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Agricultural residue gasification for low-cost, low-carbon decentralized power: an empirical case study in Cambodia

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ABSTRACT

Small-scale distributed gasification can provide energy access for low-carbon sustainable development, though current understanding of the economic and environmental performance of the technology relies mostly on assumption-heavy modeling studies. Here we report a detailed empirical assessment and uncertainty estimation for four real-world gasification power systems operating at rice mills in rural Cambodia. System inputs and outputs were characterized while operating in both diesel and dual-fuel modes and synthesized into a model of carbon and energy balance, economic performance, and greenhouse gas mitigation. Our results confirm that the best-performing systems reduce diesel fuel use by up to 83%, mitigating greenhouse gas emissions and recouping the initial system capital investment within one year. However, we observe a significant performance disparity across the systems observed leading to a wide range of economic outcomes. We also highlight related critical sustainability challenges around the management of byproducts that should be addressed before more widespread implementation of the technology.

KEYWORDS: rice husk; gasification; biochar; rural electricity enterprise; lifecycle assessment; sustainable development

1. INTRODUCTION

Improved access to modern energy carriers such as electricity or liquid and gaseous fuels in developing countries is an important enabling factor for improving health and promoting economic development and prosperity [1,2]. Bioenergy, the conversion of biomass to chemical, electric, or thermal energy products, is a renewable energy source with large carbon mitigation potential worldwide [3]. Large quantities of biomass are already used as a fuel for cooking or small-scale industry in many developing countries [4], but adoption of more modern bioenergy technologies is necessary for true sustainable development and growth of low-carbon economies [2,5].

1.1. Distributed bioenergy via agricultural residue gasification in Cambodia

Agricultural residue, the non-edible portion of crop aboveground biomass, is recognized as a sustainable and cost-effective bioenergy feedstock that avoids land use change emissions and food-versus-fuel concerns [6,7]. Rice is the dominant cropping system throughout Asia, and rice husk (also know as 'rice hull'), the fibrous outer cover of each grain, is produced in great quantity in rural areas. Rice husk is a particularly attractive feedstock as it is freely available at the rice mill, and does not require any additional collection, transport, drying, or size reduction steps. Husk has several traditional uses including as a solid fuel for brick kilns, but in many regions supply outstrips local demand [8,9]. Excess is often disposed of in the same manner as rice straw, e.g., by incorporation into agricultural soils [10,11], dumping on unused land or into waterways [9], or open burning [12–14], despite a variety of negative implications for GHG emissions, agricultural productivity, and human health.

One promising bioenergy technology is gasification of agricultural residues. Gasification is the partial oxidation of biomass in an air-restricted environment to yield a mix of flammable gases (H_2, CO, CH_4, etc., known as 'producer gas') and a solid fraction of carbonaceous ash-rich char [15,16]. Producer gas from small gasification systems can be used to generate mechanical or electrical power in dedicated gas engines [17] or fed into the intake manifold of diesel engines to offset the amount of diesel fuel necessary to maintain load (referred to as 'dual fuel' operation) at rates of up to 60 – 87% [18]. Such gasification power systems are technologically mature, tolerant of diverse feedstocks [17,19], and practical at smaller scales than combustion-based steam power systems

[20,21]. Additionally, the char byproduct of gasification has value as an agricultural soil amendment ('biochar') that can improve crop productivity and mitigate greenhouse gas (GHG) emissions in certain situations [22–24].

Rice husk bioenergy systems in particular are proliferating rapidly in Cambodia. While Abe *et al.* [25] were only able to identify a handful of small systems in 2007, by 2015 Pode *et al.* [26] found more than 50 gasification systems of <1 MW capacity, in addition to five larger steam turbine systems in the 1-10 MW range (a more efficient option at these larger scales [21]). Such systems use gasifiers imported from India or a variety of locally-made designs [27].

1.2. Bioenergy system assessment and this study

The economic viability of decentralized gasification power systems in south or southeast Asia has been assessed several times, often considering rice husk as the primary feedstock. Bergqvist *et al.* included a 300 kW scale gasification scenario in their analysis of rice-husk power generation options in the Mekong River Delta region of Vietnam, and determined that such systems have high operation and maintenance costs and are unlikely to be viable in the absence of significant additional revenues from ash byproduct sales or carbon finance [28]. In contrast, Dang *et al.* assessed gasification systems at the same scale located in the same general region and concluded that energy could be produced more cheaply this way that with fossil fuels [29]. Kapur *et al.* conducted a generalized assessment of the potential for rice husk gasification to meet the electrical demands of Indian rice mills [30]. They found that gasification would be cheaper than using on-site diesel generators for all but the smallest mills, but that it is unlikely to compete with grid electricity except at very large scales and high system capacity factors (the ratio of actual system output over a period of time to potential output if operated continuously at nameplate capacity). Ravindranath *et al.* came to a similar conclusion through a more generalized calculation, estimating that electricity from a 20 kW gasification system located in a rural area would be more expensive than grid electricity access, but cheaper than diesel generator use [5]. While these studies are highly divergent on the overall financial viability of the technology, most agree that capacity factor is a fundamental driver of system viability, i.e., that systems running for a greater fraction of the day or the year are more likely to make up initial capital investment costs [25,28,30,31].

While bioenergy is widely touted as a low-carbon renewable energy source, the actual GHG mitigation value of any particular bioenergy system is not easily predicted [2] but rather depends on a variety of site- and system-specific factors [32,33]. Basic GHG mitigation estimates focus exclusively on the GHG intensity of fossil energy sources being displaced by bioenergy production [5]. More detailed lifecycle assessment studies consider the full supply chain for both the bioenergy system and the fossil fuels being displaced, including upstream GHG emissions associated with inputs, energy use at the conversion facility, etc. [32]. Many bioenergy systems rely on waste feedstocks that would otherwise be burned or dumped with large air pollutant or GHG emissions, and crediting them for avoiding these emissions improves the overall GHG footprint [34]. The biochar co-product of gasification and pyrolysis also has carbon sequestration value and indirect benefits (improved plant productivity, reduced nitrous oxide emissions, reduced inputs of fertilizer or lime, etc.) when used as a soil amendment, capable of mitigating more GHG emissions than bioenergy alone under certain conditions [32,35,36].

While there are a wide variety of bioenergy GHG mitigation and lifecycle assessment studies in the literature, few of them focus on distributed gasification of rice husk in this region. Notably, Dang *et al.* conducted a thorough estimate of local biomass supply and demand trends in Vietnam, determining that significant amounts of rice husk and straw are available for conversion and that rice husk gasification systems co-located at rice mills would mitigate 1.6 – 1.8 $MgCO_2eq$ per Mg of husk consumed by fossil fuel substitution and avoidance of residue burning [29]. Similarly, Mai Thao *et al.* found that large-scale (5 – 30 MW) rice husk gasification in the same region avoids significant GHG emissions associated with open burning and that modern bioenergy mitigates more than traditional, even after accounting for alternate uses of the material [9].

While generalized estimates of the economic viability or GHG mitigation potential of distributed agricultural residue gasification systems have been conducted as described above, rarely are such studies combined for an integrated assessment of both economic and GHG performance (e.g., [5,29]), and even more rarely are they based on the observed performance of real-world systems (e.g., [18]). Here we present what is to our knowledge the first integrated assessment of distributed gasification facility performance, based on empirical observation of multiple small-scale rice husk gasification power systems operating at rice mills in rural Cambodia. The analysis includes carbon and energy balances of the system and detailed estimates of system net present value and GHG mitigation with full uncertainty estimation and sensitivity analysis. In addition, the potential for wider system deployment and ongoing sustainability challenges are explored.

2. MATERIALS AND METHODS

2.1. Case study technology overview

We analyzed gasification systems installed by SME Renewable Energy Ltd., a company based in Phnom Penh that provides rice husk gasification system installation and maintenance on 5-year contracts to local rice mills and industrial facilities [37]. As of June 2010, 33 SME Renewable Energy gasification systems were operating across the country. The systems studied are described in detail by Shackley *et al.* [38]. They are based on 150–300 kW downdraft-style fine biomass gasification (‘FBG’) systems from Ankur Scientific (Gujarat, India).

