INVESTIGATION OF ECONOMIC FEASIBILITY OF FUSION-BIOMASS HYBRID SYSTEM IN THE FUTURE ENERGY MARKETS

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This study analyzed the feasibility of fusion-biomass hybrid system employing different specification of blanket designs providing high temperature and low temperature. The fusion-biomass hybrid system is non-electric application of fusion energy for fuel supply or carbon capture by charcoal production. The fusion-biomass hybrid system investigated the economic analysis on fuel production and emission credit. The economic feasibility assessment is based on conceptual design of fusion, cost evaluation, experiment and market compatibility. Strategy and possibility regarding investment recovery from the energy markets were studied. The background of the study is that CO_2 emission from fossil fuel is responsible for over 60% of world GHG emission. Liquid and gas fuels are expected to keep increasing as they are not likely to be fully replaced by electricity. Bioenergy and carbon capture and sequestration (BECCS) is a prospect technology for energy supply and CO_2 cut according to IPCC report. Steady, safe and clean nuclear fusion can be an asset for fuel production and carbon removal by providing thermal heat through blanket from fusion reactor.

For low carbon-intensive fuel production, safe and stable fusion energy as baseload is the low carbon energy source that enables to provide high temperature heat (>900 ^{o}C) from the DCLL blanket. The temperature is enough to process gasification for synthetic gas production. The gas can be converted into fuel (*e.g.* synthetic gas, diesel and hydrogen) through the chemical and physical process. With the purpose of negative emission, stable solid form of carbon (charcoal) from biomass can be made by the low temperature heat (~500 ^{o}C) from several blanket designs (*e.g.* HCLL, HCCB, and WCCB, etc.). It can be regarded as carbon capture and sequestration instead of emission to the atmosphere in form of CO_2 after spoiled or incinerated. The carbon sequestration by charcoal production is considered carbon recovery to realize the world temperature by 2 ^{o}C well below the industrial era. The combination of the low carbon energy sources, biomass and fusion, can be a breakthrough for the future demand and the climate action. Different types of blankets can be applied depending on the region's or country's necessity.

The objective of the study is 1) to investigate the economic competitiveness of the hybrid system compared to typical fusion power generation, 2) to find the possibility of investment recovery and clarify the influential factors, and 3) to envision the flexible and strategic operation of the hybrid system in the future complex market mechanism.

Chapter 2 and 3 demonstrated fuel production (*e.g.* synthetic gas, diesel and hydrogen) by applying high temperature heat (>900^oC) derived from fusion energy ducted with DCLL. Endothermic reaction of biomass by the fusion power produces synthetic gas which can be converted into various energy forms selling to either electricity or fuel market. The results show that the hybrid system shows higher profit than the typical electricity generation by turbine. The result of sensitivity analysis between diesel from Fischer-Tropsch reaction and electricity from SOFC indicates that diesel production cost is more sensitive than electricity cost according to the change in the annual system operating hours while electricity cost is more sensitive than diesel cost regarding the fusion heat cost change. In terms of return on investment, diesel is more sensitive than electricity by changing the market price of diesel and electricity. It is found that a larger scale than 300 MW power does not effectively decrease the production cost. Hence, a small scale of fusion reactor, 364 MW GNOME, is adequate for the hybrid system. Diesel and hydrogen production discussed the possibility of investment recovery under the certain conditions. When GNOME reactor was applied, the levelized cost of fuel for diesel and hydrogen was calculated 0.6 $/liter and 1.54 $/kg, respectively. It clarified the degree of impact by influential factors and the possible condition for the hybrid system establishment by the modelling analysis. Among the influential factors, not only technology advancement for cost drop, but national regulation affecting plant availability and subsidy are important for the system operation from the economic aspect.

In case of charcoal production for carbon removal discussed in chapter 4, charcolization temperature and charcoal yield was obtained by conducting an experiment. Experiment proved the appropriate temperature for charcoalization and charcoal yield to define the applicable blanket design. Fixed and isolated solid carbon from atmospheric CO_2 was clarified from the viewpoint of energy conversion by charcoalization process. The experimental result of thermogravimetric analysis (TGA) proves that the all proposed blanket design concepts are possibly applied to the fusion-biomass hybrid system for charcoal production because 280 ^oC of the heating temperature under 1 hour residence time is able to convert the biomass into charcoal at the conversion ratio of 20's % for cellulose and 80's % for lignin. Emission trading market and deregulated market provide broad opportunities to operate the fusion power securing the investment recovery. The strategy of the hybrid system demonstrated in the various market mechanism by economic comparison between fusion power plant and the hybrid system. When the comparison analysis was performed between the fusion-biomass hybrid system and the fusion power plant, emission credit traded in the emission trading market is able to offset the economic loss compared to only electricity sale due to the unstable electricity price in the deregulated market. Decrease in fusion cost and increase in carbon pricing in the future makes the hybrid system a more viable option.

The combination of fusion and biomass is possible to make a contribution by electricity generation, fuel production and carbon removal effect in the future energy markets. It was clarified that the fusion with biomass can enhance the economic feasibility encouraging the fusion development policy. In the perspective of macroeconomics, the hybrid system can be established by having economic actors dealing with the performance, structure, behavior, and decision-making of an economy closely intertwined. Nation regulation limiting the system operation hours, international trade impacting the limited materials and feedstock and uncertain market situation should be harmoniously performed for the hybrid system deployment. By seeing the current trend, divestment on the fossil fuel has been made the fossil fuels as stranded assets. The divestment movement has been sparked by the social movement on "unburnable carbon" issue. It encourages people to ask for the disclosure from fossil fuel companies. This trend in the future will make a favorable environment for the fusion energy deployment.

In terms of heat sources, fossil fuel enables to provide high temperature heat and the current technology for gasification process uses fossil fuels (e.g. natural gas and coal) despite of against the climate action. Other renewables as well possible to provide the heat for gasification although intermittent resource is questionable for the steady supply. Generation IV of nuclear fission as well possible to provide outlet temperature up to 1,000 ^{o}C in the future, but the social acceptance for the nuclear safety needs to be overcome. In this sense, stable, steady, safe and clean fusion energy is an attractive heat source complementing the drawbacks of other heat sources. Fusion energy application should not be only limited to electricity generation, but spread out to fuel production or carbon capture. The market feasibility is sufficient to compete with the current technology in the sense of fuel production and emission credit trade. The future market mechanisms as well as energy and environmental policy require to shift the target to the sustainable society in both economic and environmental aspects. Flexible and strategical operation of fusion energy with biomass will be able to provide the electricity and clean fuels for the demand satisfaction, and carbon capture for net negative carbon effect. This challenge can be completed with the fusion energy. The fusion-biomass hybrid system can be an option to make a contribution to sustainability in energy and environment.