.

As for the biomass to be processed, any form of biomass, such as live vegetation or plant residue (also called dead organic matter in soil or waste, litter, detritus, etc.), can be utilized as far as it contains any organic matter. The residual dross or ashes from the carbonization and gasification processes will be returned to the original place if necessary, as these ingredients should be in the soil where the biomass or residue is collected.

The types of nuclear reactors in Generation IV Systems (The Generation IV International Forum, 2008) applicable to heat supply for carbonization and gasification processes are as follows;

For carbonization (400–500 °C) and gasification (700–850 °C)	
Very High Temperature Reactor	Outlet temperature 800–950 °C
Gas-Cooled Fast Reactor	Outlet temperature 850 °C
Lead-Cooled Fast Reactor	Outlet temperature 550–800 °C
For carbonization (400–500 °C)	
Sodium-Cooled Fast Reactor	Outlet temperature 550 °C

Considering the circumstance that biomass is distributed in wide area and in various conditions, the nuclear reactor/process plants of transportable type may be used as well as those of stationary type.

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4. Quantitative effect of the nuclear–biomass processes

The plant growth by photosynthesis absorbs about 60 GtonC/y globally from atmosphere, and the soil respiration or decay discharges almost the same amount back to atmosphere.

As a reference case of applying this process to the operation of removing atmospheric CO_2, it is postulated that a 1/10 amount of annual plant growth by photosynthesis is processed by the biomass–nuclear process.

In the following, the biomass–nuclear processes are explained with quantitative mass and energy balances;

(1) Carbon content of biomass to be processed annually is 60 GtonC × 1/10 = 6 GtonC. This amount is not necessarily a part of new growth, but it may be plant residue of past growth.
(2) Drying of biomass prior to the carbonization needs nuclear energy of 0.22 $Gton_{OE}$ for reduction of moisture content (ratio of water to dry biomass) of 50%. Here, '$Gton_{OE}$' is unit of thermal energy equivalent to 10^9 ton of oil, corresponding to 11.63×10^9 MWh. In this estimation, the vapor compression & condensation drying (VCC) process with the coefficient of performance COP = 6 is assumed. In the VCC process, latent heat is recuperated in a feed-effluent heat exchanger by compressing the effluent stream, so drying is performed only by compression power without any heat addition. Assuming 1 ton of dry biomass contains 0.4 ton of carbon, drying 6 GtonC biomass needs evaporating 7.5 Gton of water from biomass by the VCC process. If the recently developed process of self-heat recuperation drying (Fushimi et al., 2011), in which not only latent heat but also sensible heat are recuperated, is applicable, then the COP increases to about 20 and required nuclear energy reduces to 0.07 $Gton_{OE}$. In this paper, the former VCC drying process is used for the evaluation on the safe side.
(3) Carbonization of biomass needs nuclear heat of 0.24 $Gton_{OE}$, assuming 5% of the heat content of processed carbon is necessary for carbonization (Yaginuma, 2003) (Fig. 2).
(4) The yield of carbonization process is assumed to be 90%, producing 2.7 GtonC of charcoal and 2.7 GtonC of volatiles (gas and condensibles). The amounts of charcoal and volatiles produced are estimated as 45% each in the terms of carbon mass (FAO Forestry Paper 63, 1985b) (Fig. 2).
(5) Gasification of the volatiles to produce synthetic gas (Syn gas, CO + H_2) needs nuclear heat of 0.70 $Gton_{OE}$, assuming 131 kJ/mol for the endothermic reaction (Hori, 2009) (Fig. 3).

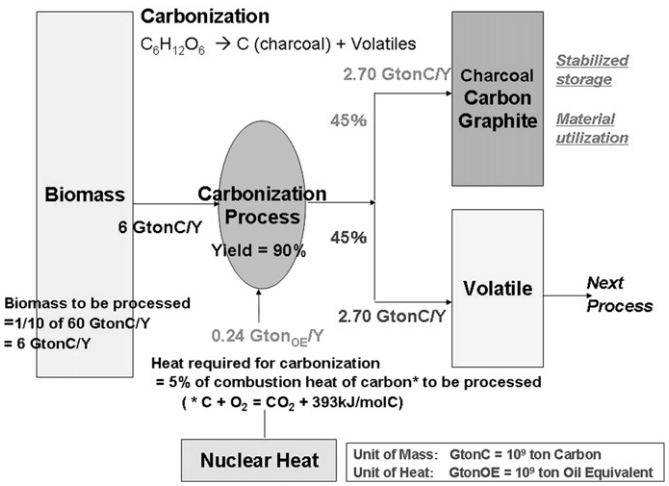

Fig. 2. Flow diagram of nuclear carbonization process (reference case).

