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Greenhouse gas mitigation and rural electricity generation by a novel two-stroke biogas engine

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A B S T R A C T

Small-scale anaerobic digestion of wet organic wastes can make positive contributions to climate mitigation, energy security and nutrient cycling in agri-food systems. However, the environmental sustainability of small-scale anaerobic digestion is undermined where lack of capacity to utilize the biogas fuel results in biomethane venting to the atmosphere, contributing to climate change. Policy support for improved manure management in Bali, Indonesia, has resulted in the installation of small (6 m^3) anaerobic digesters across 752 Bali cattle breeding units. These 752 remote rural digesters annually vent approximately 75 482 ± 37 741 m^3 of biomethane into the atmosphere as a waste, owing to lack of practical means to convert this potential fuel into useful energy. Meanwhile, most of these cattle farms lack access to electricity. This paper describes the performance of a novel, compact and versatile "BioMiniGen" system that provides convenient electricity generation from small-scale biogas production. This innovative system comprises: (i) a simple biogas desulfurizing system; (ii) a two-stroke, single cylinder (63 cc) air-cooled engine; (iii) an electric generator; (iv) an optional CO_2 removal unit. Lifecycle assessment indicated that bioelectricity generated by the BioMiniGen would have a smaller environmental footprint than Indonesian grid electricity across 11 impact categories, including a negative global warming burden owing to avoidance of biogas venting. Trade-offs included a larger abiotic depletion burden associated with manufacture of the generators. Over a five-year lifetime, each unit, costing US$500, could generate up to 5971 kWh of electricity and mitigate up to 65.1 Mg CO_2 eq., with a greenhouse gas abatement value up to US$13023. Across Bali, up to 898 ± 449 MWh yr^{-1} bioelectricity could be generated, and 1.92 ± 0.96 Gg CO_2 eq. saved. Further pilot trials are needed to ascertain realistic biogas yields from cleaned digesters managed for bioenergy generation alongside manure management. BioMiniGen technology could make an important contribution to energy security for the 1.4 billion people globally who lack access to electricity.

1. Introduction

There is an urgent need to improve the energy security of rural populations in developing countries (Muhumuza et al., 2018), and to reduce anthropogenic greenhouse gas (GHG) emissions that drive climate change (Huppmann et al., 2019) in order to meet UN Sustainable Development Goals (UN, 2018). This study evaluates the potential environmental and energy security credentials of a novel, low-cost two-stroke engine coupled with a compact 750 W electricity generator designed to run on biogas ("BioMiniGen"). The BioMiniGen was developed by the main author of this paper in Bali, Indonesia, to utilize biogas from hundreds of small-scale anaerobic digesters deployed across the island's cattle farms (Nindhia et al., 2013; Surata et al., 2014).

1.1. Cattle farming in Bali

Bali is a tropical island in Indonesia, located at coordinates 8°39′S and 115°13′E, covering an area of 5.780 km^2, and is the origin of Bali Cattle (*Bos javanicus*). This breed evolved from cattle brought by early military settlers over a hundred years ago (Bell et al., 1990), and is now extinct in west Malaysia, Bangladesh and India, whilst the population is declining on the Asian mainland (Sansinena et al.,

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2005). Bali Cattle are important to the cattle industry in Indonesia and Malaysia because they are well adapted to the tropics, highly efficient at utilizing low quality of feed, and reproduce easily (Lindsay and Entwistle, 2003). They exhibit high resistance to disease and are easy to handle (Lisson et al., 2010). Furthermore, the percentage of meat from the carcass of Bali Cattle is high, and meat is of good quality. The continued breeding of Bali cattle is considered vital to beef production in Indonesia (Sarsaifi et al., 2015), and is being promoted through a government program that supports Bali Cattle breeding on Bali to export calves across South-East Asia. The integrated farming system program introduced on Bali in January 2012 by the local government has led to the establishment of 752 registered Bali Cattle breeding units as of December 2017. Each unit consists of 21 Bali cattle (20 cows + 1 Bull) and includes a 6 m^3 fixed-dome anaerobic digester (AD) for processing of cattle dung into organic fertiliser whilst minimising odour. The primary objective was initially to improve manure management and nutrient cycling on cattle farms. Due the lack of convenient and affordable energy conversion technologies, biogas is released directly to the atmosphere, despite the lack of energy supply for these remote farms mostly located off-grid. This has become a significant source of greenhouse gas (GHG) emission in Bali, owing to the potency of methane contained in the biogas as a GHG.

1.2. Small scale anaerobic digestion

Small scale anaerobic digestion can be an environmentally efficient management option for livestock manures and other wet organic wastes, promoting nutrient cycling and providing a useful fuel in the form of biogas, contributing to climate mitigation and energy security (Boulamanti et al., 2013; Hou et al., 2017; Styles et al., 2016). There are over 40 million small scale domestic anaerobic digesters in China alone (Zuzhang, 2013). The simple small-scale biogas systems used by the cattle breeding units in Bali are similar to the rural household biogas (RHB) systems widely used in China (Hou et al., 2017), can be managed with little maintenance effort, and can be easily integrated into farm systems to improve their sustainability (Song et al., 2014). The small-scale biogas systems in Bali benefit from the tropical climate, which avoids the need for stirring or heating, therefore negating the parasitic energy or external energy demand required for RHB units in China (Hou et al., 2017). Another difference is that Bali units digest only cattle manure, and have no link to household organic waste management. Nonetheless, AD treatment of the manure can produce a high-quality fertilizer that can be used to replace synthetic fertilizer, and also reduces odour and diseases arising from management of livestock manure (Chen et al., 2010; Christiaensen and Heltberg, 2014; Vu et al., 2015; Wang et al., 2007). A major challenge for small-scale AD units is that it is expensive to purify and compress biogas into more versatile biomethane that can be stored and transported to points of demand, resulting in inefficient use of unprocessed biogas which may simply be vented to the atmosphere (Zuzhang, 2013). Owing to the high global warming potential of methane (IPCC, 2015), fugitive emissions of biogas from anaerobic digesters can negate any climate mitigation potential, and may increase overall anthropogenic GHG emissions causing climate change (Liebetrau et al., 2010; Styles et al., 2015). This issue is increasingly recognised and quantified for digesters in industrialized countries (Liebetrau et al., 2017), but there has so far been little quantification of the extent of biogas venting in developing countries.

1.3. Rural energy security

Indonesia is a large exporter of coal, though exports of petroleum products are declining and the country relies heavily on coal for its GHG-intensive electricity generation whilst being increasingly dependent on imported oil and spending a considerable amount of public money subsidising consumer energy prices (IEA, 2015). Meanwhile, lack of grid infrastructure poses a barrier to electricity provision in rural regions, as is typical across developing countries (IEA, 2018; Mandal et al., 2018). Indonesia's energy policy includes plans for expansion in renewable energy generation, and will rely on large investment in the transmission grid, alongside investment in geothermal, solar and wind generating capacity (IEA, 2015). There is an urgent need to find cost-effective methods of electricity generation in rural areas, which is likely to include decentralised and hybrid technologies (Mandal et al., 2018). Using Bali as a case study, this paper describes the performance and environmental sustainability of a novel, compact and versatile mini-generator that can be transported among small-scale anaerobic digesters to convert biogas into electricity, potentially enhancing climate change mitigation and energy security in rural areas.

