Applied Energy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Techno-economic and greenhouse gas savings assessment of decentralized biomass gasification for electrifying the rural areas of Indonesia

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HIGHLIGHTS

- The feasibility of decentralized gasification systems in Indonesia was explored.
- Two decentralized scenarios each were proposed for a village and palm oil mill, respectively.
- The global warming impact was evaluated using life cycle analysis (LCA).
- The economic feasibility was evaluated using cost-benefit analysis (CBA).
- The village and mill systems save up to 7700 g $CO_{2\text{-eq}}$/kWh and 5.8×10^4 tons $CO_{2\text{-eq}}$/year.

ARTICLE INFO

Keywords:
Biomass gasification
Biochar
Life cycle assessment
Cost-benefit analysis
Decentralization

ABSTRACT

This study explored the feasibility of decentralized gasification of oil palm biomass in Indonesia to relieve its over-dependence on fossil fuel-based power generation and facilitate the electrification of its rural areas. The techno-feasibility of the gasification of oil palm biomass was first evaluated by reviewing existing literature. Subsequently, two scenarios (V1 and V2, and M1 and M2) were proposed regarding the use cases of the village and mill, respectively. The capacity of the gasification systems in the V1 and M1 scenarios are determined by the total amount of oil palm biomass available in the village and mill, respectively. The capacity of the gasification systems in the V2 and M2 scenarios is determined by the respective electricity demand of the village and mill. The global warming impact and economic feasibility (net present value (NPV) and levelized cost of electricity (LCOE)) of the proposed systems were compared with that of the current practices (diesel generator for the village use case and biomass boiler combustion for the mill use case) using life cycle assessment (LCA) and cost-benefit analysis (CBA). Under the current daily demand per household (0.4 kWh), deploying the V2 system in 10^4 villages with 500 households each could save up to 17.9 thousand tons of $CO_{2\text{-eq}}$ per year compared to the current diesel-based practice. If the electricity could be fed into the national grid, the M1 system with 100% capacity factor could provide yearly GHG emissions mitigation of 5.8×10^4 ton $CO_{2\text{-eq}}$, relative to the current boiler combustion-based reference scenario. M1 had a positive mean NPV if the electricity could be fed into the national grid, while M2 had a positive mean NPV at the biochar price of 500 USD/ton. Under the current electricity tariff (ET) (0.11 kWh) and the biochar price of 2650 USD/ton, daily household demands of 2 and 1.8 kWh were required to reach the break-even point of the mean NPV for the V2 system for the cases of 300 and 500 households, respectively. The average LCOE of V2 is approximately one-fourth that of the reference scenario, while the average LCOE of V1 is larger than that of the reference scenario. The average LCOE of M1 decreased to around 0.06 USD/kWh for the case of a 100% capacity factor. Sensitivity analysis showed that the capital cost of gasification system and its overall electrical efficiency had the most significant effects on the NPV. Finally, practical system deployment was discussed, with consideration of policy formulation and fiscal incentives.

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http://dx.doi.org/10.1016/j.apenergy.2017.10.001
Received 28 June 2017; Received in revised form 8 September 2017; Accepted 1 October 2017
0306-2619/

1. Introduction

Bioenergy technologies have a great potential to help resolve urgent global challenges, such as lack of effective waste management and disposal, climate change, and energy and resource depletion. Extensive development of bioenergy systems has occurred in recent years, and a wide variety of systems have been proposed, with the aim of sustainably processing various biomass types and benefitting users of different social-environmental backgrounds.

For example, willow chips were converted into bioethanol via enzyme-catalyzed hydrolysis and fermentation, and electricity was generated using a biomass-fired integrated gasification combined cycle technology, both of which had more favorable environmental and energy performance than conventional fossil fuel-based energy sources [1]. Crop residue-based gasification systems feature significant climate change mitigation benefits and short climate impact mitigation periods [2–4]. Rice straw was converted into syngas (also known as producer gas) via gasification for the synthesis of dimethyl ether, which can be used as automotive fuel for diesel engines and a liquefied petroleum gas supplement for household applications [5]. Mazzola et al. [6] showed that utilizing woody biomass-based gasification could effectively reduce the levelized cost of electricity (LCOE) of isolated microgrids by 38%, relative to diesel engine-based systems. The greenhouse gas (GHG) emissions of cornstalk biomass briquette fuel was shown to be a full order of magnitude lower than that of coal in China [7].

Indonesia is the largest energy consumer in Southeast Asia (SEA), accounting for 36% of the region's energy consumption [8]. Currently, over 90% of electricity produced in Indonesia comes from fossil fuels, with coal accounting for over 50% [9], making Indonesia one of the largest greenhouse gas GHG emitters in the world. The Indonesian government plans to reduce the country's dependence on fossil fuels by increasing the share of renewable energy sources in the primary energy mix, which would contribute to reduce its GHG emission by 26% below the business-as-usual BAU value [9,10].