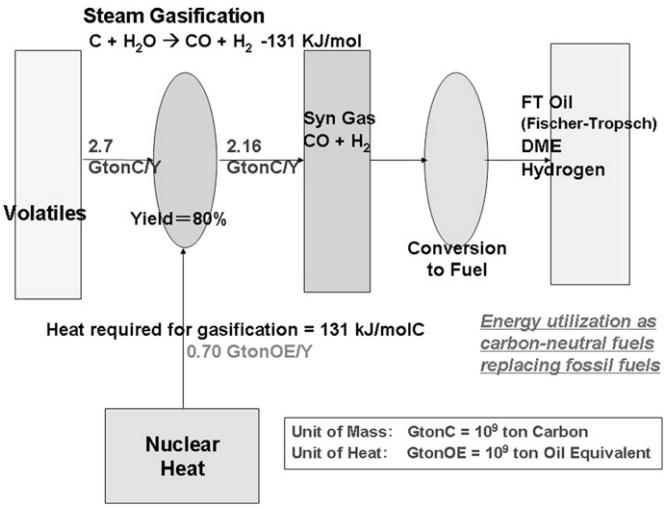

Fig. 3. Flow diagram of nuclear gasification process (reference case).

(6) The yield of gasification process is 80%, producing 2.2 GtonC of synthetic gas to be fed to conversion process for producing FT diesel oil, DME, other carbon-neutral synthetic fuels or hydrogen (Fig. 3).
(7) Summing up the above, 6 Gton carbon in the biomass is converted by the biomass–nuclear processes to the following;
  (1) Stabilized carbon such as charcoal, carbon or graphite to be used as materials or to be stored = 2.7 GtonC. This amount is to be excluded from the global CO_2 cycle, as these carbon products are stable.
  (2) Synthetic gas (CO + H_2), which is to be converted to synthetic fuels such as FT oil or DME = 2.2 GtonC. These synthetic fuels are to be used as carbon-neutral alternate fuels replacing a part of fossil fuels, so this amount is to be reduced from the fossil fuels consumption in the global CO_2 cycle.

Therefore, the sum 2.7 + 2.2 = 4.9 GtonC is to be reduced from atmosphere in 'the long term'. It should be noted that this reduction effect works in the long term, because the processed biomass which contains 6 Gton carbon would, if it remained in the soil or waste, becomes CO_2 eventually in the long term by the decay of residue.

In the course of these processes, 1.1 GtonC (0.6 GtonC in the carbonization + 0.5 GtonC in the gasification) are not converted to the products by the limitation of yield (net quantity produced or converted) in the chemical reactions, and these losses in the processes are eventually discharged into atmosphere as CO_2.

(8) According to the global carbon budget (Table 1), CO_2 increase in the atmosphere was 4 GtonC/y in the period 2000–2005. The biomass–nuclear process reduces 4.9 GtonC/y from atmosphere in the long term, so it will eventually decrease the atmospheric CO_2 by the rate of −0.9 GtonC/y or −3.3 $GtonCO_2$/y, even the world consumes the same amount of carbon-based fuels as in the period 2000–2005 (Fig. 4 and Table 2).

5. Energy required for the nuclear–biomass processes

Nuclear energy is the only energy used in these processes. As there is no combustion of biomass or fossil fuels, there is no emission of CO_2 from the energy consumed in the processes.

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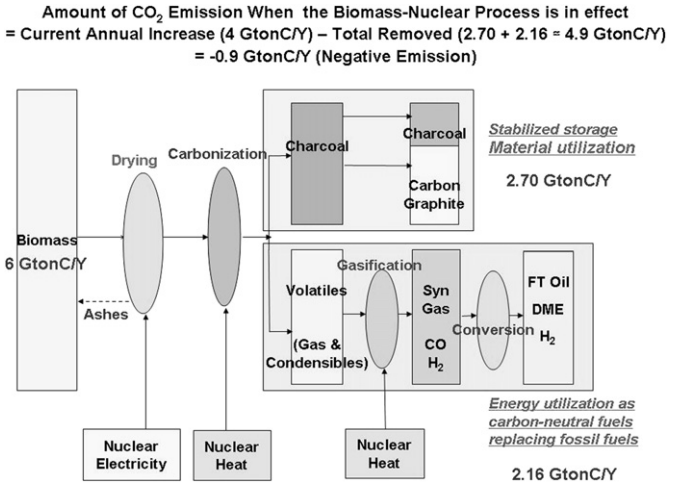

Fig. 4. Decrease of CO_2 emission by the biomass–nuclear process (reference case).

The sum of nuclear energy needed for the whole process is, assuming 50% extra margin for auxiliary power, heat losses and other losses, is 1.74 $Gton_{OE}$ as shown in Table 3 in the $Gton_{OE}$ unit.

The required nuclear energy 1.74 $Gton_{OE}$ for processing 6 GtonC of biomass is, 20.2×10^9 MWh, which corresponds to about 900 nuclear reactors of 1000 MWe (3000 MWt) power plants with 85% capacity factor.

The process requires 3.50 MWh nuclear heat per 1 ton carbon in the processed biomass or 7.48 MWh nuclear heat per 1 ton of stabilized carbon. As this process produces 7.42 MWh worth of carbon-neutral alternate fuel per 1 ton of stabilized carbon, the required and produced energy are almost balanced. In other words, amount of nuclear energy consumed in this process is converted to the almost same amount of carbon-neutral alternate fuels which can replace fossil fuels, while stabilizing about half of biomass processed as solid carbon.