The gasifiers feature wet char removal wherein char is washed out from the bottom of the reactor and then sieved out of the water stream. Producer gas cleanup consists of a vortex filter and a wet filter (‘scrubber’) to cool the gas and condense out the high molecular-weight tars, followed by a series of large-volume passive filters using rice husks, sawdust, or cloth media to remove additional contaminants. The resulting cleaned, cooled gas is fed into the intake manifold of a diesel engine, typically a repurposed truck engine mechanically coupled to the milling equipment directly or to a generator. Effluent from the char removal and scrubber streams passes through a series of settling tanks in which fine char and ash particles, condensed tars, and other contaminants settle out as a sludge mixture [27], and then through an evaporative cooling fountain before being re-circulated.

2.2. Field measurements and sample collection

After informally visiting several systems to get accustomed with typical equipment layout, formal field assessments of six operating systems were conducted in June 2010. With each system operating in dual-fuel mode, measurements of fuel consumption, rice husk consumption, and char production were made over independent but overlapping testing intervals of at least 20 minutes duration. Husk consumption and char production were estimated by weighing the material consumed or produced over the test interval with a 50 kg market scale. At one site, three shorter-duration repeated measurements were taken to assess rate variability. System fuel consumption was monitored using sight glass readings on the diesel supply tanks, typically a pair of 55-gallon drums plumbed in parallel. System operators were then asked to switch over to diesel-only operation (temporarily venting and flaring the producer gas), and the diesel consumption rate was re-measured. The production rate of sludge in the water system settling tanks was estimated based on typical cleanout frequencies and sediment depths as estimated by the system operators. Additionally, system owners were asked about alternate uses and prices for rice husk in their area, and for what price the resulting biochar might be sold.

Of the six systems visited, we were successful in gathering sufficient data to construct system carbon balances for four systems (Table A1), all located at rural rice mills and identified by the initials of the mill owners' names as K.M., Y.P., C.K., and Y.L. General characteristics of these four systems are presented in Table 1. Data on sludge production rates and local pricing of husk and char from the other systems were integrated into the broader analysis (Appendix A). Of the four systems for which carbon balances were constructed, we were able to verify a full energy balance for a single system (Y.L.)

which was set up to drive a three-phase generator (standard power factor of 0.8 assumed) powering electric milling equipment; for the other systems, we assumed the same engine efficiency to complete the energy balance.

In order to complete system carbon and energy balance, samples of key system inputs, intermediaries, and outputs were collected for laboratory analysis. Samples of both raw rice husks and produced biochar were collected from each site, stored in sealed plastic containers, and analyzed for moisture content, chemical composition, and heating value. Additionally, samples of producer gas and engine exhaust were collected for a single system (Y.L.) and analyzed for composition. Details on sampling method, analysis, and results are given for husk and char in Appendix B.2. and for producer gas and exhaust in Appendix B.3.

2.3. System mass and energy balances

The rate and composition measurements described above were integrated into an Microsoft Excel-based model of the carbon and energy balance of each system (represented schematically in Figure 1) operating in both modes, as detailed in Appendix A. The analysis assumes that the load on an individual system was constant while operating in either mode, and that diesel engine efficiency was comparable across all systems and in both operating modes. In addition to carbon and energy balances, two other system performance metrics were computed. We estimated the diesel replacement rate (DRR; i.e., the fraction of diesel fuel consumption replaced by producer gas) using our measurements of steady-state volumetric diesel fuel consumption rates ($\dot{V}$) for each system operating in diesel-only mode (DM) and dual-fuel mode (DFM):

$$DRR = 1 - \frac{\dot{V}_{DFM}}{\dot{V}_{DM}}$$

Gasifier efficiency ($\eta_{gasifier}$) [39], also known as cold gas efficiency [18], was also computed as the ratio of the chemical energy content of the producer gas relative to that of the input rice husk on a lower heating value (LHV) basis:

$$\eta_{gasifier} = \frac{\dot{m}_{gas} LHV_{gas}}{\dot{m}_{husk} LHV_{husk}}$$

2.4. GHG mitigation assessment

The mass and energy balances of individual systems were used to drive estimates of GHG mitigation relative to an alternate scenario where the rice mills are operated exclusively on diesel fuel and rice husks disposed of in an alternate manner. Results are reported in CO_2-equivalent terms on the basis of 100 year global warming potential for CH_4 and N_2O from the IPCC [40], and for particulate emissions from MacCarty *et al.* [41].

2.4.1. Avoided fossil fuel emissions

Dual-fuel operation of the engine reduces diesel fuel consumption and avoids associated emissions. A lifecycle emissions factor of 91 gCO_2eq/MJ is taken from the Argonne National Laboratory Greenhouse Gases, Regulated Emissions, and Energy Use in Transport Model (GREET 2015 v1.3; [42]) to account for CO_2 released when diesel fuel is combusted and upstream energy use and emissions associated with production of the fuel.

2.4.2. Alternate feedstock fate

Since rice husk is an agricultural byproduct that would be generated and require management regardless of the existence of the gasification system, no emissions from the initial rice cultivation or associated land use practices were considered in the analysis. However, avoided emissions from alternate forms of rice waste management (e.g., open burning or field incorporation) were included. The prevalence of different types of disposal were estimated based on a previous survey of 30 local rice mills [27] and on reports from the managers of the systems assessed here. Emissions factors for rice straw burning are detailed in Table 2; factors for field incorporation were taken from Knoblauch *et al.* [11]. Any potential impacts of fuel switching in the local brick-making sector were considered outside the scope of this analysis scope and not included.

2.4.3. Biochar

Carbon sequestration in biochar is estimated from measured biochar production rate and carbon content, as well as the estimated stability of that carbon. An average estimate of 81% of the original char carbon remaining in the soil after 100 years was used, based on three sources (Table 2). No indirect biochar effects associated with improved crop yield or reduced inputs are considered, as these effects are highly uncertain and could vary considerably with agricultural management practices (e.g., [43]).

2.4.4. Upstream and process emissions

The only significant operating input to the gasifier system besides feedstock is electricity to drive the motors and pumps associated with feedstock loading and water management. Electricity consumption was estimated from system specifications (11 kW total capacity) and assuming a 70% motor efficiency and 50% load factor. The Cambodian electric grid is primarily diesel-fuelled, and an associated footprint of 0.97 kg CO_2eq $(kWh)^{-1}$ is estimated from GREET. Any measured increases in engine exhaust CH_4

emissions in dual-fuel mode were attributed to the system; other relevant species such as N_2O or particulates were not measured or considered. Embodied emissions associated with manufacture of the gasification equipment itself are estimated based on equipment capital costs combined with estimates of the energy efficiency (540 kJ (Indian Rupee)$^{-1}$) and emissions intensity (0.073 kg CO_2eq (Indian Rupee)$^{-1}$) of the Indian manufacturing sector [44]. No GHG value was assigned to wastewater or settling tank sludge, nor did we have the capability to sample for potential fugitive emissions of producer gas [27].

2.5. Economic performance

The analysis was further expanded to estimate system net present value (NPV) based on an enterprise budget reflecting the opportunity cost of feedstock, capital equipment costs and financing, system maintenance, labor, and savings or revenues associated with diesel replacement and biochar co-production. SME Renewable Energy provides financing for 70% of system equipment cost at a 5-year fixed rate of 13% APR. Price estimates used in the analysis were based on those reported by SME Renewable Energy, supplemented as necessary with those reported in the literature for similar systems [26,27] to define parameter uncertainty ranges (see Section 2.6). Future costs and revenues were discounted at 15%. All prices were adjusted to 2010 U.S. Dollars (USD) using the US Consumer Price Index and a 4200:1 Cambodian Riel to USD exchange rate.

2.6. System variability, uncertainty estimation, and sensitivity analysis

Variability in performance between systems was addressed through construction of individual carbon and energy balances for each. Uncertainty and sensitivity analyses were conducted on system performance metrics to evaluate the robustness of these estimates.

Wherever practical, probability distribution functions were defined for model parameters to reflect uncertainty around their true value. Uncertainty in measured parameters was based on instrument limit of error propagation or, where possible and appropriate, repeated measures. In general, parameters reported by SME Renewable Energy or measured directly with a single estimate were used as central estimates, augmented with similar estimates from secondary sources as bounds to a triangular distribution. Parameters estimated from multiple measurements or multiple secondary data sources were given uniform distributions if two point estimates were available, or normal distributions if more.

Probability distributions were estimated for 40 different model parameters, a representative subset of which are detailed in Table 2. Of particular note is the uncertainty around husk consumption and char production, which reflect variance in repeated measurements taken at a single system (Y.L., n=3). These deviations are far beyond instrument limits of error and thus indicate real deviations from steady-state operation due to transients in gasifier performance and possibly system load. Furthermore they are of somewhat greater magnitude than previously-reported values for a similar system where continuous monitoring of gasifier performance, load, and specific fuel consumption was possible [18]. This variance is treated as uncertainty in our steady-state carbon and energy balance, a conservative assumption ignoring any variation in system load over time.

