Synergistic Energy Conversion Processes Using Nuclear Energy and Fossil Fuels

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ABSTRACT

This paper reviews the methods of producing energy carriers, such as electricity, hydrocarbons and hydrogen, by utilizing both nuclear energy and fossil fuels synergistically. There are many possibilities of new, innovative, synergistic processes, which combine chemical and nuclear systems for efficient, clean and economical production of energy carriers. Besides the individual processes by each energy to produce the energy carriers, the synergistic processes which use two primary energies to produce the energy carriers will become important with the features of resource saving, reducing CO2 emissions and economic production, due to the higher conversion efficiency and low cost of nuclear heat. The synergistic processes will be indispensable to the 21st century when efficient best-mixed supplies of available primary energies are crucial.

1. INTRODUCTION

Fossil fuels, in general, have the environmental problem due to the CO2 emission, and fossil fuels, except coal, have the resource problem for the future supply. As for nuclear energy, in order to meet the increasing demand for nuclear electricity in the 21st century as estimated by the International Institute for Applied Systems Analysis and World Energy Council (IIASA/WEC), timely deployment of fast breeder reactors (FBR) with Plutonium recycling is necessary for alleviating the problem of fissile fuels (U-235, Pu-239) deficiency.

To supply energy for the production of hydrogen and other energy carriers as well as electricity generation, it is essential to utilize both fossil fuels and nuclear energy in a manner to ensure the continuing supply of energy while reducing CO2 emissions, so as to solve the global problems of resources and environment in the 21st century.

Synergistic utilization of fossil fuels and nuclear energy has prospects of efficient conversion of primary energies into energy carriers and lower the cost of conversion as well as the favourable impacts on resources and environment .

There are many possibilities of new, innovative, synergistic processes, which combine chemical and nuclear systems for efficient, clean and economical production of energy carriers. These processes will become important in the 21st century with the features of resources saving, emission reducing and economic production.

2. SUPPLY CAPABILITY OF PRIMARY ENERGIES

According to the estimates of IIASA/WEC, the world primary energy demand in 2100 would be about 3.4 times of that in 2000 in the case of Middle Course (B-Case), in which fossil fuels increase 1.9 times, nuclear energy 15.8 times and renewable energies 6.5 times, as shown in Figure 1.

Fossil fuels, such as petroleum, natural gas and coal, have the environmental constraint due to CO2 emission, and petroleum and natural gas are concerned about depleting resources for the future supply.

As for nuclear energy, in order to secure continuous supply for such increasing nuclear demand in the 21st century as estimated by the IIASA/WEC, it is necessary to maintain balance of fissile fuels by timely introduction of FBR and Plutonium recycling with appropriate breeding setup to avoid supply stagnancy due to deficiency of fissile fuels.

In the IIASA/WEC estimate, nuclear energy is expected in 2100 to supply 24% of total primary energy for electricity generation. This amount of nuclear supply corresponds to the capacity of about 5,200 units of 1000 MWe plants. The supply of fissile fuel to these plants is feasible as shown in Figure 2, assuming the ultimate resources of natural Uranium 16.3 Mton, by the NEA/IAEA Red Book[i], and the recycling use of Plutonium by FBR introduced from 2030 ~ 2050 with breeding ratio of 1.2 ~1.3[4].

By optimizing the recycling use of Plutonium in FBR, it is possible to increase nuclear energy supply to 1.5 times in 2050 and 2 times in 2100 of the IIASA/WEC B-Case estimates[ii]. When nuclear energy is effectively utilized to produce hydrogen and synthetic fuels, such as hydrocarbons, in addition to generating electricity, the excess supply capacity of nuclear energy over the IIASA/WEC B-Case could replace some of the fossil fuels demand in the transportation sector, thus reducing CO_2 emission.

The estimate of primary energy supply for this Proactive Nuclear Deployment Case is also shown in Figure 1 (top), contrasting with the original IIASA/WEC B-Case (Figure 1 bottom).

