Techno-economic analysis of diesel and hydrogen production via Fusion-Biomass Hybrid Model

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Abstract. Fusion-biomass hybrid model is a new alternatives to produce more energy generating synergy effects by efficiently utilizing the high temperature heat from fusion reactor that might be considerably wasted by thermal cycle, and also energy loss from biomass combustion or biochemical processes. The underlying process of this fusion-biomass hybrid model is endothermic reaction of high temperature heat from the fusion blanket of Dual Coolant Lithium Lead. This paper aims at making an economic analysis of diesel and hydrogen production via carbon neutral process of fusion-biomass hybrid model. Thermal output change of fusion reactor matching with biomass plant capacity is investigated to know the levelized cost of fuels (LCOF). A sensitivity analysis is performed to learn the LCOF according to variables. Lastly, net present value (NPV) change depending on fusion heat cost change gives implication for the deployment in the future. The results can help in deciding which product is economically justified in the circumstances of technical and cost limitation.

1. Introduction

In order to keep the universal agreement made at COP21, bioenergy and carbon capture and sequestration (BECCS) is considered one of the most promising technologies for climate action and electricity supply [1]. This is because biomass is regarded as carbon neutral energy source as it emits absorbed amount of CO_2 from the atmosphere by photosynthesis, when it is processed for energy use. On the other hand, another option to provide stable electricity without emission will be nuclear fusion energy. ITER Tokamak in France will be a milestone to realize clean and infinite electricity generation. In addition to the increasing electricity demand, it is projected that soaring fuels demand is inevitable for economic development in both developed and developing countries [2]. BECCS incorporated in fusion energy, Fusion-biomass hybrid model, can be a new pathway to meet the fuel demand in the future.

There are previous studies about fusion-biomass hybrid model. The concept of this model incorporates the amount of endothermic heat for biomass process with nuclear fusion heat, which proves the achievement of Lawson's criteria [3]. Technical analysis of small-scale fusion reactor design, GNOME, was studied for this model application [4]. Life Cycle Assessment (LCA) was performed indicating that this model contributes a large amount of CO_2 reduction compared with a conventional biomass plant [5].

Currently biomass is widely used for heating or electricity production through combustion or biochemical processes. But it shows significant energy loss during conversion. Minimum energy loss achieves when high temperature thermal heat is applied to biomass conversion such as gasification process. The underlying biomass conversion requires high temperature heat, which nuclear fusion can provide through blanket. The produced fuels is able to decreases the dependency on fossil fuels in many countries. This paper consists of the following sections: Section 1 gives a background and introduction to the study. Section 2 explains technical description of fusion-biomass hybrid model and chemical process of biomass gasification reaction. Section 3 describes parameter and data for diesel and hydrogen cost. Section 4 shows results of levelized cost of fuels (LCOF) and the sensitivity analysis of diesel and hydrogen according to several variables change. Finally, conclusions are drawn in Section 5.

2. Process of fusion-biomass hybrid model

2.1. Technical process

The plasma temperature of millions degrees Celsius in the fusion reactor is able to achieve the optimal gasification process under the condition that the blanket has high tolerance against heat and strain. Among the reported blanket designs, Dual Coolant Lithium Lead (DCLL) is highly recognized for high temperature heat transfer. This design is considered and developed in China, Europe, and the US [6]. Two coolants, lithium lead (LiPb) and Helium (He), are selected to cool down the ferritic-martensitic (RAFM) steels of the first wall. Flow channel inserts (FCI) which is electrical and chemical insulator is applied to separate LiPb from first wall. It prevents RAFM steel from corrosion and magnetohydrohynamic (MHD) pressure drop. If SiC-fiber-reinforced SiC matrix (SiCf/SiC) material is applied, the first wall is possible to tolerate against 1,000 ^{o}C for gasification reaction [4].

