Application of nuclear produced hydrogen for energy and industrial use

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Abstract

Hydrogen can be produced from water by the thermo-chemical processes using nuclear heat or by the electro-chemical processes using nuclear electricity, or by the 'hybrid' processes combining the both processes. As these nuclear water-splitting processes make it possible to produce hydrogen without any carbon dioxide emissions, they are mainstream methods to supply hydrogen as an energy carrier or as a feed material for industrial processes.

Another method of producing hydrogen using nuclear energy is by the steam reforming/gasification reaction of fossil fuels or biomass, in which nuclear heat is supplied for the endothermic reaction heat, thus reducing the feed materials to be combusted for heat. Because of its advantages in economic competitiveness and in technical feasibility, this method will be utilized in various applications in spite of some CO_2 *emissions.*

Nuclear hydrogen is expected to be used in the diverse fields in future, where appropriate production methods are to be chosen according to the application.

In this presentation, following inspiring applications of nuclear hydrogen in prospective fields are reviewed;

1. *Oil/Fuel Industry: Upgrading of bitumen from oil sands using hydrogen produced by the nuclear-heated steam reforming of a portion of the product*

2. *Steel/Chemical Industry: Nuclear iron making by recirculation of CO formed from the reverse-shift reaction of effluent* CO_2 *with nuclear produced hydrogen by the water-splitting*

3. *Electric Utility: Synergistic power generation using both fossil and nuclear energies by electro-chemical energy conversion in a fuel cell using hydrogen from the nuclear-heated steam reforming of natural gas.*

4. *Restoration of Global Environment: Nuclear carbonization/gasification of biomass to stabilize a portion of carbon in biomass as solid carbon and to convert the remaining carbon to synthetic fuels using nuclear hydrogen, thus effectively removing* CO_2 *from atmosphere..*

Hydrogen energy in the future society

In the course of energy use, we convert the primary energies, which have the form of chemical, heat, light, potential or motion, into 'energy carriers'. An energy carrier should be convenient for delivery, storage and utilization in the course from conversion to final demands. In order to meet the growing energy demand in the world, it is essential to increase the conversion efficiency from primary energies to energy carriers, as well as to increase the utilization efficiency in final energy demands.

The predominant energy carriers we use now are 'hydrocarbons' derived from fossil fuels, and 'electricity' generated from various primary energies. On one hand, it is expected that use of hydrogen as an energy carrier is effective for energy and environment. So, the energy carriers which are being used or in sight are categorized into three as shown in Table 1, namely hydrocarbons, electricity and hydrogen.

The ratio of primary energies consumed for generating electricity to the total consumption of primary energies is 35% for the OECD countries and 30% worldwide, respectively. It is considered that this ratio will increase to 50% or more by the end of 21st century, of which substantial part is expected to be supplied by nuclear energy. Still, there remains half of primary energy consumed for production of non-electricity energy carriers such as hydrocarbons and/or hydrogen. Nuclear energy is expected to contribute in supplying these non-electricity energy carriers by way of nuclear hydrogen or other forms.

Table 1 Flow of Energy through Conversion and Utilization

Primary Energy	→	Energy Carrier (Secondary ~ Final Energy)	→	Final Demand
Fossil Fuels (Petroleum, Natural gas, Coal, etc.) **Nuclear** **Renewables** (Hydro, Solar, Wind, Biomass, etc.)	Conversion	**Hydrocarbons** (Fossil fuel products, such as Gasoline, Kerosene, Diesel oil, City gas, etc. In the Future, Synthetic fuels, including Bio fuels) **Electricity** **Hydrogen**	Utilization	Heat Light Power Transportation Electronics Communication

Table 2 shows potential energy systems for the future society. By the 'Hydrogen Economy', it is possible to diversify the primary energies to produce hydrogen, to increase the efficiency of power conversion by adopting fuel cells, and to make clean the final application process as only water is emitted. However, the same purpose could be attained by the 'All Electrified Economy' when an innovative battery (electricity storage method) with high energy density and competitive cost is developed. Also, the similar purpose can be attained by the 'Synthetic Fuel Economy', where the hydrocarbon fuels, the same convenient liquid fuels as derived from petroleum, but produced from non-petroleum fossil fuels or biomass.

