Article

Rice-Straw-Based Heat Generation System Compared to Open-Field Burning and Soil Incorporation of Rice Straw: An Assessment of Energy, GHG Emissions, and Economic Impacts

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Abstract: Rice is a staple food crop, and its production generates large volumes of agricultural waste, rice straw. Several studies have proven that open-field burning and soil incorporation are unsustainable practices of managing rice straw, but remain as prevalent methods of treating and disposing of rice straw. An alternative solution is to harness the energy from rice straw via a small-scale heat conversion system for paddy drying applications, which can reduce rice grain post-processing costs and improve paddy storage conditions. This study investigated the energy flow, Greenhouse Gas (GHG) emissions, and cost of a small-scale rice-straw-based heat generation (RBHG) system using a downdraft furnace and a dryer simulator setup. The highest input energy and GHG emissions of 92% and 68%, respectively, were from the heat generation stage. The RBHG energy ratio was between 1.4 and 1.7, and the percent net energy was between 39 and 67%. The best case of RBHG offers a possibility of a net GHG avoided ($-61 \text{ kg CO}_2\text{-eq Mg}^{-1}$), while the worst case ($856 \text{ kg CO}_2\text{-eq Mg}^{-1}$) has a net GHG emission comparable with soil incorporation. The average total cost of RBHG is $0.096 \text{ USD kWh}^{-1}$. Overall, RBHG technology has the potential to improve energy flow, GHG emissions, and the cost of rice production systems.

Keywords: rice straw; bioenergy; furnace; net energy balance; Net GHG emissions; Life Cycle Assessment

1. Introduction

Rice is one of the most staple foods in the world, providing the calorie requirement of many countries. As one of the leading food crops, its production reached up to 780 million Mg globally in 2018, covering 167 hectares of land [1]. The leading producers are Asian countries, with China, India, and Indonesia in the top three [1]. The Philippines, like its neighboring countries, primarily depends on rice as its main food source, with 80% of the population relying on rice for 40–65% of their calorie requirement [2].

The steady increase in the cultivation of rice for food rice production has given rise to the problem of rice straw waste management. About 1 to 1.5 megagrams of rice straw are produced for every megagram of paddy [2–4]. In many rice-growing countries, the most common rice straw waste

management method is open-field burning [5–11]. In the Philippines, farmers turn to open-field burning to drive away pests and to avoid the labor-intensive, manual gathering of rice straw [2,7]. In 2009, 95% of the total surplus of 10,150 Mg rice straw in the country was managed or disposed of by open-field burning [12]. Though the burning of biomass may be considered a carbon-neutral activity, it also causes the emission of toxic greenhouse gases CH_4 and N_2O [7,12]. Open-field burning also results in up to 100% nitrogen (N) loss, 25% phosphorous (P) loss, 20% potassium (K) loss, and 5–60% sulfur loss [7].

A common alternative to open-field burning is soil incorporation, or leaving the straw on the field to decompose [5,13]. The benefits of soil incorporation include a complete carbon turnover, improved soil aeration, re-oxidation of iron and other reduced substances (which accumulate during flooding), reduced weed growth, and reduced irrigation requirement [14]. However, these benefits may be offset by the disadvantages of soil incorporation, which include the risk of decreased grain yield, acetic acid formation, decrease in available nitrogen, and insufficient turnaround time for intensive cropping systems [14,15]. Moreover, soil incorporation leads to a higher global warming potential (GWP) at 8023 kg CO_2 -eq per ha, higher than open-field burning, which is at 4913 kg CO_2 -eq per ha [7]. Yield-scaled GWP measurements for complete soil incorporation, partial straw removal, complete straw removal, and complete straw burning scenarios were found to be 881, 477, 174, 453 kg CO_2 -eq per Mg straw, respectively [7]. In other studies, open-field burning was evaluated to cause 1460 kg CO_2 -eq per Mg straw [6], and soil incorporation results to 1025 kg CO_2 -eq per Mg straw [13]. These numbers highlight the comparative advantage of complete straw removal (over other scenarios mentioned), as it had the lowest GWP. After complete removal from the field, rice straw can be further processed under several alternatives.

1.1. Complete Straw Removal and the Paddy Flatbed Dryer (PFBD)

Complete straw removal from the field provides the opportunity for other off-field uses of rice straw. The other off-field rice straw management options are divided into energy solutions (direct combustion, bioethanol, and anaerobic digestion) and non-energy solutions (substrate for mushroom production, animal bedding, and fodder, biochar, and fertilizer) [3,5,6]. Among the different off-field solutions, rice-straw-based heat generation using direct combustion furnaces is one of the simplest. The heat generated may be used to dry rice paddy in a paddy dryer. There are different types of paddy dryers, but a paddy flatbed dryer (PFBD) composed of a drying bin, blower, and furnace is preferable due to its simplicity and low cost [16]. In a PFBD, hot air mixture from the furnace is directed by the blower to the grain bed, increasing the drying bin temperature to 43–45 °C. The drying time is around 4–10 h depending on the temperature and initial moisture content, the common capacity is 4–6 tons paddy per batch, while the working hours may be 16 to 20 h per day in a 40-day harvest season [16]. The motor may be diesel- or electric-powered, with a horsepower rating of 7–12 HP [16].

Currently, PFBD furnaces use kerosene or rice husk as fuel. Kerosene is a nonrenewable resource from petroleum, while rice husk is a renewable resource from rice production. Compared to rice straw, rice husk is lesser in supply but higher in demand. An existing small-scale downdraft furnace (dRF) using direct combustion technology at the International Rice Research Institute (IRRI) uses rice husk as fuel, with drying air efficiencies reaching about 80% maximum. In a related study, the IRRI dRF was retrofitted to use rice straw instead of rice husk. The optimum operating conditions for this dryer (retrofitted for rice straw feed) have recently been determined. The drying air efficiencies at the optimum conditions were between 86.1 and 88.78% [17].