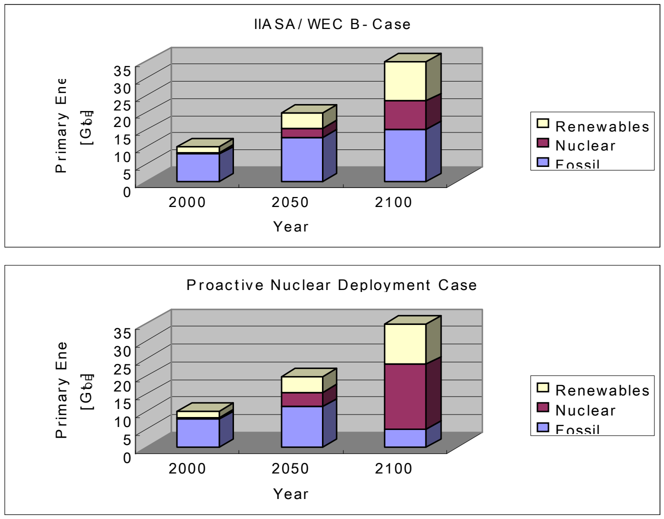

Figure 1: Primary Energy Supply for 2000-2100 WEC-B Case and Proactive Nuclear Deployment Case
Energy in Gtoe [10^9ton Oil Equivalent]

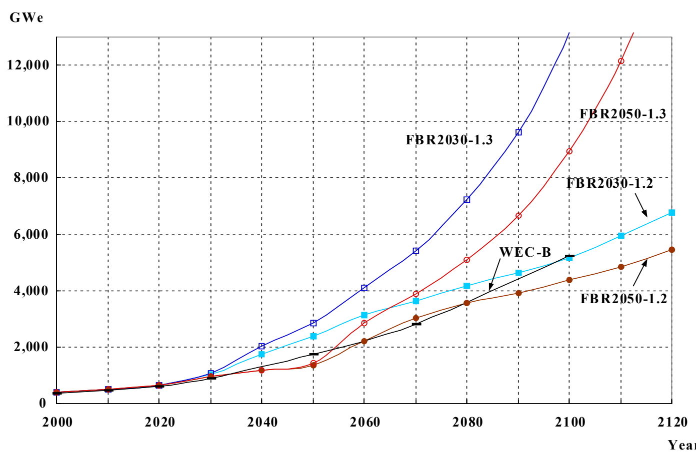

Figure 2: Nuclear supply capacity as projected
by the four transition strategies
-- Comparison with the WEC-B Case --

In such a scheme, the global supply quantity of fossil in 2100 would become smaller than it was in 2000, thus attaining stabilization of atmospheric CO_2 concentration even in the face of global increase of energy use by a factor of 3.4.

Either in the IIASA/WEC-B Case or in the Proactive Nuclear Deployment Case in Figure 1, the world has to utilize concurrently all of these primary energies in the 21st century. Therefore, it would be worthwhile to investigate ‘synergistic’ energy conversion processes by which these primary energies work together to produce energy carriers so as to obtain benefits from any combined effects to efficiency and cost, and further to environment, resource and economy as the consumption of primary energy decreases.

In the course of energy use, we convert the primary energies, which have energies, in the form of chemical, heat, light, potential or motion, into energy carriers, in the form of electricity, hydrogen and hydrocarbon, which are convenient to utilize for the final demands.

Here, the energy carries are categorized into three as shown in Table 1, namely hydrocarbons, electricity and hydrogen. In the coming future, in order to meet the growing energy demand in the world under the restriction of environment and resources, it is essential to increase the conversion efficiency from primary energies to energy carriers, as well as to increase the utilization efficiency in the final energy demands.

In the following sections, synergistic processes using both nuclear and fossil energies are reviewed and investigated as means for high efficiency energy conversion. Synergy between nuclear and renewable energies should be beneficial as well, but not discussed in this paper.

