Proposals of the agricultural products cultivation system due to Blue Tower gasification combined-cycle systems to reduce CO_2 emission

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Abstract In this paper, we proposed the greenhouse system for a paprika cultivation facility, in which the required electricity and/or heat energy would be supplied by the biomass gasification process of Blue-Tower (BT). Concretely, based on the experimental result on the biomass gasification process, we designed the entire system, and estimated the CO_2 intensity of agricultural products due to LCA methodology. Here, it was assumed that the electricity and/or heat energy through internal combustion engines or fuel cells which would be operated by the syngas fuel through BT plant were obtained. For instance, the integrated BT-SOFC (Solid Oxide Fuel Cell) combined system might be suitable due to the higher power efficiency in comparison to the BT-GE (Gas-engine) system. The net power efficiency of BT-SOFC was 19.2 %-LHV and that of BT-GE was 16.3%-LHV in consideration of the part-load operation. Also, over 80% of CO_2 intensity reduction of paprika against the conventional one would be obtained.

1 Introduction

The biomass energy system is extremely promising as one of the environmentally friendly energy systems which will contribute to the global warming protection. However, since the system is very costly at the initial stage of installation of that, not only the monetary supports but also the technological invention would be absolutely necessary.

At the present time, in the field of food business, the safety and/or security for agricultural products are required by consumers. Simultaneously, they would purchase the products by ensuring those factors, even if their prices are too expensive. Recently, the controlled agricultural product facilities have been installed for the solution of consumer's safety. For instance, the market scale was 5.3 billion yen as of 2009, and there is a projection of that of 12.3 billion yen as of 2020 [1]. However, for the facilities, the energy for cultivation of agricultural products is consumed too much. In particular, in Japan, since the atmospheric temperature in each season (i.e. winter, spring, summer and autumn) varies widely, the heat energy consumption including the electricity would be affected strongly. Also, in general, the cost of agricultural products due to the controlled facilities would be expensive in comparison to the conventional ones.

On the other hand, the biomass energy system would contribute to the global warming protection due to the energy supply with low carbon emissions. Although the R&D projects would be progressing on, there are problems on the technology, the operation cost and the feedstock handling etc. In Japan, the collection cost of biomass materials would be high. Thus, the smaller energy plant, that is, the distributed system might be much better in comparison to the bigger one with a higher efficiency.

From this background, we have developed the Blue Tower (BT) gasification system which is one of the distributed energy system. So far, we executed the studies in order to confirm the absolute proof of the chemical equilibrium reactions, and/or the heat balance in use of the experimental apparatus and/or the demo-plant (1t/d scale) at Izumo in Japan. Likewise, the studies on the handling of equipment (the plant operation) have been done there. Based on the related studies, we know about the key technologies on BT plant. For instance, we made the simulator of BT process in order to estimate the operational performance. This simulation program uses the parameters estimated by the experimental results in a room condition. Also, the estimation accuracy due to the simulator was analyzed. Kameyama et al. compared the operational result of the demo-plant to that of the simulator. Accordingly, we made sure that the simulated data were corresponding with the practice data to some extent [2]. Moreover, we have a plan to introduce the Bio-H_2 production system at Fukuoka of Japan. This plant whose scale is 15t/d is a commercial plant and the Bio-H_2 production plant will be started in April, 2012. According to the previous studies, the plant scale would be able to extend 70t/d at least. In Germany, there is a plan to construct the 70t/d BT plant in Herten. From the above background and/or the performance characteristics of BT process, we focused on the paprika harvesting facility as a model. We analyzed the CO_2 benefits on the advanced greenhouse in which the BT-SOFC (solid oxide fuel cell system) or BT-GE (gas-engine cogeneration system) is assumed to be equipped. Based on the results we estimated, we think that there is a potential to combine the fuel cell such as a SOFC. The fuel cell system can produce only electricity, although a gas-engine does heat energy and electricity. The capability of energy supply through the BT combine system might be different from the demand in the greenhouse facility. That is, in this case, the heat energy due to the gas-engine which we cannot adjust might become excess for the heat demand. On the other hand, although the electricity could be excess, the surplus energy would be purchasable to the conventional power companies. Hence, this means that the operational advantage of SOFC is better than that of gas-engine. In addition, the scale of a gas-engine is not always suitable for that of BT plant. This means that we have to consider a part-load operation.