Table 2 Potential Energy Systems for Future Society

		Economy Energy Systems for Society	Predominant Energy Carriers	Comments
Present		Fossil Fuel Products Economy	Fossil Fuel Products + Electricity	Ratio of electricity in primary energy is 35% for OECD countries and 30% worldwide at present. In the future, 50% or more worldwide.
Future ? ? ?	1	Hydrogen Economy	Electricity + Hydrogen	Hydrogen replaces the present fossil fuel products. Feasibility may be enhanced by the 'Ammonia economy'.
Future ? ? ?	2	All Electrified Economy	Electricity	By commercialization of high performance electricity storage methods, the transportation sector can be electrified.
Future ? ? ?	3	Synthetic Fuels Economy	Electricity + Synthetic Fuels	Liquid fuels are convenient to use. Synthetic fuels derived from fossil fuels at first, later from biomass.

Whether the 'Hydrogen Economy', 'All Electrified Economy' or 'Synthetic Fuel Economy' dominates the future society, depends on the progress and breakthrough of related technologies on these energy carriers. Whichever direction the future society takes, nuclear energy, which is capable of sustainable energy supply without CO2 emission, will supply a substantial part of energy to produce the selected energy carriers.

On hydrogen energy, from its characteristics and technology progress up to now, potential future courses could be estimated as follows;

- The amount of hydrogen utilized in specific processes of energy conversion and application will increase. For example, such occasions will increase as the case of stationary fuel cell, in which hydrogen is produced by the steam reforming of natural gas, kerosene or petroleum gas, and immediately consumed in a fuel cell for power generation.

- Large increase of hydrogen demands will occur in the upstream of industry, such as feed material for synthetic fuel production in the oil/fuel industry and a reducing agent for iron making in the steel/chemical industry. These hydrogen demands will be supplied effectively by nuclear energy.
- In order to make the hydrogen energy carrier to be distributed and utilized in a large scale through pipelines or by tankers, there should be a considerable degree of breakthrough in the technology and infrastructure on hydrogen delivery and storage.
- The Hydrogen Economy can rather be attained by a so-called ‘Ammonia Economy’, where ammonia (NH_3) is used as a hydrogen carrier for its easier delivery and storage characteristics. Especially, if such developments currently underway on production and application of NH_3 as the electro-chemical synthesis of NH_3 from nitrogen and water and the direct NH_3 fuel cells have made progress, the Ammonia Economy becomes feasible.

Methods for nuclear production of hydrogen

Hydrogen can be produced from any of the primary energy sources (fossil fuels, nuclear energy, and renewable energies). Nuclear produced hydrogen will be expected to supply the base load, because of its characteristics. Many processes have been proposed for production of hydrogen using nuclear energy (Fig.1).

The leading processes presently under research and development are:

- Electrolysis of water by nuclear electricity;
- High-temperature electrolysis of steam by nuclear electricity and heat;
- Thermo-chemical splitting of water by nuclear heat, or by both nuclear heat and electricity; and
- Nuclear-heated steam reforming of natural gas, or other hydrocarbons.

Although it is not certain what course the commercialization of nuclear hydrogen production will take, a typical prospect based on the current state of knowledge (Hori 2004) could be as follows:

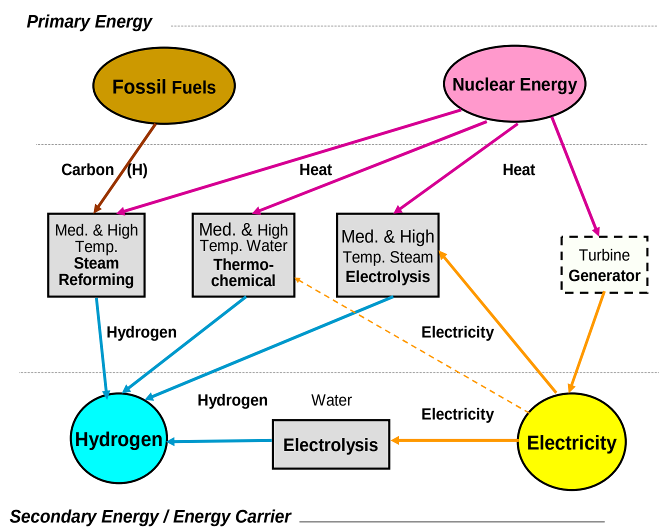

Fig.1 Methods for Hydrogen Production by Nuclear Energy

1. In the near term, electricity generated by light water reactors (LWR) can be used to produce hydrogen from water by electrolysis. This process can be commercialized, in some cases by using off-peak power, because the relevant technologies are already proven. The electrolytic synthesis method of NH_3 from nitrogen and water will be promising for a future Ammonia Economy when it is combined with nuclear electricity.
2. In the intermediate term, nuclear-heated steam reforming of natural gas, using medium-temperature reactors could be utilized, in spite of some carbon dioxide emissions, because of its advantages in economic competitiveness and in technical feasibility. Also, high-temperature reactors could be used to carry out high-temperature steam electrolysis, with higher conversion efficiency and fewer materials problems.
3. In the long term, high-temperature reactors would be coupled to thermochemical water splitting. These bulk chemical processes benefit from economy of scale, and may turn out to be the best for very-large-scale nuclear production of hydrogen for a mature global hydrogen energy economy.

Use applications of nuclear produced hydrogen

Nuclear hydrogen is expected to be used in the diverse fields in future as shown in Table 3, where appropriate production methods are to be chosen according to the application. Some of the inspiring applications are reviewed in the following;

Application to transportation sector

Utilization of hydrogen in automobiles, through fuel cell technology, is one of the primary goals of the Hydrogen Economy. There are still major problems to be solved before the commercialization of hydrogen fuel cell vehicles can be realized.

The challenges include the cost of the fuel cell, the method of storing hydrogen on board the vehicle to ensure an adequate cruising range, and the creation of hydrogen distribution infrastructure. It is expected that application technologies will evolve by breaking through the various problems we encounter now, although it might take a few decades.

Table 3 Use Application of Nuclear Produced Hydrogen

Field of Use	Application
Transportation (Airplane, Railroad, Automobile)	➢ Fuel Cells ➢ Engine
Consumer Use (Home, Building, Factory)	➢ Combined Heat and Power by Fuel Cells ➢ Mixing to City Gas
Oil / Fuel Industry	➢ Hydrogen Addition to Heavy Oils ➢ Upgrading of Bitumen from Oil Sands ➢ Producing Synthetic Gas from Coal
Steel / Chemical Industry	➢ Nuclear Iron Making ➢ Ammonia Synthesis ➢ Methanol Synthesis
Electric Utility	➢ Peak Electricity Supply ➢ Synergistic Power Generation
Restoration of Global Environment	➢ Nuclear Carbonization / Gasification of Biomass

There are other transportation applications of hydrogen fuel: for fuel cells to supply electricity to railway trains, marine vessels, and aircraft, and for jet engines to propel aircraft. (Airbus 2003) If the application of hydrogen to jet engine aircraft is actualized in the future, nuclear-produced hydrogen is the best suited to the supply at hub airports for its features of no CO_2 emission and bulk supply capability.

Nuclear upgrading of oil sands bitumen

Liquid hydrocarbon fuels such as gasoline and diesel oil derived from petroleum are far higher in energy density and far easier to transport and store, than hydrogen which is currently considered as future energy carriers for transportation. These liquid fuels will continue to be useful in the future although they emit CO_2 from engine or other combustion device at the final consuming stage,

As a substitute for petroleum, when we produce synthetic crude oil (SCO) from the oil sands, hydrogen is necessary for hydrogenation and de-sulfurization of bitumen, the oil ingredient extracted from oil sands.

