Applied Energy 177 (2016) 612–624

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

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

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HIGHLIGHTS

- Four operating small-scale distributed gasification power systems were observed.
- System carbon and energy balance, profitability, and GHG performance were assessed.
- Best systems mitigated >1 $MgCO_2eq$ (Mg feedstock)$^{-1}$ and recouped costs within a year.
- Wide variability in performance across systems; some likely un-profitable.

ARTICLE INFO

Article history:
Received 28 January 2016
Received in revised form 5 May 2016
Accepted 14 May 2016

Keywords:
Rice husk
Gasification
Biochar
Rural electricity enterprise
Lifecycle assessment
Sustainable development

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.

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 above-ground 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

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http://dx.doi.org/10.1016/j.apenergy.2016.05.100
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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 than 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