1.4. Bioelectricity from biogas

Hydrogen sulfide (H_2S) impurities in biogas result in rapid degradation of engine oils and can result in premature failure of internal combustion engines. During combustion, H_2S is oxidised to sulfur dioxide that will corrode metal components such as valves and spark plugs and cause the lubricant oil to become acidic. In order to avoid this problem, H_2S must be reduced to negligible concentrations in the biogas before combustion (Deublein and Steinhauser, 2008; Nindhia et al., 2013). The BioMiniGen has been designed specifically to utilize the small quantities of biogas produced by the aforementioned AD systems in Bali (Surata et al., 2014), and comprises the following innovative components: (i) a biogas desulfurizer; (ii) a carbon dioxide (CO_2) remover; (iii) a pre-combustion mixer for biogas, oil and air. The benefit of using a two-stroke engine is mechanical simplicity, enabling compact, lightweight design for portable use at a reasonable price compared with four-stroke engines. Unlike four-stroke engines, two-stroke engines do not have intake and exhaust valves that are particularly susceptible to corrosion by sulfide impurities, causing loss of compression. Another advantage of the two-stroke design is that the lubricant oil does not remain in the crankcase, but is combusted, thus avoiding the major problem of acidification of lubricant oil in four-stroke engines running on biogas (Deublein and Steinhauser, 2008) (any residual H_2S in biogas that by-passes desulfurization accumulates in lubrication oil, then oxidises to SO_2 that reacts with moisture to became highly corrosive sulphurous acid (H_2SO_3)).

Biogas yields in small scale digesters are highly variable. Recently, measured biogas yields in small scale Bangladeshi digesters (Rahman et al., 2019) were found to be significantly below previously estimated values (Rahman et al., 2018). Whilst the design of the BioMiniGen unit has been described in previous papers (Nindhia et al., 2013; Surata et al., 2014), this paper presents new data on operational performance of the unit and on biogas yields from Bali's farm digesters. This information is integrated into a full LCA to calculate the net environmental and energy security outcomes that could be realised from BioMiniGen deployment across all 752 small scale biogas digesters in Bali.

2. Material and method

This study was based on techno-economic and attributional LCA of BioMiniGen deployment. Detailed methodologies are described below. Gas volumes are expressed as Normal m^3 (Nm^3), at 273 K and standard atmospheric pressure (1.013 bar). Specifically for methane (CH_4), a density of 0.716 kg Nm^{-3} and a lower heating value (LHV) of 50 MJ kg^{-1} are applied (Engineering Toolbox, 2020).

2.1. Goal, scope and boundaries

The goal of this study was to assess the technical performance and environmental balance of BioMiniGen deployment to generate electricity from biogas produced by digesters installed across Bali farms. The method employed for this evaluation was attributional life cycle assessment (LCA) with expanded boundaries (Styles et al., 2018) to account for avoided release of biogas into the atmosphere (Fig. 1). Given that vast majority of Bali cattle farms are located off-grid, electricity generated through deployment of the BioMiniGen is likely to be "new", representing a valuable energy supply for these farms, rather than offsetting existing grid electricity generation. Therefore, the environmental footprint of one kWh of electricity generation (functional unit) from the BioMiniGen was benchmarked against the reference system of average Indonesian grid electricity generation and against a potential future reference system of small-scale solar photovoltaic electricity generation.

In addition to avoided venting of biogas, LCA boundaries captured the manufacture of the BioMiniGen unit, biogas storage bags, transport among Bali cattle farms and consumable chemicals needed to purify the biogas, as described in subsequent sections. We extracted data from Ecoinvent v3.5 via OpenLCA v1.7.4, using Product Environmental Footprint (PEF) life cycle impact assessment methodology (JRC, 2018). Data were normalised against per capita global burdens summarised in the latest PEF guidelines (JRC, 2018) to generate dimensionless and comparable normalised scores across impact categories.

2.2. Characteristics of small-scale biogas systems

Fig. 2 presents the small-scale biogas system used on Bali Cattle farms in Indonesia, comprising a fixed-dome anaerobic digester with a volume of approximately 6 m^3, including the hemi-spherical cap. There are 752-registered units of biogas digester in Bali, each of which treats manure from 21 cattle (20 cows + 1 Bull). Operational data were obtained from a typical biogas digester in the centre of Bali island during July 2018 (Fig. 2). Manure throughput was measured at 0.164 m^3 per day on average, mixed with 0.164 m^3 water, resulting in 120 m^3 yr^{-1} throughput. The digestate exiting the anaerobic digester is directed to a drying pool where it is dried prior to being composted to produce organic fertilizer. Each AD unit produces 0.50 Nm^3 day^{-1} of biogas with a composition (by volume) of 55% CH_4, 45% CO_2, and 100 ppm H_2S. This biogas is regarded as a waste owing to the impracticality of using it as a fuel in rural settings with currently available technologies, and is therefore simply vented to the atmosphere. The specific biogas yield is 0.00305 Nm^3 kg^{-1} fresh dung, which is very low compared with measured biogas production of 0.021 m^3 kg^{-1} fresh dung for cattle manure in small (2–10 m^3 day^{-1} biogas production) dome digesters in Bangladesh (Rahman et al., 2019). Assuming a volatile solids content of approximately 0.29 kg per kg fresh dung, biogas yields in modern European AD units would be approximately 0.050 Nm^3 kg^{-1} fresh manure (FNR, 2012). Very low measured biogas yield could reflect crusting of the substrate within the dome digesters, which are not cleaned owing to lack of demand for the biogas. Therefore, default modelling of GHG mitigation was based on avoidance of measured biogas production of 0.50 Nm^3 per unit per day, but electricity generation was also modelled for biogas yields of 3.44 Nm^3 per unit per day expected in typical, properly maintained (cleaned) dome digesters (Rahman et al., 2019) receiving 0.164 m^3 day^{-1} manure. High variability in biogas production, and the limitation of relying on biogas yield data from a single sampled digester, was represented by including an uncertainty range of ±50% (Rahman et al., 2019).

The BioMiniGen unit has been fully described in previous papers (Nindhia et al., 2013; Surata et al., 2014). The unit weighs approximately 20 kg, with a height of 0.35 m, a length of 0.40 cm, and a width of 0.35 m; thus it is small and light enough for good mobility. Major system components are summarised below.

2.3. Desulfurizer

The desulfurizer used in the BioMiniGen unit is made from waste steel cuttings. Only spiral, spring and long strands of steel cutting are selected. The cuttings are annealed at 900 °C with slow cooling to release the residual stress. Oxidation during annealing yields Fe_2O_3 and also $Fe(OH)_3$. One kg of steel cuttings is compacted into a single billet of 0.05 m diameter under a pressure of 3 tonnes. A desulfurizer for a single BioMiniGen unit contains 5 billets comprising 5 kg steel cuttings. Desulfurization proceeds according