To have a more meaningful comparison of the different alternatives for rice straw waste management concerning energy and sustainability, various studies have performed life cycle assessment (LCA).

1.2. Life Cycle Assessment in Rice Production

In rice production, the steps in the supply chain are rice cultivation, harvesting, collection, transportation, storage, and utilization of rice straw [8]. In assessing the life cycle of biofuels, the complete cycle from raw material production, processing transportation, manufacturing, storage, distribution, and utilization should be considered as each step may have a negative or positive impact on the environment, economy, or social aspects [18]. Despite the “cradle-to-grave” principle of life cycle assessment, for bioenergy studies, an arbitrary system boundary may be defined as many processes are excluded for different reasons [18]. Instead of the “cradle-to-grave,” the “cradle-to-gate” approach is sufficient for comparing different biofuel production processes [18].

1.3. Rationale of the Study

Using rice straw as fuel in paddy drying will help in averting open-field burning, as well as support the rising energy demand. At 100% collection, the renewable energy potential from rice straw can reach up to 141,800 GJ in the Philippines [12]. Studies on rice-straw-based power generation in Malaysia, Thailand, India, and Egypt show reduced Greenhouse gas (GHG) emissions and other environmental benefits [6,9,11,13,19]. Input–output energy analysis in Iran and China reports an energy ratio between 1.39 and 9.94 with both paddy and straw values in the output energies [20,21]. For small communities, a small-scale rice-straw-based heat generation system with an energy output between 100 and 300 MJ h^{−1} may be advantageous since it requires lower capital and transportation costs. A process bottleneck is found in the rice straw collection step, which is known to be labor-intensive if done manually. The other option, mechanical collection, requires high capital costs due to the use of a baler. Thus, an alternative to offer baling as a service to generate profit may improve the costs.

This study was conducted to assess the energy flow as well as the net GHG emissions of a small-scale rice-straw-based heat generation (RBHG) system for paddy drying. The cost per heat output using the IRRI downdraft furnace (dRF) was also evaluated. The results of this research aim to help in the decision and policymaking on the sustainability of rice straw waste management systems.

2. Materials and Methods

2.1. Research Study Area and System Boundaries

The research was conducted at the International Rice Research Institute (IRRI), and the data used was from the IRRI and Philippine farmer fields.

The system boundaries for both energy balance and GHG emissions are shown in Figure 1 for rice-straw-based heat generation (RBHG). There are four (4) stages: rice production at IRRI and Philippine farmer fields during the dry season, baled straw collection and transportation to a storage area 4 km away, rice straw storage in a roofed facility, and rice-straw-based heat generation using the downdraft furnace (dRF) with electric motor and blower. The three (3) initial stages can be grouped as the rice straw preparation stage. In each step, the inputs and outputs are listed; for example, in rice production, diesel consumption in agricultural equipment, rice seeds, fertilizers, pesticides/herbicides, manual labor, and land use are all inputs, while the outputs are rice straw (on the field), and rice paddy. The rice straw output from rice production is considered as input in the next stage, the rice straw collection and transportation stage. The functional unit for the energy flow and GHG emission balance is 1 Mg rice straw as fuel. The functional unit for the cost evaluation is 1 kWh of heat output as a product.

Figure 1. System boundaries for rice-straw-based heat generation (RBHG).

2.2. Data Collection

2.2.1. Assessment of the Structures

The construction of the storage center and downdraft furnace (dRF), which are referred to in this study as structures, were assessed through interviews with a civil engineer and furnace fabricator. The storage center was a roofed facility with a 200 sq. meter floor area, 3 m high, and open sides. The bill of quantities (BOQ), electricity consumption, and manual labor during construction of the two structures are listed in Table 1. The dRF included the electric motor and blower.

Table 1. Bill of quantities (BOQ), electricity consumption, and manual labor during construction of one (1) unit of structure.

Parameter	Unit	Quantity
<i>Storage center structure</i>		
Alkyd paint	kg	42
Cement cast plaster	kg	1082
Cement, Portland	kg	18,636
Concrete block	kg	42,000
Gravel	kg	44,016
Plywood	m ³	0.12
Polyvinyl Chloride (PVC) pipe	kg	6
Reinforcing steel	kg	1681
Sand	kg	39,954
Steel sheet	kg	1616
Steel, low-alloyed, hot-rolled	Kg	6
Welding, arc, steel	m	640
Electricity	kWh	1000
Manual labor construction	MJ	4576
<i>Downdraft furnace (dRF) structure</i>		
Cement, Portland	kg	250
Clay brick	kg	385
Electric motor	kg	73
Reinforcing steel	kg	324.03
Steel sheet	kg	155.05
Steel, low-alloyed, hot-rolled	kg	1
Synthetic rubber	kg	1
Welding, arc, steel	m	319.99
Electricity	kWh	78.8
Manual labor	MJ	192

2.2.2. Rice Straw Preparation

Data on rice production, collection, and transportation are found in Table 2 [7,8,22]. During rice production, the diesel consumption of machinery from the references included the rotovator, tiller, spreader, thresher, and combine harvester. Some references also included manual labor from a draught animal. Rice paddy yield (varieties: NSIC Rc222, Rc18–38%, Rc222–33%, IR74–6%, NSIC Rc18) was at an average of 4.8 Mg ha^{-1} with a range of $3.31\text{--}6.70 \text{ Mg ha}^{-1}$; while rice straw yield was at an average of 2.69 Mg ha^{-1} with a range of $2.23\text{--}3.39 \text{ Mg ha}^{-1}$ [7,22,23].

Table 2. Published agronomic inputs in dry season rice straw preparation.