Primary Energy	→	Energy Carrier (Secondary ~ Final Energy)	→	Final Demand
Fossil Fuels Nuclear Renewables	Conversion	Hydrocarbons (Including Bio-fuels and Synthetic Fuels) Electricity Hydrogen	Utilization	Heat Light Power Transportation Electronics Communication

Table 1 Flow of Energy Conversion and Utilization

3. INDIVIDUAL AND SYNERGISTIC PROCESSES OF ENERGY CONVERSION

In the production technologies, there are individual processes and synergistic processes. The individual process is a process where only one primary energy is used to supply energy for converting to an energy carrier. The synergistic process is a process, where two or more primary energies (fossil fuels and nuclear energy in this paper) are used to supply energies for converting to an energy carrier.

3.1 Individual Process

At present, fossil fuels and nuclear energy are individually producing such energy carriers as hydrocarbons, electricity and hydrogen mostly commercially, though some are still in developing stages.

Some of the examples of the individual processes for converting the primary energies to energy carriers are shown in Table 2.

Primary energies	Energy carriers		
	Hydrocarbons	Electricity	Hydrogen
Fossil fuels	➢ Petroleum refining ➢ Coal gasification	➢ Coal fired power plant ➢ Natural gas fired power plant	➢ Steam methane reforming ➢ Steam coal gasification
Nuclear energy	➢Carbon recycle CH_4 nuclear synthesis/ on-board H_2 reforming/ CO_2 fixation (Kato)	➢ PWR ➢ BWR ➢ HWR	➢ Electrolysis ➢ Thermo-chemical water splitting

Table 2: Example of Individual Process for Converting Primary Energy to Energy Carrier

In Table 2, the nuclear electricity generation is now commercially conducted, and nuclear hydrogen production is now under research and development. As for the nuclear hydrocarbon production, a nuclear synthetic methane recycling process is being developed by Tokyo Institute of Technology for on-board steam-methane reforming with calcium oxide for CO_2 sorption[6].

3.2 Synergistic Process

By creating nuclear-fossil synergistic processes (Figure 3) using the best features of both energies, high efficiency conversion from the primary energies to energy carriers will be realized.

When we use nuclear energy for energy supply purpose, available energy form is essentially 'heat'. The key point of utilizing nuclear energy in a synergistic process is to supply nuclear heat to a chemical process in which heat is required for the chemical reaction. Thus, nuclear heat is converted into chemical energy of the reaction product which may be used effectively in a subsequent process. If nuclear heat is not supplied, the heat has to be supplied from a fossil fuel by combustion or other processes, thus saving fossil fuel consumption.

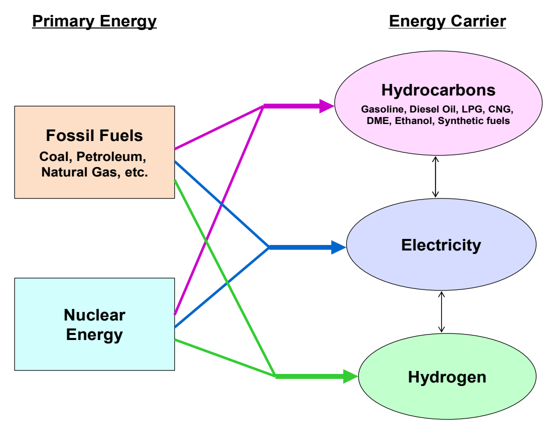

Figure 3: Synergistic Productions of Energy Carriers from Primary Energies

4. SYNERGISTIC PROCESSES USING NUCLEAR AND FOSSIL ENERGIES

Examples of the synergistic processes using both fossil fuels and nuclear energy to produce or upgrade energy carriers are reviewed in this section.

4.1 Synergistic Hydrogen Production

For production of hydrogen, steam-methane reforming (SMR) processes using natural gas are commonly adopted. The SMR process is endothermic reaction as shown by the following equation;

$$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2 \qquad -165\ \text{KJ/mol}$$

This reaction heat is usually supplied by combustion of feed natural gas itself.