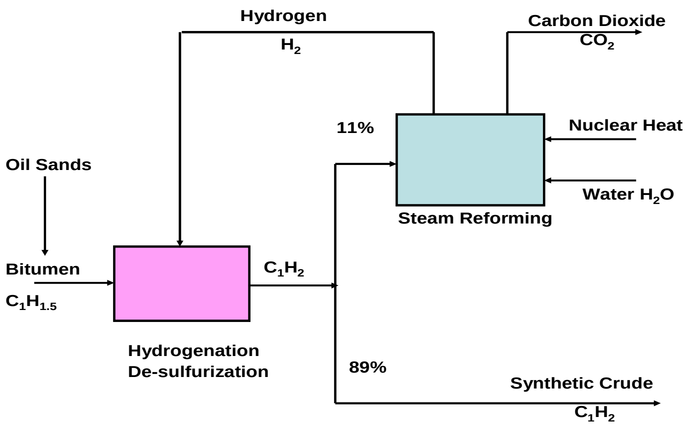

Fig.2 Nuclear Upgrading of Oil Sands Bitumen to Synthetic Crude Oil

Figure 2 is an example of applying nuclear hydrogen to the SCO production process from bitumen of oil sands, where a portion of product (11% of product SCO) is fed back to the steam reforming part to produce hydrogen. (Hori 2005 and Numata 2006)

Nuclear production of synthetic fuels

When we produce synthetic liquid fuel, such as Fischer-Tropsch (FT, diesel) oil from coal, heat is necessary for the coal gasification process to produce synthetic gas (syn gas, $CO+H_2$) and additional hydrogen is necessary to adjust the hydrogen content in the syn gas for the subsequent FT synthesis to produce FT oil.

Nuclear energy can effectively be used in these processes to supply hydrogen, heat and/or oxygen, otherwise fossil fuel consumption is inevitable to supply hydrogen and/or heat. Thus, using nuclear energy for these hydrocarbon production processes will reduce fossil fuel consumption and consequently CO_2 emission during production processes.

Synthetic fuels can be produced, in principle, from carbon, hydrogen (water), and energy. As shown in Table 4 which tabulates recent studies on nuclear production of synthetic fuels, synthetic fuels are produced from natural gas, coal or biomass as the carbon source and the nuclear hydrogen, oxygen, and/or heat as the hydrogen and/or energy source. Usually, the syn gas is formed as interim product, and then the syn gas is converted to the FT oil by the FT synthesis. Even CO_2 can be utilized as the carbon source, although it consumes much energy for conversion to fuel. (Bogart 2006, Forsberg 2006 and 2008, Hopwood 2003, Hori 2007 and 2008, Kato 2005, Kriel 2006, Numata 2006, Schultz 2009, Uhrig 2007)

Table 4 R&Ds on Nuclear Production of Synthetic Fuels

Process	Raw Materials	Nuclear Supply	Interim Products	Final Products	R&Ds	Comments
Water Splitting Steam Reform.	H_2O CH_4, H2O	Heat (1a) Heat (1b)	Hydrogen (H_2)	Feed to the Following Processes	Many Countries	Various methods of hydrogen production shown in Fig.1
Ultra Heavy Oil Upgrading	$CH_{1.5}$	Heat (Steam) Hydrogen	SCO (CH_2)	Gasoline Diesel Oil, etc.	Canada, S.Africa, U.S., Japan	Upgrading from bitumen from oil sands
Coal Gasification	$CH_{0\sim1}$	Heat (2) Hydrogen	Syn Gas ($CO+H_2$)	FT Oil (4)	S.Africa,	Reduction of CO2 emission to a half
Biomass Gasification	$(C_6H_{12}O_6)_n$	Heat (2) Hydrogen	Syn Gas ($CO+H_2$)	FT Oil (4)	U.S., Japan	Increase of efficiency and yield of conversion by nuclear energy
CO_2 Reduction	CO_2	Heat Hydrogen (3)	Syn Gas ($CO+H_2$)	FT Oil (4)	U.S. Japan	Fuel production from flue gas of coal fired power plant

Relevant Chemical Reactions;