A simplified schematic of fusion-biomass hybrid model is that a fusion reactor coupled to biomass gasification system *(see FIG. 1.)*. In case of SiC_f/SiC application, He at outlet temperature of 850 ^{o}C goes out from blanket at 8 MPa of outlet pressure to the fluid (He) in the heat exchange demonstrated in as Figure 1. LiPb at outlet temperature of 1,000 ^{o}C delivers its heat to the heat exchange. Helium fluid of the heat exchange reaches to over 900 ^{o}C after receive its heat from the two coolants (He and LiPb) from fusion reactor. The ratio of temperature change of inlet/outlet temperature in the heat exchangers is referred to Raffrary et al [7]. Input of thermal heat and waste biomass with gasification agent, steam, results in syngas production. The produced syngas can be converted into either artificial diesel by Fischer-Tropsch (FT) reaction or hydrogen by extracting from syngas and Waster-gas shift (WGS) reaction. Exhausted heat after gasification drives steam boiler to provide steam as gasification agent into gasifier for optimal performance.

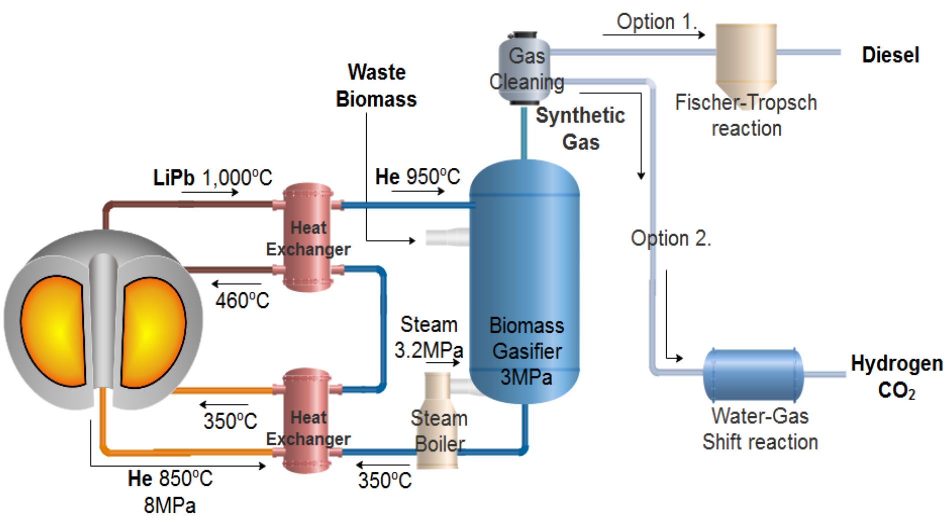

FIG. 1. Schematic of nuclear-biomass hybrid model

2.2. Biomass Process

Biomass consists of major three components, cellulose, hemicellulose and lignin [8]. The biomass feedstock in this model is assumed to use waste biomass such as municipal solid waste from cities and residues from agriculture and forestry sectors. In this study, the stoichiometric equations describe the complete conversion of representative biomass, cellulose ($C_6H_{10}O_5$), to either diesel or hydrogen. Helium fluid from the heat exchange performs steam gasification reaction. The syngas production from biomass is possible with 814 kJ (8.2 MJ/kg) of thermal heat from fusion energy [3].

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

The conversion of waste biomass to H_2-CO mixture performs at over 900 ºC with high reaction efficiency shown in Equation (1). Steam gasification or steam/oxygen gasification produces relatively higher share of H_2-CO mixture of synthetic gas [9]. The product H_2-CO gas mixture can be converted into liquid hydrocarbon by FT reaction shown in (Eq. 2).

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

The artificial liquid fuel such as diesel, kerosene or jet fuel under the specific process with adequate catalysts can be produced. For simplicity in this study, basic form $(–CH_2–)n$ is taken as the complete molecular composition of diesel. With calculation based on molecular composition of cellulose, stoichiometric diesel yield from waste biomass is 43 %.

Hydrogen can be extracted from syngas through separation process after gasification. In addition to that, the product H_2-CO gas mixture can yield more hydrogen by the WGS reaction with the existing technology. The maximum amount of hydrogen is investigated from the stoichiometric chemical equations of both biomass gasification process (Eq. 1) and WGS reaction (Eq. 3) based on cellulose. 14.4 % of hydrogen and 163.2 % of carbon dioxide are produced from waste biomass input.

