Techno-Economic and Environmental Sustainability Assessment of Rice Straw-Based Bioenergy with Carbon Capture and Utilization

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Abstract

Climate-susceptible nations are severely impacted by frequent storms, effects of sea level rise, and seasons with temperatures that already limit worker output. Though agriculture is a vulnerable industry, it can potentially reduce energy-related carbon dioxide emissions through bioenergy production. Bioenergy with carbon capture and utilization (BECCU) could be an emissions-neutral or -negative and a market-driven approach that captures CO2 and promotes sustainable agricultural waste management. This study investigates rice straw-based BECCU as an agricultural waste management. Using Aspen Plus®, bioenergy conversion of rice straw through power generation and ethanol production followed by methanol or urea production as CO2 utilization are simulated. Results from the process simulations show that 574 kW of power and 131 kg of ethanol are produced per ton of rice straw. Methanol and urea production per ton of rice straw are 717.57 kg and 1,601.84 kg in the power generation route, and 565.23 kg and 1,265.43 kg in the ethanol route, respectively. Defining the functional unit as managing rice straw as an agricultural waste, producing electricity, steam, ethanol, methanol, and urea provides environmental credits as alternative sources of these products. Still, the carbon capture process outweighs the credits resulting in a net impact in global warming and resource depletion mainly due to utility requirements. Carbon capture and utilization, however, show a benefit in land use impacts. The estimated urea production cost per kilogram is USD 0.20-0.21 and methanol is USD 0.59-0.61.

**Keywords**: Bioenergy with carbon capture and utilization (BECCU), carbon dioxide, agricultural waste, process simulation, life cycle assessment (LCA)

* 1. Introduction

Rice is a staple food for most Filipino people, with a production of 19.32 million metric tons, which means that rice farming contributes to 62% of agricultural GHG emissions in the Philippines (Climate Transparency, 2020; Philippine Statistics Authority, 2021). Rice straw is an abundant byproduct of rice farming, accounting for 50-60% of the paddy (Logeswaran et al., 2020). However, rice straw utilization is limited due to labor intensity, lack of handling equipment, and prolonged handling methods (Eleria & Vargas, 2021). Most utilization techniques are in the early stages and may be chemical, energy, or labor-intensive. As a result of the limited utilization of rice straw, farmers prevalently burn 76% of harvested land area in the open field for convenience (Mendoza, 2015).

Rice straw has similar higher heating value (HHV), proximate, and ultimate analyses to other biomass, making thermochemical conversion feasible for the complete energy utilization of rice straw, including lignin (Maguyon-Detras et al., 2020). Additionally, renewable energy, its direct use, and renewable energy electrification have the potential to cut energy-related CO2 emissions by up to 75% and agriculture, after forestry, has the second highest share of mitigation potential in agriculture, forestry, and other land use (AFOLU) (IRENA, 2019; Shukla et al., 2022). However, the conversion of rice straw to energy, particularly thermochemical conversion, produces a significant amount of CO2. As a form of renewable energy, bioenergy with carbon capture and utilization (BECCU) is emissions-neutral or --negative and a market-driven approach to produce energy without increasing land use or decreasing food sources (Babin et al., 2021; Global CO2 Initiative, 2016). Rice straw-based BECCU could cut energy-related CO2 emissions as well as agricultural GHG emissions from rice agriculture, deliver emissions-neutral or -negative products, promote sustainable agricultural waste management, and valorize second-generation biomass and captured CO2.



**Figure 1:** Hierarchy block flow diagram of BECCU systems

This study aims to quantify the environmental impacts of rice straw BECCU in the Philippines, to determine the total capital investment, operating cost, and the cost per liter of ethanol and kilogram of urea, and to compare the environmental impacts and economic performance of BECCU systems. In this study, a simulation of electricity generation and ethanol production coupled with carbon capture is performed using Aspen Plus®, whose processes are separated into hierarchy blocks as shown in Figure 1. Because of potential opportunities to limit carbon emissions, technological advancement, economic potential, and large predicted market sizes by 2030 (Global CO2 Initiative, 2016), the use of CO2 in methanol, and urea production are considered in this study. Process simulation results are used in the environmental and techno-economic assessment of rice straw-based BECCU using life cycle assessment (LCA) and cost analysis.