Uncertainty ranges of our results were estimated using a 1000-iteration Monte Carlo analysis routine automated in Excel using Visual Basic for Applications (VBA) to determine means and 90% confidence intervals for all reported performance metrics. The analysis was constrained such that any combination of extreme parameter values that caused a system carbon or energy balance to fail was rejected and another sample taken in its place. For the sensitivity analysis, the values of some representative model parameters were perturbed by 1% one at a time, and resulting percent changes in gasification efficiency, GHG mitigation, and system NPV noted.

3. RESULTS AND DISCUSSION

3.1. System performance and variability

The primary results of this analysis – estimates of NPV and GHG mitigation for all four systems modeled, including uncertainty intervals – are shown in Figure 2A. There is a wide range in economic performance, with the Y.L. and C.K. systems showing positive 5-year NPV with a high degree of confidence (point estimates of USD 127,000 and USD 78,000, respectively), whereas the confidence intervals for the other two systems widely overlap zero NPV and thus we cannot comment conclusively on their profitability. Diesel replacement per unit of husk input is high in the well-performing systems, and high husk throughputs help to amortize financing costs. In the more poorly performing systems higher relative costs and lower revenues are closer to being in balance, and initial system capital costs are paid down very slowly or not at all. In contrast, the analysis shows favorable GHG mitigation across all systems assessed with a high degree of certainty (Fig. 2A). Estimated GHG mitigation rates vary from 0.56 to 1.02 metric tons CO_2eq per ton of rice husk consumed and show a weak correlation with NPV. There is some overlap of the 90% confidence intervals for the best-performing (Y.L.) and worst-performing (K.M.) systems.

The measured diesel replacement rates and estimated gasifier efficiencies underlying this economic and GHG performance are shown in Figure 2B. Systems with high measured DRR had higher estimated gasifier efficiency as well, independent of the nominal size of the gasifier and capacity of the rice mill. The 90% confidence intervals are relatively narrow for DRR, with the C.K. and Y.L. systems showing significantly better performance (82 – 83% diesel replacement) than the K.M. system (69%). Gasifier efficiency was estimated in a less direct way that incurred more uncertainty across a greater number of parameters. As such, while point estimates across systems varied substantially, from 38 – 52% efficiency, confidence in those differences is limited. For comparison, other studies report efficiencies anywhere from 25% [39] to 77% [18].

3.2. Details of carbon & energy balance, economic performance, GHG mitigation, and sensitivity analysis for a single representative system

Characteristics of individual systems are highlighted in Tables 1 and 3, and described in detail in Appendix B.1. Below we present some additional illustrative intermediate analysis details for the carbon balance, energy balance, and individual GHG mitigation components for a single representative system. We selected the C.K. system as the most representative, since its performance on most analysis metrics is in between to that of the other three systems.

Sankey diagrams illustrating the carbon and energy balance of the C.K. system operating in dual-fuel mode are shown in Figure 3A and 3B, respectively. The input of husks dwarfs that of diesel in both carbon and heating value terms. A majority of the carbon entering the system is expelled in the engine exhaust stream (52%), with the remaining output in the form of biochar or settling pond sludge. While losing 1/4 to 1/3 of carbon input as sludge was typical across the systems assessed, the best-performing system (Y.L.) lost much less and featured greater biochar recovery and diesel replacement rates.

The energy outputs were separated into six components. Actual work output by the engine in this particular system was estimated at 18.5% of the combined lower heating value of system inputs, in the middle of the range suggested by Dasappa [21] and somewhat better than that compiled in Mai Thao *et al.* [9]. Slightly less than half of the input energy is lost as heat from either the gasifier (12.1%) or in the engine cooling system and exhaust stream (30.1%), and the remainder is attributed to the chemical energy content of biochar, sludge, and unburned exhaust gases.

System GHG balance and annualized system costs and revenues were calculated on a per-unit-feedstock basis (Mg husk; Figure 4). We estimate a net GHG mitigation of 0.70 metric tons CO_2eq per ton of rice husk consumed in the C.K. system. The largest mitigation came from diesel replacement (0.46 Mg CO_2eq (Mg husk)$^{-1}$), followed by avoided emissions from alternate husk disposal methods (0.22 Mg CO_2eq (Mg husk)$^{-1}$) and biochar carbon sequestration (0.18 Mg CO_2eq (Mg husk)$^{-1}$). Total mitigation is reduced slightly by equipment embodied emissions, system electricity use, and increased engine emissions of products of incomplete combustion while operating in dual-fuel mode, totaling 0.16 Mg CO_2eq (Mg husk)$^{-1}$.

For this system a net revenue of USD 75 per metric ton of husk processed was calculated (Figure 4). Annualized system costs are dominated by financing (USD 33 (Mg husk)$^{-1}$), with smaller contributions from system electricity consumption (USD 19 (Mg husk)$^{-1}$), labor (USD 5 (Mg husk)$^{-1}$), and maintenance costs (USD 4 (Mg husk)$^{-1}$). However, these costs are dwarfed by diesel fuel saving of approximately USD 136 (Mg husk)$^{-1}$. Cash flow analysis at a relatively aggressive discount rate of 15% suggests a 5-year system NPV of USD 79,600 and a system payback period of less than a year (Table 3).

Sensitivity of system performance metrics to some representative model parameters is shown in Figure 5. There are only a few instances of high sensitivity to an individual parameter, i.e., where a 1% change in parameter value results in a similar or greater relative change in the value of the performance metric. Our estimates of gasifier efficiency are most sensitive to the LHV of rice husk, but the value of this parameter is well-constrained in our analysis and consistent with values reported elsewhere [9]. System NPV is highly sensitive to diesel prices, suggesting that system economic viability can be affected by volatility in that market. However, the C.K. system would still have a positive 5-year NPV at diesel prices as low as USD 0.55 L^{-1}, about half the price at the time of the assessment. In addition, we also observe high sensitivity to system capacity factor, consistent with previous studies discussed in the Introduction section. System GHG mitigation is the sum of a set of largely independent factors, and thus shows low sensitivity to any of the individual parameters tested.

3.3. Important factors affecting system performance

Our field observations suggest that good economic and GHG performance is possible in these gasifier power systems despite their relatively small scale, challenging feedstock material, and remote siting. However, we observed deviations from steady-state operation for an individual system (e.g., the standard deviation of the 'Rice husk consumption' parameter in Table 2) and differences in conversion product yields across the four systems studied (e.g., the 'Char yield' parameter in Table 1). This results in significant differences in overall system performance, particularly economic performance, as indicated by minimally- or non-overlapping confidence intervals in Figure 2. Despite this inter-system variability, all of the systems studied achieve net GHG mitigation, without inclusion of biochar indirect effects which could further increase GHG mitigation. Some companies have explored leveraging this favorable GHG performance for carbon financing to improve overall system financial viability [17], but associated transaction costs are only overcome once several dozen systems are aggregated [27]..

Gatti *et al.* [27] found a similar variability in performance across their survey of rice husk gasifiers systems in Cambodia. We speculate that these performance differences might be attributable to site-specific variations in equipment sizing and configuration (particularly the biomass feeding system), moisture content of the feedstock (affected by storage method), and the technical skill and intention of the operators (e.g., attention to equipment maintenance schedules). Additional data collection and analysis is necessary to positively identify and control these sources of variability.

For an individual system, comparing continuous measurements of reactor temperature profile, system pressure drops, and end loads may facilitate the identification of specific operating conditions and operator practices that correlated with better or worse system performance. However, a relatively high degree of instrumentation would be required to fully assess the system mass and energy balance on a continuous or semicontinuous basis, which would be expensive and difficult to implement in most settings. When comparing multiple systems, diesel equivalence (the amount of diesel fuel consumption avoided per unit of feedstock mass consumed, see Table 1) is probably the best performance indicator to use, as it is relatively straightforward to measure and interpret.