In the nuclear-heated SMR process of natural gas, nuclear heat supplies the endothermic reaction heat, thus saving the natural gas consumption by about 30%. Figure 4 shows a schematic diagram of fast breeder reactor (sodium coolant) heated, membrane reformer hydrogen plant[7].

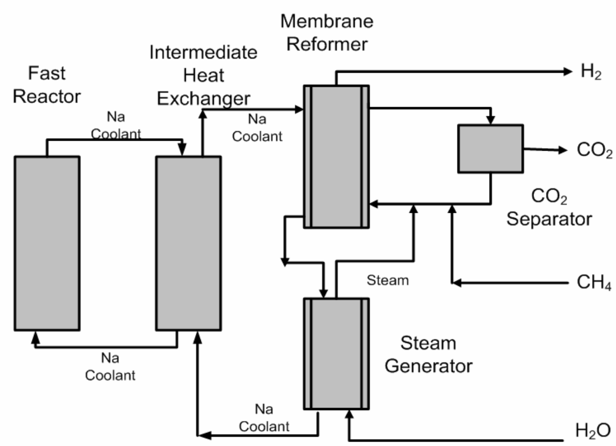

Figure 4: Schematic Diagram of Hydrogen Production by Sodium Cooled Fast Reactor-Heated Natural Gas Membrane Reformer

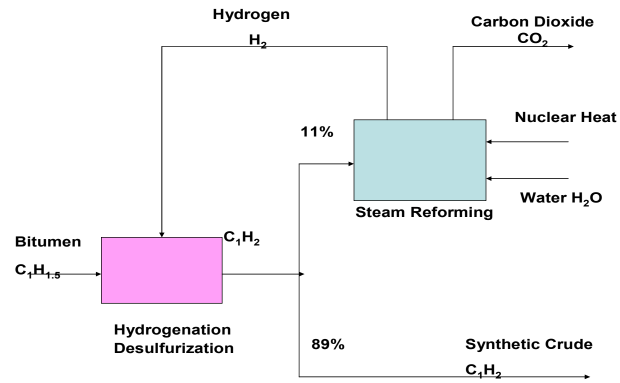

Figure 5: Schematic Diagram of Nuclear-Heated Steam Reforming for Upgrading Bitumen to Synthetic Crude

Contrary to other nuclear hydrogen production methods, such as electrolysis or thermochemical decomposition which use only water as feed material, this method consumes natural gas, but its consumption and subsequent CO_2 emission is less than the conventional method.

This process is considered to be most economical in various nuclear hydrogen production methods so far studied. Also it has least technical barriers for commercialization.

4.2 Synergistic Hydrocarbon Production

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 and electricity which are 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 oil sands, hydrogen is necessary for hydrogenation and desulfurization.

Also, when we produce synthetic liquid fuel, such as Fischer-Tropsch (FT, diesel) oils from coal, heat is necessary for the coal gasification process to produce synthetic gas (Syn gas) and additional hydrogen is necessary to adjust the hydrogen content in the Syn gas for the subsequent FT synthesis to produce FT oils.

Nuclear heat is considered to be used in these processes to supply heat and hydrogen. Otherwise, fossil fuels consumption is necessary to supply heat and hydrogen. Thus, using nuclear heat for these hydrocarbon production processes will reduce fossil fuel consumption and consequently CO_2 emission during production processes.

Figure 5 is an example of applying nuclear hydrogen to 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.

Figure 6 shows schematically how nuclear heat and nuclear hydrogen take the role of fossil fuel in supplying heat to the coal gasification process and in supplying hydrogen to the FT synthesis process.