Based on the above aspects, we executed the process designs of BT-SOFC and BT GE, and we analyzed the energy efficiencies and/or the CO_2 intensity of paprika using LCA methodology.

2 Blue Tower (BT) combined energy system

2.1 Blue Tower (BT) process

First, the schematic design of BT combined system is shown in Fig.1. According to the specification of BT plant, the feedstock which is biomass material such as woody materials etc. is decomposed at 550 ^{O}C in reductive atmosphere in the pyrolyzer, and then decomposed gas is gone up into inside of the reformer whose temperature is heated at 950 ^{O}C by heat carriers. At the reformer, the shift and/or the methane steam reforming reaction occur. The residue of chars which are decomposed in the pyrolyzer is separated from the heat carrier by the char separator, and that is moved to the combustor. The hot gas through the combustor is fed into the pre-heater. At this time, the temperature of the combustion gas would be up to about 1,000 ^{O}C. This heat carrier with a high sensible heat is used as a heat source of the reformer and/or the pyrolyzer. Also, the generated reformed gas (syngas) is washed by water or catalyst, and is fed into a SOFC or a gas engine as a fuel. In the case of BT-SOFC, the heat supply is compensated by the heat pump (COP: 5.5), and heat energy and electricity is produced directly in that of BT-GE.

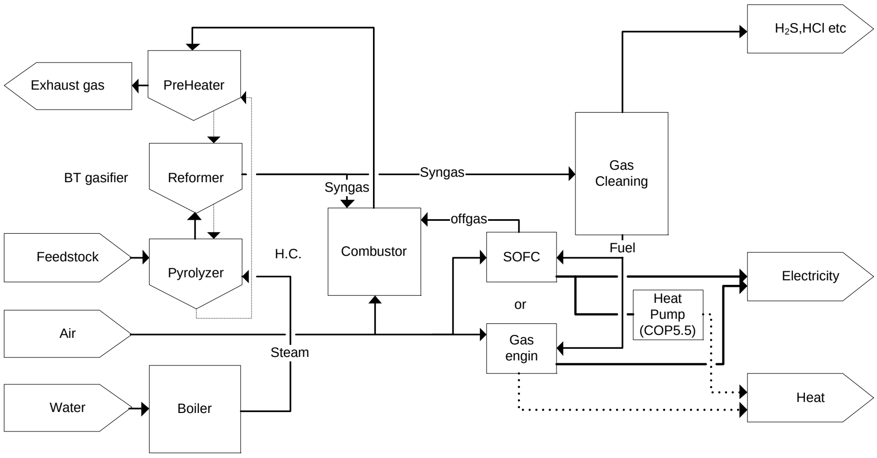


Fig.1: Schematic design of BT-SOFC or BT-GE

With regard to the gasification performance, since gaseous yields and concentrations are dependent upon the kind of materials, the operating temperature, and the inner pressure, they were examined using the gasifier apparatus which has a reformer and a pyrolyzer.

In this paper, the target feedstock is a waste woody material (Japanese cedar). Through the basic experimental tests, the syngas components and the equilibrium constants were obtained. For instance, at 550 $^{\circ}$C in the pyrolyzer and at 950 $^{\circ}$C in the reformer, and at S/C=1.0, the following reaction formula would be obtained for 1 kg of raw material at 20% moisture content.

$$\begin{aligned}&C_{33.9}H_{46.8}O_{20.3}N_{0.3}+33.9H_2O\rightarrow\\&3.34CH_4+12.9CO+34.8H_2+12.7CO_2+45.0H_2O\\&+0.15N_2+\text{Others}(\text{Char etc.})\end{aligned}\tag{1}$$

Next, using the simulator, we executed the process designs of BT-SOFC and BT-GE, respectively.