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

Hydrogen can be used as fuels for hydrogen vehicle (*e.g.* Fuel Cell Electric Vehicle (FCEV) and Plug-in Hybrid Vehicle (PHV)) and for electricity generation by Solid Oxide Fuel Cell (SOFC), while carbon dioxide is subject to be managed by carbon capture and sequestration (CCS) technology.

3. Methodology

The objective economic analysis is to find the optimal size of biomass plant matching to the fusion power. LCOF is calculated based on the scale of the model along with investment change. Sensitivity analysis shows the influential degree of each variable impacting on LCOF. The variables include total capital investment (TCI), operation and maintenance (O&M), fuel production rate, the amount of endothermic heat per waste biomass, the annual operating time and fusion heat cost. Net present value (NPV) is assessed with sensitivity analysis according to the changes of fusion heat cost and fuel price.

Feedstock cost is postulated to be zero because the waste biomass for feedstock is covered with the government tax or expenses by polluters for collection and treatment. The TCI of 1,000 ton/day (tpd) biomass plant is 503 million$ and O&M is assumed 6 % of TCI. Lifetime of the system is 30 years and 30 % of income tax is assumed. Plant availability is 7,900 hours, which is approximate one month for minor equipment refurbishment and replacement. Discount rate is 10 % assuming that high risk is expected due to the initial introduction of fusion deployment. A 7-year schedule is applied to Modified Accelerated Cost Recovery System (MACRS) for depreciation. The selected parameters are described in TABLE I.

TABLE I: PARAMETER FOR ECONOMIC ANALYSIS

Parameter		Value
Carbon Capture and Sequestration (CCS) [a]		43 \$/tCO2
Fusion heat cost [b]		21 \$/MWh_{th}
Feedstock [c]		0 \$/ton
Reference Biomass Plant [d]	Total Capital Investment	503 Million\$
	Operating and Maintenance	6% of Total Capital Investment
	Capacity	1,000 ton/day
	Operating years	30 years
	Income tax	30 %
	Discount rate	10 %
	Plant Availability	90 % (Approximate 7,900 hours)
	Depreciation	MACRS with a 7-year recovery period

[a] Average CCS cost is assumed 37 Euro/ton [11].
[b] Breakeven price \$65 MWh_e of fusion electricity generation in case of 550 ppm scenario is introduced, which decrease in fusion electricity cost is 2.3 % for first 25 years after the year of fusion introduction and 0.25 % for the subsequent years [12]. Fusion heat cost is calculated under the condition of the average 33 % of thermal efficiency.
[c] Feedstock is abandoned waste biomass from municipal, agriculture and forestry area.
[d] Total capital investment (46 \$/ton.year) and operating and maintenance cost of reference biomass plant are selected based on quantitative analysis regarding biomass plant cost analysis [13 - 19].

TCI_A and TCI_B are the total capital investments of plants A and B, and $Capacity_A$ and $Capacity_B$ are the capacities of plants A and B. The exponent x is 0.7 based on the sixth-tenths-factor rule for scaling up the biomass plant. Cost of scaling-up biomass plant size is indicated in in (Eq. 4), as the TCI increases in nonlinear scale along with plant.

$$TCI_B = TCI_A \left(\frac{Capacitiy_B}{Capacitiy_A}\right)^x \quad (4)$$

x = capacity exponent (0.7)

Income for diesel and hydrogen is changed depending on the selling price described in (Eq. 5) and (Eq. 6), respectively. Diesel income (DI_t) is based on diesel yield (D_t) and diesel price (D_p), while hydrogen income (HI_t) as well is calculated with hydrogen yield (H_t) and its selling price (H_p). In case of hydrogen income, CO_2 generation ($CO2_t$) occurs after WGS reaction that CCS cost (CCS_c) needs to be deducted from hydrogen income.