* 1. Methods
		1. Goal and Scope

This study evaluates the environmental and economic impacts of producing power and ethanol from rice straw in the BECCU scheme through combustion and syngas fermentation. The functional unit is the processing of 1 ton of rice straw from fields. The system boundaries are rice straw collection, biomass-to-energy conversion, and carbon capture and utilization. Thermochemical conversions of rice straw are highly considered because of cheaper capital cost, lower operational cost, complete utilization of rice straw, and elimination of costly and energy-intensive pretreatment (Maguyon-Detras et al., 2020). Thus, in this study, there are four system boundaries considered, namely, 1) urea from combustion, 2) urea from gasification, 3) methanol from combustion, and 4) methanol from gasification.

* + 1. Life Cycle Inventory

The foreground data are drawn from different literature sources, and inputs, outputs, and emissions from the process simulation in Aspen Plus®, while the background data are drawn from the Ecoinvent database (Ecoinvent Association, 2020).

* + - 1. Process Simulation

 

**Figure 2:** Process simulation of power generation from rice straw combustion

The rice straw is shredded and dried to remove the moisture. The dryer is simulated with RYield, which is linked with a calculator block and yields 25% of the biomass component to water, HeatX, and Sep blocks. The furnace is modeled using RYield, which is coupled with a calculator block converting the nonconventional properties of biomass into its ultimate and proximate analysis by assuming the devolatilization products, and RGibbs block under Gibbs free energy minimization and chemical equilibrium assumptions (Almena et al., 2022). The combustion product passes through a cyclone to separate the ash from high-temperature flue gas. The hot flue gas enters a HeatX block coupled with design specs in the power generation hierarchy block. Water is pumped to the heat exchanger producing a superheated steam of 565$℃$ and 164bar. Based on a vapor fraction of 1, the design spec function calculated the water flow rate entering the pump. The steam passes to a series of isentropic high-pressure (HP), medium-pressure (MP), and low-pressure (LP) turbines. The CO2 in the combustion gas is then captured in the CO2 capture system hierarchy block.



**Figure 3:** Process simulation of ethanol production through syngas fermentation

Similar to the combustion path, as shown in Figure 3, rice straw in the gasification undergoes physical pretreatment, and nonconventional properties of the biomass were converted to ultimate, proximate, and sulfate analysis. However, the RGibbs block is modeled at restricted equilibrium, specifying a temperature approach for the entire system at 700$℃$ and 335 bar. The air-to-biomass ratio is 1.21 and the steam-to-biomass ratio is 0.57 (Im-Orb et al., 2016). The produced syngas are cooled and sent to the three RStoic reactor blocks in series. The fermentation model operates at atmospheric pressure and 38$℃$ in which 70% and 5% of carbon monoxide and 50% and 2% of hydrogen gas is converted to ethanol and acetic acid, respectively (Safarian et al., 2021). The fermentation product is sent to a Flash2 block to separate the broth and gas mixture. A recycle stream is used to reintroduce some gas mixture to the reactor block such that 88kg/hr of carbon monoxide is exiting to the carbon capture system. The gas mixture from the FSplit block is fed to a stripping column to recover the ethanol broth. The final broth is distilled in a RadFrac block and passes through a molecular sieve to purify the ethanol.

The cooled and compressed gas from power generation and ethanol production enters the carbon capture system. The process simulation of the CO2 capture system is adapted directly from Aspen Plus® and is modified to maintain the stage pressure of stage 1 at 37$℃$. The captured CO2 is fed in the methanol synthesis with hydrogen gas or the urea synthesis with ammonia. The process simulation for the synthesis of methanol is adapted from the study of Kiss et al. (2016) and is modified to achieve Grade AA methanol. The distillation column is modeled using a RadFrac block coupled with design specifications varying the boilup ratio, reflux ratio, and distillate vapor fraction such that the distillate contains 99.85% methanol, the bottom product contains 99.99% water, and the stage temperature in the first stage is 32ºC. The process simulation for the urea production is adapted from Aspen Plus® but is modified such that the feed CO2 is pure. The reaction occurring in the RPlug block is modeled based on the chemical reaction kinetics studied by Chinda et al., 2019.

* + 1. Life Cycle Impact Assessment and Techno-Economic Assessment

The LCA modeling is performed using openLCA software v2.0 and the impacts are assessed using the hierarchist perspective of ReCiPe v1.13 (Huijbregts et al., 2017). The environmental impacts considered in this study are agricultural land occupation (ALOP), fossil depletion (FDP), global warming (GWP), and water depletion potential (WDP). The costs of equipment in the techno-economic assessment are evaluated within Aspen Plus® Economics. The economic indicators considered in this study are capital cost, operating cost, and cost per unit product.