Parameter	Range	Average	Sources
<i>Rice production</i>			
Seeds (kg ha^{-1})	20–100	50	[7,22,23]
Fertilizer (kg ha^{-1})			
N	58–195	125	[7,22,23]
P_2O_5	15–50	25	[7,22,23]
K_2O	8.4–30	21	[7,22,23]
Herbicide (kg ha^{-1})	0.75–1.98	1.24	[22,23]
Insecticide (kg ha^{-1})	0.50–2.87	1.45	[22,23]
Total diesel consumption of machineries (L ha^{-1})	32–145	82	[22,23]
Total manual labor (MJ ha^{-1})	423–820	618	[22,23]
<i>Rice straw collection and transportation</i>			
Total diesel consumption of machineries (L Mg^{-1})	4.79–14.10	8.30	[8]
Total manual labor (MJ Mg^{-1})	0.97–2.43	1.19	[8]

The data for mechanical collection and transportation to a storage area (4 km away from the collection area) were also based on reference studies shown in Table 2. Diesel consumption during this stage included machinery, tractor, and trailer. The manual labor during this stage included rice straw handling and driving of the machinery. On the other hand, the manual labor capacity during rice straw storage was determined by measuring the weight of rice straw handled during storage per unit time (in three replicates).

2.3. RBHG Experiments

The rice straw samples used for heat generation in the dRF were collected from the rice production (variety NSIC Rc 238) during the dry seasons of 2017 and 2018 at IRRI, which used an alternate wetting and drying water management and a cropping duration of 110 days. A square baler (CLAAS Markant 55, 45 HP) attached to a tractor (MF399, 5.8 L, 6-cylinder diesel engine) was used for baled straw collection. The moisture contents of the sun-dried rice straw samples were measured using ASAE Standard S358.2 (DEC93) Moisture Measurement for Forages Method, which ranged from 8.89 to 10.48%.

The combustion setup was based on initial experiments conducted at IRRI on the dRF using rice straw as fuel [17]. The dRF was attached to a pre-calibrated dryer simulator (7.82 m long and 0.7 m in diameter) where temperature and percent relative humidity measurements were made. The blower connected to an electric motor (TECO 3-Phase Induction Motor Type AEEF-F-YC4, 1750 RPM, 10 HP) was controlled via an automatic controller (Schneider Electric variable speed drive ATV312HD11M3 3-phase supply) attached to a power monitor (Efergy Electricity Monitoring Transmitter). The drying airflow rate was set by adjusting the cone in the dryer simulator, as well as setting the frequency of the automatic controller. Two kg of rice straw were loaded initially into the primary combustion chamber via the feed hopper. A blowtorch was used to ignite the first rice straw via the bottom ash exit, and the rice straw feed rate was manually set by weight over time measurements.

Two scenarios of optimized conditions of rice straw feed rate (SFR) and drying air flow rate (DAF) were tested based on a previous study [17]. Based on the study, Scenario 1 (using SFR: 28.06 kg h^{-1} , DAF: $4 \text{ m}^3 \text{ s}^{-1}$) resulted in a dRF heat output, CO, and NOX emissions of 332.48 MJ h^{-1} , 89.9 ppm,

and 3.17 ppm, respectively. Scenario 2 (using SFR: 20.67 kg h⁻¹, DAF: 3.03 m³ s⁻¹) resulted in a dRF heat output, CO, and NOX emissions of 231.47 MJ h⁻¹, 76.57 ppm, and 2.93 ppm, respectively. The electricity consumption of the blower in kW was monitored every 5 min through the power monitor. The bottom ash was collected and weighed after every run. The dRF operation labor capacity was determined by measuring the weight of rice straw and manual labor time in three replicates.

2.4. Methodology and Software Used for Calculation and Simulation

Rice production was allocated between the two products in terms of economic value [19] to remove the influence of rice paddy in the output. The allocation was only applied in the rice production stage since rice straw was the sole product in the next stages (rice straw collection and transportation). Equations (1) and (2) were used in the economic allocation [8,24,25].

$$\% \text{ Allocation of rice straw} = 100 * Y_{rs} * P_{rs} / (Y_{pd} * P_{pd} + Y_{rs} * P_{rs}) \quad (1)$$

$$\% \text{ Allocation of paddy} = 100 - \text{Allocation of rice straw} \quad (2)$$

where Y_{rs} is the yield of rice straw, P_{rs} is the price of rice straw based on calculations in this study, Y_{pd} is the yield of paddy, and P_{pd} is the price of paddy at 430 USD Mg⁻¹ [26] based on an exchange rate of 1 USD = 52.10 PHP [27]. The total rice production input in Table 3 was multiplied with the percent allocation for rice straw in both energy and GHG emissions.

Table 3. Calculated energy and Greenhouse gas (GHG) emissions during rice production (without allocation), rice straw collection, and transportation using secondary data.

Parameter	Energy MJ Mg ⁻¹	GHG Emissions kg CO ₂ -eq Mg ⁻¹
<i>INPUTS</i>		
<i>Rice production</i>		
Mechanized operations	867–2583	80–238
Labor	190–242	
Rice seeds	241–794	15.3–50.4
Fertilizer	1714–3973	159–352
Herbicide	101–176	5.7–9.9
Insecticide	53–199	2.9–10.9
Subtotal, rice production	3166–7967	263–661
<i>Rice straw collection and transportation</i>		
Mechanized operations	130–251	12–23
Labor	0.97–2.43	
Subtotal, rice straw collection and transportation	131–254	12–23
<i>Direct soil emissions from partial or complete straw removal</i>		174–477

The energy conversion for manual labor was based on the metabolic equivalent of task (MET) or the ratio of human metabolic rate when performing a task to the metabolic rate during rest [23]. Manual handling of rice straw with an energy output of 0.89 MJ h⁻¹ [8,23] was assumed for rice straw storage and dRF operation.

The method Cumulative Energy Demand version 1.10 was used for the conversion of the agronomic inputs to energy, through the SimaPro software, version 8.0.5.13 [28]. The software automatically multiplies all the agronomic inputs by their corresponding energy equivalents in Table 4. The calculated energies during rice production, rice straw collection, and transportation using secondary data are found in Table 3.