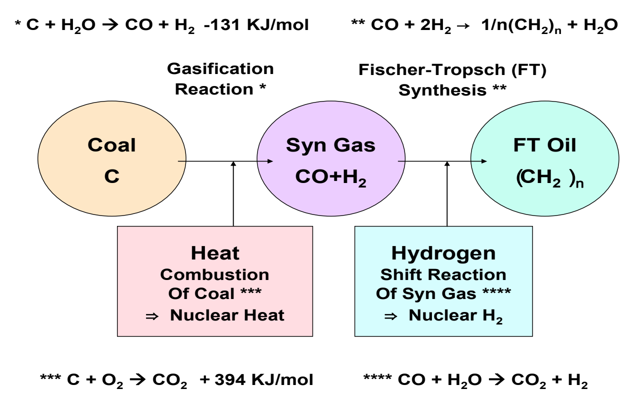

Figure 6: Supply of Nuclear Heat and Hydrogen to Coal-to-Liquid (CTL) Process (Steam Coal Gasification and F-T Synthesis)

4.3 Synergistic Electricity Generation

Proposed and tested by JAERI is a process of converting heat from a high temperature nuclear reactor to electricity inside a solid oxide fuel cell in which a partial oxidation reaction of natural gas is progressing[8].

In the partial oxidation reaction of natural gas (methane);

$$CH_4 + 1/2O_2 \rightarrow CO + 2H_2$$

the change of free energy (-273.2 KJ/mol) is far larger than the change of enthalpy (-21.7 KJ/mol).

Using this particular characteristic, nuclear heat is supplied to the fuel cell, in which the reaction is progressing; the supplied nuclear heat together with the reaction heat is converted electrochemically into electricity with high efficiency. Further, the reaction product

(CO and H_2) is produced in the same process. The conversion efficiency of 74% was measured in a small scale experiment.

Proposed and evaluated by the author is a process of producing hydrogen by nuclear-heated steam methane reforming (using a sodium-cooled fast reactor and natural gas), and then converting this hydrogen into electricity in a fuel cell (alkaline-type)[9].

The synergistic hydrogen production process using natural gas and nuclear heat is efficient and economic, and the subsequent electrochemical conversion of hydrogen into electricity in an alkaline fuel cell is also efficient. Therefore, 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 CO_2 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.

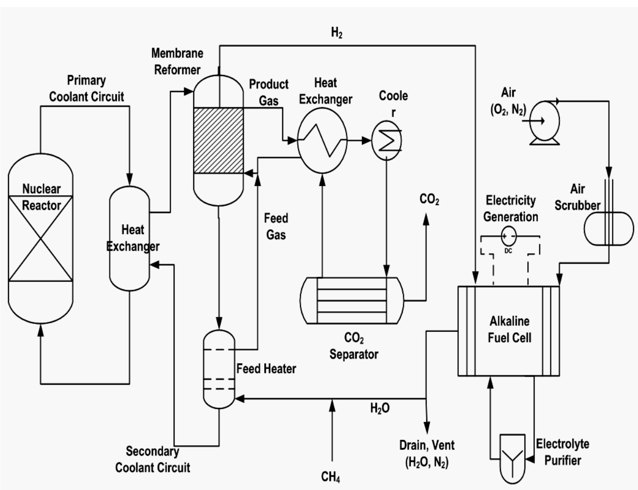

Figure 7: Schematic Diagram of Sodium Reactor Heated Natural Gas Membrane Reformer and Alkaline Fuel Cell

5. FEATURES OF SYNERGISTIC PROCESSES

The expected features of synergistic processes are;

- Saving resources of both fossil fuels and nuclear energy by processes of higher energy utilization efficiency
- Reducing CO_2 emissions by processes of higher energy utilization efficiency
- Lowering production costs by processes of higher energy utilization efficiency and by lower heat cost of nuclear energy

Some considerations on the energy utilization by synergistic processes are as follows;

In the process of electricity generation or hydrogen production from nuclear heat, there is the limitation by thermodynamic law (the Carnot efficiency at the highest), because either the electrolysis or the thermochemical water splitting process has to go through the 'heat engine' path as shown in Figure 8 (top).