- **(1a) Hydrogen Production by Water Splitting** $H_2O \rightarrow H_2 + (1/2)O_2$
- **(1b) Hydrogen Production by Steam Reforming** $CH_4 + H_2O \rightarrow CO + 3H_2$
- **(2) Hydrogen Production by Steam Gasification of Coal** $C + H_2O \rightarrow CO + H_2$
- **(3) Reduction of CO_2 by Reverse Shift Reaction** $CO_2 + H_2 \rightarrow CO + H_2O$
- **(4) Synthesis of FT Oil by Fischer-Tropsch (FT) Reaction** $CO + 2H_2 \rightarrow 1/n(CH_2)_n + H_2O$

Nuclear iron making by carbon recycling

The CO_2 emission of iron and steel industry accounts for about 40% of CO_2 emitted from all the manufacturing industry in Japan, and the cutback of this emission becomes an important issue. In the iron/steel industry, the largest emission comes from the cokes used in the reducing furnaces of iron ore.

Figure 3 shows the concept of nuclear iron making by carbon recycling being proposed by the author. The effluent CO_2 from the iron ore reducing furnace is reduced to CO by hydrogen produced by nuclear water splitting, and the CO is fed back to the reducing furnace. As the carbon is recycled, there are no consumption of cokes and no CO2 emission.

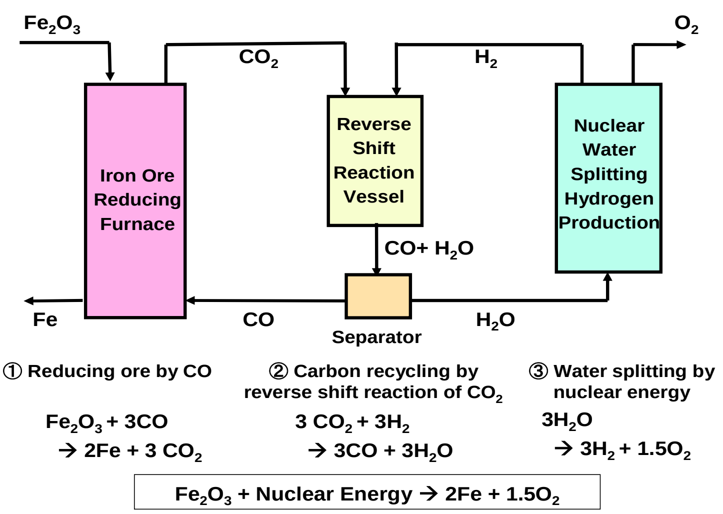

Fig.3 Concept of Nuclear Iron Making by Carbon Recycle

There are concepts of feeding nuclear hydrogen to the reducing furnace, but the CO reducing is considered better for controlling the temperature of furnace.

Synergistic power generation using both fossil and nuclear energies

The present method of nuclear power generation is to convert the nuclear heat into electricity by a heat engine (turbine generator), where the thermodynamic law limits the efficiency of conversion. Most fossil fuels plant generates electricity by the same heat engine method using the combustion heat of fuels, but recently there are some plants which convert chemical energy directly into electrical energy using fuel cells.

Proposed by the author is, as shown in Fig.4, a process combining the synergistic hydrogen production method using carbon resources (fossil fuels, biomass, CO_2, etc.) and nuclear heat, with the fuel cell power generation using this hydrogen, thus converting both chemical and nuclear energies into electricity efficiently. (Hori 2007)

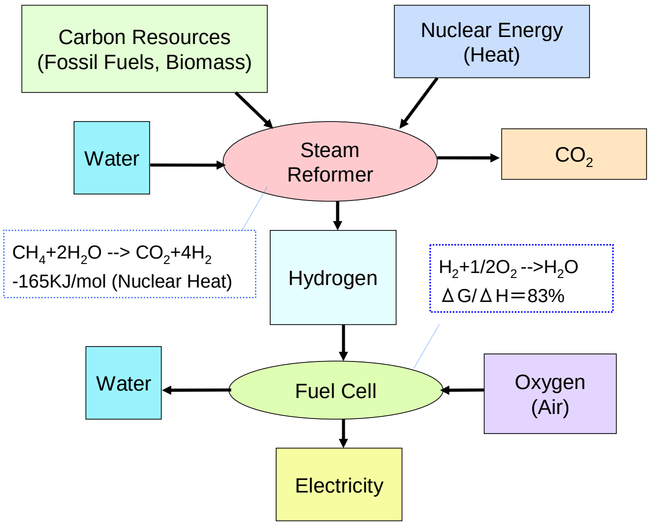

Fig.4 Concept of Synergistic Electricity Generation Using Carbon Resources and Nuclear Energy