Table 4. Energy equivalent and GHG emission factors of inputs and outputs.

Parameter	Unit	Energy Equivalent (MJ unit ⁻¹)	GHG Emission Factor (kg CO ₂ -eq unit ⁻¹)	Sources
<i>INPUTS/GHG EMISSIONS</i>				
<i>Rice production</i>				
Diesel consumption	L	44.8	4.13	[29–32]
Machine manufacture	L	15.6	1.44	[30–33]
Labor	h	0.89		[23]
Seeds	kg	26.91	1.71	[29,32]
Nitrogen	kg	60	5.75	[29,32]
P ₂ O ₅	kg	17.81	1.12	[29,32]
K ₂ O	kg	8.94	0.53	[29,32]
Herbicide	kg	300.63	16.87	[29,32]
Insecticide	kg	301.55	12.84	[29,32]
<i>Structure materials and energy</i>				
Alkyd paint	kg	99.52	6.74	[29,32]
Cement, Portland	kg	4.28	0.94	[29,32]
Concrete block	kg	0.86	0.09	[29,32]
Clay brick	kg	3.84	0.32	[29,32]
Sand	kg	0.19	0.01	[29,32]
Gravel	kg	0.19	0.012	[29,32]
Cement cast plaster	kg	1.37	0.21	[29,32]
Plywood	m ³	43,613	660.93	[29,32]
PVC Pipe	kg	68	3.4	[32,34]
Reinforcing steel	kg	23.63	2.04	[29,32]
Steel sheet	kg	33.27	2.9	[32,34]
Steel, low-alloyed, hot-rolled	kg	24	2.2	[29,32]
Welding arc, steel	m	2.63	0.21	[29,32]
Electric motor	unit	6850	537	[29,32]
Synthetic rubber	kg	87.7	2.88	[29,32]
Electricity	MJ	3.11	0.21	[29,32]
Labor	h	1.0		[35]
<i>Rice Straw Combustion</i>				
CH ₄	kg		30.5	[29]
N ₂ O	kg		265	[29]
<i>OUTPUTS/GHG AVOIDED</i>				
dRF heat output	MJ	1		
Kerosene substitute	GJ		71	[36,37]
Ash as concrete aggregate substitute	kg	0.19	0.012	[29,32]

For the GHG emissions balance, the method IPCC 2013 GWP 100a version 1.03 [28] was used for the conversion of the agronomic inputs to kg CO₂-eq based on their GHG emission factors in Table 4. Direct soil emissions during rice production were accounted for, based on the yield-scaled GWP of partial and complete straw removal of 477 and 174 kg CO₂-eq Mg⁻¹ straw, respectively [7]. The direct soil emissions measured the GWP of CH₄ and N₂O of different rice straw management practices; in this case, the scenarios' partial or complete straw removal are both applicable since rice straw was collected and used for RBHG. The calculated GHG emissions for rice production (without allocation), rice straw collection, and transportation using secondary data are found in Table 3.

To evaluate the energy depreciation of the structures (storage center and dRF), the embodied energy or energy expended by all the processes related with construction (including mining and processing of natural resources) [38] was calculated based on the BOQ and the energy equivalents in Tables 2 and 3. The structure of energy depreciation was calculated using Equation (3), and Equation (4) was used to calculate for the structure GHG emissions per Mg rice straw.

$$\text{Structure energy depreciation (MJ Mg}^{-1}\text{)} = \text{Embodied energy}/(\text{Qy} * \text{LS}) \quad (3)$$

$$\text{Structure GHG emissions (kg CO}_2\text{-eq Mg}^{-1}\text{)} = \text{Embodied GHG emissions}/(\text{Qy} * \text{LS}) \quad (4)$$

where the structure energy depreciation is in MJ Mg⁻¹ straw, the embodied energy is in MJ; Q_y is the annual capacity of the structure in Mg yr⁻¹, and LS is the life span of the storage center or dRF in years. Table 5 includes the data on the annual capacity and lifespan of the storage center and dRF. Likewise, the GHG emissions per Mg rice straw of the structures were evaluated by getting the embodied GHG emissions using the BOQ and emission factors in Tables 2 and 3.

Table 5. Investment and specifications of cost items.

Parameter	Baler	Storage Center	dRF
Investment cost (USD)	28,800	23,000	1515
Workshop for parking and maintenance (USD)	2000		
Life span (years)	5	10	5
Working time (hours day ⁻¹)	8	24	16
Maintenance and repair cost (%)	50	20	50
Working days each year (days)	60–90	300	60
Capacity (Mg yr ⁻¹)	960	80–320	19–29
Tractor rental price (USD h ⁻¹)	4.8		
Baler service management (USD man ⁻¹ day ⁻¹)	4.8 [39]		

Note: Exchange rate of 1 USD = 52.10 PHP [27].

CH₄ and N₂O emissions during the combustion of rice straw in the furnace were considered using the emission factors 0.70–9.6 g kg⁻¹ dry straw for CH₄ and 0.033–0.264 g kg⁻¹ dry straw for N₂O for dry straw, based on 10–15% moisture content [7,40–42]. The GWP of the two gases were 30.5 and 265 kg CO₂-eq kg⁻¹ for CH₄ and N₂O, respectively [29].

In terms of outputs, the contributions of the rice paddy were excluded since economic allocation was done. Thus, only two products (heat and ash) were considered. The dRF heat output was based on the study of Migo-Sumagang et al. [17]. The avoidance of kerosene combustion was accounted for in the GHG avoided. The kerosene combustion emission factor used was 71 kg CO₂ GJ⁻¹ [36,37].