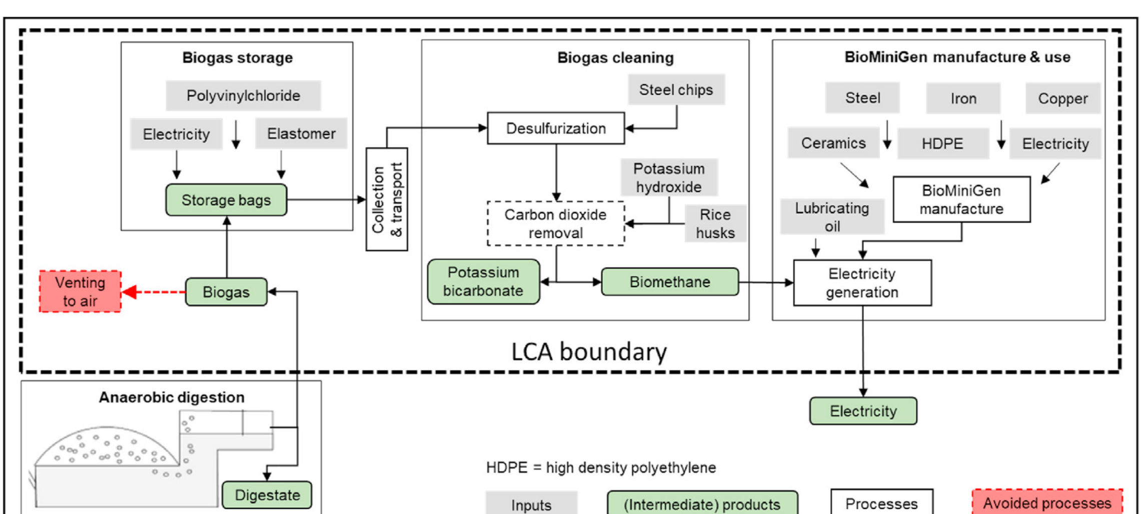

Fig. 1. Processes considered within the system boundary of the life cycle assessment.

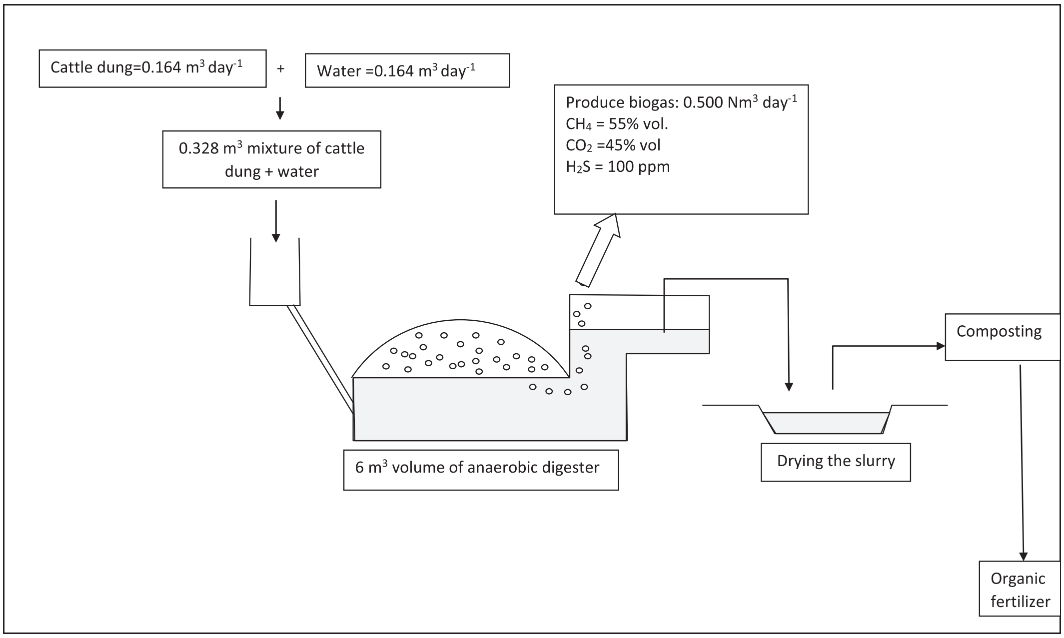

Fig. 2. Schematic of small-scale biogas system in Bali, Indonesia. The digester is filled with 0.164 Nm^3 of cattle dung per day from 21 Bali cattle, and produce 0.50 Nm^3 biogas per day under current conditions.

to the following three reactions (Jiang et al., 2011; Nindhia et al., 2013):

$$2Fe(OH)_3 + 3H_2S \rightarrow Fe_2S_3 + 6H_2O \quad (1)$$

$$Fe_2O_3 + 3H_2S \rightarrow Fe_2S_3 + 3H_2O \quad (2)$$

The final output from the desulfurization processes is a precipitate of Fe_2S_3 and water on the surface of the iron oxide, which over time reduces the desulfurization efficacy of the billets. To recover desulfurization efficacy, the reaction in Equation (3) is initiated and sulfur removed by flushing the desulfurizer with water every three months.

$$2Fe_2S_3 + 3O_2 + 6H_2O \rightarrow 4Fe(OH)_3 + 6S \quad (3)$$

2.4. Carbon dioxide remover (CDR)

This is an optional step that can improve combustion efficiency and sequester CO_2 (prevent the release of biogenic CO_2 in biogas back into the atmosphere). The biogas is purified from CO_2 (45% of biogas volume) prior to combustion by using granulates of potassium hydroxide (KOH), following the reaction described in Equation (4). A mixture of 25% granulated KOH and 75% (by mass) rice husk (rice hulls) is used as a carbon dioxide remover (CDR). The mixed rice hulls avoid agglomeration of Potassium bicarbonate ($KHCO_3$) (Eq. (4)) so that biogas can continuously pass through the CDR for purification. During purification, heat from the exothermic process is dissipated using a water jacket around the CDR pipe. Approximately 1.5 kg of KOH is needed to purify 0.50 Nm^3 of biogas containing 45% CO_2, at 40–50 °C and standard atmospheric pressure.

$$KOH + CO_2 \rightarrow KHCO_3 \quad (4)$$

2.5. Two-stroke engine

A standard two-stroke engine was adapted to run on biogas as well as gasoline, based on the innovative integration of the carburettor with an air-oil-biogas mixer (Fig. 3). The engine type is single cylinder (63 cc) with air-cooling. The compression pressure was set to reach 10 bar (1000 kPa) in order to be operated both with biogas or gasoline. The rated current of the coupled generator is 2.9 A, voltage result: 220–260 V/50 Hz/1Ph, maximum output is circa 750 W.

When the engine is fuelled with biogas, the hand control valve (1 and 2 in Fig. 3) is opened to let the lubricant oil and biogas flow to the distribution pipe (4). The hand-control valve for air (3) is set to open with adequate air for the combustion of biogas to occur. The choke valve (5) is left open to let the mixture of air-oil-biogas to freely pass the carburettor. The flow is induced by suction from the engine during starting. After the engine is running the throttle (7) is set to obtain the required output (220 V). Alternatively, when the engine is fuelled with gasoline, the hand-control valves for lubricant oil (1) and biogas (2) are closed. The hand-control valve for air (3) is fully open to let air fully enter the carburettor. The choke (5) is closed for a moment during starting to let the mixture of gasoline and lubricant oil enter the ventury (6). Once the engine is running, the choke (5) is fully open to let the air mix with gasoline and lubricant-oil. The throttle (7) is set to keep the engine running at a speed sufficient to produce the required 220 V.

