FUTURE POSSIBILITY OF CARBON SEQUESTRATION BY BIOMASS FUSION HYBRID SYSTEMS

S.KONISHI
Kyoto University
Uji/Kyoto, Japan
Email: s-konishi@iae.kyoto-u.ac.jp

S.TAKEDA
Kyoto University
Kyoto, Japan

H.NAM
Kyoto University
Kyoto, Japan

Abstract

Possibility of fusion in the future energy market is investigated considering the current trend of rapidly changing energy systems in the world under the environmental constraints. Introduction of fusion when successfully developed will have to be considered in the deregulated electricity market with mostly carbon-free sources such as renewables, fission nuclear and fire-CCS combination. Fuels such as hydrogen or synthetic hydrocarbons with biomass origin is regarded as another possibility, that has a market larger than for electricity with less competitors. Third and probably the largest potential demand is for process heat used for charcoal production from biomass. They are all suggested as innovative fusion energy applications including electricity. The paper is presented by a rapporteur and summarizes the three analyses of different aspects of energy application to be expected for fusion and suggests that selections and optimization are to be made so that return of investment would be maximized by the combination of them. The results point out that Levelized Cost of Electricity (LCOI) that is often used as a part of fusion plant design studies sometimes are not suitable for the assessment of competitiveness of the fusion energy, and further suggests the possibilities of market opportunities of fusion, particularly responding to various energy needs that should be considered in the fusion development strategy.

1. INTRODUCTION

Almost all the fusion reactor designs assume electricity, particularly steady base load in the large scale grids as the product to sell. It is understandable that many of the countries such as US has extremely large grids over 100GW capacity where a 1GW fusion plant may have negligible impact. However, future electricity grids particularly current developing or emerging countries will have much smaller grids with more vulnerability against large change of the balance, that will be unavoidable with fusion due to disruption and start up power. On the other hand in many countries including Europe, grid supply would be occupied by renewables, nuclear and other carbon free sources including fossil with CCS. When fusion will be introduced, it must face to tough competition in the market[1]. Particularly, while the importance of base load electricity in grids is believed to remain for stability reason, it is well known that in the deregulated electricity markets, price of the electricity can be very small or even negative.

In the previous design studies of magnetic confinement fusion plants[2-4], system codes calculate the quantity of materials and the Levelized Cost of Electricity (LCOE) can be obtained by deviding material cost with unit electricity to be generated. Economical competitiveness of the fusion energy can be considered by comparison of the COE with other sources, both assumes price of the electricity is stable throughout the lifetime of the plants. It should be noted, however, that even if electricity could be sold, actual income from the electricity sales could be significantly different in the deregulated market where the market value of electricity is variable. Furthermore, in the rapid change of highly advanced electricity markets in some industrialized countries with significant fraction of renewables, unexpected disturbance of the demand-supply balance due to the fluctuation of renewable sources and the grid instability is serious. In order to accommodate such fluctuation, reserve capacity to stabilize the grid with variable generation capability is regarded to be valuable and thus traded in the capacity market. Fusion not for steady state base load but for responding generation to support grid stability could be more attractive and commercially beneficial.

In the entire end use market of energy, fuels to be used for transportation and various kinds of internal combustion engines, and application for process heat are anticipated to be dominant even at the end of the century, while the fraction of electricity is increasing. Industrial, transport and consumer sectors will continue to require the fuels in the form of liquid or gas. Unlike in the case of electricity market where majority of the sources are being decarbonized and renewable, nuclear, and fossil with CCS (Carbon Capture and Sequestration) will dominate, Fuel market will have fossil sources. If fusion is expected to promote the reduction of CO_2 emission, replacing such carbon dependent fuel media is more important than winning in the competition with already clean sources.

Finally, by the agreement of COP 21 in Paris, strict reduction of CO_2 is required in almost all countries in the world. However while reduction of CO_2 emission is possible and expected, there still remain large amount of emission that cannot be captured from small sources. Biomass-CCS combination (BECCS) and Direct Air Capture (DAC) are considered to be technically possible, but their feasibility, capacity and costs are unknown. While energy resources may not be exhausted in the near future considering unconventional sources such as shale gas and oil, total capacity for the isolation of Carbon could be more limited.