In rice straw combustion, the bottom product composed of ash and unburnt combustibles is considered as a byproduct with applications in concrete aggregate replacement. Concrete, which is a mixture of Portland cement, coarse and fine aggregates, and water, depends on aggregates for 65% of its composition [43]. Many studies have shown that substituting the fine aggregates in concrete (commonly sand) with coal or municipal solid waste incinerator bottom or fly ash have exhibited higher compressive strength, expansion control, and slowing down of water penetration [43–46]. These ashes are rich in silica, which is also found abundantly in rice straw ash [47,48]. For both energy and GHG emissions, the weight of the ash byproduct was accounted as a concrete aggregate replacement using the equivalent factors for sand manufacturing and transportation [29] in Table 4.

Energy analysis was done by calculating the net energy (MJ Mg⁻¹), energy ratio, and percent net energy using Equations (5)–(7), based on the total energy input and output [8,21,49]. The net energy in GJ ha⁻¹ in Equation (8) was calculated for comparison with other studies. The net GHG emissions (kg CO₂-eq Mg⁻¹) was calculated using Equation (9), and Equation (10) was used in converting the net GHG emissions in terms of kWh, where SFR is in kg h⁻¹, dRF heat output is in MJ h⁻¹, and 1000 and 3.6 are conversion factors.

$$\text{Net energy (MJ Mg}^{-1}\text{)} = \text{Energy output (MJ Mg}^{-1}\text{)} - \text{Energy input (MJ Mg}^{-1}\text{)} \quad (5)$$

$$\text{Energy ratio} = \text{Energy output (MJ Mg}^{-1}\text{)} / \text{Energy input (MJ Mg}^{-1}\text{)} \quad (6)$$

$$\% \text{ Net energy} = \text{Net energy (MJ Mg}^{-1}\text{)} / \text{Energy input (MJ Mg}^{-1}\text{)} * 100 \quad (7)$$

$$\text{Net energy (GJ ha}^{-1}\text{)} = \text{Net energy (MJ Mg}^{-1}\text{)} * Y_{rs} / 1000 \quad (8)$$

$$\begin{aligned} & \text{Net GHG emissions (kg CO}_2\text{-eq Mg}^{-1}) \\ &= \text{GHG emissions (kg CO}_2\text{-eq Mg}^{-1}) - \text{GHG avoided (kg CO}_2\text{-eq Mg}^{-1}) \end{aligned} \quad (9)$$

$$\text{Net GHG emissions (kg CO}_2\text{-eq kWh}^{-1}) = [\text{Net GHG emissions (kg CO}_2\text{-eq Mg}^{-1}) * \text{SFR} * 3.6] / [\text{dRF heat output} * 1000] \quad (10)$$

2.5. RBHG Cost Calculations

RBHG cost depended on inputs such as fuel, labor, and materials used during heat generation. Depreciation, maintenance, and interest of the storage center and dRF (blower, motor, and furnace) were also included. Only one type of baler (CLAAS Markant 55, 45 HP) was evaluated in the cost calculations using Equation (11).

$$\text{RBHG Cost (USD kWh}^{-1}) = [\text{ML} * \text{LC} + \text{BPC} * \text{EC} + \text{SFR} * \text{RSC} + (\text{TC} + \text{DC} + \text{SC}) * \text{SFR}/1000] * 3.6/\text{dRF heat output} \quad (11)$$

where RBHG cost is in USD kWh^{−1}, dRF heat output, ML is the number of manual labor, LC is the cost of manual labor which is 0.84 USD man^{−1} h^{−1} [39], BPC is the blower electricity consumption in kW, EC is the price of electricity which is 0.20 USD kWh^{−1} [50], SFR is the rice straw feed rate in kg h^{−1}, RSC is the price of rice straw USD kg^{−1}, TC is the transportation cost in USD Mg^{−1}, DC is the furnace depreciation and maintenance cost in USD Mg^{−1}, SC is the rice straw storage depreciation and maintenance cost in USD Mg^{−1}, dRF heat output is in MJ h^{−1}, and 3.6 is a conversion factor.

The price of baled straw was based on financial analysis, taking into account investment, depreciation, interest, labor, fuel, tractor rental, tax, and transportation costs. The investment cost of a CLAAS Markant 55 baler was obtained from a baler sales company, Agri Component Corporation. All the other specifications of the baler were obtained from the manufacturer's manual. A 10% equipment transportation cost, as well as a 10% tax, were included in the total cost. Equations (12) and (13) show the calculations for depreciation and interest, respectively.

$$D = IV / (\text{LS} * Q_y) \quad (12)$$

$$\text{Ir}_s = IV * \text{Ir}_b / Q_y \quad (13)$$

where D is the depreciation of the item in USD Mg^{−1}, IV is the investment cost in USD, LS is the lifespan of the item in years, Q_y is the annual capacity in Mg year^{−1}, Ir_s is the interest of the service, and Ir_b is the bank interest (12%). Maintenance and repair costs were based on percentage factors in Table 5 multiplied to the depreciation cost. Equation (12) was also used in the dRF and storage center depreciation cost calculations, considering maintenance and repair factors. The investment cost and specifications of the storage center and dRF were obtained from a civil engineer and furnace fabricator, respectively.

Transportation cost was based on a diesel price of 0.82 USD L^{−1} [51], fuel consumption of 2.18 L Mg^{−1} for a distance of 4 km [8], driving tractor and trailer capacity of 13.13 Mg h^{−1} [8], and driving manual labor cost of 0.96 USD man^{−1} h^{−1} [39]. The calculated transportation cost was 1.86 USD Mg^{−1} for a distance of 4 km.

The annual capacity of the storage center (assuming two harvest seasons) was based on the baled straw density from literature values, ranging from 81.47 to 331 kg m^{−3}, with an average of 157.16 kg m^{−3} at 8–14% moisture content dry basis [17,48,52]. On the other hand, the annual capacity of the dRF was based on the optimized straw feed rates of 20.67 to 28.06 kg h^{−1} SFR [17].