The application of this method is shown in Fig.5, where hydrogen is produced by the nuclear-heated steam methane reforming (using a sodium-cooled reactor and natural gas), and then this hydrogen is converted into electricity in the alkaline-type fuel cell.

As the synergistic hydrogen production process using natural gas and nuclear heat is efficient and economic, and also the subsequent electro-chemical conversion of hydrogen into electricity in an alkaline fuel cell is efficient, electricity generation by combining these two processes have the following possibilities;

1. High conversion efficiency, thus saving both natural gas and nuclear energy resources
2. No combustion of fossil fuels, thus reducing CO2 emission
3. Medium temperature and low pressure process, thus lowering electricity generation cost

A preliminary evaluation shows the electricity generation efficiency of this process is about 60% (based on the sum of natural gas heat and nuclear heat), which is comparable to a natural gas advanced combined cycle power plant.

In principle, this synergistic power generation method can be applied to other carbon resources such as petroleum, coal and biomass, and to other types of fuel cell such as SOFC and PEFC.

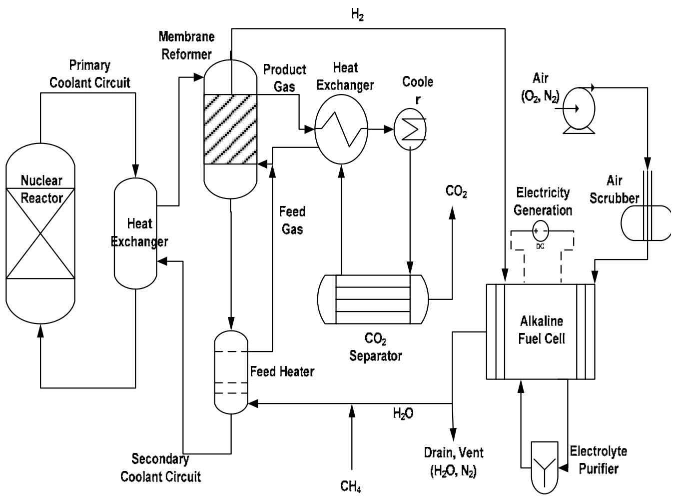

Fig.5 Application of Synergistic Electric Generation Using Natural Gas and Sodium Cooled Reactor

Nuclear carbonization/gasification of biomass for removing atmospheric CO_2

The following concept is to carry out, effectively by utilizing nuclear energy, the so-called ‘carbon minus’ or ‘negative emission’, which not only reduces CO_2 emission to the atmosphere but also removes CO_2 from the atmosphere, thus to restore the global environment by decreasing the atmospheric CO_2 concentration.

By the process of carbonization of biomass and subsequent gasification of the volatile products 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.

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 part of annual growth of biomass, which leads to the decrease of atmospheric CO_2 concentration.

The concept of this process is shown in Fig.6. 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) for use as materials or for storage, which is a stable state of carbon element, and (2) synthetic fuels such as FT diesel oil, DME or hydrogen, which can replace fossil fuels as carbon-neutral alternate fuels. (Hori 2007)

As the necessary energy in this process 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.