Considering the current and future situation of energy and environment policy in the world, possible strategy of fusion deployment requires some improvement from the previous simple electricity generation to replace large stations under the large grids. The paper considers some possible options other than base load electricity, particularly conversion of biomass material by use of heat from fusion reactor. Some alternative application of fusion energy are suggested and analysed by coauthors on, economical analyses of biomass based fuel[5] and economic performance of fusion in the bidding market of electricity[6]. The paper focuses the technical possibility of chemical conversion of biomass by the fusion as industrial process heat, particularly on the charcoal production followed by the sales of the carbon emission credit.

2. CHEMISTRY OF BIOMASS CONVERSION

A biomass gasification reaction, typically the pyrolysis of cellulose that represents the most of the organic compounds made by the photosynthesis absorbs large amount of heat at high temperature:

$$C_6H_{10}O_5 + H_2O \rightarrow 6H_2 + 6CO - 814\ kJ \qquad (1).$$

High conversion efficiency above 95% and absorption of heat by the endothermic reaction were reported previously[7]. This reaction equilibrium is favoured at higher temperature sabove 700 degree C, and 900 degree is required to complete. High temperature blankets such as DCLL[7] concept will be required to fully utilize this reaction completely.

The product gas can be used to synthesize substitute diesel by Fischer Tropsh reaction,

$$2H_2 + CO \rightarrow (-CH_2-) + H_2O + 160kJ \qquad (2)$$

or when hydrogen would be preferred, Shift reaction

$$CO + H_2O \leftrightarrow H_2 + CO_2 + 32\ kJ \qquad (3)$$

can be applied to convert the product to hydrogen. Both are possible at the temperature around 200 degree C and are already proven in industrial scale with existing technology.

This process utilizes the chemical energy of biomass that assists fusion reactor to improve the energy multiplication factor. Typically, 1 kg of cellulose has a chemical energy of 16MJ, and with additional energy of 8 KJ as process heat supplied by a fusion reactor produces 24MJ equivalent chemical energy of CO + H_2 gas mixture. Compared with the Lawson criteria that assumes 33% generation efficiency by rejecting 2/3 of fusion energy to be discarded as low grade heat, this biomass gasification multiplies fusion energy at the factor of 3, and energy balance becomes considerably easier. The product such as hydrogen or liquid fuel can substitute fossil resources and reduce carbon emission, and its market will be larger than that of electricity.

The produced fuel can generate electricity with fuel cells that can respond to the change of the demand. Small scale fuel cells are already commercially available for consumers. For a fusion reactor, it is less costly option for particularly smaller plasma devices. Figure 1 shows the simplified flow diagram of the fusion electricity generation with biomass conversion and fuel cell. Power required for plant start-up can be supplied from fuel cells, and such a system is applicable for pulsed machine, and product electricity has more flexible nature to respond demand changes.

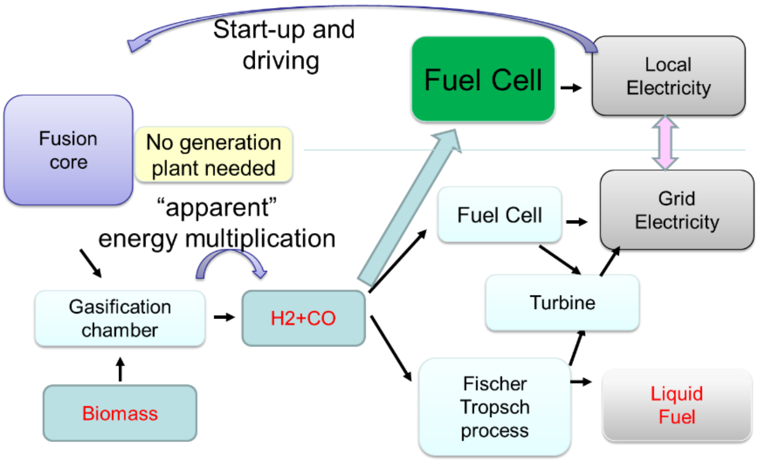

FIG. 1. Simplified flow diagram of energy use for Biomass-Fusion Hybrid. Electricity is mainly generated by the fuel cells at both local and centralized grids. Exhaust heat from Fischer Triosch process is used for turbine generator.