3. Results

3.1. Results of the RBHG Experiments

Table 6 presents the results of the RBHG experiments. In the heat generation experiments, the blower electricity consumption for Scenario 1 conditions was between 16.30 and 19.92 kW, with a mean 18.38 (1.87) kW, while that of Scenario 2 was between 11.17 and 11.81 kW with a mean of 11.48 (0.32) kW. The blower electricity consumption of Scenario 1 was higher compared to Scenario 2 due to the higher airflow rate setting of Scenario 1.

Table 6. Results of the RBHG experiments and labor energy measurements.

Scenario	Blower Electricity Consumption (kW)	ASH (kg h ⁻¹)	Stage	Labor Energy (MJ Mg ⁻¹)
Scenario 1			Storage	
Range	16.30–19.92	6–6.11		4.68–6.24
Average	18.38	6.03		5.42
STDEV	1.87	0.07		0.78
Scenario 2			dRF Operation	
Range	11.17–11.81	4–4.28		5.52–6.87
Average	11.48	4.17		6.03
STDEV	0.32	0.17		0.73

The ash output for Scenario 1 was between 6 and 6.11 kg h⁻¹, with a mean of 6.03 (0.07) kg h⁻¹, while that of Scenario 2 was between 4 and 4.28 kg h⁻¹, with a mean of 4.17 (0.17) kg h⁻¹. The ash production in Scenario 1 was higher compared to Scenario 2 due to the higher straw feed rate in Scenario 1. Naturally, Scenario 1 had higher heat output as compared to Scenario 2 [10] due to the higher straw feed rate.

The labor energy per Mg straw was between 4.68 and 6.24 MJ Mg⁻¹ with a mean of 5.42 (0.78) MJ Mg⁻¹ for storage and between 5.52 and 6.87 MJ Mg⁻¹ with mean of 6.03 (0.73) MJ Mg⁻¹ for dRF operation.

3.2. Energy Flow and GHG Emissions

The energy input per megagram straw during paddy production ranged from 2725 to 9053 MJ Mg⁻¹. Due to the much higher economic value of rice paddy as compared to straw, rice straw allocation only ranged from 3.74 to 4.92%, and the rest was allocated to the rice paddy. Table 7 shows the summarized energy flow and GHG emissions for RBHG. The allocation for rice straw in rice production based on secondary data was only between 118 and 392 MJ Mg⁻¹ for energy and between 9 and 33 kg CO₂-eq Mg⁻¹ for GHG emissions. Data on rice straw collection and transportation based on secondary data were converted to their equivalent input energy and GHG emissions, also reported in Table 7. The converted input energy and GHG emissions for the first two stages, rice straw production and rice straw collection and transportation, had comparable values.

The construction of the 200 sq. meter and 3-meter-high storage center expended a total of embodied energy of 254 GJ, equivalent to 1270 MJ per sq. meter. In terms of energy depreciation, the calculated energy depreciation per Mg of rice straw using Equation (3) ranged from 79 to 318 MJ Mg⁻¹ for the storage center (Table 7). The embodied GHG emissions for the construction of the storage center was 32,810 kg CO₂-eq, or 164 kg CO₂-eq per sq. meter. Thus, the GHG emissions per Mg rice straw ranged from 10 to 41 kg CO₂-eq Mg⁻¹ for the storage center.

Table 7. Energy flow and GHG emissions balance for RBHG.

Parameter	Energy	GHG
	MJ Mg ⁻¹	kg CO ₂ -eq Mg ⁻¹
	INPUT	EMISSIONS
<i>Rice straw production (rice production with allocation) *</i> ¹	118–392	9–33
<i>Rice straw collection and transportation *</i>	131–253	12–23
<i>Direct soil emissions from partial or complete straw removal *</i>		174–477
<i>Rice straw storage</i>		
Labor	4.7–6.2	
Storage center energy depreciation/GHG emissions	79–318	10–41
<i>Subtotal rice straw storage</i>	84–324	10–41
<i>Rice-straw-based heat generation</i>		
Labor	5.7–6.9	
Blower electricity consumption	6218–7334	496–794
dRF energy depreciation/GHG emissions	152–232	14.5–22
Rice straw combustion emissions (CH ₄ and N ₂ O)		26–316
<i>Subtotal RBHG</i>	6376–7573	537–1132
Total Energy Input/GHG Emissions	6709–8542	742–1706
	OUTPUT	AVOIDED
dRF heat output	11,198–11,849	
Kerosene combustion avoided		801–847
Ash as concrete aggregate	38–41	2.4–2.6
Total Energy Output/GHG Avoided	11,236–11,890	803–850
Net Total Energy Output/GHG Emissions	3348–4527	(-)61–856
Energy Ratio	1.4–1.7	
% Net Energy	39–67	

* based on secondary data in Table 3; ¹ multiplied by the percent allocation for rice straw, 3.74 to 4.92%.

During the heat generation stage, the construction of the furnace (dRF) expended a total embodied energy of 22.1 GJ, corresponding to an energy depreciation between 152 and 232 MJ Mg⁻¹ rice straw using Equation (4). The embodied GHG emissions in the construction of the furnace were 2100 kg CO₂-eq. Thus, the GHG emissions per Mg rice straw ranged between 14.5 and 22 kg CO₂-eq Mg⁻¹ for the dRF. The converted blower electricity consumption ranged from 6218 to 7334 MJ Mg⁻¹, while the GHG emissions ranged from 496 to 794 kg CO₂-eq Mg⁻¹ rice straw, using the emission factors in Table 4. The rest of the contributions during the heat generation stage and the outputs are also reported in Table 7.

The net total positive energy ranged between 3348 and 4527 MJ Mg⁻¹ rice straw, while the net total GHG emissions ranged between (–)61 and 856 kg CO₂-eq Mg⁻¹ rice straw, wherein the negative sign of the lower range indicates GHG avoidance instead of emission. The total net energy corresponded to an energy ratio between 1.4 and 1.7 and percent net energy between 39 and 67%.