2.2 Specification of SOFC and GE

Next, we describe the specifications of SOFC and gas-engine unit.
In this paper, we assumed that the SOFC unit scale was 200 kW which is standard type in the industrial use. The characteristics of SOFC are as follows: 1) the power efficiency is comparatively high of 50 to 60 %-LHV, 2) the operating temperature is 800 to 1,000 ^{o}C, 3) the unit scale is approximately 10 to 1,000 kW, which would be suitable as a distributed energy power station, and 4) H_2 and CO as fuels are available. Here, the specification of SOFC is shown as Table 1 [3]. The relationship between voltage and current is indicated as Eq. (2). Using Eq. (2), the power efficiency in consideration of part load operation was evaluated. The part load ratio of SOFC unit would be 81.7% against full load operation.

$$U = U_0 - RJ - b\ln(J) \tag{2}$$

Tab. 1: Data of the specification of SOFC unit

Item	Unit	Data
Unit Scale	[kW]	200
Number of unit	[-]	4
Operating Temperature	[°C]	900
Current density J	[mA/cm^2]	612
Stoichiometric ratio	[-]	1.25
Tafel slope b	[mV/dec.]	2.2
Resistance R	[ohm]	0.52
Open Circuit Voltage U_0	[mV]	950
DC/AC converter Eff.	[%]	95

Tab. 2: Performance of BT-SOFC system

Item	Unit	Data
Feedstock	[kg/h]	764.5
Cold gas efficiency	[%-LHV]	87.3
Auxiliary Power	[kW]	113.9
Partial load ratio (SOFC)	[%]	81.7
Net Power eff. vs. Feedstock	[%-LHV]	19.2
Net power scale	[kW]	540

Due to the simulation result of BT gasifier and the specification of SOFC unit, the performance of BT-SOFC system is obtained as Table 2. Here, the plant scale of

BT gasifier was assumed to be the same of 15t-dry/d in both cases of BT-SOFC and BT-GE. Here, the cold gas efficiency η_{cold} in this table was defined as Eq. (3).

$$\eta_{\mathrm{cold}} = \frac{\mathrm{Syngas}\left[\mathrm{MJ/h}\right]}{\mathrm{Feedstock}\left[\mathrm{MJ/h}\right]} \tag{3}$$

Next, on the specification of gas-engine, we used the performance parameters of which the engine was installed in the previous tests due to the BT demo-plant (see Table 3). Also, Table 4 shows the performance of BT-GE. Note that the additional feedstock is necessary in order to compensate the heat balance in each furnace, and that the total feedstock including the additional one is the same volume as that of BT-SOFC case.

Tab. 3: Data of the specification of gas-engine unit

Item	Unit	Data
Unit Scale	[kW]	215
Number of unit	[-]	3
Engine output	[PS]	318
Revolution per minite	[rpm]	1,500
Compression ratio (design)	[-]	10.0

Tab. 4: Performance of BT-GE system

Item	Unit	Data
Feedstock	[kg/h]	764.5
Cold gas efficiency	[%-LHV]	71.4
Auxiliary Power	[kW]	111.1
Partial load ratio (Gas-engine)	[%]	88.4
Net Power eff. vs. Feedstock	[%-LHV]	16.3
Net power scale	[kW]	459
Net Heat recovery eff.	[%-LHV]	28.6
Net heat supply	[MJ/h]	2,895

2.3 Energy demand of paprika greenhouse

Next, we investigated the paprika greenhouse which is a commercial facility at Miyagi of Japan. In this facility, the annual product yields are approximately 200 t/yr, and the cultivation area is 1.2 ha. The energy demand of electricity, kerosene and bunker A for lighting and heater, and the input of CO_2 gas as growth promotion agent were investigated, too (see Fig.2).

On these data, we converted the monthly basis data to time series ones. Especially, the boiler fuels of kerosene and/or bunker A were assumed to be in proportion to a difference between the minimum temperature for growing and the atmospheric one. Also, electricity was assumed to be consumed for 12 hours per a day.