2.6. Deployment scenarios

Research was undertaken to compare performance of the two-stroke engine with two types of biogas pre-treatment: (i) biogas purified from H_2S only (Method 1); (ii) biogas purified from both H_2S and CO_2 (Method 2) (Fig. 4). The latter case “sequesters” CO_2 into potassium bicarbonate (see Eq. (4)). Measured performance for Method 1 translates into net daily electrical output of 0.475 kWh from 0.50 Nm^3 biogas, representing a conversion efficiency of 17% in relation to the lower heating value (LHV) of the biogas (0.275 m^3

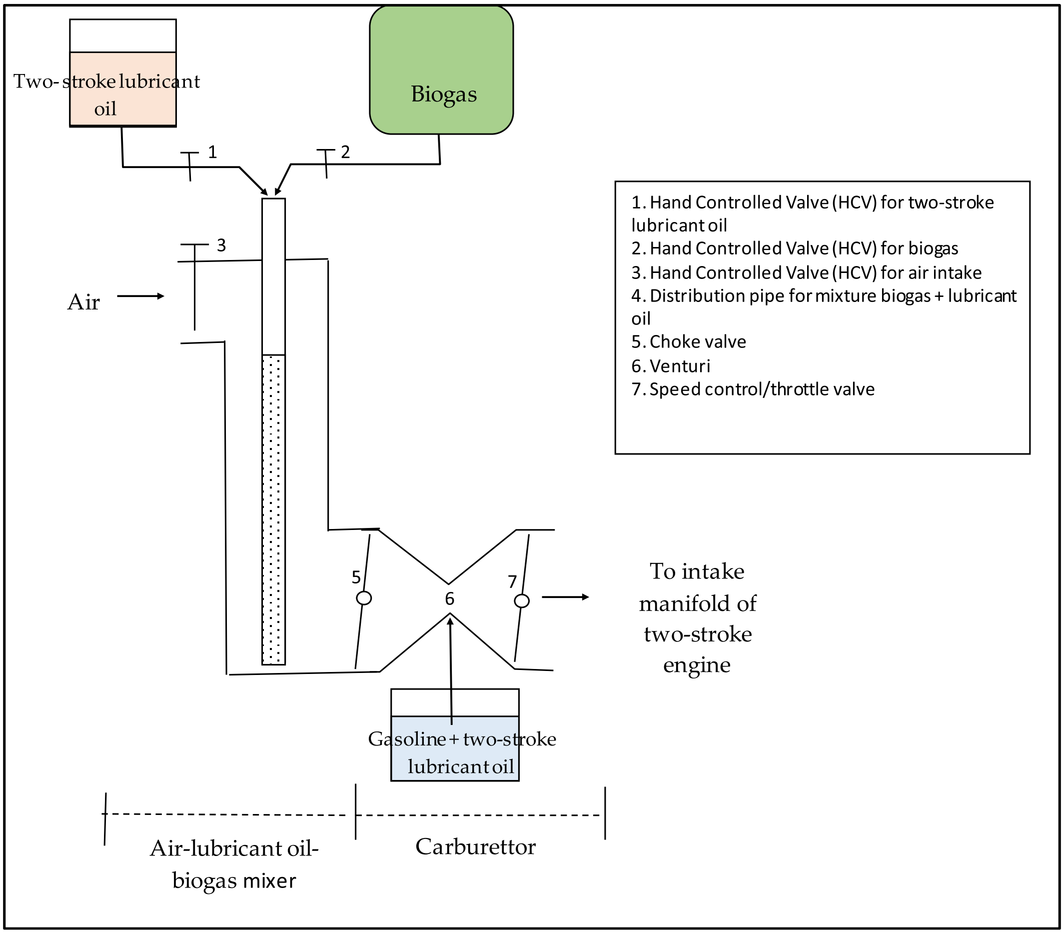

Fig. 3. Schematic combination of air-oil-biogas mixer with carburettor to enable a two-stroke engine to run using either biogas or gasoline.

CH_4 = 0.196 kg CH_4 = 9.84 MJ LHV: Engineering Toolbox, 2020), and an operating time of just over 38 min per digester per day.

In order to evaluate the full potential environmental effects of biogas utilization in the BioMiniGen unit, we considered three scenarios in which biogas was collected from all 752 Bali Cattle farms, based on extrapolation of performance for the described typical system. Scenarios represented combinations of Methods 1 & 2 (Fig. 4) at current or enhanced (following digester cleaning) biogas yields (Table 1).

A reference flow of five years of operation (conservative estimate of equipment operating lifetime) of a single MiniBioGen unit was considered, with the following assumptions to represent plausible deployment: (i) one BioMiniGen unit per farm in Sc-3, and one unit shared across 5 farms in Sc-1/Sc-2, transported an average distance of 1 km between farms by motorbike with trailer every other day. These scenarios were extrapolated up to a technical potential deployment across all 752 Bali cattle rearing farms.

2.7. Life cycle inventory data

The inventory of major inputs and outputs (activity data) for five years of operation of one BioMiniGen unit is itemized in Table 2. Note that one generator serves five farms in Sc-1 and Sc-2, and one farm in Sc-3, so that although electricity generation is increased in Sc-3 to represent higher CH_4 yields, avoided CH_4 venting per generator is just one fifth of that in Sc-1 and Sc-2 (Table 2). These activity data were multiplied by environmental burdens for corresponding unit processes obtained from Ecoinvent v3.5 (allocation at point of substitution database) (Wernet et al., 2016) based on the PEF method (JRC, 2018). Physical (energy-based) allocation was selected to allocate system burdens across co-products where necessary in upstream processes.

3. Results

Key results are summarised in Tables 3-4 and Figs. 5–6, with additional tabulated details provided in Tables S1–S3 within a supplementary information file. Main points are described below.

3.1. BioMiniGen performance

As presented in Fig. 2, the existing situation gives rise to direct venting to the atmosphere of 0.5 ± 0.25 Nm^3 of biogas per day from each anaerobic digester, containing 55% CH_4. Capturing and combusting the CH_4 contained in the biogas converts it to biogenic CO_2, with a GWP of 0, avoiding 1809 or 362 kg CH_4 venting over the operational lifetime of a BioMiniGen unit at low (Sc-1/Sc-2) or high (Sc-3) biogas yields. Measured biogas fuel consumption of 0.013 Nm^3 desulfurized biogas per minute generates 0.475 kWh per digester per day under current biogas yields (Sc-1), or 3.27 kWh per digester per day assuming higher biogas yields following digester cleaning (Sc-3) (Fig. 4). Thus, over a five year operating life, each BioMiniGen running on biogas generates between 4334 (Sc-1) and 5971 (Sc-3) kWh. Deployment of the CDR to remove biogenic CO_2 from the biogas prior to combustion could act as a form of bioenergy carbon capture and storage (BECCS), by “sequestering”