3.4. Potential contribution to rural electrification

Distributed rice residue energy systems are potentially very attractive for sustainable development in Cambodia [26]. The country has a low per capita income [25], Energy Development Index [45], and electrification rate [46] compared to its neighbors. Across the country, more that 10,000 villages (76% of total) lacked access to the national electric grid as of 2010 [25]. Per-capita electricity use is the lowest in the region, and diesel fuel prices the highest [47]. However, waste biomass from rice cultivation is abundant, as rice covers ~85% of Cambodian cultivated land and total production has more than quadrupled from 1994 to 2014 [48]. Despite this, rice yields are still relatively low in many regions, and credit limitations prevent many farmers from investing in fertilizer and irrigation [49,50]. The combination of high energy prices, wide biomass availability, and an under-capitalized agricultural sector all contribute to the attractiveness of value-adding bioenergy production.

The government of Cambodia has targeted greatly expanding electricity access over the next 15 years through a combination of grid expansion and distributed power systems based on renewables [25,26]. Distributed gasification systems could make an important contribution here as they are estimated to be more economical than photovoltaic systems or grid expansion when loads are low and distance from the existing grid high [31]. In addition, such systems could reduce demand for hydropower production on the Mekong River and its tributaries, which often has negative repercussions for biodiversity and food security [51,52].

The energy needs of our case study mills were met using less than half of the total husk they generate, so there is potential for expanding gasification system capacity and distributing the additional electricity generated to local homes through a rural electrification enterprise (REE) scheme, as described by Gatti *et al.* [27]. Previous analyses suggest that rice mill base load and residential consumer demand are highly complementary, with the addition of consumer service in the afternoon and evening greatly increasing the overall system capacity factor [17,26]. Applying our assessment numbers to data on the Cambodian rice sector and electricity usage from Pode *et al.* [26] we estimate that if all rice husk produced in the country were used for electricity generation and the balance after powering the mill distributed via REEs it would more than double current national electricity consumption outside the capital city. This is equivalent to providing electricity access to an additional 3.8 million individuals (25% percent of total population) at 2011 – 2015 average consumption levels [47], potentially doubling the fraction of the population with access to high-quality electricity supply as has been suggested previously [53]. Rice straw is an even more plentiful potential feedstock material [17] that currently presents disposal challenges in many areas. While this material incurs additional collection, transport, and size reduction burdens [8], it is attractive for its lower ash content and higher heating value.

Workforce training might become a barrier to this expansion of distributed gasification systems, which would require on the order of 6,000 new workers. Gatti et al. estimated that only 48% of mill operators have a complete knowledge of the workings of the mill, and that training for gasification system operation has been inconsistent [27]. To the extent that environment and economic performance of such systems is a function of operator skill (see section 3.3 above) workforce training becomes an essential element of the sustainable diffusion of the technology.

3.5. Sustainability challenges

Despite the positive assessment results reported here, a number of system sustainability concerns must be addressed before more widespread adoption of this technology can be recommended — a point recognized by many Cambodian mill owners themselves [27]. Environmental and health issues related to toxic elements or substances in the biochar, sludge, wastewater, and the air at the plant were analyzed by Shackley *et al.* [38], Gatti *et al.* [27], and Shackley [54]. The biochar was found to contain very low concentrations of toxic elements and organic compounds, and its use as a soil amendment would probably be possible under U.K. regulations. A switch to dry ash/char removal [27] would likely reduce both biochar contamination even further, as well as the overall volume of sludge produced. However, crystallization of the silica in rice husk may lead to significant formation of nanoparticles of quartz or cristobalite, toxic respiratory hazards [38,55], though additional research is needed to fully quantify the exposure potential [56].

Considerable concentrations of both BTEX (benzene, toluene, ethylbenzene, and xylene) and PAH (polycyclic aromatic hydrocarbon) compounds were identified in wastewater and settling pond sludge, making the regulated containment and disposal of these byproducts necessary (leakage or dumping into the local environment is currently widespread) [54]. Wastewater treatment options do exist (e.g., [18]) and have shown capability for removing problematic organic pollutants [27], though the associated costs are high [57] given the large volume of water needing treatment relative to the size and cost of the gasification system itself. Alternately, a switch to dry tar removal systems and re-processing of organic filter media could potentially eliminate the problem [27,58], though real-world experience with such systems is limited.

Finally, while agriculture residues are typically considered a waste material, rice husk is often put to productive uses, for example as fuel in brick kilns or household cookstoves, or as animal litter [9,25,26]. Studies across other agricultural areas in the region suggest that anywhere from 1/3 to 3/4 of existing rice husk is put to productive use [8,9,29], as detailed in Appendix C. The environmental benefits of gasification for power production would be reduced if diversion of husk to this high-value use caused existing husk users to switch to other less sustainable biomass feedstocks [34], introducing a leakage effect analogous to indirect land use change [59]. However, such indirect effects were considered outside the scope of our assessment as they are fundamentally highly uncertain [60] and likely to vary at fine spatial scales, making extrapolation and generalization difficult. Future scale-up of this technology should ideally be accompanied by a regionally-specific analysis of current husk uses, and potentially by regulations or subsidies to ensure that any feedstock switching induced in other economic sectors is done in a sustainable manner.

If these remaining sustainability challenges can be addressed, our results suggest a huge potential for distributed thermochemical conversion systems using various agricultural residues to provide low-cost, low-carbon power to the agricultural sector and the community in rural areas.

4. CONCLUSIONS

Detailed empirical assessment of several rice husk gasification power systems at rice mills in rural Cambodia indicates significant performance variability between systems. Well-performing systems are highly profitable, avoid significant amounts of fossil fuel use, and mitigate GHG emissions. However, systems with low gas yields and biochar recovery rates are likely economically marginal. This study expands the limited existing model-based assessment literature, grounding our understanding of technology performance in empirical observations with rigorous uncertainty propagation. We also explore potential drivers of the observed performance variability, and the potential benefits of and ongoing sustainability barriers to more widespread diffusion of this technology.

5. ACKNOWLEDGEMENTS

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Appendix A. Carbon and mass balance calculations

While a total of six SME Renewable Energy systems were visited, a variety of logistical or practical difficulties precluded the collection of a full suite of measurements of all system inputs and outputs for most sites (Table A1). Our measurements suggest that the site with the most complete data (Y.L.) was performing significantly better than the other sites assessed, replacing more diesel fuel consumption per unit of husk consumed while producing less sludge and more char. In order to get a more representative view of system performance we decided to approximate a full mass and energy balance for each additional system for which measurements of diesel fuel consumption, husk consumption, and char production rates were available (the K.M., Y.P, and C.K. systems), making assumptions about sludge production or engine efficiency as necessary to complete the balances. Though mass and energy balances could not be completed for the E.S. and C.M.

systems, we combined the measurements of tar output from those sites with that from the Y.L. site to estimate a tar production rate and uncertainty bounding for use in the K.M., Y.P, and C.K. systems.

Table A1. System measurement completion matrix.

System	**Date visited**	**Fuel use?**	**Husk input?**	**Char output?**	**Tar output?**	**Power output?**	**Mass balance?**	**Notes**
K.M.	2010/6/17	X	X	X	-	-	X	-
Y.P.	2010/6/18	X	X	X	-	-	X	Translation error likely on tar output; dismissed as an outlier
E.S.	2010/6/20	-	-	-	X	-	-	Automatic husk feed precluded mass balance estimation
C.K.	2010/6/22	X	X	X	-	-	X	-
Y.L.	2010/6/23	X	X	X	X	X	X	Only electric-only system visited
C.M.	2010/6/24	-	X	X	X	-	-	Visit shortened by inclement weather

The carbon balance for an individual system starts from the following steady-state equation:

1) $$\sum_{inputs} \dot{m}_i C_i = \sum_{outputs} \dot{m}_j C_j$$

where $\dot{m}_i$ denotes the mass flow rate of various system inputs i, C_i the associated carbon mass fraction of that input, and the subscript *j* denoting the various system outputs. Adapting this to the gasification system (including gas cleanup) and engine gives:

2) $$\dot{m}_{husk}C_{husk} = \dot{m}_{gas}C_{gas} + \dot{m}_{char}C_{char} + \dot{m}_{sludge}C_{sludge}$$

3) $$\dot{m}_{gas}C_{gas} + \dot{m}_{diesel,DFM}C_{diesel} = \dot{m}_{exh,DFM}C_{exh,DFM}$$

where the subscript *DFM* denotes dual-fuel mode and *exh* engine exhaust. A generalized energy balance for an engine or similar system can be written as follows, assuming inputs at reference temperature and pressure and exhaust to ambient pressure:

4) $$\sum_{inputs} \dot{m}_i LHV_i = \dot{W} + \dot{Q} + \sum_{outputs} \dot{m}_j LHV_j$$

where $\dot{W}$ is the rate of work done by the system (power output), $\dot{Q}$ the sum of all heat losses through cooling systems, exhaust, surface radiation, etc., and *LHV* the lower heating value of each substance. Adaptation to the gasifier (*G*) and engine (*E*) systems gives:

5) $$\dot{m}_{husk}LHV_{husk} = \dot{Q}_G + \dot{m}_{gas}LHV_{gas} + \dot{m}_{char}LHV_{char} + \dot{m}_{sludge}LHV_{sludge}$$

6) $$\dot{m}_{gas}LHV_{gas} + \dot{m}_{diesel,DFM}LHV_{diesel} = \dot{W}_E + \dot{Q}_E + \dot{m}_{exh,DFM}LHV_{exh,DFM}$$

Assuming constant load and engine efficiency under both diesel and dual-fuel operation:

7) $$\dot{m}_{diesel,DM}LHV_{diesel} = \dot{m}_{gas}LHV_{gas} + \dot{m}_{diesel,DFM}LHV_{diesel}$$

where *DM* denotes diesel mode. Most mass flows, carbon contents, and LHV values were estimated through the previously-described measurements or from secondary sources (see Table 2). However, five parameters ($\dot{m}_{gas},\ \dot{m}_{exh,DFM},\ \dot{m}_{sludge},\ \dot{Q}_E,\ and\ \dot{Q}_G$) could not be measured or estimated directly, but rather were determined by solving the system of equations 2, 3, 5, 6, and 7.

Appendix B. System performance details

B.1. System characteristics

Operational characteristics and selected monitoring results for the four systems for which carbon balances were constructed are presented in Table 1. All four gasifiers were established at rice mills of medium capacity (1.5 to 3 tons of unprocessed paddy rice per hour), for which an average specific mechanical energy consumption of 166 (17 SD) MJ (Mg paddy)$^{-1}$ was observed consistent with a previous estimate of hulling systems in India [30] but about 1.5 and 2 times the reported mill average for neighboring Thailand [20] and Vietnam [29], respectively. Valuation of rice husk and biochar varied by region; mill owners in the western part of the country where rice cultivation is widespread (i.e., Y.P., C.K., Y.L.) reported that there were no markets for biochar and limited markets for husk, whereas those in less agriculturally-intense areas to the east (i.e., K.M.) could sell husk to brick kiln operators as fuel, or either material back to farmers as a soil amendment.

Operating these systems in dual-fuel mode consumed 27 – 43% of the husk byproduct generated during the milling process and reduced engine diesel consumption by 69 – 83%, consistent with the range reported by Dasappa *et al.* [18]. The measured DRR corresponded to a fuel equivalence of 0.12 – 0.19 L diesel per kg husk. In the Y.L. system where the diesel engine was coupled to a generator, rice husk is converted to electricity at a rate of 0.66 kWh (kg husk$)^{-1}$, somewhat higher than the assumption used in previous assessments [25,26]. Biochar recovery rates varied widely, from 0.1 to 0.4 kg per kg of raw husk feedstock, with the highest rate observed at a system with a noticeably finer char screen and a much lower estimated settling pond sludge volume (data not shown), suggesting that char fines are often a primary constituent in the sludge.

B.2. Rice husk and biochar properties

A single sample of rice husk and biochar was collected from each system and shipped to the International Rice Research Institute (Los Baños, Philippines) and gravimetrically assessed for moisture content to adjust the mass measurements described above, as detailed in Table B2. Sub-samples of the dried materials were subject to elemental analysis to determine losses of C, N, P, and K during the gasification process. C and N were measured using a dry combustion method, and P and K concentrations were determined using inductively coupled plasma emission spectrometry after nitric/perchloric acid digestion. Additional sub-samples were pooled and a single measurement made for higher heating value (HHV) with bomb calorimetry by the Philippine Department of Science and Technology. The HHV of rice husk was estimated at 13.9 MJ/kg, whereas the biochar test failed to combust; this parameter in our model was thus primarily informed by values from the literature (Table 2).

Chemical composition data are reported for rice husk and the resulting biochar in Table B3. For composition, average values and standard deviations across six samples (a single sample for each system visited) are reported. Estimated retention rates are calculated based on average composition of rice husk and biochar combined with average calculated husk yield across the four sites where mass balances could be calculated. The husk feedstock has 9.5% ash content and an alkali index of 0.28 kg/GJ, well past the threshold for which slagging could be expected to occur [16]. Raw rice husk and the resulting biochar have similar carbon and nitrogen content, but the biochar is enriched in K and especially P, with estimated retention rates of 45% and 85%, respectively. Thus, the gasification process preserves a significant portion of the husk nutrient content in a solid form that can be returned to the field.

Table B2. Moisture corrections for rice husk and biochar samples from the 6 systems visited (detailed in Appendix Table A1).

	K.M.	Y.P.	E.S.	C.K.	Y.L.	C.M.
Rice husk						
Sample wet mass (g)	50.61	81.58	57.12	79.97	71.06	55.04
Sample dry mass (g)	43.21	71.43	48.85	69.87	61.74	46.32
Moisture content (%)	14.6	12.4	14.5	12.6	13.1	15.8
Biochar						
Sample wet mass (g)	98.78	174.07	164.64	206.89	113.21	146.22
Sample dry mass (g)	27.4	44.53	36.27	48.01	32.7	33.51
Moisture content (%)	72.3	74.4	78.0	76.8	71.1	77.1

Table B3. Composition of rice husk and resulting biochar averaged across samples from the six sites, with estimated retention of various elements through the gasification process.

	C (%)	N (%)	P (%)	K (%)
Rice husk	38.3 (1.24)	0.492 (0.06)	0.030 (0.007)	0.313 (0.090)
Biochar	34.3 (4.25)	0.453 (0.035)	0.095 (0.013)	0.530 (0.072)

Retention fraction	0.24	0.24	0.85	0.45

B.3. Producer gas and engine exhaust characterization

Samples of producer gas and diesel engine exhaust were collected in triplicate during both diesel and dual-fuel operation of the Y.L. system using 60 mL plastic syringes with long metal needles inserted directly into the producer gas flare line or diesel engine tailpipe, respectively, to determine chemical composition. Multiple samples were taken and purged just prior to final sample collection to minimize contamination. The collected samples were injected into 30 mL evacuated scintillation vials with septa and stored in the dark and when possible under refrigeration prior to analysis. Gas composition was measured using gas chromatography by Empact Analytical (365 S Main St., Brighton, Colorado, USA 80601).

Table B4. Composition of producer gas and engine exhaust in both diesel and dual-fuel modes. Shown are average values and standard deviations based on samples collected in triplicate at the Y.L. site.

	H_2	O_2/Ar	N_2	CO	CO_2	CH_4
	% (molar)					
Producer gas	11.6 (1.2)	2.9 (1.9)	54.6 (2.5)	18.0 (1.8)	10.0 (1.3)	2.5 (0.3)
Exhaust, dual-fuel mode	0.2 (0.01)	8.9 (0.3)	80.4 (0.3)	0.5 (0.04)	9.9 (0.2)	0 (0.01)

Exhaust, diesel mode	0 (0.04)	12.7 (0.3)	82.0 (0.3)	0 (0.0)	5.2 (0.1)	0 (0.01)

Chemical composition of producer gas and engine exhaust from both diesel and dual-fuel mode operation are shown in Table B4. The measured producer gas composition suggests a heating value of 4.8 MJ/m^3, in line with typical values [18,31]. The exhaust gas composition data hints at increases in products of incomplete combustion under dual-fuel operation, though more extensive sampling would be necessary to fully quantify impacts on NO_X, particulates, and other air pollutants.

Appendix C. Existing uses of rice husk

Current rice husk utilization rates and surpluses have been evaluated several times in this region, as summarized in Table C1 below. Junginger et al. looked at neighboring northeastern Thailand and estimated that 1/2 to 3/4 of total husk produced was put to use in brick making, noodle factories, or used as animal bedding or soil amendment, at a typical price of 1.70 – 10.00 USD Mg^{-1} [8]. The authors concluded that these high usage rates and relatively high costs present a challenge to bioenergy system development. Dang et al. conducted a detailed survey of energy demand and biomass use across more than 100 enterprises in the Mekong Delta region of Vietnam and found that 72% of rice husk production was consumed in brick kilns, rice driers, and household use, with a typical husk price of 6.40 USD Mg^{-1} [29]. They estimate that supply is ample for biomass-based power generation at prices lower than that for grid-based power. In contrast, Mai Thao et al. focused on the same region and found that cooking and brick-making likely consumed only 1/3 of rice husk supply [9]. Since the surplus husk is typically open-burned or dumped in canals, they suggest its diversion to bioenergy production as a strategy for limiting air pollutant and GHG emissions from disposal. Taken together, all three studies suggest that surplus rice husk exists in the region, though the fraction may range anywhere from 1/4 to 2/3 of total rice husk production.