On the other hand, when paprika is grown in the greenhouse, CO_2 gas as growth promotion agent is necessary. The exhaust gas through the BT combined system can be substitute for the conventional gas.

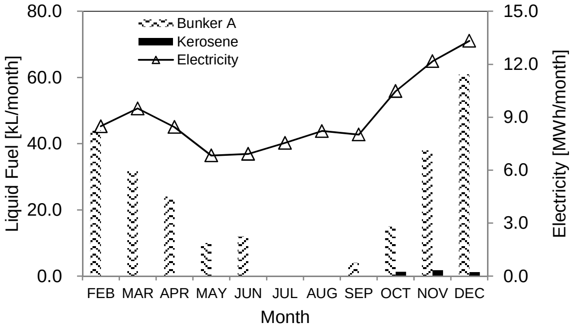


Fig.2: Energy demand in the paprika greenhouse (1.2 ha)

Thus, we considered the alternative of CO_2 gas from the conventional gas of fossil resources origin. In addition, the annual product yield would be able to increase due to more CO_2 gas. In the future, we will investigate the characteristic of paprika cultivation due to the CO_2 growth promotion agent. Here, the consumption of CO_2 gas in the greenhouse would be analyzed statistically, assuming that the gas is consumed through photosynthesis. That is, this volume would be proportional to the product of duration of bright sunshine and an intensity of radiation.

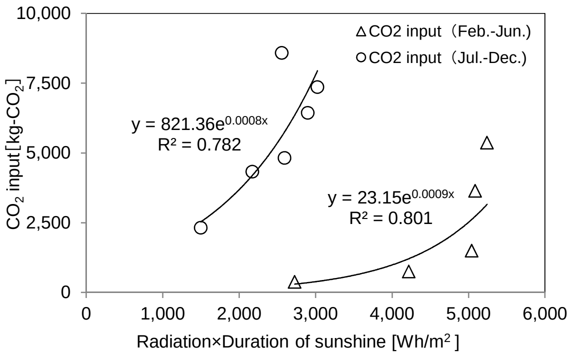


Fig.3: Statistical result of CO_2 consumption as growth agent

Fig.3 shows the statistically estimated result of CO_2 consumption. Also, in the system analysis due to LCA, fertilizers of N, P_2O_5 and K_2O were taken into consideration as indirect factors. Here, the annual consumption weight of each fertilizer was 2,874 N-kg/yr, 877 P_2O_5-kg/yr and 2,759 K_2O-kg/yr, respectively.

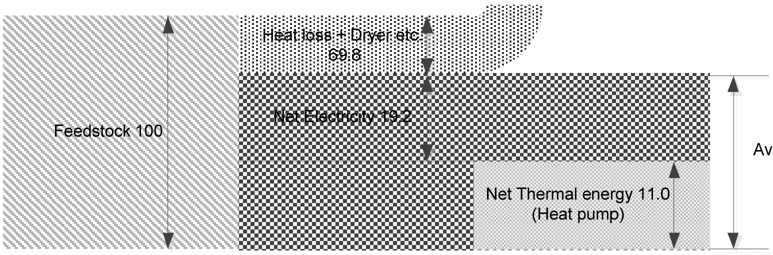
2.4 Energy balance of paprika greenhouse

Next, using the estimated energy demand data, we analyzed the energy balance in the case of BT-SOFC or BT-GE. As we mentioned before, the effective energy supply (electricity and/or heat energy) to the greenhouse is more important in order to reduce CO_2 emission. However, in general, there is a discrepancy between energy supply and demand. For instance, due to the limitation on the scale of gas-engine, the supplied energy by the system might not be able to satisfy the energy demand in the paprika greenhouse. Since the heat-to-power ratio of the engine is fixed, the excess energy (heat energy) would be generated. Inversely, the electricity might become surplus energy. However, this energy is purchasable to the conventional power company due to the regulation of Feed-in Tariff (FIT). Also, when we consider the combination of energy supply system with the gasifier such as BT process, the syngas volume does not always correspond with the supply capacity of SOFCs or gas-engines. That is, the status of part load operation comes up, and the energy conversion ratio would become worse.