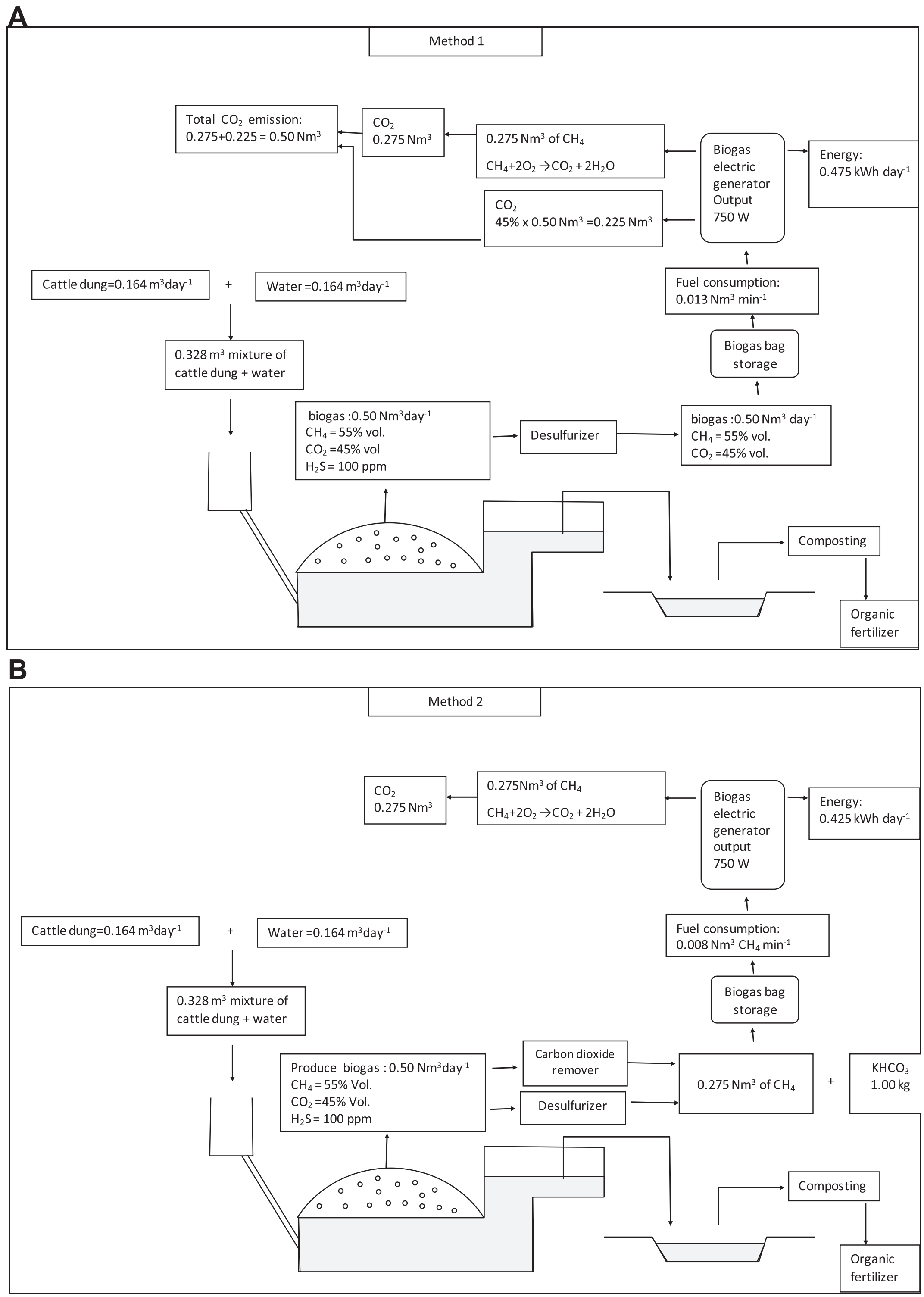

Fig. 4. Schematic representation of mass balance for operation of BioMiniGen unit using biogas that has been desulfurized (top, Method 1) or both desulfurized and scrubbed of carbon dioxide (bottom, Method 2) prior to fuelling the two-stroke engine linked with electric generator.

Table 1
Summary of scenario permutations considered for BioMiniGen (BMG) deployment.

Scenario	Digester cleaning	Biogas yield	Avoided biogas release	CO_2 removal	Daily BMG operating time (mins)
1	No	Measured	Measured	No	190
2	No	Measured	Measured	Yes	172
3	Yes	Rahman et al. (2019)	Measured	No	262

Table 2
Inventory of activity data for the reference flow of five years of operation of one BioMiniGen unit across the three scenarios.

Stage or process	Input or output	Unit	Quantity		
			Sc-1	Sc-2	Sc-3
Engine & generator manufacture (BioMiniGen units with five year lifetime)	Steel	kg	2.0	2.0	2.0
	Iron	kg	1.0	1.0	1.0
	Aluminium	kg	10	10	10
	Copper	kg	5.0	5.0	5.0
	Plastic HDPE	kg	0.7	0.7	0.7
	Injection moulding	kg	0.7	0.7	0.7
	Ceramic	kg	0.3	0.3	0.3
	Polymer + Elastomer	kg	1	1	1
Biogas storage bags manufacture	PVC	kg	50	50	70
	Blow moulding	kg	50	50	70
Transport	Motorcycle-trailer	km	4563	4563	0
Desulfurization	Steel chips	kg	5	5	5
	Annealing	kg	5	5	5
CO_2 removal	Potassium hydroxide	kg	0	13 688	0
	Rice husk	kg	0	41 063	0
	Biogenic CO_2 removal	kg	0	−4033	0
Combustion	Lubricating oil	kg	60	60	83
	Fuel energy LHV	MJ	90 438	90 438	123 930
Electricity generation	Electricity generated	kWh	4334	3878	5971
Avoided CH_4 venting	Avoided CH_4 emission	kg	−1809	−1809	−362

Table 3
Environmental burdens per kWh of electricity generated by the BioMiniGen unit in Sc-1 to Sc-3, compared with burdens per kWh of Indonesian grid electricity (reference system) or solar photovoltaic (SPV). Red-shading indicates larger burdens for BioMiniGen electricity than reference (grid) electricity.

Impact category	Unit	Grid elec.	Sc-1		Sc-2		Sc-3		SPV elec	
Abiotic resource depletion	kg Sb eq.	**7.9E-08**	4.5E-06	5546%	5.7E-05	72049%	3.1E-06	3782%	3.4E-06	4251%
Acidification	Mol. H+ eq.	**5.9E-03**	2.2E-03	-63%	5.4E-02	802%	1.4E-03	-76%	5.7E-04	-90%
Fossil resource depletion	MJ eq.	**1.1E+01**	5.0E+00	-56%	1.1E+02	877%	3.2E+00	-72%	8.6E-01	-92%
Freshwater ecotoxicity	CTU eq.	**1.0E+01**	9.0E+00	-11%	9.3E+01	817%	6.3E+00	-38%	6.6E+00	-35%
Freshwater eutrophication	kg P eq.	**1.5E-03**	2.3E-04	-85%	4.8E-03	213%	1.7E-04	-89%	7.2E-05	-95%
Human toxicity, cancer effects	CTUh eq.	**1.1E-07**	4.1E-08	-62%	6.4E-07	497%	2.9E-08	-73%	1.1E-08	-89%
Human toxicity, non-cancer effects	CTUh eq.	**3.6E-07**	4.3E-07	19%	3.8E-06	978%	3.0E-07	-16%	9.8E-08	-72%
Ionizing radiation HH	kBq U235 eq.	**1.4E-02**	2.8E-02	101%	7.9E-01	5608%	1.8E-02	27%	9.2E-03	-34%
Global warming potential	kg CO_2 eq.	**1.0E+00**	-1.5E+01	-1500%	-8.2E+00	-881%	-2.0E+00	-290%	7.7E-02	-93%
Marine eutrophication	kg N eq.	**1.4E-03**	3.7E-04	-74%	9.5E-03	577%	2.1E-04	-85%	1.0E-04	-93%
Ozone depletion	kg CFC-11 eq.	**4.7E-08**	4.4E-08	-5%	5.8E-07	1138%	2.4E-08	-48%	9.6E-09	-79%
Photochemical ozone formation	kg NMVOC eq.	**3.1E-03**	5.5E-03	75%	3.2E-02	907%	2.4E-03	-23%	3.1E-04	-90%
Terrestrial eutrophication	Mol. N eq.	**1.2E-02**	3.9E-03	-68%	9.7E-02	708%	2.2E-03	-81%	9.3E-04	-92%

biogenic CO_2 as potassium bicarbonate salt (Eq. (4)), thus resulting in biogenic C sequestration of 4033 ± 2017 kg CO_2 over five years in Sc-2 (Table 2). Results of pilot trials found that fuel consumption was 0.008 Nm^3 of straight biomethane per minute to generate a constant output of 750 W from the electric generator, yielding 0.425 kWh per digester per day under current biomethane yields (Sc-2) (Fig. 4), or 3878 kWh over five years (Table 2).