Figure 2 shows the comparison of the cost of conventional generation turbine and fuel cell against the fusion power of the reactor[8]. It is clearly understood that fuel cell can provide more cost efficient option for electricity generation for fusion reactor with particularly small fusion power. Since unit capacity of fuel cell is much smaller than turbine, modular generator is advantageous at smaller scale, while turbines have scale merit.

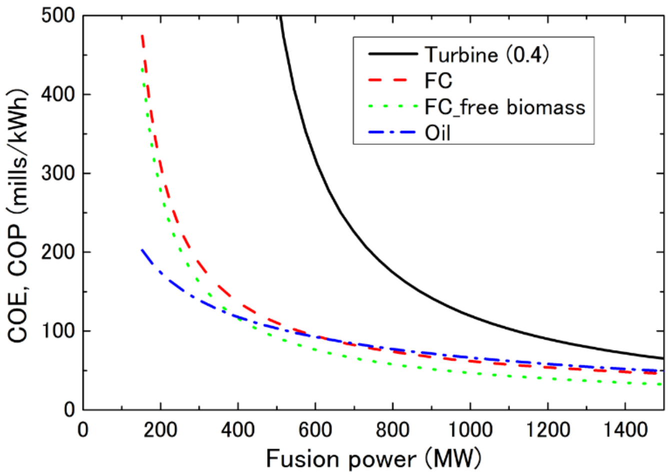

FIG. 2. Cost of the electricity from conventional turbine and fuel cells as the function of fusion power of a single reactor. Production cost for artificial oil is also shown at the equivalent product energy. Because the unit capacity of the fuel cells are small and thus modular, smaller generation is favourable for fuel cells.

This paper further proposes another new type of the biomass conversion reaction as the application of fusion energy, that is charcoal making process, or dry distillation;

$$(CH_{1.6}O_{0.6}) = C + 0.4H_2 + 0.6H_2O - 451kJ \qquad (4)$$

where biomass is assumed to be woody and includes large fraction of lignin. Compounds are simplified and normalized for a carbon atom. This reaction requires much larger heat to completely separate Carbon from hydrogen and water molecules.

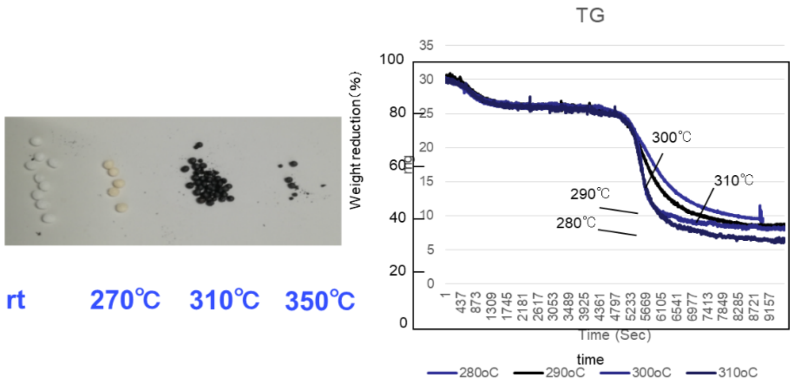

FIG. 3. Charcoal production from cellulose. Left: appearance of the reaction product against temperature. Reaction occurs at 310 degree completely, and above it sintering and weight loss of charcoal occurs. Right: Weight loss of cellulose heated at constant temperature increase. Reaction occurs at above 280 degree C.

Figure 3 shows the charcoal production from cellulose at different temperature. In the thermos gravimetry (right) at the constant temperature increase suggests that the conversion to charcoal occurs at around 280 degree C, and rapidly complete at around 310 degree C. Vaporised “still” products represented as tar is also obtained that will probably need further pyrolysis to utilize the reactions (2) and (3). Most important feature of this reaction (4) is its reaction temperature that is suitable for water or helium cooled blankets for the first generation DEMO reactors. Combined with the “Hybrid effect” described previously, this charcoal production will be one of the easiest strategy as the process heat application of fusion. However, higher temperature will be needed to fully utilize the liquid by-product of this charcoal making reaction, that is a mixture of complicated organic compounds mixture. The final product is represented as reaction (1). It is pointed out that the commercial Solid Oxide Fuel Cells (SOFC) is operated at the temperature in the 700 degree – 900 degree C range, and the conversion of tar and still can be a part of the oxidation reaction in the cell.