Here, Fig.4 shows the result of energy balance by which the excess energy is considered due to the energy demand in the greenhouse. Note that the supply energy in the case of BT-GE does not satisfy the energy demand. It is assumed that the annual operation days of BT plant are 300 days/yr in both cases.

According to Fig.4, on the percentage of available energy, the point of BT-SOFC case is more advantageous than that of BT-GE. Since only electricity due to SOFC is produced in BT-SOFC case, there is not any waste energy. That is, this would contribute to the operation cost abatement.

(a) BT-SOFC



(b) BT-GE

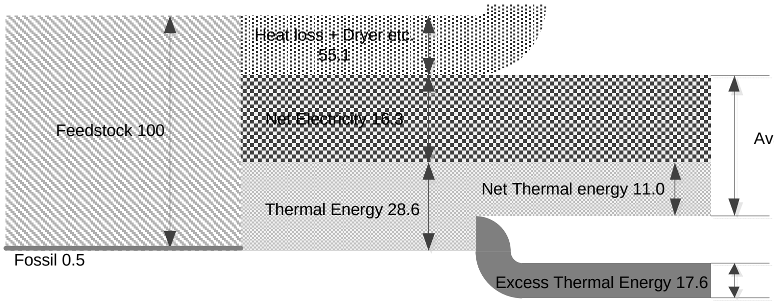


Fig.4: Energy balances of BT-SOFC / BT-GE cases

3 LCA for paprika cultivation

In the LCA concept of this paper, the direct factors and the indirect ones have to be considered. In our definition, fossil fuel energy inputs (primary energy basis) and the electricity are included in the direct factors. Also, chemical fertilizers are included in the indirect ones. Note that another greenhouse gases such as N_2O and CH_4 are not taken into consideration. In the previous biomass LCA analyses, the pre-processing process of chipping, transportation and drying of biomass materials, and the energy conversion process of a production energy of electricity and/or heat, through an energy system are included [4]. In addition, the paprika harvesting process has to be added to the entire life cycle stage.

In this paper, a target is to estimate life cycle inventories (CO_2 intensity) of BT-SOFC and BT-GE.

3.1 System boundary

Following ISO 14041 guidelines, we defined the system boundary in the biomass energy system. The system boundary consists of the processes of pre-processing, energy conversion and paprika harvesting (see Fig.5).

We argued on every energy input (electricity/heat energy) from each process in the entire life cycle. In the pre-processing process, there are sub-processes of chipping, transportation by 10t-trucks, and drying. In the energy conversion process, BT-SOFC or BT-GE case of which we estimated the energy efficiency etc. is considered.

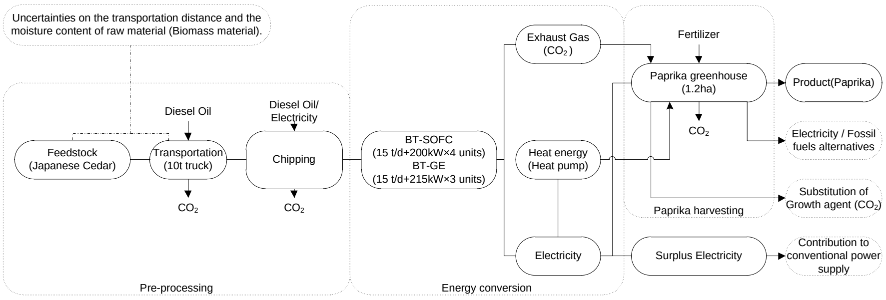


Fig.5: System boundary

The CO_2 benefits are obtained due to the alternative of conventional electricity and/or heat energy, and the substitution of CO_2 gas of growth agent. Although the electricity alternative due to the surplus electricity supply is thought, we did not consider the benefit since we do not know the time series data of electricity supply in the power company well in this paper.

3.2 Functional unit and specific CO_2 emission in each fuel

The target product on which we focused is a paprika. Thus, the functional unit is assumed to be the unit per a produced paprika.