Table 4
Key economic parameters related to deployment of a single BioMiniGen (BMG) unit over a five-year operational lifetime, including (equipment) cost per kWh and value of CO_2 abatement.

	MBG	Elec. Generated		Net CO_2 eq. avoided		
	$	kWh	$/kWh	Mg	$ ($20/t)	$ ($200/t)
Sc-1	500	4334	0.115	−65.1	−1302	−13023
Sc-3	500	5971	0.084	−11.9	−238	−2377

3.2. Environmental footprint of bio-electricity

Electricity generated from the measured yield of biogas (Sc-1) has a smaller environmental footprint than reference (Indonesian grid average mix) electricity across nine of the 13 impact categories considered (Table 3). Fig. 5 displays normalised scores across nine pertinent impact categories for electricity generated in Sc-1 to Sc-3 compared against grid electricity, and solar PV electricity based on Ecoinvent v3.5 data for “electricity production, photovoltaic, 3 kW slanted-roof installation multi-Si panel”. At higher biogas yields

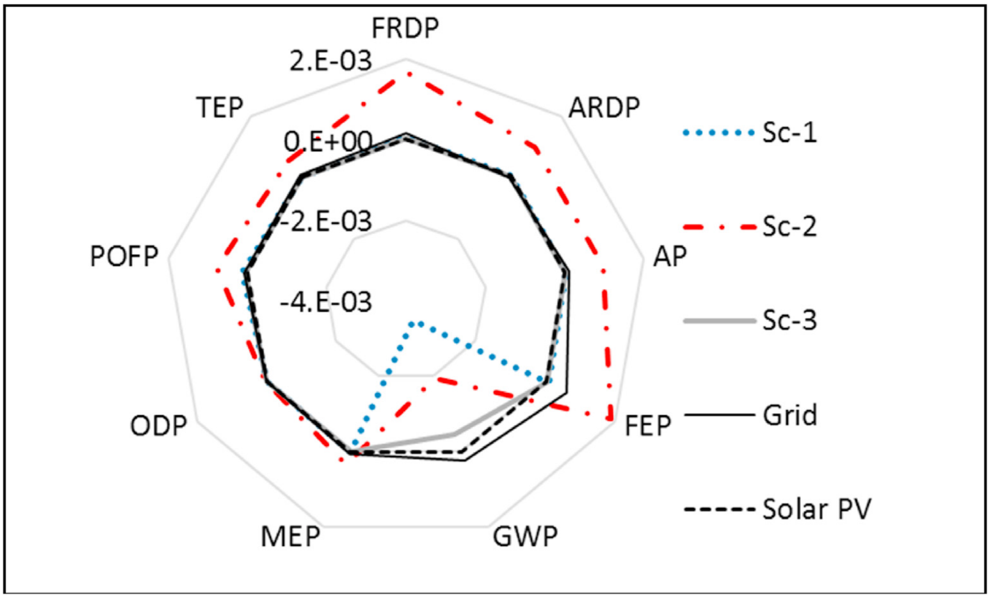

Fig. 5. Comparison of normalised scores across nine environmental impact categories (abiotic resource depletion potential, fossil resource depletion potential, acidification potential, freshwater eutrophication potential, global warming potential, marine eutrophication potential, ozone depletion potential, photochemical ozone formation potential and terrestrial ecotoxicity potential) for Sc-1 to Sc-3 and alternative electricity generation.

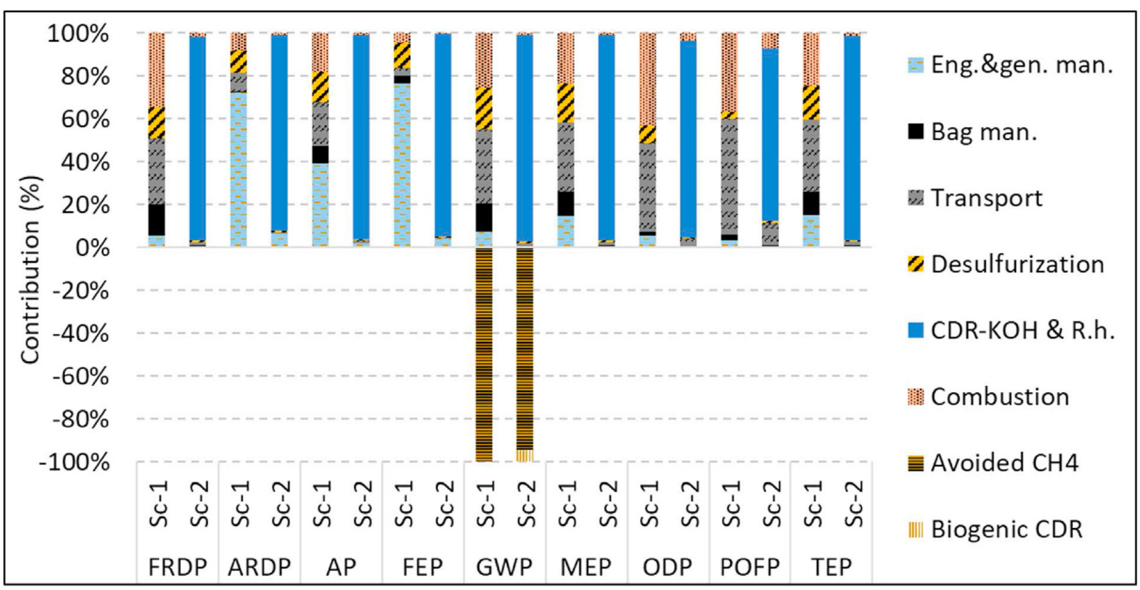

Fig. 6. Contribution of processes to environmental burdens (and burden avoidance) across nine environmental impact categories (abiotic resource depletion potential, fossil resource depletion potential, acidification potential, freshwater eutrophication potential, global warming potential, marine eutrophication potential, ozone depletion potential, photochemical ozone formation potential and terrestrial ecotoxicity potential) for Sc-1 & Sc-2. Processes include engine and generator manufacture, bag manufacture, carbon dioxide remover (CDR) with KOH & rice husk (R.h.), avoided CH_4 venting and biogenic CDR.

(Sc-3), bio-electricity incurs smaller burdens than grid electricity across 11 impact categories. However, deployment of the CDR incurs significant environmental burdens (Fig. 6), primarily from production of the large quantities of KOH required (Table 2), resulting in environmental underperformance compared with grid electricity, except for global warming potential (Table 3; Fig. 5). Whilst solar PV electricity generation displays the best overall environmental performance, biogas electricity generation is the only GHG-negative technology owing to avoided biogas venting. Every kWh of electricity generated in Sc-1 is associated with net abatement of 15 kg CO_2 eq., reducing to abatement of 2 kg CO_2 eq. in Sc-3 (Table 3) owing to a higher ratio of electricity generation to avoided biogas venting (Table 2).