* 1. Results and Discussion

**Table 1:** Power, ethanol, methanol, and urea production from 50,000kg/h rice straw

|  |  |  |
| --- | --- | --- |
| Process Option | Main Product | Secondary Product |
| Methanol from combustion | 28,706 kWh power generation | 35,878 kg/h methanol |
| Urea from combustion | 80,091 kg/h urea |
| Methanol from gasification | 6,554 kg/h ethanol | 28,261 kg/h methanol |
| Urea from gasification | 63,271 kg/h urea |

Process simulation results showed a gross 28,706 kilowatts of power or 9,553 liters of ethanol is produced from 50,000 kilograms of rice straw while producing 45,724 or 36,016 liters of methanol and 80,092 or 63,272 kilograms of urea, respectively, as shown in Table 1. The steam generation from gasification routes is 8,664 kilowatts higher than combustion routes because the heat from the flue gas of combustion is harnessed to electricity, drying of rice straw, and preheating of air. The CO2, however, in the combustion route is 10,000 kilograms higher as the carbon in gasification participated in the synthesis of ethanol. The percent conversion of CO and H2 in the three-series reactor are 98 and 89%.

The environmental impacts of rice straw BECCU systems are shown in Figure 4. Per ton of rice straw, emissions of 382.4 kg CO2e are avoided from the open field burning based on the carbon content of the rice straw (Jenkins et al., 1998). Net negative GWP of 396.0823 kg CO2e, ALOP of 23.57 m2a, and FDP of 112.75 kg oil-equivalent is credited from electricity generation, and a GWP of 142.8050 kg CO2e, ALOP of 231.36 m2a, and FDP of 35.98 kg oil-equivalent is avoided from ethanol production.

**Figure 4:** Cradle-to-grave life cycle environmental impacts of rice straw BECCU systems [Multiplied by factors on the x-axis per ton of rice straw.]

Credits from the co-production of electricity, steam, ethanol, methanol, and urea have a negative contribution to global warming potential (19.3-31.48%, 8.63-14.08%, 5.94-8.02%, 15.66-23.30%, and 118.18-211.65%, respectively). However, the production of ammonia, hydrogen, and steam for the carbon capture process outweighs the credits resulting in a net positive life cycle GWP. Agricultural land occupations and natural land transformation potential show a net negative impact in all BECCU systems. The net negative impacts in ALOP are mainly derived from credited co-products. The co-production of electricity, ethanol, methanol, and urea credited net-negative fossil depletion potential, but is outweighed by the process requirements in the carbon capture block. Water depletion potential is mainly caused by the carbon capture system, but production of methanol and urea avoided 6.23-7.91 and 109.46-138.56 m3 water-equivalent, respectively.

**Table 2:** Techno-economic indicators of rice straw BECCU

|  |  |  |
| --- | --- | --- |
|  | Capital Cost | Operating Cost |
| Urea from combustion | USD 230,447,498.54 | USD 99,881,206.63 |
| Urea from gasification | USD 152,189,663.13 | USD 13,435,071.36 |
| Methanol from combustion | USD 233,944,464.06 | USD 142,776,734.74 |
| Methanol from gasification | USD 151,672,565.63 | USD 46,824,092.25 |

The capital and operating expenses of rice straw BECCU systems are shown in Table 2. Fifty percent of the purchased equipment cost in the combustion route is incurred in the combustion of rice straw, while 36% of the equipment cost in the gasification route is from syngas fermentation and ethanol purification. The cost of the raw materials ammonia and hydrogen constitute 75-82% of the operating expense. The production cost per kilowatt-hour of power is USD 0.09, and the cost per kilogram of ethanol is 0.34. The steam generated is used for internal steam consumption. The production cost of per kilogram of urea is USD 0.20-0.21 and methanol is USD 0.59-0.61.

* 1. Conclusion

This work has evaluated the techno-economic and environmental sustainability of rice straw BECCU systems. The results suggest that generated electricity has greater environmental impact savings in terms of GWP and FDP. The net GWP, FDP, and WDP of urea from combustion have the least impact among the cases because of avoided emission primarily from urea production. However, the economic indicators state otherwise. The capital cost is higher for the combustion route mainly because of the purchased cost of the compressor. The operating expenses incurred mainly in purchasing raw materials such as ammonia in urea production and hydrogen in the production of methanol. The current study can be extended to the incorporation of ammonia and hydrogen synthesis to probe the opportunities for environmental impact and economic savings from the purchase of ammonia and hydrogen.

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