The energy data is as follows. For instance, the lower heating value of biomass material is 13.2 MJ/kg at the moisture content of 20 wt. %. Those of fossil fuels are 36.4 MJ/L of bunker A, 34.1 MJ/L of kerosene and 35.5 MJ/L of diesel oil, respectively. Table 5 shows the specific CO_2 emissions, for each fuel with biomass materials, respectively.

Tab. 5: Data of the specific CO_2 emissions

Item	Specific CO_2 emission	Note
Feedstock	0.0 g-CO_2/MJ-Fuel	at 20 wt.% (moisture content), Japanese Cedar, HV:13.23 MJ/kg
Diesel	74.4 g-CO_2/MJ-Fuel	Chipping, Transportation, HV: 35.50 MJ/L
Bunker A	76.9 g-CO_2/MJ-Fuel	Paprika production (Boiler)
Kerosene	73.6 g-CO_2/MJ-Fuel	Paprika production (Boiler)
Electricity	123.1 g-CO_2/MJ-Fuel	Paprika production (Ventilation and lightning)
Fertilizer (N)	5.67 kg-CO_2/kg	Indirect CO_2 emission
Fertilizer (P_2O_5)	0.88 kg-CO_2/kg	Indirect CO_2 emission
Fertilizer (K_2O)	1.85 kg-CO_2/kg	Indirect CO_2 emission

In the pre-processing process, there are sub-processes of chipping, transportation, and drying of feedstock. In particular, in the processes of transportation and/or drying, we have to consider uncertainties, since the initial moisture content of feedstock and/or the collection distance from the departure position to the plant are not known. Thus, the CO_2 emission in this study was estimated using the Monte Carlo simulation in order to consider these uncertainties.

3.3 CO_2 intensity in paprika greenhouse

Based on the system boundary and the results of energy balance in each case, we estimated the CO_2 intensity of paprika (see Fig.6).

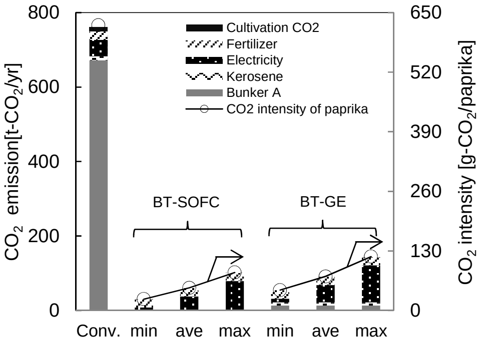


Fig.6: CO_2 intensity of a paprika product

Here, the specific CO_2 emissions of electricity are 47 to 449 g-CO_2/kWh of BT-SOFC and 56 to 564 g-CO_2/kWh of BT-GE, respectively. Compared to the conventional CO_2 emission (443 g-CO_2/kWh), there would be the condition of which CO_2 can be reduced to some extent. However, the CO_2 intensities of paprika due to the proposed cases were lower than the conventional case. In the conventional case, the CO_2 intensity of 629.6 g-CO_2/paprika was estimated. On the other hand, in BT-SOFC or BT-GE case, 25.0 to 82.8 g-CO_2/paprika or 44.5 to 117.7 g-CO_2/paprika was estimated, and the CO_2 abatement ratios against the conventional intensity were 86.7% to 96.0% and 81.1 to 92.9%, respectively. That is, in the case that BT-SOFC was installed, the much CO_2 reduction benefit would be obtained.

4 Conclusion

Although the initial cost of BT-SOFC is still expensive, the technological barrier might be less. Compared to the case of BT-GE, there would be an advantage of CO_2 intensity. Also, the power efficiency through BT-SOFC was 19.2 LHV-%, which is affected by the method of heat energy supply, and the performance would be better than the same biomass energy system. On the cost reduction measure, the subsidy might be necessary at the initial promotion stage. Also, the surplus energy sales and/or the increase of "willingness to pay" due to the carbon-footprint are likely to improve the biomass project condition. In the future work, we investigate the acceptability on the sale price of paprika, in which CO_2 reduction cost is included.

5 References

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