Aside from GHG emissions, the main environmental advantages of biogas electricity relative to Indonesian grid electricity arise in the freshwater eutrophication and marine eutrophication impact categories (Fig. 5). Presumably this reflects high NO_x emissions from combustion of coal and oil that dominate Indonesia's grid electricity generation. Normalised scores indicate that Sc-2 makes a particularly large relative contribution to depletion of fossil resources (Fig. 5). In fact, generation of bio-electricity with CDR leads to nine times more fossil resource depletion than average grid electricity (Table 3), almost entirely attributable to the large quantities of fossil resources used to produce KOH (Table 2 & Table S2).

For standard biogas combustion (in the absence of environmentally-costly CDR), manufacture of the BioMiniGen unit is the main source of abiotic resource depletion and marine eutrophication burdens (Sc-1 in Fig. 6). Motorcycle transport across farms is an important contributor to most other impact categories (Fig. 6). Contributions are similar for Sc-3 (data not shown), except BioMiniGen burden shares are smaller and transport is not a relevant process (each farm has its own a BioMiniGen unit) − hence lower overall burdens for Sc-3 compared with Sc-1 (Table 3; Fig. 5). The annealing of steel chips for desulfurization and the manufacture of plastic bags for biogas storage contribute modest but significant shares of environmental burdens across most impact categories (Fig. 6). Rice husks were considered as a waste product in this analysis, but if they were treated as a co-product of rice cultivation, so that cultivation burdens were allocated to them on an energy basis, then the GWP savings reported for scenario 2 would be negated.

3.3. National scenario

In total, 130 ± 65 and 898 ± 449 MWh yr^{-1} of electricity is generated across the 752 digesters in Sc-1 and Sc-3, respectively. Partial economic analysis indicates that this electricity could be moderately more expensive than the average grid electricity price of US $0.094 in Indonesia (Statista, 2019) under very low biogas yields in Sc-1, whilst it could be competitive with grid electricity prices under higher biogas yields (Sc-3) (Table 4).

After accounting for life cycle GHG emission from BioMiniGen deployment, net GHG abatement associated with avoided biogas venting equates to 65.1 and 11.9 Mg CO_2 eq. per unit over five years. Based on near-term recommended carbon pricing of a few tens to a few hundreds of US$ per tonne of CO_2 (Tol, 2018), this would equate to an abatement value of between US$ 238 and US$ 13 023 per unit (Table 4). Cumulatively, the 752 anaerobic digesters across Bali Cattle farms emit 75 482 ± 37 741 m^3 CH_4 per year. Accounting for the global warming potential (GWP) of CH_4 i.e. 36 kg CO_2 eq. per kg CH_4 (IPCC, 2015; JRC, 2018), this represents a contribution of 1.96 Gg CO_2 eq. yr^{-1} to Indonesia's emission budget. Deployment of the BioMiniGen could effectively abate these emissions. Life cycle accounting for all GHG emissions associated with BioMiniGen deployment in Sc-1 indicates that net GHG abatement equates to 1.92 Gg CO_2 eq. yr^{-1}.

4. Discussion

The establishment of 752 anaerobic digesters across Bali cattle-breeding units has facilitated the management of cattle manure, reducing odour and producing valuable digestate biofertilizer. The biogas is not utilised owing to the cost and practicality of converting it into a useful energy form, in part because these farms are often located away from households, and also because conventional energy is still readily available at an affordable price (MEMRI, 2018). The implications of BioMiniGen deployment are discussed below.

4.1. Energy security and GHG mitigation

Biogas venting from simple anaerobic digestion systems is not uncommon in various countries, owing to e.g. storage constraints (Bond and Tempelton, 2011; Hou et al., 2017). However, venting of biogas, specifically the biomethane component, to the atmosphere, results in a significant contribution to Bali's GHG inventory (1.96 Gg CO_2 eq. yr^{-1}). This study demonstrates the technical viability of a modified two-stroke engine running on desulfurized biogas as a potential solution to this problem. In addition to neutralising the climate impact of biomethane by converting it to biogenic CO_2 (global warming potential = 0), widespread deployment of the two-stroke engine and generator could supply up to 898 MWh of electricity annually to rural Bali farms. This new supply of electricity could make an important contribution to rural energy and food security, powering e.g. water pumps needed to expand the irrigation network across Indonesia (Fao, 2018). Whilst this new bio-electricity is unlikely to offset any fossil fuel use in the short-term among largely off-grid farms, it could play an important role in a portfolio of decentralised renewable energy sources which could avoid the need for expensive rural extension of the centralised electricity grid (IEA, 2015). In particular, the dispatchable electricity generation provided by the BioMiniGen unit could usefully complement more intermittent electricity generation from renewable sources such as wind and solar (Bahrs and Angenendt, 2019), reducing the need for expensive battery storage. Previous studies have demonstrated that bioenergy can be a cheaper option for decentralised off-grid energy generation (Mahapatra and Dasappa, 2012). The ability to run on gasoline when biogas is not available further enhances the flexibility of the BioMiniGen unit to deliver full rural energy security.

Globally, 2.7 billion people rely on biomass (primarily wood) for cooking (Kaygusuz, 2012), whilst up to 1.4 billion people lack access to electricity, and the majority of populations in rural areas of developing regions of the world depend on traditional biomass in lieu of electricity (Muhumuza et al., 2018). This results in serious socio-economic consequences, including poor health from indoor air pollution and deforestation to provide wood fuel, that impede fulfilment of numerous UN sustainable development goals. Small-scale decentralised electricity generation can avoid some of the challenges associated with grid-based rural electrification, including expensive and unreliable grid infrastructure, lack of political will and institutional weaknesses (Muhumuza et al., 2018). Biogas is an excellent, renewable fuel source for rural areas in developing countries because it can be generated from a wide range of feedstocks, including manures, household food waste and sewage, and vegetation (Bond and Templeton, 2011). It can be used directly for cooking in stoves to reduce indoor air pollution (Lewis et al., 2017), potentially a lower cost conversion pathway compared with the BioMiniGen. However, there remains an urgent need for decentralised rural electricity generation to improve the lives of the 1.4 billion people who currently lack access to it. In fact, the BioMiniGen is ideally sized to satisfy the small electricity demand of rural households in developing countries. Muhumuza et al. (2018) cite an IEA analysis that shows newly electrified rural households each require just 250 kWh annually, increasing to 800 kWh yr^{-1} over five years. A single BioMiniGen could supply between one and ten households with this eve of demand.

4.2. Environmental co-benefits and trade-offs

Although this study did not apply weighting factors across environmental impact categories, normalised scores for bioelectricity generation from biogas suggests that GHG mitigation is the most significant environmental effect of the BioMiniGen system. Compared with grid electricity generation, bioelectricity also incurs smaller acidification, eutrophication and fossil resource depletion burdens per kWh of electricity generated. However, there are also a few trade-offs, including larger abiotic resource depletion, human toxicity and photochemical ozone formation (smog) burdens for bioelectricity, caused by manufacture of the motor and generator, motorcycle transport and annealing of steel chips needed for desulfurization. Normalised scores suggest that these trade-offs are comparatively minor when the biogas is used without CO_2 pre-treatment, compared with GHG mitigation and other co-benefits, suggesting that the overall environmental outcome of deploying BioMiniGen units to utilize biogas in Bali would be positive. Notably, many of these upstream impacts associated with component manufacture may arise outside of Bali, and possibly also outside of Indonesia, thus not contributing to territorial (inventoried) emissions and impacts. Ultimately, some of these trade-offs could be mitigated through use of recycled materials in the motor and generator (Yellishetty et al., 2011), and through measures to improve the efficiency of the annealing process. Such measures could also close the gap between bioelectricity and solar PV across the majority of impact categories where solar electricity has a smaller environmental footprint.