Table C1. Estimates of productive use of rice husk in southeast Asia.

Study	Region	Typical price (USD Mg^{-1})	Industry use fraction[1]	Household/ farm use fraction[2]	Estimated surplus
Junginger et al. [8]	Northeastern Thailand	1.70 – 10.00	0.5 – 0.75		0.25 – 0.5
Deng et al. [29]	Mekong Delta, Vietnam	6.40	0.45	0.27	0.29
Mai Thao et al. [9]	Mekong Delta, Vietnam	-	0.09	0.26	0.66

[1] Includes rice drying or milling, brick-making, noodle factories

[2] Includes cooking, alcohol production, animal feed or bedding, soil amendment

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7. FIGURE CAPTIONS

Figure 1. Schematic showing material and energy flows for a SME Renewable Energy rice husk gasification power system. For a detailed technical scheme, see Shackley et al. 2012 [38].

Figure 2**Error! Reference source not found.**. Performance of individual systems. A) Estimated GHG mitigation and 5-year net present value for the four systems for which carbon and energy balances could be constructed. B)**Error! Reference source not found.** Measured dual-fuel mode diesel replacement rates and estimated gasifier efficiencies. Error bars show 90% confidence intervals based on model Monte Carlo analysis, or simple propagation of instrument limit of error in the case of DRR.

Figure 3. Carbon (A) and energy (B) balances for the C.K. rice mill gasification power system operating in dual-fuel mode.

Figure 4. Individual source contributions to total greenhouse gas mitigation (left bar and axis) and annual costs & revenues (right bar and axis) for the C.K. system.

Figure 5. Sensitivity of system gasifier efficiency, net present value, and net lifecycle greenhouse gas abatement to various model parameters, expressed as percent change in system performance relative to a 1% increase in the model parameter value.

8. TABLES

Table 1. System characteristics and operational parameters for all four gasification systems modeled.

Parameter	**Units**	K.M.	Y.P.	C.K.	Y.L.
Facility characteristics					
Mill capacity	t paddy h^{-1}	2	1.5	2	3
Husk production[a]	kg h^{-1}	0.4	0.3	0.4	0.6
Gasifier system capacity	kW_e	200	200	200	300
Engine make	-	Hino V22	Mitsubishi D90A	Hino V22	Hino V25
Husk storage	-	covered	covered	open	covered
Husk valuation?	-	yes	no	no	yes
Char valuation?	-	yes	no	no	no
Operation measurements					
Diesel mode diesel consumption	L h^{-1}	25.8	17.6	29.4	36.8
Dual-fuel mode diesel consumption	L h^{-1}	8.0	4.1	5.2	6.3
Dual-fuel mode husk consumption	kg h^{-1}	150.6	104.2	170.5	164.7
Generator output[b]	kW_e	n.a.	n.a.	n.a.	131.1
Performance summary					
Diesel equivalence	L (kg husk)$^{-1}$	0.12	0.13	0.14	0.19
Electricity yield	kWh (kg husk)$^{-1}$	-	-	-	0.66
Char yield	kg (kg husk)$^{-1}$	0.10	0.28	0.22	0.40
Fraction of husk used	%	38	35	43	27

[a] assuming paddy is 20% husk by mass

[b] not available for purely mechanical systems

Table 2. Representative model parameters used for the C.K. system.

Parameter	**Units**	**Distribution**	**Values**[a]	**Source**
Specific to C.K. system				
Dual-fuel mode diesel consumption	L hr^{-1}	Normal	5.18 (0.13)	Measurement, with error propagation based on instrument limit of error
Rice husk consumption	kg husk (hr)$^{-1}$	Normal	171 (39)	Measurement, with variability based on repeated measures (n=3) at Y.L. system
Char yield	kg (kg husk)$^{-1}$	Normal	0.22 (0.04)	Measurement, with variability based on repeated measures (n=3) at Y.L. system
Sludge yield	kg (kg husk)$^{-1}$	Normal	0.28 (0.15)	Approximation based on measurements from E.S., Y.L., and C.M. systems (Table A1)
Same for all systems modeled				
Engine efficiency	-	Normal	0.36 (0.01)	Monte Carlo analysis of Y.L. diesel mode energy balance[b]
Rice husk LHV (wet basis)	MJ (kg husk)$^{-1}$	Triangle	10.7/10.9/13.3	Central estimate from measurement, range from [9]
Sludge LHV	MJ (kg sludge)$^{-1}$	Triangle	6.3/23.3/40.2	Assuming sludge a 3/4 char, 1/4 aromatic hydrocarbon (naphthalene) mix
Husk opportunity cost	USD (Mg husk)$^{-1}$	Triangle	3.00/7.50/16.45	Based on one estimate from SME Renewable Energy and two reported by system owners. Set to zero for western systems (Y.P., C.K., Y.L.)
Char price	USD (Mg char)$^{-1}$	Triangle	2.18/5.45/11.94	Re-scaling of husk opportunity cost based on the mean of one system owner estimate and two estimates reported by [27]
Diesel price[c]	USD L^{-1}	Normal	0.96 (0.26)	Based on one estimate from SME Renewable Energy and two from [27]

Electricity price	USD kWh^{-1}	Normal	0.29 (0.08)	Based on one estimate from [26] and two from [27]
Capital costs	USD	Uniform	60,000 – 80,000	Range provided by SME Renewable Energy[d]
Annual maintenance costs	USD y^{-1}	Uniform	0 – 3,200	Range reported in [27]
Labor rate	USD day^{-1}	Uniform	2.00 – 4.50	Based on one estimate from SME Renewable Energy and one from [27]
Capacity factor	h operation (y)$^{-1}$	Uniform	2,030 – 2,700	Based on one estimate from [26] and one from [27]
Husk fraction otherwise burned	-	Uniform	0.04 – 0.17	Based on responses from mill owners and [27]
Husk fraction otherwise paddy dumped	-	Uniform	0 – 0.17	Based on responses from mill owners and [27]
Biochar stability	Fraction remaining after 100y	Normal	0.81 (0.12)	Based on estimates from [11,23,61]
Open-burning particulate emissions rate[e]	g (kg husk)$^{-1}$	Normal	12.2 (3.5)	Average of four sources [14,62–64]

[a] For uniform distributions, total range. For triangular distributions, minimum, peak, and maximum values. For normal distributions, mean and standard deviation.

[b] Assuming same efficiency for all systems.

[c] Wholesale price paid by mill owners, not consumer pump price.

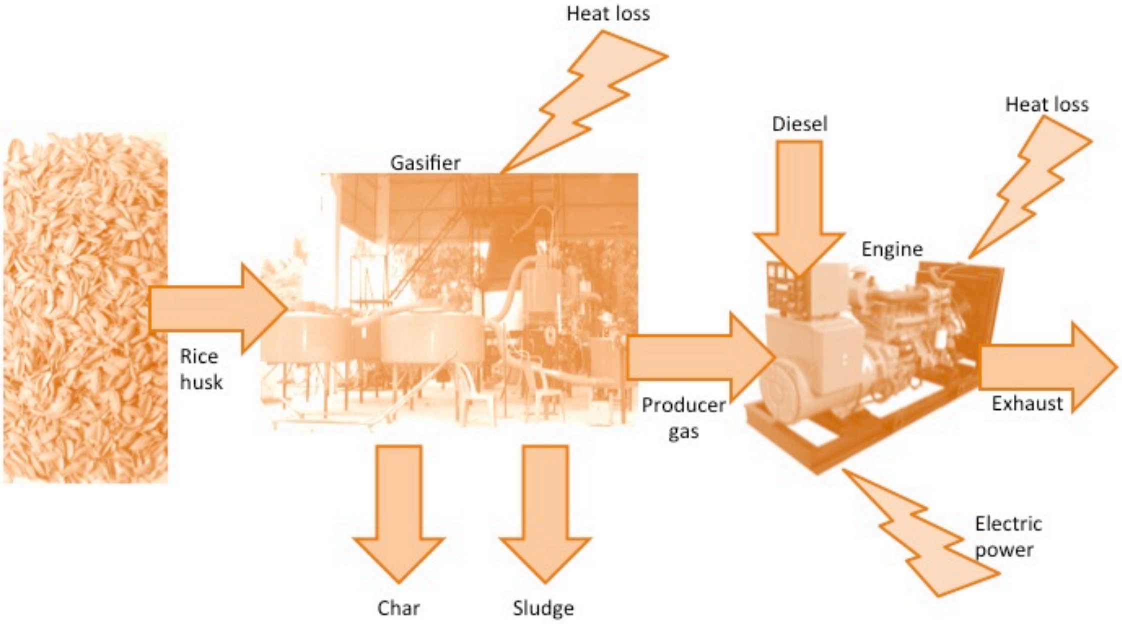
[d] Per-kW gasifier capital costs reported by [17,25,27,28,31] vary widely by manufacturer and scale, so no attempt is made to supplement the range reported by SME Renewable Energy.