The plant growth by photosynthesis absorbs about 60 GtonC/y (GtonC=10^9 ton of carbon) globally from atmosphere, and the soil respiration or decay discharges almost the same amount back to atmosphere. Assuming that a 1/10 amount of annual plant growth is processed by the biomass-nuclear process, the effect on global carbon cycle is estimated as follows;

1. Carbon content of biomass to be processed annually is 6 GtonC.
2. The carbonization process produces 2.7 GtonC of charcoal and 2.7 GtonC of volatiles (gas and condensibles) assuming 90% yield.
3. The gasification process produces 2.16 GtonC of synthetic gas to be fed to conversion process to produce alternate fuels assuming 80% yield.
4. The sum of stabilized carbon and alternative fuels carbon is 2.70+2.16 = 4.86 GtonC.
5. The sum of nuclear energy needed for the whole process (drying + carbonization + gasification) is, assuming 50% margin for auxiliary power and heat losses: (0.168+0.235+0.704) x 1.5 = 1.66 GtonOE (GtonOE=thermal energy equivalent to 10^9 ton oil)

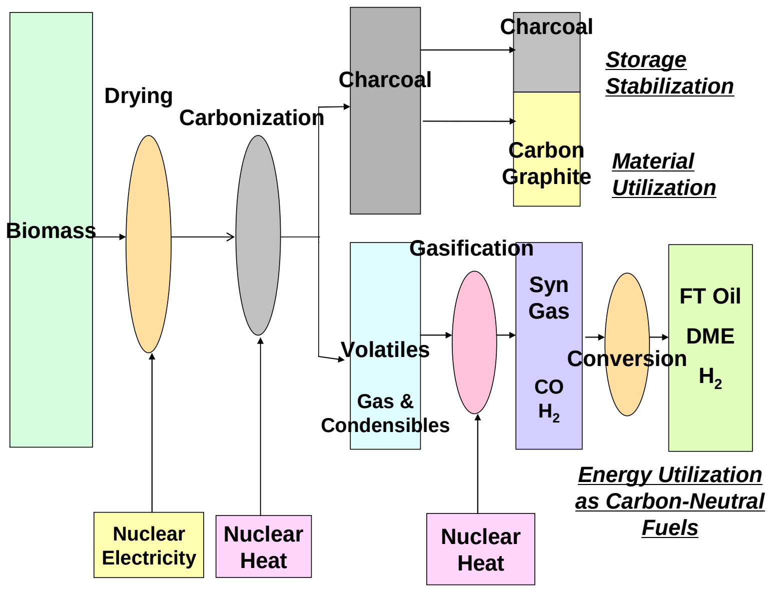

Fig.6 Concept of Nuclear Biomass Carbonization and Gasification

According to the global carbon budget by IPCC AR4 report, the fossil fuels emission was 7.2 GtonC/y and the atmospheric increase was 4.1 GtonC/y in 2000-2005. The biomass-nuclear process removes about 4.9 GtonC/y from atmosphere in the long term, so it will eventually decrease the atmospheric CO_2 concentration.

According to the IIASA/WEC Global Energy Perspectives, the world nuclear capacity will increase, for supplying nuclear electricity, from 0.5 GtonOE in 2000 to 2.7 GtonOE in 2050 and 8.3 GtonOE in 2100. (Nakicenovic 1998) The maximum capable nuclear supply, incorporating the optimized Pu-recycling using fast breeder reactors, will be 4.0 GtonOE in 2050 and 18.3 GtonOE in 2100. (Hori 2000) So, the nuclear energy needed for the biomass-nuclear process, 1.66 GtonOE, can be supplied by the spare nuclear capacity, that is difference of the maximum capable and the WEC perspectives for electricity.

Stabilizing the atmospheric CO_2 by carbonization is just a reverse operation to restore the coal 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 these few hundred years.

Conclusion

1. Nuclear energy is expected to contribute in supplying non-electricity energy carriers by way of nuclear produced hydrogen.
2. Large increase of hydrogen demands will arise in the upstream of industry, and will be supplied effectively by nuclear energy.
3. Nuclear produced hydrogen is expected to be utilized in diverse fields, where appropriate production methods are to be chosen according to the application.
4. In the nuclear-fossil fuels or nuclear-biomass synergistic processes, following advantages are expected;
   - By avoiding the combustion of fuels for heat supply, saving of fuel consumption and consequent reduction of CO_2 emission can be achieved.
   - By efficient processes utilizing both nuclear energy and fuel, conservation of both energy resources can be achieved.
   - By low heat cost of nuclear energy, favorable impacts to economy can be achieved.

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