$$DI_t = D_t \times D_p \quad (5)$$

$$HI_t = H_t \times H_p - CO2_t \times CCS_c \quad (6)$$

The levelized cost of fuel calculation is widely introduced assuming the variables such as investment cost, types of technology, risk and the situation of regions and countries, etc. Levelized cost calculation is total expenses of total capital investment (TCI), operation and maintenance ($O\&M_t$), fusion heat cost (FHC_t) and feedstock cost (FC_t) divided by and fuel production in the year t (F_t). The first year of the cost is not discounted and there is no system energy output to be degraded [10]. It is based on discounted cash flow analysis considering the discount factor (r) and the time of value (t) indicated in (Eq. 7)

$$Levelized\ Cost\ of\ Fuel = \frac{\sum_{t=1}^{n} \frac{TCI + O\&M_t + FHC_t + FC_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{F_t}{(1+r)^t}} \quad (7)$$

The net present value (NPV) is the cumulative value (revenues – expenses) adjusted to the reference time. The beginning of expenditures or the start of operation is set to be the "present" time. Total cash inflow and outflow of cash is calculated with consideration of depreciation (D) and tax (T). Total cash flow is considered by the time-value of money shown in (Eq. 8).

$$Net\ Present\ Value = \sum_{t=0}^{n} \frac{((DI_t \text{ or } HI_t) - O\&M_t - FHC_t - D) \times (1-T) + D}{(1+r)^t} \quad (8)$$

4. Analysis Result

Mass flow and energy balance of two difference fuel production scenarios by the fusion-biomass hybrid model are described in *FIG. 2*. Considering 1,000 tpd of input matching to the 95 MW of fusion energy, the fuel production is either annual 141,300 ton of diesel or 47,300 ton of hydrogen with 90% of plant availability. Artificial diesel can be handled by current infrastructure and the hydrogen can be used for hydrogen vehicles and fuel cell. The representing biomass, cellulose, has 16 MJ/kg of dry heat value that annual heat value is 5.26 PJ. As the low heat value for diesel is 42 MJ/kg and for hydrogen is 120 MJ/kg, the energy output reaches 116 % (6.1 PJ) for diesel and 108 % (5.7 PJ) for hydrogen comparing to the biomass. The fusion energy is possible to increase the overall energy efficiency by the endothermic reaction.

Additionally, the size of the biomass plant can be varied by feedstock input rate. The size of the biomass plant increases matching to the thermal output of fusion reactor. The effects of fusion output on biomass plant size and LCOF are shown in *FIG. 3*. LCOF changes between 1,000 tpd and 10,000 tpd shows from $0.41/kg to $0.24/kg for diesel and from $1.21/kg to $0.73/kg for hydrogen. As the plant size increases, particularly over 3,500 tpd, the slope of the cost decreases