Apart from its environmental concerns related to electricity generation, Indonesia has also experienced great difficulty in expanding its current national grid and related energy services to remote rural areas, largely due to its archipelago geography and forested countryside. Low population density and electricity demand, along with low paying capacity of rural residents, make the long-distance transmission of centralized electricity prohibitively expensive [11]. As a result, there were still over 10 million households without access to electricity in 2016 [12]. Decentralized power generation therefore represents perhaps the best solution to the country's rural electrification dilemma. This decentralization could be accomplishe by transmitting electricity from distributed energy resources to surrounding households via "mini-grids". Such decentralized systems are particularly suitable in the use cases of remote, mountainous villages where electricity access is a central economic and social issue [13]. However, for the electrification of rural areas, power generation systems based on the fossil fuels are generally less economically feasible than those based on renewable energy resources [14]. Overall, decentralized renewable energy systems should therefore be proposed for electrifying rural areas.

Indonesia has the highest biomass energy potential in the SEA region, with oil palm biomass being the dominant biomass source [15]. The country produces more palm oil than any other nation, accounting for 52% of global production in 2012–2013 [16]. Gravimetrically, only 10% of a palm tree will be converted to oil products, while the rest of a tree becomes waste biomass [17]. Solid oil palm biomass waste includes oil palm fronds and trunk (OPF and OPT), produced from pruning and felling during field plantation operations, as well as empty fruit bunches (EFB), palm kernel shells (PKS), and palm mesocarp fibers (PMF), generated as a byproduct of the palm oil production process in mills. This oil palm biomass has not been fully utilized for power generation, and the current biomass waste combustion-based method of power generation causes problems typical to biomass combustion, such as considerable air pollutant emissions and limited energy efficiency. Biomass gasification is an environmentally friendly alternative for power generation from oil palm biomass. Prior studies (*e.g.,* Ariffin et al. [18], Atnaw et al. [19], Guangul et al. [20], Guangul et al. [21], Ogi et al. [22]) have shown that oil palm biomass has a great potential as feedstock for gasification for energy production. Moreover, gasification is suitable for small-scale decentralized applications, which conforms well with the relatively small electricity demand for rural households [23,24]. Finally, biochar, a fixed carbon byproduct of the gasification process, can be used as a soil amendment to facilitate carbon sequestration and climate change mitigation [25].

Environmental and economic evaluation must be conducted prior to the deployment of energy systems in order to consider the needs of various stakeholders, including policymakers, private investors, and end users. First, policymakers are interested in the environmental benefits (*e.g.* GHG mitigation) of the system relative to existing processes, which can be estimated through life cycle assessment (LCA). Second, investors desire profitability, as their investment interests are dependent on the commercial viability of the system, as evaluated using cost-benefit analysis (CBA). Indeed, one of the major barriers to the success of existing decentralized bioenergy systems has been their commercial infeasibility [26]. Third, the electricity should be affordable to the end users, which is critical for the long-term viability of the project [27]. However, most of the existing studies evaluated the feasibility of decentralized bioenergy systems using only environmental or only economic criteria. There has yet to be a comprehensive study evaluating both the techno-economic feasibility and the environmental sustainability of bioenergy systems that are designed to address needs of all relevant stakeholders.

In this work, we study the potential of decentralized gasification systems in the disposal of oil palm biomass and the electrification of rural areas in Indonesia in terms of both their techno-economic feasibility and environmental sustainability. The techno-feasibility of the gasification technology is firstly reviewed based on existing studies. Then, two gasification-based system designs are proposed with respect to villages and mills and are compared with existing practices from environmental and economic perspectives using LCA and CBA, respectively. The conditions supporting commercial viability of gasification-based systems are identified. The practical deployment of the systems is also discussed.

2. Methodology

2.1. System and scenario design

This work considers a representative palm oil mill that is supported by 9000 ha (on average) of plantations, distributed throughout the surrounding villages [28]. The average population of a village was 1217 [29], while the average size of a household was 4.3 people [30], which suggests an average of *ca* 300 households per village. To consider the variation of household number, 300 and 500 households per village are considered and the whole village shares a single gasification system. According to the "PIR Trans" smallholder oil palm farming program, each household owns a 2-ha plot [31,32]. The production of oil palm biomass in Indonesia is summarized in Table 1. Sung [33] estimated

Table 1
Production of oil palm biomass in Indonesia [10].

	Oil palm biomass	Production (dry ton ha^{-1} yr^{-1})
Field biomass	OPF	11
	OPT	2.8
Mill processing biomass	EFB	1.6
	PKS	1.1
	PMF	1.7