[e] Emissions factors for CH_4 and N_2O compiled from same sources, but not shown.

Table 3. Summary of financing and annual profitability for the four systems

Parameter	**Units**	**Values**			
Financial details – same for all systems					
Total system capital cost	USD	70,000			
Fraction of total costs financed	%	70			
Owner down payment	USD	21,000			
Loan APR	%	13			
Loan duration	months	60			
Yearly loan payment total	USD (y)$^{-1}$	13,400			
System-specific results		**K.M.**	**Y.P.**	**C.K.**	**Y.L.**
Annual net revenue	USD (y)$^{-1}$	26,500	19,100	43,400	57,800
Annual profit	USD (y)$^{-1}$	13,100	5,800	30,000	44,400
5-year net present value, 15% discount rate	USD	22,900	-1,700	79,600	127,900

891 ## 9. FIGURES



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893 Figure 1.

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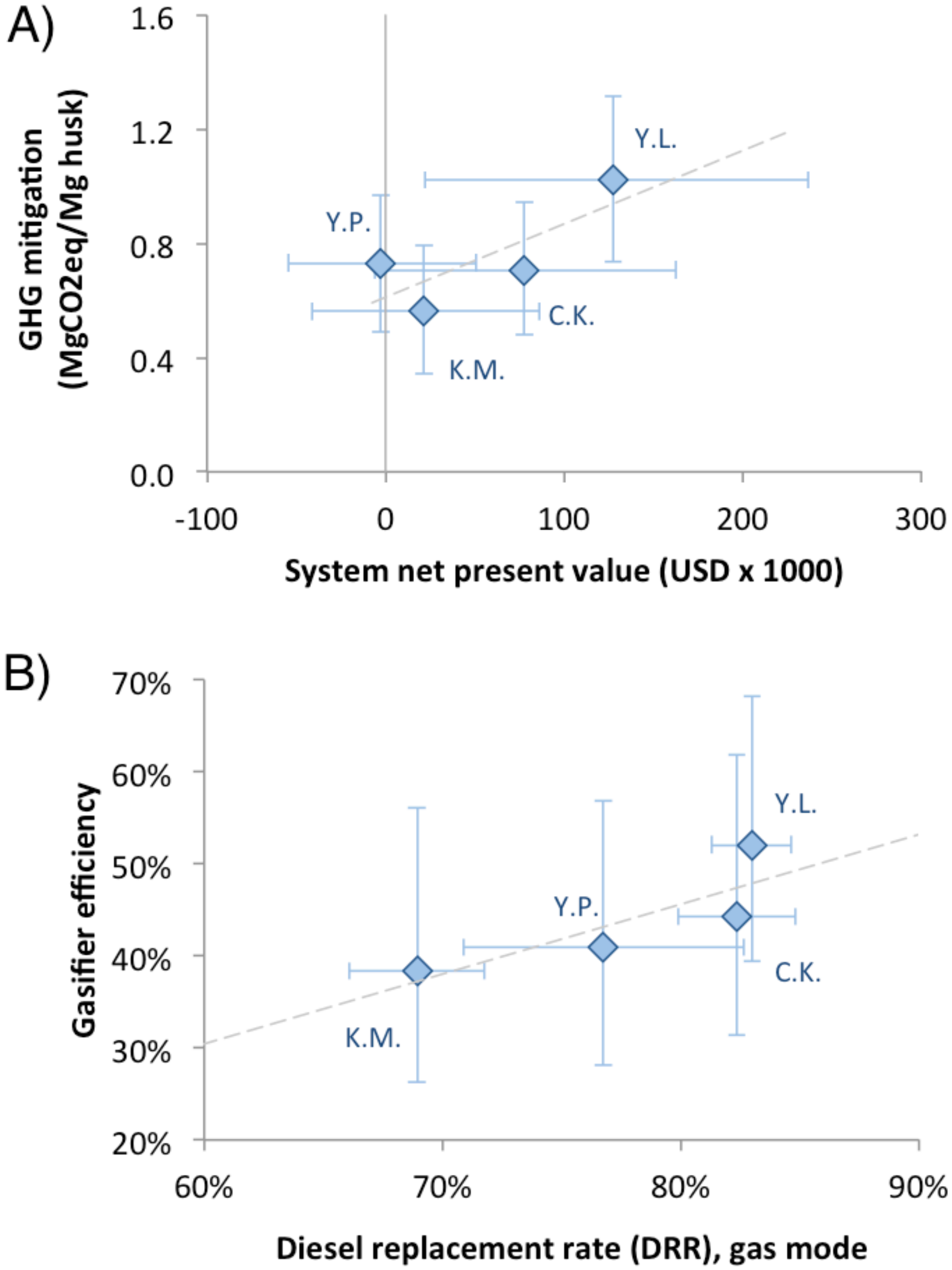

A)
GHG mitigation (MgCO2eq/Mg husk)
1.6
1.2
0.8
0.4
0.0
-100
0
100
200
300
System net present value (USD x 1000)
Y.L.
Y.P.
C.K.
K.M.
B)
Gasifier efficiency
70%
60%
50%
40%
30%
20%
60%
70%
80%
90%
Diesel replacement rate (DRR), gas mode
Y.L.
Y.P.
C.K.
K.M.

Figure 2.