Figure 2 summarizes the percentages of the energy flow and GHG emissions. During the heat generation stage, the blower electricity consumption required the highest input energy at an average of 97% of the total input energy (Figure 2a). The furnace energy depreciation was only at an average of 3% of the total input energy in this stage, and the manual labor energy is almost negligible at an average of 0.09%. Blower electricity consumption also emitted the highest GHG at an average of 77% of the total emissions during the heat generation stage (Figure 2a). Rice straw combustion emissions from the release of CH₄ and N₂O accounted for an average of 21% (Figure 2a), followed by furnace construction emissions at 2% in the heat generation stage.

Figure 2. Percentages of input energy and Greenhouse gas (GHG) emissions in the (a) heat generation stage, (b) rice-straw-based heat generation (all stages).

In terms of the total input energy and GHG emissions for all the stages, the highest input energy was during the heat generation stage, at an average of 92% of the total input energy, and an average of 68% of the total GHG emissions for all stages (Figure 2b). The rest of the stages ranged from 2 to 3% of the total input energy. Direct soil emissions followed as the next highest contributor of GHG emissions in all stages at an average of 27%, while the rest of the stages ranged from 1 to 2% of the total GHG emissions (Figure 2b).

In the outputs, the heat product dominated the total input energy, while the ash byproduct had minimal contribution (Table 7). Nevertheless, it was important to consider the use of the ash byproduct as a means of waste disposal. GHG emissions from the avoidance of kerosene combustion (801 to 847 kg CO₂-eq Mg⁻¹) is higher compared to combustion emissions from rice straw (26 to 316 kg CO₂-eq Mg⁻¹).

3.3. Cost Calculations

In the cost calculations, rice straw production and baling were grouped as the cost of baled straw. The estimated cost of baled straw in the Philippines ranged from 17.8 to 22.2 USD Mg⁻¹ straw. However, for a profitable straw baler service provider with a time of capital return from 1.4 to 2.8 years, baled

straw price is around 33 USD Mg⁻¹ straw. Transportation cost for a 4 km distance was 1.86 USD Mg⁻¹ straw. In terms of the dRF heat output, the cost of a storage center, labor for dRF operation, electricity, and dRF are presented in Table 8. The total cost ranged from 0.0796 to 0.1127 USD kWh⁻¹.

Table 8. Cost of rice-straw-based heat generation (RBHG) in the Philippines.

Inputs	Cost		Percentage of Average Value
	USD Mg ⁻¹ Rice Straw	USD kWh ⁻¹ Heat Output	%
Rice straw	33	0.0106	11.04
Transportation	1.86	0.0006	0.62
Storage center maintenance and depreciation	18.2–69	0.0059–0.0222	14.58
Labor for dRF operation	59.9–81.2	0.0193–0.0261	23.59
Blower electricity consumption	111–131	0.0357–0.0421	40.47
dRF maintenance and depreciation	23.6–34.4	0.0076–0.0111	9.70
Total cost	248–350	0.0796–0.1127	100

4. Discussion

The lower range of the input energy during paddy production of this study is comparable with similar studies, which had values between 1730 and 2520 MJ Mg⁻¹ [9,19]. The lower range of the straw collection and transportation is also comparable with that of rice straw collection from similar studies, which ranged between 38 and 110 MJ Mg⁻¹ [9,19]. As for the higher range of the input energy, the difference may be due to the manual labor considered in the study. The GHG emissions during collection and transportation are lower compared to similar studies (132 to 394 kg CO₂-eq Mg⁻¹) [6,13,19], possibly due to the shorter distance considered in this study.

Heating value and moisture content affect the performance and efficiency of combustion [5,17,53]. There is a loss in heating value due to the adsorption of water vapor, oxidation, and biochemical reactions during storage [48,54]. Thus, it was necessary to include storage in the life cycle analysis of RBHG. A roofed facility with minimal features was chosen in this study. Comparisons were made with more complex residential structures in terms of input energy and GHG emissions per sq. meter to verify the simplicity of the presumed structure. Results show that the assessed input energy and GHG emissions of the presumed storage center are expectedly lower compared to more complex residential houses with input energies between 3000 and 9740 MJ per sq. meter [55,56] and GHG emissions of 165 to 665 kg CO₂-eq per sq. meter [57,58]. The resulting input energy of the storage center was wide-ranged due to the wide range of annual storage capacity considered, which depended on factors such as rice straw density and availability.

The measured labor energy for storage and dRF operation is comparable to the labor energy reported from another study, which is 4.78 MJ Mg⁻¹ for manual straw handling (collecting rice straw to the bund, loading, and unloading) and 6.41 MJ Mg⁻¹ for manual piling of rice straw [8,23]. The closeness with literature values may be explained by the fact that the dRF operation included similar activities such as weighing and feeding of straw into the hopper for combustion.

The blower electricity consumption required the highest input energy during the heat generation stage and also emitted the highest GHG. The significant input energy and GHG emissions from electricity consumption included the contributions from power generation and transmission [29], with factors of 3.11 MJ MJ⁻¹ and 0.21 kg CO₂-eq MJ⁻¹ for input and GHG emissions, respectively (Table 4). Thus, other types of motors, such as diesel-powered, may be explored to decrease the input energy and GHG emissions.

In terms of the total input energy and GHG emissions for all the stages, the highest input energy and GHG emissions were during the heat generation stage. The results can be attributed to the blower electricity consumption during heat generation, which required the highest input energy and emitted the highest GHG. The percent net energy output of RBHG is lower compared to that of a small-scale anaerobic digestion study, which is around 71 to 85% [8]. The difference may be attributed to the high

input energy during the heat generation stage, specifically the high blower electricity input energy. The energy ratio or energy use efficiency is also comparable to the results of input–output energy analyses from literature (1.39 to 1.72) in Iran [20,49,59], but lower than the values from a study in China (6.81 to 9.94) [21]. It is important to note that the mentioned input–output studies directly considered the energy values of paddy and straw in the output energy and excluded the energies in rice straw processing. RBHG net energy converts to 10.59 GJ ha^{-1} using Equation (8). Comparing the energy flow of RBHG with that of rice straw soil incorporation and open-field burning, RBHG adds more value to the energy flow since the outputs of soil incorporation (1.35 GJ ha^{-1}) and open-field burning (0.34 GJ ha^{-1}) only include rice straw as fertilizer, with corresponding nutrient losses [14].