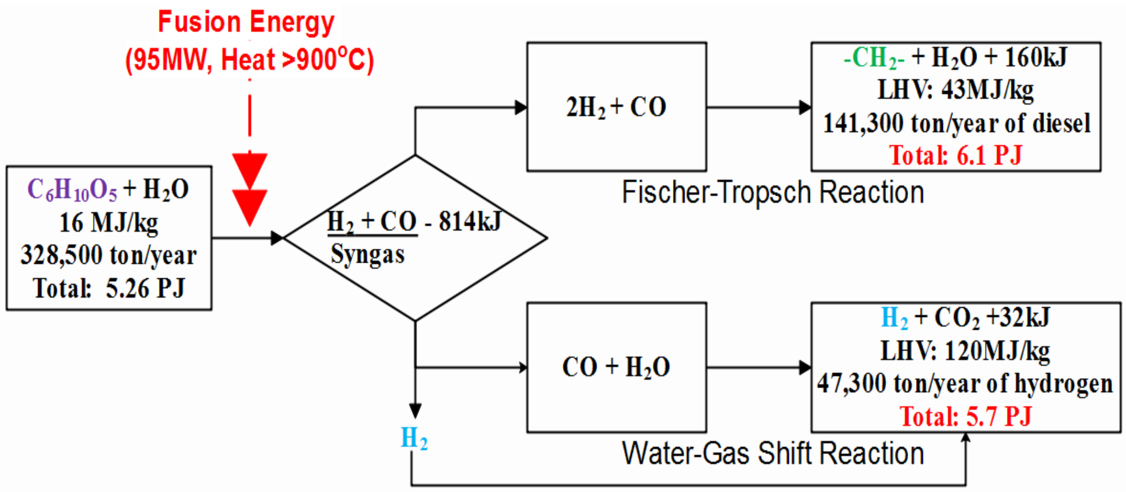

FIG. 2. Mass flow and energy balance

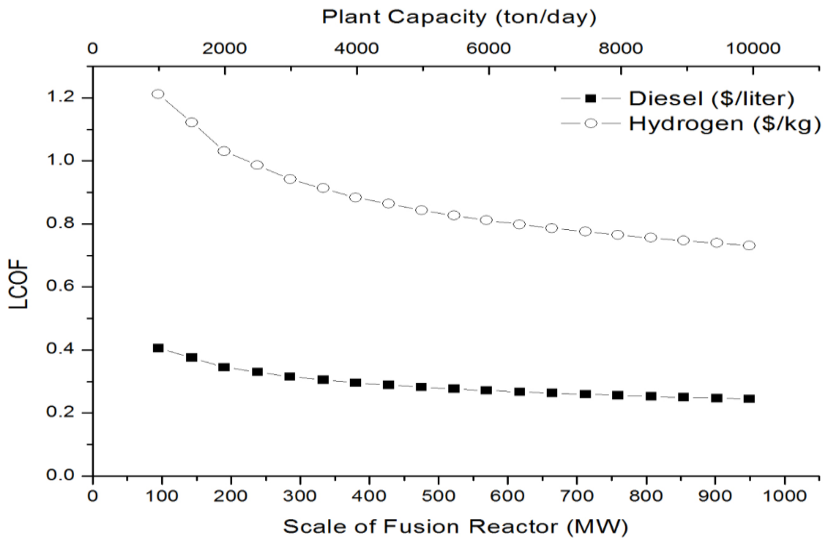

FIG. 3. LCOF change depending on fusion capacity and biomass plant capacity

by less than 1 %, meaning that the benefits of lower cost may not be worth the significant increase in plant size or capital cost.

The most influential factor is fuel production followed by operating time of a year as shown in *FIG. 4*. 10 % increase in fuel production leads to 9 % decrease in LCOF, while 11 % increase in LCOF by 10 % drop of production amount. 10 % increase in the operating time shows LCOF drop by 7 %, whereas LCOF goes up by 9 %. Fuel production can be varied depending on the catalysis and technology level, while the operating time is highly depended on the technical issue and the labor policy or other regulation implemented by government. The endothermic heat is likely to be varied due to various lignocellulose composition of biomass that ±10% of thermal heat absorption shows ±2 % price changes. ±10 % expenses changes of TCI and O&M result in ±3 % and ±5 % of LCOF fluctuation. The fusion heat cost changes shows the least impact (±2 %) on the LCOF change.

Considering all variables of discount rate, tax and depreciation, the breakeven price is found to be $0.73/liter for diesel and $2.65/kg for hydrogen. Sensitive analysis of fusion heat cost change from -30 % to +30 % described in *FIG. 5*. The diesel price changes from $0.65/kg to $1.07/kg, which NPV drops from +376 million$ to -364 million$. Additionally, hydrogen price is between $2.4/kg and $3.6/kg and NPV fluctuates from +444 million$ to -443 million$. It is

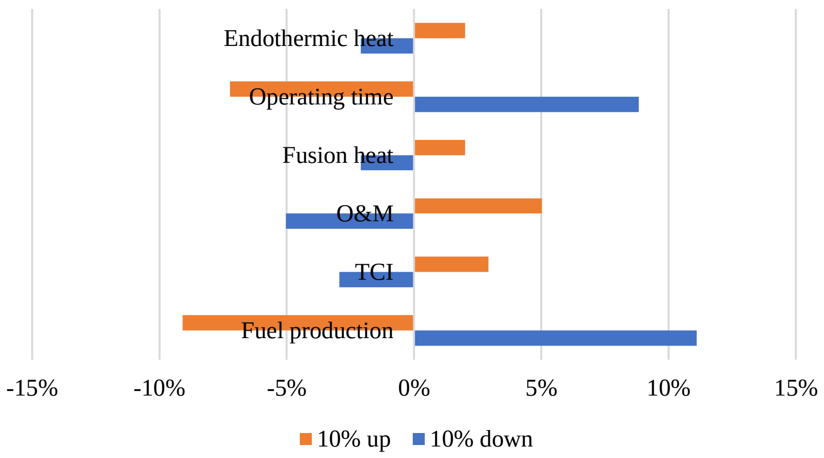

FIG. 4. LCOF change according to variables change (±10%)