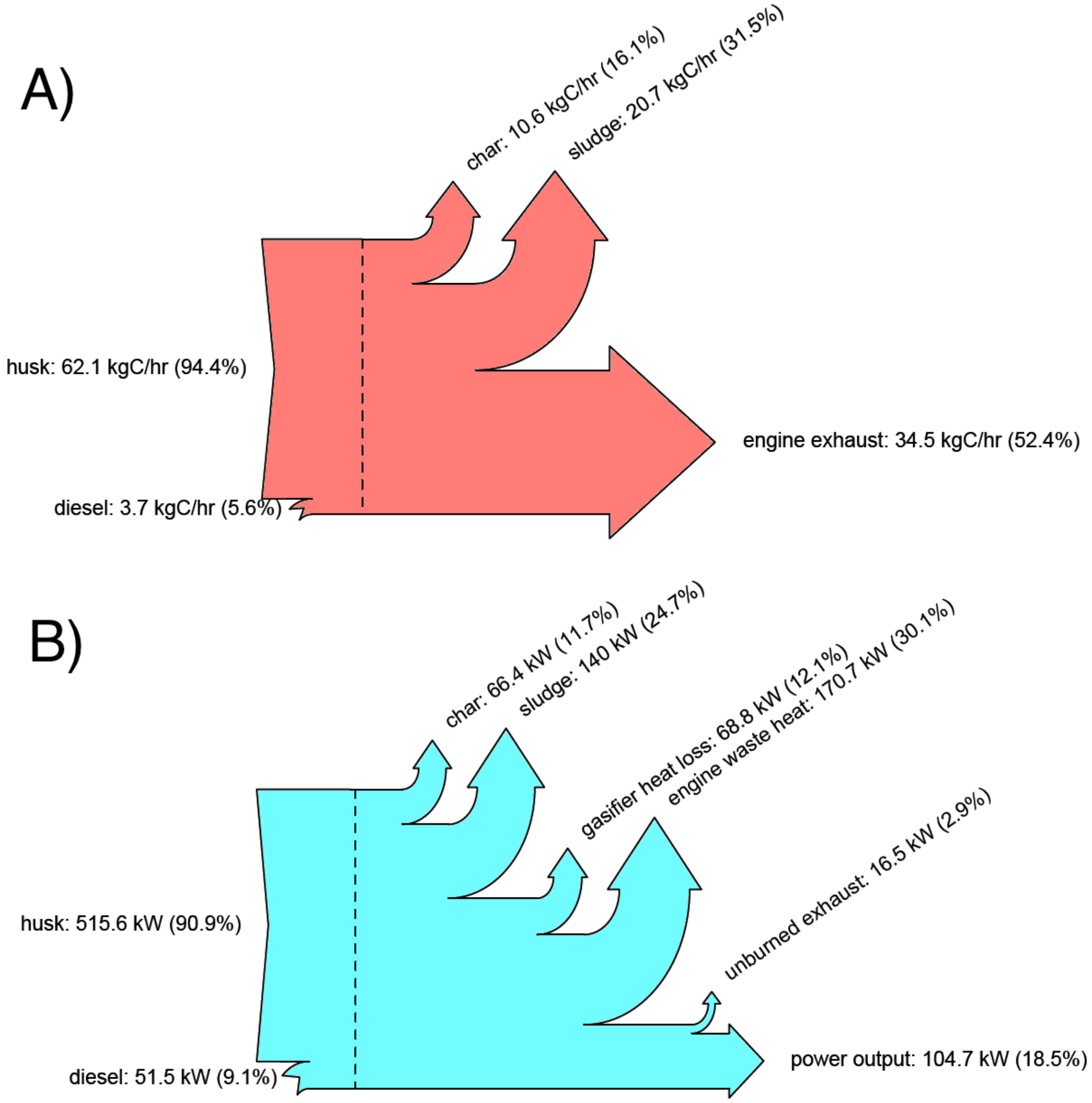
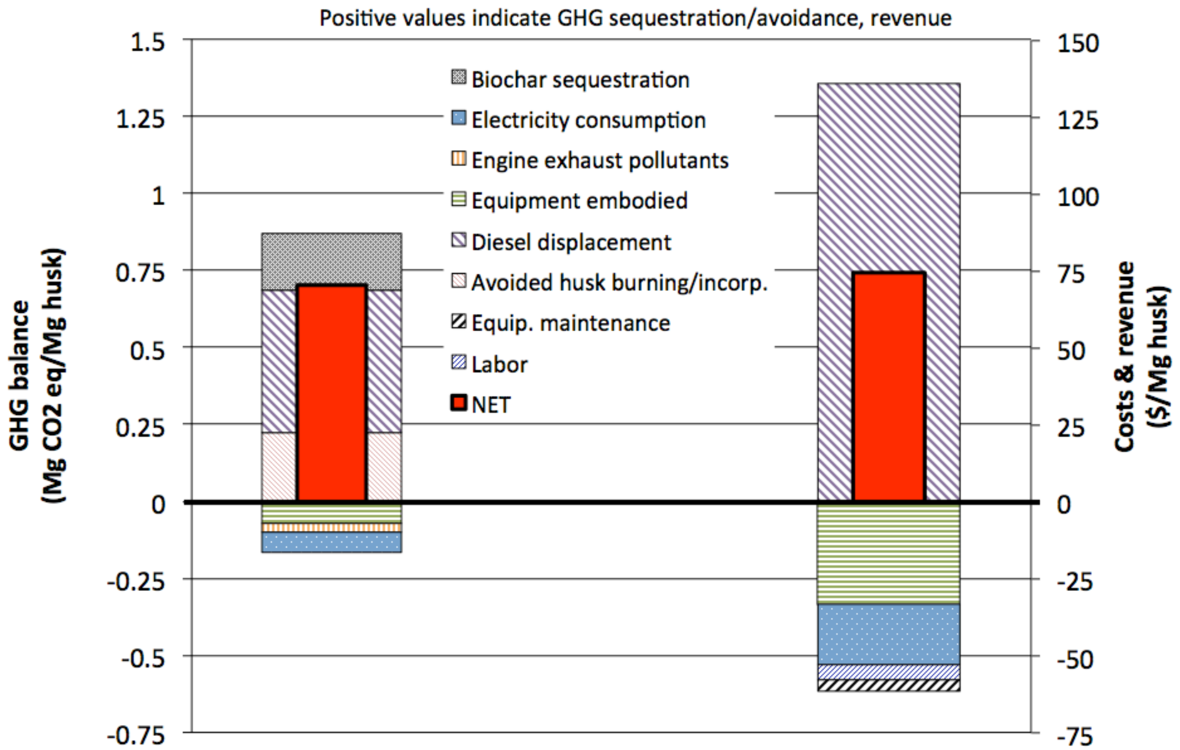

A)
char: 10.6 kgC/hr (16.1%)
sludge: 20.7 kgC/hr (31.5%)
husk: 62.1 kgC/hr (94.4%)
engine exhaust: 34.5 kgC/hr (52.4%)
diesel: 3.7 kgC/hr (5.6%)
B)
char: 66.4 kW (11.7%)
sludge: 140 kW (24.7%)
gasifier heat loss: 68.8 kW (12.1%)
engine waste heat: 170.7 kW (30.1%)
unburned exhaust: 16.5 kW (2.9%)
husk: 515.6 kW (90.9%)
power output: 104.7 kW (18.5%)
diesel: 51.5 kW (9.1%)

Figure 3.

901 

902 Figure 4.

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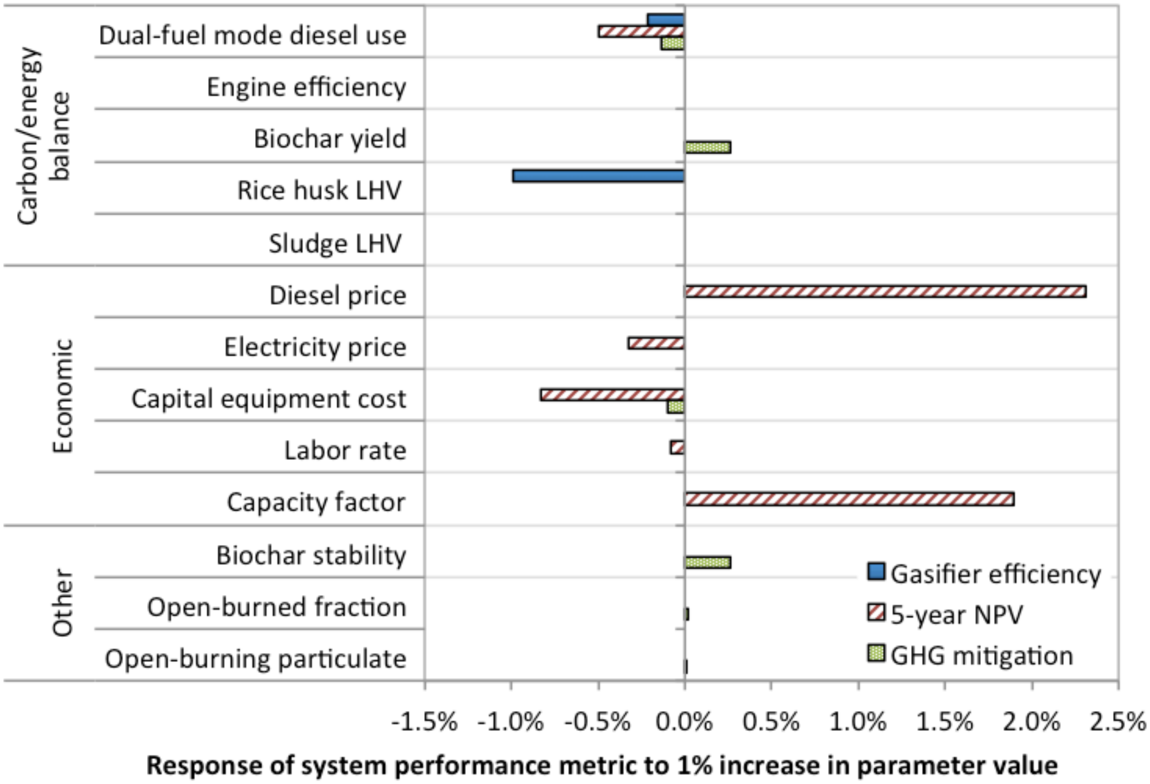

Carbon/energy balance
Dual-fuel mode diesel use
Engine efficiency
Biochar yield
Rice husk LHV
Sludge LHV
Economic
Diesel price
Electricity price
Capital equipment cost
Labor rate
Capacity factor
Other
Biochar stability
Open-burned fraction
Open-burning particulate
Gasifier efficiency
5-year NPV
GHG mitigation
-1.5%
-1.0%
-0.5%
0.0%
0.5%
1.0%
1.5%
2.0%
2.5%
Response of system performance metric to 1% increase in parameter value

Figure 5.