Biomass made by the plants contain both Cellulose and Lignin. Typical woody biomass is considered to contain ca. half lignin and cellulose and converted to charcoal, as in the reaction (4). Absorbing heat by the endothermic reaction in reaction (4) is greater than reaction (1). In order to avoid oxidation, the reactor is isolated from air. In the experiment of chemical reaction, steam is used as cover gas to remove oxygen from atmosphere in the reactor vessel. As seen in the reaction (1), water vapour is also used to promote the gasification that partially oxidize carbon to CO while hydrogen gas is liberated. In this chemical process of biomass, therefore, drying pre-treatment that is usually required for most of the biomass is not necessary, and facilitate energy saving.

Chemical process system and the type of the reactor for this charcoal production reaction (4) and gasification (1) is essentially similar, probably rotary kiln type for continuous operation. But the required temperature is lower, and the ratio of the water vapour for the reactant is different to control the yield of char. While efficiency of reaction (1) was 97% in the previously reported experiment[9] with sufficient steam, insufficient water resulted generation of char in the lignin pyrolysis and the majority of the reactant is converted to solid carbon. The dry distillation process is widely known, but the endothermic reactions (1) and (4) with external heat source is not known and innovative as energy/environmental application.

3. CHARCOAL FROM BIOMASS REGARDED AS EMISSION CREDIT

The product solid char is separated and can be stored as it is or sintered if hotter temperature from fusion is available. This biomass-fusion hybrid system will provide an innovative carbon sequestration method that originally is recovered from atmosphere by the photosynthesis by grasses or trees. What this system provides is the isolation of CO_2 from the earth cycle including fossil combustion, and stabilizes it as solid carbon. This carbon product is extremely stable, as seen in the case of coals in the world. Typical flow of the energy and carbon is illustrated in the fig.4.

Product solid carbon from biomass-fusion plant is a visible and measurable evidence of the captured CO_2 from the atmosphere, and can be “sold” in the emissions trade market. This capture, stabilization and isolation from the atmosphere can be done on the site of fusion plant with various biomass feedstock at desired time and place selected by the fusion plant. However, it can be regarded as the recovery of released CO_2 from any place and time in the world. Because of the nature of the solid carbon and emission credit, this trading can occur at the time when the carbon is recognized as emission credit. It is likely that a third party, probably public organization or NPO will be a neutral mechanism that evaluate certify the emission reduction [10].

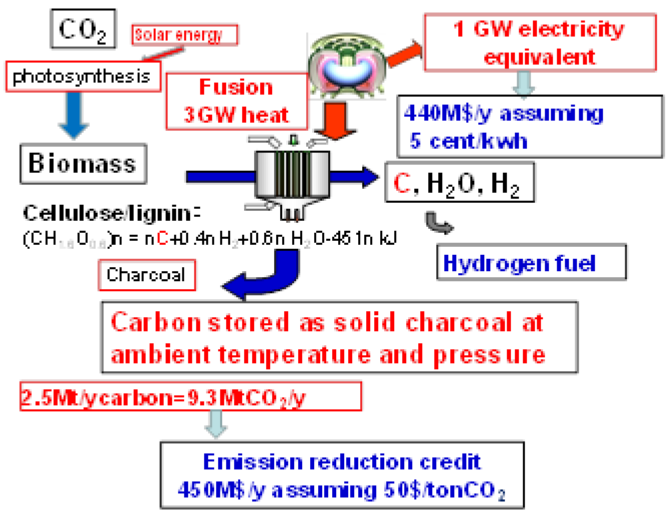

FIG. 4. Charcoal production by biomass-fusion hybrid plant.

The Paris agreement on the reduction of CO_2 emission [11] is accepted by most of the countries in the world, and if it would be implemented, we will run out of the “carbon budget” beyond 2040[12], and emission credit will be more and more valuable as a limited resource. The currently deployed CCS technology based on the separation of CO_2 from the exhaust of industry followed by the pressurized underground storage requires difficult geological criteria to meet, and technical, social, and environmental risk management, and processing energy[13]. No other alternative has been proposed yet. However the solid carbon storage at ambient pressure is stable and easy, and less environmental/social constraints is anticipated. At least, some countries including Japan where stable geological site is very limited for long term storage of pressurized CO_2 in the underground structure, this technology could be a viable alternative.