The use of annealed steel chips provides a simple, affordable option to desulfurize biogas so that hydrogen sulfide impurities do not cause rapid engine corrosion, but slightly offsets the net fossil energy and GHG mitigation potential of the generated bioelectricity. However, additional treatment of the biogas to remove biogenic CO_2, whilst enhancing direct GHG mitigation by up to 6%, dramatically increased upstream emissions and fossil energy use associated with potassium hydroxide production, reducing overall GHG mitigation and negating any life cycle fossil energy depletion benefits compared with grid electricity. Thus, we conclude that the additional cost and environmental impact of removing biogenic CO_2 from the biogas is not worthwhile. This reflects high costs found for larger scale carbon capture and storage systems, hitherto (Leung et al., 2014).

4.3. Deployment potential

Lahimer et al. (2013) reviewed the challenges facing economic deployment of decentralised electricity generation in developing countries from diesel generators, wind, solar PV and pico-hydro power, but did not consider biogas. As mentioned above, biogas is an excellent energy source in rural areas owing to the diverse range of feedstocks that can be used to produce the multitude of conversion pathways it is suited to (from simple stove cooking, through electricity generation to transport fuel). Various types of engine can be fuelled with biogas (Surata et al., 2014). One example is the external combustion Stirling engine (Zhu et al., 2018), though it can be complex to adapt for small scale biogas systems (Colmenar-Santos et al., 2016). A major downside of most engines is that they are large, heavy and expensive to manufacture (Paul and Engeda, 2015) compared with the compact two-stroke engine design used in the BioMiniGen unit. The proposed BioMiniGen unit is portable and user-friendly, providing a convenient option for energy conversion that can be shared among many farms, thus improving affordability. The partial economic analysis undertaken here suggests that, whilst potentially being moderately more expensive than grid electricity under low biogas yields, electricity generation with the BioMiniGen could be less expensive than alternative off-grid solutions such as a hybrid wind-solar-diesel system evaluated for rural Bangladesh that generates electricity at a cost 0.37$/kWh (Mandal et al., 2018). There remains a need for a full economic evaluation of BioMiniGen deployment, considering maintenance costs and, in the case of sharing among farms, transport costs. Mass uptake would likely require policy support, e.g. in the form of subsidies and/or regulation of biogas venting, along with support for adequate maintenance (Bond and Templeton, 2011). From a policy perspective, any economic evaluation should include a cost-benefit analysis of GHG mitigation achieved per dollar spent. Analysis presented in this paper demonstrates that the economic value (avoided social costs) of net GHG mitigation over the operational lifetime of BioMiniGen units is likely to be considerably greater than their purchase price. This would suggest that modest subsidies for deployment could be highly cost-effective in terms of climate policy. Purchasing a BioMiniGen unit would make most financial sense for farmers where biogas yields realised from the digested cattle dung are close to or above average (Rahman et al., 2018, 2019; Saitawee et al., 2014). In order to realise such yields, the biogas digesters installed in Bali cattle farms since 2012 are likely to require substantial cleaning to remove the thick layers of scum likely responsible for very low biogas yields measured in this study. Successful deployment of BioMiniGen technology may therefore require effective dissemination of best practice guidance, e.g. via agricultural extension services, alongside targeted financial support. Whilst deployment of simple biogas systems has been demonstrated over decades in countries such as China and India, there has been a failure to successfully deploy such systems more widely across other developing countries – despite their potential advantages for energy security. Bond and Templeton (2011) report that up to 50% of biogas plants are non-functional owing to inadequate maintenance, and that operational support networks will need to be established alongside infrastructure in order for deployment to be successful.

4.4. Limitations and further study

The technical performance of the BioMiniGen unit has been well established in testing since initial development (Surata et al., 2014). However, this study relied on somewhat uncertain biogas yield data from a single sampled digester on Bali, applying sensitivity analysis to account for variable biogas yield potential. Pilot trials of BioMiniGen deployment across a random sample of biogas digesters could provide more certainty on the electricity generating capacity and GHG abatement potential of farm biogas on Bali, underpinning development of a robust business model for deployment. Such a pilot trial would highlight any practical barriers to wider deployment small-scale rural digesters globally. Key aspects that require further investigation include:

- Biogas yields (venting) across digesters
- Biogas leakage rate from capture and storage in large bags (or alternative storage systems)
- Logistical optimisation of BioMiniGen deployment in terms of numbers of farms served by a single unit (depending on spatial distribution of farms), timing and use of generated electricity
- Optimal management of digestate to minimise ammonia emissions and maximise nutrient uptake in crops or grass for cattle
- Design of policy incentives that reflect the social value of avoided methane venting

5. Conclusion

The environmental sustainability of small-scale anaerobic digestion can be undermined owing to limited options for effective use of the low-grade, unprocessed biogas fuel, which may result in venting to the atmosphere, contributing to climate change. It is expensive to purify and compress biogas into more versatile biomethane, and small-scale rural digesters risk being abandoned owing to difficulty maintaining efficient operation. Bali island in Indonesia perfectly illustrates this challenge via current operation of 752 small scale (6 m^3) digesters that were recently installed under an initiative to improve the management of cattle manure. It is not currently practical to use the 75 482 ± 37 741 m^3 CH_4 vented from these predominantly remote rural digesters, resulting in an annual contribution to Bali's annual GHG inventory of 1.96 ± 0.98 Gg CO_2 eq. This study evaluated the performance of a novel, versatile "BioMiniGen" system that could provide a cost-effective and convenient way for farmers to generate electricity from these digesters. The BioMiniGen unit comprises: (i) a simple biogas desulfurizing system; (ii) a two-stroke, single cylinder (63 cc) air-cooled engine; (iii) an electric generator; (iv) an optional CO_2 removal unit. Lifecycle assessment indicated that bioelectricity generated by such a unit would have a smaller environmental footprint than Indonesian grid electricity across 11 impact categories, including a negative global warming burden owing to avoidance of biogas venting. However, there were a few trade-offs, such as increased abiotic resource depletion potential associated with manufacture of the BioMiniGen units. Over a five-year lifetime, each US$500 BioMiniGen unit could generate up to 5971 kWh of electricity and mitigate up to 65.1 Mg CO_2 eq., with a climate mitigation value somewhere between US$238 and US$13023. Across Bali, up to 898 $\pm$ 449 MWh yr^{-1} bioelectricity could be generated, and 1.92 $\pm$ 0.96 Gg CO_2 eq. saved. Policy support to stimulate deployment of this technology is therefore likely to be cost-effective if projected energy security and climate mitigation benefits can be realised in practise. Pilot trials would be useful to ascertain this. More widely, this technology has huge potential to contribute towards improved energy security for the 1.4 billion people globally who lack access to electricity in rural areas of developing countries.

CRediT authorship contribution statement

Tjokorda Gde Tirta Nindhia: Conceptualization, Methodology, Investigation, Writing - original draft, original draft, Writing - review & editing, review & editing. **Morag Mc Donald:** Supervision, Writing - review & editing, review & editing. **David Styles:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, original draft, review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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