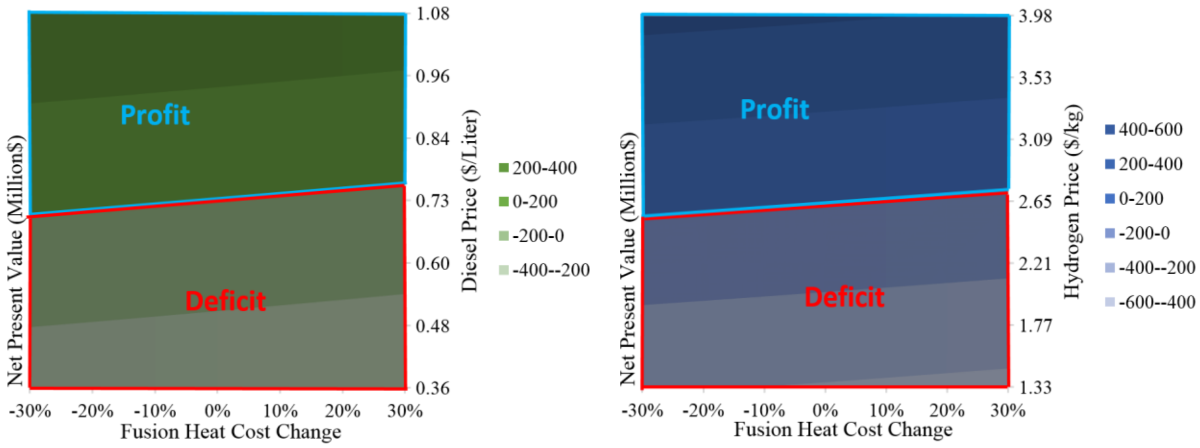

FIG. 5. Sensitivity analysis of (a) diesel price and (b) hydrogen price (CCS cost: \$43/tCO_2)

found out that the range of NPV fluctuations according to the fusion heat cost change turns out to be more sensitive in diesel than in hydrogen. As fusion thermal heat cost contributes to NPV of the fusion-biomass hybrid model, it is possible to lower diesel and hydrogen price if a fusion reactor either requires less construction cost or produces thermal heat more efficiently due to technical advancement in the future.

5. Conclusion

The techno-economic analysis of diesel and hydrogen production by the fusion-biomass hybrid model was performed. It is found that non-electric application of fusion reactor ducted with DCLL blanket is possible to achieve high energy efficiency by using waste biomass. Under the selected parameter, LCOF is \$0.41/Liter for diesel and \$1.21/kg for hydrogen from 1,000 tpd of biomass plant matching with small scale of 95 MW fusion reactor. If the larger scale than 330 MW fusion reactor is in operation, the decreasing rate of LCOF is relatively flat. It is considered that application of 364 MW scale of GNOME [4], a small scale Tokamak design, is adequate to the fusion-biomass hybrid model.

The fusion heat cost will gradually decline by cumulative knowledge and skill on fusion technology, which is proved by Learning Factor [20]. The proven safety of fusion energy will not be likely to increase as high expense as nuclear fission regarding the assurance of nuclear safety. Also external cost related to environment issue hardly impacts fusion investment that declination of fusion reactor investment will be realized once it is further standardized and optimized. Hence, the NPV will be expected higher due to the fusion technology advancement and development. Since the fusion power produces safe, stable and high temperature thermal heat comparing to renewables and widely-used fission reactors, this model has a high potentiality to penetrate the future market and commit CO_2 reduction. Produced clean fuels, artificial diesel and hydrogen, will put an emphasis on the necessity of fusion energy decreasing both fossil fuel dependency and CO_2 emission.

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