Furnace combustion emissions are comparable or lower than open-field burning, which ranged from 453 to $1460 \text{ kg CO}_2\text{-eq Mg}^{-1}$ straw [6,7]. Combustion in a controlled environment such as the dRF can improve the efficiency and completion of the process [17] over the uncontrolled open-field burning. To compare RBHG with soil incorporation and open-field burning scenarios, it was essential to consider the direct soil emissions in complete or partial removal of rice straw, as shown in Table 7. Direct soil emissions in the complete straw removal scenario come from the incorporation of the remaining rice straw stubbles that favor CH_4 formation, as well as N_2O emissions during fertilizer application [7]. The net GHG emissions imply that the best case of RBHG would result in net GHG avoidance, indicated by the negative value ($-61 \text{ kg CO}_2\text{-eq Mg}^{-1}$). The best case of RBHG is better compared to the yield-scaled GWP of soil incorporation with emissions of 881 and $1025 \text{ kg CO}_2\text{-eq Mg}^{-1}$ [7,13], and open-field burning with emissions of 453 and $1460 \text{ kg CO}_2\text{-eq Mg}^{-1}$ [6,7]. On the other hand, the worst case of RBHG is just comparable with that of soil incorporation.

The average net GHG emissions in this study convert to $0.12 \text{ kg CO}_2\text{-eq kWh}^{-1}$ using Equation (10), lower compared to the literature value of rice-straw-based electricity generation ($0.845 \text{ kg CO}_2\text{-eq kWh}^{-1}$) in Malaysia [19], higher than that in Thailand ($0.043 \text{ kg CO}_2\text{-eq kWh}^{-1}$) [60], and comparable with that in India ($0.15 \text{ kg CO}_2\text{-eq kWh}^{-1}$) [13]. Studies on rice-straw-based electricity generation show that transportation may contribute a significant portion of the total GHG emissions [9,13,19]. As an example, transportation GHG emissions were up to 42% in a study where the distance of the rice straw collection area to the power plant was 250 km [19]. In another study, transportation contributed up to 81.68% for a rice-straw-based electric power plant [9]. On the other hand, the distance considered in this study was only 4 km. As a result, collection and transportation only contributed 1% of the GHG emissions during the rice preparation stage. For a small-scale RBHG system, a long distance from the rice straw collection area to the dRF unit is not required since individual dRF units may be installed near the rice fields. Thus, small-scale systems may improve the overall GHG emissions with respect to transportation.

The estimated cost of baled straw in the Philippines ranged from 17.8 to 22.2 USD Mg^{-1} straw, but it was set to 33 USD Mg^{-1} for a profitable straw baler service provider. This value was lower compared to 38 USD Mg^{-1} , which was the information gathered from farmers in Nueva Ecija, Philippines [8]. Rice straw cost only accounted for 11.04% of the total cost of RBHG (Table 8). Blower electricity consumption accounted for the highest cost (40.47%), followed by labor (23.59%) and storage (14.58%). Alternatives to an electric motor and storage may be explored to drive down the cost. Transportation contributed only 0.62% to the cost, due to the short distance between the rice straw collection and the storage center and furnace. Thus, the energy conversion area must be located strategically to drive down transportation costs [5]. The average total cost of RBHG is $0.096 \text{ USD kWh}^{-1}$, lower compared to the paddy drying cost of 0.13 to $0.15 \text{ USD kWh}^{-1}$ in the Philippines [61,62]. The cost is also lower compared to a 500 kW steam power plant ($0.21 \text{ USD kWh}^{-1}$) in Japan within a 3 km distance [63], but slightly higher compared to the cost of a 5 MW rice-straw-based electricity generation system in Thailand within 70 km from the collection point ($0.0889 \text{ USD kWh}^{-1}$) [60]. The cost is comparable with the selling price of pelletized rice straw in Japan from literature (0.29 USD kg^{-1} straw) within a 20 km radius from the collection point [64].

5. Conclusions

The highest contributor among all the stages (rice straw production, straw collection and transportation, storage, and heat generation) in the total input energy and GHG emissions was from the heat generation stage due to the blower electricity consumption. Because of the short distance assumed in this study (4 km), collection and transportation only contributed 1% of the total GHG emissions in the rice straw preparation stage. The RBHG energy ratio was between 1.4 and 1.7, and the percent net energy was between 39 and 67%; RBHG improves the net energy flow over soil incorporation and open-field burning since the last two options only consider rice straw as fertilizer with nutrient losses. The best case of RBHG offers a possibility of a net GHG avoided ($-61 \text{ kg CO}_2\text{-eq Mg}^{-1}$) in contrast with soil incorporation and open-field burning, while the worst case has a net GHG emission comparable with soil incorporation. Blower electricity consumption accounted for the highest cost, followed by labor cost. Thus, alternatives to an electric motor and storage may be explored to drive down not only the input energy and GHG emissions but also the cost of RBHG. In contrast, transportation contributed the lowest cost, due to the short distance considered (4 km). The average total cost of RBHG ($0.096 \text{ USD kWh}^{-1}$) was lower compared to the paddy drying cost in the Philippines.

The results of this study show that RBHG adds more value to the energy flow compared to soil incorporation and open-field burning. A small-scale RBHG system may also be advantageous over rice-straw-based electricity generation since long distances from the rice straw collection point may not be required, as individual furnace units may be installed near rice fields. Overall, RBHG is a technology with the potential to improve the energy flow, GHG emissions, and the cost of rice production systems.

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