The figure 4 also shows a comparison and conversion of the value of carbon emission credit and electricity to be generated by a same fusion plant. Since both electricity and solid carbon can be a product of fusion energy, 3GW fusion heat is equivalent to 1GW electricity to be generated by a large scale turbine. With same amount of fusion heat, 2.5Mton per year of charcoal, corresponding to 9.3Mton/y of CO_2 can be produced. Assuming 5 cent/kwh of value of electricity, 50 $/ton CO_2 is the breakeven price of the emission credit. When the value of the CO_2 is greater than this value, selling it makes more profit than electricity sales. Depending on the value of emission credit, that is difficult to anticipate at this time, it could be easier market for fusion to be deployed.

Because transport, some industrial and residential heat sectors unavoidably release CO_2, net negative emission by human activity with biomass is inevitable [14]. While electricity sector and some other carbon intensive industries can apply CCS, the emission can be reduced only to close to zero and never goes to negative. Biomass CCS (BECCS) is one of the very few possible solutions to accomplish negative emission by photo synthesis. Figure 5 shows an example(delived from [14]) of the outlook of required CCS capacity to compensate the total CO_2 emission from not only electricity generation but from all the emissions by all human activities to be prevented or compensated to stabilize the concentration in the air. It is obvious that CCS demand by electricity (A) in the fig.5 is only a part of the entire CO_2 sources such as transport, heat, fuel and material production processes(B). Regardless of the future energy scenario and market, CCS by fusion-biomass hybrid has a large potential to provide emission credit to (A+B).

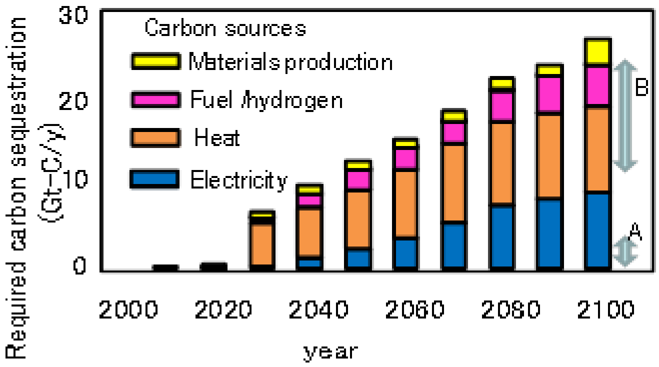

FIG. 5. Required carbon sequestration to meet the carbon budget by Paris agreement. Fusion has a possibility to contribute both small fraction for Electricity(A), and significantly larger part of the rest(B) by providing negative carbon for other sectors.

5. CONCLUSION

Steady state, base load electricity in the large scale grid has been a default target for fusion development originated in mid 20th century when rapid increase of world population together with very high economical growth rate in the OECD countries was observed. Although it will still play a major role in the developing and emerging countries, world situation of the energy and environmental problem, particularly climate change issue requires drastic change of the target toward the sustainable development of humankind. If the objective of the development of fusion energy is to facilitate the sustainable energy supply for human beings, strategy and target would require more flexibility to meet various possibilities in the future. The biomass-fusion hybrid concept, and possible options of application of fusion energy for process heat that will generate gas and liquid fuel media , and the emissions credit market will be worth consideration. There, fusion has fewer competitors that will have environmental constraints, and fusion can provide **net negative emission** not only for electricity, but for all kinds of CO_2 sources.

Ultimate amount of carbon to be captured and stabilized is estimated to be order of 7 Tton[13] to settle down the CO_2 concentration in the earth atmosphere to be. With the conversion rate suggested above, 100,000 unit-operation year of 3GW fusion power equivalent will be needed to return the additionally released carbon since the beginning of industrial revolution and mining coal. This new fusion-biomass hybrid can provide the solution to return the CO_2 concentration to the age before the industrial revolution by returning them back to coal mines and oil wells. This study proposes an innovative option of fusion application that could potentially be larger and more important than electricity generation, and justifies the investment of fusion development to be eventually recovered from the future market.

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