6. Supply capability of nuclear energy

According to the IIASA/WEC Global Energy Perspectives (IIASA-WEC, 1998), the world nuclear capacity will increase, for supplying nuclear electricity, from 0.5 $Gton_{OE}$ in 2000 to 2.7 $Gton_{OE}$ in 2050 and 8.3 $Gton_{OE}$ in 2100. The maximum capable nuclear supply, incorporating the optimized Pu-recycling using fast breeder reactors, will be 4.0 $Gton_{OE}$ in 2050 and 18.3 $Gton_{OE}$ in 2100 (Ono et al., 2000; Hori, 2000) (Table 4).

The nuclear energy needed for the biomass process, 1.74 $Gton_{OE}$, can be supplied by the spare capacity, which is difference of the maximum capable and the WEC perspectives for electricity (Table 4).

Table 2
Global carbon budget with the biomass–nuclear process (reference case).

Global Carbon Budget 20XX~ (Numbers rounded)

Atmosphere ⇓ Decrease: - 0.9 GtonC/y = - 3.3 $GtonCO_2$/y		
⇑ Land Sum: 1.1 GtonC/y		⇓ Ocean Sum: 2 GtonC/y
⇓ 113 GtonC/y	⇑ 114.1 GtonC/y	⇓ 92 GtonC/y ⇑ 90 GtonC/y
⇓ Photosynthesis 113 GtonC/y	⇑ Plant Respiration 50 GtonC/y	
	⇑ Decay of Residue 54 GtonC/y	
	⇑ Land Use Change 2 GtonC/y	
	⇑ Fossil Burning 4.8 GtonC/y	⇑ : CO_2 flux to from land or sea to atmosphere
	⇑ Bio Process & Fuel Burning 3.3 GtonC/y	⇓ : CO_2 flux from atmosphere to land or sea
	= Stabilized Carbon 2.7 GtonC/y	

Table 3
Necessary amount of nuclear energy (reference case).

Nuclear energy needed for the biomass–nuclear process [GtonOE]	
Drying	0.22
Carbonization	0.24
Gasification	0.70
Subtotal	1.16
50% increase for auxiliary power, heat loss and other losses	0.58
Total	1.74

Table 4
Spare capacity of nuclear energy for non-electricity application.

Supply capability of nuclear energy for 2000–2100. Unit: GtonOE/Y [10^9 ton Oil Equivalent per Year]

	2000	2050	2100
Nuclear demand for electricity generation[a]	0.5	2.7	8.3
Maximum nuclear supply capability[b]	–	4.0	18.3
Spare capacity for non-electricity application	–	1.3	10.0

Nuclear energy necessary for the biomass–nuclear processes = 1.74 GtonOE/Y.

[a] Nuclear demand for electricity generation: by WEC global energy perspectives middle course (B case) http://www.iiasa.ac.at/.

[b] Maximum nuclear supply capability incorporating the optimized pu-recycling with fast breeder reactors (LWR->FBR Transition Timing = 2030, Breeding Ratio = 1.3): By Ono et al., 2000, JNC TN9400 2001-028 (December, 2000) and Hori, 2000, NEA meeting on nuclear production of hydrogen (October 2000).

7. Merits of the biomass–nuclear processes

- ◇ In the 'carbon burning' conventional processes of carbonization and gasification of biomass, heat necessary for endothermic reaction, drying, heat-up, and/or temperature keeping is supplied by combustion of biomass itself, its product or fossil fuels.
- ◇ In the 'synergistic' biomass–nuclear processes in which nuclear heat is supplied to carbonization and gasification processes, following advantages are expected;
  - ➢ Neither of biomass, its products nor fossil fuels is used for combustion to supply heat.
  - ➢ No CO_2 is emitted by combustion.
  - ➢ Higher product yield and conversion efficiency are attained in the processes, enhancing the resource saving, emission reduction and noble use of biomass.

8. Concluding remarks

- ◇ Stabilizing the atmospheric CO_2 by carbonization is an essential operation to restore the coal, oil and other fossil fuels which had been formed underground from plant remains over geologic years, and which have been mined and burned by the mankind for the past few hundred years.
- ◇ The nuclear energy utilization for the biomass carbonization and gasification processes makes the operation effective and efficient, and consequently helps attain the goal of sequestering excess CO_2 from atmosphere as expeditiously as possible.
- ◇ The actual amount of biomass to be processed by this process will be determined assessing the seriousness of CO_2 buildup in atmosphere, effect and cost of the on-going emission control measures, and anticipated effects of this process to ecosystems.

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- ◇ Woods and their residues will be the most important biomass for this process, but other biomass and their residues will also be important.
- ◇ As the anthropogenic CO_2 emission has been global, our restoration operation will be global and massive. We could and should achieve the operation mission using the biomass and nuclear technologies advanced until now and to be developed in the coming decades.

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