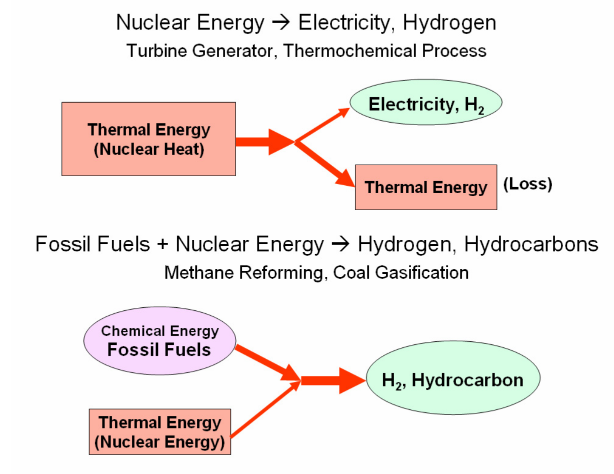

Figure 8: Thermodynamics of Energy Conversion from Nuclear to Energy Carriers

In the hydrogen production from fossil fuels, if it is chemical to chemical conversion such as by the steam-methane reforming reaction or by the steam-coal gasification reaction, there is no such thermodynamic limitation by the Carnot efficiency. In these reaction processes, the endothermic heat of reaction is conventionally supplied by combustion of fossil fuel itself. If this endothermic heat is supplied from nuclear heat, full stoichiometric conversion of fossil fuels to hydrogen moles and effective conversion of nuclear heat to hydrogen heat can be achieved as shown in Figure 8 (bottom).

In Table 3 are shown typical values of heat conversion factor for various hydrogen production methods using nuclear energy.[iii] There also shown is a value for conventional steam reforming using natural gas only. The heat conversion factor is defined here as ratio of hydrogen heat to input primary energy heat, that is nuclear heat, natural gas heat or sum of nuclear heat and natural gas heat, all in the low heat value (LHV). The nuclear-heated steam reforming using the membrane reformer gives a highest heat conversion factor of 0.85. This example shows the high efficiency feature of synergistic energy conversion.

Generally, in synergistic energy conversion processes, the energy contributed by fossil fuel is more than the energy contributed by nuclear energy in quantity, therefore the contribution of nuclear energy is auxiliary in energy quantity. A typical value of saving fossil fuel consumption by synergistic process would be 30% as in case of hydrogen production by the nuclear-heated natural gas reforming.

Hydrogen Production Process	Energy Source	Nuclear Electricity (Elect./Heat =32~50 %)	Nuclear Electricity & Heat (High Temp)	Nuclear Heat (High Temp)	Nuclear Heat (Medium Temp*)	Natural Gas Heat (Combust-ion)
	Raw Material	Water	Water	Water	Natural Gas Water	Natural Gas Water
	Production Process	Electrolysis	Hot Electrolysis	Thermo-Chemical	Steam Reforming	Steam Reforming
Heat Conversion factor	(H_2 Heat) / (Nuclear Heat) [-]	0.25~0.4	0.45	0.5	0.85*	0.8**

Heat conversion factor is based on the low heat value.

* (H2 Heat) / (Nuclear Heat + Natural Gas Heat) for the case of recirculation-type membrane reformer, assuming efficiency of reactor heat utilization = 60%, yield of hydrogen from methane = 95%

** (H2 Heat) / (Natural Gas Heat)

Table 3: Heat Conversion Factor Producing Hydrogen from Nuclear and Fossil (Low Heat Value)

6. CONCLUDING REMARKS

Following advantageous effects are expected;

- By avoiding the combustion of fossil fuels for heat supply, saving of fuel consumption and consequent reduction of CO_2 emission can be achieved, which lead to the 'noble' use of fossil fuels.
- By efficient processes utilizing both fossil fuels and nuclear energy, conservation of both energy resources can be achieved.
- By efficient resource utilization and by low heat cost of nuclear energy, favourable impacts to economy can be achieved.

It is expected that new, innovative, synergistic processes are created and these energy conversion processes become important in the 21st century for resource saving, emission reducing and economic production.

7. REFERENCES

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